THEORETICAL CONSTRAINTS ON EARLY EARTH'S ENVIRONMENT

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(Received August 25, 2008; Accepted September 10, 2008)

(Abstract)

The only geological evidence for the early Earth is zircon which suggests existence of continental crust and oceans at 4.404 billion years ago. Based on the record of the lunar impact craters, it has been considered that heavy bombardment of small solar system bodies to the Earth-Moon system occurred during the first several hundred million years. There is however another possibility that an intense, but short-term impact event (called the cataclysm) might have occurred at around 3.9 billion years ago, which could have been caused by rapid migration of the giant planets. The atmospheric composition during the early Earth was reducing, irrespective of source of volatiles. This may have been favorable for the prebiotic synthesis of organic materials and so the origin of life. The early Earth might have been globally glaciated because the heavy bombardment produced a large amount of impact ejecta which consumed the atmospheric CO_2 effectively through chemical weathering followed by carbonate precipitation. However, the effects of mantle overturn and large-scale resurfacing on the early Earth's environment remains unknown.

(Keywords)

early Earth, Hadean, heavy bombardment, impact, carbon cycle, snowball Earth

1. Introduction

Environment of the early Earth, from 4.55 to 4.0 Ga (billion years ago) has been largely unknown, because there is almost no geological evidence for this time interval. This period is called "Hadean".

For the Hadean environment, we usually assume an extremely hot climate, very intense volcanism and hydrothermal activity, heavy bombardment of extraterrestrial objects, large tides because of the Moon orbit much closer to the Earth, and a reducing composition of the atmosphere and ocean [e.g., 1-3]. While some of these factors may be reasonable, others would be still uncertain.

It has been known that there are zircon grains of the Hadean age [4]. Recent studies of oxygen isotopic composition of the zircons provide information on the environmental conditions for the Hadean Earth: existence of continental crust and oceans since the earliest history of the Earth [5-8].

On the other hand, there is reduced carbon with low carbon isotope ratio in the sedimentary rocks of the earliest Archean age, suggesting that photosynthetic activity could have already operated by 3.8 Ga [9-15]. It is therefore probable that life emerged during the earliest Archean or even during the Hadean.

Considering the only geological evidence from the Hadean Earth is zircon grains, theoretical constraints on the Hadean Earth is required for further understanding of the Earth's earliest environment. Because environmental condition of the Hadean Earth should be important to consider the origins of life on Earth, it is useful to summarize the present understanding of the early Earth.

In this paper, the recent studies on the early Earth's environment will be reviewed, and the possible conditions for the Hadean Earth will be discussed.

2. Geological evidence for the early Earth

The oldest known material on Earth is a mineral called zircon. Zircon ($ZrSiO_4$) is a common trace mineral that is highly resistant to erosion, weathering, and metamorphism. Detrital zircons of the Hadean age have been found within 3-Gyr-old quartzitic rocks in Mt. Narryer and Jack Hills in the Narryer Gneiss Terrain, Yilgarn Craton, Western Australia [4]. Among the zircon grains, the oldest age obtained so far with U-Pb dating is 4404±8 Ma (million years ago) (Fig. 1) [5].

The zircons are zoned with respect to rare earth elements and oxygen isotopic composition. In particular, oxygen isotopic composition ($\delta^{18}O$ value) of the zircon shows values ranging from 7.4 to 5.0 ‰ [5]. Heavy oxygen isotopic composition is produced by low-temperature interactions between rocks and liquid water, suggesting that the rocks which melted to form the magma included components that had been at the surface in the presence of liquid water. In other words, the zircon formed from an evolving magmatic source, probably a granitic melt, which contained a significant component of re-worked continental crust formed in the presence of oceans.

The zircon therefore suggests that there were continental crust and oceans on the Earth before 4404 Ma [5].

The zircon grains with the age of 3910 to 4280 Ma also have large $\delta^{18}O$ values ranging from 5.4±0.6 to 15.0±0.4 ‰, suggesting the interactions with continental crust and oceans [6]. These zircons also show hafnium isotope ratio with large positive and negative deviations from those of the bulk Earth [7, 8], suggesting the development of a Lutetium-Hafnium reservoir and widespread depletion of the upper mantle. This also implies the formation of continental crust by 4.4 to 4.5 Ga and its rapid recycling into the mantle.

Because the Earth is thought to have formed at 4.55 Ga, it appears that continental crust and oceans formed at the very beginning of the Earth's history.

The Acasta Gneiss in the Slave craton in Northwestern Territories, Canada, is known as the oldest rock on the Earth, which is dated 4031±3 Ma (Fig. 1) [16-18]. It is suggested that tonalitic magmas was produced by partial melting of pre-existing crust, implying existence of continental crust and liquid water before 4.0 Ga.

