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Antiquity of the Oceans and Continents

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Abstract

Tracing the origin of the oceans and the division of the crust into distinct oceanic and continental realms relies on incomplete information from tiny vestiges of surviving oldest crust (>3.6 billions years old). Billions of years of tectonism, melting and erosion have obliterated the rest of that crust. Oceans and continental crust already existed almost four billion years ago because water-laid sedimentary rocks of this age have been found and because tonalites dominate in gneissic sequences dating from this period. Tonalites are igneous rocks produced by partial melting of hydrated basaltic crust at convergent plate boundaries. Collisional orogenic systems produced granites by partial melting of tonalite crust 3.7-3.6 billion years ago. Thus the oldest rocks can be understood in terms of a plate tectonic regime. The chemistry of even older detrital zircons may argue for continental crust and oceans back to 4.4 and 4.2 billion years ago, respectively. Maybe only within the first 200 million years was Earth's surface hot, dry and predominantly shaped by impacts.

Keywords

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Antiquity of the Oceans and Continents

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Tracing the origin of the oceans and the division of the crust into distinct oceanic and continental realms relies on incomplete information from tiny vestiges of surviving oldest crust (>3.6 billions years old). Billions of years of tectonism, melting and erosion have obliterated the rest of that crust. Oceans and continental crust already existed almost four billion years ago because water-laid sedimentary rocks of this age have been found and because tonalites dominate in gneissic sequences dating from this period. Tonalites are igneous rocks produced by partial melting of hydrated basaltic crust at convergent plate boundaries. Collisional orogenic systems produced granites by partial melting of tonalite crust 3.7–3.6 billion years ago. Thus the oldest rocks can be understood in terms of a plate tectonic regime. The chemistry of even older detrital zircons may argue for continental crust and oceans back to 4.4 and 4.2 billion years ago, respectively. Maybe only within the first 200 million years was Earth's surface hot, dry and predominantly shaped by impacts.

KEYWORDS: Early Earth, zircons, Acasta, Isua, Akilia, Jack Hills, oceans, continents

INTRODUCTION

There must have been a time long ago when geological processes were vastly different from today's. Major questions related to this are: How old are the oceans? When did the crust divide into distinct basaltic oceanic and granitic continental domains? When did plate tectonics begin to dominate over impacts as the main process crafting the crust? Understanding this beginning makes study of the earliest Earth exciting and centres on interpretations of the tiny fragments of crust discovered from Earth's first billion years, i.e. pre-3.5 Ga (e.g. Black et al. 1971; Moorbath et al. 1973; Compston and Pidgeon 1986; Bowring and Williams 1999). This article focuses on evidence that the oceans, continental crust and some form of plate tectonics all existed four billion years ago, and maybe even earlier.

THE OLDEST GEOLOGICAL RECORD (4.4–3.6 Ga)

Almost undeformed and unmetamorphosed volcanic and sedimentary rocks have survived from 3.5 billion years ago, greatly aiding interpretation of the early Earth. However, a major problem for interpreting the oldest, ≥3.6 Ga geological record is that the evidence occurs in gneiss complexes where the original character of the rocks has been mostly obliterated (FIG. 1A). Fine-scale resolution of the chronology of these gneiss complexes is an important starting point for establishing the timing of events on the early Earth. This has been made possible by zircon dating using the coupled ^{235}U–^{207}Pb and ^{238}U–^{206}Pb radioactive decay systems (shortened to U/Pb). Sensitive, high mass-resolution ion microprobes date domains typically 20 µm wide by 1 µm deep within single zircons. Guided by cathodoluminescence imaging, individual igneous growth and recrystallised domains can be dated in this way to obtain accurate, complex geological histories for zircon populations from single rocks (FIG. 1B). U/Pb zircon analysis by thermal ionisation mass spectrometry can now date single fragments of large grains, and also provides valuable information on the early Earth (e.g. Crowley et al. 2002). There are now numerous accurate U/Pb zircon dates on the oldest rocks and minerals, with errors of only a few million years (i.e. only 0.1% of a >3.5 Ga age).

