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# The terrestrial craddle of life

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**Abstract.** The Miller and Urey experiment in which amino acids were produced by electrical discharges in an atmosphere of water, methane, and ammonia was dismissed as being inconsistent with the secondary origin and the oxidizing character of the atmosphere. Since then, it has been found that simple geochemical arguments favor a dry accretion of the Earth and late delivery of water from the outer Solar System forming the primordial hydrosphere. This ocean of water must have interacted with the underlying terrestrial magma ocean, the existence of which is now well documented by evidence from the extinct radioactivity of $^{146}Sm$ ($T_{1/2} = 103$ Ma) in Archean rocks. Water-hot rock interaction, with its hallmark reaction of serpentinization, produced enormous amounts of $H_2$, which interacted with nitrogen and carbon dioxide to form $CH_4$ and $NH_3$. From this follows that the Miller and Urey experiment should be reinstated as the main template of the origin of life.

Sustainable life needs nutrients that can be steadily resupplied, most notably phosphate for which mid-ocean ridges act as a sink. In the modern world, phosphate is brought to the ocean by the erosion of continents, which are the hallmark of plate tectonics. On Earth, the elevation contrast between continents and abyssal plains is a result of plate tectonics: granitic rocks form by dehydration and melting of wet basaltic rocks at subduction zones. Life does not seem to be sustainable without plate tectonics, and plate tectonics in turn seems to result from the injection of water into the mantle by the subduction process, which "softens" mantle material and enhances convection. The earliest continental crust of modern affinity identified so far is attested to by Hadean detrital granitic zircons ($ZrSiO_4$) present in the Archean Jack Hills conglomerates (West Australia). This crust seems to have formed by remelting a primordial ~4.35 Ga old crust extremely enriched in incompatible elements and which may have been derived from the early differentiation of the planet.

The emergence of life therefore is conditioned by the interaction between magma and water, which excludes small planets such as the Moon, and possibly Mars, with a thick lithosphere of buoyant plagioclase. Life survival depends on a regime of plate tectonics, which again excludes Mars with its stagnant lithospheric lid, and Venus which probably lost its continents some 700 Ma ago after most of its surface water was engulfed into the mantle. It is also unlikely that a "water world" such as Europa may sustain Earth-like forms of life.

## 1. INTRODUCTION

The production of amino acids in a flask filled with methane, ammonia, hydrogen, and water vapor by discharging electrodes (Miller, 1959; Miller & Urey, 1959) laid the ground work for the experimental attempts to produce the first compounds that would eventually lead to the origin of life. Such a gaseous mixture was intended to represent the composition of the Earth's primordial atmosphere, which in these days was thought to be related to the gas of the protoplanetary nebula and therefore dominated by hydrogen and other extremely reduced gaseous species. The perception that the primordial atmosphere

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of the Earth must have been blown off by the powerful radiations emitted by the Sun in its T-Tauri phase emerged from the rare-gas evidence that relative planetary and solar rare gas abundances are very different (Pepin, 1992). The secondary origin of the terrestrial atmosphere is now widely accepted and whether it formed by outgassing of the Earth's interior when the Earth still had a magma ocean, by more progressive outgassing related to the volcanic history of our planet, or was acquired by the late addition of material from the outer Solar System (Owen & Bar-Nun, 1995; Morbidelli et al. 2000) leaves no room for a reduced environment as would have been the case for a hydrogen-dominated nebular gas. All these criticisms led to the abandonment of the Miller-Urey scheme for producing the early life components (Kasting, 1993) and contributed to the enigma of how biological material, so prone to oxidation even under mildly oxidizing conditions, could appear under an atmosphere dominated by carbon dioxide, water, and nitrogen.

