Geological Society, London, Special Publications

The oldest rocks on Earth: time constraints and geological controversies

Balz S. Kamber, Stephen Moorbath and Martin J. Whitehouse

Geological Society, London, Special Publications 2001, v.190;
p177-203.
doi: 10.1144/GSL.SP.2001.190.01.13

The oldest rocks on Earth: time constraints and geological controversies

BALZ S. KAMBER[1], STEPHEN MOORBATH[2] & MARTIN J. WHITEHOUSE[3]

[1] *Department of Earth Sciences, University of Queensland, Brisbane, Queensland 4072, Australia*
[2] *Department of Earth Sciences, University of Oxford, Oxford OX1 3PR, UK* (*e-mail*: stephen.moorbath@earth.ox.ac.uk)
[3] *Laboratory of Isotope Geology, Swedish Museum of Natural History, Box 50007, SE – 10405 Stockholm, Sweden*

Abstract: Ages in the range 3.6–4.0 Ga (billion years) have been reported for the oldest, continental, granitoid orthogneisses, whose magmatic precursors were probably formed by partial melting or differentiation from a mafic, mantle-derived source. The geological interpretation of some of the oldest ages in this range is still strongly disputed.

The oldest known supracrustal (i.e. volcanic and sedimentary) rocks, with an age of 3.7–3.8 Ga, occur in West Greenland. They were deposited in water, and several of the sediments contain ^{13}C-depleted graphite microparticles, which have been claimed to be biogenic.

Ancient sediments (*c.* 3 Ga) in western Australia contain much older detrital zircons with dates ranging up to 4.4 Ga. The nature and origin of their source is highly debatable. Some ancient (magmatic) orthogneisses (*c.* 3.65–3.75 Ga) contain inherited zircons with dates up to *c.* 4.0 Ga. To clarify whether zircons in orthogneisses are inherited from an older source region or cogenetic with their host rock, it is desirable to combine imaging studies and U-Pb dating of single zircon grains with independent dating of the host rock by other methods, including Sm-Nd, Lu-Hf and Pb/Pb.

Initial Nd, Hf and Pb isotopic ratios of ancient orthogneisses are essential parameters for investigating the degree of heterogeneity of early Archaean mantle. The simplest interpretation of existing isotopic data is for a slightly depleted, close-to-chondritic, essentially homogeneous early Archaean mantle; this does not favour the existence of a sizeable, permanent continental crust in the early Archaean.

By analogy with the moon, massive bolide impacts probably terminated on Earth by *c.* 3.8–3.9 Ga, although no evidence for them has yet been found. By *c.* 3.65 Ga production of continental crust was well underway, and global tectonic and petrogenetic regimes increasingly resembled those of later epochs.

On the Earth's surface, crust must have been forming soon after accretion. There is apparently no direct record of these rocks, although detrital zircons of up to 4.4 Ga (billion years) have been found in much younger sedimentary rocks. The age of the oldest terrestrial rocks is therefore not an issue of rock formation but of rock preservation, and the oldest known rocks must have formed in a way that allowed their preservation. Study of cratonic lithospheric mantle shows that the present continents grew together with a buoyant lithospheric mantle keel that helped resist the destructive forces of mantle convection. The age of the oldest preserved terrestrial rocks is therefore closely connected with the magmatic and tectonic style that operated on Earth.

Estimates for the age of the oldest known in-situ terrestrial rocks approach the age of the so-called 'late heavy' meteorite bombardment experienced by the inner solar system (3.8–3.9 Ga). The earliest lunar surface (>4 Ga), although heavily cratered, has partly survived the late heavy meteorite bombardment so that, by analogy, the absence of in-situ terrestrial rocks exceeding 4.0 Ga cannot be entirely attributed to eradication by impact. However, the close approach of conservative estimates for the age of the oldest in-situ terrestrial rocks (*c.* 3.8 Ga) and the end of the heavy meteorite bombardment may not be fortuitous. During the impact regime, massive thermal release from the Earth may not have permitted (at least periodically) the existence of a liquid hydrosphere, which is a pre-requisite for plate tectonics and for the existence of a biosphere. In our view, the birth of plate tectonics and the creation of a biosphere

From: LEWIS, C. L. E. & KNELL, S. J. (eds). *The Age of the Earth: from 4004 BC to AD 2002*. Geological Society, London, Special Publications, **190**, 177–203. 0305-8719/01/$15.00

marked the time from which terrestrial rocks stood a good chance of being preserved.

Since publication of a previous review on the oldest terrestrial rocks (Moorbath *et al.* 1986), the research focus on the early Archaean geological record has broadened. While the exact growth history of the continents is still debated, the principal aim of many geochemical studies has shifted to establish whether the oldest terrestrial rocks carry a 'memory' of differentiation processes that might have occurred hundreds of millions of years before their formation. To this question has been added the issue of emergence of terrestrial life and the associated establishment of a permanent hydrosphere. Ratios of radiogenic isotopes are the most widely used tool to probe the time window for which there is no known rock record. Because these ratios are sensitive to accurate decay correction, establishing the correct age of the oldest rocks, as precisely as possible, is a prerequisite for meaningful geochemical studies. Most of the present controversies about the early Earth concern interpretation of isotope data, not the quality of the data. The age of the oldest terrestrial rocks has therefore lost none of its relevance.

In this review, we concentrate on the beginning of the observed geological and geochronological record, involving rocks older than 3.5–3.6 Ga. Most emphasis will be placed on the early Archaean (pre-3.6 Ga) rocks of southern West Greenland, which constitute the largest, most varied, best exposed and most closely investigated terrain of the oldest known terrestrial rocks.

Ancient rocks and modern dating methods

The oldest granitoid gneisses of magmatic origin (orthogneisses), widely regarded as typical of continental crust, are claimed to be in the range 4.0–3.6 Ga on several continents, although evidence within the older part of this range is still inadequate. The oldest known supracrustal (volcanic and sedimentary) rocks, from West Greenland, are debated to be between 3.9 and 3.7 Ga (for references see later). Most of these subsequently highly metamorphosed supracrustal rocks were originally deposited in water. They are enveloped by younger granitoid gneisses, but the basement on which they were deposited is not yet identifiable. However, there is some evidence (see later) that this basement was not sialic (continental) in character.

The former presence of even older rocks than the above is proved by the important discovery of detrital zircons, with high-resolution ion-microprobe U-Pb dates in the range 4.4–3.9 Ga, in much younger quartzites and conglomerates at Jack Hills and Mount Narryer in western Australia (for references see later). Furthermore, some ancient orthogneisses also show indisputable evidence for the presence of much older, inherited zircons.

Introduction of rapid and precise ion-probe dating of single zircon grains has supplemented and, for some workers, entirely replaced conventional dating techniques. This has proved to be a mixed blessing. Dates obtained from orthogneiss (and other) whole-rock regressions have been regarded by some as too imprecise or unreliable for adequate age resolution, whilst constraints on mantle and crust evolution imposed by initial Sr, Nd and Pb isotope ratios obtained from isochron and errorchron regressions have been disregarded, often for no convincing reason. In ancient orthogneisses, with a complex geological history, it has become fashionable to regard the oldest date(s) from the commonly observed wide range of zircon U-Pb dates as yielding the age of their magmatic precursors, sometimes without adequate (or indeed any) independent age evidence. This raises the question of possible zircon inheritance, because it has been known for many years from conventional zircon U-Pb measurements that many magmatic rocks contain inherited zircons derived from much older crustal sources (e.g. Pidgeon & Compston 1992; Mezger & Krogstad 1997; Miller *et al.* 2000).

Very precise zircon U-Pb dates are commonly used to back-calculate initial isotopic ratios (most often Nd) from Sm-Nd (and other) analyses of the host rock, on the further assumption that the rock has remained a closed system to parent and daughter isotope migration since the quoted zircon U-Pb age. It is shown later from published examples that reliable initial isotopic ratios can only be obtained where the zircon U-Pb age is identical with the independently known age of the host rock, and where the rock has remained a closed system to migration of parent and daughter isotope since time of rock formation. When these conditions are not met, a wide range of apparent initial isotopic ratios can be expected for a given rock suite, which yields no valid information whatever on the isotopic nature of the magmatic protolith of the zircon host rock. Despite these uncertainties, repeated claims have been made (for references see later) for extreme isotopic heterogeneity (especially in Nd) of the early Archaean mantle source region of the oldest magmatic rocks.

Such heterogeneity is unexpected because the early mantle was almost certainly hotter, less viscous and more vigorously convective than in later geological times. In contrast, a more rigorous combination of ages and initial isotopic ratios (especially in Nd) for early Archaean mantle-derived rocks suggests a small, homogeneous depletion of the mantle (high Sm/Nd) relative to the chondritic uniform reservoir (CHUR). This could be a genuine corollary to mantle differentiation and removal from the mantle of a small amount of crustal protolith material in earliest Archaean times (e.g. Nägler & Kramers 1998).

Despite the great practical advantages offered by single-grain ion-probe zircon U-Pb techniques, the problem of zircon inheritance in orthogneisses can only be addressed when ion-probe analysis is guided by precise identification of different age zones (if any) within a single grain, representing different crystallization episodes. Even with the inadequate transmitted-light photomicrography of former years, it was noticed that the oldest ion-probe dates resided in cores of grains, surrounded by younger magmatic or metamorphic zones. Even so, the oldest core ages were often taken to represent the age of the host rock. With recent routine introduction of effective imaging techniques, such as cathodoluminescence (CL) and back-scatter electron (BSE), it is possible to map out a single grain into separate zones of crystallization as a basis for high-spatial resolution ion-probe dating of each zone (e.g. Fig. 1). Combined with independent age work on the orthogneiss, this facilitates distinction between inherited, comagmatic and metamorphic sectors within a single zircon grain. Similarly, ion-probe work on imaged zircons is necessary for elucidating the crystallization history of detrital grains from ancient sediments and metamorphosed sediments, in order to derive an age for the source region and to set an upper age limit of deposition.

Progress is being made by combining ion-probe U-Pb dating with Hf isotope analysis on separate age zones of single zircon grains (Kinny *et al.* 1991; Amelin *et al.* 1999, 2000). Since zircon is the principal carrier of Hf in rocks, this combined technique is potentially more informative than combined, conventional Lu-Hf work on whole rocks and whole zircons, especially when their age and genetic relationships are not independently established.

We now review some early Archaean case histories which have been described and debated in the literature.

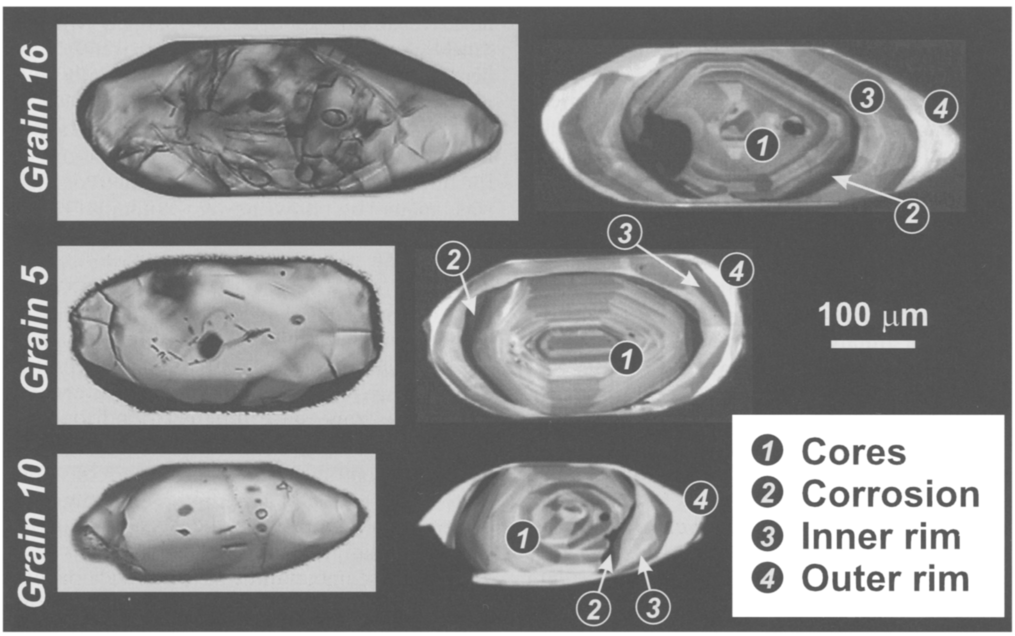

Fig. 1. Comparative transmitted light optical microscope images (left) and cathodoluminescence (CL) images (right) of three grains from sample GGU 110999, showing the much greater resolution of complex internal structure available from CL. These and similar images were used by Whitehouse *et al.* (1999) to guide the placement of their *c.* 30 μm diameter ion-probe analytical sites. In this particular sample, almost all zircon grains yield CL images showing the same internal subdivision into cores (>3.8 Ga), corrosion overgrowths (*c.* 3.74 Ga), inner rims (*c.* 3.65 Ga) and outer rims (*c.* 2.7 Ga). An age spectrum from this sample is given in Whitehouse *et al.* (1999).

Acasta gneisses, northwestern Canada: the oldest rocks on Earth?

We begin our case studies with the Acasta gneisses which, for the past ten years, have been widely quoted as the oldest rocks on Earth. The Acasta gneiss complex occupies an area of some 50 km^2 along the western margin of the Slave craton, an Archaean granite–greenstone terrain in the northwestern part of the Canadian Shield, with an area of 190 000 km^2. The Acasta gneisses provide a formidable test-case for the interpretation of ages and isotopes.

Bowring & Williams (1999) reported zircon U-Pb dates of 4.03–4.00 Ga for the Acasta orthogneisses, following earlier reports of a 3.96 Ga age (Bowring *et al.* 1989). They claim that these zircon dates reflect the time of magmatic crystallization of the tonalitic-to-granodioritic precursors. Such ancient samples of continental crust potentially carry much isotopic and trace element information to provide constraints on the earliest evolution of the Earth. Bowring & Housh (1995) and Bowring & Williams (1999) claim that whole-rock Nd isotope ratios of individual Acasta gneiss samples, when corrected back to the oldest zircon dates of 4.0–3.6 Ga, indicate extreme geochemical heterogeneity of early Archaean mantle, with initial ε_{Nd} (a measure of the initial $^{143}Nd/^{144}Nd$ ratio) values ranging from -4 (enriched) to $+4$ (depleted). Bowring and colleagues claimed, without discussion of physical implications, that separate, chemically distinct mantle domains existed for a few hundred million years before Acasta gneiss formation. Furthermore, they take this to imply that a chemically differentiated continental crust, comparable to its present mass, was in existence a few hundred million years after Earth accretion.

Moorbath *et al.* (1997) noted a striking co-linearity of published and new Sm-Nd whole-rock data on 34 samples of Acasta gneisses, yielding a regression age of 3371 ± 59 Ma (mean square weighted deviate (mswd) $= 9.2$) with an initial $\varepsilon_{Nd} = -5.6 \pm 0.7$. (The mswd is a statistical measure for the degree of scatter about a regression of data points; it does not provide a measure of the 'correctness' of any age or initial ratio derived from a regression line, as has recently been argued by Nutman *et al.* 2000.) Moorbath *et al.* (1997) argued that Nd isotope systematics had been set or reset at *c.* 3.37 Ga and could therefore not be used to draw any conclusions on the Nd isotope geochemistry of the Earth's mantle at *c.* 4.0 Ga, or on the amount of continental crust present at that time. Bowring & Williams (1999) countered by stating that they found no *c.* 3.4 Ga zircons in their analysed rocks and that the co-linearity of Sm-Nd data found by Moorbath *et al.* (1997) had no age significance. Bowring and colleagues did not publish their own Sm-Nd data plotted on isochron diagrams because they appear to regard the linear array as a mixing line, so that calculated ages and initial isotopic ratios have no geological age significance.