The Global 4.0–3.6 Ga Rock Record

Rocks preserved from the 4.0–3.6 Ga period occupy about a millionth of Earth's crust; the remainder were destroyed by tectonic activity, melting and erosion over billions of years. These old rocks have been discovered in Greenland, Australia, Canada (three localities), Antarctica and China (summary in Nutman et al. 1996 apart from Stevenson et al. 2006 for the most recent Canadian one). Some 4.0–3.6 Ga detrital zircons have survived in post-3.6 Ga sedimentary rocks but are not discussed further here because they provide no additional information to that obtained from surviving 4.0–3.6 Ga rocks. Earth's oldest known rocks are 4.03–3.96 Ga old (Bowring and Williams 1999) and form small domains (<< 1 km^2) in the *Acasta Gneisses* of northwestern Canada. The Acasta Gneisses are migmatites—rocks formed from several generations of deformed and metamorphosed igneous intrusions—from which it is difficult to obtain samples of only one generation for chemical and isotopic study (Bowring and Williams 1999).

The oldest gneiss complexes are composed of >90% of rocks of intrusive origin, now strongly deformed (FIG. 1A). Rare areas of relatively little deformation show that these usually formed from older tonalitic and younger granitic components. Tonalites are potassium-poor intrusive rocks generated by melting of hydrated mafic crust after transformation into garnet amphibolite or eclogite, probably in the ancient equivalent of subduction zones (summary by Martin et al.

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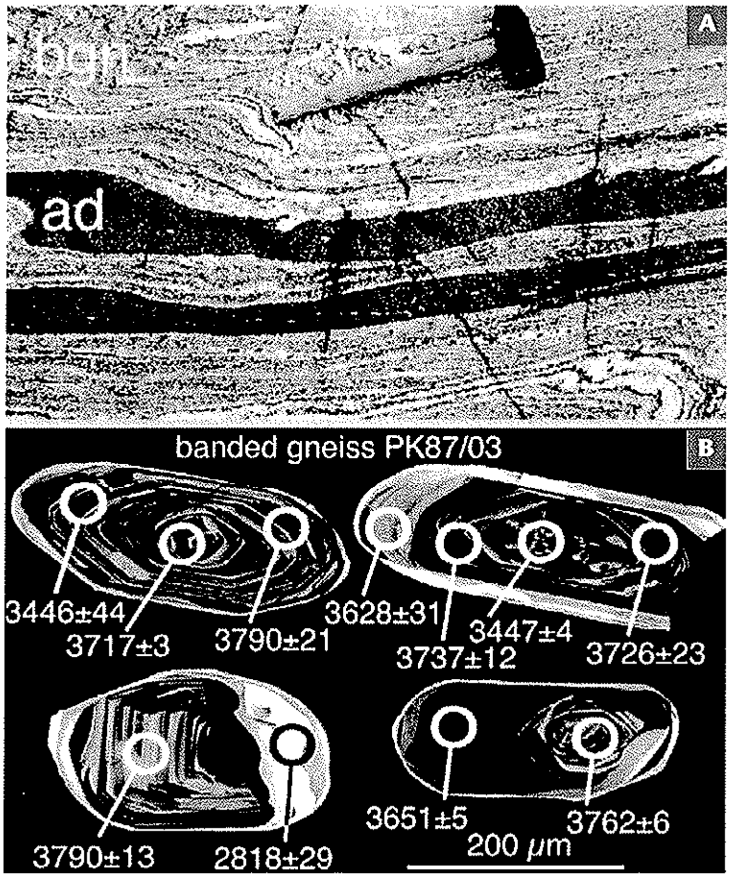

FIGURE 1 (A) Typical banded gneiss (bgn) consisting of older tonalite (>3.7 Ga, grey) and younger granite (3.65 Ga, white), Itsaq Gneiss Complex, Greenland. The gneiss was cut by a mid-Archean dyke, now an amphibolite (ad), which was strongly deformed at 2.7 Ga. (B) Cathodoluminescence images of typical zircons separated from banded gneiss. Zircons were embedded in epoxy resin and sectioned prior to imaging. 3.79 Ga oscillatory-zoned igneous zircons were partly replaced and overgrown during high-grade metamorphism and deformation over the following one billion years. Dates are expressed in millions of years, with 1σ analytical errors.

