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Research paper

Origin of the Earth: A proposal of new model called ABEL

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ABSTRACT

The Earth was born as a dry planet without atmosphere and ocean components at 4.56 Ga, with subsequent secondary accretion of bio-elements, such as carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) which peaked at 4.37–4.20 Ga. This two-step formation model of the Earth we refer to as the advent of bio-elements model (ABEL Model) and the event of the advent of bio-elements (water component) as ABEL Bombardment. It is clear that the solid Earth originated from enstatite chondrite-like dry material based on the similarity in oxygen isotopic composition and among other isotopes. On the other hand, Earth's water derives primarily from carbonaceous chondrite material based on the hydrogen isotopic ratio. We present our ABEL model to explain this enigma between solid Earth and water, as well as secondary accretion of oxidizing bio-elements, which became a precursor to initiate metabolism to emerge life on a highly reductive planet. If ABEL Bombardment had not occurred, life never would have emerged on the Earth. Therefore, ABEL Bombardment is one of the most important events for this planet to evolve into a habitable planet. The chronology of ABEL Bombardment is informed through previous researches of the late heavy bombardment and the late veneer model. ABEL Bombardment is considered to have occurred during 4.37–4.20 Ga, which is the concept to redefine the standard late heavy bombardment and the late veneer models. Also, ABEL Bombardment is the trigger of the transition from stagnant lid tectonics to plate tectonics on this planet because of the injection of volatiles into the initial dry Earth.

1. Introduction

What is the origin of Earth's water? From ancient times, people have considered that water comes from the Earth's interior based on the observation that magma erupted from volcanoes comprises a water component. There is little doubt that the water component originates from Earth's modern interior, in the form of hydrous minerals in the mantle rather than liquid water like an ocean. Based on such observation or empirical rule, people have generally considered the water component to have been originally stored in the Earth's interior, and spouted out through time to be accumulated on the surface of the Earth in the form of oceans.

Since the proposal of plate tectonics (e.g., Le Pichon, 1968; Morgan, 1968; McKenzie, 1969) and a more recently revealed dynamic whole Earth system including superplume and three-layer model of continents of solid Earth (e.g. Maruyama et al., 2007; Kawai et al., 2009), it has become clear that the water component has come from the Earth's interior until about 1.0 Ga dominated by decompressional melting by an upwelling mantle (Maruyama et al., 2014), while surface water has been carried into the deep mantle down to 660 km in depth as hydrous minerals along subduction zones only since 600 Ma (Maruyama, 1994; Maruyama and Liou, 2005). However, the original source of water component has remained unknown.

In the science community with particular focus on planetary-formation theory, it has been vaguely considered that the Earth had an atmosphere and ocean from the beginning of the formation of the Earth. Classic models of planetary formation theory were provided by Safronov (1969, 1972) and Hayashi et al. (1985), the latter being the so-called Kyoto model (Fig. 1). These models were followed by studies based on numerical calculation by a special purpose computer focusing on N-body simulation (e.g. Kokubo and Ida, 1995; Ida et al., 2001). More recently the Grand Tack model (Walsh et al., 2011) was proposed, which explains Jupiter migrating

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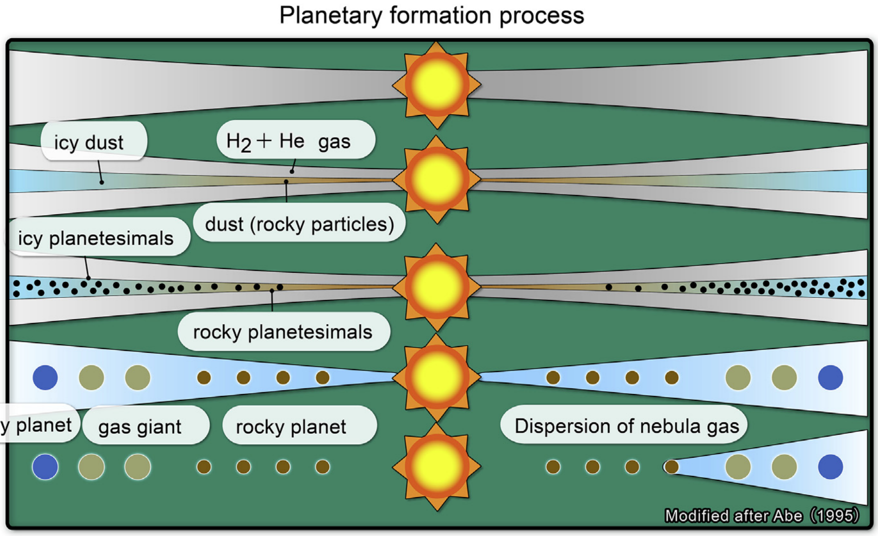


Figure 1. Planetary formation process. Simplified cartoon showing the step-wise formation of a primordial planetary system from the rotating gas nebula (top), through fine-grained mineral dust particles with chemical differentiation (middle), formation of planetesimals and their accretion to become asteroids within a gas envelope or free gas (middle bottom), and the final formation of three groups of planets (rocky, gas Giants with ice-rock planetary core, and Icy planets), as a function of distance (AU). The timing of gas dispersion is debated. Note the difference between the figure on the right vs. the figure on the left at the bottom. Figure was modified after Abe (1995).

inward from far beyond Jupiter to deliver asteroids or icy planetesimals and then return to its present position after the formation of the rocky planets including the Earth. Following this model, O'Brien et al. (2014) suggested that water was transferred to the Earth through this process. However, these new models are not consistent with evidences given from material science, such as chemical zoning seen in the present asteroid belt and solar system (DeMeo and Carry, 2014). However, apart from the varieties of interpretation of formation processes of the solar system or a planetary body, one point in common among their models is that the Earth has maintained its atmosphere and ocean since its birth (Fig. 2; Fanale, 1971; Matsui and Abe, 1986; Zahnle et al., 1988, 2007; Ikoma and Genda, 2006). All of the models explain that the atmospheric and oceanic components were provided by a degassing process as secondary products of the accretion of solid Earth.

On the other hand, Astrolithology has a long history as a research subject in the field of astronomy since the works by pioneers such as Urey (1952), Anders (1964), and Ringwood (1959, 1966). Such research began from the classification of meteorites based on the existence of chondrule (e.g. Urey and Craig, 1953). Basically, a meteorite is a "conglomerate" signifying the aggregation of condensates from the solar nebula under a non-equilibrium process including calcium-aluminum-rich inclusions (CAI) and chondrules formed at temperatures over 1000 °C and matrix minerals formed far below 100 °C. Such meteorite material mixed with chondrules is thus classified as chondrite, which is subclassified as oxidized chondrite and dry (reductive) chondrite. The most reductive one is enstatite chondrite, while the most oxidized one is CI chondrite. The asteroid belt is divided into inner part (mainly reductive enstatite chondrite) and an outer part (water-rich carbonaceous chondrite), which indicates the temperature of the matrix of the meteorite as a function of distance from the Sun. In other words, the further the distance from the Sun, the more hydrated the chondrites becomes. Based on this, researchers suggested that the accretion of the Earth began with highly reduced material without volatile elements, with oxidized elements enriched in volatiles being accreted at a subsequent stage (Ringwood, 1977, 1979; Ringwood and Kesson, 1977; Wänke, 1981; Wänke and Dreibus, 1988), which evolved from the so-called late veneer model that was first proposed by Anders (1968). The inhomogeneous accretion model mainly devised by Ringwood and Wänke strengthened the late veneer model that could not explain the Earth's formation process with regards to CI chondritic Earth's composition such as siderophile elements. Recently, Albarède (2009) provided chronological data based on I-Xe and U-Pb chronometers, suggesting that the late veneer event occurred at 100 ± 50 Ma after the T-Tauri phase.

Due to the technological advancement of equipment that could be used to analyze isotopic ratios, Clayton and his colleagues revealed that the solid Earth has an isotopic composition equivalent to that of enstatite chondrites regarding oxygen (Clayton et al., 1984; Clayton and Mayeda, 1996). Subsequently, the origin of the Earth began to be discussed based on isotopic data. Such analytical data has been accumulated gradually, which includes Pb isotopic analysis by Albarède (2009), Ti isotopes by Zhang et al. (2012), Sr isotopes by Moynier et al. (2012), S isotopes by Labidi et al. (2013), Pd-Ag systematics by Schönbächler et al. (2010), Hf-W systematics by Willbold et al. (2011), Touboul et al. (2007, 2012, 2015), Kruijer et al. (2015), and Ru-Mo isotopes by Dauphas et al. (2004) and Fischer-Gödde et al. (2015).

With continued technological advancement, sample return missions became available to capture particles of solar wind, comets, or other materials by using spacecraft such as the Genesis mission for solar atmosphere and the Deep Impact for cometary debris by the National Aeronautics and Space Administration (NASA). These missions brought actual samples from the Universe which have been analyzed. Examples include samples from comets Halley (Balsiger et al., 1995; Eberhardt et al., 1995), Hyakutake (Bockelée-Morvan et al., 1998), Hale-Bopp (Meier et al., 1998), and Garradd (Bockélee-Morvan et al., 2012). Analyses of the D/H ratio of hydrogen isotope from the returned samples, on the other hand, indicate that Earth's water originates from meteorites from the asteroid belt (Eberhardt et al., 1995; Geiss and Gloeckler, 1998; Lécuyer et al., 1998; Robert, 2001), contradicting the oxygen isotopic compositions that show the Earth being made from enstatite chondrite. Therefore, the formational process of the Earth has thus far remained unknown and controversial.

Previously proposed inhomogeneous accretion by a series of papers by Ringwood (1977, 1979), Ringwood and Kesson (1977), Wänke (1981), Wänke and Dreibus (1988), for example, and

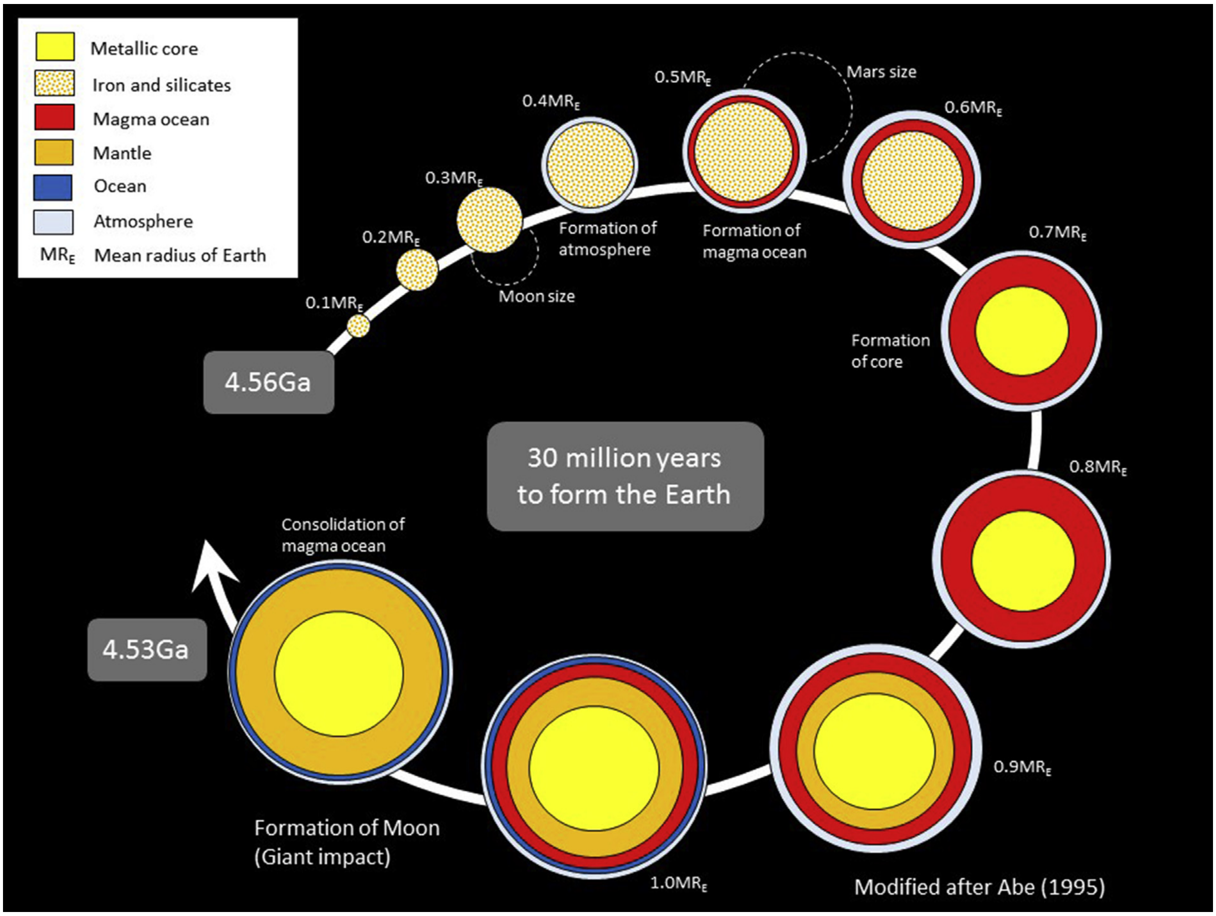


Figure 2. Formation process of the Earth. Schematic illustration of the successive formation of the layered Earth, from asteroid to the fully-layered Earth with atmosphere and ocean at 4.53 Ga. Note the step-wise differentiation at 0.3 MRE (mean radius of the Earth) (keeping atmosphere), 0.5 MRE (Mars) (initiation of magma ocean on the surface), and 0.7 MRE (segregation of core), giant impact at 4.53 Ga, and the re-emergence of ocean shortly thereafter. Figure was modified after Abe (1995).

chronological data by Albarède (2009) have yielded significant information concerning the formation process of the Earth. However, their models fall short of explicitly explaining the formation process such as in the case of the Ringwood and Wänke model which explains the gradual transition of mother meteorites of the Earth from enstatite chondrite-like material to carbonaceous chondrites, or the chronological evidence by Albarède (2009) for the late veneer event which remains undiscussed in terms of the meaning of the late veneer through the history of the Earth.

In this paper, we integrate these previously proposed models to provide a solution to the dilemma between enstatite chondrite and carbonaceous chondrite as the primary source materials of the Earth. Also, we show the meaning of the accretion of carbonaceous chondrites to evolve into life-sustaining planet. Our 2-step formational model of the Earth (Fig. 3C), which we refer to as the advent of bio-elements (ABEL) model, provides an overarching explanation of the whole process of the Earth from its formation to its eventual habitable state supported by both material science and chronological consideration.

