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Research Paper

Nine requirements for the origin of Earth's life: Not at the hydrothermal vent, but in a nuclear geyser system

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ABSTRACT

The origin of life on Earth remains enigmatic with diverse models and debates. Here we discuss essential requirements for the first emergence of life on our planet and propose the following nine requirements: (1) an energy source (ionizing radiation and thermal energy); (2) a supply of nutrients (P, K, REE, etc.); (3) a supply of life-constituting major elements; (4) a high concentration of reduced gases such as CH_4, HCN and NH_3; (5) dry-wet cycles to create membranes and polymerize RNA; (6) a non-toxic aqueous environment; (7) Na-poor water; (8) highly diversified environments, and (9) cyclic conditions, such as day-to-night, hot-to-cold etc.

Based on these nine requirements, we evaluate previously proposed locations for the origin of Earth's life, including: (1) Darwin's "warm little pond", leading to a "prebiotic soup" for life; (2) panspermia or Neo-panspermia (succession model of panspermia); (3) transportation from/through Mars; (4) a deep-sea hydrothermal system; (5) an on-land subduction-zone hot spring, and (6) a geyser systems driven by a natural nuclear reactor. We conclude that location (6) is the most ideal candidate for the origin point for Earth's life because of its efficiency in continuously supplying both the energy and the necessary materials for life, thereby maintaining the essential "cradle" for its initial development. We also emphasize that falsifiable working hypothesis provides an important tool to evaluate one of the biggest mysteries of the universe – the origin of life.

1. Introduction

Some of the most important debates in modern science focus on the origin of Universe, the origin and evolution of life, and the development of human brain to acquire the knowledge that enables human beings to successfully inquire into the mysteries of Universe. The ancestors of modern life on Earth are thought to have had appeared at about 4.1 Ga (Bell et al., 2015). This was during the mysterious Hadean Eon, leaving no physical evidences except for tiny particles of zircon crystals (Wilde et al., 2001). However, it is critical for the origin of life research to understand the Hadean surface environment as the cradle of life and conditions that generated and sustained life.

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Hypotheses of birthplace of life have been proposed since Darwin's time. These include the following: (1) the classic concept of 'Darwin's warm little pond', involving an organic soup either on-land or in tidal flats (Darwin, 1859; Oparin, 1957; Deamer, 1997), (2) the panspermia model that explains life as arriving from the extraterrestrial Universe (Arrhenius, 1908) and Neo-panspermia as succession model of Panspermia (Sutherland, 2016), (3) the idea that life was originated from Mars (Kirschvink and Weiss, 2003), (4) the proposal that life was initiated in a mid-oceanic ridge hydrothermal system (Corliss et al., 1981) or in an alkaline hydrothermal vent (Kelley et al., 2001), (5) the idea that life was born under island arc volcanic environments related to a primordial continent (Mulkidjanian et al., 2012), and (6) the recently proposed nuclear geyser model that life was born at geyser environment driven by a natural nuclear reactor on the Hadean primordial continent (Ebisuzaki and Maruyama, 2017) (Fig. 1). However, conditions to bear life have not yet clearly defined in previous studies. In this paper, we pick up significant requirements for the birthplace of life with reasonable justification. Based on these requirements, we evaluate respective birthplace hypotheses and speculate the most likely site is for life's birthplace.

2. Models for the birthplace of life

Fig. 1 summarizes hypotheses for the birthplace of life on Earth. In following section, each hypothesis is briefly introduced.

2.1. The classic concept: small ponds on land or a shallow marine environment (tidal flats)

Since Darwin's time, it has been generally considered that tidal flats along the continental margins could provide an ideal environment for the emergence of life. The classic concept of 'Darwin's warm little pond' (Darwin, 1859) was the first insightful model to explain life's emergence. The "warm little pond" was considered to provide essential requirements for the formation of life, including supplies of ammonia and phosphoric acids, as well as light, heat, electricity, and other factors that facilitated the synthesis of complex organic compounds through the repeated dry-wet cycles and dehydration-hydration cycles, though these factors were not initially considered very deeply. Subsequently, Oparin (1924, 1957) suggested that life was generated in "coacervates", which are immiscible semi-permeable spherical droplets of micelles comprising large organic molecules that rained into the sea from a reduced atmosphere. However, the reduced Hadean atmosphere that Oparin (1924, 1957) and Miller (1953) assumed has been refuted by later numerical calculations for Earth's primordial atmosphere, suggesting that there were oxidized CO_2–H_2O–N_2 compounds comprising an atmosphere that achieved a surface pressure of about 400 bars shortly after Earth's formation (e.g., Abe and Matsui, 1986; Zahnle et al., 1988). These results question the validity of the classic concept.

2.2. Panspermia and Neo-Panspermia

The model of panspermia was proposed by Arrhenius (1908), who suggested that the first life was extraterrestrial, and that it came to Earth from sources that are spread through the universe. This model is based on an assumption that life was initiated and evolved elsewhere in the universe, perhaps even very early in the evolution, subsequently spreading throughout space. In spite of the lack of direct evidence, some researchers continue to support this concept (e.g. Crick and Orgel, 1973; Hoyle and Wickramasinghe, 1999). According to this model, life forms that ultimately arrive at

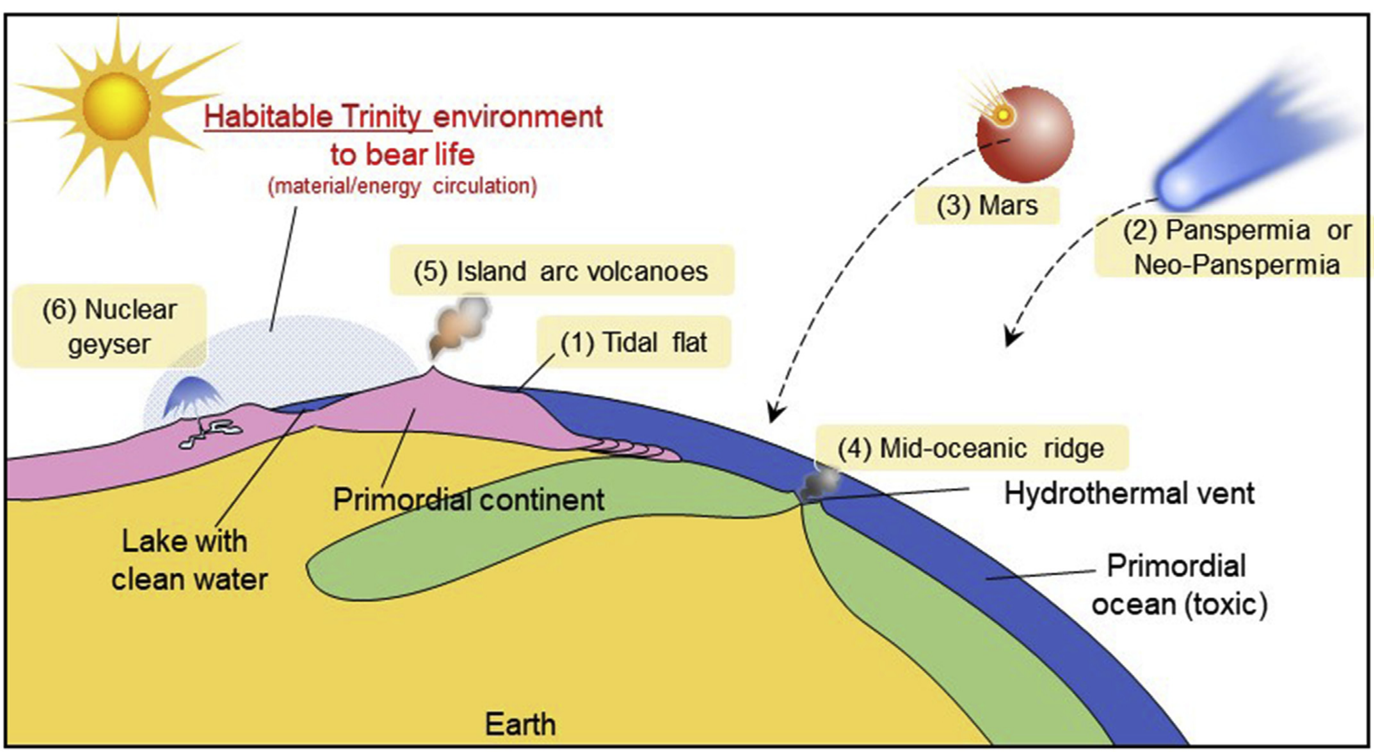

Figure 1. Proposed sites for the birthplace of life on Earth. (1) Classic concepts, including Darwin's warm little pond (Darwin, 1859) with a primordial soup, or a shallow marine tidal flat (Oparin, 1957), (2) Panspermia (Arrhenius, 1908) or Neo-Panspermia (Sutherland, 2016), (3) Mars (Kirschvink and Weiss, 2003), (4) a mid-oceanic ridge hydrothermal system (Corliss et al., 1981) or in an alkaline hydrothermal vent (Kelly et al., 2001), (5) a hydrothermal environment with island arc volcanoes (Mulkidjanian et al., 2012), and (6) a nuclear geyser system on the Hadean primordial continent (Ebisuzaki and Maruyama, 2017).

Earth are able to survive long-term travel during temperatures of −270 °C that prevail in space. Also life would be able to survive the very high temperatures achieved when its carriers (comets, meteors) penetrated Earth's atmosphere and collided with the surface.

Recently a hybrid variant of the panspermia theory has been proposed, which we tentatively name the "Neo-Panspermia" model. This theory hypothesizes that meteors and/or cosmic dust deliver to Earth the advanced building block of life (BBL) such as glycol aldehyde, cyanamide, urea, cyanoacetaldehyde, cyanoacetylene, and schreibersite as well (e.g., Sutherland, 2016). Discoveries of organic matter from Murchison meteorite (Levy et al., 1973) and Tagish Lake meteorite (Pizzarello et al., 2001; Sephton, 2002) indicate the possibility of organic material delivered from the outer space. This model claims that Earth's life can be automatically generated if the necessary BBLs are constantly supplied from the space to an appropriate point on Earth's surface, such as a pond on the landmass (Fig. 2).

2.3. Mars origin

Recent ideas suggest that the first life originated on Mars and was subsequently conveyed to Earth within a meteorite (McKay et al., 1996; Sleep and Zahnle, 1998; Weiss et al., 2000; Kirschvink and Weiss, 2003). According to this model, early Mars provided a better habitat for the initiation of life than did Earth, and a Martian lifeform could be transferred to Earth by ejection during an impact event. Because Mars' gravitational acceleration is much lower than that of Earth (Mars's size is one tenth of that of the Earth), this ejection mechanism is much more likely to have occurred as a Mars-to-Earth transfer than the reverse. Evidence of "microorganisms" in one particular Martian meteorite. The Allan Hills 84001 (ALH84001) was offered in support of this model (McKay et al., 1996; Thomas-Keprta et al., 1998, 2000, 2001).

2.4. Deep-sea hydrothermal vents at mid-oceanic ridge

Previous studies reported the discovery of hyperthermophile microbes in the mid-oceanic ridge (MOR) hydrothermal vents in a deep-sea environment with an average depth of 2.5 km (e.g. Corliss et al., 1981; Barros and Hoffman, 1985), where various microorganisms are observed and survive up to temperatures of 130 °C (e.g. Jannasch and Mottl, 1985). Moreover, several large multi-cellular animals, such as mussels (Smith, 1985) and shrimps (Nuckley et al., 1996), are also found where sunlight does not reach (e.g., Baross and Hoffman, 1985; Gold, 1992; Deming and Baross, 1993; Wirsen et al., 1993). The presence of this ecosystem in the deep sea, using chemical energy rather than sunlight, is regarded as one of the breakthrough findings of the diversity of biological environments. Life is known to be tough and robust even in extreme environments, such as extremely low-temperature region (< −50 °C in winter) on Antarctica or Himalaya-Tibet regions. Therefore, it has been considered that life could survive even in deep sea with high temperature and no sunlight. In particular, the discovery of hyperthermophile microorganisms in this environment led many biologists to presume that the birthplace of life is at mid oceanic ridge, because, according to the phylogenic tree of life based on ribosomal RNA, thermophile microorganisms plot very close to the root of life between the two domains of bacteria and archaea (Woese et al., 1990) (Fig. 3).