2005). The granites were produced by remelting of predominantly tonalite crust during superimposed orogeny (Friend and Nutman 2005). In the *Itsaq Gneiss Complex* of Greenland (summary in Nutman et al. 1996), tonalites of different ages (FIG. 2) dominate and are infiltrated by granites, whereas in the Narryer Gneiss Complex of Western Australia, granites predominate with only rare surviving tonalites (Kinny and Nutman 1996). Volcanic and sedimentary rocks form <10% of the >3.6 Ga rock record. The volcanic and sedimentary rocks are scattered through the gneisses as enclaves and tectonic slivers. These range in size from the 35 km long *Isua supracrustal belt* of the Itsaq Gneiss Complex down to one-metre pods. Gabbros and ultramafic rocks are more widespread, and occur in small amounts in most >3.6 Ga gneiss complexes (see Nutman et al. 1996). Small areas of weakly deformed rocks have been found in the Itsaq Gneiss Complex. These rocks provide important information on the early Earth that is harder to obtain from other localities, and therefore they are emphasised in this article.

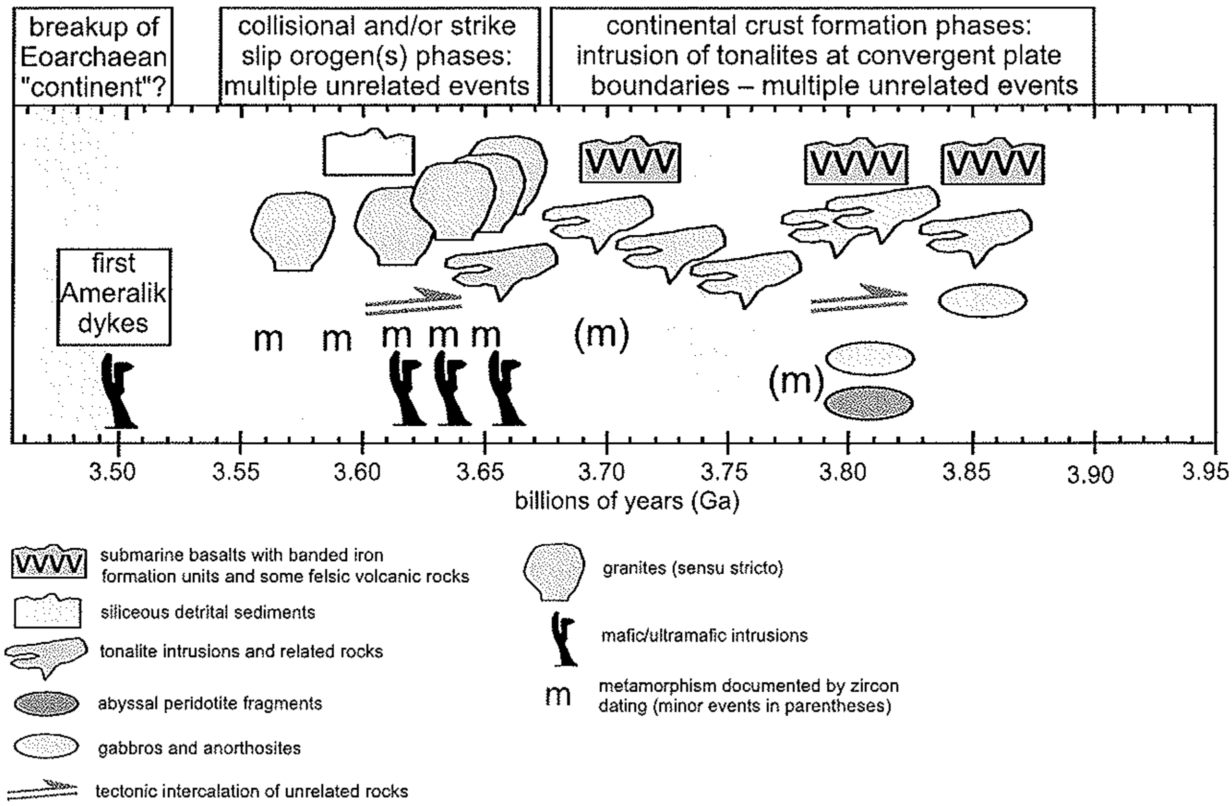

FIGURE 2 Schematic evolution for the Itsaq Gneiss Complex, southwest Greenland. This interpretation is based on extensive fieldwork coupled with zircon dating of more than 100 rocks (Friend and Nutman 2005). The figure illustrates the complexity of crustal evolution shown by all surviving fragments of oldest crust. Each pictogram represents a generation of rocks whose age is known from zircon dating. Each generation of granite and tonalite has a single population of oscillatory-zoned igneous zircons (Nutman et al. 1996, 2000; Friend and Nutman 2005). The figure is arranged such that generations of volcanic and sedimentary rocks are shown near the top, granites and tonalites in the middle, and mafic intrusions and abyssal peridotite (mantle) fragments near the base.

Antiquity of Oceans from the Oldest Water-laid Sediments and Basalts