Ample U-Pb and Sm-Nd age evidence has recently emerged that major magmatic, metamorphic and migmatitic events occurred in and around the Acasta region at *c.* 3.38–3.35 Ga (Stern & Bleeker 1998; Yamashita *et al.* 2000), indistinguishable from the Sm-Nd regression age of *c.* 3.37 Ga of Moorbath *et al.* (1997). It is clear that the Sm-Nd isotopic system in the Acasta gneisses was set or reset at this time. We concur with Bowring & Williams (1999) that the problem of the true age of these complex, partially melted, highly tectonized, migmatitic gneisses is a semantic issue. Because we believe that, for the purpose of inferring mantle geochemistry, the term 'age' requires geochemical and isotopic integrity of the rocks (rather than only that of some of its components, i.e. zircon, as proposed by Bowring & Williams 1999) we maintain that 'the age of the Acasta gneisses is only *c.* 3.37 Ga, although both the zircon U-Pb ages (4.0 to 3.6 Ga) and the very negative initial ε_{Nd} of -5.6 obtained from the Sm-Nd regression provide incontrovertible evidence for the existence of a substantially older precursor' (Moorbath *et al.* 1997).

A further claim for the significance of a wide range of initial ε_{Nd} values in the Acasta gneisses for identifying *c.* 4.0 Ga mantle heterogeneity was made by Bowring & Williams (1999). However, Whitehouse *et al.* (2001) demonstrated that the interpretation of the Sm-Nd regression age of *c.* 3.37 Ga either as a Nd isotope homogenization event or as a mixing line precludes the application of Acasta gneiss Sm-Nd data to constrain the geochemical evolution of the Earth in its first 500 Ma. In this connection, Amelin *et al.* (1999, 2000) reported preliminary results of a combined Hf isotope and U-Pb age study on *c.* 3.6 Ga zircons from the Acasta gneiss. These zircons contained no evidence for a strongly depleted or enriched early Archaean mantle component.

Itsaq gneiss complex, southern West Greenland

This is the largest known and best exposed terrain of early Archaean rocks on Earth, on which an extensive, multidisciplinary literature has built up since the pioneering field work of

V. R. McGregor in the late 1960s (McGregor 1973). The earliest determinations provided an age of c. 3.75–3.65 Ga for the regional gneisses and supracrustal rocks (e.g. Black *et al.* 1971; Moorbath *et al.* 1972, 1973; Baadsgaard 1973). The first phase of the age work was reviewed by Moorbath *et al.* (1986). Only the salient features of the large amount of recent and ongoing work are reviewed here. Regional descriptions are omitted, but can be found in the references. Following the recommendation of Nutman *et al.* (1996), irrespective of its necessity, we here use the term Itsaq orthogneisses, or simply Itsaq gneisses, for the former Amîtsoq gneisses. These workers combined all the varied early Archaean rocks of this region into the so-called Itsaq gneiss complex.

Age of the Itsaq orthogneisses

The age of these lithologically complex, variably deformed, granitoid orthogneisses is currently the focus of much debate. We have regressed the published, conventional whole-rock isotopic data (Fig. 2) from the Itsaq gneisses, with the following results.

(i) Rb-Sr. Age $= 3660 \pm 67$ Ma (million years), initial $^{87}Sr/^{86}Sr = 0.7006 \pm 9$ mean square weighted deviate (mswd) $= 33$, number of samples (n) $= 78$ (Moorbath *et al.* 1972, 1975, 1977; Baadsgaard *et al.* 1976, 1986*a*).

(ii) Sm-Nd. Age $= 3640 \pm 120$ Ma, initial $\varepsilon_{Nd} = 0.9 \pm 1.4$, mswd $= 10$, $n = 26$ (Baadsgaard *et al.* 1986*b*; Moorbath *et al.* 1986, 1997; Shimizu *et al.* 1988).

(iii) Pb/Pb (whole rock and selected feldspar). Age $= 3654 \pm 73$ Ma, intersection of Pb/Pb regression with primary growth curves of Stacey & Kramers (1975) and Kramers & Tolstikhin (1997) are 3.65 Ga and 3.66 Ga respectively, mswd $= 17.6$, $n = 83$ (Moorbath *et al.* 1975; Gancarz & Wasserburg 1977; Griffin *et al.* 1980; Kamber & Moorbath 1998).

These regressions are by no means perfect isochrons, and the scatter of points about the regressions in excess of analytical error, as measured by the mswd, is due *either* to open-system behaviour of parent and/or daughter isotopes during regionally well-attested late Archaean and mid-Proterozoic metamorphism, *or* to a small degree of heterogeneity in initial Sr, Nd and Pb isotope ratios for different Itsaq gneiss components, *or* to a combination of these. However, we regard the weighted mean of 3655 ± 45 Ma from all three methods as a well-constrained emplacement age for the bulk of the magmatic precursors of the Itsaq orthogneisses. It is unlikely that agreement between the three methods is the result of pervasive regional resetting of ages during metamorphism, because of the very different geochemical behaviour of the three isotopic systems. Initial Sr, Nd and Pb isotopic constraints indicate derivation from a mantle-like source for the magmatic precursors at c. 3.65 Ga, and not from resolvably older reworked sialic crust.

Many Itsaq gneisses studied by the ion-probe have yielded at least some zircon U-Pb dates at c. 3.65 Ga, and this is seen as the age of a major crust-forming event by Nutman *et al.* (1996) and by McGregor (2000). However Nutman *et al.* have also reported many older zircon dates from which they conclude that the Itsaq gneisses had a complicated earlier history, having been added to and modified in several discrete events from c. 3.9 Ga to 3.6 Ga. No consideration was given to the possibility that dates >3.65 Ga might represent inherited zircons. Bennett *et al.* (1993) and Nutman *et al.* (1996) persistently claim:

(i) that Itsaq gneiss samples in this age range cannot be resolved in age and initial ratio from amongst the scatter of analysed whole-rock regression points (see above);

(ii) that high-grade metamorphism and partial melting at c. 3.65 Ga has reset ages and initial isotopic ratios in older rocks, even to the extent of erasing previous isotopic memories in granitoid rocks;

(iii) that individual zircon dates in the range c. 3.9–3.6 Ga can be used to back-calculate reliable initial Nd isotope ratios for the host rock.

The arguments against these three points are as follows (noting that the claims in (ii) and (iii) above are, in any case, incompatible).

(i) It cannot be entirely discounted that the quoted whole-rock regressions (see above) contain individual points from some older rocks. However, careful and detailed whole-rock (plus selected mineral) regressions on individual rock units claimed to be ≥3.8 Ga would be quite easily resolvable from c. 3.65 Ga, especially in the Pb/Pb system. Regrettably, not many independent age data are yet available for rocks regarded by Bennett *et al.* (1993) and Nutman *et al.* (1996, 1999) as >3.65 Ga (but see below).

(ii) Regional-scale metamorphic resetting of Rb-Sr, Sm-Nd, Pb/Pb whole-rock systems in coarse-grained granitoid rocks is implausible and, in any case, cannot preserve mantle-like initial Sr, Nd and Pb isotope ratios in rocks

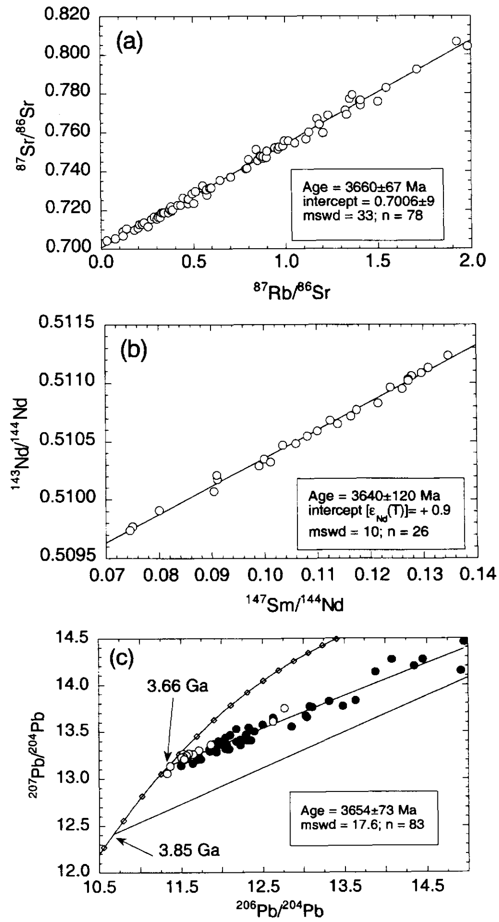

Fig. 2. Isochron diagrams for Itsaq orthogneisses (data sources given in Kamber & Moorbath 1998). (**a**) Rb-Sr regression line calculated for 78 Itsaq orthogneisses (samples with $^{87}Rb/^{86}Sr > 2$ omitted due to susceptibility to later isotope exchange) yields a 3.66 Ga age. Note the lack of scatter of the low Rb/Sr samples, arguing against derivation from variably fractionated reservoirs, including pre-existing continental crust. Rather, the initial Sr isotope ratio is compatible with derivation from a largely undepleted mantle. (**b**) Sm-Nd regression of 26 Itsaq orthogneisses yields a similar age of 3.64 Ga. The significance of this age and the initial isotope composition have been discussed by Moorbath *et al.* (1997). (**c**) Common Pb diagram for Itsaq orthogneisses in which whole-rock data points are shown as solid circles and leached feldspar data as open circles. The combined data set ($n = 83$) defines a regression age of 3.65 Ga (solid line through data points). The important aspect of the regression is that plausible mantle evolution curves (here Kramers & Tolstikhin (1997) – open diamond symbols) are intersected at a time (3.66 Ga) indistinguishable from the regression age. Due to the relatively short half-life of ^{235}U (parent of ^{207}Pb), the $^{207}Pb/^{204}Pb$ and the $^{207}Pb/^{206}Pb$ ratios of the terrestrial reservoir evolved very quickly in early Archaean times. This is illustrated by the large difference in Pb isotope composition (see arrows) between 3.85 Ga mantle and 3.66 Ga mantle in the selected model. A hypothetical isochron of a 3.85 Ga mantle-derived sample suite (solid line starting at 3.85 Ga) is shown to highlight the magnitude of the difference between observed data and those expected if the Itsaq granitoid gneisses were indeed 3.85 Ga old.

as old as 0.2–0.3 Ga at the time of resetting, because of the very different Rb/Sr, Sm/Nd and U/Pb ratios of granitoid and mafic (mantle-like) rocks. In this respect, the Pb/Pb system is extremely sensitive, particularly for the Itsaq gneisses, because of their extremely low U/Pb ratios and correspondingly uniquely (i.e. for terrestrial rocks) unradiogenic present-day Pb isotope ratios (e.g. Black *et al.* 1971; Gancarz & Wasserburg 1977). Their Pb/Pb regression line (age $= 3654 \pm 73$ Ma) intersects, by a short extrapolation, the Kramers & Tolstikhin (1997) terrestrial Pb isotope evolution curve at 3.66 Ga, providing no leeway for development in a significantly older crustal environment (Fig. 2c). As emphasized by Kamber & Moorbath (1998), the $^{207}Pb/^{206}Pb$ compositions of 3.85 Ga and 3.65 Ga mantle Pb on the primary growth curve differ by some 13%, far outside analytical uncertainties (typically *c.* 0.15%). There is as yet no hint from published Pb isotope ratios that any Itsaq gneiss began its existence in the crust as long ago as 3.85 Ga or, indeed, significantly in excess of *c.* 3.65 Ga.

(iii) Bennett *et al.* (1993) used a range of observed zircon U-Pb dates of *c.* 3.9–3.7 Ga for the Itsaq gneisses, in conjunction with Sm-Nd analyses, to calculate initial ε_{Nd} values in the range -4.5 to $+4.5$ for the mantle source region of their magmatic precursors. This implied a locally very heterogeneous mantle reservoir, with all its consequences for transient mantle–crust differentiation in earliest Earth history. For analogous reasons to those outlined for the Acasta gneisses earlier, these claims were criticized (Moorbath *et al.* 1997; Kamber & Moorbath 1998; Whitehouse *et al.* 1999) on the grounds that the oldest U-Pb dates might represent inherited zircons and that the true magmatic age of the protoliths of the Itsaq gneisses was close to *c.* 3.65 Ga, when they were differentiated from a relatively homogeneous mantle reservoir.

The continuing debate about inherited versus comagmatic interpretation of zircon U-Pb dates in the Itsaq gneisses came to a head on the small island of Akilia in the outer part of the Godthaabsfjord region (Fig. 3). Here a large enclave of the so-called Akilia supracrustals (McGregor & Mason 1977; see also next section) was claimed to be discordantly cut by a thin, gneissic granitoid sheet with ion-probe zircon U-Pb dates of up to 3.87 Ga (Mojzsis *et al.* 1996; Nutman *et al.* 1997*a*). Indeed, Nutman *et al.* (1996) had earlier published a range of zircon dates from 3.87 Ga to 3.62 Ga from a small region on and around Akilia island. The putative pre-3.87 Ga supracrustal enclave was of special interest, because apatite grains in a metamorphosed iron-rich sediment yielded isotopically light $\delta^{13}C$‰ values of −20 to −50, interpreted by Mojzsis *et al.* (1996) as biological in origin. These authors stated that

> '... the late heavy bombardment (>3800 Ma), documented in the lunar record has been speculated to place an upper limit on the age of a continuous terrestrial biosphere (Chyba 1993). The evidence for life ... overlaps this critical time period and shows that if the accretion models are realistic, such a bombardment did not lead either to the extinction of life or the perturbation of the finely laminated >3850 Ma BIF (banded iron-formation) preserved on Akilia island' (Mojzsis *et al.* 1996, p. 59).

In a detailed Pb isotope study on whole rocks and feldspars from the presumed discordant granitoid sheet on Akilia island, Kamber & Moorbath (1998) failed to find any evidence for isotopic compositions significantly older than 3.65 Ga and surmised that the oldest U-Pb dates of >3.8 Ga referred to inherited zircons. This was supported in a new ion-probe study by Whitehouse *et al.* (1999), in which CL imaging was used for the first time in the early Archaean rocks of Greenland. These authors studied zircons from the crucial granitoid sheet (and other rocks) and revealed a previously undocumented zircon growth history. Several samples contained zircon grains with >3.8 Ga cores of magmatic origin, further magmatic overgrowths at 3.65 Ga, and some metamorphic overgrowth at *c.* 2.7 Ga. (Fig. 1). The >3.8 Ga cores were regarded by Whitehouse *et al.* (1999) as inherited, with apparent dates ranging down to *c.* 3.65 Ga reflecting differential Pb loss. The 3.65 Ga magmatic zones in zircon grains were interpreted as the true age of the host rock. This contrasts with the published views of Mojzsis *et al.* (1996) and Nutman *et al.* (1997*a*), interpreting >3.8 Ga dates as the magmatic age of the host rock, with *all* younger ages reflecting Pb loss and/or metamorphic recrystallization. Whitehouse *et al.* (1999) concluded that the true minimum age of the Akilia supracrustal rocks of possible biological significance is 3.65 Ga, and not 3.85 Ga,

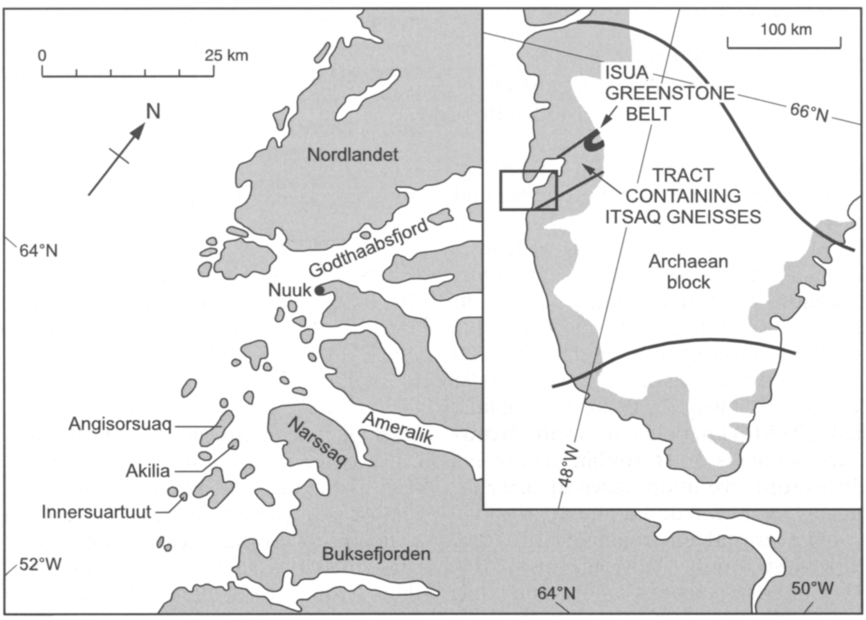

Fig. 3. Sketch-map of the principal early Archaean rock units and localities of southern West Greenland, discussed in the text.

thus making significant overlap with the >3.8 Ga period of lunar and presumed terrestrial bolide impact highly questionable.