Besides this discovery, geochemical evidence looked supporting the MOR as the birthplace of life, because recent studies have revealed that hydrogen is released at MORs through the process of serpentinization where peridotite is exposed (Charlou et al., 2002; Takai et al., 2004; Kelley et al., 2005; Russell et al., 2010). It has long been considered that hydrogen as a reduced gas can promote the synthesis of amino acids, as clearly demonstrated by the early experiments of Miller (1953), who produced amino acids through gas flow experiments with ammonia, hydrogen, carbon monoxide, methane, and water vapor as starting materials. Therefore, the production of hydrogen at MOR was assumed to play an important role for the birthplace of life.

Geologists have also known that mid-oceanic ridge basalts (MORBs) in the Hadean Earth were not similar to those of modern Earth. Because of the higher mantle potential temperatures by over 300 K, the Hadean MORB magmas were mostly komatiites (e.g. Takahashi, 1986), which are compositionally similar to peridotites or serpentinites. Thus, the Hadean MORBs must have produced even more hydrogen, and provided more reduced conditions due to

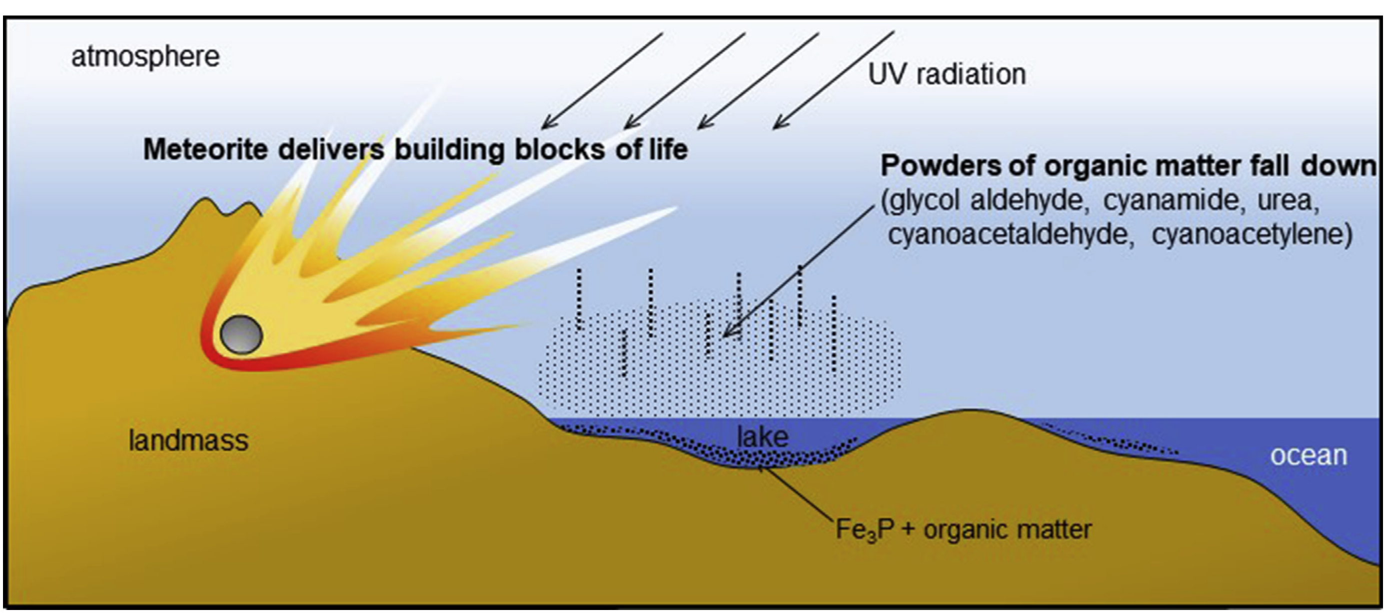

Figure 2. The model of Neo-Panspermia. The Neo-Panspermia model proposes that meteors and/or cosmic dusts deliver necessary BBLs for generating life, after the formation of Earth's ocean and atmosphere, and constantly do so even today.

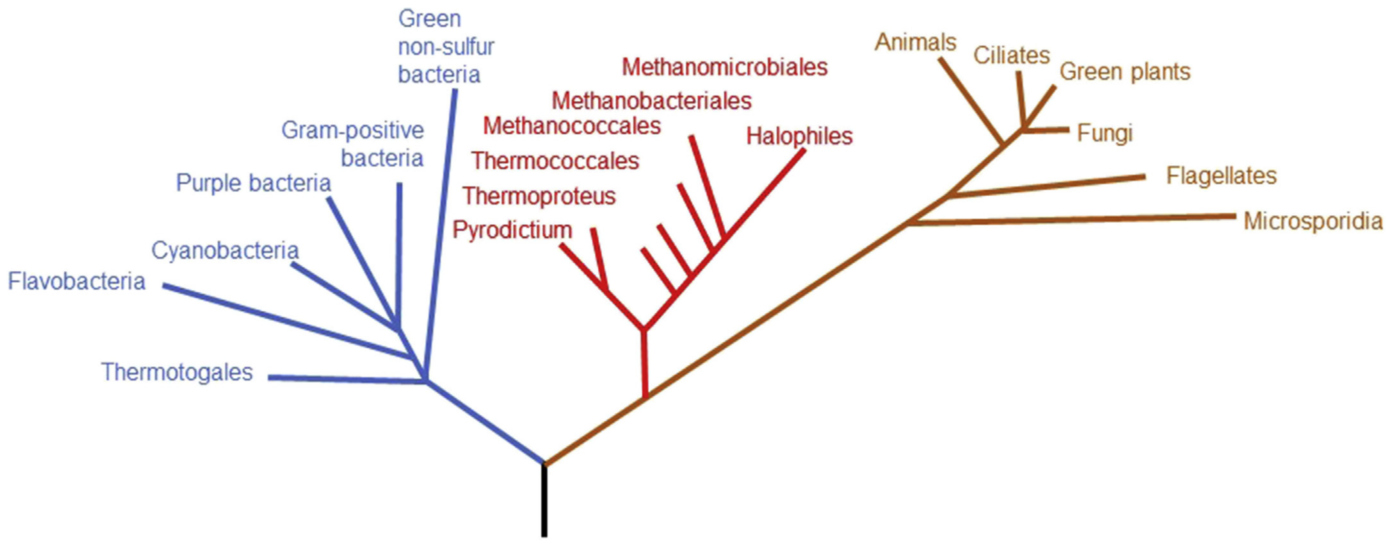

Figure 3. Phylogenetic tree of life by Woese et al. (1990). The relationships among Eukarya, Archaea and Bacteria are shown, all having evolved from Progenote (Woese and Fox, 1977) or LUCA, the "last universal common ancestor" (Fox et al., 1980). Note that all living organisms are plotted at the tops of tree branches, and are connected their roots downwards to the LUCA. If parallel gene transfer is common, the tree of life does not indicate genetic relationships, particularly before 2.0 Ga (Doolittle, 1999). However, if evolution is dominantly controlled by increasing pO_2 after 2.0 Ga, then the tree of life could be reconstructed as a function of pO_2. In that case hydrogenobacteria and sulfur bacteria could be the most primitive microbes in terms of their functional genes.

serpentinization. These factors lend support to the theory that the life originated during Hadean or Archean MOR (Russell et al., 1988, 1994; Russell and Hall, 1997; Kelley et al., 2001, 2005; Martin and Russell, 2003). Thus, the creation of the organic world from inorganic material marks a turning point in Earth history, and deep-sea hydrothermal systems at MOR has been thought to be the birthplace of first life, termed "LUCA(s)" for "last universal common ancestor(s)" (Fox et al., 1980).

2.5. Island arc volcanoes; hydrothermal field

Mulkidjanian et al. (2012), summarizing geochemical requirements with phylogenomic scrutiny of the inorganic ions as the universal components of modern cells, reconstructed the hatcheries of the first cells as the birthplace of life. They focused on ubiquitous ions and primitive proteins with some functional and fundamental systems, and showed the necessity of K^+, Zn^{2+}, Mn^{2+} and PO_4^{3-} to maintain vital functions. According to their model, proto-cells must have evolved in habitats with a high K/Na ratio, with relatively high concentration of Zn and Mn, and phosphorus compounds, like phosphate (Table 1). Because P does not react chemically in an oxidized environment, an anoxic atmosphere must have existed at the time of life's origin. They proposed that the most probable site for meeting these requirements was fumaroles on primordial continent, where volcanic gas was erupted (Fig. 4). Volcanic gas from fumaroles does not include much Na, and K is dominant. Also the concentration of K is relatively high in the volcanic front of subduction zones, more so than in the case of MORBs, and fumaroles can concentrate more K in the vapor phase from the primary magma.

2.6. Geyser system driven by a natural nuclear reactor

The nuclear geyser model is recently proposed hypothesis for the birthplace of life by Ebisuzaki and Maruyama (2017). The breakthrough of this hypothesis comparing to previous models is that they clearly stated the necessity of (1) extremely high energy density to promote prebiotic chemical evolution, and (2) the energy/material circulation to mix up reducing and oxidizing material to produce BBL.

First, they pointed out extremely high energy density is required to produce fundamental BBLs including reducing gases to lead for the emergence of life, and only one solution is ionizing radiation by natural nuclear reactor composed of uranium ore. Living organism is made up of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). More than 95% of the bulk composition of living organisms consists of these four elements. CO_2, H_2O, and N_2 are the major sources for C, H, O, and N to produce BBLs. Yet, CO_2, H_2O, and N_2 are thermodynamically very stable on the surface environments on both the modern and Hadean Earth. Therefore, despite being the most critical element for synthesizing amino acids, it is significantly difficult to synthesize NH_3 from N_2 in the atmosphere to utilize for synthesizing BBL. To overcome this difficulty, a natural nuclear reactor is the most ideal. This is because the ionizing radiation from a natural nuclear reactor can break down triply bonded N_2 into protons,

Table 1
Approximate concentrations of key ions in various environments. Mulkidjanian et al. (2012) focused on ubiquitous ions and primitive proteins with some functional and fundamental systems, and showed the necessity of K^+, Zn^{2+}, Mn^{2+} and PO_4^{3-} to maintain vital functions. According to their model, proto-cells must have evolved in habitats with a high K/Na ratio, with relatively high concentration of Zn and Mn, and phosphorous compounds, like phosphate.

Ion	Modern sea water (mol/L)	Anoxic water of primordial ocean (mol/L)	Cell cytoplasm (mol/L)
Na^+	0.4	>0.4	0.01
K^+	0.01	~0.01	0.1
Ca^+	0.01	~0.01	0.001
Mg^+	0.05	~0.01	0.01
Fe	10^{-8} (mostly Fe^{3+})	10^{-5}	10^{-3}–10^{-4}
Mn^{2+}	10^{-8}	10^{-6}–10^{-8}	10^{-6}
Zn^{2+}	10^{-9}	$<10^{-12}$	10^{-3}–10^{-4}
Cu	10^{-9}(Cu^{2+})	$<10^{-20}$(Cu^+)	10^{-5}
Cl^-	0.5	>0.1	0.1
PO_4^{3-}	10^{-6}–10^{-9}	$<10^{-5}$	~10^{-2} (mostly bound)

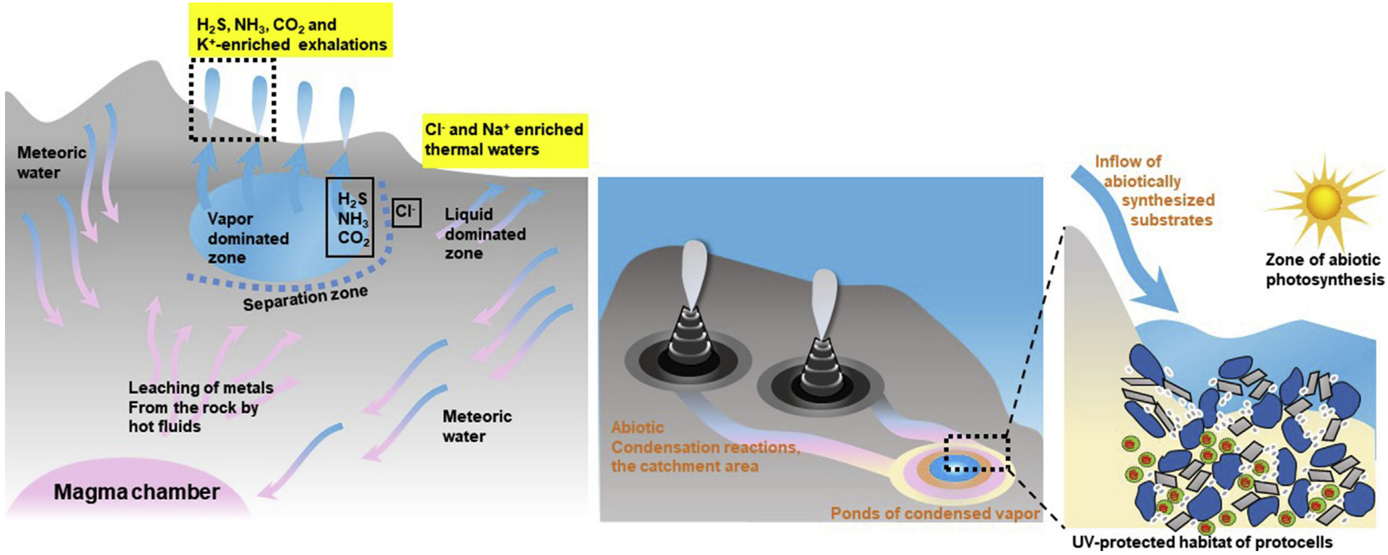

Figure 4. The birthplace of life at an island arc fumarole (Mulkidjanian et al., 2012). K-rich water on land can be made through two steps of fluid separation; first directly from the magma (left), which is then followed by K-rich fluids emanating from fumaroles by liquid or vapor separation (middle and right).

neutrons, and large number of electrons in areas adjacent to a uranium ore body, and the same thing will happen for other materials, such as CO_2, H_2O, and organic matter. All these materials are broken into high energy radical particles such as aqueous electrons. After such a process, broken substances react with each other to form other material including BBLs.