The oldest sedimentary rock on Earth, about 3.8 to 3.7 Ga, is contained in the Isua greenstone belt in southwestern Greenland (Fig. 1). In the Isua supracrustal rock, the presence of ^{13}C-depleted reduced carbon (the δ^{13}C values of -5.9 to -24.9 ‰) has been reported [9-13]. Because the difference in δ^{13}C values between inorganic and organic carbon (magnitude of carbon isotopic fractionation) indicates carbon fixation by autotrophs employing the Calvin cycle, Schidlowski [12] proposed biological (photosynthetic) origins of these reduced carbon which was later in reequilibration with carbonate, although this interpretation has been controversial. Mojzisis et al. [13] showed that there are carbonaceous inclusions with low δ^{13}C values of -30 to -37 ‰ in apatites from banded iron formation in Isua and the sedimentary rocks in Akilia Island. There are not any known abiotic processes which can explain the data. The reduced carbon may have been therefore biogenic, although the age of the Isua samples might be much younger [14]. On the other hand, Rosing [15] found the reduced carbon of 2 to 5 micrometer graphite globules whose δ^{13}C values are about -19 ‰ in turbiditic and pelagic sedimentary rocks with well-preserved sedimentary structures. Based on the data and the mode of occurrence, he insists that the reduced carbon represents biogenic detritus, perhaps derived from planktonic organisms [15].

Structures interpreted as the oldest (3465 Ma) cyanobacterial microfossils have been found in Apex cherts of the Warrawoona Group in Western Australia [19, 20]. If it were the case, oxygen-producing photosynthesis began at least from 3465 Ma. It is however revealed that the microfossil-like structures should be secondary artifacts formed from amorphous graphite within multiple generations of metalliferous hydrothermal vein chert and volcanic glass [21]. Because the micron-sized filament-like structures and also the stromatolite-like structures can be formed inorganically [22, 23], it is difficult to identify biological activities in Precambrian only from the morphologies.

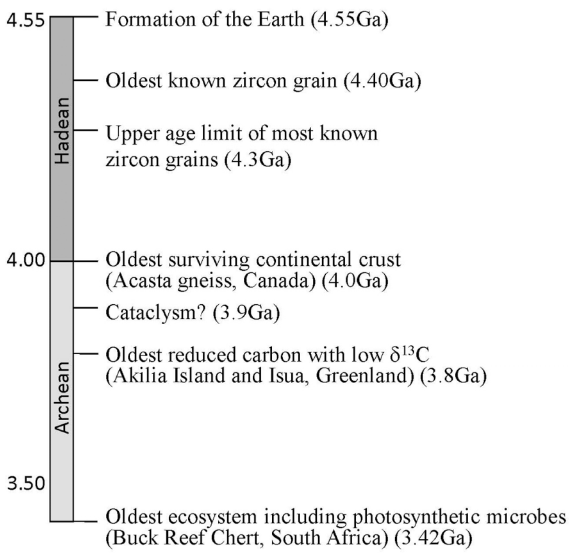

Figure 1. The earliest history of the Earth.

On the other hand, there is convincing evidence for the existence of an ecosystem including photosynthetic microbes at 3416 Ma in the Buck Reef Chert in South Africa [24]. The isotopic composition of carbonaceous matter is -35 to -20 ‰ which is consistent with fixation by autotrophs. The presence of siderite, lack of primary ferric oxides, and the restriction of microbial mats to shallow water which may reflect confinement to the euphotic zone (<150 m) indicate that anoxygenic photosynthetic microbes were active at that time [24].

Together with the possibility of biological origin of reduced carbon found in the Isua supracrustal rock, it is possible for the origins of life to have been before 3.8 Ga, or even during the Hadean. All the geological evidence for the Hadean is, however, the zircon grains. We therefore need theoretical constraints on the Hadean Earth for further discussion of the earliest environment of the Earth.

3. Theoretical constraints on the early Earth

3.1. Late heavy bombardment

Based on the impact cratering record on the Moon, heavy bombardment of extraterrestrial bodies to the Earth-Moon system for the first several hundred million years has been suggested. Assuming an exponential decrease of impact flux with time, the frequency of impact on the early Earth would have been 10^3 to 10^9 times the present flux (Fig. 2) [25]. During the Heavy Bombardment period, there were several impact events with an impact energy corresponding to the total evaporation of the ocean [26, 27]. This might have damaged the earliest biosphere on the Earth, if it existed, and resulted in multiple origins and extinctions of life [26, 27].