Even if biological molecules based on reduced carbon chemistry could be successfully synthesized in an oxidizing environment, a nagging question is that of biological cycles. It is well understood that in the modern world, life quickly uses up all the available nutrients, typically the phosphate and nitrate needed for the energy cycle and to make nucleic acids. Most of the modern biological productivity is located next to continents, whether it draws its resources from the nutrients carried to the sea by the rivers or from the upwelling of deep seawater along the continental margins adequately oriented with respect to the dominant winds. In most magmatic and metamorphic rocks, phosphate is hosted in apatite, the general composition of which is $Ca_5(PO_4)_3(F,OH,Cl)$. Were the terrestrial continents to be removed, life would quickly disappear. Terrestrial continents are a unique feature in our Solar System and can be identified by the double maximum on the hypsometric curve (the histogram of elevations), one at a depth of $\sim$4500 m corresponding to the abyssal plains and the other at $\sim$200 m above sealevel corresponding to the plains dominating most continents after the major reliefs have been eroded away. Continents are conspicuously absent from Venus, Mars, and the Moon. They owe their origin to the presence of buoyant magmatic rocks with high silica contents, which we will hereafter summarily refer to as granite. Granites react with the silica-poor rocks making up planetary mantles: they cannot be melts from the deep planetary interiors and hence represent low-temperature ($<800^\circ$ C) melts of hydrous basaltic crust. Granites are the hallmark of plate tectonics. Life on Earth, which seems indelibly related to the presence of continents, therefore owes its existence to the unique dynamic regime of our planet.

The present work focuses on the sequence of events that provided the geological environment for the origin of life, *i.e.,* an ocean of seawater on top of a magma ocean, and the favorable conditions for its preservation, the rapid emergence of subaerial silica-rich continents that could act as a permanent source of nutrients. It will be shown that nowhere in the Solar System other than on Earth were such favorable conditions met. The ongoing quest for extra-terrestrial life thus should be most successful for exoplanets that share the uncommon geodynamic characteristics of the Earth.

## 2. THE ORIGIN OF TERRESTRIAL WATER AND THE SOURCE OF HYDROGEN AND OTHER REDUCED GASES

The amount of water present in the deep mantle can be assessed from water concentrations in basaltic melts. A back-of-the-envelope estimate leads to the same amount of water being present at depth in the mantle as in the ocean. Such a simple calculation is superficially consistent with the common perception that both the atmosphere and the ocean largely owe their existence to the outgassing of the mantle through volcanic activity. The underlying assumption of this model therefore is that the Earth accreted with most of its current volatile inventory. This view is, however, untenable since the Earth is extremely depleted in volatile elements with respect to the undifferentiated material of the Solar System as represented by the solar photosphere and carbonaceous chondrites. When the temperature of the solar nebula decreases, elements condense in groups: the refractory elements (e.g., Ti, Ca, Al, Fe) come first, then the alkali elements and the group of high-temperature chalcophile elements (Zn, Cu, Ga), followed by the group of low-temperature chalcophile elements (Pb, Tl, Hg), and finally by the volatile atmophile elements (N, H, rare gases) (Fig. 1). The main argument made elsewhere (Albarède, submitted) rests on the comparison of a very refractory element, U, which condenses at $\sim 1600^\circ$ K (Lodders, 2003), with significantly more volatile elements such as K, Rb, and Cs, which condense at $\sim 1000^\circ$ K. The K/U ratio of a planet therefore is a measure of its volatile depletion. Similar arguments can be used for Rb and Cs. With respect to carbonaceous chondrites, the Earth lacks about 85% of the nebular K, Rb, and Cs inventories, Mars lacks 90%, and the Moon 95%. The conspicuous depletion in elements that condense at 1000 K show that the Earth, Moon, and Mars cannot have retained much hydrogen, which condenses at temperatures $<300$ K. The similar depletion of K, Rb, and Cs, which have very different atomic masses, indicates that the volatiles were not lost from the planetary gravity field. It rather shows that the temperature in the inner Solar System never fell below the point