In addition, they explained systematic energy/material circulation as a key to synthesize more complex organic compounds. They combined natural nuclear reactor (uranium ore) and geyser to propose a new hypothesis named Nuclear Geyser model (Fig. 5). According to this model, a natural nuclear reactor provides abundant high energy particle through ionizing radiation to promote chemical reaction to produce numerous BBLs. Basically, reducing material is produced underground while oxidizing material appear on the surface environment. Geyser splash drives mixing of reducing and oxidizing material. Through the activity of nuclear geyser system, primordial life is assumed to be born. Also they explained this site could supply all necessary components to

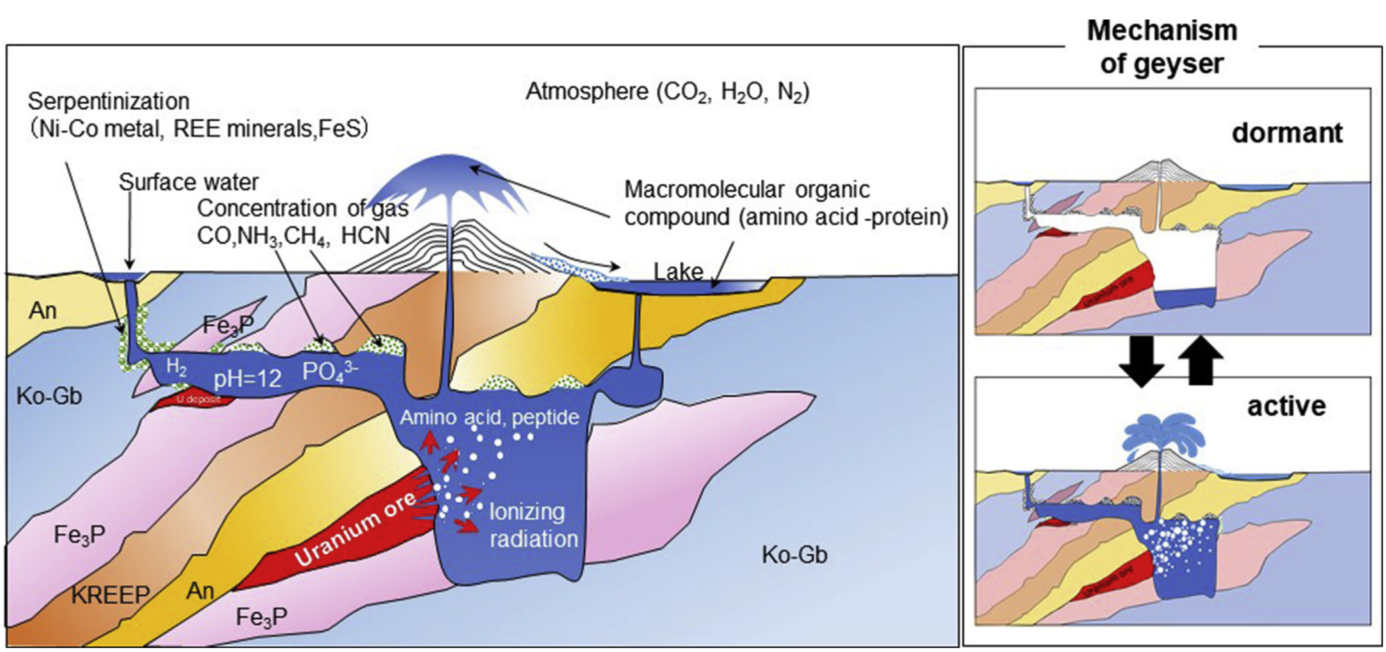

Figure 5. The nuclear Geyser model as the birthplace of first life. (Left) Schematic figure of the nuclear geyser system. Surface river water drains into underground caves. Once the main cave is filled with water and it boils up, geyser splash will toss off something from the cave onto surface environment. A necked narrow passage connecting caves controls periodic splash of the geyser by continuously supplying surface water. The natural nuclear reactor works periodically depending on its water content, between dormant and active phases. The exposed wall rocks of the geyser are not only uranium ore but also KREEP basalt, serpentinite, and schreibersite (Fe_3P) that supply important nutrients. The irregular-shaped ceiling of cave works as the container of reduced gasses to enable the synthesis of amino acids. (Right) The fundamental mechanism of the geyser. While water does not fill the reactor room, it remains dormant. Once water covers the reactor, it becomes an active phase. When the underground cave is filled with boiled water, it splashes. Although there are two types of potential heat source; either the volcanic magma or the natural nuclear reactor, the latter is emphasized in this model to promote chemical reaction to produce BBLs.

generate life, such as HCN, nitriles, glyceraldehyde, and glycolaldehyde (Fig. 6).

The original proposal for a natural nuclear reactor was by Zel'dovich and Khariton (1940a, b), and Kuroda (1956) theoretically predicted that a natural nuclear reactor would be found on the Earth. Such a natural nuclear reactor was then discovered in the Gabonese Republic in central Africa in 1972 (Bodu et al., 1971; Neuilly et al., 1972; Gauthier-Lafaye and Weber, 2003; Ndongo et al., 2016). Through discussions about natural nuclear reactors and related radiation effects to promote the chemical reactions to form organic compounds, some recent proposals were made that such reactors could have contributed to beginnings and evolution of life (e.g. Adam, 2016). However, Ebisuzaki and Maruyama (2017) first proposed a comprehensive model of a nuclear geyser system as the birthplace of Earth life with the mechanism to form necessary BBL.

3. The birthplace of life: key factors

Since Darwin's time, necessary conditions or environmental setting for the emergence of life has long been discussed, although previous studies generally focused on a few aspects of life's emergence, and did not evaluate the essential points. For example, the topic of the formation of cell membrane, or synthesis of some sort of organic compounds, have been investigated, but it has not been proposed how and where both reactions proceeded to form life. We summarize the necessary conditions for birthplace of life based on the review of previous multidisciplinary studies ranging from biological to astronomical viewpoints. Based on these, we identify nine requirements for the emergence of life on a planet (Table 2). In the following section, we evaluate the significance of each of requirements.

3.1. Energy source: ionizing radiation (non-thermal energy) and thermal energy

To synthesize organic compounds, it is well known that nitrogen (N) is required for chemical reactions to proceed in spite of very strong triple bonding of N_2. To break this triple bonding, the Haber-Bosch process was invented, utilizing high temperatures (500–600 °C) and high pressures (200–1000 atm) to facilitate reactions of N by overcoming a high activation energy barrier. In nature, however, such conditions cannot be maintained to facilitate the necessary reactions of N to produce BBL.

To initiate chemical reaction of triply bonded N_2, a reasonable energy source is radioactive non-thermal energy during uranium disintegration and it is the only one solution to destabilize N_2 as well as H_2O, and CO_2 to facilitate chemical reaction. The necessary

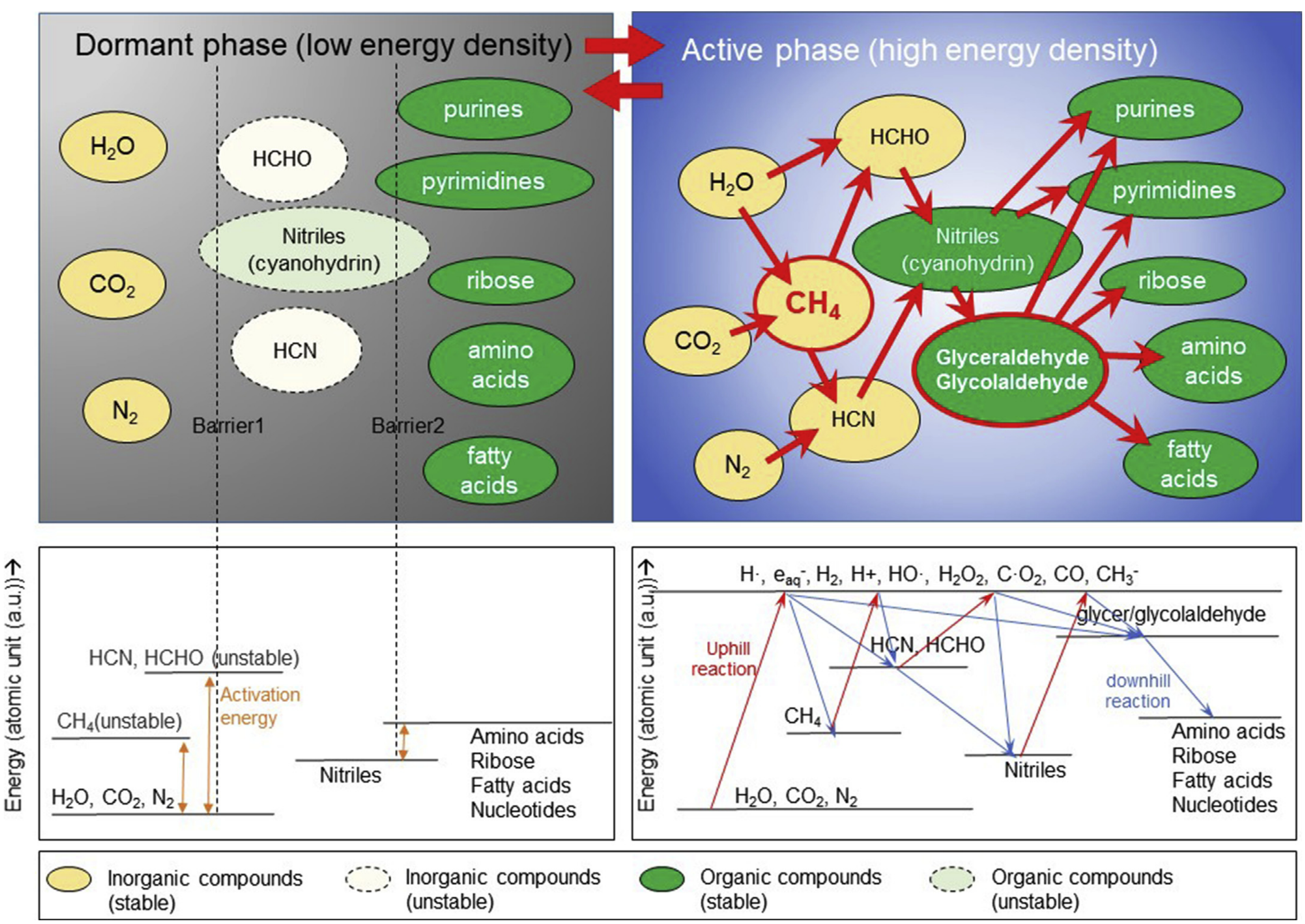

Figure 6. Chemical reaction proceeding in a natural nuclear geyser. (Left) Diagram shows chemical material in the dormant phase. During dormant phase or low radiation levels of natural reactor, each material does not react with each other, remaining as H_2O, N_2, HCHO, HCN, amino acids, and fatty acids. There are two large activation barriers shown as Barrier 1 and 2. This occurs because of the lack of activation energy. (Right) Reaction process in the active phase. Once the system reaches the level to activate the geyser system, abundant high-energy particles, such as aqueous electrons, are provided to promote chemical reaction between any kind of available material, such as nitriles, glyceraldehyde and glycolaldehyde to form other complex organic compounds. Ionizing radiation provides the only means to overcome activation energy problems (Ebisuzaki and Maruyama, 2017).

