Review of the oldest (4400–3600 Ma) geological and mineralogical record: Glimpses of the beginning

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Review of the oldest (4400–3600 Ma) geological and mineralogical record: Glimpses of the beginning

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Known occurrences of rocks from the first billion years (>3550 Ma) form a minuscule ~10,000 km² of Earth's surface. The largest areas are in Greenland (Itsaq Gneiss Complex), Labrador and Western Australia, with smaller ones elsewhere in Greenland and in Antarctica, China and the Acasta area, Canada (containing the oldest-known terrestrial rocks at ~4030 Ma). 4000–4400 Ma detrital zircons in sediments at Mt Narryer and the Jack Hills, Western Australia are another important part of the first billion years record. The Itsaq Gneiss Complex (Greenland) has the largest domains of least strain and migmatisation, with the most recognisable (amphibolite facies) sedimentary, volcanic and plutonic structures. These show a "normal" Earth by ~3800 Ma, with a hydrosphere, life and division of the lithosphere into granitic and mafic components of unremarkable composition. There is no apparent geological evidence for the effects of impacts. Isotopic and petrographic work on ancient Western Australian zircons implies granites and hydrosphere were present on Earth 4400–4200 million years ago. Isotopic studies of first billion years rocks and minerals show that juvenile granitoids were added repeatedly to continental crust in the Archaean, core formation occurred in the first 100 million years and also the mantle differentiated early on into chemically distinct domains.

Introduction

At the end of the 1960s there was a perverse situation in that the Apollo missions had already given geologists and geochemists ancient lunar rocks to study, but at that time Earth's first billion years (4550–3550 Ma) geological record was unknown. At the start of the 1970s, >3600 Ma rocks were first recognised in West Greenland (see below) and are now recognised at several places around the world. There has since flourished a new branch of geology—study of the earliest Earth via observation and measurement. Recent *Nature* articles (Wilde et al., 2001; Mojzsis et al., 2001) describing new results from very ancient zircon grains including one with a possible age of 4400 Ma, combined with the search for evidence of life on Mars and in the earliest terrestrial geological record (e.g., Mojzsis et al., 1996) have renewed interest in the identification and study of early Archaean terrains. The purpose of this article is to review what has been learnt from the currently-known >3600 Ma terrestrial geological record, and also to consider the prospects of finding more ancient rocks and minerals.

It is important to stress that accurate knowledge of Earth's first billion years is a broad multidisciplinary science, with people of different backgrounds equally important. Field geologists together with geochronologists play a critical role in first documenting ancient rocks. However, geologist's field observations in these difficult terrains by no means hold the monopoly on the truth (e.g. on lithostratigraphic correlations between isolated outcrops), but it is often underrated how important they are in providing the context to interpret sophisticated laboratory results obtained from samples. The very different skills of analytical instrument design and developing laboratory techniques are also essential in progress in understanding the early Earth. Examples of major contributions of this sort are (i) the prototype large ion microprobe SHRIMP I for *in situ* isotopic (particularly U/Pb) and trace element analysis of ~20 μm wide domains, built by Bill Compston, Steve Clement, mechanical engineers and electronics experts at the Australian National University and (ii) development in the Royal Ontario Museum by Tom Krogh and associates of methods for obtaining precise U/Pb dates from single zircons by IDTIMS (isotope dilution, thermal ionisation mass spectrometry) methods. These two developments have been particularly important in providing a precise (<±0.3%) and accurate chronology of the whole Archaean geological record. Without the advent of instruments such as large ion microprobes, and developments in ICPMS and IDTIMS technologies and analytical chemistry, our knowledge of the early Earth would be of far more limited scope and less certain.

The study of the first billion years geological record has two purposes:

First, does the oldest terrestrial geological record give evidence of a very young "non-uniformitarian" Earth? We define here the uniformitarian Earth as having a retained hydrosphere and biosphere, with its lithosphere divided into mafic oceanic and felsic continental domains—whose form and structure is governed by internal convection. Sometime in the very distant past, the structure and composition of the lithosphere should have been strongly influenced or governed by large impacts, which might have delivered enough energy to Earth's exterior to exclude a permanent hydrosphere and made life on the surface impossible. This hypothetical lithosphere might have resembled the moon's, with its shocked and brecciated gabbro/anorthosite "primordial" crust and "seas" of flood basalts marking the largest impact sites. However, as shown below, the geological record appears uniformitarian, to certainly ~3850 Ma, and probably to well before 4000 Ma.

The second purpose is what does the first billion year rock and mineralogical isotopic record tell about chronology and nature of

Earth's accretion and its early differentiation into compositionally distinct reservoirs? Also, when was established the present interacting system of mantle, hydrosphere and atmosphere moderated by the biosphere—which is the hallmark of most, and maybe all of the observed geological record? These questions not only look inwards at the Earth but also outwards to the other planets, meteorites and the early solar system.