2. Facts given through previous research

2.1. D/H signature of a carbonaceous-chondrite marking the origin of Earth's water

Water of Earth's ocean, fresh water from lakes, crustal water, and mantle-derived water all have a deuterium/hydrogen (D/H) value of $(149 \pm 3) \times 10^{-6}$ (Lécuyer et al., 1998). On the other hand, the D/H of hydrogen of the solar atmosphere at 4.5 Ga is estimated to be $(21 \pm 5) \times 10^{-6}$ (Geiss and Gloeckler, 1998), while D/H of a comet is over 300×10^{-6} (Eberhardt et al., 1995). Through this kind of analysis of carbonaceous chondrites, the value of D/H of Earth's hydrogen ranges between 130×10^{-6} and 150×10^{-6}. Therefore, it is clear that Earth's hydrogen is almost the same value as carbonaceous chondrites (Fig. 4). Although, some samples from carbonaceous chondrites exceptionally show values exceeding 300 thought to be derived from outside the Oort cloud with unknown reason (Eberhardt et al., 1995). However, judging from the overall D/H, there is little doubt that Earth's water predominantly originated from carbonaceous chondrite comparable to the composition of the outer part of the asteroid belt (Robert, 2001). This is in contrast to the hydrogen in the ocean being H_2 gas from the primordial nebula, in which case the primordial ocean would have formed when the magma ocean solidified through the extensive reaction between H_2 gas with oxygen from the rocky planet or magma ocean. This latter explanation for Earth's water, however, is not supported by the above D/H information.

2.2. Oxygen isotopic signature of an enstatite-chondrite marking the origin of the solid Earth

Carbonaceous chondrites have long been considered to be the source material of the Earth (e.g. Latimer, 1950; Urey, 1952), mainly because they reasonably explain the origin of its atmospheric and oceanic components. However, if the Earth was formed from only carbonaceous chondrite, then the Earth should have a greater

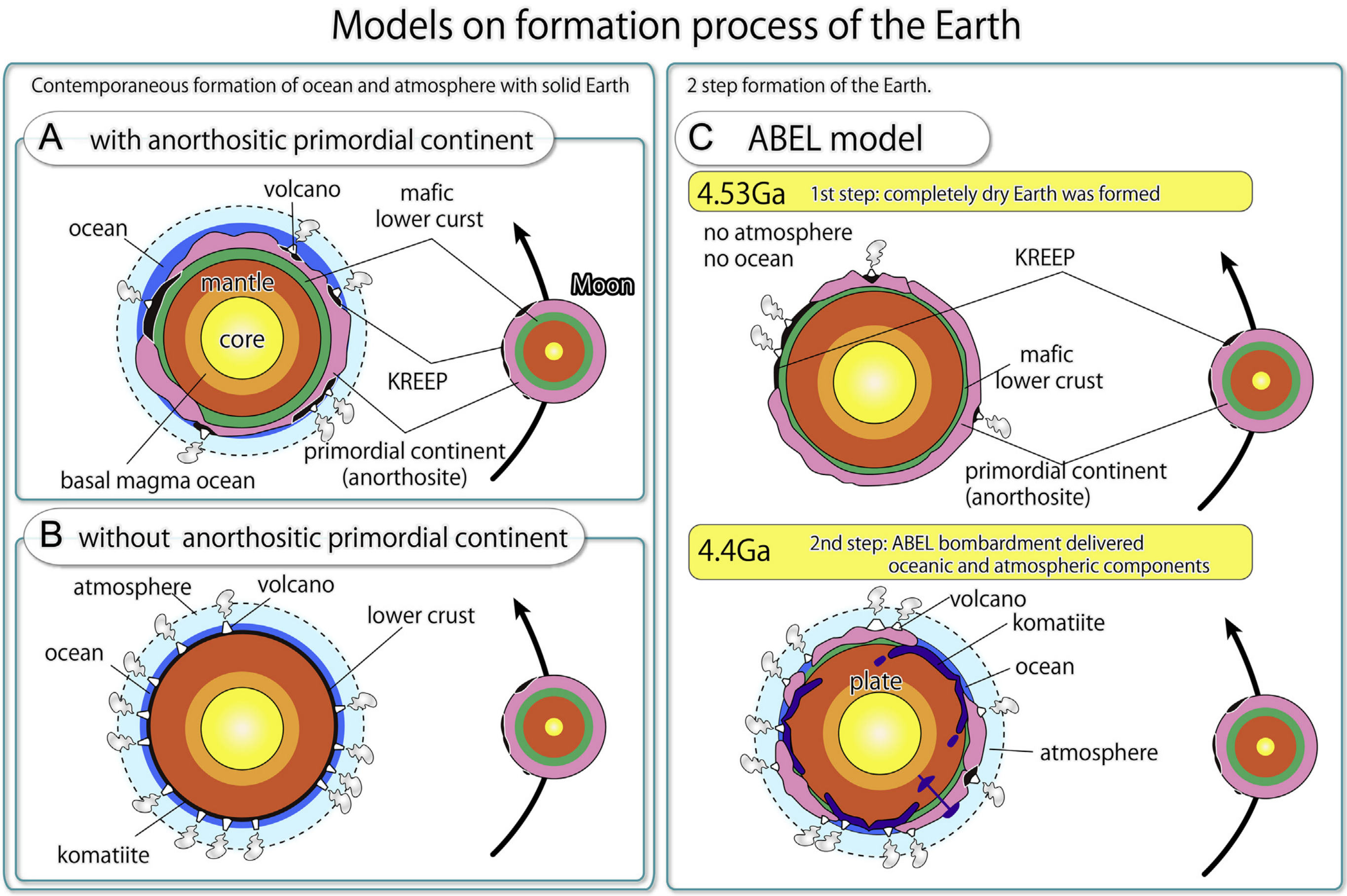


Figure 3. Models for the Hadean Earth-Moon system: (A) the presence of anorthositic primordial continents and ocean on the Earth, but neither an ocean nor atmosphere on the Moon immediately following the giant impact; (B) komatiitic and basaltic (not anorthositic) primordial crusts on the Earth covered by an ocean, while the Moon comprising an anorthositic primordial continent, believed by most geologists; and (C) our newly proposed 2-step formation ABEL model of the Earth-Moon system, with Earth being completely dry during its initial formation at 4.53 Ga, with subsequent accretion of the atmospheric and oceanic components at 4.4 Ga.

amount of ocean on its surface. Even though the water content of carbonaceous chondrite can vary from 2% to 20%, theoretical calculations show that the Earth would have a 400 km-deep ocean if formed by the former minimum. If it is in the case of the latter maximum, then the ocean's depth would reach 4000 km. Even if the bulk silicate Earth (BSE) can be explained by carbonaceous chondrites in a general sense, volatile elements of the Earth are inconsistent with carbonaceous chondrite.

Crucial binding requirement is provided from the oxygen isotopic composition. According to the ratio of δO and δ^{18}O of oxygen isotope, that of the Earth plots on the line called terrestrial fractionation (TF), whereas carbonaceous chondrite, ordinary chondrite, and R chondrite plot away from TF. This indicates that the origin of solid Earth is enstatite chondrite-like material rather than carbonaceous chondrite material (Fig. 5) (Clayton et al., 1984; Javoy, 1995; Clayton and Mayeda, 1999; Javoy et al., 2010). Additionally, considering the oxygen isotopic composition of the Earth, EH chondrite is the most likely origin of solid Earth due to the difference in iron content (Urey and Craig, 1953; Clayton and Mayeda, 1996; Javoy, 1998). Enstatite chondrite is distributed to the inner most area of the asteroid belt, which is around 2 AU, according to spectroscopic observation (e.g. Kallemeyn and Wasson, 1986). The Earth locates at 1 AU from the Sun. Therefore, there is no doubt that the original material of Earth was completely dry, although the proof of the bulk chemical composition will be a subject for further research. In a recent study, Herwartz et al. (2014) showed a subtle difference of Δ^{17}O between the Moon and the Earth: $\Delta^{17}O_{Moon} - \Delta^{17}O_{Earth} = 0.012‰$. Also, enstatite chondrites and the Earth have different Δ^{17}O values: $\Delta^{17}O_{EC} - \Delta^{17}O_{Earth} = 0.050‰$. It is highly likely that the formation process of the Earth and Moon is the cause. Both planetary bodies cannot follow an exact formation pathway because while the source material is the same, accreted materials introduced during a subsequent stage will lead to compositional variance. Even though there is such difference in resulting planetary composition, it does not deny that the source material of the Earth and Moon is enstatite chondrite-like material.

Moreover, other elemental isotopic compositions have been investigated, which include nitrogen (Javoy and Pineau, 1983, 1991; Javoy et al., 1984, 1986; Cartigny et al., 1997), molybdenum and ruthenium (Dauphas et al., 2004), osmium (Meisel et al., 1996), and radiogenic ^{53}Cr and non-radiogenic ^{54}Cr (Birck et al., 1999; Trinquier et al., 2007). The details of these investigations, which are summarized in Javoy et al. (2010), support that the solid Earth formed dominantly by enstatite chondrite material.

One of the most important considerations in the analyses of elemental isotopes is that they can only be used to evaluate the model explaining how the Earth or Moon was formed. In other words, elemental isotope information cannot provide the story of planetary formation through time, because such information is only a "snapshot" of the planetary conditions at that specific time. For

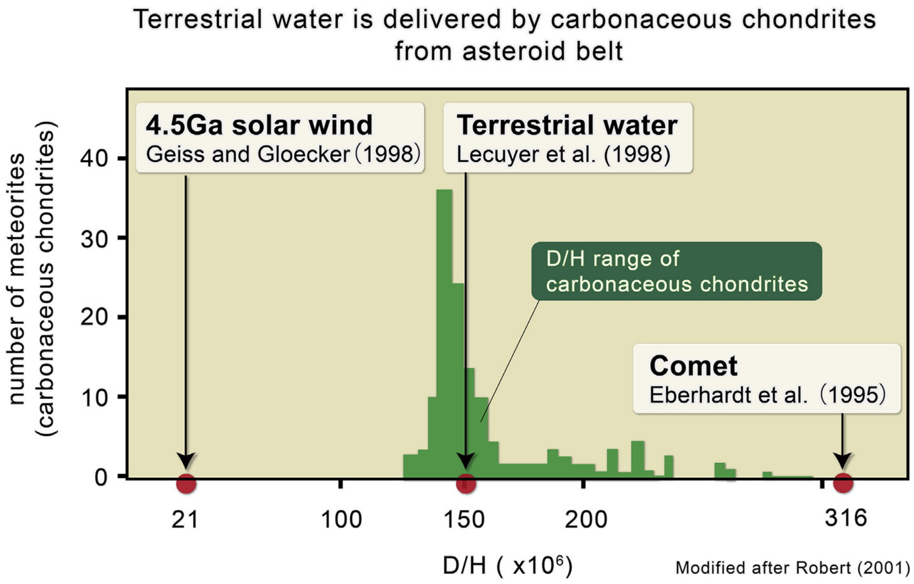
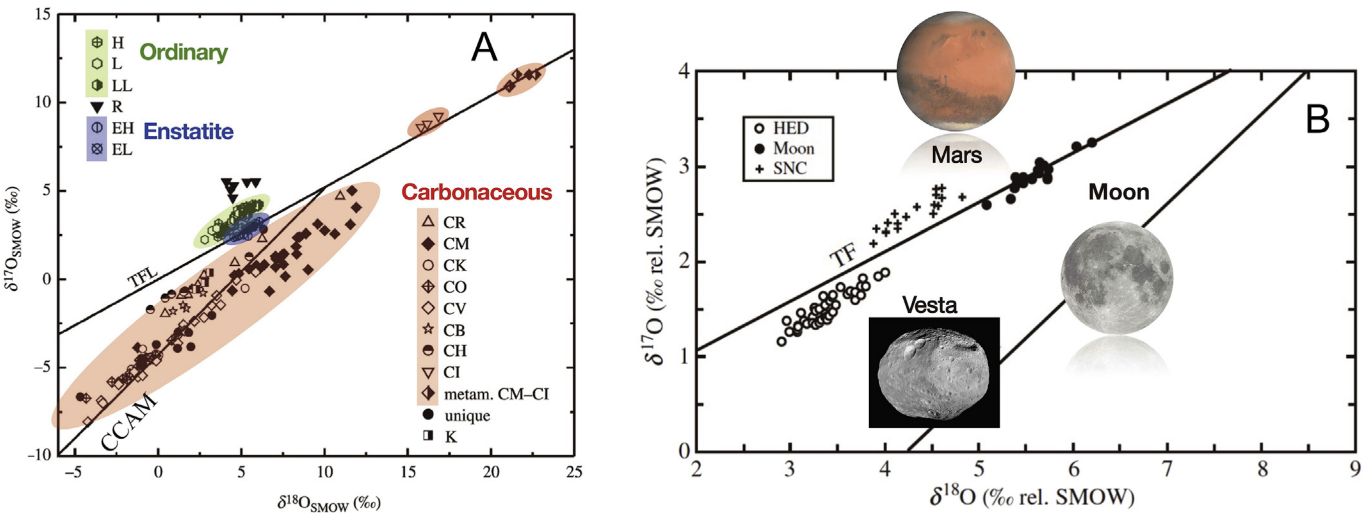


Figure 4. The origin of water on the Earth. The D/H of Earth's ocean approximates the value of carbonaceous chondrite, while distinct from the analyzed D/H of either the solar atmosphere at 4.5 Ga or of a comet (Robert, 2001).

example, Dauphas et al. (2004) performed a mass balance calculation and concluded that the terrestrial isotopic composition was well reproduced by a mixture of 91% enstatite, 7% ordinary, and 2% carbonaceous chondrites. His estimate is regarded as reasonable in terms of the mixing ratio of source meteorites of the Earth, but it does not indicate the accretion process. On the other hand, the composition of the Earth has been changing through time. Even if the collected sample for analysis had undoubtedly originated from the Earth, whether the sample reflects the composition of the source rock of the primitive Earth or more recent rocks generated from the mantle material, which are well mixed by convection, remains unknown. As such, the process of sample collection is critical to discuss the history of the Earth. Also, reproducing a combination of varied types of chondrites shows that analysis of only one example cannot determine the accretion process of planetary bodies. Therefore, to reveal the origin of the Earth and its accretion process followed by the Moon-forming event, as a long-standing mystery, a working hypothesis is necessary to test and verify. So far, a number of researchers have approached this enigmatic question using varied analytical data, as mentioned in the introduction part. These data are undoubtedly critical to validate the model, and all of them are consistent with the ABEL model (described later).

2.3. Earth and Moon have the same origin

Oxygen isotopic compositions of both the Earth and the Moon plot on the TF line (Clayton and Mayeda, 1996; Newton et al., 2000), suggesting that both have the same origin (Fig. 5). This fact does not fit with the giant impact theory, which explains that the Moon was made by the collision between a Mars-sized impactor recently named Theia (Halliday, 2000) and proto-earth (Hartmann and Davis, 1975; Cameron and Ward, 1976; Wetherill, 1986). Ringwood (1989a) rejected this model based on three reasons separately from oxygen isotopic composition. They are: (1) a low intrinsic dynamical



Modified after Clayton (2003), Krot et al. (2005)

Figure 5. Oxygen isotopic composition. (A) Plots of isotopic compositions of oxygen, in which case enstatite chondrite plots on the terrestrial fractionation (TF) line, while ordinary and carbonaceous chondrites do not. (B) Plots of isotopic compositions of oxygen for Mars, the Moon, and Vesta. The Moon plots on TF line corresponding to the Earth. Figure was modified after and Clayton (2003) and Krot et al. (2005) (courtesy by Yoshinori Tange).

