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# Oldest rocks, earliest life, heaviest impacts, and the Hadean–Archaean transition

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Many geologists have their own favourite part of the vast geological time scale, from which there is plenty to choose for all types of pure and applied research, and for detailed speculation. My own favourite is that ancient time range during which the Earth's surface changed from something quite unfamiliar and shaped by largely non-uniformitarian processes, to something increasingly recognisable in uniformitarian terms. That has been referred to as the Hadean–Archaean transition, often defined by arbitrary time boundaries like 4.0, 3.9, and 3.8 Ga, which are not necessarily associated with any specified event horizon.

The first and last sentences of the chapter on the Hadean Earth in Jonathan Lunine's well-known textbook *Earth – Evolution of a Habitable World* (1999) read as follows:

"The period from the formation of the Earth, some 4.56 billion years ago, to the time when the oldest rocks still in existence were formed, roughly 3.8–4.0 billion years ago, is called both the Hadean era and Priscoan eon of Earth. The term Hadean, referring to the Greek version of hell, is well chosen, because all evidence that we have is that the Hadean Earth was very hot and extremely active, with widespread volcanism and frequent impacts of debris left over from planetary formation."

"The Hadean Earth, while vastly different from the present planet, set the stage for what was to follow. By 3.8–4.0 billion years ago, the growth of continents, the stabilisation of liquid water, and the decreasing impact rate, made for an increasingly predictable and benign environment. Increasing environmental stability characterised the transition from the Hadean era to the Archaeon eon of Earth."

Some of this makes good sense and serves as a starting point for looking at some major event horizons in this 3.8–4.0 Ga time range.

The first thing to ask is where, and how old, are the oldest rocks on Earth (for review, see Kamber et al., 2001)? It appears that the largest, best exposed, best preserved terrain of the oldest known early Archaean rocks occurs in southern West Greenland, with undisputed dates in the range of 3.82–3.65 Ga, some of which were established more than 30 a ago. The nearly 3.8 Ga Isua supracrustal belt (also known as Isua greenstone belt) comprises a great variety of metamorphosed, variably deformed volcanic and sedimentary rocks, including basalts (with pillow lavas), felsic volcanics, chemical sediments (e.g., chert, banded iron-formation), clastic sediments (now garnet-mica schists) and other minor rock types (for review and references see Appel et al., 2003). The presence of genuine, primary carbonate sediments is still much debated. It is quite certain that most, if not all, of these rocks were deposited in water. There was clearly no shortage of water on the Earth's surface at around 3.8 Ga. Maybe planet Mars was still flowing with surface water then, or it might already have partially or completely lost its surface water, some to space and some to a vast underground reservoir. We shall certainly find out before long!

The Isua supracrustal belt is bounded on its northern side by granitoid gneisses of magmatic origin ("orthogneisses"), reliably dated at 3.70–3.65 Ga (for summary, see Crowley, 2003). Geochemical evidence suggests that

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these are tonalite–trondhjemite–granodiorite (TTG) gneisses (known as Amîtsoq or Itsaq gneisses) characteristic of the protoliths of genuine continental crust, differentiated from a geochemically slightly depleted, mafic Archaean source region. These gneisses exhibit both tectonically conformable and intrusive relationships with the adjacent Isua supracrustal belt, and both rock units are cut by a dense doleritic dyke swarm (the Ameralik dykes), of which the oldest components have been dated at 3.4–3.5 Ga (Nutman et al., 2004). The orthogneisses could well mark the initiation of subduction-related processes and the onset of uniformitarian continental crust production. The Ameralik dyke swarm is the oldest known continental dyke swarm on Earth.

To the south of the Isua supracrustal belt there is a terrain of several hundred $km^2$ of well exposed, weakly deformed granitoid orthogneisses with zircon U–Pb dates as old as 3.82 Ga, which is regarded as their true age of emplacement (Nutman et al., 1999; Crowley, 2003). These orthogneisses are rich in man-to-mountain sized enclaves which include mafic/ultramafic metamorphosed magmatic rocks, varied amphibolitic gneisses, and chemical sediments, such as banded iron-formation. These enclaves must be at least 3.82-Ga old. This extraordinary terrain has not been studied much, and only a few geologists have visited the area. After so much intense current interest in, and exploration of, the ancient surfaces of Moon and Mars, here we have a sizeable terrain of easily accessible plus-3.8-Ga rocks crying out for detailed exploration and research, at a small fraction of the cost of interplanetary research! In my view, in these enclaves in 3.82-Ga gneisses, there is probably a better chance than anywhere else on Earth of actually finding bits and pieces of genuine Hadean crust and, possibly, physical remnants of the late heavy bombardment (LHB), of which more below.