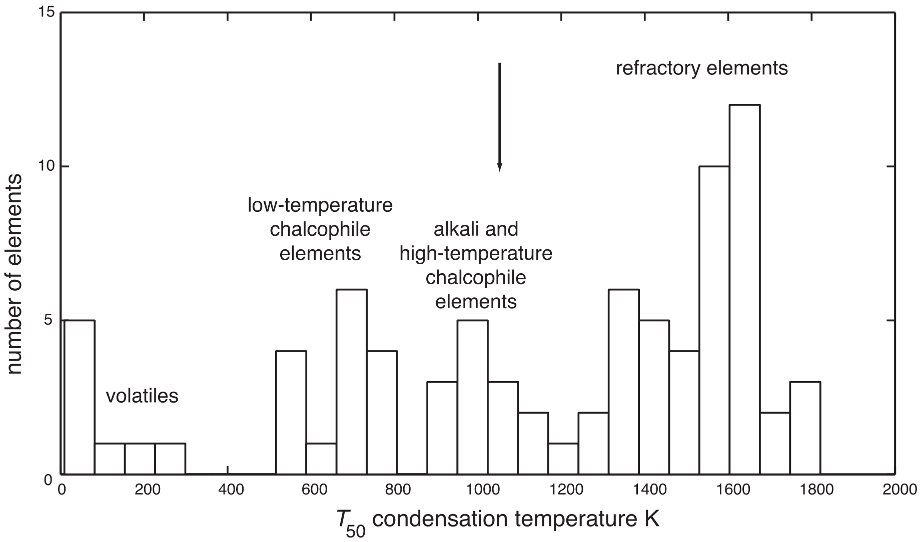


**Figure 1.** Histogram of temperatures at which elements condense from the solar nebula. $T_{50}$ stands for the temperature at which 50% of the original nebular inventory of the element has been condensed (Lodders, 2003). Depending on the elements and the accretion rate, the condensation is essentially complete within 50–150° C. Note the gaps between the different groups, which explain why a planet depleted in K (the arrow) cannot hold much water.

at which these elements started accreting before the nebular gas was blown off by the T-Tauri winds, i.e., within the first 3–5 Ma of Solar System history. The Earth and the other planets were therefore born dry and volatile-poor and the origin of the terrestrial ocean consequently must be sought elsewhere.

Orbital dynamics calculations provide an adequate answer to this question as they show that the migration of Jupiter and the other giant planets destabilized the small bodies located behind the "snow line", an imaginary line depicting the onset of water condensation in the planetary nebula, presumably located between Jupiter and the asteroid belt, and sent enough icy material into the inner Solar System to account for the terrestrial ocean (Chambers et al. 1998; Morbidelli et al. 2000). The thermal state of the Earth at this point is now relatively well understood: the combination of the release of gravitational energy from accretion, including core segregation, and the heat produced by the decay of $^{26}$Al ($T_{1/2} = 0.75$ Ma) was such that the upper mantle, and possibly the lower mantle as well, were totally molten. This is the very successful concept of the magma ocean, which is almost universally accepted for the Moon and the small planets on account of their low gravity: the flotation of plagioclase, a buoyant mineral very stable under the low-pressure conditions maintained by weak gravity, created a buoyant lithospheric lid, which can be seen today as the lunar highlands, and isolated the magma from the planetary surface. On Earth, the magma ocean concept recently received tremendous impetus from evidence that the now extinct $^{146}$Sm ($T_{1/2} = 103$ Ma) was extant in variable proportions

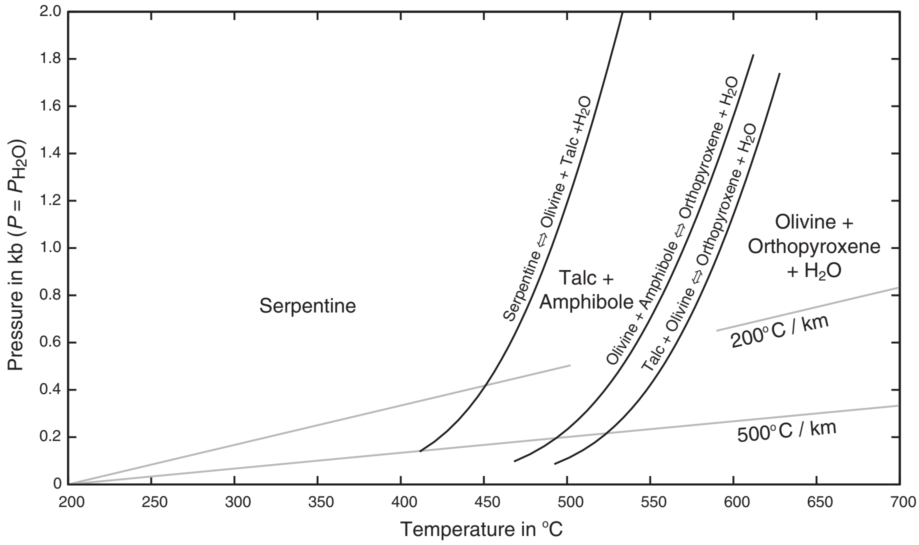


**Figure 2.** Representative mineral reactions between the top of the magma ocean and the overlying hydrosphere. The reactions have been calculated using the thermodynamic data of Robie & Hemingway (1995). Hydrous rocks containing serpentine, talc, or amphibole form a layer at the top of the olivine, pyroxene, and plagioclase cumulates and keep this crust buoyant, which slows down the cooling of the magma ocean. The thickness of the hydrous layer can be calculated by assuming a strong conductive temperature gradient of 200 or 500° C per km and a pressure gradient of 0.3 kb per km. A surface temperature of 200° C is assumed.

in the primordial mantle (Caro et al. 2003; Boyet et al. 2003). The early criticism of the terrestrial magma ocean concept on the basis that magma quickly irradiates its heat into space (Davies, 1998) did not take the absorption of radiation by the hydrous atmosphere into account.