The 3550 Ma geological record

Known preserved first billion years geological provinces are in global terms minuscule, and underlie ~10,000 km^2—about the combined size of several large cites like Beijing and São Paulo. There are three large terrains, the Itsaq Gneiss Complex in the Nuuk region of Greenland (e.g., McGregor, 1973; Nutman et al., 1996; Figure 1), the Uivak Gneisses (and their inclusions) in neighbouring parts of northeast Labrador (e.g., Collerson et al., 1976; Schiøtte et al., 1989) and the Narryer Gneiss Complex in Western Australia (e.g., de Laeter et al., 1981; Myers, 1988; Nutman et al., 1991). Unfortunately, the Narryer Gneiss Complex is very poorly exposed, reducing considerably the area of ≥3550 Ma rocks to study. In addition to these three large terranes there are several smaller ones, such as <20 km^2 Mt Sones and nearby nunataks in Antarctica (e.g., Black et al., 1986; Harley and Black, 1997), <20 km^2 for 4030–3600 Ma parts of the Acasta Gneisses, Northwest Territories, Canada (e.g., Bowring and Williams, 1999; Stern and Bleeker, 1998) and also <1000 km^2 in two additional >3550 Ma terrains in West Greenland (e.g., the newly-discovered Aasivik terrane, Rosing et al., 2001, Figure 1). Not all occurrences of the most ancient rocks are in remote polar regions or deserts. In northeastern China, there are two occurrences of ~3800 Ma rocks (Liu et al., 1992; Song et al., 1996), totalling ~1km^2—one of these outcrops in a park in Anshan city! In addition, elsewhere there are some limited exposures of gneisses (e.g. Ancient Gneisses in southern Africa) which are either marginally in the "first billion years" or for which a great age has not been widely accepted.

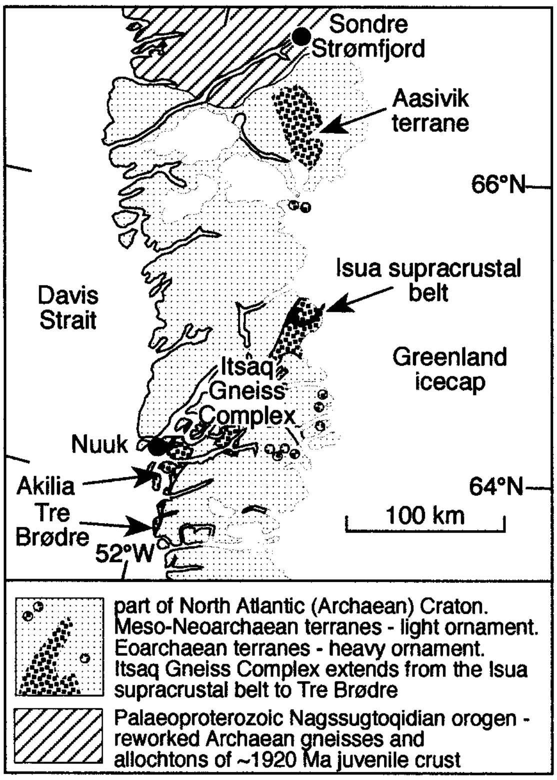

***Figure 1** Location of known Eoarchaean rocks in West Greenland. They probably form one or more (Neoarchaean) allochthonous bodies, extending for >400 km.*

Another part of the first billion years geological record are 4400–3600 Ma detrital zircons found in younger sediments. They are most abundant in ~3000 Ma quartzites at Mt. Narryer and the Jack Hills, intercalated with the Narryer Gneiss Complex (Froude et al., 1983; Wilde et al., 2001; Mojzsis et al., 2001), in some ~3500 Ma? quartzites ~150 km east of Beijing, China (Liu et al., 1992) and also important in ~3200 Ma quartzites in the Beartooth Mountains, Wyoming, USA (e.g., Mueller et al., 1998).

In addition to the rareness of the earliest rocks, another complication is that they are always within gneiss complexes and have suffered multiple amphibolite facies or granulite facies metamorphism. Consequently, most of the >3550 Ma geological record consists of highly strained migmatites (see back cover of this issue of *Episodes*), from which it is hard to extract detailed information on the protoliths. In extreme cases combined heat and deformation can blend together units of different age and origin into a virtually homogeneous gneiss, providing an undecipherable puzzle for geologists/geochemists. For the most readily interpretable and reliable information on early Earth magmatism, sedimentation and volcanism geologists try and avoid these complexities altogether by finding domains of lowest strain and least *in situ* migmatisation.

The >3550 Ma geological record—uniformitarian or exotic?

More space is devoted here to >3550 Ma rocks of West Greenland (Figure 1) than any other area. This is because they constitute the largest, most continuous exposures, they have been studied in most detail, and they contain very rare occurrences of the best preserved first billion years geological record in low strain domains (e.g., Figure 2).

Itsaq Gneiss Complex (includes former Amîtsoq gneisses), West Greenland

The ~3000 km^2 of >3550 Ma rocks of the Nuuk region of southern West Greenland (Figure 1) were the first of their type to be recognised. In the late 1960s, as a graduate student, the late Vic McGregor was trying to persuade the geological establishment of that time that some amphibolite facies gneisses containing the Ameralik dykes (locally discordant tabular amphibolite bodies) were the oldest in the region (see back cover). Eventually in 1970, the first isotopic (Pb-Pb whole rock) measurements on his samples were undertaken in

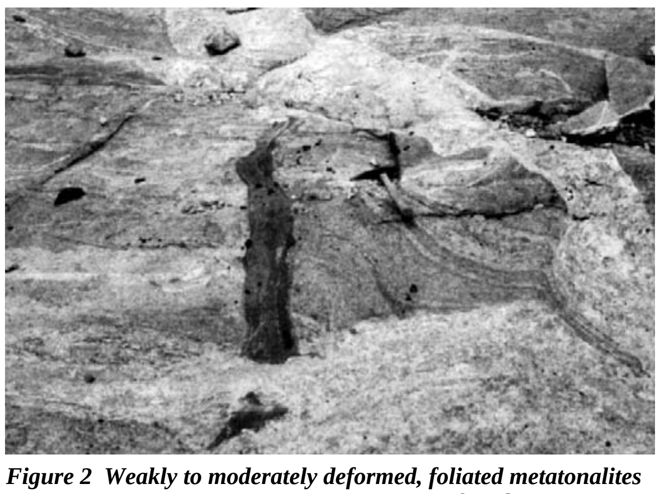

***Figure 2** Weakly to moderately deformed, foliated metatonalites (light grey) cut by vertical ("Inaluk") dykes of mafic diorite and gabbro (dark grey), and then by inclined (white) undeformed leucogranite sheets (Nutman and Bridgwater, 1986). At this locality there has been no deformation since ~3650 Ma when the granite sheets were intruded (Nutman et al., 1996, 2000)!*