Table 2
Nine requirements for emergence of life. For the emergence of life on the planet, there are several essential requirements to be fulfilled. See text for discussion.

	Environmental factors	Nuclear geyser system	Hydrothermal system	Mars[c]	Universe[d]
1	Energy source (ionizing radiation + thermal energy)	Yes	No	Yes	Yes
2	Supply of nutrients (P,K, KREEP etc.)	Yes	? [a]	Yes	No
3	Supply of life constituent elements (C, H, O, N)	Yes	? [a]	Yes	Yes
4	Concentration of reducing gas	Yes	No	? [b]	No
5	Dry/wet cycle	Yes	No	Yes	No
6	Na-poor water	Yes	No	Yes	No
7	Non-toxic water environment	Yes	No	? [b]	No
8	Diversified environments (Ocean: pH, salinity, heavy metals, Atmosphere: Temperature & Pressure, Continent: varied geology)	Yes	No	? [b]	No
9	Cyclic change	Yes	No	No	No

[a] For some elements, Yes. But for others, No.
[b] No evidence, but presumably Yes.
[c] Mars kept ocean for the first 400 million years after the formation.
[d] Universe does not have liquid water in the matrix.

reactions would be particularly effective in close proximity to the core of the natural nuclear reactor, where nearly all molecules would be broken. With increasing distance from the core of the natural nuclear reactor, the broken molecules (high energy intermediates) would start reacting to synthesize both inorganic and organic matter with the supply of abundant electrons from the nuclear reactor. These are the distinct advantages of a natural nuclear reactor for promoting the chemical reactions needed to synthesize organic compounds, including a wide variety of BBLs (Ebisuzaki and Maruyama, 2017). Through a continuous supply of aqueous electrons and active chemical products, numerous kinds of simple or macromolecular organic compounds will be produced. A natural nuclear reactor is only one supplier of high energy enough to facilitate production of BBL on Hadean Earth (Fig. 6).

The important point here is that thermal energy cannot play a role as same as non-thermal energy because organic compounds are broken at temperatures above 100 °C. Because the ionizing radiation from a natural nuclear reactor is a non-thermal energy source, it is a key to promote the synthesis of organic compounds. On the Hadean Earth, such natural nuclear reactors were likely very widespread because the primordial continental crust was remarkably enriched in uranium (U) and thorium (Th) (Ebisuzaki and Maruyama, 2017). The remnant of such a natural nuclear reactor formed at 2.3–2.2 Ga has been well-documented at the Oklo site in Gabon Republic, Central Africa (Bodu et al., 1971; Lancelot et al., 1975). This example suggests that similar natural nuclear reactors could be present on the Hadean continental landmass, particularly due to the high concentration of U in Hadean landmass. Because U cannot enter the crystal structure of mantle minerals, such as olivine or pyroxene due to its large ionic radius, U concentrations in the Hadean crust could have been 1000 times more than that in the present day mantle. This high abundance of U functioned as a natural nuclear reactor, and it could have served as the energy source to promote the chemical reactions for forming BBLs (Maruyama and Ebisuzaki, 2017).

3.2. Supply of nutrients (K, REE, P, etc.)

C, H, O, and N make up 95% of living organisms, and the remaining 5% is made up by nutrients such as potassium (K), phosphorus (P), iron (Fe), calcium (Ca) and magnesium (Mg). C, H, O, and N are supplied by the atmosphere and ocean, while the remaining nutrients are derived from the landmass, which provides a total of 29 elements including minor and trace elements (Ochiai, 2008). Although nutrients are minor constituents, living organisms cannot emerge without them.

On the modern Earth, the essential nutrients for life are derived from granitic continents enriched in K, P, rare earth elements (REEs), and other elements. However, on the Hadean Earth, immediately after the consolidation of its magma ocean, granite was not present, because the formation of granite only occurred when plate tectonics began. Although the operation of plate tectonics initiated after the appearance of the ocean between 4.37 Ga and 4.20 Ga (Maruyama et al., 2018), a sufficient amount of granitic rocks could not have accumulated during Hadean time. Thus, the first life required an alternative source of nutrients than what could be supplied by granites.

The alternative source must be the primordial continents, which would be rocks similar to those currently exposed on the Moon. These rocks are dominantly anorthosite together with KREEP basalts (Arai and Maruyama, 2017; Dohm et al., 2018). KREEP basalt was formed after 85% of the Moon's magma ocean solidified, resulting in a final residue of Fe-rich basaltic melts (Arai and Maruyama, 2017). The petrochemical characteristics of KREEP basalt include enrichment or super-enrichment in (1) high field strength elements (HFSE), such as zirconium, niobium, hafnium, REE, thorium, uranium and tantalum, and (2) large ion lithophile elements (LILE), such as potassium, rubidium, caesium, strontium, and barium. The final 15% residue must have (1) solidified to be the mafic lower crust under the primordial continents, (2) intruded into the upper felsic crust, or (3) erupted on the surface of the primordial continents. The nutrients derived from primordial continent must have played a critical role in feeding the first life on the primordial continents.

3.3. Supply of life's main constituent elements (C, H, O, and N)

No one has questions about the necessity of C, H, O, and N for life, because more than 95% of individual body of living organism is composed of C, H, O, and N. Combined with the supply of nutrients (K, REE, P, etc.) (as stated at section 3.2), the supply of life-constituting elements (C, H, O, and N) is critical to sustain life. A concept of the "Habitable Trinity" (Dohm and Maruyama, 2015) simply shows such a condition, which holds that the co-existence of suppliers of all necessary elements; i.e. the atmosphere, ocean, and landmass, and the supplying system is driven by the Sun, promoting material and energy circulation (Fig. 7). Most planetary scientists adhere to a prevailing concept of the habitable zone, focusing on the presence of liquid water. They regard this concept as the most important condition for the potential presence of life, however, living organisms cannot survive with water only. The presence of the Habitable Trinity conditions must be emphasized in considering the emergence and survival of life.

3.4. Concentration of highly reduced gas

Prebiotic chemistry requires reducing material, such as H_2, CO, CH_4, NH_3 and HCN, to promote the synthesis of amino-acids to lead to the origin of life (Miller, 1953; Bada and Lazcano, 2003; Sutherland, 2016). This was clearly demonstrated in the early experiments of Miller (1953). However, major difficulties arise in the mechanism to accumulate these gasses in nature. Reduced gasses are diffused into open atmosphere or ocean, after they are produced through serpentinization, which is the case at mid-oceanic ridges or surface environment. To overcome this problem, an

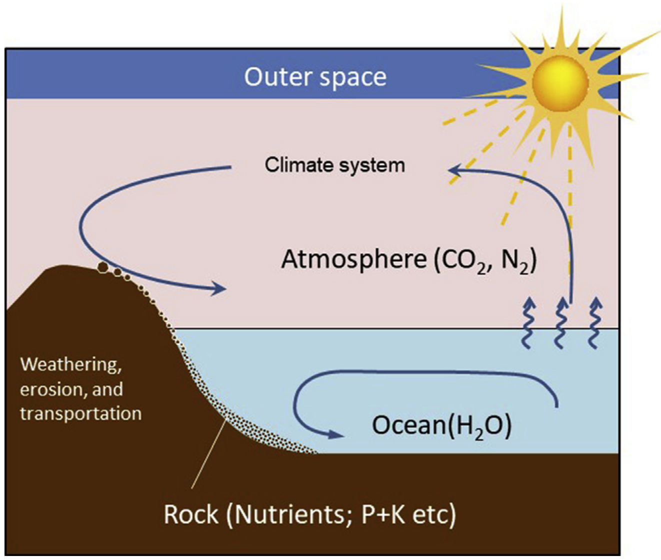

Figure 7. Habitable Trinity model. To evolve into a habitable planet, co-existence of atmosphere, ocean, and landmass with a driving force (Sun) is one of the most critical condition. It is obvious that life cannot live with water only. The supply of nutrients derived from landmass is critical for the emergence of life (Dohm and Maruyama, 2015).

underground cave is an ideal site, because the reducing gas produced could be accumulated over time on the ceiling of the cave.

3.5. Dry-wet cycles

Alternating dry and wet conditions are necessary for the emergence of life, as exemplified by a suite of diverse prebiotic chemical reactions including polymerization of amino acids to peptides and synthesis of RNA from nucleotides by repeated dehydration-hydration in tidal flats, that has been repeatedly emphasized (e.g. Oparin, 1957; Miller, and Urey, 1959; Miller and Bada, 1988; Deamer, 1997, 2016; Damer and Deamer, 2015). The tidal impact of the Moon was much stronger during the Hadean than at present. While the modern Moon's effects cause repeated dry and wet conditions on tidal flats twice a day, this cycle must have been every 5 hours in the early Hadean, immediately after the Giant Impact (Benz et al., 1989; Canup and Asphaug, 2001). It is worthwhile to recall that the presence of a landmass on the Hadean Earth inevitably leads to conditions that make the formation of BBLs possible by dry-wet cycles. If no landmass would be present, the resulting ocean planet could not have the dry-wet cycles. Such a planet could not lead to the stepwise synthesis of BBLs.

3.6. Non-toxic water environment (less salt, less heavy metals, and neutral pH)

For life, water must be moderately clean, which we call non-toxic water environment. The reason why we emphasize it as one of requirements is Hadean ocean was too toxic to live.

Based on the recently proposed ABEL model (Fig. 8; Maruyama and Ebisuzaki, 2017), the solid Earth was formed by enstatite chondrite-like dry material at 4.567–4.530 Ga, and water components were secondary accreted through ABEL Bombardment between 4.37 Ga and 4.20 Ga by carbonaceous chondrites from outer asteroid belt. Enstatite chondrites contain sulfur and halogens, such as Cl, in addition to schreibersite (Fe_3P), which must have been concentrated on the primordial continents through solidification of magma ocean because they cannot enter into mantle silicates (Pasek, 2015; Maruyama and Ebisuzaki, 2017). Moreover, carbonaceous chondrites are composed of not only large amounts of H_2O, but also CO_2, N_2, SO_2, halogens such as Cl and F (McDonough and Sun, 1995). Through the ABEL Bombardment, halogens and metallic elements were dissolved into accreted H_2O, which formed the primordial ocean, indicating that the primordial ocean must have been remarkably toxic with ultra-high acidity and salinity, as well as a high abundance of heavy metallic elements. According to estimates of the chemical composition of the primordial ocean by averaged volatile composition inferred from CI chondrite compositions (e.g., Maruyama et al., 2013), it must have been about 50% sulfidic and 50% H_2O with considerable amounts of HCl, HNO_3, and HF, suggesting a $pH < 0.1$. Under such highly acidic condition, large amounts of metallic elements such as Fe, Mn, Mg, Cu, Zn, Pb, Mo, Hg would be dissolved in the ocean. Moreover, salinity in the Hadean ocean must have been 5–10 times more than today (Saito et al., submitted). Hadean MORs would be covered by such a highly toxic ocean. These constraints do not permit Progenote(s), or LUCA(s) to appear in an ocean.

To overcome this difficulty for the emergence of life, a huge landmass is necessary, because clean water gets accumulated on a landmass as forms of ponds, lakes, swamps, or wetlands through global hydrological circulation by the climate system, where proto-life could utilize water to evolve into the first life.

With time, water-rock (landmass) interactions can change the chemistry of the primordial ocean through hydrological material circulation. Water-rock interaction is due to reaction between flattered rock particles and water. To flatten rocks, weathering, erosion, and transportation process is necessary, which is enabled by the presence of landmass, but it will take a very long time. For example, even at the onset of Phanerozoic, ca. 600 Ma, the salinity of the ocean was still twice of the present ocean (Knauth, 2005). Therefore, water-rock interactions took about 4 billion years to cleanse ocean perfectly for life where metazoans can readily survive. Therefore, landmass should not be small. To clean up toxic ocean over 4 billion years, the landmass has to be huge. However, to make such a huge landmass above sea-level, the amount of accreted water by the ABEL Bombardment to generate the primordial ocean becomes a critical constraint. The planet-wide depth of the primordial ocean needs to have been 4 ± 1 km (Maruyama et al., 2013). If ocean was deeper than about 5 km, the landmass could not appear above sea level. If it was less than 3 km thick, plate tectonics could not initiate because of the absence of hydration at mid-oceanic ridges. Either result would disrupt the Habitable Trinity, resulting in a failure to make the Earth habitable.