Some heat may (or may not) be taken out of this particular debate, because detailed mapping in 1999 of this specific locality on Akilia island by Myers & Crowley (2000) has failed to find any convincing evidence for a discordant, intrusive relationship between the gneiss sheet and the Akilia supracrustal rocks. Myers & Crowley (2000, p. 110) state that 'the rocks on Akilia indicate a complex history of intense ductile deformation in which most geological features were attenuated, rotated and transposed into a new tectonic fabric'. This means that no conclusions can be drawn about the relative age of the gneiss sheet and the Akilia supracrustal rocks. Clearly it is essential for direct age measurements to be made on the Akilia rocks themselves (see next section). Myers & Crowley (2000, p. 114) furthermore consider that 'the possibility of any trace of early Archaean 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 Archaean, appears miraculous'.

Despite the continuing debate, the existence of genuine in-situ Itsaq orthogneisses with an age >3.65 Ga is, of course, a distinct possibility. Thus, Nutman *et al.* (1999) report CL-imaged zircons dominated by single-component oscillatory-zoned prismatic grains with dates close to 3.8 Ga from a terrain of relatively undeformed tonalitic and quartz–dioritic orthogneisses south of the Isua greenstone belt (see later section), some 150 km northeast of Nuuk. Nutman *et al.* (1999) regard this terrain as the best-preserved suite of *c.* 3.8 Ga felsic igneous rocks yet documented.

A detailed lutetium–hafnium (Lu-Hf) isotope study by Vervoort & Blichert-Toft (1999) on juvenile rocks through time and their bearing on mantle–crust differentiation demonstrates that no early Archaean samples show evidence for derivation from a crustal reservoir (i.e. none has negative ε_{Hf} values). They suggest that relative lack of Hf isotope heterogeneity and absence of negative ε_{Hf} in early Archaean rocks argues against existence of present-day volumes of continental crust in the early Earth. Nevertheless, their comparison of initial Hf and Nd isotope ratios for the Itsaq gneisses may be unrealistically complicated. The apparent initial ε_{Nd} and ε_{Hf} values range from -4.5 to $+4.5$ and from 0 to $+4$ respectively. Although Vervoort & Blichert-Toft (1999) recognize that the wide dispersion of initial ε_{Nd} values is due to later disturbances in the Sm-Nd system and does not represent initial isotopic variations in the early Earth, their range of calculated ε_{Hf} values may still be unrealistically wide. Three factors could have caused overestimation of the range of recorded initial Hf isotope compositions.

(i) As outlined by Patchett (1983), despite the low diffusivity of Hf, zircon is not immune to metamorphic disturbance of its original Hf isotope composition. Because most Lu in a granitoid is generally hosted by minerals other than zircon, relatively radiogenic Hf will accumulate in the matrix and may be incorporated into recrystallized or newly grown zircons (Whitehouse *et al.* 1999). If sufficient time has elapsed between original magmatic zircon growth and metamorphic recrystallization, significant amounts of unsupported (radiogenic) Hf could be incorporated into zircons and cause artificial spread in recalculated initial Hf isotope ratios.

(ii) There is a possibility that at least some of the zircons in these rocks are inherited (see above), particularly in view of the fairly wide range of zircon U-Pb dates (3.82–3.64 Ga) of Bennett *et al.* (1993). Inherited zircons whose age exceeds that of the entraining melt by several hundred million years are expected to have evolved to a less radiogenic Hf isotope composition (generally negative ε_{Hf} values) than the whole rock or contemporaneous mantle. However, it is plausible that during incorporation into a 3.65 Ga melt, inherited zircons could have sequestered relatively radiogenic Hf from their surrounding older rock volume.

(iii) There is disagreement between the eucrite meteorite-based ^{176}Lu decay constant and determinations based on counting experiments. Whilst a slower decay, which is indicated by the most recent experiments (Nir-El & Lavi 1998), would not significantly reduce the spread in initial Hf isotope ratios for early Archaean low Lu-Hf samples, it would, nevertheless, result in less positive ε_{Hf} values (Patchett & Vervoort 2000). This in turn would indicate derivation from a less depleted mantle and hence the existence of only minor amounts of continental crust.

Age of the Akilia association

This sequence of rocks was first named by McGregor & Mason (1977), who described it as metamorphosed basic, ultrabasic and sedimentary rocks enclosed in the *c.* 3700 Ma old

Amîtsoq (now Itsaq) gneisses in the Godthaab region, West Greenland. McGregor & Mason furthermore consider that the rocks of the Akilia association are fragments of a greenstone-belt type of sequence that was intruded and disrupted by the granitic parents of the Itsaq gneisses.

As outlined in the previous section, Akilia metasedimentary rocks on Akilia island are important on account of possibly biogenic components (Mojzsis *et al.* 1996; Nutman *et al.* 1997*a*). Following on from earlier arguments, we now summarize direct evidence to suggest that the Akilia association rocks on Akilia island and nearby Innersuartuut island are probably no older than *c.* 3.7 Ga.

(i) A biotite-schist with a precursor of volcano-sedimentary origin gave an ion-probe zircon U-Pb date of 3685 ± 8 Ma (Schiøtte & Compston 1990). They regarded this as the original age of the Akilia association, and viewed an older group of zircons at 3756 ± 22 Ma as xenocrysts, i.e. derived from older rocks.

(ii) Sm-Nd data of Bennett *et al.* (1993) on four gabbroic rocks from the Akilia association plot on a statistically valid isochron (mswd < 1) and yield an age of 3677 ± 37 Ma (Moorbath & Kamber 1998). Note that Bennett *et al.* (1993) did not regress their own Sm-Nd data, because their ideas are constrained by the 3.87–3.78 Ga zircon U-Pb dates which are regarded as the true age of supposedly discordant granitoid sheets. Moorbath & Kamber (1998) regarded the Sm-Nd age of 3677 ± 37 Ma as a close estimate for the age of not only the gabbroic components of the Akilia association on these islands, but also for the closely associated banded iron formation lithologies containing apatite with graphite inclusions of possible biological origin (Mojzsis *et al.* 1996).

(iii) Pb/Pb analyses by Kamber & Moorbath (1998) on feldspars and whole rocks from a suite of mafic Akilia association rocks from Akilia island and Innersuartuut island yield extremely unradiogenic Pb isotope compositions which plot so close to the Itsaq gneiss regression and its intersection on the primary growth curve (see previous section) that an age resolution between Itsaq gneisses and Akilia association rocks is not possible. There is no apparent contribution from any $\geq$3.8 Ga crustal material.

In addition to these direct lines of evidence, we note that the putative early-life-bearing Akilia association rock has yielded *c.* 2.7–2.6 Ga low-Th/U zircons interpreted by Nutman *et al.* (1997*a*) as the result of late Archaean metamorphism, as well as *c.* 3.64–3.42 Ga zircons reported recently by Mojzsis & Harrison (1999). The latter show a range of Th/U ratios from *c.* 0.4 to <0.01 (which, we suggest, indicates more than one origin), with higher Th/U zircons overlapping in value with those interpreted by Schiøtte & Compston (1990) as being volcanic in origin, and low U/Th zircons probably being metamorphic in origin. If the Akilia association enclaves are >3.85 Ga, as proposed by Nutman *et al.* (1997*a*), and the adjacent Itsaq gneisses truly record a long history (*c.* 200–300 Ma) of magmatic and thermal events as claimed by Nutman *et al.* (1996), then the Akilia enclaves will undoubtedly also have experienced these events. Given the tendency for metamorphic zircons to grow during the first high-grade metamorphic event to affect a rock (e.g. Söderlund *et al.* in press), the apparent absence of >3.65 Ga metamorphic zircon in the Akilia association rocks is surprising. Such an absence may, however, be easily explained if the true age of the Akilia rocks is less than *c.* 3.70 Ga.

The evidence summarized above suggests that the protoliths of the Akilia association rocks on Akilia island were deposited between *c.* 3.70 and 3.65 Ga, and are thus some 150 to 200 Ma younger than proposed in previous work (Mojzsis *et al.* 1996; Nutman *et al.* 1997*a*). There is no overlap with any period of massive bolide impacts on the moon, widely regarded as terminating at *c.* 3.8 Ga (e.g. Wilhelms 1987; Ryder 1990). Indeed, recent work by Cohen *et al.* (2000) provides strong evidence from ^{40}Ar-^{39}Ar studies of lunar impact melts supporting the occurrence of a short, intense period of bombardment in the Earth–Moon system peaking at *c.* 3.9 Ga.

The Isua greenstone belt (IGB)

The IGB (also known as the Isua supracrustal belt) lies some 150 km northeast of Nuuk, the capital of Greenland (Fig. 3), within the regional early Archaean gneisses (Allaart 1976). It comprises rocks of volcanic, volcanoclastic, clastic (Fedo 2000) and chemical–sedimentary origin with a wide range of chemical compositions, most (if not all) of which were deposited in water. These are the oldest (3.7–3.8 Ga) known rocks of their type on Earth (if, as we argued above, the true minimum age for the Akilia association is 3.65 to 3.70 Ga, and not >3.85 Ga as claimed). The main metavolcanic rock unit in the IGB is a mafic (basaltic) rock, mostly metamorphosed to fine-grained talc–chlorite schists.

Two of the principal sedimentary rock types are banded iron formation (BIF), and a massive garnet–biotite $\pm$ hornblende schist probably derived from a mafic volcanogenic sediment. IGB rocks underwent intense multiple deformation, peak metamorphic recrystallization at 550°C (Boak & Dymek 1982) and widespread metasomatic alteration (Rose *et al.* 1996; Rosing *et al.* 1996) which have partly obscured original lithology and chemistry. Localized low-strain domains containing conglomerates, pillow lavas, discordant contacts and relict sedimentary structures are present (e.g. Nutman *et al.* 1984; Appel *et al.* 1998; Fedo 2000). The IGB is currently being remapped in detail within the framework of the Isua Multidisciplinary Research Project (Appel & Moorbath 1999). It was reported long ago that Isua graphite yields fractionated carbon isotope values somewhere between biogenic-C and carbonate-C, interpreted by Schidlowski *et al.* (1979) and Schidlowski (1988) as indicating the existence of a significant biomass by the time of Isua sedimentation. More recently, Rosing (1999) identified ^{13}C-depleted carbon microparticles of possible biogenic origin in what are described as turbiditic and pelagic marine IGB metasedimentary rocks.

Of all currently known early Archaean terrains the IGB is unique in that it contains true, physically recognizable metasediments (both clastic and chemical) and an abundance of metamorphosed mafic volcanic rocks, some of which preserve primary volcanological features. It has long been suspected that the geochemistry and particularly the isotope record of these lithologies might contain a memory of predepositional geological history of a time window not otherwise accessible. We first discuss age constraints on the deposition of the sediments and volcanic rocks themselves and then evaluate the more speculative issue of interpreted isotope geochemical features.

Direct age constraints on the deposition of IGB lithologies

There is general agreement that the plutonic rocks (now gneisses) immediately surrounding the IGB are younger than the belt itself and that some contacts are tectonically discordant or intrusive. No granitoid, gneissic basement to the IGB has been recognized, and none of the pebble conglomerates in the belt contain recognizable gneissic clasts. This precludes determination of an absolute maximum age of deposition and attempts at dating the IGB therefore rely on direct age information (summarized in Table 1) as well as minimum age constraints by dating cross-cutting igneous rocks.

Since the early 1970s, conventional dating with Rb-Sr, U-Pb, Pb/Pb and Sm-Nd methods (summarized by Moorbath *et al.* 1986) has given an age range of *c.* 3.75–3.70 Ga for IGB lithologies. More recent attempts at directly dating IGB rock units have yielded similar results. Moorbath *et al.* (1997) determined a more precise 58-point Sm-Nd regression date of 3776 ± 56 Ma for combined Isua metasediments. The approach of combining diverse metasediments was later criticized by Bennett & Nutman (1998). In response, Kamber *et al.* (1998) pointed out that a regression of schist data alone (24 points) yielded a very similar result of 3742 ± 49 Ma. Frei *et al.* (1999) determined a Pb/Pb regression age of 3691 ± 22 Ma for a magnetite-enriched fraction from the major BIF deposit at Isua. This is in excellent agreement with an earlier Pb/Pb isochron age of 3698 ± 70 Ma determined on bulk-rock BIF by Moorbath *et al.* (1973). While Frei *et al.* (1999) interpreted their Pb/Pb regression date as the age of earliest metamorphism, we prefer to interpret 3.7 Ga as the most likely age of deposition. The strongest evidence for a 3.71 Ga deposition age of the Isua BIF (as well as associated lithologies) was presented by Nutman *et al.* (1997*b*) who dated zircons (by ion-probe U-Pb) from BIF, schists and an associated felsic volcanic band. More recently, Blichert-Toft *et al.* (1999) obtained a Sm-Nd regression with an age of 3712 ± 26 Ma for a combined IGB dataset (amphibolites, schists and clastic sediments). The same rocks yielded a Lu-Hf regression date of 3593 ± 15 Ma which Blichert-Toft *et al.* (1999) interpreted to indicate Hf mobility during subsequent geological events. However, Villa *et al.* (2001) recalculated the Lu-Hf regression age with the more recently determined Lu decay constant by Nir-El & Lavi (1998) and obtained an age of 3729 ± 16 Ma, in perfect agreement with all other age constraints.

In an important study, Gruau *et al.* (1996) found that a suite of metabasalts from the IGB demonstrated such a high degree of open-system behaviour that even single outcrops did not yield uniform initial ε_{Nd} values. Blichert-Toft *et al.* (1999) and Albarède *et al.* (2000) had to screen their combined Sm-Nd and Lu-Hf datasets using geochemical criteria (i.e. omit data points) because of problems related to element mobility and partial isotope resetting, particularly in metabasalt samples. There is thus no direct age constraint for the sometimes pillowed metabasalts. Nutman *et al.* (1997*b*) interpreted weighted mean ^{207}Pb-^{206}Pb dates for two discordant tonalitic sheets which yielded ages of 3791 ± 14 and

Table 1. *Recent and selected older radiometric age data for Isua greenstone belt*

Lithology	Method	Age (Ma)	±	Source	Remarks
Volcano-sediment Unit B1	Ion-probe U-Pb zircon	3708	3	Nutman *et al.* (1997*b*)	Interpreted by original authors as dating the entire metabasic-dominated part of the belt
Clast-rich sample from graded meta-volcanic rock	Ion-probe U-Pb zircon	3718	4	Nutman *et al.* (1997*b*)	Sample is from base of graded unit immediately overlying Unit B1
'Dirty' meta-banded iron formation	Ion-probe U-Pb zircon	3707	6	Nutman *et al.* (1997*b*)	Average of three oldest dates, interpreted by original authors as dating zircons of volcanic origin
Meta-banded iron formation	Pb-Pb step-leaching regression	3691	22	Frei *et al.* (1999)	Interpreted by original authors as dating a metamorphic event immediately after deposition
Meta-banded iron formation	Pb-Pb regression	3698	70	Moorbath *et al.* (1973)	Interpreted by original authors to date deposition of sediment
Kyanite schist	Ion-probe U-Pb zircon	3711	6	Nutman *et al.* (1997*b*)	Sample also yielded morphologically distinct metamorphic zircons of late Archaean age
Mica schists	Sm-Nd whole rock	3742	49	Kamber *et al.* (1998)	Regression of compiled data interpreted to date age of deposition
Mica schists, amphibolites and clastic meta-sediments	Sm-Nd whole-rock regression Lu-Hf whole-rock regression	3712 3729	26 16	Blichert-Toft *et al.* (1999)	Interpreted by original authors to either have no age significance or to date later resetting. Note that Lu-Hf age is recalculated using Nir-El & Lavi (1998) Lu decay constant, following Villa *et al.* (2001)
Felsic (meta-volcanic?) rock, Unit A6	Ion-probe U-Pb zircon Conventional U-Pb zircon	3806 3813	2 9	Compston *et al.* (1986) Baadsgaard *et al.* (1984)	If this unit is of volcanic origin, it would constitute an earlier phase of magmatism (and sedimentation) than that recorded by the rest of the belt

3798 ± 4 Ma, respectively, as minimum ages for pillow basalt extrusion. There is no *a priori* reason to believe that the IGB could not contain lithological packages that are unrelated in time and space. Indeed, ductile shear zones transect the IGB into mappable tracts and domains (Fedo 2000) that may not share a common origin. The possibility that the IGB contains >3.79 Ga lithologies clearly remains (Nutman *et al.* 1997*b*) but is not directly relevant for the discussion of isotopic signatures which were obtained on samples that are 3.71 Ga in age.