Oxford by Lance Black, then a post-doctoral fellow with Stephen Moorbath, and demonstrated the survival of ≥3600 Ma terrestrial materials (Black et al., 1971). McGregor called the >3600 Ma gneisses cut by the Ameralik dykes the Amîtsoq gneisses, whereas the younger gneisses not cut by the dykes were called the Nûk gneisses. Amîtsoq gneisses was a useful term in the 2 decades after it was introduced, but has led to confusion because it lumps together different groups of rocks of different origin and age (see Nutman et al., 2000 for discussion). Thus in the 1990s McGregor and coworkers coined the phrase Itsaq Gneiss Complex (Nutman et al., 1996) for all the ≥3600 Ma rocks in the Nuuk region (i.e. the Amîtsoq (ortho)gneisses, the Isua supracrustal belt and the diverse suites of "Akilia association" supracrustal rock, metagabbro and ultramafic rock inclusions)—in order to stress their diverse origins and spread of ages (Figure 3).

Moorbath et al. (1973) showed that the 35 km long Isua supracrustal belt in the north of the complex (Figure 1) was 3800–3700 million years old. This is still the largest-known body of early supracrustal rocks and remains the most studied part of the first billion years geological record. The Isua supracrustal belt and Akilia (island) are two of the most familiar names in early Archaean geology and early-life literature. They should not be treated interchangedly (section 3.5) as they are 150 km distant (Figure 1) and have very different geologic histories (Nutman et al., 2000).

The Itsaq Gneiss Complex is in Neoarchaean tectonic contact with adjacent Meso-Neoarchaean orthogneiss-dominated complexes, with all of these rocks subsequently intruded by Neoarchaean crustally-derived granites (*sensu stricto*) (Friend et al., 1987, 1988, 1996). The Itsaq Gneiss Complex is currently interpreted as a tectonostratigraphic terrane juxtaposed with unrelated younger rocks between 2820–2720 Ma, which were then folded together and underwent amphibolite facies metamorphism between 2720–2700 Ma (McGregor et al., 1991; Friend et al., 1996). In the Itsaq Gneiss Complex, Neoarchaean tectonothermal events were superimposed on similar earlier ones. Consequently, high cumulate ductile deformation (± *in situ* migmatisation) has obscured original relationships between different rocks throughout much of the Complex (McGregor, 1973). However, thanks to strain partitioning, there are areas of relatively low Neoarchaean and older strain, which in fortuitous localities coincide. These areas with least total strain are most abundant in the northern end of the complex (Bridgwater and McGregor, 1974) and are currently the subject of detailed study by several research groups.

Sedimentary and volcanic structures and stratigraphy in the Isua supracrustal belt—evidence on the early surficial environment

Stratigraphy, volcanic and sedimentary structures provide vital information on surficial processes, the hydrosphere, atmosphere and influx of cosmogenic material. In the ≥3550 Ma geological record, such information can be used as a measure of "uniformitarianism". Presently, the most extensive and well-preserved record of this sort is in the 3800–3700 Ma Isua supracrustal belt. However, in interpretation of these rocks, it should not be ignored that they have suffered variable and locally intense modification during metasomatism (e.g., Rosing et al., 1996). Bridgwater and McGregor (1974) reported conglomeratic structures in its felsic rocks, and Allaart (1976) added discoveries of water-lain rounded chert pebble conglomerates, now studied in great detail by Fedo (2000). Nutman et al. (1984a) described metagreywackes with recognisable Bouma sequences from the northwest of the belt (first seen by McGregor in the 1970s) and graded felsic volcanosedimentary rocks plus chert breccias in the northeast of the belt. Maruyama et al. (1992) and Komiyama et al. (1999) described their discoveries of rare, spectacularly well-preserved pillow lavas interlayered with chert and pillow fragment breccias, missed in all previous studies (e.g., by Nutman et al., 1984a). These are now being studied further under new research initiatives (e.g., Appel et al., 1998). These studies have so far revealed nothing unusual about surficial processes at 3800–3700 Ma, with now several reports of subaqueous volcanic rocks and shallow to deeper water sediments resembling those in younger terranes. Conversely, there has been one report of possible cosmic chromite grains in BIF of the belt (Appel, 1979), but so far no definitive geochemical or sedimentary evidence of widespread ejecta deposits or shock features have been found in the earliest sedimentary record.

From the earliest studies, it was noted that the Isua supracrustal belt had a crude, bilateral symmetry to the outcrop of different lithologies (Bridgwater and McGregor, 1974). Using lithological correlations, the facing directions of then known relict sedimentary and volcanic structures and a reasonable assumption 17 years ago that all rocks of the belt were approximately the same age, Nutman et al. (1984a) erected a stratigraphic scheme for the belt. Renewed work on the belt in the early 1990s showed that this stratigraphy was wrong, and it was criticised and abandoned by Nutman et al. (1996, 1997a) and then later repeatedly criticised by others (most recently by Myers, 2001). Key factors for Nutman et al.'s abandonment of this stratigraphy were (i) recognition by Maruyama et al. (1992) of volcanic structures in a large amphibolite unit interpreted by all previous workers as a large altered gabbroic sill, and (ii) zircon geochronology (Nutman et al., 1996, 1997a) which demonstrated that the belt contains packages of volcanosedimentary rocks differing in age by ~100 million years. However, within these different packages, there is in places a semblance of stratigraphy, where "successions" of lithologies are consistent over many kilometres along strike. Presently, these are still the largest remnants of early Archaean "stratigraphy" to work on, and they resemble lithological associations in younger volcanosedimentary sequences, such as in some late Archaean greenstone belts.