3.7. Na-poor water

Modern cell cytoplasm is extremely poor in Na^+, while conversely it is enriched in K^+, and also enriched in PO_4^{3-}. This indicates that the first cells is originated from highly reduced conditions that were highly depleted in Na^+ ions and conversely enriched in K^+, Zn^{2+} and Mn^{2+}. As Mulkidjanian et al. (2012) proposed, the birthplace of life would be such a site. The specific example is a subduction-zone volcanic fumarole on land, instead of mid-oceanic ridge hydrothermal region. If the Hadean Earth was covered by KREEP basalt-bearing thick continental crust, and plate tectonics started, the mafic lower crust composed of KREEP gabbro would have produced extremely K-enriched arc magmas at subduction zones or metasomatically modified slab-melt by partial melting of a KREEP lower curst. In this sense, subduction-zone volcanoes satisfy this condition, and it should be noted that solidified KREEP basalt can also provide a K-rich environment.

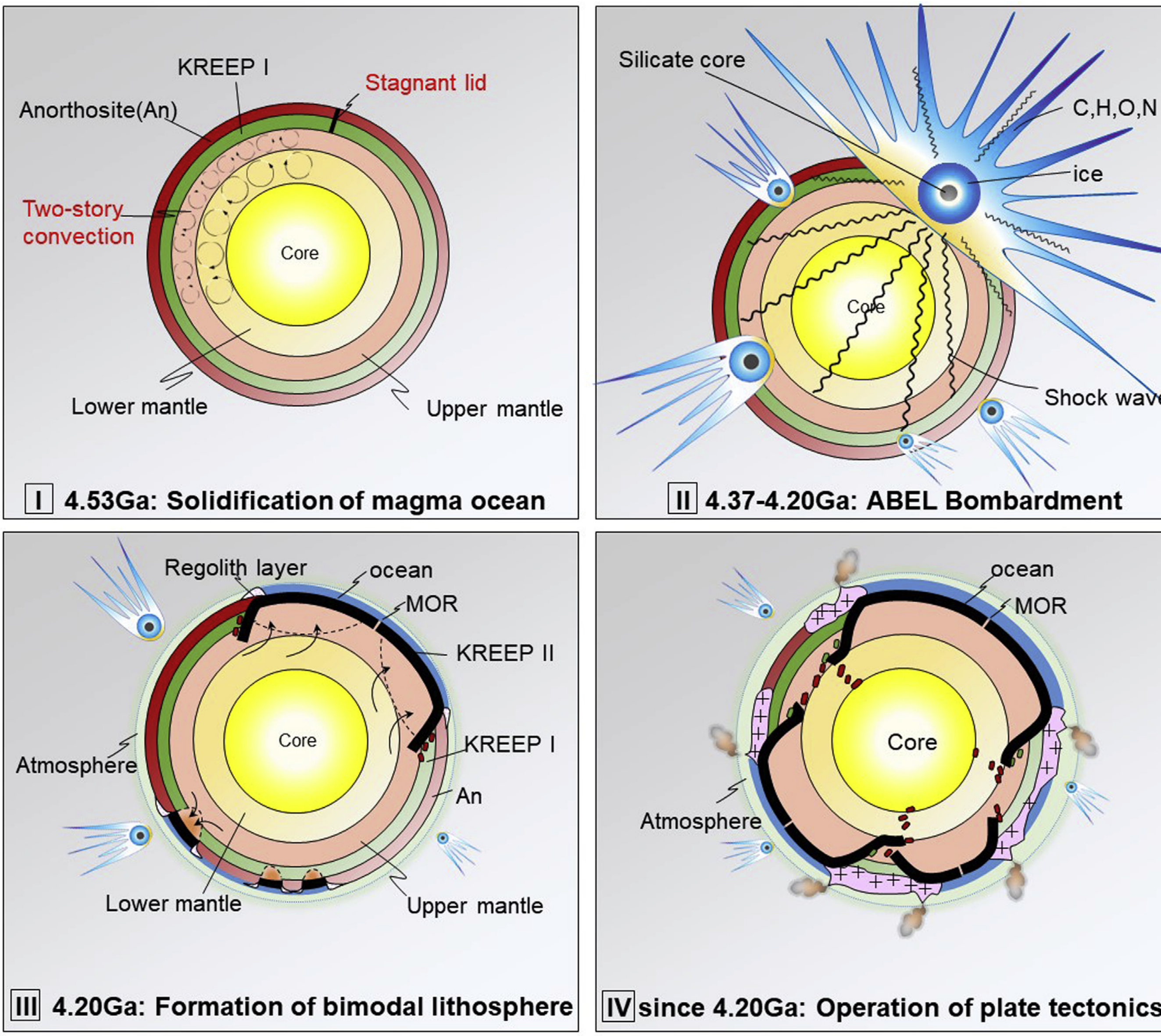

Figure 8. The ABEL model. The Earth formed through two steps. The Earth was born as a dry rocky planet at 4.53 Ga. The Earth's atmosphere and ocean were secondary accreted by the ABEL Bombardment (4.37–4.20 Ga) (Maruyama and Ebisuzaki, 2017).

3.8. Highly diversified environments

The building blocks of life evolve from (1) combining the inorganic materials of CO_2, H_2O, N_2 together with varieties of nutrients, through (2) simple organic species of amino acids, ribose, nucleic acids, and simple proteins, which in turn lead to (3) enzymes, cycles, and ribozymes, then to a RNA-DNA world, and finally to (4) the first progenotes, or LUCAs. Membranes and cell walls must also develop during the earlier stages of this sequence, and finally all building blocks must get inserted into the cell through a stepwise process. The possible pathways from simple inorganic matter to the first life with self-replication functions, must pass through an immense number of chemical reactions (Fig. 9).

To allow these reactions step-by-step to go forward, the inevitable first step is to synthesize numerous kinds of BBLs, requiring the different pH, pO_2, temperature, salinity and chemical conditions related to the catalytic minerals, even contrasting conditions, e.g., oxidized vs. reduced, or acidic vs. alkaline, at the same time at different place. Then, products have to be merged one by one to generate more complex BBLs through time and environments. To enable these continuing and complex processes, the presence of a highly diversified surface environment on the Hadean Earth is necessary, and it can provide the sole solution (Fig. 10 Left). Particularly, the appearance of huge landmass enriched in nutrients is the most critical. If there is no landmass, a "water-world" Earth with a homogeneous surface environment appears, in which case, there is no possibility to have life (Fig. 10 Right). Highly diversified on-land environments with particularly localized and heterogeneous environments, are key to the origin of life.

The highly diversified surface environments of the Hadean Earth are schematically illustrated in Fig. 10 (left), which shows a bird-eye view of 4.3 Ga Earth with large primordial continents, composed of anorthosite (called PAN, MAN, and FAN), KREEP basalts filling in cratered basins created by ABEL Bombardments, serpentinized Mg

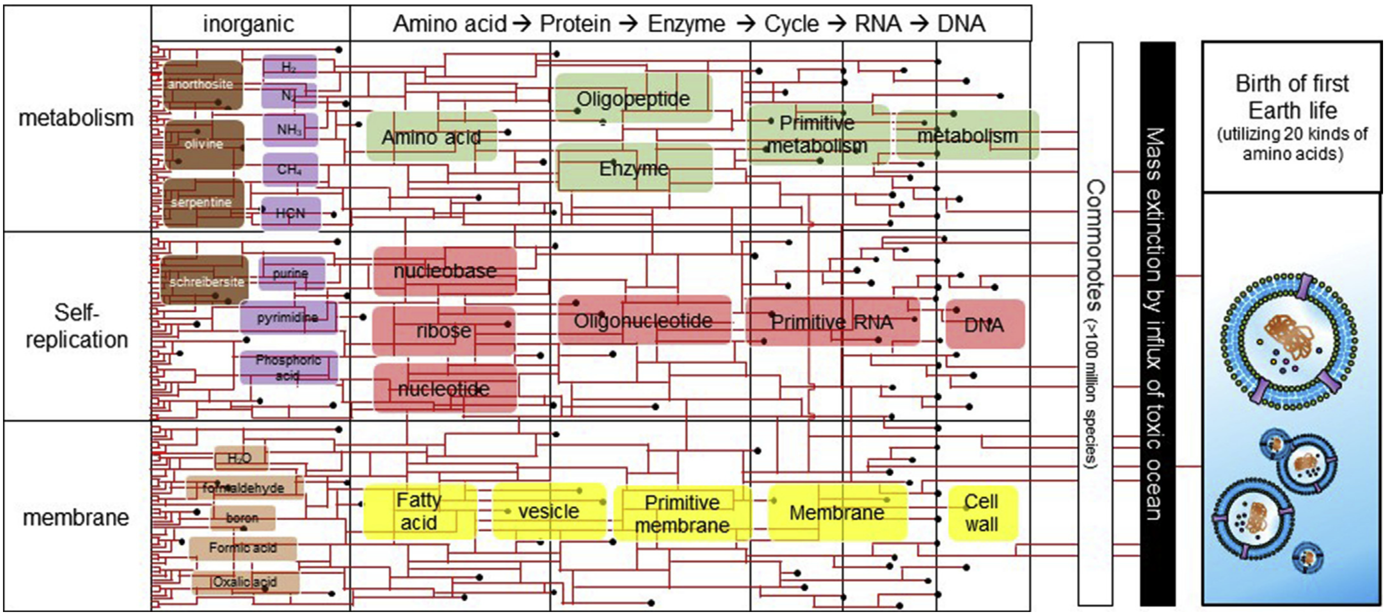

Figure 9. The reaction network to generate the first life. The chart shows three basic functions of life, (1) metabolism, (2) self-replication, and (3) the formation of membranes. The chemical reaction from inorganic matter to the first life involve innumerable complex organic components (building blocks of life). It remains unclear how many and which pathways of reaction networks were used, and what crossings there were among the three categories of metabolism, self-replication and membrane creation, toward the birth of the first living organism.

suites (komatiites), newly formed andesite volcanic rocks and their plutonic equivalents at subduction zones, U-ores associated with minerals such as schreibersite (Fe_3P), and a variety of rock-forming minerals of Fe-oxides, Ni-Co alloys, Zn, Cu, Pb, Mn, native iron, oxides, sulfides, molybdenite (MoS_2) and other key minerals to generate the necessary metallic proteins. In addition to a variety of rocks and minerals, topological diversity is also provided, such as highlands, lowlands, tropical area, glaciated area, deserts, wetlands, lakes, swamps, and rivers on land. They can provide different conditions according to site both physically and chemically, e.g. temperature, humidity, and chemical composition of lakes or rivers. Weathering, erosion, and transportation promoted by climate can provide various nutrients to surrounding region with complex chemical composition.