Small sulphide mineralizations within the IGB contain galena (lead sulphide) which has the least uranogenic Pb isotope ratios (i.e. lowest $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$) known on Earth (Appel *et al.* 1978; Richards & Appel 1987). The ratios are as low as $^{206}Pb/^{204}Pb = 11.15$ and $^{207}Pb/^{204}Pb = 13.04$, which demonstrate that this uranium-free galena Pb was separated from a source region with a finite U/Pb ratio some 3.75–3.80 Ga ago

Initial isotope constraints from IGB metasediments

While no direct evidence exists for the nature of the basement onto which the IGB was deposited, it appears reasonable to expect that clastic sediments might hold clues to its age and nature. For example, a 4.1 Ga granitoid basement would have evolved by 3.71 Ga to initial Nd, Sr, Pb and Hf isotope ratios resolvably different from juvenile crust or mantle. Because many of the aforementioned whole-rock isotope studies yield ages that are concordant with each other and with the 3.71 Ga U-Pb zircon age constraints, their regression intercepts should be valid approximations for the isotope compositions of the source rocks.

Moorbath *et al.* (1986) concluded, based on a survey of then-published isotope work, that initial Nd and Sr isotope ratios recorded by regression lines of IGB lithologies are similar to those of coeval mantle. In other words, these initial isotope ratios do not permit a lengthy (>100 Ma) crustal pre-history. Since then, further whole-rock regression lines for Sm-Nd and Lu-Hf (Moorbath *et al.* 1997; Kamber *et al.* 1998; Blichert-Toft *et al.* 1999) have confirmed this view and there is general agreement that a substantially older, evolved basement is not visible in the initial isotope ratios of clastic sediments. Nutman *et al.* (1997*b*) have tentatively identified rare siliceous rocks of possible clastic sedimentary origin. These contain zircons which range widely in age, but two samples yield age clusters between 3.8 and 3.9 Ga. Irrespective of whether these rocks are metasomatized metagranitoids or clastic sediments, their zircon age distribution indicates that there was some kind of a pre-3.71 Ga IGB substratum but that it was not sufficiently old to leave a discernible record in the initial isotope ratios of clastic rocks.

It is, of course, clear that a relatively wide range is obtained when initial isotope ratios are calculated for individual samples (using an assumed appropriate age of deposition). This range largely reflects uncertainty in assumed age, assumption of a constant daughter/parent ratio, and potential influence of later isotope resetting. Jacobsen & Dymek (1988) proposed that the Sm-Nd whole-rock system in the Isua 'sediments' remained closed during metamorphism, thus interpreting the spread in individually calculated initial ε_{Nd} as a primary sedimentary signature due to variable mixing of pre-3.8 Ga continental crust with 3.8 Ga juvenile crust with very different initial ε_{Nd} values. However, as pointed out by Gruau *et al.* (1996), the wide variation of apparent initial ε_{Nd} (-1.0 to $+5.0$) can instead be attributed to disturbance during late Archaean metamorphism, as recorded by mineral ages.

A survey of conventional dating methods on IGB rocks thus suggests that some rock units yield concordant multi-method regression ages that are within error identical with U-Pb zircon ages and that yield mantle-like initial isotope signatures. The view that IGB represents a relatively juvenile terrain is in apparent conflict only with Harper & Jacobsen's (1992) claim for the existence of a measurable ^{142}Nd anomaly in an Isua 'metabasalt'. Because of the short half-life (102 Ma) of the now-extinct ^{146}Sm, a true ^{142}Nd anomaly would most certainly indicate a source with an age in excess of 4.2 Ga. The analytical controversy about the reality of the effect has not been entirely resolved (Jacobsen & Harper 1996; Sharma *et al.* 1996). Here we point out that the relevant sample originates from a thick horizon of quartz–mica–garnet schist, a strongly metamorphosed sediment. The postulated ^{142}Nd anomaly, if real, of this rock would therefore imply erosion from a source that had remained isolated for at least 0.5 Ga. In the absence of other terrestrial rocks with ^{142}Nd anomalies and given that none of the other isotope systems support the effect at Isua, Harper & Jacobsen's (1992) observation cannot be used to question the deposition of the IGB onto a relatively juvenile basement.

In contrast to the clastic sediments of the IGB, which appear to be relatively locally derived,

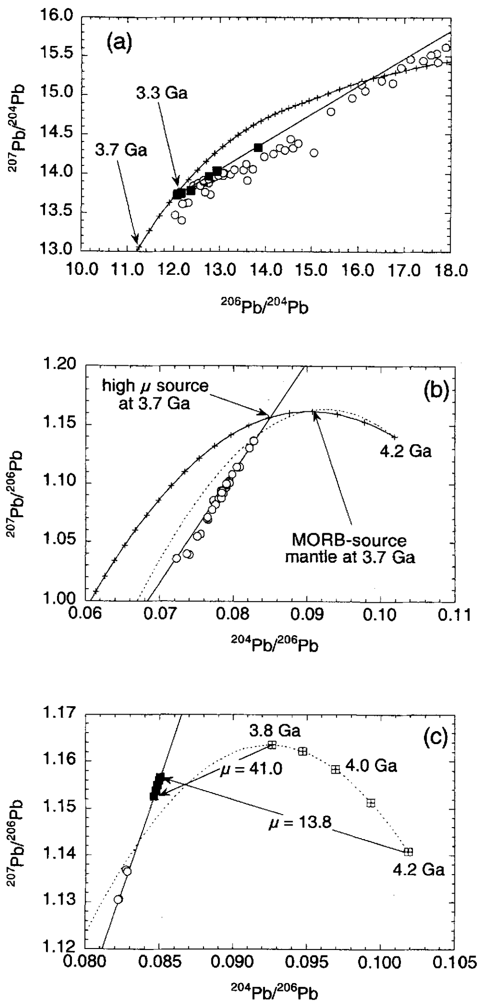

Fig. 4. Pb isotope diagrams. (**a**) IGB metasediments in $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ isotope space. Undifferentiated data points (open circles) are garnet-mica schists (unpublished) and leached carbonates ($n = 30$; Table 2). The data define trends subparallel to the BIF data of Moorbath *et al.* (1973) – solid squares connected by regression line – which has a slope corresponding to *c.* 3.7 Ga. The important point is that regressions calculated for the chemical sediments (i.e. BIF and carbonate) intersect plausible mantle evolution curves (here Kramers & Tolstikhin (1997) – solid line connecting plus marks) at loci corresponding to much younger dates (i.e. *c.* 3.3 Ga). This indicates that the Pb which co-precipitated with these sediments had evolved for some time in an environment with a substantially higher μ than the mantle. (**b**) The same point is illustrated in a $^{207}Pb/^{206}Pb$ versus $^{204}Pb/^{206}Pb$ diagram. The Kramers & Tolstikhin (1997) mantle evolution curve (broken line shown from 4.2 Ga) evolves from right to left in this diagram. Also shown is a model reservoir (solid line connecting + marks) that separated from the mantle at 4.2 Ga and evolved with a μ of 13.8. After 500 Ma (i.e. at the time of deposition of BIF and carbonate, open circles), this reservoir would have evolved to a Pb isotope composition representing the initial for the present-day BIF isochron (solid line connecting open circles). (**c**) Blow-up of (b) highlighting the relationship between μ and separation time of the modelled high μ reservoir. Shown again is the Kramers & Tolstikhin (1997) mantle curve (broken line starting at 4.2. Ga) and the least radiogenic BIF data (open symbols) as well as the BIF isochron (solid line). Five different high-μ model reservoirs were calculated by using mantle separation ages of 4.2, 4.1, 4.0, 3.9 and 3.8 Ga (crossed squares). The 4.2 Ga separation model is identical to that shown in (b). With decreasing mantle separation age, the required μ increases in the steps 13.8, 15.3, 17.9, 23.3, 41.0. Note that all modelled initial Pb isotope compositions (solid squares) plot clearly above the mantle curve (i.e. to the left in the conventional diagram).

chemical sediments can potentially yield chemical and isotope signatures that reflect integration over a much larger area if they formed in a basin that was in contact with open ocean waters (provided, of course, that oceans existed). Moorbath *et al.* (1973), in their study of the Pb isotope systematics of BIF from the IGB, noted that the BIF recorded a distinctly higher first-stage $^{238}U/^{204}Pb$ (μ_1) of 9.9 compared to the Itsaq gneisses (8.6). They concluded that the significantly different two-stage time-integrated μ_1 values of 9.9 and 8.6 must indicate different immediate precursors. The full significance of their finding can only be retrospectively appreciated because of recent advances in the understanding of terrestrial Pb isotope evolution (Zartmann & Haines 1988; Kramers & Tolstikhin 1997; Kramers *et al.* 1998; Collerson & Kamber 1999; Elliott *et al.* 1999). Here we discuss Moorbath *et al.*'s (1973) BIF Pb isotope data and additional new Pb isotope data (Table 2) in the framework of modern terrestrial Pb isotope models.

In Figure 4a, a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, we plot the Pb isotope compositions of IGB sediments. Shown separately are the most significant published data points of the BIF unit for which the actual regression line is also drawn. The important observation, implicit in Moorbath *et al.*'s (1973) finding of a high first-stage μ_1, is that the BIF regression intersects possible mantle evolution curves (here Kramers & Tolstikhin 1997) at a much younger date (*c.* 3.3 Ga) than the deposition age (3.71 Ga). The most likely explanation for this observation is that the Pb that was incorporated into the

Table 2. *Pb isotope data for Isua carbonate rocks*

Sample	Method	$^{206}Pb/^{204}Pb$	±	$^{207}Pb/^{204}Pb$	±	$^{208}Pb/^{204}Pb$	±	Corr-Coeff (7/6)	Corr-Coeff (8/6)
248486/A	wr	12.814	0.039	13.931	0.044	32.610	0.103	0.949	0.998
248486/A	1M HCl	12.570	0.008	13.850	0.010	32.511	0.023	0.953	0.964
248486/A	6M HCl	12.606	0.020	13.866	0.022	32.626	0.052	0.975	0.992
248486/A	1M HNO_3	13.215	0.008	13.957	0.010	33.005	0.023	0.947	0.964
248486/A	HF	12.585	0.006	13.851	0.007	32.215	0.019	0.965	0.951
248486/B	wr	13.317	0.040	14.049	0.045	33.345	0.101	0.949	0.998
248486/B	1M HCl	12.759	0.008	13.898	0.010	33.186	0.024	0.956	0.966
248486/B	6M HCl	12.877	0.021	13.926	0.023	33.597	0.056	0.979	0.993
248486/B	1M HNO_3	15.019	0.020	14.236	0.020	35.425	0.050	0.978	0.990
248486/B	HF	13.048	0.008	13.940	0.009	32.571	0.022	0.961	0.962
248486/D	wr	12.719	0.038	13.885	0.044	32.395	0.098	0.949	0.998
248486/D	1M HCl	12.406	0.016	13.813	0.018	32.226	0.043	0.984	0.989
248486/D	6M HCl	12.504	0.023	13.844	0.026	32.518	0.060	0.980	0.994
248486/D	1M HNO_3	12.740	0.005	13.845	0.007	32.424	0.018	0.951	0.947
248486/D	HF	12.634	0.008	13.848	0.010	32.129	0.023	0.960	0.965
248486/G	wr	12.968	0.039	13.976	0.044	32.833	0.099	0.949	0.998
248486/G	1M HCl	12.559	0.164	13.813	0.181	32.507	0.424	0.994	1.000
248486/G	6M HCl	12.625	0.023	13.867	0.026	32.683	0.060	0.973	0.994
248486/G	1M HNO_3	13.493	0.007	14.013	0.008	33.204	0.020	0.940	0.953
248486/G	HF	12.727	0.008	13.910	0.010	32.373	0.023	0.949	0.965
248487/A	wr	13.090	0.039	14.007	0.044	33.098	0.100	0.949	0.998
248487/A	1M HCl	12.630	0.011	13.884	0.013	33.415	0.032	0.971	0.979
248487/A	6M HCl	12.733	0.031	13.900	0.035	33.819	0.083	0.979	0.997
248487/A	1M HNO_3	13.558	0.019	14.089	0.020	33.896	0.049	0.982	0.990
248487/A	HF	13.052	0.009	13.970	0.011	32.484	0.026	0.967	0.970

Pb isotopes were measured at the Universities of Oxford (whole rocks) and Queensland. Queensland data were obtained on a multi-collector TIMS in static mode using pyrometer temperature control (1300–1325°C). During the relevant period, NBS SRM 981 yielded the following reproducibilities: $^{206}Pb/^{204}Pb = 16.911 \pm 28$; $^{207}Pb/^{204}Pb = 15.458 \pm 36$; $^{208}Pb/^{204}Pb = 36.600 \pm 114$.

All reported ratios are fractionation corrected ($-0.057 \pm 17\%$/amu, $n = 12$; calculated from all ratios). Internal errors quoted at 2 sigma level are similar to or better than external reproducibilities.

Of each rock, a whole-rock (wr) split was measured and a separate aliquot was subjected to a step-wise dissolution in Teflon beakers with (i) 1M HCl (10 min at room temperature); (ii) 6M HCl (20 min at room temperature); (iii) 1M HNO_3 (24 h at 110°C); (iv) 12M HF (24 h at 130–150°C).

chemically precipitated BIF had a very different isotope composition from coeval mantle. Other possible chemical metasediments, such as carbonates, plot co-linear with the BIF data (Fig. 4a) and also indicate evolution of Pb in a high μ environment prior to incorporation in the carbonate. Regression lines through data from clastic sediments (e.g. garnet–mica schists), while also plotting subparallel, intersect the mantle evolution curve at c. 3.6 Ga (much closer to the actual deposition age). In our view, the difference in apparent mantle evolution intersection age of the BIF data is significant and deserves further treatment.

Of critical importance is the question of how high a plausible μ of Earth's early Archaean surface could have been. In Figure 4b, a $^{207}Pb/^{206}Pb$ versus $^{204}Pb/^{206}Pb$ diagram, the evolution of one possible Pb isotope model is shown (i.e. defined to intersect the BIF regression line at 3.71 Ga). The two parameters that define this model are an early mantle separation age, here chosen as 4.2 Ga, and an elevated μ of 13.8 compared to that of model MORB-source mantle (after Kramers & Tolstikhin 1997). Obviously the younger the mantle separation age, the higher the μ in the reservoir from which the BIF Pb derived. Figure 4c shows that for a separation age of 3.8 Ga, the required μ is 41. Separation ages between 4.2 Ga and 3.8 Ga will yield μ values ranging from 13.8 to 41 (Fig. 4c). High model μ values (13.8–41) would normally be associated with continental crust, and marine high μ Pb could, in this case erroneously, be interpreted to argue that the early Archaean surface Pb was dominated by continental run-off. This is, however, not a possibility because the first terrestrial Pb paradox (e.g. Kramers & Tolstikhin 1997), Nb-Th-U systematics (Collerson & Kamber 1999) and further evidence (as outlined before) strongly argue against a voluminous early continental crust in the modern sense. An interesting solution is found by inspection of Pb isotope systematics of lunar rocks. It is, unfortunately, not possible to directly compare lunar rocks with terrestrial Pb isotope evolution because the Moon experienced a different mode of siderophile element fractionation (e.g. Kramers 1998) and because the bulk silicate Moon's initial μ is unknown (e.g. Tatsumoto *et al.* 1987). The important observation, however, is that the μ of different lunar lithologies is highly variable and that some of the highest μ values are found in mare basalts. Tatsumoto *et al.* (1987) argued that, while poorly defined, the Moon probably evolved with a μ in the range of 19 to 55, much lower than the μ of mare basalts (around 300). Nyquist & Shih (1992) highlighted the roles of ilmenite and trapped liquids as potential agents for strong U/Pb fractionation. Whether broadly comparable volcanism existed on Earth remains an elusive question but, if so, it would imply that substantial areas of the planet (such as covered by mare on the Moon) could have been covered by basaltic rock with a μ of at least six times the bulk silicate Moon. Scaled to the Earth's bulk silicate μ (c. 8), this would translate to a potential surface μ of almost 50. The high $^{207}Pb/^{206}Pb$ ratio of the IGB chemical sediments could therefore be explained by weathering of basaltic crust (possibly produced by impact melting) with an age of c. 200 Ma (approximately the culmination age of heavy meteorite bombardment, cf. Cohen *et al.* 2000) at the time of erosion.