The reaction of incoming icy bolids with the surface of the largely molten Earth produced a crust of hydrous minerals that prevented rapid cooling of the magma ocean (Kasting et al. 1993; Boyet et al. 2003). On an otherwise anhydrous planet, cooling of the surface magma would produce Fe, Mg-rich minerals, essentially olivine and pyroxenes, which are more dense than their parent melt: newly formed crust would, as commonly observed on top of erupting lava lakes, quickly founder into the molten silicates, and the magma ocean would quickly disappear. Reaction of water with olivine and pyroxene at temperatures of up to 600–800° C produces a sequence of hydrous minerals, notably serpentine, talc, and amphibole, all less dense than the underlying magma (Robie & Hemingway, 1995) (Fig. 2). The buoyancy added to the olivine-rich layer formed above the magma by hydrous minerals was sufficient to support a several km-thick crust and strongly reduce heat loss by irradiation. Such a mechanism of interaction between lava and atmospheric water is clearly responsible for the final cooling and top-down crystallization of basaltic lavas such as seen for the 1965 Makaopuhi eruption in Hawaii (Wright & Okamura, 1977). The presence of water vapor in the atmosphere constitutes an additional and potent barrier to radiative heat loss (Matsui & Abe, 1986).

A corollary to the formation of a buoyant hydrous crust on top of the magma ocean is that it reinstates steady conditions of abundant hydrogen, methane, and ammonia production at the surface of the Earth as first imagined by Miller and Urey. The most important process is the serpentinization of olivine, which produces hydrogen through the reduction of water by $Fe^{2+}$ (O'Neill & Barnes, 1969):

$$\begin{array}{ccc} 3Fe_2SiO_4 + & 2H_2O & \Leftrightarrow \\ \text{(olivine)} & \text{(solution)} & \end{array}$$
$$\begin{array}{ccccc} 2Fe_3O_4 & + & 3SiO_2 & + & 2H_2 \\ \text{(magnetite)} & & \text{(quartz)} & & \text{(gas)} \end{array} \tag{2.1}$$

Silica liberated in this reaction reacts with water and Mg-olivine to form the buoyant serpentine:

$$\begin{array}{cccc} 3Mg_2SiO_4 + & SiO_2 & + \; 4H_2O & \Leftrightarrow \\ \text{(olivine)} & \text{(silica)} & \text{(solution)} & \end{array}$$
$$\begin{array}{c} 2Mg_3Si_2O_5(OH)_4 \\ \text{(serpentine)} \end{array} \tag{2.2}$$

Hydrogen liberated by serpentinization reacts with atmospheric $CO_2$ and $N_2$ to give methane and ammonia:

$$\begin{array}{c} 4H_2 + CO_2 \Leftrightarrow CH_4 + 2H_2O \\ 3H_2 + N_2 \Leftrightarrow 2NH_3 \end{array} \tag{2.3}$$