3.9. Cyclic changes, such as day and night

Cyclic changes provide an important factor for maintaining life cycles, as seen in the fundamental processes in which life is associated with periodic fluctuations (e.g. Hanczyc et al., 2003; Lambert,

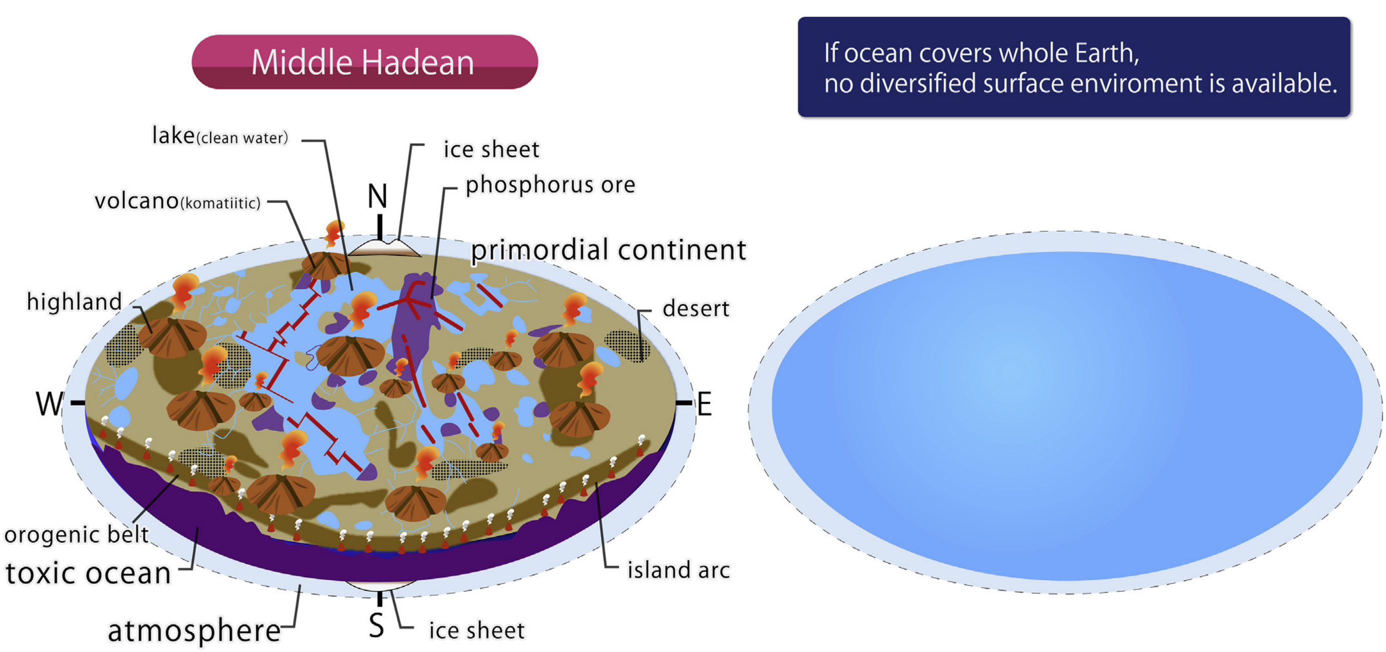

Figure 10. Diversified earth and monotonous earth. Hadean Earth is thought to be a highly diversified environment (left). If an ocean covers whole Earth (right), it would be monotonous, with no diversified surface environment and hence, no possibility for the emergence of life.

2008). Periodic environmental change, such as temperature, pH, inorganic organic ions and anions, must have affected the earliest steps of the life-forming process, e.g., low-temperature conditions result in regular crystallization of specific organic compounds, whereas high-temperature conditions promote random orientation of the crystalized organic compounds, with 60 °C as the critical transition temperature. This temperature fluctuation may be related to the folding-unfolding of DNA, fragmentation-reconnection, and several steps for self-replication processes in the RNA-DNA world. It is assumed that the cyclic changes in the surrounding water chemistry would affect the fundamental processes of pre-biotic chemical evolution, and functions coded in genes may provide a kind of "fossil" of environmental cyclic changes.

One of the driving forces for this kind of periodicity is the self-rotation of the Earth (the day-night cycle), and another would be the tidal effect of the Moon. The Hadean Moon was moving at a one-third closer orbit to the Earth with an orbital period of 5 hours (Benz et al., 1989; Canup and Asphaug, 2001), which meant that the tidal force was much stronger than at present and the tidal cycles were also faster (Fig. 11).

4. The birthplace of life: evaluation of potential sites

The principal candidates for the birthplace of life were introduced in section 2. Here we evaluate those birthplace models in the light of the fundamental conditions required for the birthplace of life that were described in section 3 (Table 2). We then assess the most probable model based on these requirements.

4.1. Mid-oceanic ridge: not birthplace of life, but a secondary origin

Among several birthplace hypotheses, Hadean MOR hypothesis seems to be supported by majority of researchers. However, looking into nine requirements listed in Table 2, it indicates that none of the requirements are met under the hydrothermal system at a MOR in the Hadean Earth.

(1) Energy source; ionizing radiation (non-thermal energy) and thermal energy

The only energy source at MOR is the heat from underlying magma. To promote the chemical reaction between stable N_2, H_2O, and CO_2, thermal energy supplied at MOR is not enough. For example, to make NH_3 (needed to synthesize amino acids) from N_2, temperatures over 500 °C are necessary to achieve the very high activation energy level. However, it is extremely difficult to reach such a high temperature at a MOR. Even if it were possible, almost all BBLs would be broken at such a high temperature (Miller and Bada, 1988). In other words, thermal energy, even if it can achieve high enough temperatures, cannot contribute effectively to synthesize organic compounds.

(2) Supply of nutrients (K, REE, P, etc.)

The supply of nutrients, particularly coupled elements, such as P and K, is critical to bear life. Hadean MOR magma is depleted in both P and K (e.g. 1/400, Maruyama et al., 2013), because it was produced by higher degrees of partial melting of mantle peridotites (Takahashi, 1986; Maruyama et al., 2013). Therefore, MOR cannot supply necessary elements in balance for BBLs like phosphoric acids, suggesting MOR was not suitable site to emerge life, or rather worse in this regard.

(3) Supply of main life constituent elements (C, H, O, and N)

MOR is a highly aqueous environment, so there is no problem to supply H and O. The biggest problem is the supply of N, because N is

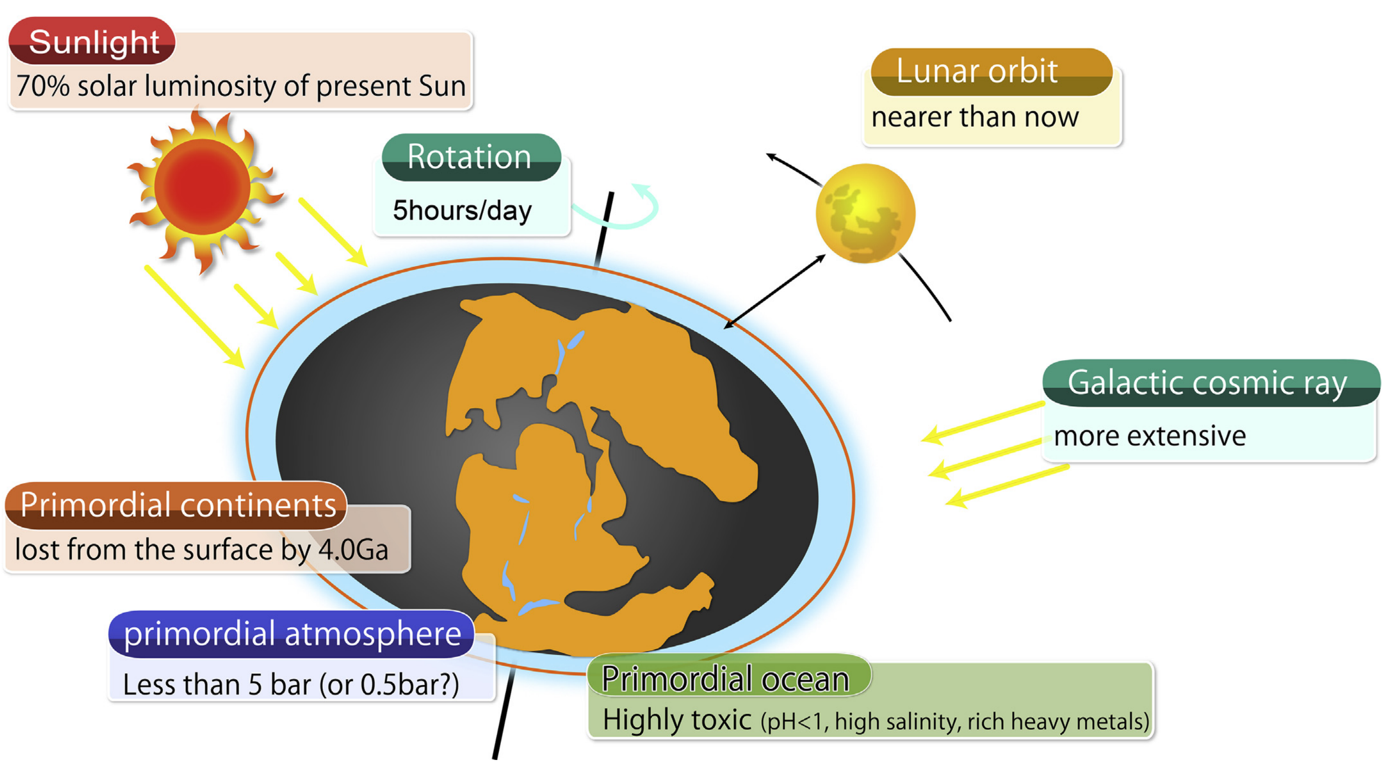

Figure 11. Hadean surface environments of the Earth. Hadean surface environment experienced various types of cyclic phenomena, associated with a closer Moon, faster self-rotation of the Earth, and the faint young Sun.

the most difficult component to provide at MOR through magmatism from underlying mantle. Basically, N is distributed in the primordial atmosphere, and not in the solid Earth throughout the formation of primitive Earth. This is because there is no N-bearing mantle minerals. Therefore, Hadean mantle lacked N. However, N is indispensable for the synthesis of amino acids, and there is no way to synthesize amino acid and other complex organic compounds at MOR without N. If life has to originate at the MOR, there should have a mechanism to enable continuous supply of N, but such a model has not been proposed yet.

It could be argued that small amount of N dissolved from the atmosphere in the modern mantle, albeit this is not adequate for the Hadean mantle. Originally, N cannot be incorporated in the mantle minerals, so the supply of N from the mantle is impossible. The presence of N in the mantle is due to material circulation through plate subduction. The material circulation from trench turbidites into the mantle could take in organics within clay minerals produced on the surface environment. In the case of rare mica, when clay minerals dehydrate they generate K-mica, Na-mica and Ca-mica that can survive under low temperature Phanerozoic mantle conditions. This process causes release of N from mantle, however it initiated only in the Phanerozoic through change in subduction zone geothermal gradients (Maruyama et al., 2014). Therefore, the minor presence of N in the mantle cannot be applied to Hadean period. Also, minor ammonium can be observed in the dehydrated gas derived from MORBs, which is also after the Phanerozoic. In addition, the amount of such N is lower than the minimum values required to synthesize amino acids (e.g. Schlesinger and Miller, 1983; Cleaves et al., 2008). Therefore, the supply of N at MOR is impossible to emerge life.

(4) Concentration of highly reduced gas

If MOR is the birthplace of life, the site must supply reduced gasses, such as NH_3, HCN, KCN, CO, and CH_4, to produce organic compounds. The modern peridotite system at MOR does not produce any reduced gasses because the amount of H_2 is not enough due to the absence of komatiite, but Hadean MOR could be more reduced with the presence of komatiitic rocks (Russell and Hall, 1997). In the Hadean, komatiite lava flows were erupted, where most sulfur escaped as gasses (Maruyama et al., 2013). Olivine-enriched (>60%) solidified lava flows offered an excellent material for the production of a reduced environment through H_2 production, indicating MOR might be suitable site to give reduced gasses during the Hadean. However, gasses could not be adequately concentrated to promote complex organic compounds because MOR hydrothermal vent is an open system. The concentration level of reduced gas at MOR seems to be too diluted to promote reactions leading to the building blocks of life. Hence, there is no possibility of accumulation of reduced gases at MOR, suggesting MOR cannot be a birthplace of life.

(5) Dry-wet cycle

MOR hydrothermal system completely fails to provide dry-wet environment to promote protein-forming reactions (polymerization) through dehydration-hydration cycle (e.g. Miller and Bada, 1988; Deamer and Georgiou, 2015). The concept of a dry-wet cycle is a classic but basic requirement for the emergence of life as pointed out by Oparin (1924, 1957), Dyson (1982), Deamer (1997), Damer and Deamer (2015) and others. MOR hydrothermal system cannot provide this important cyclic nature, thus it is impossible to be the birthplace of life.

(6) Non-toxic water environments (less salt, less heavy metals, and neutral pH)

Hadean primordial ocean was too toxic; (1) a high salinity over 5–10 times of present salinity, (2) super-acidic like pH < 0.1, and (3) ultra-enriched in heavy metals such as Fe, Mn, Mg, Cu, Zn, Pb, Mo, and Hg (e.g., Maruyama et al., 2013). MOR is, hence, underlain by a toxic ocean, therefore life cannot be born in such an environment. Eventually, life could enter an ocean to live, however, it is assumed after Archean or more effectively after 635 Ma when salinity was down to double of present (Saito et al., submitted). Thus, our ocean has not been a mother of life, nor the place of birth.

(7) Na-poor water

Hadean MOR environment is enriched in Na and nearly devoid of K, indicating a contrastingly opposite chemistry to cytoplasm of life. It means there is no chance for life to emerge at Hadean komatiitic MOR.