In summary, geological, isotopic and geochemical records of the Earth's oldest identifiable sediments indicate the absence of a substantially older local basement. In contrast, chemical sediments offer a tantalizing glimpse of a Moon-like pre-3.8 Ga terrestrial surface.

Initial isotope constraints from IGB metavolcanic rocks

Basaltic volcanics are the major probes for reconstruction of mantle depletion history by most radiogenic isotope systems (Sm-Nd, Lu-Hf and Re-Os) and some geochemical proxies (e.g. Nb-Th). It is therefore not surprising that attempts have been made at using the IGB metabasalts for constraining the degree of depletion (or enrichment) of the early Archaean mantle. Unfortunately, such attempts are facing a multitude of problems that relate to unsystematic sampling strategies, deformational and metamorphic overprints, metasomatism, and a general lack of reliable trace element characterization of the rocks that are somewhat carelessly grouped under the term 'metabasalts' or 'supracrustals'. There is no doubt since publication of the meticulous reports by Gruau *et al.* (1996) and Rosing *et al.* (1996), respectively, that isotopic and geochemical resetting and metasomatic overprint, particularly in the depleted metabasalts, require utmost care in interpretation of back-corrected initial isotope values of these rocks. Two recent papers by Blichert-Toft *et al.* (1999) and Albarède *et al.* (2000) have attempted to use Isua 'supracrustals' to search for a memory of early differentiation processes. These authors claim, based on the same data set, that the 3.8 Ga mantle was geochemically structured and that this structure was partly inherited from the initial differentiation of the Earth. The claims of the first publication by Blichert-Toft *et al.* (1999) have since been shown to be invalid (Villa *et al.*, 2001), due to: (i) use of an inadequate Lu decay constant; (ii) unsupported back-correction of parent isotope decay 100 Ma past the isochron age; (iii) inherent assumption of the existence of an isotopic mantle array; (iv) complete disregard of other geochemical and geochronological constraints derived from Isua and elsewhere.

Much of this criticism applies especially to the arguments of Albarède *et al.* (2000). These authors, too, back-calculate ^{147}Sm and ^{176}Lu decay to 3.8 Ga despite the fact that their samples define 3.7 Ga regression dates. Totally irrespective of the significance of the 3.7 Ga regression dates (i.e. rock formation ages versus isotope resetting ages), parent decay cannot under any circumstances be back-corrected past that time. Any conclusion drawn from such a violation of this simple isotopic principle is therefore by definition flawed and needs no further discussion here. Although geochemical study of basalts is naturally preferred over study of more evolved igneous rocks for much of the geological record, this intuitive choice may not be the best for the early Archaean. We suggest that because of the general lack of older continental basement and sediment, and their much higher incompatible trace element contents compared to basalts, evolved igneous rocks offer a better chance to reconstruct the degree of early mantle depletion.

Northern Labrador, Canada

The early Archaean rocks of the Saglek–Hebron area of northern Labrador have many similarities with the penecontemporaneous evolution of rocks in the Godthaabsfjord region of southern West Greenland, with which they were once contiguous (Bridgwater & Collerson 1976; Bridgwater *et al.* 1978; Collerson & Bridgwater 1979), but far less age and isotope work has been published than on the West Greenland rocks. Conventional dating by Rb-Sr, U-Pb, Pb/Pb and Sm-Nd methods, summarized by Schiøtte *et al.* (1986), clearly indicated an early Archaean age >3.5 Ga, but also showed that the so-called Uivak gneisses were much more disturbed by late Archaean events than the approximately equivalent Itsaq (then called Amîtsoq) orthogneisses of West Greenland. Ion-probe zircon U-Pb dates based on maximum ^{207}Pb/^{206}Pb ratios from three separate Uivak gneiss samples agree within error at 3732 ± 6 Ma, interpreted as age of emplacement of the magmatic precursors (Schiøtte *et al.* 1989). A few of these gneisses contain rounded zircon inclusions (observed by photomicrography) with dates up to 3863 ± 12 Ma, regarded as inherited from an older source region.

The early Archaean Nulliak (supracrustal) assemblage was broken up by intrusion of the protoliths of the Uivak gneisses and then deformed, metamorphosed and metasomatized (Nutman *et al.* 1989). The Nulliak assemblage is regarded as broadly equivalent in age and origin to the IGB and Akilia association rocks of West Greenland (see earlier). The three oldest ion-probe zircon U-Pb dates with a mean of 3776 ± 8 Ma were obtained on an acid metavolcanic rock from the Nulliak assemblage. This was regarded by Schiøtte *et al.* (1989) as the age of deposition of the volcanic precursor.

We comment here briefly on a Sm-Nd study of mafic/ultramafic gneisses by Collerson *et al.* (1991). These authors obtained geochemical and Sm-Nd isotope data on two suites of rocks. The first is a group of ultramafic gneisses that occur interleaved with 3.7 Ga Uivak I gneisses. Based on their major element composition, these ultramafic gneisses were interpreted as tectonically emplaced fragments of lithospheric mantle. They yielded a Sm-Nd isochron date of 3.82 ± 0.12 Ga with an intercept corresponding to a strongly positive ε_{Nd} of 3.0 ± 0.6. According to Collerson *et al.* (1991), the radiogenic initial Nd isotope composition would support an origin of the protoliths in the subcontinental lithospheric mantle, which is widely regarded as a depleted residual reservoir. Some later studies, however, have misquoted the large degree of depletion shown by these gneisses as indicating strong and early depletion of the depleted (MORB-source) mantle (Bowring & Housh 1995; McCulloch & Bennett 1994). Collerson *et al.* (1991) noted that the radiogenic initial Nd of these rocks is in conflict with their light rare-earth-element enrichment (relative to chondrite). This was explained in terms of re-enrichment shortly before tectonic emplacement at *c.* 3.7 Ga. In a more recent study, Wendt & Collerson (1999) analysed the same samples for Pb isotope compositions. Pb isotopes failed to shed further light on the early Archaean history as the U-Pb system in many of these samples appears to have been disturbed during subsequent geological events.

The second group of rocks studied by Collerson *et al.* (1991) comprised five subsamples of metakomatiite taken from a single outcrop. These depleted rocks, which differ in their major- and trace-element chemistry from the lithospheric mantle suite, yield an age of 3.83 ±

0.17 Ga with an initial ε_{Nd} of 0.23 ± 1.58. This implies that these komatiites could have been derived from a largely undepleted mantle source. Such an interpretation is supported by the 3.85 ± 0.16 Ga Pb-Pb regression age and model μ_1 of 7.9 obtained on these samples by Wendt & Collerson (1999). The Pb isotopes thus also indicate that the peridotite source of these melts was largely undepleted. Wendt & Collerson (1999) included in their regression a sample of metabasaltic komatiite from a different outcrop. In contrast to the U-Pb system, the Sm-Nd regression parameters change markedly when the metabasaltic komatiite sample is included. Collerson *et al.* (1991) obtained a combined regression date of 4.02 ± 0.19 Ga with an initial ε_{Nd} of -2.11 ± 2.33. While they noted that, within (the large) errors, the fitting parameters agreed with those of the metakomatiite proper regression, they appear to attach more significance to the combined result. The negative ε_{Nd} of the combined regression was thus interpreted to indicate contamination by continental crust (with low time-integrated Sm/Nd) of a melt from an ultradepleted peridotite source. We question the use of a single datum point, such as the metabasaltic komatiite, to calculate speculative early mantle parameters because: (i) Pb isotopes fail to show such mantle complexity, but agree with a younger age of the metakomatiites and an origin from an undepleted mantle; and (ii) the metabasaltic komatiite sample has an unreasonably negative ε_{Nd} of -4.12 at 3.8 Ga.

Other early Archaean regions

Only brief summaries are given here of regions where presence of in-situ early Archaean rocks is claimed or suspected. The list is not exhaustive, and we do not review rocks younger than 3.5 Ga. Published evidence may be insufficient or inconclusive, particularly when based solely on unimaged zircon grains from orthogneisses. The most frequent supporting evidence for claims of early Archaean ages from zircon dates consists of isolated maximum Sm-Nd model ages (T_{DM}, based on a conventional depleted-mantle model). Sometimes they are broadly concordant with zircon U-Pb dates, but any discordance may be due to uncertainty in interpretation of the zircon date, or to Sm-Nd open-system behaviour. In most of the cases summarized below, much more work is required in order to clarify the true geochronological and geological significance of the reported early Archaean dates.

Australia

The oldest terrestrial mineral ages yet reported until very recently are in the range 3.91 to 4.27 Ga for detrital zircons from much younger (*c.* 3.1 Ga) quartzites in the Mount Narryer complex and from the Jack Hills metasedimentary belt, both in the Yilgarn craton of western Australia (Froude *et al.* 1983; Compston & Pidgeon 1986; Maas & McCulloch 1991; Maas *et al.* 1992). The ion-probe data from Jack Hills were supported by precise U-Pb isotope dilution of detrital zircons (Amelin 1998), with an age range of 3.82–4.11 Ga.

Very recently, detrital zircon grains with U-Pb ages as old as 4.3 to 4.4 Ga have been reported from western Australia (Wilde *et al.* 2001; Mojzsis *et al.* 2001), with the oldest grain analysed yielding an age of 4404 ± 8 Ma. This whole topic is discussed in more detail in a later section.

The oldest known in-situ gneisses in western Australia do not approach the detrital zircon dates. The Manfred complex in the Yilgarn craton yields a zircon U-Pb date of 3.73 Ga (Kinny *et al.* 1988), together with approximate Sm-Nd and Pb/Pb regression dates of *c.* 3.68–3.69 Ga (Fletcher *et al.* 1988). The enclosing Meeberrie orthogneiss complex contains multiple generations of magmatic zircons at *c.* 3.6–3.7 Ga (Kinny & Nutman 1996).

In the ancient Pilbara craton, Nelson *et al.* (1999) quote a zircon U-Pb date of 3655 ± 6 Ma from a banded gneiss as the oldest age. From an angular unconformity beneath rocks of the *c.* 3.46 Ga Warrawoona Group, Buick *et al.* (1995) demonstrate a record of emergent, buoyant continental crust at *c.* 3.5 Ga.

South Africa and Zimbabwe

Numerous conventional and single zircon U-Pb measurements show that the Ancient Gneiss Complex of Swaziland, which forms the basement to the *c.* 3.5–3.2 Ga Barberton Greenstone Belt, contains tonalitic orthogneisses with an age of *c.* 3.65 Ga (Compston & Kröner 1988; Kröner & Todt 1988; Kröner *et al.* 1991, 1996; Kröner & Tegtmeyer 1994). Sporadic Sm-Nd (T_{DM}) model ages go back to 3.7–3.8 Ga.

Stratigraphical and structural aspects of the formation of the Kaapvaal craton of southern Africa have been summarized by De Wit *et al.* (1992), whilst chronological correlation between the Kaapvaal craton and the Pilbara craton of western Australia is described by Nelson *et al.* (1999). In both cases, crustal development began at *c.* 3.65 Ga.

The oldest gneisses of Zimbabwe yield conventional Rb-Sr and Pb/Pb ages of *c.* 3.5 Ga, with some Sm-Nd (T_{DM}) ages of up to *c.* 3.6 Ga (reviewed by Taylor *et al.* 1991). Horstwood *et al.* (1999) report zircon U-Pb evidence suggesting that *c.* 3.5 Ga basement (the 'Sebakwian protocraton') underlies much of the Zimbabwe craton. Ancient, detrital zircons of *c.* 3.7–3.8 Ga have been reported in much younger greenstone-belt sediments (Dodson *et al.* 1988; Nägler *et al.* 1997).

Of particular significance is a Re-Os study of chromites from age-constrained (2.7–3.5 Ga) ultramafic inclusions in the Zimbabwe craton (Nägler *et al.* 1997). The data show that the Zimbabwean subcontinental lithospheric mantle (SCLM) began to separate from asthenospheric mantle just before 3.8 Ga and grew quasi-continuously throughout the Archaean. Similar studies elsewhere have shown that in Archaean cratons the time of SCLM Re depletion broadly matches the formation ages of the overlying crust (Pearson *et al.* 1995*a*, *b*; Shirey & Walker 1998). No Os isotope evidence has yet been reported for pre-4.0 Ga separation of SCLM from the mantle.

West Africa

A 3.05 Ga orthogneiss from northern Nigeria contains zircons with inherited cores at 3.56 Ga (Bruguier *et al.* 1994). Zircon U-Pb dates of *c.* 3.5 Ga are reported from orthogneiss in the West African craton of Mauretania, whilst Sm-Nd (T_{DM}) model ages of 3.9–3.5 Ga are reported for adjacent metasediments (Potrel *et al.* 1996).

Antarctica

Black *et al.* (1986) reported ion-probe U-Pb data for zircons from a granulite orthogneiss from Mount Sones, Enderby Land. They regarded the oldest zircon data of 3927 ± 10 Ma as the magmatic age of the tonalite precursor of the orthogneiss. A Sm-Nd (T_{DM}) model age of *c.* 3.85 Ga is quoted by Black & McCulloch (1987). In our view, the true significance (i.e. whether comagmatic or inherited) of this frequently quoted zircon date is uncertain, and much more work is required.

United States

Xenocrystic zircon dates are reported from middle to late-Archaean gneisses in Wyoming by Aleinikoff *et al.* (1989). More recently, Mueller *et al.* (1996) report an ion-probe zircon U-Pb date of *c.* 3.5 Ga from a Wyoming trondhjemitic gneiss. Detrital zircon grains with an age of 3.96 Ga have been reported from a 3.3 Ga quartzite in Montana (Mueller *et al.* 1992).

China

Zircon U-Pb dates in the range 3.6–3.85 Ga have been reported from metasediments in the Qianxi complex of the Sino-Korean craton (Liu *et al.* 1990, 1992). Biao *et al.* (1996) present a model of crustal evolution from 3.8 Ga to 2.5 Ga in the Liaoning province of northeastern China, starting off with two ion-probe zircon U-Pb dates of 3804 ± 5 Ma and 3812 ± 4 Ma, which are interpreted as the age of intrusion of the trondhjemitic protolith of the Baijafen granite. Much more work is required!

Discussion

Age claims for the oldest terrestrial rocks are crucially dependent on the dating methods used. To achieve a convincing synthesis, clearly documented field relationships must be combined with appropriate geochemical and multi-method isotopic approaches (e.g. U-Pb, Pb/Pb, Sm-Nd, Lu-Hf, Rb-Sr). Zircon U-Pb dating in isolation may not be definitive in deciding whether zircon in an orthogneiss is comagmatic with its host rock, or inherited from an older source rock. This, in turn can lead to ambiguity in interpreting initial Nd and Hf isotope ratios in the host rock, not least when combined with subsequent open-system behaviour in the Sm-Nd system, particularly for low-Nd rocks. The Lu-Hf system is less prone to open-system behaviour but, since zircon is the main carrier of Hf in a rock (i.e. very low Lu-Hf), any inherited zircon will itself contain inherited Hf with a different isotopic composition from that in comagmatic zircon. Furthermore, since almost all Hf resides in zircon and almost all Lu resides in the matrix (surrounding the zircon), a later thermal event may result in diffusive transfer of radiogenic Hf from matrix to zircon, where it is unsupported by Lu decay.