The strongly deformed amphibolite facies volcanic and sedimentary rocks that dominate the Isua supracrustal belt are tectonic fragments of unrelated 3.7 and 3.8 Ga sequences (Nutman et al. 1997). Rocks with surviving volcanic and sedimentary structures form a tiny amount of the belt. In these rocks, Komiya et al. (1999) recognised unambiguous relicts of pillow structures in amphibolites (FIG. 3A). Because pillow structures form when basalt lavas are erupted under water on the seafloor, they prove the submarine origin of these Isua amphibolites. The associated Isua quartz–magnetite banded iron formations (BIFs) are water-laid sedimentary rocks (Moorbath et al. 1973). Their generally fine-scale banding is a deformational structure (FIG. 3B LEFT), and only in rare, relatively undeformed zones is genuine sedimentary layering preserved (FIG. 3B RIGHT).

The island of Akilia consists of Itsaq Gneiss Complex gneisses derived from multiple generations of strongly deformed 3.85–3.62 Ga tonalites and granites (Nutman et al. 1996, 2000). The gneisses contain lenses of amphibolite and layers of siliceous rocks (FIG. 3C). These are all more strongly deformed and thus are harder to interpret than some of the Isua rocks. Magnetite-bearing varieties of the Akilia siliceous rocks have been interpreted as sedimentary in origin because they have trace element signatures similar to Isua BIF (Friend et al. 2002) and show iron isotope fractionation unlike that in igneous rocks (Dauphas et al. 2004). A 3.84 Ga minimum age has been proposed for Akilia amphibolites and associated siliceous layers (e.g. Nutman et al. 2000), but doubts have been voiced concerning this age (e.g. Whitehouse et al. 1999). Isua currently remains the universally accepted site of the oldest direct evidence for oceans, as shown by 3.8–3.7 Ga BIF sedimentary rocks and pillow lavas, while debate continues on whether the Akilia rocks push this direct evidence for oceans back to ≥3.85 Ga. Other localities with >3.6 Ga volcanic or sedimentary rocks are definitely the Saglek area of Labrador (Canada) and possibly near the northern edge of the Superior Province on the shores of Hudson Bay (Canada).