Kamber et al. (2003) recently reported that Pb isotope characteristics of these 3.82-Ga gneisses are quite different to those of the well-studied, nearby 3.65–3.70-Ga gneisses (see above) and they suggest that these older gneisses were derived from a mafic source region which had itself separated from the mantle as early as ca. 4.2–4.3 Ga. Kamber et al. (2003) suggested that this source region was the Hadean basaltic crust which, in the probable absence of the subduction process, encased the early Earth. From these two isotopically contrasted groups of orthogneisses, a fundamental change in global tectonic regime was proposed between about 3.8 and 3.7 Ga, with the protoliths of the two groups of orthogneisses tapping quite different mafic regimes at depth.

Still on the subject of the oldest rocks, we take a brief look at the Acasta gneisses from the Slave Craton in the NW corner of the Canadian Shield, which are widely claimed to be the oldest in-situ terrestrial rocks at close to 4.0 Ga. This is a complex area of a few $km^2$ of strongly metamorphosed and deformed granitoid gneisses which contain some zircons with U–Pb dates up to 4.03 Ga, as shown by Sam Bowring and colleagues since 1989 (e.g., Bowring and Williams, 1999). Moorbath et al. (1997) made a detailed Sm–Nd study on a large suite of Acasta gneiss samples, which revealed a regression (errorchron) age of 3371 ± 59 Ma, with an initial $\epsilon$-$^{143}$Nd value of −5.6 ± 0.7. This negative value, in combination with the oldest zircon date, clearly demonstrates the existence of some kind of 4-Ga-old precursor. But strong doubt remains (Kamber et al., 2001) whether the exposed Acasta gneiss is really 4.0-Ga old, or whether it is only 3.37-Ga old, in broad agreement with other reported regional ages. In contrast to the early Archaean gneisses of Greenland, the Acastas do not preserve a coherent Pb isotope or Rb–Sr isotope memory (Moorbath et al., unpublished work), because they are such profoundly disturbed rocks. The term "age" of a rock unit surely requires geological, geochemical and isotopic integrity of the rocks as a whole, and not just of zircon. That is why there is still room for doubt as to what the term "age of the Acasta gneiss" really means.

Let us, therefore, return to Greenland for the putatively oldest known in situ rocks close to 3.82 Ga. That only leaves some 30–40 Ma to the end of the LHB on the moon at around 3.85 Ga, with major craters like Imbrium and Orientale (Wilhelms, 1987). There is general consensus that saturation bombardment, such as that on the Moon, must have occurred on Earth at the same time and in proportion to the Earth's much greater gravitational attraction. So far, no field evidence for LHB impacts has been found in the oldest Greenland rocks. How then can one reconcile the apparently total restructuring and renewal of the Earth's surface within a time range of some 30–40 Ma? In this connection, I am impressed by papers like that of Jones et al. (2002) on impact-induced melting and the development of large igneous provinces. Here are three short quotations:

"...our contention (is) that the phenomenon of pressure-release melting, or decompression melting, is the key to understanding the volume of melt generated during large impacts..."

"...decompression melting will occur virtually instantaneously in hot mantle whenever there is sufficient reduction in pressure beneath a large impact..."

"...large craters would have been auto-obliterated by impact volcanism and they will appear very different to conventional craters..."

So I speculate that the relatively short-term combination of many large-scale, deep impacts, voluminous decompression melting, massive impact-induced volcanism, auto-obliteration and consequent renewal of surface features, resulted by the end of the LHB at around 3.85 Ga in a juvenile terrestrial surface almost ready for magmatic and sedimentary environments like those of southern West Greenland. The main thing to note is that the catastrophically damaging impact process could itself be the prime cause of the "normalisation" of the Earth's surface so soon after ca 3.85 Ga, with the predominant global outpouring of basalt. In contrast, on the much smaller, cooler Moon, resurfacing and obliteration of impact-related features was clearly not nearly as effective, although lunar volcanism has also been attributed to large-scale impacts (Elkins-Tanton et al., 2004).