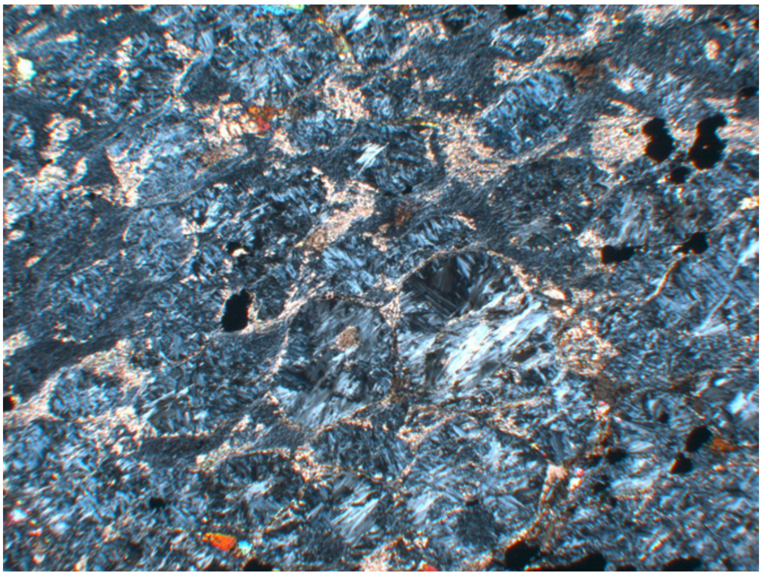

**Figure 3.** Serpentinization of a 3.9 Ga dunite (olivine-rich rock) from Isua, West Greenland (horizontal dimension ∼1 cm). The globular shapes are ghosts of olivine crystals replaced by serpentine. The light-color matrix is dominated by carbonates.

Serpentinization is commonly observed in olivine-rich rocks (Fig. 3). Production of hydrogen and methane upon interaction of seawater with hot olivine is ubiquitous in hydrothermal vents and in the water column along mid-ocean ridges (Welhan & Craig, 1983; Charlou et al. 1998). The biogenic implications of the production of reduced gas has been discussed by Sleep et al. (2004). Although the early atmosphere is unlikely to sustain large concentrations of hydrogen (lost by Jean's escape) and methane (oxidized and photolized), the existence of niches rich in $H_2$, $CH_4$, and $NH_3$ at the bottom of the ocean, particularly common as a result of intense volcanic activity, must have created a continuous stream of opportunities for the synthesis of prebiotic molecules. How these opportunities disappeared with the rise of atmospheric oxygen remains a matter of conjecture. The critics of Miller and Urey's hypothesis considered the stability of reduced gases at equilibrium within an established atmosphere and found that these gases were bound for very fast removal. The answer to these criticisms is that the sources of $H_2$, $CH_4$, and $NH_3$ are as widespread and sustainable as magmatic activity. Clearly, the path to understanding the origin of life paved by Miller and Urey, but which fell into oblivion for about 30 years, should now be explored with renewed interest.

The duration of the magma ocean stage is poorly constrained. The figure of 30 Ma emerging from the interpretation of the apparent $^{146}$Sm-$^{142}$Nd age of the Earth (Boyet & Carlson, 2005) and of apparent $^{182}$Hf-$^{182}$W age of the core still has to meet with unanimous agreement. One of the major difficulties is the age of the lunar magma ocean formed after the collision between the proto-Earth and a Mars-sized object and which may have lasted at least 60 Ma as judged from $^{182}$Hf-$^{182}$W evidence (Touboul et al. 2007), or as long as 120 Ma if also taking $^{146}$Sm-$^{142}$Nd evidence (Boyet & Carlson, 2007) into account. These were chaotic times for the Earth's surface with widespread opportunities for life to appear under temperature conditions favorable to the production of reduced gases and prebiotic molecules.

## 3. FROM THE MAGMA OCEAN TO PLATE TECTONICS

The conditions just described for the origin of life were probably not restricted to the Earth only. Hot water and olivine certainly existed on almost every planet including the Moon, Mars, and Venus. As suggested in the introduction, if the primordial forms of life did not survive on these planets to evolve into a modern form of biology, the cause must be that the resources it needed were quickly exhausted in the environments particular to these planets. Clearly, what marks two major first-order differences on Earth with respect to the Moon, Mars, and Venus are plate tectonics and the existence of continents, which fulfill the demands of modern life sustainability by providing a steady flux of nutrients to the ocean.

The role of water in geodynamics and for the origin of continents is relatively well-understood. Water "softens" silicates and makes mantle convection easier (Karato et al. 1986; Hirth et al. 1996). In contrast, too much water removes the "yield stress", which is the minimum stress that can be applied before material starts deforming, and therefore hampers the formation of tectonic plates. Convection in the dry mantles of the Moon and Mars was not vigorous enough and their gravity fields are weak. A stagnant lithosphere grows top-down and cannot bend because it is too stiff: this is the stagnant lid regime. None of these planets has a dichotomy that can be assigned to a contrast between continents and oceans. Convection in the mantle of Venus is apparently very vigorous but did not develop plates either (the planet was completely resurfaced 600–800 Ma ago (Phillips et al. 1992)). Venus hypsometry clearly shows a planet with no continent-ocean dichotomy (Rosenblatt et al. 1994). One of us (Albarede, submitted) suggested elsewhere that the reason is that Venus' oceans were completely subducted prior to $\sim$700 Ma ago. In contrast, the Earth's mantle has the proper rheology to sustain plate tectonics: enough water for strong convection, strong gravity to bend plates, not enough water for the plates to be quickly entrained by the underlying mantle. The formation of a basaltic crust at mid-ocean ridges, the hydration of this crust at the bottom of the ocean, and its melting at subduction zones to produce granitic melts that eventually rise and gather as continents, are all events that can be traced back to plate tectonics being the dominant feature of the terrestrial geodynamic regime.