(8) Highly diversified environments

MOR is located as deep as 2.5 km below sea-level at present, and presumably 3.1 km in the Precambrian, thus totally covered by monotonous ocean, indicating no possibility of diversified environments around MOR since the middle Hadean. To produce numerous kinds of BBLs, even contrasting conditions, e.g., oxidized vs. reduced, or acidic vs. alkaline, have to be provided to proceed to a series of chemical reactions. MOR in an ocean cannot meet this condition.

(9) Cyclic nature

Cyclic nature means the repetition of rising and lowering of temperature, wet and dry conditions, and cyclic change of composition of atmosphere or water. MOR is in open sea where cyclic nature cannot be maintained basically, due to free diffusion of material, constant and 100% moisturization and stable temperature, suggesting no chance for life to emerge.

(10) Result: MOR is not birthplace, but a secondary site for life

Considering the nine requirements mentioned in this study, MOR cannot be the birthplace of life. Some workers invoke MOR with catalysts that can promote organic synthesis, such as FeS/FeS_2, or other transition metal sulfides. There are some reports these can even fix N_2 (e.g. Schoonen and Xu, 2001; Dörr et al., 2003), though there is no conclusive evidence. However, such a discussion is basically limited to a few products like FeS. Birthplace should supply numerous kinds of BBLs. Therefore, it is difficult to say that MOR is the site where life could emerge because only some BBLs could be produced. Birthplace must produce all necessary products to emerge life.

On the other hand, it is obvious that ecosystem has been present at MOR, and chemo-autotrophic hyperthermophiles and metazoans are confirmed. In particular, hyperthermophile is known to appear close to the root of the phylogenetic tree (e.g. Martin and Russell, 2003), which preserves the earlier nature of microorganisms. Microbes similar to methanogen has been also confirmed at 3.5 Ga MOR (Ueno et al., 2001). Those facts indicate hyperthermophile entered MOR environment in early stage of the Earth's history as well as methanogen. MOR is a stable environmental domain to guarantee nearly constant temperature and geochemical characters since the operation of plate tectonics over 4.0 billion years. If there is no environmental change, life do not need to evolve. Therefore, it is no wonder that micro-organisms of MOR remain as relatively primitive biological characters, although they are not the primordial ones. MOR can be a trans-migrant site for life to survive in spite of the extreme environment, but it is not the birthplace of life.

4.2. Panspermia, neo-panspermia and mars origin

The fundamental problem of the Universe origin hypothesis (Panspermia, Neo-Panspermia, and Mars origin) is not explaining the process or mechanism to emerge life. Panspermia and Mars origin hypothesis clearly suggests that life was not born on the Earth, but lacked the explanation about when and how life could emerge in the Universe, and how life could survive in the Universe during the journey or the shock of the impact when they reached to the Earth, or how they evolved on the Earth after the arrival. As Neo-panspermia model explains, even if key substances, e.g. RNA or DNA, were delivered from the Universe, there is no proof for the emergence of first life. We are seeking clues on the birth of first life from these BBLs.

For the sake of argument, it can be assumed that life came from outside of the Earth, like Mars or exoplanet. In such case, life must travel with all other organisms forming their ecosystem, because life cannot survive with only one species. If life had come from the other planet, such ecosystem must fit to the Earth's environment when they migrate to the Earth. There are so many conditions for life to survive, e.g. atmospheric composition such as O_2 and CO_2, oceanic pH, and the most important thing is food. Such a set of coincidences for all necessary conditions is almost impossible. The Earth's ecosystem evolved with terrestrial environment over time, which is co-evolution between life and earth and being applicable since prebiotic stage of the emergence of life. Therefore, it is highly unlikely that transported ecosystem fitted to Hadean environment.

However, universe origin hypothesis is favored by some researchers. We therefore explain what happens when material is delivered to the Earth from the outer space. Fig. 12 is a schematic illustration of asteroid bombardment on the Earth. An exceptionally large asteroid that could hit the Earth is estimated to be about 1000 km in diameter (Fig. 12B), which is equivalent to the size of Ceres in the asteroid belt. This sized asteroid can cause the formation of a crater with one-order-of-magnitude larger diameter immediately after its impact. The temperature induced by the collision will rise to more than 20,000 K (Davies, 1972; Hiesinger and Head, 2006), which can vaporize even the asteroid itself. At the same time, a similar mass of the solid Earth will turn to gas, which will be enriched in oxygen by more than 50 mol%, suggesting it would oxidize the primordial atmosphere. For example, the well-known Meteor Crater in Arizona (about 1.2–1.5 km in diameter) was formed by the impact of iron meteorite with diameter of

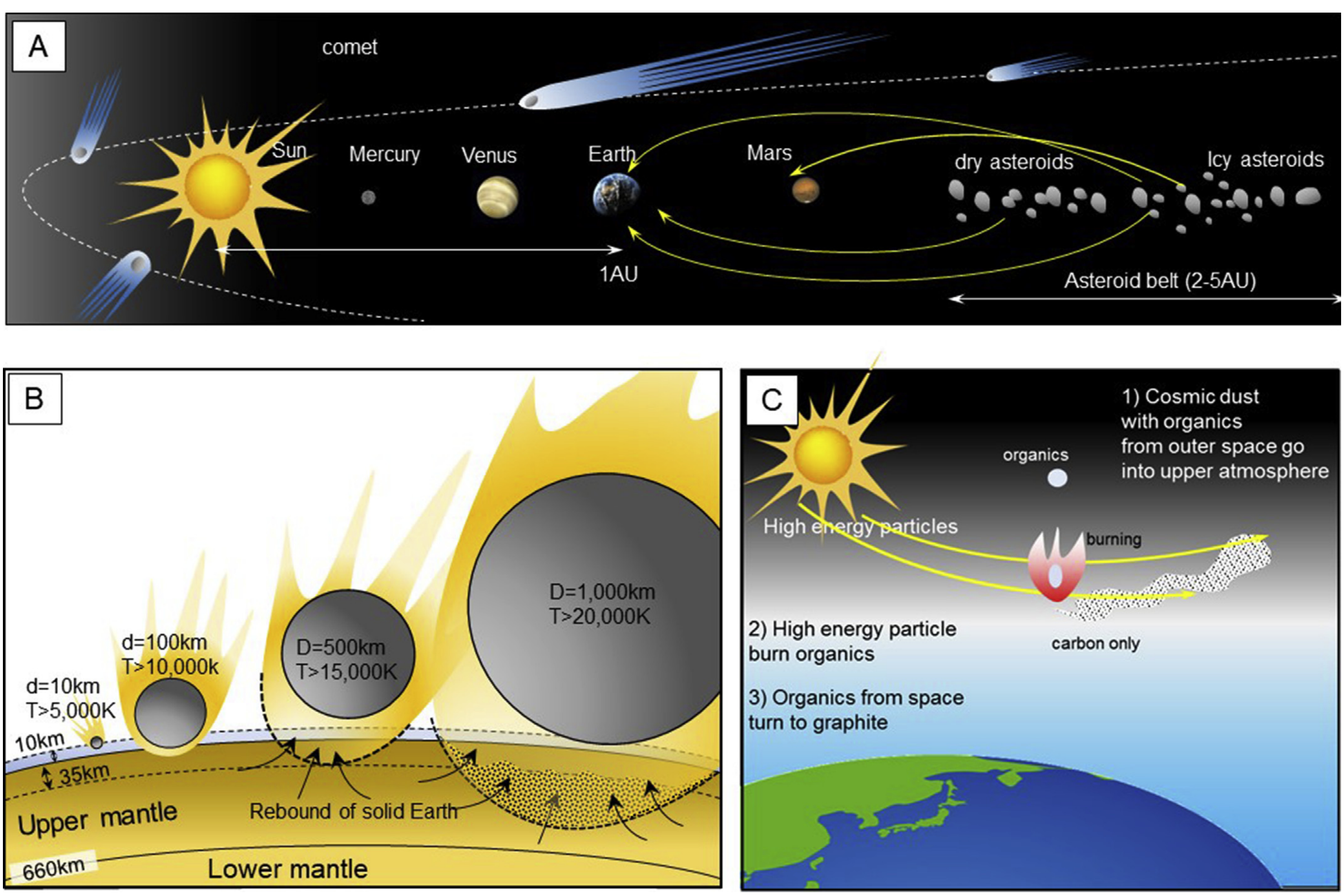

Figure 12. The solar system and materials from outside of the Earth. (A) Schematic illustration of the solar system within 5 AU. Meteors come to the Earth from the asteroid belt at 2–5 AU. Also, comets come near to Earth periodically. (B) The impact of the meteor bombardment is shown schematically. The excavated impact crater gets filled during mantle rebound by KREEP II basalts, which progress gradually over millions of years as mantle upwelling leads to de-compressional melting (Maruyama et al., 2018). Such a tectonic rebound scenario is applicable regardless of the size of impacting asteroid. (C) Cosmic dust containing organic molecules cannot reach to the surface of the Earth because the dust is burned in upper atmosphere due to high energy particle radiation. Any organic molecules in the cosmic dust turn to carbon.

20–30 m. However, the bulk of this iron meteorite evaporated and little remained around the impact crater. Even if the asteroid had contained volatiles (water), they would have evaporated due to the heat by the impact, which would cause a near-instantaneous volume increase (ca. 1000 times) due to phase change from water to gas. Likewise, organic matter, such as amino-acids, purine, and nucleotides contained in meteorite, would all have turned into inorganic gas. Evaporated gas will diffuse and oxidize in the atmosphere, so that nothing but the crater would be left after the impact event. Even in situations that the ground preserves solid meteorite fragments, containing organic molecules, these compounds would never come out from inside of meteorite spontaneously to enter the ocean or atmosphere. Eventually, they would be buried by sediments thereby preventing them from being reused on the surface to constitute BBLs.

What about cosmic dust or ice composed of or containing organic matter that is thought to be delivered from the space to the surface of the Earth? Planetary scientists have long believed that the influx of organic matter in icy dust has been nearly negligible ever since the Earth originated in the earliest Hadean, and more specifically, after the end of the heavy bombardment (the ABEL Bombardment in our model). Though Frank et al. (1986) proposed a highly controversial hypothesis that an influx of small comets with organic matter enters into the Earth's upper atmosphere at a rate of 10^{12} kg/yr, which would equal to the total volume of atmosphere if it continued over 5×10^6 yr. However, this suggestion was rejected by Dessler (1991) who pointed out both theoretical and observational problems with such an immense flux of icy comets entering Earth's upper atmosphere. If the Frank hypothesis would be correct, Earth's past sea-level changes would record the effects. However, there is no consistent geological evidence for such an influence. Wasson and Kyte (1987) calculated average deposition rate of comic flux as 9 ± 3 ng Ir cm^{-2} Ma^{-1} on the basis of the Ir abundance of Pacific deep-sea sediments deposited at 33–67 Ma, except for K/T boundary clays. Assuming a chondrite/ice ratio of 0.2, the ice flux can be estimated to be 2500 times smaller than that proposed by Frank et al. (1986). Thus, the geologic evidence preserved in deep-sea sediments does not support the idea that organic matter could have been continuously transported to Earth's surface from the outer space over the past 4.0 Ga.

It is possible that cosmic dust can be delivered to the planets of Inner zone of the solar system periodically by comets, as exemplified by the Halley Comet in 1986 imparted icy dust from its long tail over periods lasting from a few days to a month depending on the orbital traces (Fig. 12A). What would be the fate of such dusts containing ice and organic matter? Once such cosmic dust comes into Earth's upper atmosphere of the Earth, i.e. the ionosphere, temperatures will rise up due to high-energy particles. Depending on the kind of influx materials, temperatures can reach up to 2000 °C. Therefore, cosmic dust cannot maintain any organic molecules under such extremely high temperatures because the organic compounds would turn to be graphite. Any ice would evaporate and be blown away to the outer solar system (Fig. 12C). Therefore, this idea is inconsistent with both simple physics and the geological evidence.

On the other hand, the idea of Mars-origin appear to have an advantage, particularly from the evidence of "microbe" reported from the ALH84001, as described in section 2. Actually, Mars might have possibility to bear life, as tested by the nine requirements listed up in this paper (Table 2). The history of Mars and Earth shows close resemblance, and the Martian surface environment experienced similar evolution with Earth (e.g. Dohm et al., 2018). Mars is hypothesized to have Earth-like habitable trinity, and there was possibility to meet all nine requirements in the past. However, complex organic matter or biosignature has not yet been discovered on Mars even after investigations by Mars rover, Curiosity (Ming et al., 2014; Freissinet et al., 2015), which indicates that life was not born on Mars, although the listed requirements were fulfilled.