To digress briefly, some Isua clastic metasediments contain a W isotope anomaly derived from the $^{182}Hf$–$^{182}W$ system (half-life of 9 Ma), and the only conceivable way for that to occur on Earth is for the sediments to contain a meteoritic component (Schoenberg et al., 2002). Meteorites contain $^{182}W$ isotope anomalies because their parent bodies differentiated only a few millions of years after formation of the solar system. So far, this is the only direct evidence for meteorite impacts before 3.8 Ga!

Everything so far discussed is obviously crucial for the timing of the origin of life, an event still almost as inscrutable as the origin of the Universe itself. For some years, the accepted dogma has been that life started on Earth at around 4 Ga, even during the period of devastating impacts. But there is not a shred of evidence for this assertion, nor even a hint of physical plausibility. It is wishful thinking, attracted by a nice, round number. In addition, it is extremely unlikely that any primitive life that formed on the Hadean surface significantly before 4.0 Ga could possibly have survived the LHB and the subsequent global volcanic resurfacing. And yet, geological and environmental evidence from the 3.7–3.8 Ga Isua sedimentary rocks suggests that warm, wet, nutritious surface conditions were already available for a primitive biosphere (an analogy, perhaps, with Darwin's "warm little ponds").

Unfortunately, claims for genuine biomarkers (based on $^{13}C$-depletion in graphite particles) in some early Archaean rocks from Greenland have not been compelling, to say the least. The main publicity (e.g., Mojzsis et al., 1996; Nutman et al., 1997) has centred on the small island of Akilia on the coast of southern West Greenland, some 150 km SW of the Isua supracrustal belt (see above). Here there is a 5-m-wide exposure of banded quartz-pyroxene rocks, identified by the quoted authors as chemical sediments closely related to banded iron-formation, arguably more than 3.85-Ga old, which contain $^{13}C$-depleted graphite grains claimed to be of biological origin. Every aspect of these rocks, both in the field and in the laboratory, has been hotly contested for 8 a in many papers. However, it has become evident that most of the essential minimum requirements for reliable characterisation of Earth's oldest biotracers have not been fulfilled for the Akilia island (and perhaps other) rocks. Thus, Whitehouse and Fedo (2003) maintain:

"All internal features of the critical, supposedly life-bearing (Mojzsis et al., 1996) quartz-pyroxene rock can be explained by a combination of metasomatism, high-grade metamorphism and tectonic transposition forming the heterogeneous, sheared, boudinaged and, in places, finely banded lithology seen today."

"Primary evidence for a banded iron-formation origin is completely lacking and, without such support, the carbon isotope arguments for early biogenic activity become irrelevant. Furthermore, intense deformation has affected all lithological contacts so that claimed geochronological constraints from intrusive gneisses cannot be substantiated."

Not only is the correct identification and genetic affinity of the Akilia island rocks in grave doubt, but there is also the more general question of the validity of using $^{13}C$-depletion in strongly metamorphosed and metasomatised rocks as a valid biotracer. Thus, van Zuilen et al. (2003) state that:

"...the isotopic composition of graphite in supracrustal rocks subjected to high-grade metamorphism does not in general serve as a reliable biomarker, since epigenetic processes may yield graphite with isotopic characteristics that overlap with those of putative biosignatures."

This is especially relevant for the Isua supracrustal belt (see above), where it was earlier proposed (e.g., Schidlowski, 1988; Mojzsis et al., 1996) from C isotope ratios in graphite that a major microbial ecosystem existed there some 3.8 Ga ago. However, it has been shown (van Zuilen et al., 2002, 2003) that graphite in the Isua rocks is associated solely with metasomatic, non-biogenic carbonates which were formerly thought to be of sedimentary origin, in which the $FeCO_3$ component has undergone thermal disproportionation to $Fe_2O_3$, $CO_2$ and C. At present, only one occurrence of graphite in a genuine metasediment at Isua is seriously debated as a potential biotracer (Rosing, 1999) but, in my view, here there may also be serious metamorphic and tectonic complications for a biogenic interpretation.

Thus, the search for biogenic tracers at 3.7–3.8 Ga in the Greenland rocks has not yet reached a consensus. In this, it parallels current disputes on the possible biogenicity of "organised elements" in 3.4–3.5 Ga sediments from Australia and South Africa, which some regard as genuine cellular biostructures and others as inorganic artefacts (e.g., Schopf, 1993; Brasier et al., 2002).