If it is not entirely clear how the Earth's mantle inherited just the right amount of water to start off plate tectonics, some constraints can be placed on when this happened. The oldest coherent crustal segment on Earth is at Isua (West Greenland) and is 3.8 Ga old (Nutman et al. 1997). The oldest identifiable rock samples come from deformed decametric layers in younger gneisses at Acasta (Canada) and are 4.1 Ga old (Bowring et al. 1990). The oldest minerals on Earth occur as detrital zircons in the matrix of Archean Jack Hills conglomerates (Pilbara, Western Australia) and the oldest age referred to so far is 4.4 Ga (Wilde et al. 2001). Zircons are minerals that only occur in noticeable abundance in granitic rocks (they are soluble in basaltic melts). Abundant zircons therefore fingerprint the presence of granites and hence continents. As for most zircon ages, also the Jack Hills mineral U-Pb ages were obtained on individual spots

$\geq 50\,\mu$m in diameter in the beam of an ion probe (Secondary Ion Mass Spectrometry). These data received additional attention when the oxygen isotope compositions were measured and excesses of oxygen-18 were found with respect to normal mantle-derived magmas, indicating that the source rock of the Jack Hills granite contained sedimentary material formed under low-temperature conditions (Wilde et al. 2001; Mojzsis et al. 2001; Cavosie et al. 2004): although the age of the oldest zircon presenting an excess of oxygen-18 was $\sim$4.3 Ga, two conclusions were drawn: continents existed by 4.4 Ga and coexisted with a liquid ocean.

Recent work on Jack Hills zircons rely on the $^{176}$Lu-$^{176}$Hf chronometer to investigate the model age and the nature of the crustal protolith (the source rock) of the Jack Hills granite. The strength of Hf isotopes in zircons stems from the very low parent/daughter (Lu/Hf) ratio of zircons, which allows these minerals to essentially freeze the Hf isotopic composition of the parent melt at the time the zircons formed: only a reduced set of assumptions is then necessary to assess the Lu/Hf ratio of the protolith. Given that Hf is a very incompatible (melt-loving) element and Lu a compatible (solid-loving) element, the Lu/Hf ratio inferred for the protolith can be used to assess whether it is similar to modern continental crust or to other types of material, e.g., basaltic. Harrison et al. (2005) argued that there is a spread in U-Pb ages and in the Lu/Hf ratio of the protolith and suggested that continents started to form very early ($<$150 Ma after accretion). One of the ambiguities of the early geochronological studies of Jack Hills however is the broad range of ages observed in the Hadean zircon population (4.4 to 3.9 Ga) (Cavosie et al. 2004), which contrasts with the $\sim$200 Ma range usually observed for detrital zircons from younger orogenic events (e.g., Iizuka et al. submitted). Blichert-Toft & Albarède (2008) focused on a restricted set of Hadean zircons carefully selected for their lack of defects, fractures, zoning, and inclusions and for which ion probe U-Pb ages were known, and determined both the Pb-Pb ages and the Hf isotopes on the same dissolved single zircon grains. The resulting histogram of Pb-Pb ages came out remarkably simple as a single population with a mean age of 4.1 Ga and a rather narrow spread of $\pm$0.1 Ga (Fig. 4). Even samples having old (4.3) or young (3.3) ion probe ages gave ages consistent with a unique orogenic event at 4.1 Ga. The Hf model age of the Jack Hills granite protolith was inferred to be 4.30–4.36 Ga (Fig. 5). Recent data presented by the Bristol group (Hawkesworth et al. 2008) are entirely consistent with this interpretation. When combined with chronological evidence from Acasta (Bowring et al. 1990) and Enderby Land, Antarctica (Harley & Black, 1997), it therefore seems that the 4.1 Ga event is the oldest orogenic episode recorded so far in Earth history and establishes that by that time plate tectonics had begun.