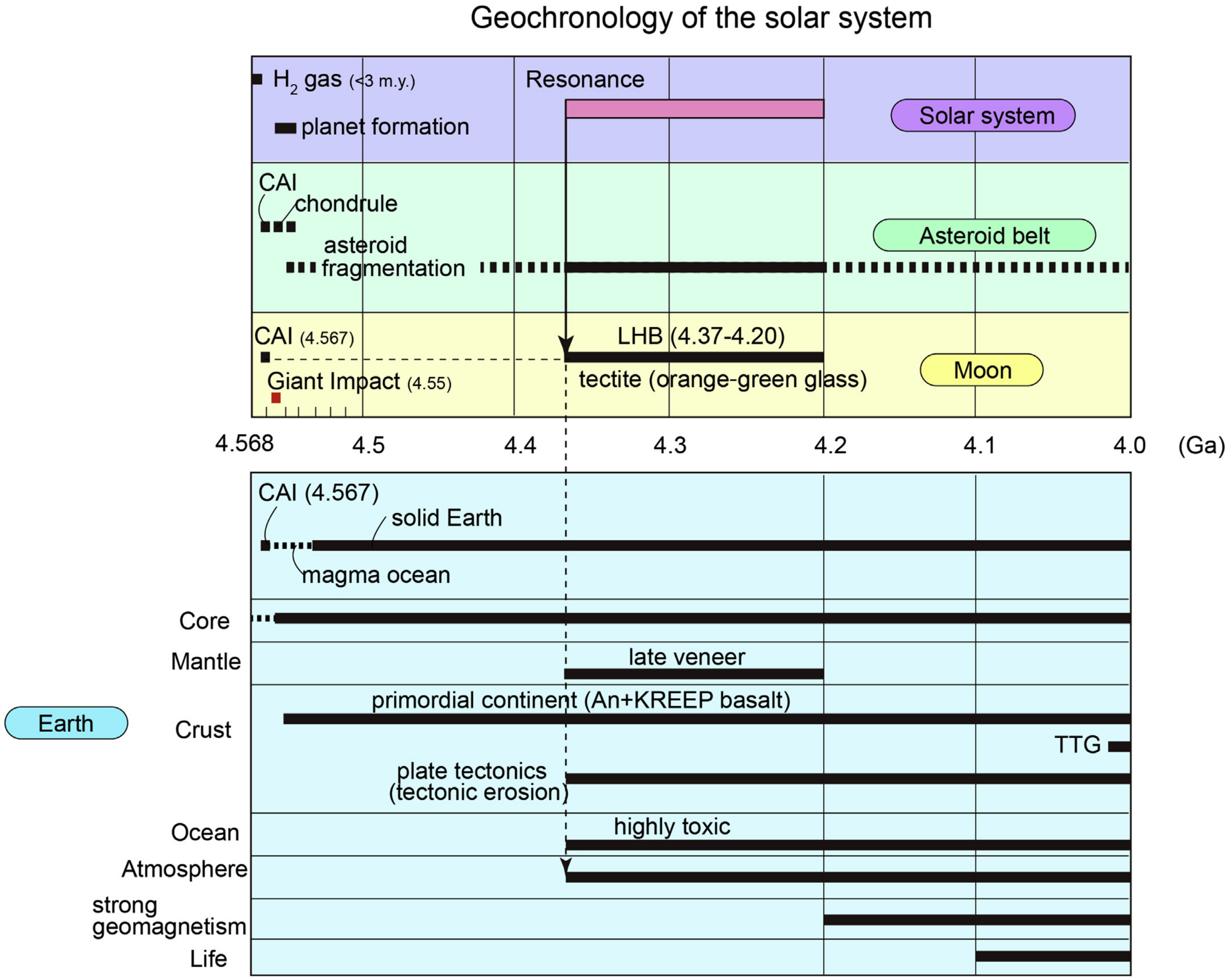


Figure 6. Geochronology of the Solar System, asteroid belt, the Moon, and Earth during the Hadean. The gas envelope dispersed within the first 3 million years after the CAI formation, and presumably rocky planets had formed by 4.55 Ga, which is the solidification age of the Moon's magma ocean. The LHB event dominantly occurred at 4.20–4.37 Ga.

probability, (2) a giant impact, which would cause the geochemical signature to be quite different from that of current Earth, and (3) the collision mechanics causing the Moon to be derived mainly from the impactor's mantle, which is contrary to the geochemical evidences that suggest protolunar material was derived from the Earth's mantle. A reasonable alternative to the giant impact theory is the impact-induced fission model in which case a small planetary body brushed the magma ocean of the Earth' mantle to form the Moon (Hartmann and Davis, 1975; Ringwood, 1989b). Or, a glancing planetary body would be able to give a similar effect to eject Earth's mantle into orbit (Wänke and Dreibus, 1988; O'Neill, 1991). Clearly, the consistency of the oxygen isotopic composition does not satisfactorily support the giant impact hypothesis.

Accepting the fact that the origin of the Earth and Moon was the same, the cooling ratio and evolutional speed of each planetary body is clearly different due to the size. However, both planetary bodies must follow the same mechanism of planetary evolution, from viewpoints of physics and geochemistry. The Moon had cooled down quickly due to its small size by 1.5 billion years after its formation, with activity mostly terminated at this time, except for mainly minor gas extraction. In other words, the geological record of the surface of the Moon should be representative of the early stage of planetary evolution of the Earth.

According to the research using lunar rocks returned to Earth during the Apollo program, the lunar surface is revealed to be covered by anorthosite (PAN, MAN, FAN), KREEP basalt, komatiite, Fe-Ti basalts, and also a unique mineral, schreibersite (highly reduced phosphorous mineral) (Wood et al., 1970; Taylor and Jakeš, 1974; Snyder et al., 1992; Krotev, 2005; Boyet and Carlson, 2007). The uranium (U), lead (Pb), and phosphorus (P) are known to be left in final residue of the magma ocean through crystal fractionation (Borg et al., 2004; Pasek, 2015). Therefore, after the consolidation of the magma ocean, the lunar surface was enriched in these elements, as observed. In other words, the surface of the early Earth (in Hadean) also had similar conditions that resulted in the geology of the Moon.

2.4. Hadean geochronology of the Earth, Moon, asteroid belt, and solar system

The Hadean rocks are now absent on the Earth while such "Hadean" rocks are exposed dominantly on the lunar surface, as a result of the contrasting size of the two planetary bodies. The mass

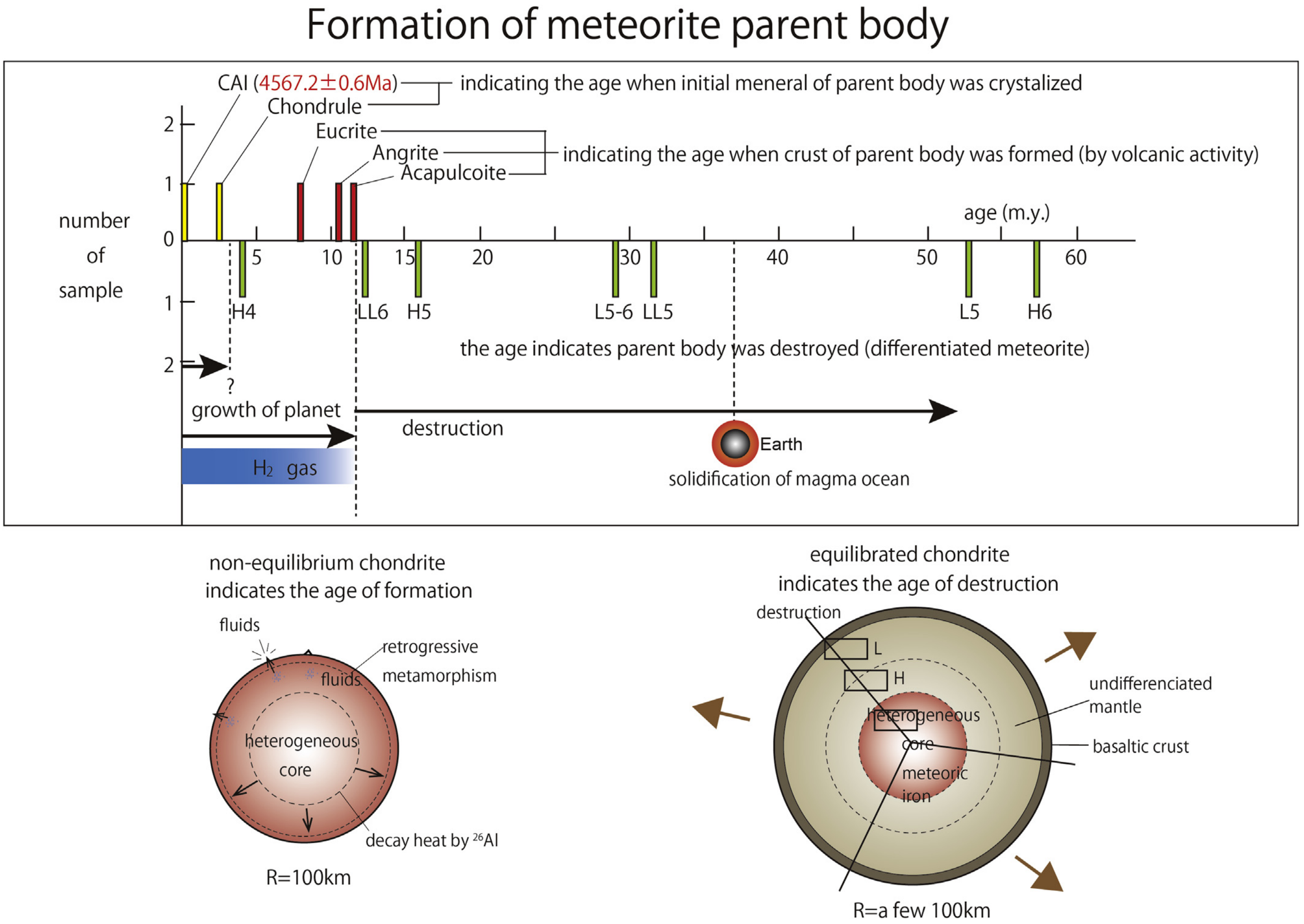


Figure 7. The process of planetary formation. The meteorite parent body grows through time, and its body becomes differentiated. Once the parent body is destructed, its fragments with varying rock characteristics and geochemistry appear. This is the origin of a variety of meteorites with different alteration.

of the Earth is ca. 80 times larger than Moon. Therefore, the smaller Moon quickly cooled to form primordial continents on the surface, whereas the larger Earth continues to have a hot mantle, which activates mantle convection to drive plate tectonics and generate extensive magmatism at both plate boundaries and hotspots. On the Moon, however, silicate magmatism stopped at ca. 3.0 Ga. To argue what kind of rocks were present on the Hadean Earth (e.g. komatiite, fractionated basalts (Elkins-Tanton, 2008), primordial continental crust such as anorthosite (pure anorthosite, mafic and ferroan anorthosite), KREEP basalts (gabbros) and others (Santosh et al., 2017)), experimental, petrologic, and geophysical considerations are crucial for determining lunar geology, petrology, and geochronology.

Nevertheless, the early Hadean records on the Moon are poorly preserved because of Late Heavy Bombardments (LHB) (Mottmann, 1977). This is due to the excavation of the lunar surface at mantle depths up to more than 100 km by bombardment followed by shock metamorphism under a hydrous condition to cause ultra-high temperature metamorphic recrystallization (e.g. Hopkins and Mojzsis, 2015). The LHB event, thus, caused the obliteration of the earliest records on the Moon including the solidification of the magma ocean; therefore, the solidification age of the Moon is still controversial, while it is presumably at 4.46 ± 0.04 Ga (Norman et al., 2003) but remaining indeterminate (Borg et al., 2015) (Fig. 6).

Hence, geology, petrology, and geochemistry of the asteroid belt and the geochronology of meteorites will help to understand the earliest history of the Earth while growing from a nebula gas through to the Earth-Moon system. A summary of the Hadean history of the Solar System to elucidate the history of Earth is shown in Fig. 6, depicting the early evolution of the Solar System soon after its birth; this includes the formation of calcium-aluminum-rich inclusions (CAI) initiating at 4567 ± 0.6 Ma, which was slightly earlier than chondrules (Amelin et al., 2002, 2010).

The formation of planetesimals must be earlier than the growth of asteroids such as Vesta-like planetary bodies ca. 500 km in diameter. An assumed parental body of HED meteorites, and those equivalents have been dated by Pb isotopes (Hopkins et al., 2015). The formation and eruption of basaltic melt on asteroids can be dated 3–5 millions years after CAI formation (Fig. 7) (Lugmair and Marti, 1977; Steiger and Jäger, 1977; Smoliar et al., 1996), which strongly constrain the age of the planetary formation. In spite of the relatively small size of the planetary bodies (radius being less than 100 km), their deep mantle can be heated up to 1200 °C through the decay of ^{26}Al to generate basaltic melting. Moreover, the fragmentation of asteroids to expose the metallic core, which results in iron meteorites, and deep mantle in differentiated asteroids would give a quench timing at 4 K in the Universe; the result gives an earliest age to be less than 8 million years after the formation of CAI (Fig. 7). Assuming the initiation of fragmentation, instead of continuous growth to a much larger asteroid, reflects the dispersion of enveloping H_2 nebular gas outwards in the Solar System; the youngest age 3–4 Myr would give the minimum age of hydrogen gas escape at the asteroid belt. The Earth-

Moon system at 1.0 AU must have been stripped of the gas envelope less than 3–4 million years after CAI formation (Fig. 7).

The LHB event has been well measured through analyses of the Apollo samples, not only by Ar/Ar dating, but also zircon U-Pb dating. Fig. 8 is a summary of zircon dating by U-Pb isotope system compiled by Borg et al. (2015) and Hopkins and Mojzsis (2015). Landing sites are also shown in the index map in Fig. 8. The zircon dates largely range between 4.20 Ga and 4.37 Ga with minor age peaks up to 3.9–3.8 Ga. Some grains clearly indicate crystallization from impact melt, thus demonstrating precise impact ages (i.e., 4.37 Ga as the oldest). Several ages of the Apollo samples dating back to 4.53 Ga do not satisfy multiple isotope systematics, probably due to the ultra-high temperature (UHT) heating by shocked impact heating over 1600 °C, which exceeds the zircon melting temperature (Hopkins and Mojzsis, 2015). Noteworthy is the relatively long lasting LHB over 170 million years (Fig. 7).

Summarizing the history of the Solar System, the gas envelop dispersed within the first 3 million years after the CAI formation, and presumably the rocky planets (i.e., Mercury, Venus, Earth, and Mars) had grown by 4.55 Ga, which is assumed based on the solidification age of the Moon's magma ocean. The LHB event occurred dominantly in an estimated period of time ranging from 4.37 to 4.20 Ga, long after the consolidation of the magma ocean at 4.53 Ga. Such a picture of planetary formation is generally consistent with the Tandem Planet Formation model (Ebisuzaki and Imaeda, submitted), which describes planets being rapidly formed within the first 10^6 years at two distinct sites where the boundaries of a magnetorotational instability suppressed regions of the proto-planetary disk. Since the rocky planets were theorized to have formed at the inner site (less than 1–1.5 AU), the temperature would have been as high as 1000–1300 K, and the volatiles completely liberated. The icy material accumulated at the outer formation site (5–30 AU), on the other hand, would have been impeded from entering the inner Solar System within 1 AU until the velocity dispersion of the planetesimals had sufficiently increased due to gravitational interaction after gas dispersion.