Tectonic intercalation of unrelated rocks—Eoarchaean collisional tectonics?

Eoarchaean tectonic intercalation of unrelated rocks was reported in the Itsaq Gniess Complex by Nutman (1984)—notably documentation of an early mylonite marking the northern edge of the Isua supracrustal belt. Maruyama et al. (1992) and Komiyama et al. (1999) proposed that the Isua supracrustal belt is a duplex complex, which includes Eoarchaean layer-parallel faults between "tops" of BIF/chert units and "overlying" metabasaltic amphibolites, whereas Rosing et al. (1996) and Nutman et al. (1997a, in press) proposed that the belt contains thicker panels of (unrelated) supracrustal rocks in Eoarchaean tectonic contact with each other. Models of the style of Nutman et al. (1997a) have been adopted in more recent remapping of the belt (Myers, 2001). Thus there is gaining acceptance that Eoarchaean tectonics included intercalation of unrelated packages of rocks—a common feature in collisional orogens of all ages. This is adding weight to favouring various plate tectonics models governing the evolution of the oldest recognised crust (e.g., from Talbot, 1973 to deWit, 1998).

Compilation of geological information and Australian National University, Hiroshima University, and National Institute of Polar Research (Tokyo) SHRIMP U/Pb zircon dating of 70 rocks (>2000 zircon analyses) from the Itsaq Gneiss Complex (Figure 3) indicates the presence of several suites of supracrustal and plutonic rocks developed over ~300 million years (Nutman et al., 1993, 1996). On the basis of regional whole rock isochrons with large errors and poor statistical validity, Moorbath et al. (1997) and Kamber and Moorbath (1998) offered an alternative explanation, that rocks mostly formed between 3650–3600 Ma, apart from the Isua supracrustal belt. Here, using arguments set out in Nutman et al. (2000) we will follow our interpretation of the complex as containing rocks up to 300 million years different in age. Events vary between different parts of the Complex, which constitutes more than one Neoarchaean slice, probably derived from different parts of a larger Eoarchaean terrane.

Up to ~3680 Ma, the Complex is interpreted as displaying growth of new crust by successive emplacement of isotopically juvenile tonalites into piles of (tectonically imbricated?) supracrustal

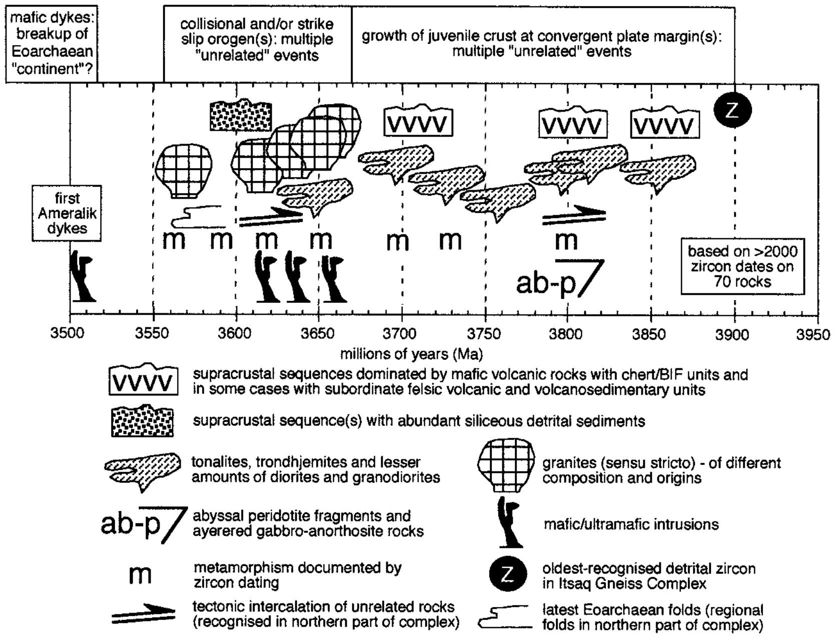

Figure 3 Summary of events and phases in the >3500 Ma evolution of the Itsaq Gneiss Complex, Greenland. See text for details and references.

rocks dominated by mafic volcanics, intercalated with abyssal peridotite slices (Friend et al., in review). In the period 3670–3560 Ma crustal evolution was more diverse, with multiple episodes of crustally-derived granites and mantle-derived mafic intrusions (e.g., Nutman et al., 1984b, 2001; Nutman and Bridgwater, 1986) plus some tonalites and locally supracrustal sequences with abundant detrital sediments. In this period zircon geochronology records several high grade metamorphic events (Nutman et al., 2000). There is evidence for further tectonic intercalation/thrusting between 3610–3640 Ma (Nutman et al., in press), followed by regional folding before 3510 Ma (probably pre-syn metamorphism at 3580–3560 Ma). Furthermore, thermobarometry on rare relicts of ~3600 Ma granulites indicated that by that time the crust had considerable thickness (>25 km) with "normal" apparent thermal gradients (Griffin et al., 1980).

Although known in less detail, the other large Eoarchaean terranes of Labrador (e.g., Schiøtte et al., 1989; Collerson et al., 1991; Collerson and Regelous, 1995), and the Narryer Gneiss Complex (e.g., Myers, 1988; Nutman et al., 1991; Kinny and Nutman, 1996) also show complicated series of events. These records steer us away from simplistic models of all rocks in any ancient complex being related and having formed in a single "mega-event" like an impact. Instead they seem to be the products of many overlapping events, probably occurring at or near convergent plate margins over 200–300 million years.