We again emphasize the importance of Pb isotope modelling on feldspars and whole rocks for determining the timing of mantle–crust differentiation of the magmatic protoliths of orthogneiss complexes. The extremely high degree of age resolution in the Pb/Pb system is especially useful in those early Archaean orthogneisses (and other rocks) with such low U/Pb ratios that even their present-day Pb isotope composition lies close to the primary Pb/Pb growth curve (e.g. Kramers & Tolstikhin 1997; Kamber & Moorbath 1998).

Bearing the above factors in mind, we regard the following age and isotope scenarios for early Archaean rocks as plausible on the basis of the reviewed evidence. Detailed reference to published work is not repeated below; please refer to previous sections.

The oldest in-situ orthogneisses

By *c.* 3.65 Ga, production of magmatic precursors of typical trondhjemite–tonalite–granodiorite (TTG) gneisses was in progress on a global scale, as confirmed by all dating methods. They are similar in lithology and chemistry to the voluminous TTG gneisses of later epochs and were probably formed by similar petrogenetic mechanisms, involving partial melting of the mantle or of mantle-derived mafic rocks, or differentiation of mantle-derived melts (e.g. Arth & Barker 1976; Martin 1986; Stern & Hanson 1991). This is largely borne out by initial Sr, Pb and Nd isotope ratios, frequently obtained from Rb-Sr, Pb/Pb and Sm-Nd whole-rock and feldspar (for Pb/Pb) regressions, which do not permit a long-term pre-magmatic crustal residence time. Despite frequent significant geological scatter, we place greater confidence in regression ages than some recent workers, especially where there is consistency between different methods and where mixing relationships are unlikely. In this connection, an argument often levelled at the whole-rock regression method is that it generates only average values for the emplacement parameters of a range of non-cogenetic orthogneisses (e.g. Nutman *et al.* 1996), although such arguments about cogenicity are themselves based on the assumption that interpretations of single-grain zircon U-Pb dates are correct.

Potentially promising claims (Nutman *et al.* 1999) for the existence of *c.* 3.8 Ga in-situ orthogneisses south of the Isua region in West Greenland have been made solely from zircon U-Pb data. The claim of a *c.* 4.0 Ga age for the Acasta gneiss of northern Canada (see earlier) needs to be assessed in the light of the intense reworking that these rocks underwent much later, although the existence of a *c.* 4.0 Ga precursor is not in serious doubt from zircon U-Pb and Sm-Nd data. The evidence reported for other 3.8–3.9 Ga claims for in-situ orthogneisses (e.g. Antarctica, China: see earlier) is simply inadequate for a firm conclusion. Much more multi-isotopic work, in combination with detailed zircon imaging, is required to substantiate these claims.

The oldest in-situ supracrustal rocks

Certainly by 3.75–3.70 Ga, and possibly by 3.80–3.75 Ga, a wide range of volcanic rocks, volcanogenic sediments, clastic sediments and chemical sediments were being deposited under marine conditions, as exemplified by the IGB of West Greenland (see earlier). There is as yet no geological evidence for sialic basement to the IGB, nor any compelling age or isotopic evidence in IGB rocks for significant crustal residence time. However, possibly detrital zircons as old as 3.80–3.85 Ga have been reported (Nutman *et al.* 1997*b*), and Pb isotope ratios on chemical sediments suggest a contribution from a much older source (see pp. 189–191).

The picture that emerges from IGB rocks is of predominantly mafic volcanic centres, associated with deposition of shallow-water, coarse- to fine-grained, clastic volcanogenic sediments, as well as deeper-water chemical sediments, such as chert and magnetite-BIF. Carbon isotope evidence suggests that life might have been present (Rosing 1999). No evidence for major bolide impact has yet been found.

The IGB rocks and analogous Akilia and Nulliak associations (see earlier) may be typical of conditions on the Earth's surface at *c.* 3.70–3.75 Ga. The preservation of banded iron formations and pillowed basalts documents the presence of a liquid hydrosphere. Magmatism was typically bimodal (dominantly mafic, subordinately felsic). By comparison with younger Archaean terrains, it appears that magmatic, sedimentary and tectonic styles that dominated until 2.5 Ga were already in operation by 3.7 Ga. Due to the strong metamorphic and metasomatic overprints on these early Archaean volcanic rocks, reliable trace element interpretations could be an elusive goal. Magmatic processes in this time range may be more readily delineated using the more pristine, highly evolved, regional granitoid plutonic rocks which surround the IGB.

The oldest inherited zircons

There is plenty of evidence for detrital zircons in the range *c.* 4.4–3.8 Ga in younger sediments and metasediments from several regions, with the oldest and most spectacular ages occurring in western Australia. In this region, Amelin (1998) thinks that 'the old zircons might have been incorporated through assimilation of sedimentary rocks containing pre-3.9 Ga components by *c.* 3.4 Ga granitoid magmatism'.

The existence of such ancient zircons demonstrates the existence of evolved, intermediate- to high-silica rocks as far back as *c.* 4.4 Ga. The origin and true nature of this crust are unknown, but earlier workers (e.g. Maas & McCulloch 1991; Maas *et al.* 1992) favoured the view from geochemical work, based on rare-earth-element patterns and trace-element ratios, that the detrital zircons were derived from a differentiated continental source of substantial thickness rather than from felsic differentiates within dominantly mafic, oceanic-type crust. More recently, detrital zircons from western Australia in the range of 4.3–4.4 Ga are regarded (Wilde *et al.* 2001; Mojzsis *et al.* 2001) as evidence for the existence of full-scale continental crust. Moreover, an enriched ^{18}O isotope signature is regarded by these authors as the result of low-temperature interaction between the source rock (possibly basaltic rock?) for the original zircon-bearing granitoids and liquid water and, therefore, as evidence for oceans at 4.3–4.4 Ga. These preliminary conclusions remain to be confirmed and must be discussed in the context of the following observations.

(i) Zircon is the only datable accessory mineral that can survive a complex geological history. The survival of accessory minerals is therefore inherently biased towards silicic source rocks, and accessory minerals from very ancient mafic precursors either cannot be dated or did not survive weathering and erosion processes. From the discovery of ancient zircons alone, it cannot be excluded that their provenance could have been from felsic differentiates within a dominantly mafic crust, analogous, for example, to the felsic supracrustal rocks from the Isua greenstone belt at *c.* 3.71–3.81 Ga.

(ii) Amelin *et al.* (1999) reported Hf isotope data for 37 individual zircon grains with U-Pb ages up to 4.14 Ga from the Mount Narryer gneiss complex. They found that none of the grains had a depleted mantle signature, but that many were derived from a source with a Hf isotope composition similar to that of chondritic meteorites. This argues strongly against very early, large-scale differentiation of the mantle to produce major amounts of sialic crust.

(iii) Zircons may have crystallized from chemically evolved impact melts between *c.* 4.4 and 3.8 Ga. If any genuine pre-impact zircons survive from a particular event they might even show shock structures, as suggested by Amelin (1998).

(iv) As a possible analogy to the existence of pre-4.0 Ga terrestrial felsic rocks, it should be noted that zircon-bearing granites and quartz–monzodiorites have been recorded amongst the recovered lunar fragments (Nyquist & Shih 1992). Zircon U-Pb dates from these evolved rocks are in the range 4.32–3.90 Ga, but mostly fall in the upper parts of this range (Meyer *et al.* 1996). The quoted authors conclude that the formation of lunar granite appears not to have been restricted to a single episode in lunar history as, for example, during final solidification of the magma ocean. Rather, it appears to be the result of localized differentiation of individual plutons intruded into the lunar crust.

(v) The ^{18}O-rich isotopic composition in the most ancient (4.3–4.4 Ga) terrestrial zircon grains does not necessarily have to reflect a low-temperature hydrothermal history of the magma source. Halliday (2001) expressed concerns that subsequent diffusional exchange might have affected the O isotope composition of these grains. Furthermore, in view of the fact that the O isotope composition of even the post-3.8 Ga Archaean oceans remains to be determined, we regard the preliminary interpretation of hydrothermal exchange as speculative.

The above discussion has focused on ancient detrital zircons. As will be evident from previous sections, some of the oldest in-situ orthogneisses of magmatic origin contain inherited zircons dating back to 4.0–3.8 Ga, and it is very plausible that older ones may be discovered.

Mantle evolution and differentiation

Critical assessment of Nd and Hf isotope data for early Archaean mantle-derived rocks provides no compelling evidence for large-scale heterogeneities in the depleted mantle. This suggests that apparent enriched-to-depleted heterogeneities may be due to uncertainties in U-Pb, Sm-Nd and Lu-Hf interpretations or may relate to local mantle characteristics that are irrelevant for global differentiation. Based on the absence of evidence for very early depletion of the mantle (and, implicitly, very early growth of continental crust) we conclude, with posthumous apologies to Richard Armstrong, that the volume of early Archaean continental crust was small, and that the scarcity of known outcrops of early Archaean continental crust in part reflects that fact.

Armstrong's (1991) 'no-growth' model for continental crust volume versus time evolution apparently received renewed support from studies of Nb-U systematics of late Archaean basalts (Sylvester *et al.* 1997; Kerrich *et al.* 1999). These studies concluded, based on depletion of U (with respect to Nb) in these rocks, that the volume of continental crust 2.7 Ga ago was similar to the present. However, this interpretation is not supported by Nb-Th systematics, which are expected to show an equivalent degree of depletion (Collerson & Kamber 1999). The answer to this apparent paradox is found in the solution to the second terrestrial Pb paradox in which the present-day Th/U ratio of the mantle is much lower than the time-integrated ratio recorded by Pb isotope systematics of MORB. Kramers & Tolstikhin (1997) and Elliott *et al.* (1999), on the basis of terrestrial Pb isotope systematics, solved the second terrestrial Pb paradox by postulating a strong decrease in the depleted mantle's Th/U ratio after 2.0 Ga. This decrease reflects increased recycling of crustal U once a pandemic oxidizing atmosphere was established (at *c.* 2 Ga). Collerson & Kamber (1999) and Kamber & Collerson (2000), in a study of terrestrial Nb-Th-U systematics, elaborated on the implications of a dynamic mantle Th/U for previous claims of early growth of continental crust based on U depletion alone. They found that in the depleted mantle the Nb/Th ratio is the reliable proxy for the continental crust volume while the Nb/U ratio is additionally influenced by oxygenation of the atmosphere and cannot, therefore, be used to claim support for Armstrong's (1991) 'no-growth' model. On the contrary, Nb/Th, like critically assessed Nd and Hf isotope data, also points to a slow start for continental growth.

A third class of constraints for terrestrial differentiation involves forward transport models that aim at reproducing present-day isotope and trace-element characteristics of the silicate reservoirs (e.g. Zartman & Haines 1988). These models depend on a large number of input parameters, and do not provide unique solutions to differentiation. Nevertheless, some constraints are valid for a wide range of plausible input parameters. Notably, the combination of an average continental Nd isotope mantle extraction age of 2 to 2.5 Ga with the existence of the first terrestrial Pb isotope paradox (i.e. the fact that modern basalts and continental crust plot to the right of the meteorite isochron) is inconsistent with a 'no-growth' continental crust. This is because the large degree of recycling required to achieve the mean continental mantle extraction age would effectively eradicate the first Pb isotope paradox (Kramers & Tolstikhin 1997). Other constraints from forward modelling are more strongly dependent on input parameters and the solutions need to be evaluated not only with how well they fit present data but also with constraints on past evolution. The emerging picture from modelling Pb and Nd isotope systematics (Nägler & Kramers 1998) is that the continental volume increased with time as a roughly S-shaped function. This is fully supported by Nb-Th-U systematics of the mantle, which confirm the importance of changing erosion rates with time for the crust volume versus time curve.

A significant contribution towards understanding differentiation is the determination of the Re-depletion age of subcontinental lithospheric mantle (Shirey & Walker 1998). Such studies of Archaean cratons show that, on average, continents are of similar age to their underlying lithospheric mantle keel. This intuitively confirms geodynamical predictions (e.g. Bickle 1986) for the preservation potential of continental plates. It also appears that any pre-4.0 Ga crust, short of tectonic incorporation into younger continental lithosphere, will have stood little chance of preservation. The implication is that any possibly enriched pre-4.0 Ga crust (as on the Moon) will have been recycled back into convecting mantle without any lasting effect on further differentiation. It cannot be excluded that transition-zone (670 km and 2900 km) mantle heterogeneities could have formed and persisted if large-scale accumulation of majorite and/or perovskite accompanied pre-4.0 Ga crust extraction. Such mantle heterogeneities are alluded to in some isotope studies that recalculate initial isotope ratios for individual samples to the age of the 'most probable' deposition age determined by U-Pb zircon geochronology (e.g. Bennett *et al.* 1993; Bowring & Housh 1995; Blichert-Toft *et al.* 1999; Albarède *et al.* 2000). For reasons outlined throughout this review, we remain sceptical about the validity of these claims.

We still await convincing claims for earliest mantle heterogeneity. Because on the Moon (with which the early Earth may have had some similarities) the U-Pb system experienced a high degree of fractionation, we hope that such studies will include a treatment of Pb isotope systematics.

Summary

We now summarize briefly the salient features arising from the above review of the oldest terrestrial rocks.

The oldest, reliably dated, in-situ granitoid rocks of magmatic origin (orthogneisses), regarded as broadly representative of the type of continental crust formed throughout the rest of Earth history, mostly give ages in the range 3.65–3.75 Ga, and probably up to 3.81 Ga. Claims for older ages back to *c.* 4.0 Ga are still inadequately documented because they are based solely on U-Pb dates of the refractory, recyclable mineral zircon, which could have been inherited from older rocks of unknown type and origin. Such rocks may no longer exist in-situ, or they may not yet have been discovered. Published claims for the existence of true continental crust and oceans back to *c.* 4.4 Ga based on very few detrital zircon grains in much younger metasedimentary rocks from western Australia require far more persuasive and detailed documentation and debate. At this stage of knowledge, alternative explanations for the origin of these zircons are equally, if not more, compelling.

The oldest reliable dates, from in-situ chemical and detrital sedimentary rocks and volcanic rocks (i.e. supracrustal rocks), give ages in the range 3.71–3.81 Ga. They show indubitable evidence for deposition in water (even the volcanic rocks frequently occur as pillow lavas). ^{13}C-depleted graphite microparticles in chemical sediments (subsequently strongly deformed and metamorphosed) from two groups of localities in West Greenland are claimed to be biogenic in origin. Here we summarize evidence to show that the probable age of deposition is in the range of 3.68–3.75 Ga, and not >3.87 Ga as claimed by some workers. Thus these rocks are *c.* 100–200 Ma younger than termination of the putative terrestrial equivalent of the main lunar impact episode at *c.* 3.85–3.90 Ga. Widely publicized claims for temporal overlap of the earliest putative biogenic components (the ^{13}C-depleted graphite microparticles) with massive global impacts are not required from the available age data.

Initial radiogenic isotope ratios (e.g. Nd, Pb, Hf) of reliably dated ancient (<3.8 Ga) orthogneisses from several regions are most simply interpreted as the result of magmatic differentiation from a slightly depleted, close-to-chondritic, essentially homogeneous early Archaean mantle. These results argue strongly against the existence of a sizeable, permanent continental crust prior to *c.* 3.8 Ga.

B.S.K. is supported by Swiss National Science Foundation grant 8220-050352 and M.J.W. acknowledges support from the Swedish Natural Science Research Council (NFR). R. Goodwin provided expert technical assistance with the Greenland Pb-isotope analyses. We thank C. L. E. Lewis and N. Rogers for their helpful reviews.

References

Albarède, F., Blichert-Toft, J., Vervoort, J. D., Gleason, J. D. & Rosing, M. 2000. Hf-Nd evidence for a transient dynamic regime in the early terrestrial mantle. *Nature*, **404**, 488–490.

Aleinikoff, J. N., Williams, I. S., Compston, W., Stuckless, J. S. & Worl, R. G. 1989. Evidence for an early Archean component in the middle to late Archean gneisses of the Wind River Range, West-Central Wyoming – conventional and ion microprobe U-Pb data. *Contributions to Mineralogy and Petrology*, **101**, 198–206.

Allaart, J. H. 1976. The pre-3760 old supracrustal rocks of the Isua area, central West Greenland, and the associated occurrence of quartz-banded ironstone. *In*: Windley, B. F. (ed.) *The Early History of the Earth*. Wiley, London, 177–189.