The Earth has nearly completely lost its record of the earlier events, with only zircon ages remaining which yield information consistent with that of the Moon dating back to 4.37 Ga. For this reason, the Early Hadean events are extrapolated from information

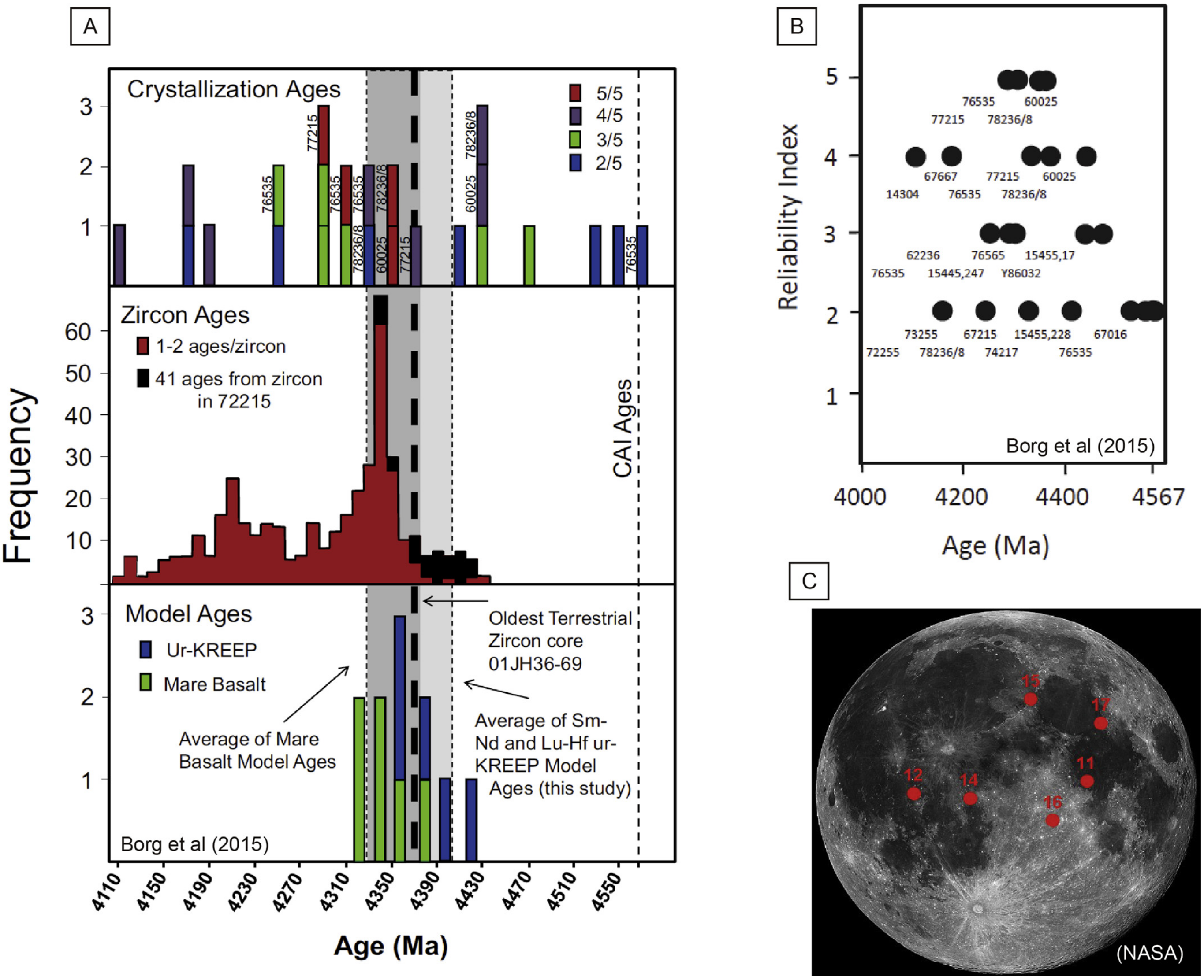


Figure 8. Lunar events documented by zircon ages derived from Apollo samples (after Borg et al., 2015) acquired during the National Aeronautics and Space Administration (NASA) Apollo program at the various landing sites. (A) Histogram of ages derived from the lunar samples (Borg et al., 2015). (B) Plot of isochron ages of rocks from the lunar highlands versus a reliability index of age determination (see Borg et al., 2015 in details). (C) Landing sites of the Apollo missions. (Credit: NASA).

remaining in the asteroid belt (meteorites), LHB records on the Moon, and detrital Hadean zircons from Western Australia's Jack Hills metasedimentary rocks dated at 3.0 Ga (e.g. Borg et al., 2015).

Tarduno et al. (2015) has reported the oldest yet observed relatively strong geomagnetic field recorded within 4.2 Ga zircons from Jack Hills. In addition, 4.1 Ga organic carbons within magmatic zircons give the oldest recorded presence of primitive life (Bell et al., 2015). Mineral inclusions within Hadean zircons suggest the presence of TTG (tonalite-trondhjemite-granodiorite) melts (Wilde et al., 2001; Valley et al., 2002), probably reflects the operation of plate tectonics, including the presence of liquid water, back to 4.37 Ga.

3. The proposal of the ABEL model

Here, we propose a self-consistent and comprehensive model explaining the formation of the Earth since its early evolution that can fit all observational results delivered from material science.

3.1. Formation of dry Earth at 4.56 Ga

As the Earth's orbit was far inside the snowline (2.7 AU) when it formed, the main constituent material of the Earth must be enstatite chondrite-like, and thus the Earth-Moon system which formed at 4.56 Ga had no atmosphere and ocean components, but rather a completely reductive environment (Maruyama et al., 2013) (Fig. 9). P and U are left in a final residue through the consolidation of a magma ocean, so that the surface of the Earth had schreibersite (Fe_3P) and U deposits universally at its surface, which is similar to the observed lunar surface even though being severely modified by bombardment.

3.2. Birth of a Habitable Trinity planet by ABEL Bombardment

At 4.37 Ga, a large amount of carbonaceous chondrite bombarded the solid reductive Earth due to gravitational scattering by three gas giants including Jupiter and Saturn (Nesvorný, 2011; Cloutier et al., 2015), and this event delivered atmospheric and oceanic components to the dry Earth for the first time (Albarède, 2009; Maruyama et al., 2013). Following the delivery of oxidized components onto the reductive Earth, the explosive chemical reaction had begun (Pasek et al., 2007), which initiated the prebiotic chemical evolution leading to the emergence of life (Fig. 10). Due to the delivery of the life-constituent elements on the Earth, we name this model the advent of bio-elements (ABEL) model, with the bombardment event that delivered the bio-elements being named ABEL Bombardment. If this event had not occurred, life would not have emerged on the Earth. Therefore, ABEL Bombardment is the most important event for this planet to evolve into a habitable planet.

The most significant point of our ABEL model is the formation of a completely dry Earth as the first step. The completely reductive Earth is followed by secondary accretion of oxidized elements such as C, H, O, and N, which created an atmosphere and ocean following the ABEL Bombardment. Previous works suggested inhomogeneous accretion by two end members of reductive and oxidizing materials (Wänke and Dreibus, 1988). But they theorized a gradual shift of materials from dry to being oxidized, which is in stark contrast to our newly proposed ABEL model, which clearly indicates two distinct steps with the first step being the formation of a completely dry Earth followed by the accretion of volatiles through ABEL Bombardment to form a second-step oxidized Earth enveloped by ocean and atmosphere. Moreover, the mixing of both reductive and oxidizing materials on the surface of the Earth was critical to initiating prebiotic chemical evolution. In other words, life would not have emerged if the dry reductive Earth had not formed during the first step.

Additionally, the important concept hidden in the background is Habitable Trinity (Dohm and Maruyama, 2015). To emerge life on the Earth, there is no doubt that the Earth must have water, but the presence of water itself does not mean the birth of life, as has long been the view since the 1950s (e.g., Strughold, 1953; Huang, 1959, 1960; Dole, 1964; Shklovski and Sagan, 1966; Kasting et al., 1993). To synthesize the building blocks of life (amino acid, protein, and any other organic compounds), it is necessary to have atmospheric and landmass components in addition to a water component. At the same time, these three components (atmosphere, ocean, and landmass), interacting through hydrological cycling driven by the Sun, need to continue numerous steps of chemical reactions to produce more complex organic compounds. This is the pass to reach the birth of life. Here, we emphasize that the initial ocean mass must be very limited to enable landmass to appear over the ocean to source nutrient for life and to initiate plate tectonics (Maruyama et al., 2013). The concept of Habitable Trinity will be the most significant index for the exploration of life in the Universe, which will be replacing the habitable zone concept.

4. Evidences to support the ABEL model

4.1. Late veneer or late heavy bombardment (LHB) and its chronology

Platinum group elements (PGEs) strongly correlate with the presence of iron, therefore almost all of the PGEs were moved to the core in the very first stage of the segregation of the Earth's core, theoretically (e.g. Ringwood, 1966; Ringwood and Kesson, 1977). However, the abundance of PGEs in the modern upper mantle derived from lamproite magma is high; for example, a mean Ir abundance is 3.5 ± 0.5 and Ir abundance is 0.0009*CI chondrites (Becker et al., 2006). This suggests that the highly siderophile elements were delivered secondarily after the Earth's core had been segregated. Thus the "late veneer" model appeared to explain the relatively high PGEs in the primitive mantle peridotite. One of the most remarkable points of this idea is to be able to also explain that the terrestrial water originated from the "late veneer" event as well as the PGEs, because meteorites should have contained both volatiles including water components and PGEs.

The original proposal of the late veneer scenario was by Anders (1968). This event was discussed by Wänke (1981) who suggested that the Earth's accretion started with highly reductive material which gradually transitioned into more oxidized material, based on the model by Ringwood (1960, 1966, 1977, 1979). Their model, as inhomogeneous accretion with two end-member materials, was furthermore improved by Ringwood (1984), Wänke and Dreibus (1988), Carr and Wänke (1992) and Ringwood (1992), but the model was not chronologically well-constrained in addition to vague processes during the gradual accretion of reductive and oxidized materials as two end-members. Recently, Albarède (2009) concluded that the late veneer occurred at 4.4 Ga based on both U-Pb and I-Xe ages. He explained that the planetary formation process started at the T-Tauri phase of the Sun based on U-Pb dating, suggesting 4.56 Ga as the oldest age of CAI. The timing of segregation of the Earth's core should have been 4.53 Ga by Hf-W dating. This is 30 million years after the T-Tauri phase, equivalent to the time of the consolidation of the lunar magma ocean (see a summary by Borg et al. (2015)).

On the other hand, the chronology of LHB has also long been discussed. Schaffer and Schaeffer (1977) provided the peak age of bombardments, called cataclysm, as 4.0–3.9 Ga based on K-Ar dating using samples from the landing sites of Apollo missions 14, 16, and 17. Also, other recent chronological studies are summarized in Fig. 11, suggesting (1) an exponential decay model (Neukum and Ivanov, 1994; Neukum et al., 2001), (2) multiple cataclysms as several distinct

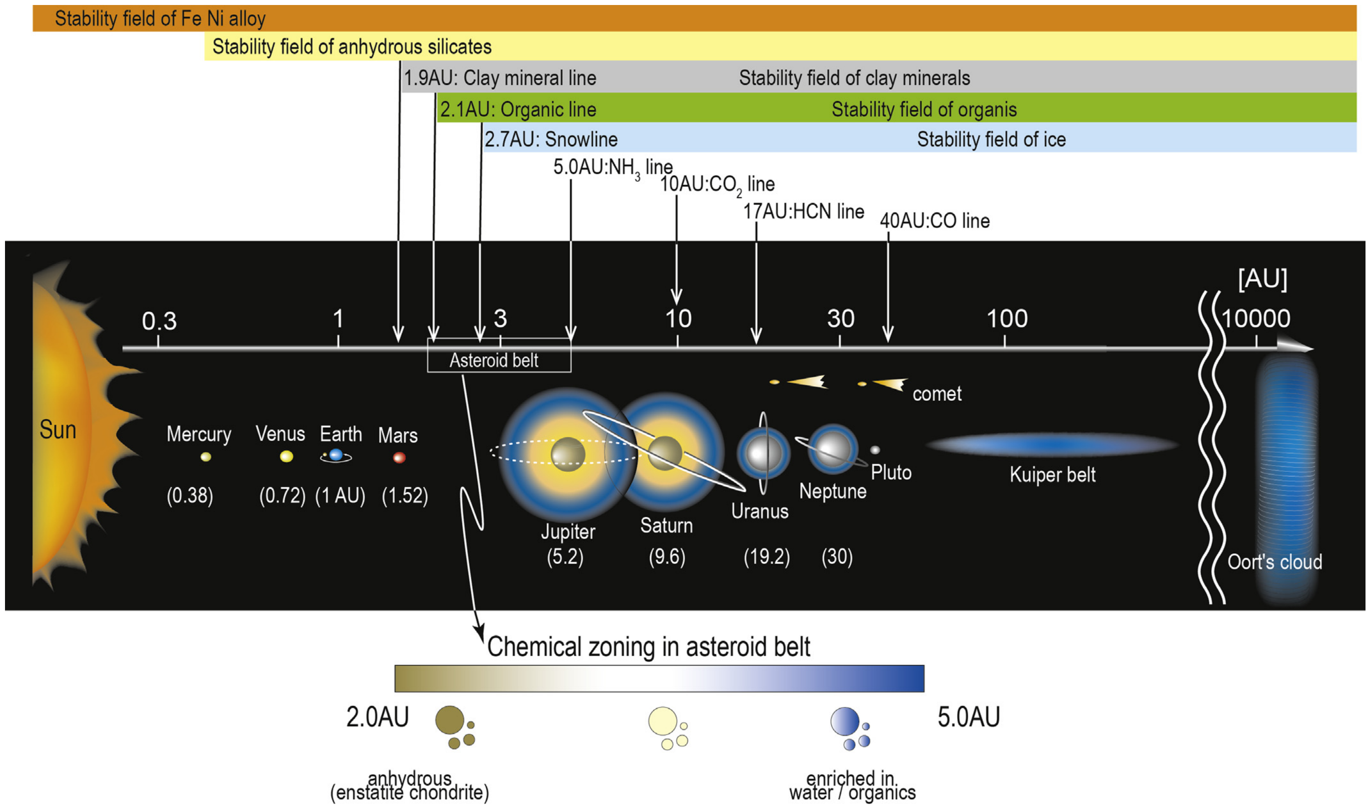


Figure 9. Progressive chemical zonation of the Solar System at ca. 4.56 Ga. Progressive chemical zoning of proto-planetary mineral dusts in the nebula disc is seen as a function of distance from the Sun (AU). Organic matters at 2.1 AU (Kouchi et al., 2002), snowline at 2.7 AU (170 K) (Hayashi, 1981), CO_2 at 10 AU, and CO at 40 AU are shown (Öberg et al., 2011; Schwarz and Bergin, 2014), with a clay mineral line assumed to occur at 1.9 AU. Note that the inner stability limit of the hydrous phase is at 1.8–1.9 AU, quite far from AU = 1 where Earth was formed under a completely dry condition. The major rock type of proto-Earth was enstatite chondrite-like, as inferred from the oxygen isotope ratio, but in reality plus Ca- and Al- and Mg-components are also necessary (Javoy et al., 2010). The inner part of icy planet evolved to gas giants which have grown to icy planets larger than 10 MRE (mean radius of the Earth) to keep nebular gas around the seed not to escape H_2 gas (Ebisuzaki and Imaeda, submitted). These gas giants are Jupiter and Saturn, and presumably one more at least to cause three-planet resonance. This caused heavy bombardment (ABEL Bombardment; mentioned in Section 4.2) at 4.37 Ga, which continued for more than 170 million years (Fig. 6). Presence of a series of volatile isograds suggests the progressive chemical zonation of planets even in the Kuiper belt.