It is however known that there is no impact melts older than about 4.0 Ga in the lunar highland samples [28]. Recent study of lunar meteorites also shows the lack of impact melt older than 3.92 Ga [29]. These facts might suggest that a very intense impact event occurred at around 3.9 Ga (Fig.2) [30]. This episode is called a "terminal lunar cataclysm" or "late heavy bombardment".

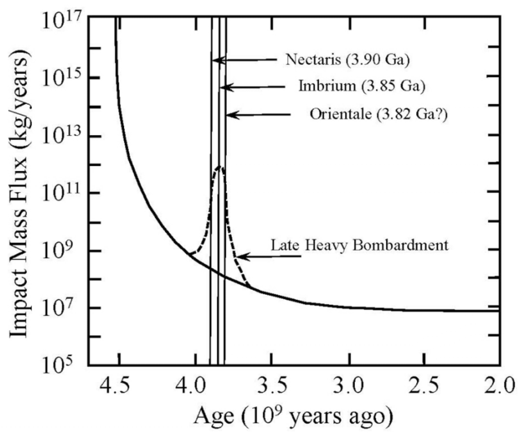

Figure 2. Impact flux to the Earth. Solid curve represents the flux with exponential decay, and dotted curve represents the late heavy bombardment (i.e., the cataclysm). Ages of the major impact basin on the Moon are indicated (modified from Koeberl (2006) [30]).

The cataclysm hypothesis might explain why there is no terrestrial material other than zircon grains from the Hadean Earth and why the oldest sedimentary rock left on the Earth is 3.85-Gyr-old Isua supracrastal rock.

A mechanism for the cataclysm about 650 million years after the formation of the Earth and Moon may be explained by gravitational perturbation induced from the rapid migration of the giant planets at that period [31-33]. The planetesimal disk outside the orbits of the giant planets and the asteroid belt were destabilized, which resulted in a massive delivery of planetesimals to the inner Solar System [31].

It is however noted that the extremely intense flux of impact in the first hundred million years could have destroyed crustal rocks formed before 4.0 Ga and reset K-Ar ages of the lunar rock samples by shock effects [25]. In that case, an apparent peak in the lunar rock age distribution is expected even when the impact flux decreased monotonically.

In either case, impacts must have significantly affected the surface environment of the Earth, and so the origin and early evolution of life. It is therefore really important to reconstruct the impact history of the Earth-Moon system during the first several hundred million years.

3.2. Mantle convection

Magma oceans were probably formed by giant impacts in the last stage of the Earth's formation. Water vaporized to form a steam atmosphere which, in turn, affects surface temperature through absorption of infrared radiated from the surface. As the surface temperature decreases with decreasing heat flux from the interior of the Earth, magma ocean evolved from a super-liquidus (completely molten) state to a partial melting (partially molten) state. Proto-crust formed when the steam atmosphere collapsed to form proto-ocean.

There was still an internal magma ocean beneath the proto-crust during the earliest history of the Earth. Heat transport was controlled by melt-solid separation rather than thermal convection, and chemical differentiation of the mantle proceeded [34]. This stage would have continued several hundred million years until the geothermal heat flow from the interior of the Earth decreased to 1 to 0.1 W/m^2 [34]. After this stage, solid-state convection has been working in the mantle until today. It is therefore suggested that there was an internal magma ocean, and so extensive volcanism and hydrothermal activities are expected to have occurred during the early Earth.

Heat production due to decay of radioactive elements, such as ^{235}U, ^{238}U, ^{232}Th, and ^{40}K, in the mantle was about 4 times higher than that of today (about 30 pW/kg, i.e., mantle heating rate of 1000 K/Gyr), hence vigor of mantle convection should have been far strengthened compared to the present one. According to a study of numerical simulation of the mantle convection under such a condition, there are several characteristic features of the mantle convection [35]. Strong internal heating of lower mantle induces mantle overturn which causes vigorous magmatic activity. As a consequence, large-scale resurfacing (formation of magma pond) occurs repeatedly [35].

It is suggested that the Hadean Earth may have been characterized by chaotic plate motion, frequent mantle overturn and large-scale resurfacing, hence very unstable surface condition. This is consistent with virtually no geological evidence left in the first several hundred million years. Such a condition may not be appropriate for early evolution of life, if life emerged during the Hadean.

3.3. Composition of early atmosphere

A growing Earth was surrounded by protoplanetary disk gas (so-called the "solar nebula", composed mainly of H_2 and He) in which planetesimals accreted with each other [e.g., 36, 37]. The proto-Earth could have captured the solar nebula gas as a primordial atmosphere, because the gravity was strong enough to capture the surrounding gas when the mass of the proto-Earth was larger than 1/100 of the present Earth's mass (about the mass of the Moon) [34]. As a consequence, a primordial atmosphere of the Earth was very reducing.