Eoarchaean igneous record

O'Nions and Pankhurst (1974) published REE patterns for a selection of Itsaq Gneiss Complex orthogneisses. The REE patterns varied between samples and were clear evidence of the petrogenetic diversity of the oldest crust. Since then, there have been profuse major, trace and RE element petrogenetic studies on ≥3600 Ma rocks, which have all underscored the petrogenetic diversity and relative "normalness" of the igneous rocks in the oldest crust as first realised in the 1970s. Nothing has been found resembling in composition or structure the lunar crust or expected products from an early terrestrial "magma ocean". For granitoids, dominant are tonalite suites like those found throughout the Archaean (e.g., McGregor, 1979; Collerson and Bridgwater, 1979; Nutman et al., 1999), but also found are composite granite–quartzmonzonite–ferrogabbro suites resembling some post-Archaean "within-plate" granitoid suites (e.g., Nutman et al., 1984b, 1996) and leucogranites (Nutman and Bridgwater, 1986). Modern studies have concentrated as much as possible on low strain zones, with those in and around the Isua supracrustal belt having so far provided the most information. Figure 2 shows north of the belt moderately to weakly foliated (locally folded) 3690 Ma metatonalites, first cut by weakly deformed mafic/ultramafic dykes, and then by undeformed 3650 Ma granite sheets (Nutman and Bridgwater, 1986; Nutman et al., 1996, 2000). Rare occurrences of undeformed 3800 Ma metatonalites occur to the south of the belt (Nutman et al., 1999)!

Oldest evidence for life and a hydrosphere in the Itsaq Gneiss Complex—by 3700 Ma or 3850 Ma?

In the 3800–3700 Ma Isua supracrustal belt, West Greenland, there are water-lain detrital and chemical sediments (e.g., Moorbath et al., 1973; Allaart, 1976; Nutman et al., 1984a; Komiyama et al., 1999; Fedo, 2000). Isotopically-light carbon in graphite from metasediments in the belt gives evidence for biological activity at the time these sediments were deposited (Schidlowski et al., 1979; Mojzsis et al., 1996; Rosing, 1999). Thus there is considerable direct evidence for life and a hydrosphere on Earth by 3700 Ma.

150 km to the southwest on Akilia island (Figure 1) there is debate over whether there is evidence for life and hydrosphere at ≥3850 Ma. At the southwestern tip of Akilia there is a large (>100 m across) body of Eoarchaean amphibolite to granulite facies mafic and ultramafic rocks derived at least in part from volcanics, in which there are layers of BIF/metachert. On the basis of field relations (sheets of tonalite within this body) combined with ion microprobe zircon U/Pb dating (Figure 4) it has been proposed that the BIFs and mafic rocks are ≥3850 Ma old (Nutman et al., 1996, 1997b, 2000; Mojzsis and Harrison, 2000). Ion microprobe *in situ* carbon-isotopic analysis of graphite inclusions in apatites from metacherts at this locality revealed "light" carbon (Mojzsis et al., 1996). These "chemofossils" led these authors to propose that this locality has direct evidence of emergence of terrestrial life and a hydrosphere before 3850 Ma (Mojzsis et al., 1996; Nutman et al., 1997b). These interpretations, particularly the ~3850 Ma age determinations for rocks, have been contested and criticised on the basis of excellent U/Pb zircon dating and petrography (but interpreted without taking full account of the field geology) by Whitehouse et al. (1999) and by a Pb-Pb whole rock and feldspar errochron of 3654±73 Ma (with a very low indication of validity given by MSWD=17.6) on regional collections of whole rocks and feldspars from the Itsaq Gneiss Complex (Kamber and Moorbath, 1998). Furthermore, Myers and Crowley (2000) disputed that a tonalite body (G93/05—dated at ~3850 Ma) is a discordant sheet within the amphibolites, with BIF units on southwestern Akilia. Figure 4 shows the relationship between the dated tonalite body and neighbouring lithologies, with representative zircon images and dates obtained from the tonalite. This locality is one of continuing debate. If finally generally accepted that these rocks are ≥3850 Ma old, then they comprise the oldest known part of the sedimentary, volcanic and biological record.

Evidence for a hydrosphere back to 4400–4300 Ma and the lunar versus terrestrial cratering record

Further back in time, evidence for a hydrosphere becomes more indirect as >3900 Ma sediments have not yet been discovered. The oldest-known terrestrial rocks are ~4030 Ma components in the Acasta

Gneisses, Canada (Stern and Bleeker, 1998; Bowring and Williams, 1999). In composition some of these resemble tonalites which dominate the Archaean geological record, and which are produced by partial melting in the garnet stability field of hydrated mafic rocks (e.g., Martin, 1999). Hence, following the adage "No water no granites—no oceans no continents" of Campbell and Taylor (1983), the nature of these rocks permits a hydrosphere by ~4000 Ma.

Zircons grow predominantly from granitic (*sensu lato*) melts. Thus when >4000 Ma detrital zircons from quartzites at Mt. Narryer and the Jack Hills in the Narryer Gneiss Complex were first discovered, it was realised that they were permissive of "continental" crust on Earth before 4000 Ma (Froude et al., 1983). Petrographic investigation of >4000 Ma zircons discovered monazite and quartz inclusions (Maas et al., 1992; Wilde et al., 2001), and most recently oxygen isotope studies of these grains show that they grew from a granitoid melt whose source material had undergone low temperature hydrothermal alteration (Wilde et al., 2001; Mojzsis et al., 2001). This is now strong evidence for a hydrosphere as early as 4300–4400 Ma.