bombardment episodes (Tera et al., 1974), (3) sawtooth cataclysm having peak bombardment at 4100 Ma (Morbidelli et al., 2012), and (4) the unimodal cataclysm known as LHB (Ryder, 1990, 2002) (refer to Zahnle et al., 2007). Recently, Hopkins and Mojzsis (2015) analyzed a large number of zircons from lunar samples and showed (6) cumulative age-frequency plots of Apollo 14's zircon $^{207}Pb/^{206}Pb$, comparing to (5) previously determined zircon ages by Nemchin et al. (2009, 2010) and Taylor et al. (2009). $^{207}Pb/^{206}Pb$ ages can yield highly accurate chronological results, therefore a frequency and peak age based from $^{207}Pb/^{206}Pb$ gives an almost exact timing of the LHB. This age also represents the recrystallized age of zircons by bombardment, as the surface rocks had melted due to intense bombardment and recrystallized with the temperature above 1600 °C. According to Borg et al. (2015) and Hopkins and Mojzsis (2015), the accurate period of the LHB is now concluded to be 4.37–4.20 Ga, which is the middle of the Hadean, with a minor peak appearing until 3.9 Ga. Therefore, the LHB event was much older than the previously proposed 3.8–4.0 Ga. In other words, this bombardment event is not "late" in the early Archean, rather "middle" in the Hadean time. This result is almost coincident with the result delivered by Albarède (2009). Also taking into consideration that there is general tendency for K-Ar dating to show younger ages than actual ones, estimated to be about 200 million years, as well as this method no longer being regarded as the best method to indicate the age, a doubt about LHB timing has risen. Schaffer and Schaeffer (1977) determined that the LHB period was 4.0–3.9 Ga, but this is consistent with a general tendency for K-Ar dating to show a younger age. Marchi et al. (2014) proposed that the LHB occurred at about 4.10 Ga, but it is more likely that the LHB period was 4.37–4.20 Ga with minor additional peaks until 3.90 Ga based on zircon dating utilizing Apollo samples by Borg et al. (2015) and Hopkins and Mojzsis (2015).

Based on these two evidences listed above for late veneer and LHB, which were recently delivered from more accurate isotopic analysis, it can be said that the late veneer and LHB are actually the same event, which delivered water components as well as PGEs. In this paper, to clarify the chronology of the event and to emphasize the nature of the bombardment to deliver oceanic and atmospheric components for the emergence of life, we redefine this bombardment event as ABEL Bombardment, which occurred during 4.37–4.20 Ga in the middle of Hadean time (Fig. 11). The ABEL event is proposed as an unifying model to explain the LHB/late veneer, which includes the abundance of PGEs in the mantle and the supply of water on the Earth to lead the pathway to the emergence of life. From this aspect, ABEL Bombardment is the most critical event through the Earth's history to be a habitable planet.

4.2. Oxidized mantle by the ABEL event derived from the redox state of zircon

Another observational fact supporting our ABEL model is given by the graph by Yang et al. (2014) for the redox condition of zircon (Fig. 12). By analyzing the redox condition of zircon, which was crystallized from the host magma after the formation of the Earth until now through utilizing the difference between Ce^{3+} and Ce^{4+}

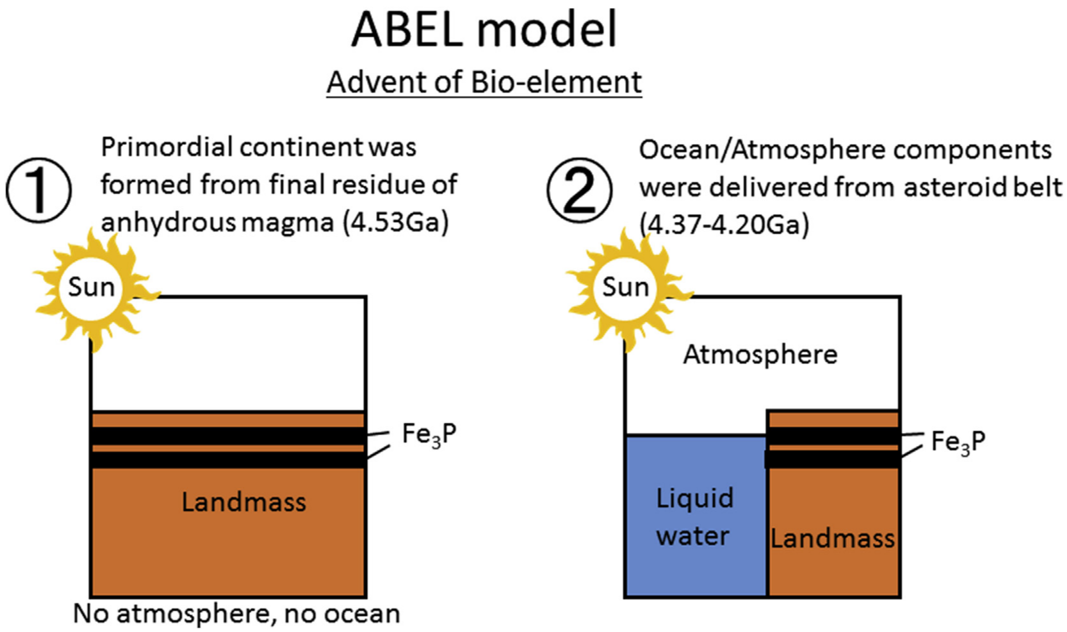


Figure 10. Origin of the Earth formed through two steps of our newly proposed ABEL model. The Earth was formed first as dry planet dominated by enstatite chondrite-like source materials, followed by accretion by carbonaceous chondrite material during ABEL Bombardment events during 4.37 Ga to 4.20 Ga. The ABEL Bombardment event delivered bio-elements to the Earth.

(Fig. 12), they showed the redox ratio of the host magma between 4.4 Ga and modern day. Their results indicated that a value between 10 and 900 for the past 3.5 Ga, while the Hadean ratio between 2 and 20 on average, showing that there was a gradual transition of the redox ratio between 4.4 Ga and 3.5 Ga from 2 to 100. Fig. 12A shows the texture of the oldest (4.4 Ga) zircon. The age of this oldest zircon may be incorrect, possibly as old as 4.37 Ga, in part judging from the textural evidence that a single zircon crystal is dominated by heterogeneous domains, and a single 4.4 Ga spot never indicates the oldest core of a zoned crystal. Fig. 12B clearly shows that the older zircon records a more reductive compositional magma in Hadean time which gradually oxidized through time. This also indicates that volatiles as oxidizing agents, in particular water components, were delivered and added to the mantle since 4.4 Ga. Robert et al. (1992) also explained internal mixing between surface and mantle had well progressed to be homogeneous from a particular viewpoint of oxygen isotopic compositions, which is consistent with the oxidation event that we have suggested above.

Fig. 13 shows the image of a cross section of the Hadean Earth when vasts amount of carbonaceous chondrites from the outer asteroid belt bombarded the Earth during 4.37–4.20 Ga due to gravitational scattering by gas-giant triplets further discussed below. When asteroids or small planetary bodies enriched in volatiles bombarded the Earth, projectile material and target material were instantaneously converted to gas to be part of a primordial atmosphere in the impact-induced “fire event”, along with the formation of a few to 1000 km-diameter craters on the Earth’s surface. Upon cooling, micrometer- to millimeter-sized, fine-grained particles solidified from the gas to eventually descend to and accumulate on the Earth’s surface. The heat energy induced by the impact in the mantle or shallower parts of the crust would then be absorbed into the solid Earth. If intense bombardment had occurred, the upper mantle would heat up to melt through subsequent mantle rebound. This process is consistent with the observation that most impact craters have central peaks, which mark the rebound of a ductile deep interior with or without magmatism (e.g. Jahn and Riller, 2009; Spray et al., 2010).

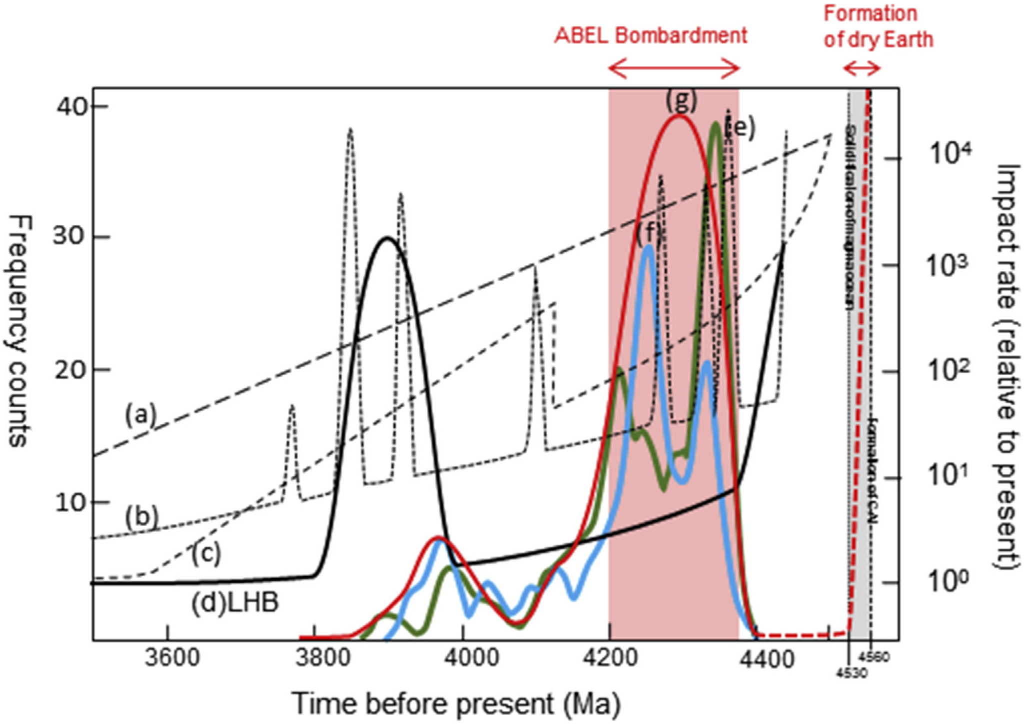
An inhomogeneous density of crater distribution causes an inhomogeneous distribution of temperature due to heating by the underlying mantle, which causes more accelerated mantle convection. In Fig. 13, the right side of the Earth is meant to be heated selectively due to bombardments. At this stage, the primordial Earth was accreted to the size of the current Earth, which had already had a thick primordial continent consisting of anorthosite and KREEP basalt and Komatiite. The underlying lower mantle is thought to have been anhydrous during this period, with the region underlying the lower mantle where basal magma ocean might have existed or had already solidified.

5. Discussion

5.1. Advantages of the ABEL model and overcoming the difficulties of previously proposed models

The formation of an ocean and atmosphere has long been considered to be contemporaneous with the primary accretion of planetesimals, such as the primary accretion of the Earth, while the subsequent Moon-forming giant impact would have likely changed the total amount of volatile (e.g. Safronov (1969, 1972), Kyoto model by Hayashi et al. (1985), improved Kyoto models by Abe and Matsui (1986, 1988), and more recently advanced N-body simulation models by Kokubo and Ida (1995) or Ida et al. (2001)). All of them deemed the formation process of the Earth as a synchronous event of the solid Earth and its ocean.

Recognizing the presence and meaning of the snowline at 2.7 AU, far outside of 1 AU of the Earth’s orbit, Oka et al. (2011) interpreted that the snowline migrated through time so as to deliver small amounts of water to the Earth at 1 AU based on several assumptions. However, if so, then what about Mars which exists nearer to snowline than the Earth? Mars must have been exposed to the accretion of icy components during a much longer time to have accumulated more water components on its surface. However, the observed Martian surface from the Noachian period to modern-day does not support the idea of a migrating snowline. Instead, relatively small



Modified after Hopkins and Mojzsis (2015)

Figure 11. The newly proposed ABEL Bombardment model occurring roughly between 4.4–4.2 Ga. According to recent analysis by Hopkins and Mojzsis (2015), the actual age of the LHB is 4.4–4.2 Ga, rather than the commonly cited age of 3.8–4.0 Ga.

amounts of water have been reported for Mars, generally referred to as Oceanus Borealis (Baker et al., 1991), and Carr and Wänke (1992) also estimated only ca. 400 m-deep ocean could have formed if ice or water between the grain boundaries in surface sediments less than a 10 km depth was squeezed out to Martian surface, which is a significantly small amount comparing to the ocean mass of the Earth. Moreover, the migration of the snowline from 2.7 to 1 AU seems to be too unrealistic to have occurred during the final stage of planet formation. Therefore, migration of the snowline does not yield a rational explanation for other planets or the distribution pattern of the asteroid belt.

Since the first discovery of exoplanets in 1995, observational research has rapidly progressed, with more than 4700 exoplanets including candidates having been found as of 2016 (http://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html). Perhaps what has been the most surprising is the presence of Super-Earths and Hot Jupiters, which have been observed to be common in the Universe. In particular, the discovery of a Hot Jupiter orbiting around 0.3 AU from the central star (nearly Mercury's orbit of our solar system) had not been envisioned. Some researchers assume that these observational facts should indicate the migration of planets following their formation. For example, Walsh et al. (2011) proposed the Grand Tack model, suggesting that all volatiles were transported from 5–10 AU with both Jupiter and Saturn to within Mars's orbit (i.e., 1.5 AU) along with their driven migration of both planetesimals and asteroids. However, this model contains a serious contradiction in that too much water must have been accumulated on the terrestrial rocky planets, such as the Earth-Moon system and Mars. On the contrary, the Earth has only 0.023 wt.% of water against the whole Earth. Moreover, the remaining original chemical zonation in the asteroid belt from 1.9 to 5.0 AU never supported such extensive disturbance by the inward migration of the gas giants from 5–10 AU to 1.5 AU, with subsequent return back to 5–10 AU. Likewise, the Grand Tack model has a similar contradiction as in the case of the migrating snowline by Oka et al. (2011).