The geochemical characteristics of the 4.30–4.36 Ga old protolith of the Jack Hills granite, however, came out as a major surprise. Detailed modeling requires that its Lu/Hf ratio was significantly lower than any crustal rock known today, with the exception of the unique Archean rock suite known as Tonalite-Trondhjemite-Granodiorite (TTG) (Jahn et al. 1981). These rocks are known to be substantially enriched in very incompatible elements (Martin, 1986; Kamber et al. 2002), which Blichert-Toft & Albarède (2008) argued is a characteristic inherited from the extreme differentiation of the magma ocean in the presence of garnet. In other words, the 4.30–4.36 Ga old protolith of the Jack Hills granite was either a remnant of a primitive terrestrial KREEP-like crust (KREEP originally being defined as the latest melts left by the differentiation of the lunar magma ocean) or the product of melting of material directly derived from this early

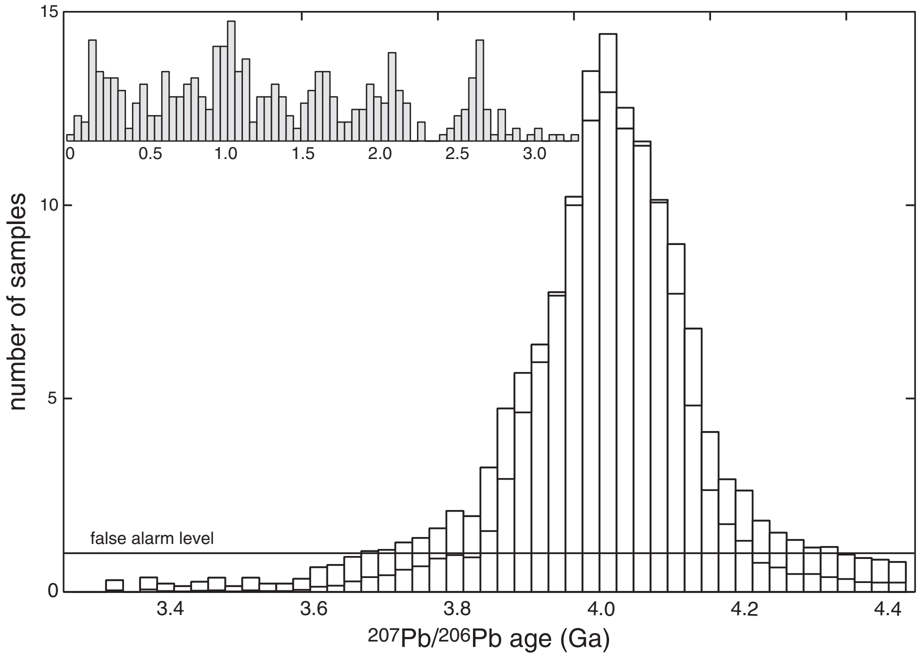


**Figure 4.** Pb-Pb ages of Hadean Jack Hills zircons obtained by wet chemistry (Blichert-Toft & Albarède, 2008). Over 100 zircons were selected for their lack of inclusions, zoning, or cracks. They correspond to a well-defined ∼200 Ma long tectonic crust-forming event at 4.1 Ga, very similar to the younger tectonic events recorded in detrital zircons from the major rivers (inset, Iizuka et al. submitted). The Jack Hills zircons therefore record the oldest evidence of plate tectonics so far. The boxes on top of each bin represent the 95 % confidence level.

differentiation. Whichever interpretation is the most suitable, enough is known to assess that the advent of plate tectonics and the rise of modern-style continents probably took place between 4.3 and 4.1 Ga ago. If the conditions under which life managed to survive up to this critical point can be understood, a major step forward towards understanding the origin of life will have been made.

## 4. LIFE AND PLATE TECTONICS

Among the chemical components necessary to sustain the origin of life (nutrients), those being severely "biolimited" are nitrogen, phosphorus, iron, and zinc (Broecker, 1974). These four elements are currently strongly depleted in the surface ocean. Along the line of the argument made in the previous section, it will be assumed that life's early phase was located in the deep water next to hydrothermal vents, where it could escape oxidation by atmospheric gases and UV radiations. Any successful form of life must have mastered the utilization of nutrients. Synthesis of amino acids, phospholipids, and later proteins, nucleic acids, and adenosine triphosphate (ATP) needed C, N, and P for the control of biological cycles. Shuttling of electric charges heavily depends on elements with multiple redox states, Fe (and to a lesser extent Cu and V), while protein synthesis needs the Lewis acid properties of Zn.