The lunar surface shows clear evidence of major bombardment, lasting to after 3900 Ma (e.g., Baldwin, 1974). It has been assumed by some planetologists that Earth had a similar history of bombardment, which was then highly influential in development of its Eoarchaean crust (Lowman, 1989). If so, it has been argued that repeated delivery of large amounts of energy to Earth's surface would not have permitted a retained hydrosphere and hence surface life before ~3900 Ma. Recent models suggest however that the Earth could have undergone early bombardment without total loss of the hydrosphere. For example, Arrhenius and Lepland (2000) suggested that the lunar cratering record reflects collisions in the period 4000–3500 Ma of a receding moon with a series of small, original satellites of the Earth and their debris. Effect on Earth of these encounters would be small. Thus the model of Arrhenius and Lepland (2000) permits a cool and relatively tranquil Earth surface before 4000 Ma. This could allow a retained hydrosphere and a suitable setting for life to emerge, well before the oldest documented chemofossils and water-lain sediments from West Greenland.

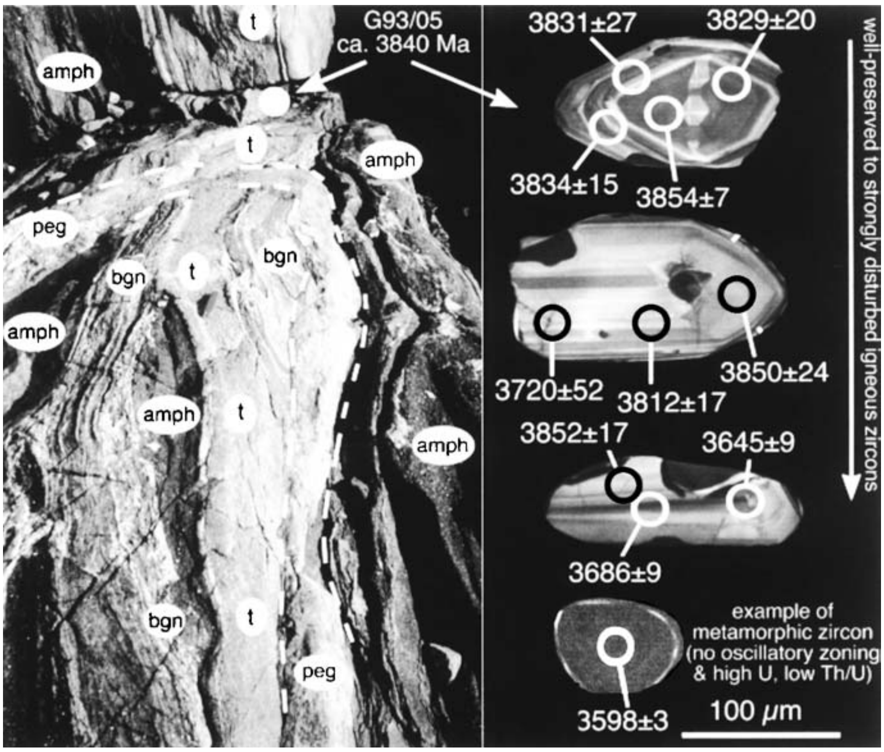

Figure 4 (left-hand side) Field relations of a tonalite body with adjacent rocks on Akilia, West Greenland. t = tabular homogeneous tonalite body from which sample G93/05 was dated. bgn = banded grey heterogeneous gneisses. amp = banded amphibolites derived at least in part from volcanic protoliths. peg = folded late Archaean pegmatite. (right-hand side) Examples of dated zircons from G93/05. The age and relationship of the tonalite body t is debated. We would argue that it is a discordant intrusive sheet (note its left-hand side contact with bgn and amph) with an age of ~3850 Ma, making the amphibolites older. Myers and Crowley (2000) doubt the tonalite body is a discordant sheet and Kamber and Moorbath (1998) and Whitehouse et al. (1999) doubt its great age.

Constraints on Earth's formation and early history from the isotopic study of >3550 Ma rocks and minerals

Since Black et al. (1971) there has been 30 years of isotopic study of terrestrial >3550 Ma rocks and minerals. A large amount of this study has been primarily for age determinations, but some has been specifically targeted on broader aspects of early terrestrial evolution. It should be noted that some younger samples also can give information on the early Earth. For example, excess ^{129}Xe in some mantle-derived samples relative to atmospheric xenon has been attributed to early major degassing of the Earth before the total decay of now extinct ^{129}I (half life 17 million years; e.g., Staudbecker and Allegre, 1982). The first landmark findings in the 1970s based on first billion years samples were largely from whole rock studies, whereas later ones have increasingly used mineral analyses. Improvements in ion microprobe and laser ablation ICPMS technologies are giving greater analytical precision and the possibility to examine new geochemical problems. Hence in this field analysis on an intra-grain (20-50 μm) scale will increase in importance.

So far, it has been demonstrated that the core separated and the planet was largely degassed in the first few tens of million years, and that the mantle differentiated early on into chemically distinct regions, which have never been rehomogenised. Juvenile material has been added repeatedly to the "continental" crust from the mantle.

Age of the Earth and timing of core separation: The moon, meteorites and Pb isotopic studies of ancient K-feldspars and galenas from Greenland

The oldest rock ages from the moon of 4562±70 Ma (Alibert et al., 1994) and numerous age determinations of meteorites starting with 4556 Ma constrain the age of the Earth. In addition, arguments based on the comparative $^{182}W/^{184}W$ systematics (^{182}W is produced from ^{182}Hf with a half life of only 9 million years) of terrestrial samples, chondrites and Fe-meteorites place a time of ~60 million years between start of accretion and core "closure" (Lee and Halliday, 1996).

Looking inwards to Earth, since the 1950s (Patterson, 1956) Pb isotopic compositions of terrestrial materials combined with those of meteorites have been used to study the age of the Earth and early fractionation processes like core formation (Pb is strongly siderophile relative to U and Th, thus likely is preferentially segregated into the core). From the 1970s to the present (Gancarz and Wasserburg, 1977 to Kramers and Tolstikin, 1997), the most primitive composition on all terrestrial Pb isotopic evolution curves has been provided by ancient high Pb concentration, low U-, K-feldspars and galenas from the Itsaq Gneiss Complex of Greenland.