Contrary to the above models, the ABEL model can overcome these difficulties, including the supply of a very limited amount of water and other volatiles observed on the terrestrial planets. It was Albarède (2009) who first pointed out that there must have been a delivery of volatile components completely after the consolidation of the Earth's magma ocean based on isotopic measurements of U-Pb and I-Xe. Nevertheless, he did not stress the significance of the late arrival of volatiles in terms of the ocean's birth. The ABEL model not only gives a satisfactory explanation for the formation process of the solid Earth, ocean, and atmosphere, but also informs on the origin of the parent bodies that yielded the Earth's composition. Yet another advantage is that the ABEL model has no conflicts with other observational facts. Finally and most critically, the ABEL model provides the means for the initiation of the prebiotic chemical evolution which led to the emergence of life on the Earth, because of the mixing of reductive material and oxidized material during the theorized ABEL event.

5.2. *ABEL Bombardment and accreted water component*

Through productive discussions of the abundance of PGEs in the mantle, the amount of accreted PGEs which accumulated during late veneer event (equivalent to ABEL Bombardment as detailed above) has been calculated. Fig. 14 shows three estimates of the total mass of accreted materials (CI chondrite), derived from respective assumptions. Morgan et al. (2001) estimated an accreted mass of meteorites (totaling 0.5×10^{22} kg) based on: (1) the proportion that accounts for gravitational focusing of impactors (Earth:Moon = ∼50:1); (2) the amount of impactor mass that created the lunar impact basins with ca. 1×10^{20} kg; and (3) an average geocentric impact velocity (6 km/s) of the impactors which

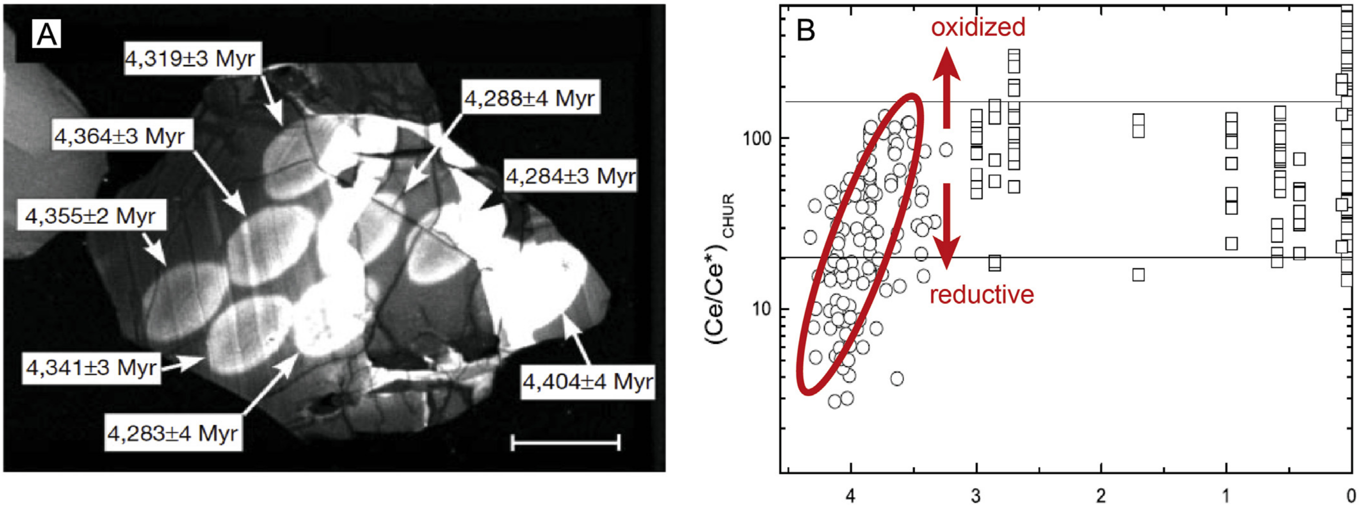


Figure 12. (A) Cathodoluminescence image of zircon by Wilde et al. (2001). (B) Chondrite-normalized Ce-anomalies of zircons by Yang et al. (2014). Left picture shows a part of a zircon dated to be 4.40 ± 4 million years old, while other parts show younger ages some of which near 4.20 Ga. The right figure indicates the redox state of the mantle of the Earth, which had gradually oxidized through time (as indicated by the red circle).

created impact basins (Bandermann and Singer, 1973) with size estimates of the major impact basins on the Moon.

If accreted materials were of average carbonaceous-chondrite composition with 20 wt.% water, then the total mass of accreted water (0.1×10^{22} kg) approximates the mass of the Hadean ocean (0.16×10^{22} kg) estimated by Maruyama and Liou (2005) and Maruyama et al. (2013). The latter Hadean-ocean estimate was calculated based on geological constraints from the 3.9 Ga Isua, 3.5 Ga Pilbara, and Barberton terrains by Maruyama et al. (2013). If 0.16×10^{22} kg of ocean mass was given by Morgan's estimated amount of chondrite, the water content of carbonaceous chondrite would be 32 wt.%.

If ABEL Bombardment lasted 170 million years, we estimate that an increasing rate of the sea-level would have been 17 mm/1000 year. In addition, if the density of chondrite is assumed to be 3.44 g/cm^3 (Macke et al., 2011), we reckon that the rock powder made by accreted chondrite would have accumulated at a rate of 17 mm/1000 year. Furthermore, by simply comparing to the sedimentation rate of deep sea sediments like chert at 1 mm/1000 year. We calculate that the accretion rate of rock powder of chondrite is about 20 times faster than the general sedimentation which has been occurring on the surface of the Earth during the Phanerozoic.

Likewise, two other estimations by Becker et al. (2006) and Walker (2009) are described below. Becker et al. (2006) estimated a total accreted mass of meteorites $(0.3–0.5) \times 10^{22}$ kg, based on the systematics given by impact crater diameter, impactor mass, and impact velocity, which require the value between 30 and 50 as an Earth/Moon mass influx ratio. Becker et al. (2006) finally concluded that the total mass accreted to the Moon was about 1×10^{20} kg and that to Earth about $(0.3–0.5) \times 10^{22}$ kg, which is equivalent to the 0.1% total mass of the Earth. On the other hand, Walker (2009) utilized more specific elemental data, such as Ir and Os, to estimate the accreted total amount of highly siderophile elements (HSE). According to his estimation, if volatile-rich carbonaceous chondrites bombarded the Earth, the total mass could be as much as 3×10^{22} kg. If the Hadean ocean mass is given by this amount of chondrite, the water content of CI chondrite is reckoned to be 19 wt.%. These estimates seem to be consistent with progressive zonation of a hydrous phase in the modern asteroid belt which is dry at 2.0 AU, relatively limited amounts of water up to 2.7 AU, and increasing water to the outer margin at 5.0 AU where ca. 20 wt.% water is present, as shown by both the Tagish Lake and Murchison chondrites.

When comparing these three estimations, the amounts of accreted materials through the bombardment have an order of magnitude difference. However, we are able to say conversely that the estimation is only an order of magnitude difference, and it is not too far from the assumption based on researches of the whole Earth history.

5.3. *The clue for the origin of Earth's water: the chemical zoning in the asteroid belt, formation of asteroids, and its destruction by collision*

Chemically inhomogeneous distribution of asteroids in the Solar System has been already described in various papers, based on planetary formation theory starting from solar nebula (e.g., summary given by Smith (1982)). Roughly speaking, the inner part of the Solar System is occupied by reductive material, while oxidizing material increase towards the outer margin. This can be explained as the function of the temperature depending on the distance from the Sun (Fig. 9).

Our future strategy is to reveal planetary formation mechanism, with the key being to understand the remaining unknown chemical zoning in the Solar System. Such unknown zones are not where planets had formed, but rather the asteroid belt where huge planets could not form. As related knowledge, the existence of the snowline at 2.7 AU under 170 K (phase change boundary from H_2O gas to H_2O ice) is already known, originally estimated by calculation (Hayashi, 1981) and is regarded as the function of the distance from the Sun. Likewise, an organic line has been estimated to occur at 2.1 AU (Kouchi et al., 2002) and a clay mineral line at 1.9 AU. Additionally, for any elemental compound such as NH_3 at 5 AU under 57 K, CO_2 at 10 AU under 42–52 K, HCN at 17 AU under 38 K, and CO at 40 AU under 18–22 K (Öberg et al., 2011; Schwarz and Bergin, 2014) (Fig. 9), there are chemical-compound boundary lines within the Solar System. Such boundary lines for each compound define the chemical composition of planet where planetary bodies form, as a function of temperature. This method is backed by the concept of regional metamorphism, which is a common concept for geologists, and it can explain metasomatic-metamorphic recrystallization of rocks as a function of increasing pressure and temperature.

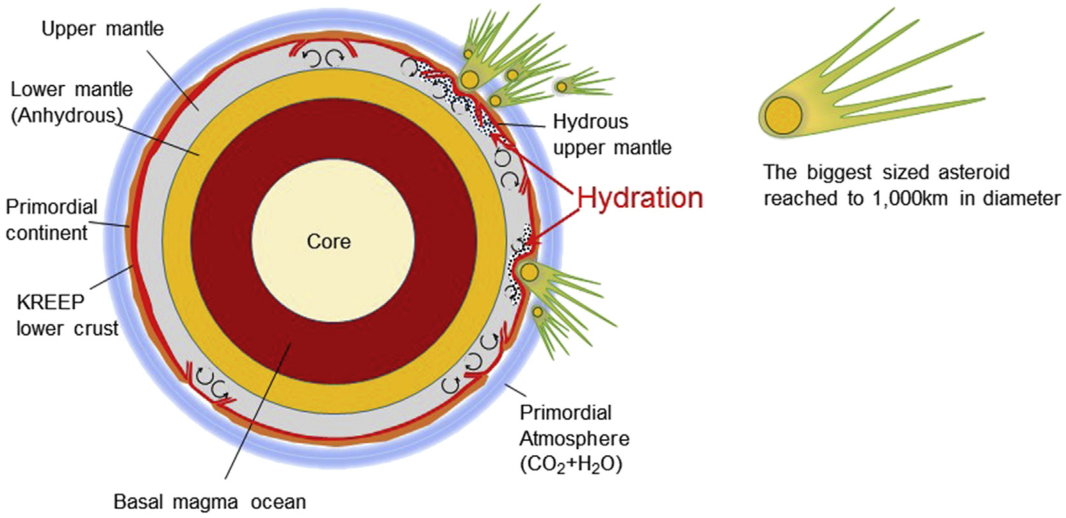


Figure 13. Hydration of the upper mantle and accretion of PGEs. The underlying mantle being hydrated due to large asteroid impacts. Following the bombardment, hydration occurs at local to regional scales, hence the hydrous upper mantle is distributed heterogeneously (stippled part of figure). Whereas mantle upwelling of the hydrous mantle delivers the hydrous melt, in other non-hydrated parts of the globe, dry melt is produced. This is due to the local heterogeneity of the oxidized mantle, where the broad band tendency of oxidizing occurs through time until 3.5 Ga. Through mantle convection, the whole mantle is oxidized, as shown by zircon analysis (Fig. 12).

5.4. *Trigger of ABEL Bombardment; the presence of a hypothetical "Black Sheep" gas giant next to Jupiter*

The ABEL Bombardment occurred at 4.37–4.20 Ga, more than 200 million years later than the T-tauri stage, therefore, this event is regarded to be unrelated to the main part of the planetary formation process. If so, there should be another trigger for the ABEL Bombardment to deliver appropriate amount of volatiles including water to the terrestrial rocky planets.

One possible scenario is as follows. Three gas-giant triplets; Jupiter, Saturn, and a theorized planet "Black Sheep" were formed first. Gravitational scattering among these three kicked out the "Black Sheep" and triggered the ABEL Bombardment of the Earth. The "Black Sheep" is thought to be in the Kuiper Belt (Nesvorný, 2011), or maybe forced out of the Solar System. Presumably, the Kuiper Belt contains old icy bodies which had existed in inner part of the Solar System like "Black Sheep" (Fig. 15). As such, the Kuiper Belt contains the set of significant clues for the research in planetary science to further unravel the evolutional history of the Solar System.

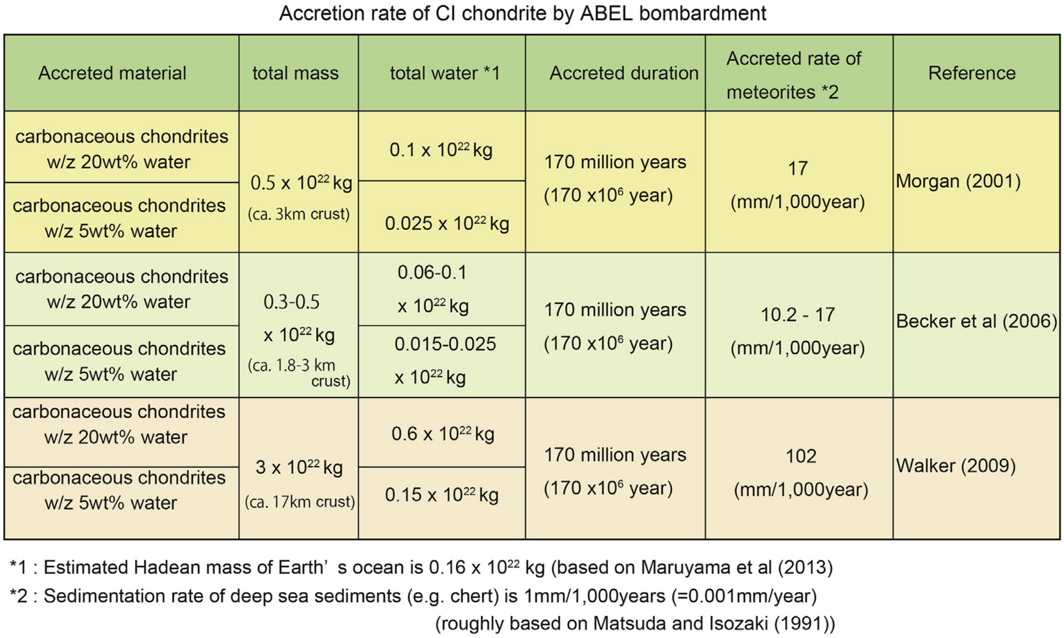
5.5. *Zircon interpretable portrait of the ABEL Bombardment*

The modern Earth has no Hadean rocks, however, highly resilient tiny crystals of zircons are all that remain. U-Pb dating indicates they formed later than 4.37 Ga, long after the solidification of the magma ocean at 4.53 Ga. In other words, zircons appear not to have formed between 4.53 and 4.37 Ga.

On the other hand, the Moon still preserves a Hadean rock record. The lunar surface has been covered by primordial continents composed of anorthosite and KREEP (Fig. 16) as old as 4.53 Ga by model ages. This is because the Moon had cooled down quickly due to its relatively small size. Lunar mantle convection did not have enough energy to change the surface by plate tectonics and subsequent extensive volcanism, therefore extremely old rocks still remain on the Moon. However, the lunar surface is in a poor state of preservation because numerous bombardments have severely modified it. Asteroid collisions formed impact craters of ranging sizes, with possibly the largest one being referred to as the Lunar Procellarum Basin on the nearside of the Moon (Whitaker, 1981), which reaches 3200 km across (Fig. 16A) and likely generated ten-meter-thick regolith layers emplaced as ejecta deposits. Because of the impact, the zircons would have been recrystallized due to shock metamorphism and thus resetting the zircon age. After the series of bombardments continued for 170 million years, surface materials, which include primordial crustal basement rocks and regolith layers, were well mixed, particularly in the case of the bombardment of giant impacts such as the hypothesized Procellarum event. Therefore, zircon ages from the lunar surface should have varied from the oldest (~4.53 Ga) to quite younger (e.g., 3.90 Ga) ones. However, there are no zircons dated between 4.53 and 4.37 Ga as noted above (Fig. 16B). This fact strongly indicates that there were not heavy bombardments on the Moon before 4.37 Ga, after the solidification of the lunar magma ocean at 4.53 Ga, and this situation being counterpart to that of the Earth.