Amelin, Y. V. 1998. Geochronology of the Jack Hills detrital zircons by precise U-Pb isotope dilution analysis of crystal fragments. *Chemical Geology*, **146**, 25–38.

Amelin, Y., Lee, D. C., Halliday, A. N. & Pidgeon, R. T. 1999. Nature of the Earth's earliest crust from hafnium isotopes in single detrital zircons. *Nature*, **399**, 252–255.

Amelin, Y., Lee, D. C. & Halliday, A. N. 2000. Early-middle Archaean crustal evolution deduced from Lu-Hf and U-Pb isotopic studies of single zircon grains. *Geochimica et Cosmochimica Acta*, **64**, 4205–4225.

Appel, P. W. U. & Moorbath, S. 1999. Exploring earth's oldest geological record in Greenland. *EOS Transactions of the American Geophysical Union*, **80**, 257–264.

Appel, P. W. U., Moorbath, S. & Taylor, P. N. 1978. Least radiogenic terrestrial lead from Isua, West Greenland. *Nature*, **272**, 524–526.

Appel, P. W. U., Fedo, C. M., Moorbath, S. & Myers, J. S. 1998. Recognizable primary volcanic and sedimentary features in a low-strain domain of the highly deformed, oldest known (3.7–3.8 Gyr) greenstone belt, Isua, West Greenland. *Terra Nova*, **10**, 57–62.

Armstrong, R. L. 1991. The persistent myth of crustal growth. *Australian Journal of Earth Sciences*, **38**, 613–630.

Arth, J. G. & Barker, F. 1976. Rare-earth partitioning between hornblende and dacitic liquid and implications for genesis of trondhjemitic-tonalitic magmas. *Geology*, **4**, 534–546.

Baadsgaard, H. 1973. U-Th-Pb dates on zircons from the early Precambrian Amîtsoq gneisses, Godthaab District, West Greenland. *Earth and Planetary Science Letters*, **19**, 22–28.

Baadsgaard, H., Lambert, R. S. & Krupicka, J. 1976. Mineral isotopic age relationships in the polymetamorphic Amîtsoq gneisses, Godthaab District, West Greenland. *Geochimica et Cosmochimica Acta*, **40**, 513–527.

Baadsgaard, H., Nutman, A. P., Bridgwater, D., Rosing, M., McGregor, V. R. & Allaart, J. H. 1984. The zircon geochronology of the Akilia association and Isua supracrustal belt. *Earth and Planetary Science Letters*, **68**, 221–228.

Baadsgaard, H., Nutman, A. P. & Bridgwater, D. 1986*a*. Geochronology and isotopic variation of the early Archaean Amîtsoq gneisses of the Isukasia area, southern West Greenland. *Geochimica et Cosmochimica Acta*, **50**, 2173–2183.

BAADSGAARD, H., NUTMAN, A. P., ROSING, M., BRIDGWATER, D. & LONGSTAFFE, F. J. 1986*b*. Alteration and metamorphism of Amîtsoq gneisses from the Isukasia area, West Greenland: Recommendations for isotope studies of the early crust. *Geochimica et Cosmochimica Acta*, **50**, 2165–2172.

BENNETT, V. C. & NUTMAN, A. P. 1998. Extreme Nd isotope heterogeneity in the early Archean – fact or fiction? Case histories from northern Canada and West Greenland – Comment. *Chemical Geology*, **148**, 213–217.

BENNETT, V. C., NUTMAN, A. P. & MCCULLOCH, M. T. 1993. Nd isotopic evidence for transient, highly depleted mantle reservoirs in the early history of the Earth. *Earth and Planetary Science Letters*, **119**, 299–317.

BIAO, S., NUTMAN, A. P., DUNYI, L. & JIASHAN, W. 1996. 3800–2500 Ma evolution in the Anshan area of Liaoning Province, northeastern China. *Precambrian Research*, **78**, 79–94.

BICKLE, M. J. 1986. Implications of melting for stabilisation of the lithosphere and heat loss in the Archaean. *Earth and Planetary Science Letters*, **80**, 314–324.

BLACK, L. P. & MCCULLOCH, M. T. 1987. Evidence for isotopic equilibration of Sm-Nd whole-rock systems in early Archean crust of Enderby Land, Antarctica. *Earth and Planetary Science Letters*, **82**, 15–24.

BLACK, L. P., GALE, N. H., MOORBATH, S., PANKHURST, R. J. & MCGREGOR, V. R. 1971. Isotopic dating of the very early Precambrian amphibolite gneisses from the Godthaab District, West Greenland. *Earth and Planetary Science Letters*, **12**, 245–249.

BLACK, L. P., WILLIAMS, I. S. & COMPSTON, W. 1986. Four zircon ages from one rock – the history of a 3930 Ma-old granulite from Mount Sones, Enderby Land, Antarctica. *Contributions to Mineralogy and Petrology*, **94**, 427–437.

BLICHERT-TOFT, J., ALBARÈDE, F., ROSING, M., FREI, R. & BRIDGWATER, D. 1999. The Nd and Hf isotopic evolution of the mantle through the Archean. Results from the Isua supracrustals, West Greenland, and from the Birimian terranes of West Africa. *Geochimica et Cosmochimica Acta*, **63**, 3901–3914.

BOAK, J. L. & DYMEK, R. F. 1982. Metamorphism of the ca. 3800 Ma supracrustal rocks at Isua, West Greenland: implications for early Archaean crustal evolution. *Earth and Planetary Science Letters*, **59**, 155–176.

BOWRING, S. A. & HOUSH, T. 1995. The earth's early evolution. *Science*, **269**, 1535–1540.

BOWRING, S. A. & WILLIAMS, I. S. 1999. Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. *Contributions to Mineralogy and Petrology*, **134**, 3–16.

BOWRING, S. A., WILLIAMS, I. S. & COMPSTON, W. 1989. 3.96 Ga gneisses from the Slave province, Northwest Territories, Canada. *Geology*, **17**, 971–975.

BRIDGWATER, D. & COLLERSON, K. D. 1976. The major petrological and geochemical characters of the 3600 Ma Uivak gneisses from Labrador. *Contributions to Mineralogy and Petrology*, **54**, 43–59.

BRIDGWATER, D., COLLERSON, K. D. & MYERS, J. S. 1978. The development of the Archaean gneiss complex of the North Atlantic region. *In*: TARLING, D. H. (ed.) *Evolution of the Earth's Crust*. Academic Press, London, 19–69.

BRUGUIER, O., DADA, S. & LANCELOT, J. R. 1994. Early Archean component (>3.5 Ga) within a 3.05-Ga orthogneiss from northern Nigeria: U-Pb zircon evidence. *Earth and Planetary Science Letters*, **125**, 89–103.

BUICK, R., THORNETT, J. R., MCNAUGHTON, N. J., SMITH, J. B., BARLEY, M. E. & SAVAGE, M. 1995. Record of emergent continental crust *c*. 3.5 billion years ago in the Pilbara Craton of Australia. *Nature*, **375**, 574–577.

CHYBA, C. F. 1993. The violent environment of the origin of life: progress and uncertainties. *Geochimica et Cosmochimica Acta*, **57**, 3351–3358.

COHEN, B. A., SWINDLE, T. D. & KING, D. A. 2000. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. *Science*, **290**, 1754–1756.

COLLERSON, K. D. & BRIDGWATER, D. 1979. Metamorphic development of early Archaean tonalitic and trondhjemitic gneisses, Saglek area, Labrador. *In*: BARKER, F. (ed.) *Trondhjemites, Dacites and Related rocks*. Elsevier, Amsterdam, 205–273.

COLLERSON, K. D. & KAMBER, B. S. 1999. Evolution of the continents and the atmosphere inferred from Th-U-Nb systematics of the depleted mantle. *Science*, **283**, 1519–1522.

COLLERSON, K. D., CAMPBELL, L. M., WEAVER, B. L. & ZENON, A. P. 1991. Evidence for extreme mantle fractionation in early Archaean ultramafic rocks from northern Labrador. *Nature*, **349**, 209–214.

COMPSTON, W. & KRÖNER, A. 1988. Multiple zircon growth within early Archean tonalitic gneiss from the Ancient Gneiss Complex, Swaziland. *Earth and Planetary Science Letters*, **87**, 13–28.

COMPSTON, W. & PIDGEON, R. T. 1986. Jack Hills, evidence of more very old detrital zircons in Western Australia. *Nature*, **321**, 766–769.

COMPSTON, W., KINNY, P. D., WILLIAMS, I. S. & FOSTER, J. J. 1986. The age and Pb loss behaviour of zircons from the Isua supracrustal belt as determined by ion microprobe. *Earth and Planetary Science Letters*, **80**, 71–81.

DE WIT, M., ROERING, C., HART, J. R. *ET AL*. 1992. Formation of an Archaean continent. *Nature*, **357**, 553–562.

DODSON, M. H., COMPSTON, W., WILLIAMS, I. S. & WILSON, J. F. 1988. A search for ancient detrital zircons in Zimbabwean sediments. *Journal of the Geological Society, London*, **145**, 977–983.

ELLIOTT, T., ZINDLER, A. & BOURDON, B. 1999. Exploring the kappa conundrum: the role of recycling in the lead isotope evolution of the mantle. *Earth and Planetary Science Letters*, **169**, 129–145.

FEDO, C. M. 2000. Setting and origin for problematic rocks from the >3.7 Ga. Isua Greenstone Belt, southern West Greenland: Earth's oldest coarse clastic sediments. *Precambrian Research*, **101**, 65–78.

FLETCHER, I. R., ROSMAN, K. J. R. & LIBBY, W. G. 1988. Sm–Nd, Pb–Pb and Rb–Sr geochronology of the Manfred Complex, Mount Narryer, Western-Australia. *Precambrian Research*, **38**, 343–354.

FREI, R., BRIDGWATER, D., ROSING, M. & STECHER, O. 1999. Controversial Pb-Pb and Sm-Nd isotope results in the early Archean Isua (West Greenland) oxide iron formation: preservation of primary signatures versus secondary disturbances. *Geochimica et Cosmochimica Acta*, **63**, 473–488.

FROUDE, C. F., IRELAND, T. R., KINNY, P. D., WILLIAMS, I. S., COMPSTON, W., WILLIAMS, I. R. & MYERS, J. S. 1983. Ion-microprobe identification of 4100–4200 Myr old terrestrial zircons. *Nature*, **304**, 616–618.

GANCARZ, A. J. & WASSERBURG, G. J. 1977. Initial Pb of the Amîtsoq gneiss, West Greenland, and implications for the age of the Earth. *Geochimica et Cosmochimica Acta*, **41**, 1283–1301.

GRIFFIN, W. L., MCGREGOR, V. R., NUTMAN, A., TAYLOR, P. N. & BRIDGWATER, D. 1980. Early Archaean metamorphism south of Ameralik, West Greenland. *Earth and Planetary Science Letters*, **50**, 59–74.

GRUAU, G., ROSING, M. D. B. & GILL, R. C. O. 1996. Metamorphism and Sm-Nd remobilization in the >3.7 Ga Isua supracrustal belt of West Greenland: implications for isotope models of early earth differentiation. *Chemical Geology*, **133**, 225–240.

HALLIDAY, A. N. 2001. In the beginning. *Nature*, **409**, 144–145.

HARPER, C. L. & JACOBSEN, S. B. 1992. Evidence from coupled ^{147}Sm-^{143}Nd and ^{146}Sm-^{142}Nd systematics for very early (4.5 Ga) differentiation of the Earth's mantle. *Nature*, **360**, 728–732.

HORSTWOOD, M. S. A., NESBITT, R. W., NOBLE, S. R. & WILSON, J. F. 1999. U-Pb zircon evidence for an extensive early Archean craton in Zimbabwe: A reassessment of the timing of craton formation, stabilization, and growth. *Geology*, **27**, 707–710.

JACOBSEN, S. B. & DYMEK, R. F. 1988. Nd and Sr isotope systematics of clastic metasediments from Isua, West Greenland: identification of pre-3.8 Ga differentiated crustal components. *Journal of Geophysical Research*, **93**, 338–354.

JACOBSEN, S. B. & HARPER, C. L. 1996. Comment on 'The issue of the terrestrial record of ^{146}Sm'. *Geochimica et Cosmochimica Acta*, **60**, 3747–3749.

KAMBER, B. S. & COLLERSON, K. D. 2000. Variability of Nb/U and Th/La in 3.0 to 2.7 Ga Superior Province ocean plateau basalts: implications for the timing of continental growth and lithosphere recycling – Comment. *Earth and Planetary Science Letters*, **177**, 337–339.

KAMBER, B. S. & MOORBATH, S. 1998. Initial Pb of the Amîtsoq gneiss revisited: implication for the timing of early Archaean crustal evolution in West Greenland. *Chemical Geology*, **150**, 19–41.

KAMBER, B. S., MOORBATH, S. & WHITEHOUSE, M. J. 1998. Extreme Nd-isotope heterogeneity in the early Archaean – fact or fiction? Case histories from northern Canada and West Greenland – Reply. *Chemical Geology*, **148**, 219–224.

KERRICH, R., WYMAN, D., HOLLINGS, P. & POLAT, A. 1999. Variability of Nb/U and Th/La in 3.0 to 2.7 Ga Superior Province ocean plateau basalts: implications for the timing of continental growth and lithosphere recycling. *Earth and Planetary Science Letters*, **168**, 101–115.

KINNY, P. D. & NUTMAN, A. P. 1996. Zirconology of the Meeberrie Gneiss, Yilgarn Craton, Western Australia: An early Archaean migmatite. *Precambrian Research*, **78**, 165–178.

KINNY, P. D., WILLIAMS, I. S., FROUDE, D. O., IRELAND, T. R. & COMPSTON, W. 1988. Early Archean zircon ages from orthogneisses and anorthosites at Mount Narryer, Western-Australia. *Precambrian Research*, **38**, 325–341.

KINNY, P. D., COMPSTON, W. & WILLIAMS, I. S. 1991. A reconnaissance ion-probe study of hafnium isotopes in zircons. *Geochimica et Cosmochimica Acta*, **55**, 849–859.

KRAMERS, J. D. 1998. Reconciling siderophile element data in the Earth and Moon; W isotopes and the upper lunar age limit in a simple model of homogeneous accretion. *Chemical Geology*, **145**, 461–478.

KRAMERS, J. D. & TOLSTIKHIN, I. N. 1997. Two terrestrial lead isotope paradoxes, forward transport modelling, core formation and the history of the continental crust. *Chemical Geology*, **139**, 75–110.

KRAMERS, J. D., NÄGLER, T. F. & TOLSTIKHIN, I. N. 1998. Perspectives from global modelling of terrestrial Pb and Nd isotopes on the history of the continental crust. *Schweizerische Mineralogisch-Petrographische Mitteilungen*, **78**, 169–174.

KRÖNER, A. & TEGTMEYER, A. 1994. Gneiss-greenstone relationships in the Ancient Gneiss Complex of southwestern Swaziland, southern Africa, and implications for early crustal evolution. *Precambrian Research*, **67**, 109–139.

KRÖNER, A. & TODT, W. 1988. Single zircon dating constraining the maximum age of the Barberton greenstone belt, southern Africa. *Journal of Geophysical Research*, **93**, 15 329–15 337.

KRÖNER, A., BYERLY, G. R. & LOWE, D. R. 1991. Chronology of early Archaean granite-greenstone evolution in the Barberton Mountain Land, South Africa, based on precise dating by zircon evaporation. *Earth and Planetary Science Letters*, **103**, 41–54.

KRÖNER, A., HEGNER, E., WENDT, J. I. & BYERLY, G. R. 1996. The oldest part of the Barberton granitoid-greenstone terrain, South Africa: Evidence for crust formation between 3.5 and 3.7 Ga. *Precambrian Research*, **78**, 105–124.

LIU, D. Y., SHEN, Q. H., ZHANG, Z. Q., JAHN, B. M. & AUVRAY, B. 1990. Archaean crustal evolution in China: U-Pb geochronology of the Qianxi Complex. *Precambrian Research*, **48**, 223–244.

LIU, D. Y., NUTMAN, A. P., COMPSTON, W., WU, J. S. & SHEN, Q. H. 1992. Remnants of ≥3800 Ma crust in the Chinese part of the Sino-Korean craton. *Geology*, **20**, 339–342.