The K-feldspars with the least radiogenic Pb measured in terrestrial silicates are from rather mafic granites in a ~3630 Ma composite intrusion. This intrusion contains remelted older crustal material (back to 3850–3800 Ma?) and via associated gabbros, mantle-derived material as well (Nutman et al., 1984b). Several K-feldspar separates have significantly different Pb-isotopic ratios (Gancarz and Wasserburg, 1977; Kamber and Moorbath, 1998). This could be due to either some "pollution" by more radiogenic Pb during partial recrystallisation of the K-feldspars in younger tectonic events, or that K-feldspars from different rock samples have variable amounts of crustal Pb derived from remelted older crust versus mantle-derived Pb. These K-feldspar Pb compositions certainly cannot be taken as reflecting that of the mantle at 3630 Ma.

Some galenas in 3800–3700 Ma Isua supracrustal belt rocks have the least radiogenic terrestrial Pb isotopic compositions yet measured (Appel et al., 1978; Richards and Appel, 1987). However, the galena's isotopic compositions vary, and they commonly occur in late, sometimes cross-cutting veins (Appel et al., 1978) and from our observations also as strands and discordant veins in Eoarchaean mylonites. Given these considerations, even the most primitive Pb of these galenas can only provide maximum constraints on mantle compositions at 3800 or 3700 Ma. They may still reflect some time of crustal evolution in a uranium and thorium-bearing environment prior to isolation of the lead into the galenas. Considering such complexities in the setting of the old K-feldspars and galenas is important in using their Pb isotopic compositions to derive information on the earliest Earth.

Window onto the Eoarchaean mantle from Os isotopic studies

The Re-Os isotopic characteristics of mantle peridotites are providing a new perspective on deep chemical reservoirs and mantle evolution. This is due to the contrasting behaviour of this system and its relative insensitivity to secondary alteration in peridotites compared with the lithophile element based Rb-Sr and Sm-Nd isotopic systems. Within the Itsaq Gneiss Complex, Os isotopic study of whole rocks and their olivine and aluminous spinel separates from rare relicts of well preserved ~3800 Ma abyssal peridotites trapped in the crust at ~3800 Ma (Friend et al., in review) are providing the first direct constraints on the Os isotopic evolution of the early mantle (Bennett et al., in review). The new results indicate that the highly siderophile elements Re and Os were present in the 3800 Ma mantle at approximately chondritic abundances. As it is generally considered that the highly siderophile component of the silicate Earth was emplaced post-core formation by the addition of a meteoric "late veneer" (e.g., Chou, 1978), the results from the early peridotites constrain the timing of this component in that it must have been added to the Earth and homogenised into the mantle and be available for sampling by 3800 Ma. Additionally, the Os isotopic compositions of the Eoarchaean peridotites provide no evidence for the presence of large amounts of stored mafic crust in the early Archaean mantle.

Nd and Hf isotopic evidence for upper mantle depletion early in the Earth's history

Initial whole rock Nd isotopic compositions indicate that the Eoarchaean mantle contained reservoirs that had experienced long term depletion in light REE and by inference other incompatible elements (e.g., Hamilton et al., 1983; Collerson et al., 1991; Bennett et al., 1993). Collerson et al. (1991) undertook measurements directly on ~3800 Ma upper mantle relicts within the Uivak gneisses of north-eastern Labrador. Most other measurements were on granitic (*sensu lato*) and mafic rocks whose precursor materials were thought to have had short crustal residence since mantle extraction.

The timing and severity of this differentiation is of considerable interest in constraining early terrestrial evolution. Some workers (e.g. Moorbath et al., 1997) would argue for lesser degree of early depletion, such that 3800–3700 Ma rocks display maximum ε_{Nd}(3800) values of only +1.5 to +2.0. This would be in accord with differentiation events starting before 4300 Ma and with a quasi-linear increase in ε_{Nd} in the upper mantle to the values of ~+10 observed in modern MORB. This is permissive of a "steady state" model for mantle structure and crustal growth through time. Other workers have argued for more strongly depleted domains in the early mantle, such that 3800 Ma rocks derived from it could have ε_{Nd}(3800) of +3.0 to +4.0 (Collerson et al., 1991; Bennett et al., 1993). This degree of depletion is observed in the early lunar mantle (Carlson and Lugmair, 1988). Unmodified, such strongly depleted terrestrial mantle reservoirs would give rise to modern MORB with ε_{Nd}(3800) >>+10. Various models could account for the subsequent buffering of mantle isotopic composition. For example, McCulloch and Bennett (1994) suggested that in a cooling Archaean Earth, changes in convectional style after 3750 Ma meant that previous uppermost highly depleted mantle reservoirs were modified by mixing/buffering with underlying less-depleted domains. Regardless of the degree of mantle depletion, all researchers agree that the Nd isotopic system requires that the Eoarchaean mantle was already depleted, probably as a result of very early extraction of incompatible element enriched (mafic or felsic) crust.

An interesting twist to the Nd story is the search for live ^{146}Sm (half life = 103 million years which decays to ^{142}Nd) in Eoarchaean rocks when they formed. This would be detected by deviations from the present-day ^{142}Nd/^{144}Nd ratio (a ^{142}Nd anomaly) and combined with the type of lithology in which any anomalies were found, would provide more clues on the timing and nature of very early planetary fractionation events. Harper and Jacobsen (1992) suggested that rare Isua supracrustal belt samples might have very small ^{142}Nd anomalies—whose veracity is a subject of debate and remeasurement by other geochemists.