Impact degassing of volatiles from planetesimals due to hypervelocity impact may have also contributed primordial atmosphere during the main accretionary phase. It is probable that the atmosphere derived from impact degassing contained abundant H_2O, hence the surface of the proto-Earth may have been under the runaway greenhouse condition [38-40].

The runaway greenhouse condition is achieved only when the sum of the energy input to the planetary surface due to net solar incident flux, planetesimal impacts, and geothermal heat flux is larger than 310 W/m^2 [41-43]. Under the runaway greenhouse condition, the surface of the planet is covered with magma ocean because there is an excess energy input larger than the upper limit of outgoing radiation from the steam atmosphere, resulting in a runaway increase in the surface temperature. It is suggested that metallic iron in the magma ocean was segregated to form the core. At that time, chemical reactions of volatile elements with metallic iron resulted in formation of reducing atmosphere. In the presence of metallic iron and silicates in the magma ocean, oxygen fugacity is controlled by the iron-wüstite buffer [44, 45]. In such an atmosphere, H_2/H_2O and CO/CO_2 may be >1 and ~5, respectively [34].

This primordial atmosphere might have been, however, largely removed. One possible process is hydrodynamic escape due to heating of hydrogen-rich atmosphere by strong X-ray and extreme ultraviolet (XUV) radiation thought to have been emitted from the young Sun [e.g., 46, 47]. Another possible process is atmospheric loss due to giant impacts of Mars-sized proto-planets during the late accretionary stage [48]. It appears that the planetary atmosphere could have escaped by giant impact when the planet was covered with an ocean, rather than covered with a steam atmosphere [48]. It is therefore possible that a significant fraction of the pre-existing atmosphere of the Earth might have been lost owing to the giant impacts at the last stage of accretion.

After the moon-forming giant impact, the atmosphere of the Earth was composed mainly of silicate vapor at first, and then, evolved to water vapor [49]. Hence the steam atmosphere appeared again. Cooling of the steam atmosphere resulted in the formation of the ocean and atmosphere on the Earth. The chemical composition of the atmosphere at that time depends on an existence of metallic iron in the pre-existing magma ocean and on the quenching temperature of the chemical reactions. When the quenching temperature of the reactions is lower than 800 K, abundance of CH_4 increases significantly [52].

There is however still the source of volatiles to the Earth's surface. It is well known that the upper mantle of the Earth today contains highly siderophile elements much more than that predicted from the equilibrium with metallic iron [50]. It is therefore considered that accretion of oxidizing materials, such as CI chondrites or icy planetesimals (comets), should have occurred after the end of core formation (late veneer hypothesis). It is generally believed that the late veneer might have supplied H_2O and CO_2 to the Earth's surface for several hundred million years, and created oxidizing atmosphere [51].

However, even the CI chondrite, the most oxidizing materials in the solar nebula, should form a reducing atmosphere with abundant H_2 and CO [52]. The CI chondrite contains organic matter (reduced form of carbon) of 3.5 wt% which should be oxidized by 32.6 wt% of ferric iron. The typical content of iron in CI chondrite is, however, at most 20 wt%, resulting in a deficiency in oxygen to oxidize all the reduced carbon. As a consequence, the atmosphere formed by late veneer of CI chondrite should have been also reducing [52].

It is therefore suggested that the atmosphere in the early Earth was almost certainly reducing.

The atmosphere has been oxidized owing to the escape of H_2 to space. The reducing gases such as CO, CH_4, and NH_3 are known to be unstable when there is water vapor. They should be oxidized by OH radicals formed through photochemical reactions of water vapor, resulting in the formation of H_2 which would escape to space [53, 54].

The mechanism for H_2 escape may be hydrodynamic escape due to large XUV flux from the young Sun. The timescale of H_2 escape determines a life time of reducing atmosphere on Earth, although the precise timescale have not been established yet. According to the recent study [55], the timescale of H_2 escape might be longer than that previously thought. When we assume the hydrogen escape flux of about 6×10^{15} molecules m^{-2} s^{-1} [55] for the solar XUV flux of about 10 times the present value at 3.8 Ga [56], the hydrogen equivalent to the terrestrial ocean escapes to space in 500 Myr [52].

It is therefore concluded that there has been reducing atmosphere for the first several hundred million years during the Earth's history. This might have been favorable for the prebiotic synthesis of organic materials and so the origin of life on Earth.