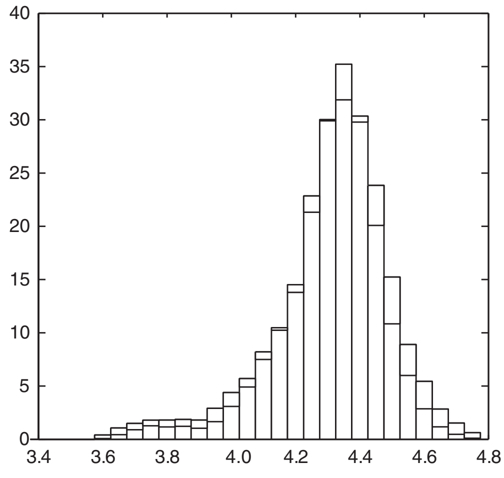


**Figure 5.** Model age of the protolith of the Jack Hills granites (the crust that generated the granite host to the zircons). This granite formed from a ~4.35 Ga old crust. The $^{176}Lu/^{177}Hf$ (parent/daughter) ratio of $0.005 - 0.01$ consistent with this age indicates that this crust was very enriched in incompatible elements and therefore was geochemically similar to the lunar KREEP (Blichert-Toft & Albarède, 2008). The protolith may represent a product of the magma ocean differentiation.

Very little can be said about whether the first organisms managed rapidly to fix atmospheric nitrogen or simply used ammonia produced by reaction with hydrogen in hydrothermal vents. The presence of nitrate in the modern ocean requires rather high Eh (oxidizing) conditions similar to those of the $H_2O$-$O_2$ couple. Oceanic nitrate most likely emerged as a modern phenomenon associated with the oxidation of nitrogen by atmospheric oxygen and is largely irrelevant to early life. Cycling of seawater saturated in $N_2$ at the surface of the ocean through the hydrothermal vents provided enough nitrogen for this element to not be the limiting nutrient. The modern N : P (Redfield) ratios of both biological matter and seawater are both equal to ~15 (e.g., Gruber & Sarmiento, 1997), which suggests that life finds no particular advantage in depleting one nutrient faster than another. The issue is that mid-ocean ridges are not a source but a sink of phosphorus: Wheat et al. (2003) assessed that the combination of ridge-crest and low-temperature hydrothermal activity absorbs $3.6 \times 10^{10}$ mol y$^{-1}$ of phosphorus, which is to be compared with a total of $7.8 \times 10^{10}$ mol y$^{-1}$ for the sum of river flux and other sources. Should modern continents become quickly flooded and the riverine flux of phosphorus to the sea shut down, this element would disappear from the ocean in about 20,000 years. It is hard to imagine how teeming life can escape, at least on the long term, a control by phosphorus delivered by continents (van Cappellen & Ingall, 1994), which substantiates the idea that life sustenance necessitates the presence of emerged continents.

After the discovery of microbes in the ice overlying the Vostok lake beneath the Antartica ice sheet (Karl et al. 1999), it was suggested that life could be present under the thick ice of some other planetary bodies, such as Europa, and that "ocean worlds" of planets outside the Solar System could actually harbor life. Such systems would have to rely on nutrient supplies that would greatly differ from those we know at the surface of the Earth and in the ocean. In other words, life on a planet with no continents should be very different from life on Earth.

## 5. CONCLUSIONS

With due consideration to serpentinization reactions at the interface between seawater and the magma ocean, which produce abundant hydrogen, methane, and ammonia, even in an oxidizing atmosphere of secondary origin, the Miller and Urey experiments should be given renewed attention. These particular conditions are limited to Earth-like planets with a strong gravity field. Life sustenance, however, needs a steady supply of nutrients: among these, phosphate, which is actually consumed, and not produced, by mid-ocean ridges, needs to be provided by the erosion of emerged continents. Continents are indelibly linked to plate tectonics, which most likely appeared between 4.1 and 4.35 Ga ago, as a result of hydrous basalts being sunk into the mantle. "Ocean worlds", such as Europa and exoplanets, are unlikely to harbor a teeming life.

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