More recently, the investigation of early mantle fractionation and depletion has been made from the perspective of Hf isotope study of whole rocks and of Eoarchaean zircons whose ages are known by U/Pb dating. Some studies (Vervoort et al., 1996) confirmed existence of early-depleted reservoirs in the mantle, but questioned the degree of depletion proposed by Collerson et al. (1991) and Bennett et al. (1993). However, other integrated whole rock Hf and Nd isotopic studies (Albarede et al., 2000) support earlier whole rock Nd isotopic evidence for high degrees of early depletion, and are in accord with the ideas of some mantle mixing/buffering event after 3750 Ma, as proposed by Bennett et al. (1993). Preliminary single-grain Hf isotopic studies have been made on ~4000 Ma detrital zircons from Western Australia (Amelin et al., 1999). These results have slightly positive to negative ε_{Hf}(4000), permissive of derivation shortly before from a non-depleted mantle reservoir or from remelting of older crustal rocks derived a long time before from depleted mantle.

Sr and Nd isotopic studies showing addition of juvenile material to a ?growing crust

In the early 1970s, the low initial ^{87}Sr/^{86}Sr ratios on the first "Amitsoq" isochron suites showed that the newly discovered ancient Greenland rocks were dominated by juvenile additions to the crust, rather than representing reworked much older ("primordial") crust (Moorbath et al. 1972). This was a key contribution in recognising that juvenile material had been added to the crust throughout the Archaean (Moorbath, 1975). Subsequently, multiple Nd isotopic studies (above) of Eoarchaean tonalites agree with this important result. However, it is a misconception to use these observations in isolation to argue for an increasing mass of continental crust. Although it is now well demonstrated that continents have grown throughout Earth history, this is only one side of the continental mass-balance equation with the magnitude of the flux of continental material back into the mantle more difficult to constrain (e.g., Bowring and Housch, 1995).

Prospect of further discoveries of more ancient rocks and minerals

With ~10,000 km^2 exposure currently known, study of the first billion years is a "needle in a haystack" problem, with a key aspect being to find more areas of >3550 Ma rocks for study. In these discoveries, integrated geological and geochronological studies are considered important, however non-geological (chance) factors have also contributed. Thus several important finds during reconnaissance geological surveying were more due to chance than geological logic (which emerged after the first age determinations were produced).

Search has traditionally taken place in Archaean basement terranes. In northeast China and the Acasta district of Canada, the oldest rocks are inclusions in younger Archaean granitoids and gneisses (e.g., Bowring and Williams, 1999; Liu et al., 1992; Song et al., 1996). However, it is now known that the ~3000 km^2 >3550 Ma Itsaq Gneiss Complex of Greenland is an entirely mylonite-bounded allochthonous body in a Neoarchaean orogenic belt (e.g., Friend et al., 1987, 1988, 1996). Thus future discoveries of new >3550 Ma terranes could even be as allochthons in post-Archaean orogenic belts. Furthermore, in Greenland and Antarctica, it is unknown how extensive the Itsaq Gneiss Complex and the Mt Sones gneisses are under the icecaps. Through parts of Africa, South America and central and northern Asia there are large tracts of relatively poorly known basement rocks. Particularly from these regions, there is potential to find new first billion years terranes of considerable size. Also given the small size of some of the presently known occurrences (down to ~1 km^2), there are possibilities of new, smaller discoveries in relatively well-known geological terranes. Given the scarcity of the first billion years record, all new occurrences have the potential of adding some new information on the earliest Earth.

Potential and methodologies for finding even older rocks in relatively well-known first billion year terrains should also be considered. Naturally, the small areas of low strain provide the most accessible information. However, by far more abundant in the record are highly deformed polyphase migmatites, which may have some valuable information hidden away in them—honest thought needs to be given on how to study such rocks. For example, in the migmatites of the Narryer Gneiss Complex, search has been made for intact >4000 Ma rocks, as a source for the >4000 Ma zircons in the intercalated Mt. Narryer and Jack Hills quartzites. In the quartzites, Nutman et al. (1991) calculated that >4000 Ma grains constitute on average ~1% of the detrital zircon population. If this represents the proportion of >4000 Ma rocks in the Narryer Gneiss Complex, then using the laws of gambling, >250 gneiss samples would have to be analysed to try and locate a >4000 Ma gneiss, to be 95% confident that such rocks outcrop at a ≥1% level in the complex (Nutman et al., 1991)! Such a dating programme would be a monumental undertaking and would not necessarily achieve its objective. Such perspectives have to be considered, rather than solely classical field geology. This is because the Narryer Gneiss Complex consists of poorly-exposed, generally strongly deformed, polyphase migmatites (Myers, 1988; Kinny and Nutman, 1996), whose components of different age (3730–3450 Ma) are of mostly unexceptional appearance. Thus unless there was the fortunate discovery in a low strain area, it cannot be argued that classical field geology criteria alone would be the crucial factor in discovery of any intact >4000 Ma rocks in the migmatites of the complex. Finding a >4000 Ma component in the highly strained migmatites is just as likely to arise from a decision to sample based on non geological context, such where one had stopped to eat lunch!

Dedication

This article is dedicated to the late Vic McGregor (1940–2000), whose tenacity as a field geology graduate student in his 20s led to the isotopic proof (Black et al., 1971) of the first early Archaean rocks in Greenland. Over many years, his inspiration and friendship have been important to us.

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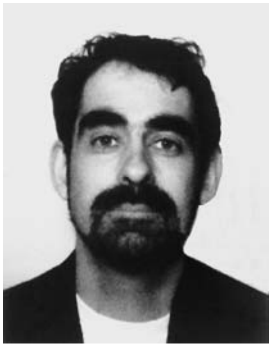

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