4. Carbon cycle and Hadean snowball Earth

The Moon-forming impact created a silicate vapor atmosphere which lasted probably for 1000 years [49] (Fig. 3). And then, a steam atmosphere was left on the surface of the Earth. Because of very high geothermal heat flow from the interior, the runaway greenhouse condition is maintained, resulting in the surface temperature of 1500-2000 K and the surface of the Earth being covered with magma ocean [49]. Because of a negative feedback mechanism for the surface temperature due to solubility equilibrium of water vapor with magma ocean [38-40], this stage would have lasted for about 2 million years [49].

As the mantle froze, the steam atmosphere became unstable and condensed to form a warm (500 K) water ocean [34, 49]. The cooling time of 100 bar atmosphere is about 700 years, and the duration of heavy rain is 150 to 250 years with average net precipitation of 4000 to 7000 mm/year [34].

The atmospheric composition of this stage might have been reducing, but the dominant greenhouse gas may have been CO_2. If there were 100 bar of CO_2, warm ocean stage would have lasted for 10 to 100 Myr, depending on the timescale of subduction of seafloor carbonates into the mantle.

The climate of the Hadean Earth was, then, controlled by carbon cycle which might have been quite different from that at present. The supply of CO_2 via volcanism to the atmosphere was probably much more efficient than today. If the continental crust was very little, chemical weathering of seafloor basalt followed by carbonate precipitation could have been the dominant CO_2 sink. It might have occurred mainly at mid-ocean ridge system.

There may have been, however, another dominant sink of CO_2 during the Hadean: chemical weathering of abundant ultramafic volcanics and impact ejecta, followed by carbonate precipitation [49, 57-59]. The Heavy Bombardment (described in the section 3.1) should have produced large amount of impact ejecta which included very fine particles and were effectively weathered to consume CO_2, resulting in global glaciations [49,57-59].

In the snowball Earth condition, the surface of the Earth is completely covered with ice. However, because of very high geothermal heat flow during the early Earth, the thickness of ice shell over the ocean was very thin, probably 10 to 100 m thick. Such a thin ice shell may have been easily destroyed by large impact events, which might have triggered a brief impact summer [49].

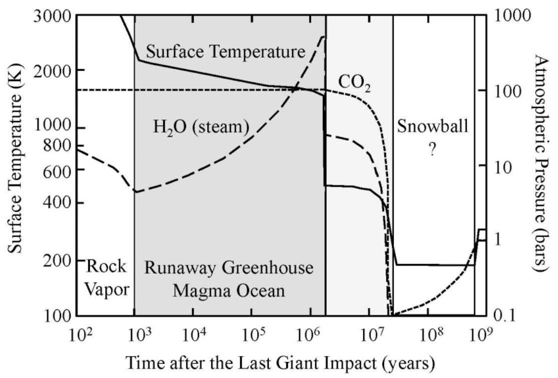

Figure 3. Schematic diagram of the early evolution of atmosphere and climate of the Earth. Solid curve is surface temperature, dashed curve is amount of H_2O in the atmosphere, and dotted curve is amount of CO_2 in the atmosphere (modified from Sleep (2006) [49]).

The possibility of the early ice-covered Earth may be tested by observation of terrestrial planets around young stars in the future. Such a “snowball planet” may exist as a typical type of water-rich terrestrial planets in the extrasolar planetary systems [60], because globally ice-covered is one of the stable climate states of the water-rich terrestrial planets.

It is however noted that a net result due to competition between the effects of the Heavy Bombardment and the intense volcanism due to frequent mantle overturn has not been studied so far. Very high heat flux localized due to intense volcanism and resurfacing, and/or efficient recycling of subducted CO_2 to the surface might have prevented the early Earth from complete freezing. Further studies are therefore required to understand the climate of the Hadean Earth.

5. Conclusions

The early Earth’s environment has been largely unknown because there is no geological evidence other than zircon grains in this period. However, oxygen isotopic composition of the zircons suggests existence of continental crust and ocean before 4.404 Ga. The atmospheric composition during the early Earth must have been reducing even when the atmosphere formed by degassing from CI chondrite (the most oxidizing material in the solar nebula). During the early Earth, the Heavy Bombardment of extraterrestrial objects occurred, which might have resulted in global glaciations. However, the effects of intense volcanism and large-scale resurfacing on the early Earth’s environment remain uncertain.

Acknowledgments

I would like to thank Dr. Akihiko Yamagishi for the reviews and helpful comments. This research was partially supported by a Grant-in-Aid for Scientific Research (No. 18340128) of the Japan Society for the Promotion of Science.

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