As shown in Fig. 16B and C, age distribution and frequency of zircon crystals can indicate the timing of heavy bombardment semi-quantitatively. For example, from the view point of age distribution, bombardment during 4.37–4.20 Ga is an order of magnitude greater than the later bombardment during 4.20–3.90 Ga. This indicates that bombardments were much more frequent earlier than later. Or, impacts by bigger asteroids occurred earlier. Likely, the formation age of the possibly largest impact crater, Procellarum, corresponds to the highest peak of the bombardment at 4.37 Ga. This is consistent with impact crater geology of the Moon, because a large number of younger craters formed within the Lunar Procellarum Basin. Moreover, the rim of Procellarum is ambiguous (Fig. 16A). This indicates that it is the oldest and has been highly modified by subsequent bombardments, although more extensive analysis on lunar zircons is necessary to discuss further details.

Fig. 16C shows the summary of radiometric ages of 6 types of Apollo-returned lunar rocks. The types are: (1) mare basalt, which partly infill impact crater basins, especially prevalent in impact basins contained within the Lunar Procellarum Basin (e.g., Wilhelms et al., 1987), (2) high-grade metamorphic rocks (melt-bearing and melt-free granulite facies rocks), (3) alkali rocks, (4) granite/felsite, (5) KREEP basalts, and (6) magnesian suite pluton and ferroan anorthosite (basement rocks), based on the extensive



Accretion rate of CI chondrite by ABEL bombardment

Accreted material	total mass	total water *1	Accreted duration	Accreted rate of meteorites *2	Reference
carbonaceous chondrites w/z 20wt% water	0.5 x 10^{22} kg (ca. 3km crust)	0.1 x 10^{22} kg	170 million years (170 x10^{6} year)	17 (mm/1,000year)	Morgan (2001)
carbonaceous chondrites w/z 5wt% water		0.025 x 10^{22} kg			
carbonaceous chondrites w/z 20wt% water	0.3-0.5 x 10^{22} kg (ca. 1.8-3 km crust)	0.06-0.1 x 10^{22} kg	170 million years (170 x10^{6} year)	10.2 - 17 (mm/1,000year)	Becker et al (2006)
carbonaceous chondrites w/z 5wt% water		0.015-0.025 x 10^{22} kg			
carbonaceous chondrites w/z 20wt% water	3 x 10^{22} kg (ca. 17km crust)	0.6 x 10^{22} kg	170 million years (170 x10^{6} year)	102 (mm/1,000year)	Walker (2009)
carbonaceous chondrites w/z 5wt% water		0.15 x 10^{22} kg			

*1 : Estimated Hadean mass of Earth' s ocean is 0.16 x 10^{22} kg (based on Maruyama et al (2013)

*2 : Sedimentation rate of deep sea sediments (e.g. chert) is 1mm/1,000years (=0.001mm/year) (roughly based on Matsuda and Isozaki (1991))

Figure 14. Accretion rate of CI chondrite by the ABEL Bombardment. Based on the discussions for the abundance of PGEs in the mantle, the amounts of accreted PGEs accumulated during the ABEL Bombardment have been estimated with 3 models. The upper estimation was given by Morgan et al. (2001), the middle one by Becker et al. (2006), and the lower one by Walker (2009), respectively. An estimated ocean mass of the Hadean Earth (0.16×10^{22} kg) compares with the three estimates listed above. The accretion rate of meteorites is 17 mm/1000 year, which is much faster than the sedimentation rate of chert as deep sea sediment. The estimated Hadean mass of the Earth's ocean is based on Maruyama et al. (2013), with the sedimentation rate of deep sea sediments is based on Matsuda and Isozaki (1991).

compilation by Stöffler et al. (2006). Analytical methods include ^{40}Ar/^{39}Ar, Rb-Sr, Sm-Nd, U-Pb, and Pb-Pb.

Systematic differences are evident in the lunar rocks, reflecting the geologically different stratigraphy expected by the mode of occurrence. One of typical rock types to show systematic differences is the mare basalt, which contains water-bearing melt inclusions in olivine. The lunar mare basalt rock samples, which range in age from 3.15 to 3.85 Ga, support the presence of volatiles in the lunar interior. The other exemplary type to discuss changing planetary conditions is the oldest rocks referred to as basement rocks, which are composed of anorthosite and magnesian suite pluton ranging 4.30–4.55 Ga, which do not contain any hydrous minerals, suggesting that there were no volatiles when the magma ocean had solidified at 4.53 Ga (Albarède, 2009), and later following solidification until 4.30 Ga. These two rock types clearly indicate the Moon was dry and volatiles were delivered some time later, at least before the mare basalt was emplaced on the lunar surface.

The key observational fact is the appearance of KREEP II, granites, or alkali rocks after 4.35 Ga. Alkali rocks are speculated to be formed by partial melting of the basement rocks through volatile injection, and their ages range from 4.35 to 4.0 Ga. This clearly indicates that the lunar volatiles were delivered by this time through bombardments, which is the same case for the production of granite/felsite. These geochronological data strongly support the ABEL Bombardment event.

KREEP basalts ranging in age from 4.35 to 3.80 Ga could be formed by mantle rebound accompanying ABEL bombardment or larger impacts following 4.20 Ga. The eruption of magma onto the lunar surface would be delayed 100–200 Myr or even longer because of the slow upwelling of the mantle to reach to the point enabling de-compressional melting. The age of the youngest KREEP basalt is 3.80 Ga, which is the eruption age of the magma, although even minor bombardment after ABEL Bombardment had stopped by 3.9 Ga (Fig. 16B).

Metamorphic rocks such as melt-bearing or granulite facies basement rocks is younger than the rock types discussed above and the age ranges between 4.25–3.70 Ga with a sharp peak at 3.8–3.7 Ga. Melt-bearing metamorphic rocks tend to be younger than the granulite-facies metamorphic rocks formed over 800–900 °C back to 4.25 Ga (Fig. 16C). The extensive ABEL Bombardment ages (4.37–4.20 Ga) is slightly older than the age of the metamorphic rocks, which experienced the shocked regional metamorphism. These ^{40}Ar-^{39}Ar ages may indicate the cooling age of the rocks or the final bombardment events to be fragmented at the deep crust and thermally metamorphosed to be removed to the surface as fragmented blocks.

From the viewpoint of regional metamorphism research on the Earth over the past 100 years, it should be pointed out that the presence of a catalytic agent like volatiles is critically important. Because, without volatiles, igneous rocks never change to granulite facies metamorphic mineral assemblages. For example, UHP-HP metamorphism associated with ancient subduction zones, seen in Kokchetav in Kazakhstan, Su-Lu-Dabie in central China, or the Alps region, is preserved gabbroic dry rocks at 100–200 km depths and under 700–1000 °C without volatiles. On the other hand, these rocks are quickly recrystallized on the return back to the surface if volatiles become available. They are recrystallized under amphibolite facies at mid-crustal depth with a temperature range of 400–500 °C (e.g., Maruyama et al., 2010).

Importantly, the metamorphic recrystallization can occur only when volatiles are present in the planetary interior. At least, lunar oldest rocks did not contain hydrous minerals, therefore, lunar volatiles must have been delivered some time after solidification of the lunar magma ocean, and before the production of the metamorphic rocks.

After the appearance of the metamorphic rocks, subsequent mantle convection yielded flood basalts only on the lunar nearside until 3.15 Ga. Such recorded activity is much less prevalent on the lunar farside, especially when compared to that recorded with the giant Lunar Procellarum Basin. This is because the oldest and largest Procellarum impact had the most influence on the evolution of the Moon following its formation. Due to the collision that resulted in the Lunar Procellarum Basin on the nearside of the Moon, rebound of the lunar mantle on the nearside occurred, which caused the extension of the nearside and tectonic compression on the farside causing the crustal overlapping on continental crust. Lunar geology clearly demonstrates lithospheric thinning on the nearside of the Moon by bombardments to generate the oceanic lithosphere regionally, but failed to create a bimodal lithosphere globally. Presumably a water ocean never appeared on the Moon, because its relatively small planetary size, which fated the history of the Moon.

5.6. *The implication to Hadean Earth*

According to the reviewing work of lunar impact craters by Wilhelms et al. (1987) and Stöffler et al. (2006), they are classified into four groups: (1) larger than 2500 km, (2) 1200–500 km, (3) 499–300 km and (4) less than 300 km in diameter. The total number of craters is 2 for (1), 28 for (2), and 15 for (3), respectively, while (4) is innumerable. The exceptionally large-sized craters are the theorized Procellarum (3200 km in diameter) and the South Pole-Aitken (2500 km in diameter). These huge-sized craters were created by impactors nearing 250–300 km across, whereas group (2) 50–120 km across, and group (3) 30–50 km across, respectively. The bombardment to make these large impact craters, assessed through numerical simulation and the deep structure beneath the craters, is well-demonstrated by the seismic observation for the Earth's impact craters such as the Chicxulub crater in the Yucatan Peninsula, Mexico, which coincides with the K/T boundary when the dinosaurs became extinct. The size of Chicxulub crater is ca. 180 km across, and generated by only a 10 km-sized impactor. Thus, it is easy to imagine that the size of lunar impact craters is one order of magnitude larger, compared to the size of the craters that remain on the modern Earth. Considering the difference in planetary evolution between the Earth and Moon, one critical difference is their planetary size. The Earth is ca. 50 times larger than the Moon in mass, which would have influenced the total number of asteroids that impacted their surfaces. The Earth must have had a more frequent bombardment with much larger impactors than in the case of the Moon.

The possibly largest lunar impact crater, Procellarum on nearside, about 3200 km across as highlighted above, would have been created by an impact projectile estimated to be 300–400 km in diameter. If so, more gigantic asteroids likely bombard the Hadean dry Earth. Presumably, such asteroids would have approximated Ceres (icy asteroid, 950 km in diameter and density equaling 2.1 g/cm^3, orbiting at 2.8 AU) or Pallas (icy-rocky asteroid, 1100 km in diameter and density equaling 4.2 g/cm^3, orbiting at 2.9 AU). The collisions of such dwarf-planet size during ABEL Bombardment would have resulted in remarkably huge impact craters on the Earth (e.g., 10,000 km in diameter), which corresponds to the size of the Pacific Ocean (Marchi et al., 2014). If there were such huge impacts, it can be easily imagined that the target primordial continental crustal materials must have been destroyed by instantaneous evaporation due to temperatures reaching over 20,000 K, depending on the size (Davies, 1972; Hiesinger and Head, 2006), in addition to the mechanical fragmentation reaching great depths and lateral extents away from the impact site causing resurfacing through shock metamorphism. The extensive bombardment would have resulted in the formation of magma ponds, which can be stable over 10,000 years until solidification. Extensive deformation and related metamorphic recrystallization by the bombardment meant that high-grade metamorphism up to the granulite facies (800–900 °C) had occurred both in the primordial continental crust and underlying mantle. Therefore, nearly perfect recrystallization

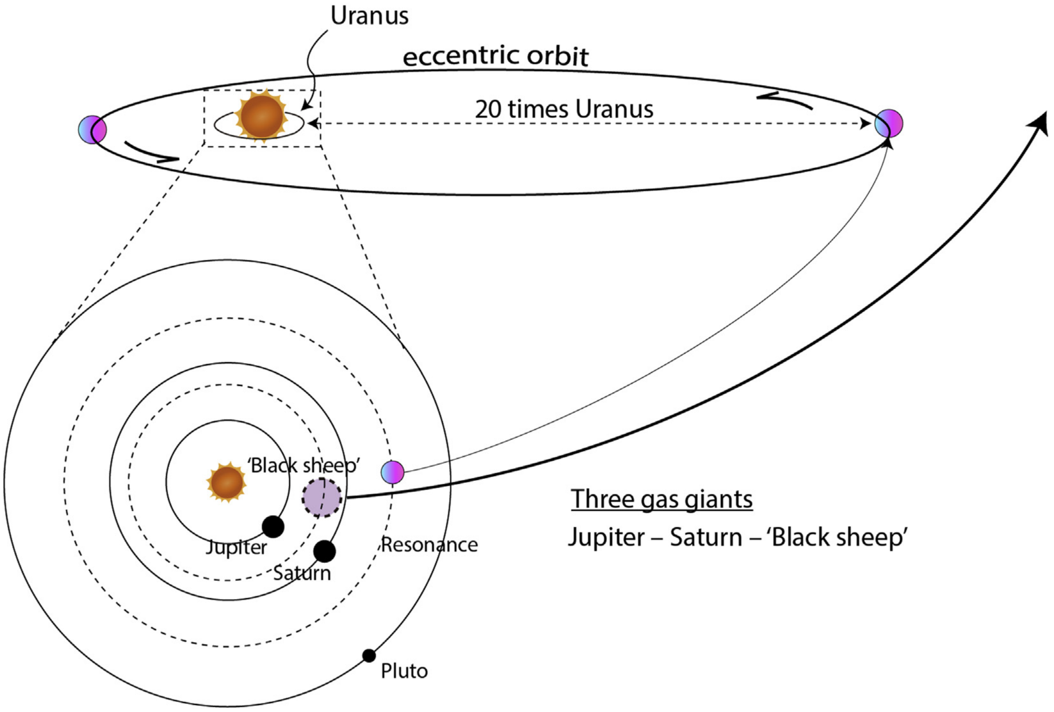


Figure 15. Black Sheep gas-giant planet. There are exotic planets (i.e., "Black Sheeps"), which are not consistent with suggested chemical zonation trend, and if such planets are highly eccentric, then their history can be examined. This includes determining whether a "Black Sheep" is "kicked-out" from the inner zone to the outer part of the Solar System (courtesy of Shintaro Azuma).