Referring once more to Akilia island (see above), reports from recent conferences (e.g., The Goldschmidt

Conference, 2004), together with intense pre-publication publicity, show that even the very existence of graphite in the relevant Akilia rocks is now strongly disputed.

Now some remarks about the search for Hadean crust itself. Is it possible to discern what the Earth's surface was like before deposition of the oldest surviving rocks and perhaps even before the Late Heavy Bombardment? Maybe limited analogies are possible with the early basaltic surfaces of Moon and Mars. I prefer the model of a predominantly mafic/ultramafic Hadean crust on Earth. There is no compelling geological, geochemical or radiogenic isotope evidence for a primordial world – encircling crust of sial or granite (e.g., Taylor and McLennan, 1995).

I am entirely sceptical of recent claims from detrital zircons up to 4.3 Ga (even one at 4.4 Ga) old for the existence of continental crust and oceans on Earth at 4.4 Ga (Wilde et al., 2001; Peck et al., 2001) with all the associated global tectonic implications. Such zircons, which are found in much younger sediments in West Australia, may simply represent felsic differentiates and partial melts from a dominantly mafic, magmatic 4.3–4.4 Ga Hadean crust. Indeed, such felsic rocks could be analogous to lunar granitoid rocks with zircon U–Pb dates in the range 4.32–3.90 Ga (Nyquist and Shih, 1992), which were regarded as representing localised, differentiated plutons of different ages. Here is a quote from a recent rare-earth-element (REE) study on ancient zircons by Whitehouse and Kamber (2002):

"Regardless of the cause of light REE overabundance, our study shows that simple application of zircon/melt distribution coefficients is not an unambiguous method for ascertaining original melt composition. In this context, recent studies that use REE data to claim that > 4.3 Ga Hadean detrital zircons originally crystallised from an evolved magma, in turn suggesting the operation of geological processes in the early Earth analogous to those of the present day (e.g., subduction and melting of hydrated oceanic crust), must be regarded with caution. Indeed, comparison of terrestrial Hadean and > 3.9 Ga lunar highland zircons show remarkable similarities in the light REE, even though subduction processes that have been used to explain the terrestrial zircons have never operated on the Moon."

The presence of high $^{18}O$ in the outer zones of Hadean zircons suggests the presence of zircon–water interaction at or near the Earth's surface as long ago as 4.3–4.4 Ga, but it seems premature to refer to the presence of "oceans" in any modern tectonic sense (Wilde et al., 2001; Peck et al., 2001). Furthermore, since the >4.0 Ga detrital zircon grains are found in much younger (<3.6 Ga) sediments, it is possible that high $^{18}O$ compositions in zircons may have resulted from diffusional exchange with a hydrous environment during long-term recycling.

Thus, extreme caution is justified in extrapolating isotopic and geochemical data from Hadean zircons to postulate global tectonic environments ("continents and oceans") which characterise the mature Earth.

Another promising line of research is the search for $^{142}Nd$ isotope anomalies, which has only recently become feasible with spectacular improvements in mass spectrometry. The two Sm–Nd decay schemes are $^{147}Sm$–$^{143}Nd$ (half-life of 106 Ga) and $^{146}Sm$–$^{142}Nd$ (half-life of 103 Ma). Debate on whether or not the oldest Greenland rocks (3.6–3.8 Ga) contain $^{142}Nd$ isotope anomalies has been going on since 1992, but earlier work was beset with analytical uncertainties. Recent work by a group from Paris has clearly shown that the oldest Greenland gneisses and supracrustal rocks contain positive $^{142}Nd$ isotope anomalies (Caro et al., 2003, 2005). Since $^{146}Sm$ had virtually become extinct by ca. 4.2 Ga, one would not expect to find $^{142}Nd$ isotope anomalies in 3.6–3.8 Ga rocks if there had been complete, unrestricted mantle–crust mixing until that time. It is clear that the 3.6–3.8 Ga rocks were derived directly or indirectly from regions of pre-Isuan mantle or lithosphere which had survived intact since the time of early Earth differentiation at around 4.4 Ga (Caro et al., 2003), and had escaped complete homogenisation at least until 3.6–3.8 Ga. This type of work promises to yield much information on the structure and mobility of the early mantle and lithosphere, and the genetic relationship between mantle and earliest crust. It would be of great interest to learn how late in geological history any pockets of $^{142}Nd$ anomalies actually survived.