Formation and Evolution of 3.9–3.6 Ga Continental Crust Using the Plate Tectonic Model

Plate tectonic processes are sufficient to explain 3.9–3.6 Ga crust formation, deformation and metamorphism in the Itsaq Gneiss Complex (Friend and Nutman 2005). In the vicinity of the Isua supracrustal belt, intrusive, volcanic and sedimentary rocks of different ages had been juxtaposed along early mylonitic shear zones and already folded by 3.6 Ga (Nutman et al. 1996, 1997, 2002; Crowley et al. 2002). This style of geological evolution probably reflects the operation of some form of plate tectonics by 3.8–3.6 Ga, in which compression at destructive plate margins caused the interleaving of unrelated rocks (Komiya et al. 1999; Hanmer and Greene 2002). Zircon dating of more than 100 Itsaq Gneiss Complex samples, combined with fieldwork, has led to an understanding of the typical evolution of ancient crust (FIG. 2). Multiple generations of 3.85–3.6 Ga intrusive rocks are recognised. From 3.85 to 3.69 Ga, episodic growth of new continental crust took place via emplacement of tonalites, derived from partial melting of hydrated basalt, into sequences of basalt with BIF layers. This was followed between 3.65 and 3.55 Ga by episodic granite production through melting of tonalite crust, as well as by high-grade metamorphism and complex deformation. These events are interpreted to reflect collisional and/or strike-slip orogenic phases (Friend and Nutman 2005). In other examples of the world's oldest gneiss complexes (e.g. the Narryer Gneiss Complex of Western Australia; Kinny and Nutman, 1996), 3.65–3.55 Ga was an important period for high-grade metamorphism and granite formation. This might reflect an early 'global' collisional orogeny, during which blocks of crust dominated by tonalite were amalgamated to form a larger domain of continental crust.