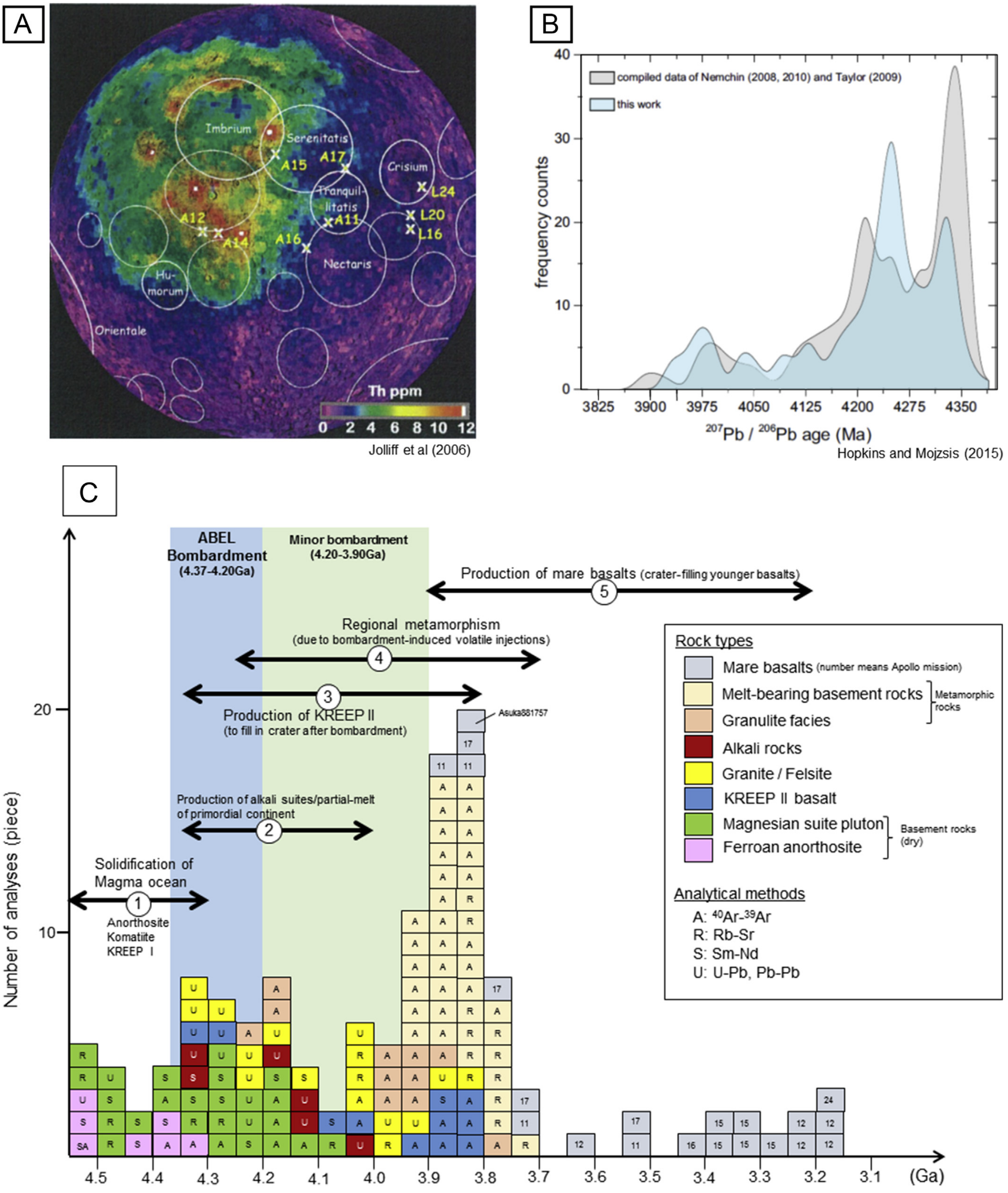


Figure 16. Picture of the newly proposed ABEL Bombardment interpreted through zircon ages of lunar rocks returned during the Apollo program. (A) Th map of the Moon based on Clementine data (Jolliff et al., 2006). Figure shows the distribution of impact craters, and KREEP II basalts (secondary generated KREEP basalts) largely highlighted by the elevated Th regions, with the prominent quasi-circular feature at the upper left roughly outlining the theorized Lunar Procellarum Basin first proposed by Whitaker (1981). Also shown are the lunar landing sites, which includes those of the NASA Apollo (A) and Soviet Luna (L) programs. (B) Zircon age population diagram by Hopkins and Mojzsis (2015). (C) The summary of radiometric ages of lunar rocks based on data compiled by Stöffler et al. (2006). Considering the occurrence of Ferroan anorthosite and magnesian suite plutons composed of anhydrous minerals, the Moon was initially dry following its formation until 4.37 Ga. After the injection of volatiles, the Moon formed metamorphic rocks, as well as granite and alkali rocks.

upon cooling and solidification destroyed the original igneous texture. Moreover, the extensive melting is present for the catastrophically fragmented blocks (breccias), as well as partial recrystallization for any kinds of rocks on primordial highland rocks (Stöffler et al., 2006).

The scenario given by the ABEL model for Earth history is crucial to understand the birth of a habitable planet. The available indirect evidence is only from Moon summarized above and in Section 5.5.

5.7. *The Earth history through the ABEL Bombardment: stagnant lid tectonics to plate tectonics*

When the magma ocean on the Earth was solidified at 4.53 Ga, the Earth must have had layered structure with both mantle and crust without atmosphere and ocean (Fig. 17A). The chemically layered structure was composed of: (1) dunite-dominated lower mantle (high-temperature peridotite dominated by olivine component), (2) lherzolite-dominated upper mantle (low-temperature peridotite enriched in basaltic component), and (3) primordial continental crust underplated by ca. 100 km thick KREEP lower crust (primary KREEP basalt, named KREEP I). Worth mentioning, KREEP I crust contains ca. 400 times more abundant radiogenic elements such as U, Th, and K. Also, it is important to understand that the lower mantle material did not melt until the event of mantle overturn at 2.6 Ga, which resulted in the bottom of lower crust to heat up, leading to A-type magmatism, as well as inactive mantle dynamics in the so-called mid-Proterozoic "Boring mid-Proterozoic".

After the solidification of the magma-ocean, the surface of the Earth should have had a silent period until 4.37 Ga due to the lack of a heavy bombardment event. As a result, the Earth formed a global rigid continental lithosphere as thick as 100–150 km, suggesting no horizontal/vertical movement like modern plate tectonics. Yet, the mantle temperature was high enough to produce basaltic melt by lherzolite-dominant upper mantle through the upwelling and downwelling of plumes (Fig. 17A). This planetary state of the Hadean Earth should have had stagnant lid tectonics as discussed by works led by Solomatov (Solomatov and Zharkov, 1990; Moresi and Solomatov, 1995; Solomatov, 1995; Solomatov and Moresi, 1996).

When the ABEL Bombardment by icy asteroids began, the asteroid materials were driven deep within the Earth's interior

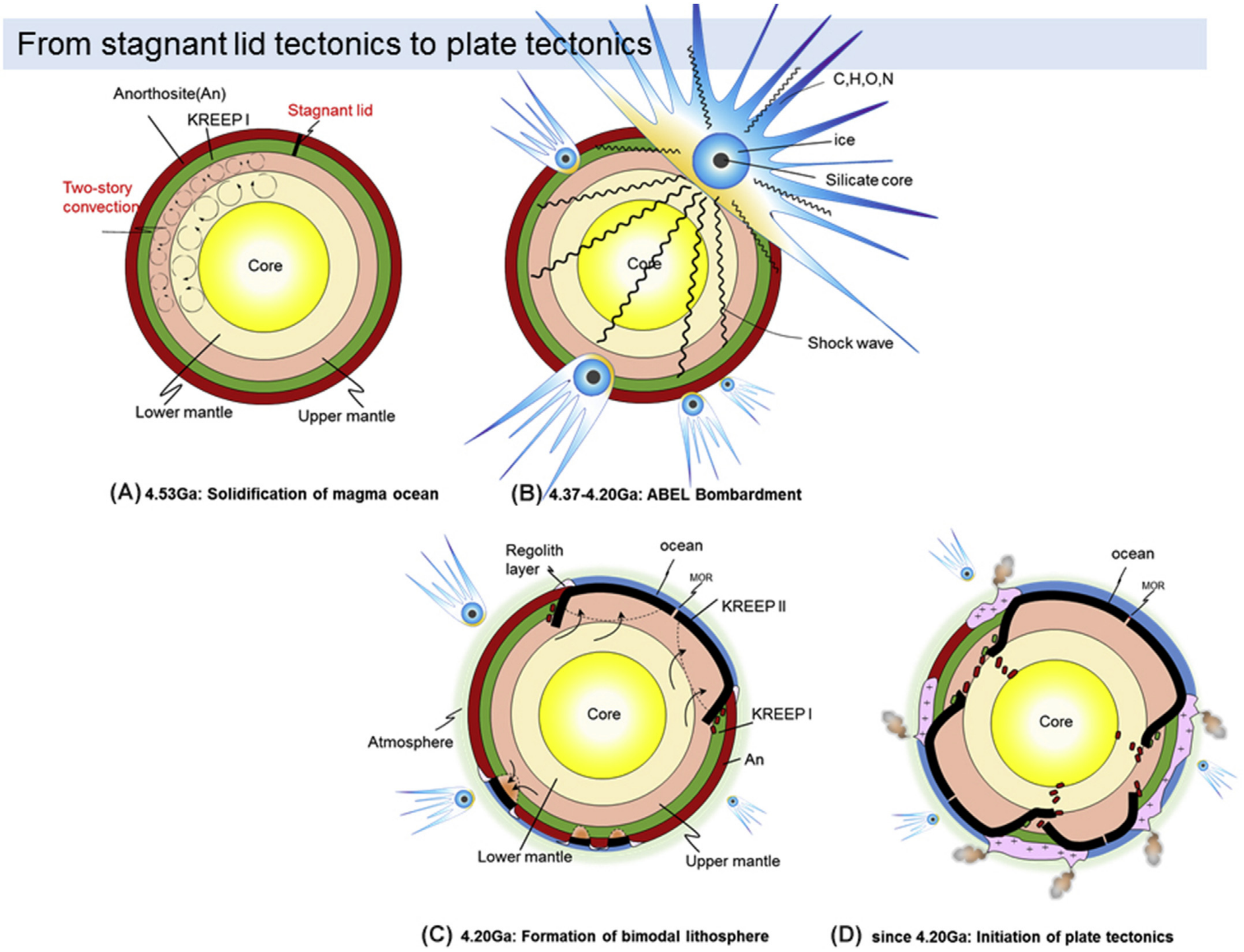


Figure 17. Schematic portrayal of the history of Earth through (A) layered structure beginning to form at 4.567 Ga (Growth tectonics), with stagnant lid tectonics operating after the solidification of the magma-ocean from 4.53 Ga until the beginning of ABEL Bombardment at 4.37 Ga. (B) Bombardment tectonics initiating due to the ABEL Bombardment at 4.37 Ga and lasting until 4.20 Ga; this included huge-sized asteroids generating shock waves, breaking the rigid continental lithosphere, and resulting in the formation of 3000–10,000 km-diameter impact craters. (C) ABEL Bombardment leading to the formation of the oceanic lithosphere and resulting in the initiation of plate tectonics through eclogitization. (D) Transition from stagnant lid tectonics to plate tectonics completes. Ultimately, the current style of plate tectonics was initiated by ABEL Bombardment, providing an answer to the once enigmatic question of when and how plate tectonics was initiated.

(Fig. 17B). In some cases, they penetrated deep enough to input volatiles such as H_2O and CO_2 into the whole upper mantle resulting in a decrease in both viscosity and melting temperature. Due to the ABEL impacts, the mantle likely rebounded closer to the surface of the Earth over a time period of about 200 million years. Such process could have generated a huge amount of KREEP II to fill in the impact craters. The diameters of the asteroids are assumed to range from 100 to 1000 km, as described in Section 5.6. Presumably, 1000 km-class impactors are only a few up to five through the Earth history, and they formed impact craters 10,000 km in diameter, which is 1/4 of the Earth's circumference. The total number of 500 km-class impactors are estimated to have been about ten or more, and the 300–100 km class impactors greater than 100. All of these asteroids, particularly the largest class, would have destroyed the rigid primordial continental lithosphere whose size is estimated to approximate the Pacific Ocean. Rigid continental crust was replaced by the oceanic lithosphere softened by the formation of a water ocean, because CO_2 would have been selectively transferred into the mantle by the initiation of subduction (Azuma et al., 2017).

The phase transformation of the eclogitic lower crust and oceanic mafic crust through infiltration of water-rich fluids along the Pacific Ocean-sized crater, reaching 10,000 km across, would have created a strong slab-pull force at the outer rim of the huge impact crater, combined with mantle upwelling under the mid-oceanic ridge within the crater. This is the critical trigger for the transition from the stagnant lid tectonics to plate tectonics in the Earth's history. Thus, the ABEL model provides the answer to the once enigmatic question of when and how plate tectonics was initiated.

After the initiation of plate tectonics, the anorthositic primordial continents continued to be transported into the bottom of lower mantle along the subduction zone (Fig. 17D).

5.8. Importance of ABEL-driven mixing between reductive substances and oxidized substances for the origin of life

The ABEL model explains that the Earth formed at 4.56 Ga without components to produce an atmosphere or ocean, and thus initially being a highly reductive naked rocky planet. At 4.4 Ga, carbonaceous chondrites bombarded the Earth, being directed from the outer asteroid belt to fall on the surface of the Earth, and thus the planet having been given elements for the formation of both an atmosphere and an ocean for the first time. This two-step formation of the Earth is consistent with evidences derived from material science as discussed in Section 3.

Another significant indication given by the ABEL model is that secondary accretion of bio-elements should have been related to the origin of life, in particular, the initiation of metabolism. Synthetic experiments of life, which originated in the Miller-Urey experiment, require both oxidized material (H_2O) and reductive material (CH_4, NH_3, H_2) to produce amino acid, which is the main building blocks of life. As this experiment shows, it is significant that chemical reaction between these conflicting materials is necessary to synthesize organic matters. This result indicates that this planet did not have atmospheric nor oceanic components at the beginning. In other words, the highly reductive primordial Earth initiated chemical reaction to emerge life only after oxidized components interacted with reductive material of the primordial Earth. Pasek et al. (2007) demonstrated that an organic phosphorous compound is synthesized by corrosion of reductive schreibersite, which is the chemical reaction to produce the building blocks of life. Reductive gas is easily produced through reactions between water and anorthosite, KREEP basalts, and komatiite. Such environments had appeared universally during middle Hadean Earth.

As explained above, the ABEL model gives coherent and consistent scenario from the formation of the Earth to series of prebiotic chemical evolution to lead the emergence of life.

6. Conclusions

The Earth formed by two steps. First, the most reductive enstatite-like chondrite material accreted to form a completely dry Earth at 4.56 Ga. Therefore, the Earth did not have atmosphere and ocean components at that time. Second, icy asteroids composed of carbonaceous chondrites subsequently bombarded the Earth, directed from the outer part of the asteroid belt due to gravitational scattering by Jupiter, Saturn, and a lost "Black Sheep" gas giant at ca. 4.4 Ga to deliver an atmosphere and ocean on to the dry Earth. This two-step formation model of the Earth is referred to as the ABEL (advent of bio-elements) model. In addition, the bombardment to deliver water (as well as volatiles and PGEs) is called the ABEL Bombardment, which is the most critical event to bear and evolve life on this planet.

Following the ABEL Bombardment, mixing between reductive material and oxidized material initiated the reaction for metabolism, which is the first trigger to reach to the emergence of life on the Earth. In other words, a completely reductive planet must be formed to enable life to emerge.

Additionally, the ABEL Bombardment enabled the transition from stagnant lid tectonics to plate tectonics to make a Habitable Trinity planet by injection of volatiles into the dry Earth.

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