Returning full circle to the beginning of this lecture, where then could one provisionally place the boundary between the Hadean and the Archaean? A reasonable compromise seems to be between the effective termination of the putative Late Heavy Bombardment (using the lunar analogy) and the oldest recognisable magmatic and sedimentary terrestrial rocks. That would be between about 3.85 and 3.82 Ga, and this will undoubtedly be refined with future research. This interval may be termed the "Hadeo-Archaean" (Fig. 1) during or by which time the Hadean Earth's surface had fully restructured itself by global basaltic volcanism, water-dominated erosion and sediment transport (a much more complete version of similar processes on Mars). This powerfully active "Hadeo-Archaean" interval comprises a period of immense change in surface environment of the early Earth within just a few tens of millions of years. I think it is the most influential and exciting part of the Earth's entire geological time scale.

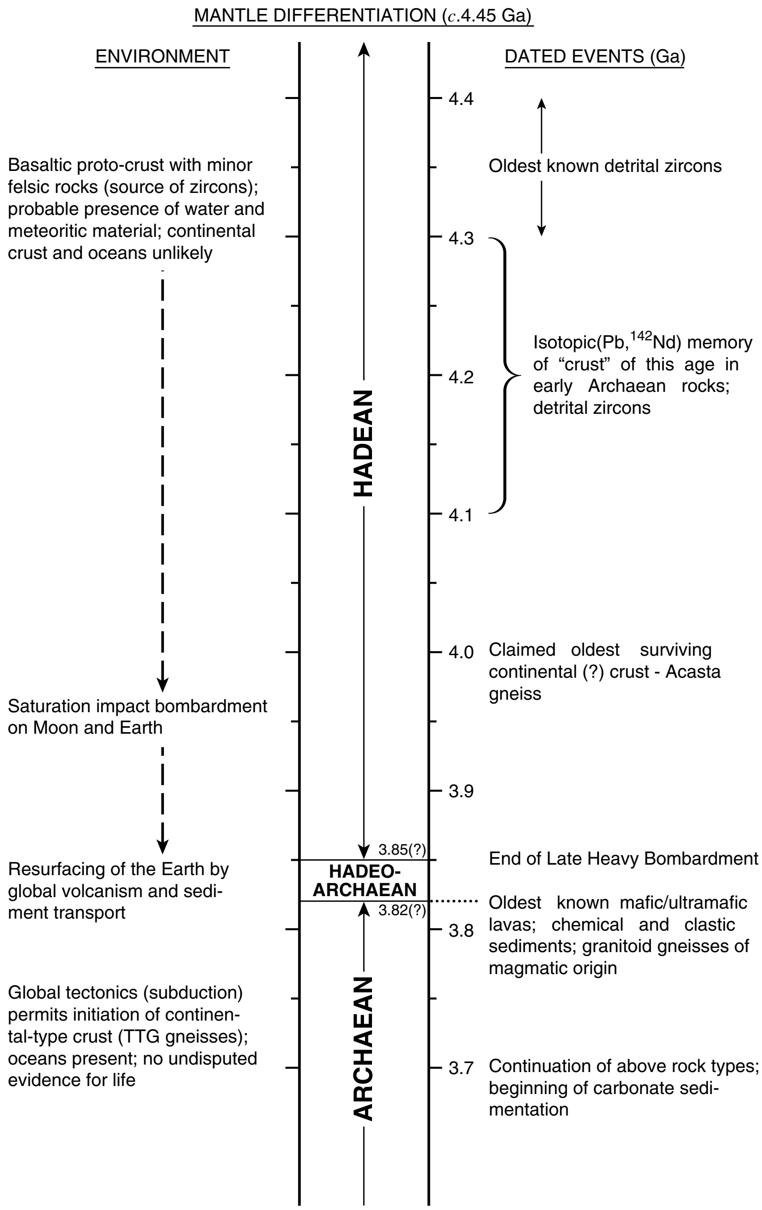


Fig. 1. Processes, environments and dated events on the early Earth discussed in the text, with special emphasis on the Hadeo-Archaean interval.

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