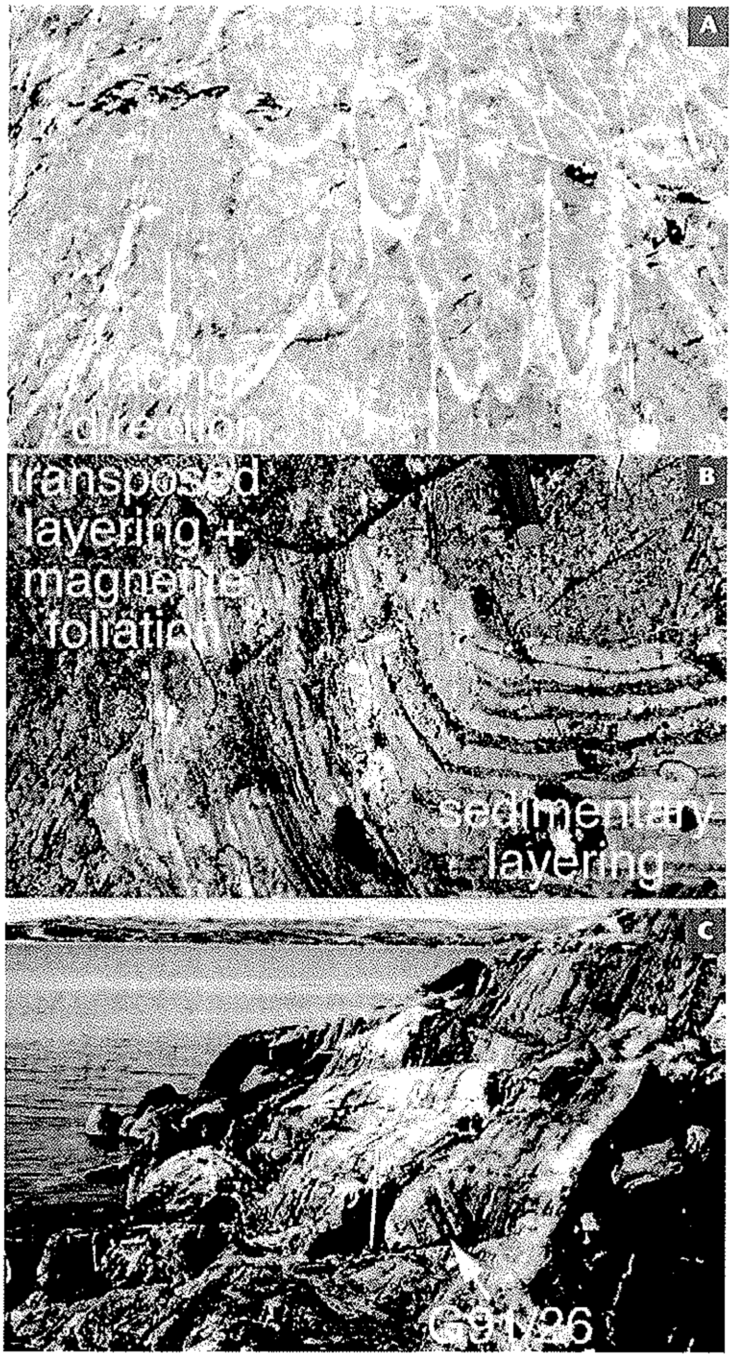

FIGURE 3 Candidates for the oldest volcanic and sedimentary rocks from the Itsaq Gneiss Complex, southwest Greenland. **(A)** Rare pillow lava structure in Isua amphibolites (discovered by Komiya et al. 1999). The shape of the pillows is well-enough preserved to allow determination of the top direction (arrow indicates facing direction). **(B)** Low-strain area of the water-laid banded iron formation in the Isua supracrustal belt. Original, albeit deformed, sedimentary layering (right) is rotated, strongly attenuated and overgrown by a magnetite foliation to form the typical regional banding in these rocks (left). **(C)** Approximately 5 m thick siliceous layer in amphibolites, Akilia Island. G91/26 marks the site of a magnetite-bearing unit with trace element and iron isotope signatures similar to those in Isua BIF. This is the contested candidate for Earth's oldest preserved sediment.

Understanding the Pre-4.0 Ga Earth Using the Oldest Detrital Zircons, Western Australia

The oldest fragments of Earth's geological record are rare 4.4–4.0 Ga, <500 μm detrital zircons (Fig. 4) from Precambrian metaquartzites in the Yilgarn Craton of Western Australia. These zircons are mostly from the Jack Hills (Compston and Pidgeon 1986; Mojzsis et al. 2001; Wilde et al. 2001), but have also been recovered from other Yilgarn localities (e.g. Wyche et al. 2004). Rare >4.0 Ga zircons have also been found in 2.7–2.6 Ga Yilgarn granites (Nelson et al. 2000).

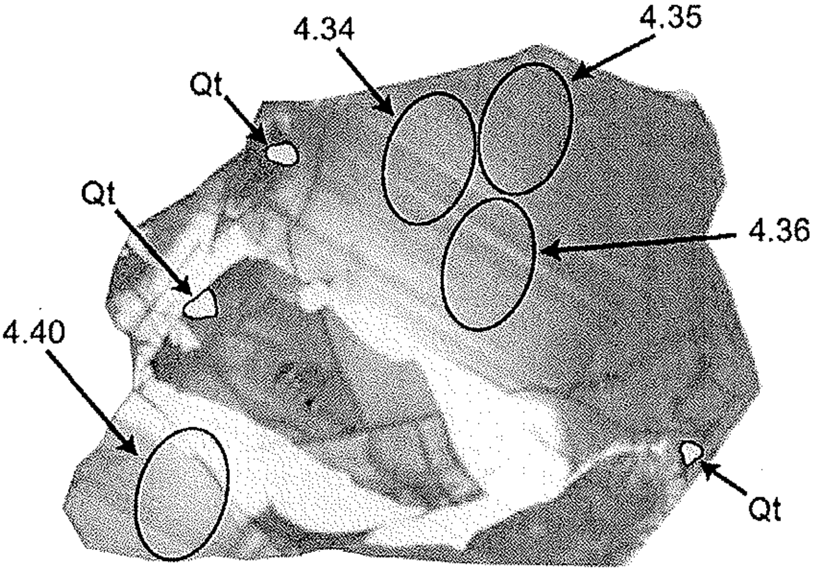

Figure 4 False colour cathodoluminescence image of the 200 μm diameter, approximately 4.4 Ga Jack Hills zircon. This zircon is the oldest-known part of Earth. Ion microprobe analytical sites are indicated by black ellipses with ages in billions of years. Qt denotes quartz inclusions in the zircon crystal. Image supplied by John Valley