McCulloch, M. T. & Bennett, V. C. 1994. Progressive growth of the Earth's continental crust and depleted mantle: Geochemical constraints. *Geochimica et Cosmochimica Acta*, **58**, 4717–4738.

McGregor, V. R. 1973. The early Precambrian gneisses of the Godthaab district, West Greenland. *Philosophical Transactions of the Royal Society of London*, **A273**, 343–358.

McGregor, V. R. 2000. Initial Pb of the Amîtsoq gneiss revisited: implications for the timing of early Archaean crustal evolution in West Greenland – Comment. *Chemical Geology*, **166**, 301–308.

McGregor, V. R. & Mason, B. 1977. Petrogenesis and geochemistry of metabasaltic and metasedimentary enclaves in the Amîtsoq gneisses, West Greenland. *American Mineralogist*, **62**, 887–904.

Maas, R. & McCulloch, M. T. 1991. The provenance of Archean clastic metasediments in the Narryer Gneiss Complex, Western Australia – trace-element geochemistry, Nd isotopes, and U-Pb ages for detrital zircons. *Geochimica et Cosmochimica Acta*, **55**, 1915–1932.

Maas, R., Kinny, P. D., Williams, I. S., Froude, D. O. & Compston, W. 1992. The Earth's oldest known crust: A geochronological and geochemical study of 3900–4200 Ma old detrital zircons from Mt. Narryer and Jack Hills, Western Australia. *Geochimica et Cosmochimica Acta*, **56**, 1281–1300.

Martin, H. 1986. Effect of steeper Archaean geothermal gradient on geochemistry of subduction zone magmas. *Geology*, **14**, 753–756.

Meyer, C., Williams, I. S. & Compston, W. 1996. Uranium-lead ages for lunar zircons: Evidence for a prolonged period of granophyre formation from 4.32 to 3.88 Ga. *Meteoritics and Planetary Sciences*, **31**, 370–387.

Mezger, K. & Krogstad, E. J. 1997. Interpretation of discordant U-Pb zircon ages: An evaluation. *Journal of Metamorphic Geology*, **15**, 127–140.

Miller, C. F., Hatcher, R. D., Ayers, J. C., Coath, C. D. & Harrison, T. M. 2000. Age and zircon inheritance of the Eastern Blue Ridge plutons, southwestern North Carolina and northeastern Georgia, with implications for magma history and the evolution of the Southern Appalachian orogen. *American Journal of Science*, **300**, 142–172.

Mojzsis, S. J. & Harrison, T. M. 1999. Geochronological studies of the oldest known marine sediments. *In*: *Ninth Annual, V. M. Goldschmidt Conference*. Lunar and Planetary Institute, Houston, Contribution No. **971**, 201–202.

Mojzsis, S. J., Arrhenius, G., McKeegan, K. D., Harrison, T. M., Nutman, A. P. & Friend, C. R. L. 1996. Evidence for life on Earth before 3800 million years ago. *Nature*, **384**, 55–59.

Mojzsis, S. J., Harrison, T. M., & Pidgeon, R. T. 2001. Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago. *Nature*, **409**, 178–181.

Moorbath, S. & Kamber, B. S. 1998. A reassessment of the timing of early Archaean crustal evolution in West Greenland. *Geology of Greenland Survey Bulletin*, **180**, 88–93.

Moorbath, S., O'Nions, R. K., Pankhurst, R. J., Gale, N. H. & McGregor, V. R. 1972. Further rubidium-strontium age determinations on the very early Precambrian rocks of the Godthaab district, West Greenland. *Nature*, **240**, 78–82.

Moorbath, S., O'Nions, R. K. & Pankhurst, R. J. 1973. Early Archaean age for the Isua Iron Formation, West Greenland. *Nature*, **245**, 138–139.

Moorbath, S., O'Nions, R. K. & Pankhurst, R. J. 1975. The evolution of early Precambrian crustal rocks at Isua, West Greenland – geochemical and isotopic evidence. *Earth and Planetary Science Letters*, **27**, 229–239.

Moorbath, S., Allaart, J. H., Bridgwater, D. & McGregor, V. R. 1977. Rb-Sr ages of early Archaean supracrustal rocks and Amîtsoq gneisses at Isua. *Nature*, **270**, 43–45.

Moorbath, S., Taylor, P. N. & Jones, N. W. 1986. Dating the oldest terrestrial rocks – fact and fiction. *Chemical Geology*, **57**, 63–86.

Moorbath, S., Whitehouse, M. J. & Kamber, B. S. 1997. Extreme Nd-isotope heterogeneity in the early Archaean – fact or fiction? Case histories from northern Canada and West Greenland. *Chemical Geology*, **135**, 213–231.

Mueller, P. A., Wooden, J. L. & Nutman, A. P. 1992. 3.96 Ga zircons from an Archean quartzite, Beartooth Mountains, Montana. *Geology*, **20**, 327–330.

Mueller, P. A., Wooden, J. L., Mogk, D. W., Nutman, A. P. & Williams, I. S. 1996. Extended history of a 3.5 Ga trondhjemitic gneiss, Wyoming province, USA: Evidence from U-Pb systematics in zircon. *Precambrian Research*, **78**, 41–52.

Myers, J. S. & Crowley, J. L. 2000. Vestiges of life in the oldest Greenland rocks? A review of early Archaean geology in the Godthaabsfjord region, and reappraisal of field evidence for >3850 Ma life on Akilia. *Precambrian Research*, **103**, 101–124.

Nägler, T. F. & Kramers, J. D. 1998. Nd isotopic evolution of the upper mantle during the Precambrian: Models, data and the uncertainty of both. *Precambrian Research*, **91**, 233–252.

Nägler, T. F., Kramers, J. D., Kamber, B. S., Frei, R. & Prendergast, M. D. A. 1997. Growth of subcontinental lithospheric mantle beneath Zimbabwe started at or before 3.8 Ga: A Re-Os study on chromites. *Geology*, **25**, 983–986.

Nelson, D. R., Trendall, A. F. & Altermann, W. 1999. Chronological correlations between the Pilbara and Kaapvaal cratons. *Precambrian Research*, **97**, 165–189.

Nir-El, Y. & Lavi, N. 1998. Measurement of the half-life of ^{176}Lu. *Applied Radiation and Isotopes*, **49**, 1653–1655.

Nutman, A. P., Allaart, J. H., Bridgwater, D., Dimroth, E. & Rosing, M. 1984. Stratigraphic and geochemical evidence for the depositional environment of the early Archaean Isua supracrustal belt, Southern West Greenland. *Precambrian Research*, **25**, 365–396.

Nutman, A. P., Fryer, B. J. & Bridgwater, D. 1989. The early Archean Nulliak (supracrustal) assemblage, Northern Labrador. *Canadian Journal of Earth Sciences*, **26**, 2159–2168.

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 record of early crustal evolution (3,900–3,600 Ma). *Precambrian Research*, **78**, 1–39.

NUTMAN, A. P., MOJZSIS, S. J. & FRIEND, C. R. L. 1997*a*. Recognition of ≥3850 Ma water-lain sediments in West Greenland and their significance for the early Archaean Earth. *Geochimica et Cosmochimica Acta*, **61**, 2475–2484.

NUTMAN, A. P., BENNETT, V. C., FRIEND, C. R. L. & ROSING, M. T. 1997*b*. ~3710 and ≥3790 Ma volcanic sequences in the Isua (Greenland) supracrustal belt; structural and Nd isotope implications. *Chemical Geology*, **141**, 271–287.

NUTMAN, A. P., BENNETT, V. C., FRIEND, C. R. L. & NORMAN, M. D. 1999. Meta-igneous (non-gneissic) tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua supracrustal belt, southern West Greenland: constraints on early crust formation. *Contributions to Mineralogy and Petrology*, **137**, 364–388.

NUTMAN, A. P., BENNETT, V. C., FRIEND, C. R. L. & MCGREGOR, V. R. 2000. The early Archaean Itsaq Gneiss Complex of southern West Greenland: the importance of field observations in interpreting age and isotopic constraints for early terrestrial evolution. *Geochimica et Cosmochimica Acta*, **64**, 3035–3060.

NYQUIST, L. E. & SHIH, C. Y. 1992. The isotopic record of lunar volcanism. *Geochimica et Cosmochimica Acta*, **56**, 2213–2234.

PATCHETT, P. J. 1983. Importance of the Lu-Hf isotopic system in studies of planetary chronology and chemical evolution. *Geochimica et Cosmochimica Acta*, **47**, 81–91.

PATCHETT, P. J. & VERVOORT, J. D. 2000. The poorly determined decay constant of ^{176}Lu. AGU Spring Meeting, Baltimore. American Geophysical Union, S445.

PEARSON, D. G., CARLSON, R. W., SHIREY, S. B., BOYD, F. R. & NIXON, P. H. 1995*a*. Stabilisation of Archaean lithospheric mantle: A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. *Earth and Planetary Science Letters*, **134**, 341–357.

PEARSON, D. G., SNYDER, G. A., SHIREY, S. B., TAYLOR, L. A., CARLSON, R. W. & SOBOLEV, N. V. 1995*b*. Archean Re-Os age for Siberian eclogites and constraints on Archean tectonics. *Nature*, **374**, 711–713.

PIDGEON, R. T. & COMPSTON, W. 1992. A SHRIMP ion microprobe study of inherited and magmatic zircons from four Scottish Caledonian granites. *Transactions of the Royal Society of Edinburgh*, **83**, 473–483.

POTREL, A., PEUCAT, J. J., FANNING, C. M., AUVRAY, B., BURG, J. P. & CARUBA, C. 1996. 3.5 Ga old terranes in the West African Craton, Mauritania. *Journal of the Geological Society, London*, **153**, 507–510.

RICHARDS, J. R. & APPEL, P. W. U. 1987. Age of the least radiogenic galenas at Isua, West Greenland. *Chemical Geology*, **66**, 181–191.

ROSE, N. M., ROSING, M. T. & BRIDGWATER, D. 1996. The origin of metacarbonate rocks in the Archaean Isua supracrustal belt, West Greenland. *American Journal of Science*, **296**, 1004–1044.

ROSING, M. T. 1999. ^{13}C-depleted carbon microparticles in >3700-Ma sea-floor sedimentary rocks from west Greenland. *Science*, **283**, 674–676.

ROSING, M., 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.

RYDER, G. 1990. Lunar samples, lunar accretion and the early bombardment of the Moon. *EOS (Transactions of the American Geophysical Union)*, **71**, 322–323.

SCHIDLOWSKI, M. 1988. A 3800-Million-Year isotopic record of life from carbon in sedimentary rocks. *Nature*, **333**, 313–318.

SCHIDLOWSKI, M., APPEL, P. W. U., EICHMANN, R. & JUNGE, C. E. 1979. Carbon isotope geochemistry of the 3700 myr-old Isua sediments, West Greenland: Implications for the Archaean carbon and oxygen cycle. *Geochimica et Cosmochimica Acta*, **43**, 189–199.

SCHIØTTE, L. & COMPSTON, W. 1990. U-Pb age pattern for single zircon from the early Archaean Akilia association south of Ameralik fjord, southern West Greenland. *Chemical Geology*, **80**, 147–157.

SCHIØTTE, L., BRIDGWATER, D., COLLERSON, K. D., NUTMAN, A. P. & RYAN, A. B. 1986. Chemical and isotopic effects of late Archaean high-grade metamorphism and granite injection on early Archaean gneisses, Saglek-Hebron, northern Labrador. *In*: DAWSON, J. B., CARSWELL, D. A., HALL, J. & WEDEPOHL, H. H. (eds) *The Nature of the Lower Continental Crust*. Geological Society, London, Special Publications, **24**, 261–273.

SCHIØTTE, L., COMPSTON, W. & BRIDGWATER, D. 1989. Ion probe U-Th-Pb zircon dating of polymetamorphic orthogneisses from northern Labrador. *Canadian Journal of Earth Sciences*, **26**, 1533–1556.

SHARMA, M., PAPANASTASSIOU, D. A., WASSERBURG, G. J. & DYMEK, R. F. 1996. The issue of the terrestrial record of ^{146}Sm. *Geochimica et Cosmochimica Acta*, **60**, 2037–2047.

SHIMIZU, H., NAKAI, S., TASAKI, S., MASUDA, A., BRIDGWATER, D., NUTMAN, A. P. & BAADSGAARD, H. 1988. Geochemistry of Ce and Nd isotopes and REE abundances in the Amîtsoq gneisses, West Greenland. *Earth and Planetary Science Letters*, **91**, 159–169.

SHIREY, S. B. & WALKER, R. J. 1998. The Re-Os isotope system in cosmochemistry and high-temperature geochemistry. *Annual Reviews in Earth and Planetary Sciences*, **26**, 423–500.

SÖDERLUND, U., MÖLLER, C., ANDERSSON, J., JOHANSSON, L. & WHITEHOUSE, M. (in press). Zircon geochronology in polymetamorphic gneisses in the Sveconorwegian orogen, SW Sweden: ion microprobe evidence for 1.46–1.42 and 0.98–0.96 Ga reworking. *Precambrian Research*.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, **26**, 207–221.

STERN, R. A. & BLEEKER, W. 1998. Age of the world's oldest rocks refined using Canada's SHRIMP: The Acasta gneiss complex, Northwest Territories, Canada. *Geosciences Canada*, **25**, 27–31.

STERN, R. A. & HANSON, G. N. 1991. Archean high-Mg granodiorite – a derivative of light rare-earth-element-enriched monzodiorite of mantle origin. *Journal of Petrology*, **32**, 201–238.

SYLVESTER, P. J., CAMPBELL, I. H. & BOWYER, D. A. 1997. Niobium/uranium evidence for early formation of the continental crust. *Science*, **275**, 521–523.

TATSUMOTO, M., PREMO, W. R. & UNRUH, D. M. 1987. Origin of lead from green glass of Apollo-15426 – a search for primitive lunar lead. *Journal of Geophysical Research*, **92**, E361–E371.

TAYLOR, P. N., KRAMERS, J. D., MOORBATH, S., WILSON, J. F., ORPEN, J. L. & MARTIN, A. 1991. Pb/Pb, Sm-Nd and Rb-Sr geochronology in the Archean Craton of Zimbabwe. *Chemical Geology*, **87**, 175–196.

VERVOORT, J. D. & BLICHERT-TOFT, J. 1999. Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. *Geochimica et Cosmochimica Acta*, **63**, 533–556.

VILLA, I. M., KAMBER, B. S. & NÄGLER, T. N. 2001. The Nd and Hf isotopic evolution of the mantle through the Archean. Results from the Isua supracrustals, West Greenland, and from the Birimian terranes of West Africa – comment. *Geochimica et Cosmochimica Acta*, **65**, 2017–2021.

WENDT, J. I. & COLLERSON, K. D. 1999. Early Archaean U/Pb fractionation and timing of late Archaean high-grade metamorphism in the Saglek-Hebron segment of the North Atlantic Craton. *Precambrian Research*, **93**, 281–297.

WHITEHOUSE, M., KAMBER, B. S. & MOORBATH, S. 1999. Age significance of ion-microprobe U-Th-Pb zircon data from early Archaean rocks of West Greenland – a reassessment based on new combined ion-microprobe and imaging studies. *Chemical Geology*, **160**, 204–221.

WHITEHOUSE, M. J., NÄGLER, T. F., MOORBATH, S., KRAMERS, J. D., KAMBER, B. S. & FREI, R. 2001. Discussion: Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. *Contributions to Mineralogy and Petrology*, **141**, 248–250.

WILDE, S. A., VALLEY, J. W., PECK, W. H. & GRAHAM, C. M. 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, **409**, 175–178.

WILHELMS, D. E. 1987. *The Geologic History of the Moon*. United States Geological Survey Professional Papers, **1348**.

YAMASHITA, K., CREASER, R. A., JENSEN, J. E. & HEAMAN, L. M. 2000. Origin and evolution of mid- to late-Archean crust in the Hanikahimajuk Lake area, Slave Province, Canada; evidence from U-Pb geochronological, geochemical and Nd-Pb isotopic data. *Precambrian Research*, **99**, 197–224.

ZARTMAN, R. E. & HAINES, S. 1988. The plumbotectonic model for Pb isotopic systematics among major terrestrial reservoirs – A case for bi-directional transport. *Geochimica et Cosmochimica Acta*, **52**, 1327–1339.