The ancient zircons contain inclusions of quartz (Cavosie et al. 2005) and thus were produced from silica-saturated igneous rocks, suggesting that granites (sensu lato) existed before 4.0 Ga (e.g. Wilde et al. 2001). The >4.0 Ga Jack Hills zircons have isotopically heavy oxygen ($\delta^{18}O$ = 5.0 to 7.3 per mil) compared with the mantle, giving rise to proposals that well before 4.0 Ga, granites had been produced by melting of older crust previously hydrated by cool surface waters (Mojzsis et al. 2001; Wilde et al. 2001; Valley et al. 2005). The strands of evidence for this proposal are the focus of debate and scrutiny. If this is correct, granitic 'continental' crust and oceans (or at least cool surface conditions with standing water) occurred very early in Earth's history. The preservation of these very old zircon crystals indicates that magma oceans had solidified to form crust by 4.4 Ga, though the nature of this crust and the composition of the source rocks of the 4.4–4.0 Ga zircons are not resolved: Were these zircons derived from tonalites formed by melting of pre-4.0 Ga hydrated basalt in a world dominated by oceanic crust? Or were they derived from low-temperature granites formed by melting, under an essentially modern tectonic regime, in a 4.4–4.0 Ga world containing extensive continental crust (Watson and Harrison 2005; Harrison et al. 2005)?

THE YOUNG EARTH

Oceans, as well as crust divided into distinct domains of hydrated basalt and granitic continents, were definitely established by almost 4 Ga and maybe as early as 4.4 Ga. An inherent feature of this crustal dichotomy would have been linear crustal accretion and collisional orogeny at convergent plate boundaries (de Wit 1998), although the architecture of these systems may have differed from that at modern plate boundaries. However, it is increasingly apparent that an arid, hot surface, with a crust entirely unlike today's, was restricted to the earliest part of Earth's history. This earliest terrestrial crust may have been like the Moon's crust, but on Earth, four billion years of geological activity have obliterated it.

An important unresolved issue is whether the volume of continental crust before 3.6 Ga was similar to or larger than today (Armstrong 1991), or if it increased as Earth aged (summarised by Bennett 2003). This question concerns destruction rates of early crust and is separate from the undeniable evidence that, since at least 4.0 Ga, new crust of tonalite was formed repeatedly by partial melting of an oceanic crust of hydrated basalt (summarised by Bennett 2003 and Martin et al. 2005).

Earth suffered numerous impacts in its earliest history (Glikson 2005; Koeberl 2006). However, since 3.8 Ga (oldest water-laid sediments) and maybe since 4.4 Ga (zircons from the oldest igneous rocks produced by partial melting of hydrated source materials), impact energy did not preclude the existence of oceans, and impacts were not the main crust-forming process. Instead, Earth's early crust would have been shaped by an early form of plate tectonics driven by greater internal heat (Davies 2006), with impacts only disrupting this process. Discoveries of relatively undeformed metasediments (like those in Fig. 3b) offer greater hope of finding the impact layers that must have been more common on the early Earth but that have largely eluded geochemical searches.

No rocks and minerals formed during Earth's first 150 million years, i.e. prior to 4.4 Ga, have survived for direct geological observation. Despite this, Nd and Hf isotope signatures from 4.4–3.6 Ga rocks and minerals provide evidence of a planetary-scale event during Earth's first 100 million years, an event that entailed major chemical fractionation in the mantle and probably featured an early magma ocean (e.g. Caro et al. 2003; Bennett 2003). These isotopic signatures are the only records of processes occurring prior to the beginning of a geological record in 3.6–4.4 Ga rocks and minerals.

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