4.3. Island arc volcanoes: hydrothermal field

Image of the environment of the birthplace of life described in this model (Mulkidjanian et al., 2012) reflects the actual geological site of Earth as well as the nuclear geyser model. The model of on-land hydrothermal field suggested good factors such as the chemical composition of cytoplasm, and the specific site to sustain hydration-dehydration process. However, it still lacked the comprehensiveness to elucidate the birthplace. Particularly, absence of the energy source to raise energy density is critical. Also, their explanation does not include the possibility of highly reduced environment to produce HCN, CH_4, H_2, and NH_3 for synthesis of basic BBLs. Therefore, this model is still insufficient to discuss a birthplace.

4.4. Geyser system driven by natural reactor with sufficient energy density: most probable site for the birth of life

Nuclear Geyser model is only one hypothesis that can meet all nine requirements listed in Table 2. One of the most critical conditions is energy density to promote prebiotic chemical reaction between thermodynamically stable substances such as N_2, H_2O, and CO_2. As shown in Fig. 13, the Sun's energy is not enough to promote chemical reactions to produce important BBLs that require high activation energy levels, indicating that life cannot emerge on the surface of the Earth only with the Sun. Only one solution to make continuous chemical reaction on Hadean Earth is the presence of natural nuclear reactor to provide abundant high energy particles such as aqueous electron to make complex organic molecules from inorganic, which can easily clear energy uphill problem (Fig. 6). As Fig. 13 shows, the threshold value of energy density to proceed the prebiotic chemical evolution from inorganic compounds up to simple peptides is above 10^{-2} W/cm^2 far stronger than Hadean Sun radiation to the Earth. Even hydrothermal vent ranges of 10^{-3}–10^{-4} W/cm^2 about one to two order of magnitude lower than the threshold value. Although it depends on the size of the reactor, energy density at 1m away from the core of nuclear reactor ranges of 10^{+1}–10^{-2} W/cm^2 offering a good value to synthesize BBLs. If material is too close to the nuclear reactor, it is broken, however, material is located at an ideal distance, it effectively involves in chemical reaction. Therefore, natural nuclear reactor plays the most important role to promote chemical reaction to produce BBLs.

However, the presence of nuclear reactor itself is not sufficient to lead to the emergence of life. Combination between a geyser and natural nuclear reactor construct the perfect system that would meet several critical conditions to bear life. The advantages of nuclear geyser system are as follows. (1) Formation of highly reduced volatiles such as H_2, CO, CH_4, NH_3 and even HCN through water-rock interaction between wall rocks and inflow of surface water into the caves with the help of ionizing radiation by natural nuclear reactor, in spite of oxidized atmospheric composition of the surface environment (Fig. 5). (2) The reduced gasses generated are concentrated on the ceilings of geyser cave, which maintains the reduced local environment. (3) With the flow of water into geyser cave, reduced gas, high energy particles, intermediate activated organic matters, and other products react among one another through ionizing radiation to form more complex organic compounds, such as amino-acids and peptides can be progressing with increasing distance from the natural reactor. (4) Periodic splash of geyser system caused by phase change of water/vapor 1:1000, brings BBLs to the surface to be exposed to oxidizing environment. (5) In a small lake on the surface (Darwin's warm little ponds), wet-dry cycle would polymerize amino-acids to proteins and finally to RNA or form membranes through evaporation by strong tidal forces. The most fruitful water-site for life forms was lacustrine environment on primordial continent, such as lakes, rivers, wet lands like swamps (Monnard and Deamer, 2002), which was provided through global hydrological cycle driven by climate system (Maruyama et al., 2013). The materials produced on the surface oxidized environment are then brought down into the geyser cave again in the process of material circulation. (6) Inside of geyser lacks high-temperature condition above 100 °C, because of periodic eruption of boiling water and vapor. Therefore, nuclear geyser system would prevent the synthesized RNA and DNA from being destroyed, which provides unique characteristics as a birthplace. Also, periodic splashing sustains cyclic nature within the nuclear geyser system, which can be advantageous to change the water chemistry, because solubility of inorganic ions, anions and organics depends on temperature. This would help the evolution from RNA to DNA world.

Generally, it is assumed that life cannot live with radiation because the decay of U^{235} has been regarded to be deadly for life, although there are many radio-resistant bacteria even on modern Earth, such as *Deinococcus radiodurans* (Makarova et al., 2001; Rothschild and Mancinelli, 2001; Ishino and Narumi, 2015). The recently discovered bacteria, *Rubrobacter radiotolerans* can survive under 4000 times stronger radiation than the lethal level of human being, that is 400 times stronger than the critical level of Bacillus coli (Saito, 2007). Its resistance level is twice than that of *D. radiodurans*. The presence of this kind of life suggests that life has experienced radioactive environment and produced the survival program in DNA.

Nuclear Geyser model is the first proposal which combines radiation physics, geological validity on Hadean Earth, and the birth of life with a coherent explanation of its process from inorganic to first life. At present, nuclear geyser model has no rebuttal evidences with the listed nine requirements (Table 2), although further investigations in future might lead to the refinement or rebuttal of this model.

5. Discussion

5.1. Significance of chemical oversaturation in the incubator as a cradle of life

Each of the listed requirements in Table 2 is significant when we discuss the emergence of the first life. If even one of the requirements cannot be satisfied, life would not commence on Earth. However, in addition to meeting all the nine conditions, there is another important collateral condition to be emphasized, which is chemically oversaturated condition For example, although the presence of a reducing gas, such as H_2 and HCN, is a necessary requirement, its mere presence is not sufficient. The reducing gas must be concentrated in order to form organic molecules. Presence itself cannot lead to the emergence of life, thus, the incubator of the first life needs to provide chemically oversaturated conditions. The same principle can be applied to water-rock interactions. The wall

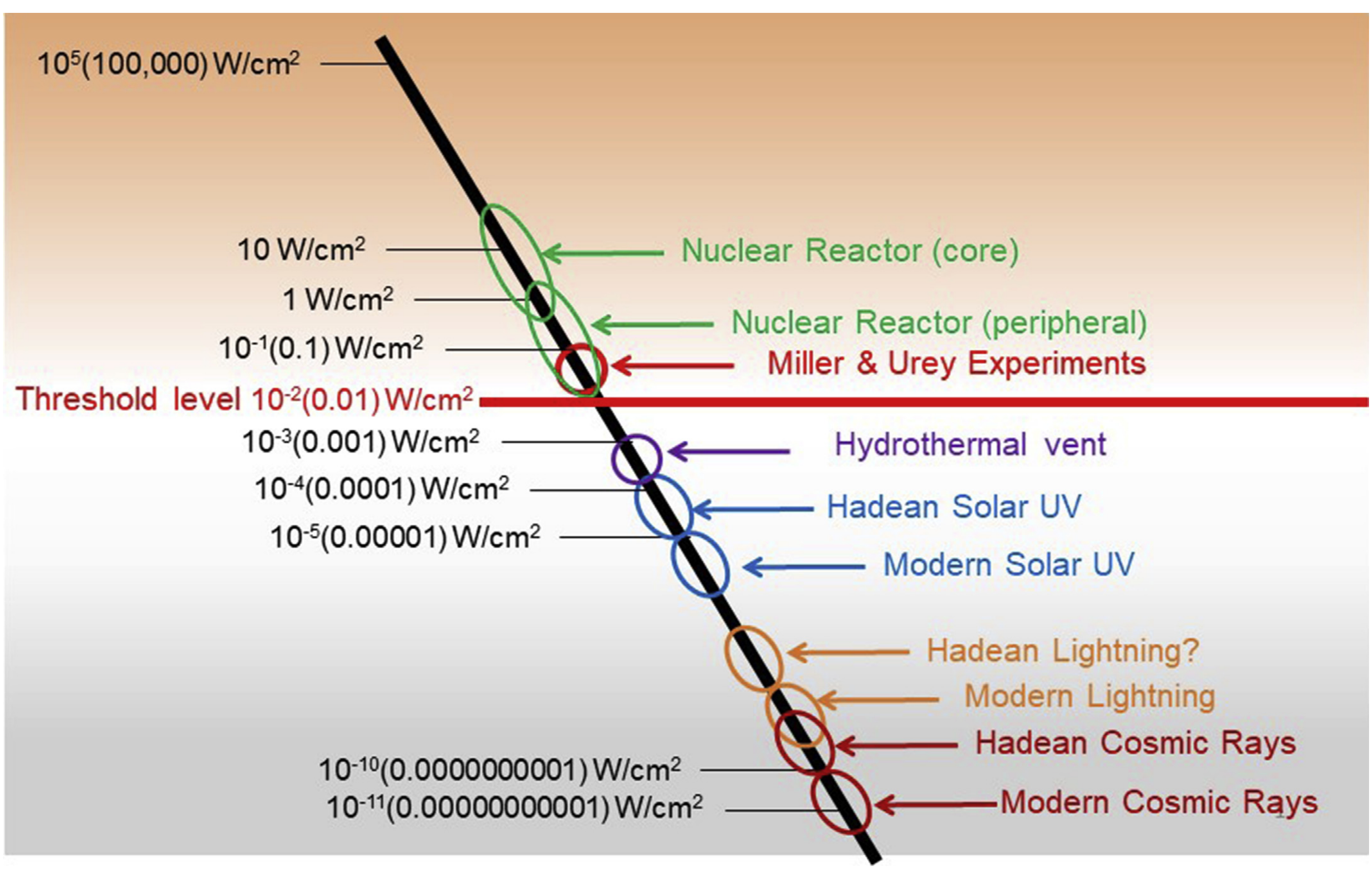

Figure 13. Energy densities and the threshold value needed to resolve the energy uphill problem for the origin of life. The horizontal bold red line is the threshold value. Note that the energy level from the Hadean and modern Sun is insufficient to overcome the energy uphill problem (the activation energy).

rocks of the inner geyser system, such as anorthosite, komatiite and KREEP basalts, would also have various kinds of secondary minerals because of water-rock interactions. For example, magnetite, Fe–Ni alloys, pentlandite, brucite, serpentine minerals, and pyrite are secondary minerals that form in serpentinite: Fe-S, (Zn, Fe)S, MoS, PbS, and TiO_2 form in KREEP basalt; and carbonates and Ca–Al silicates form in anorthosite. These minerals play a role as catalytic minerals that produce metallic proteins and enzymes to polymerize more complex BBLs. However, to yield these secondary minerals from their host rocks (serpentinite, KREEP basalts, and anorthosite), they must contain the necessary components at greater than thermodynamically oversaturated levels through water-rock interaction. The mere presence of these components of the secondary minerals in the host rocks is not sufficient, and oversaturation is required.

5.2. Debate on the birthplace of life: conditions for life's birth differ from those of its evolution

What we need to emphasize here is that the conditions for the birth of life are different from those of its subsequent evolution. In other words, the nine requirements listed in Table 2 are not necessarily met in life's evolutional stage. Once life was initiated with necessary functions such as metabolism, membrane, and self-replication, the situation is quite different. The emergent life would then be able to survive through adaptive evolution even in extreme environments like a MOR hydrothermal vent. Significant point is to distinguish the origin and the evolution when we discuss life. "The origin of life" is the research for creation of life from abiotic substance, while "the evolution of life" is to discuss that how life could adapt to different environmental conditions including changes in ecosystem. Therefore, nine requirements proposed in this paper is only applicable to the point of origin, not to the evolutional stage.

In addition, the site to meet all nine requirements is in very rare circumstances even on Hadean earth. Probably both geysers and uranium ores are ubiquitous in Hadean as we stated in earlier section. However, it is not easy to clear listed conditions one by one. Even if geyser could be combined with uranium ore as a natural reactor, it will be another difficult condition to have necessary Hadean rocks within a nuclear geyser to form necessary BBLs. Also, it could be difficult to have an ideal underground space to promote prebiotic chemical reactions with suitable material circulation. These collateral environmental conditions make the birthplace more complicated. Considering these difficulties, the places that meets all the nine requirements cannot be many. It might be only one site on the Earth.

Generally, it has been vaguely considered that the first life was born everywhere on the Hadean Earth if the conditions are right; specifically, the presence of water and reduced atmosphere. The aim of this paper is to point out that there are more requirements to satisfy the birthplace of life, and the birthplace could be only one point on an entire Earth, like the origin of human being along the African Rift Valley.

5.3. New tree of life derived from geology: what is life living around Hadean hydrothermal vent at mid-oceanic ridge?

In the Hadean, plate tectonics destroyed all primordial continents and carried them into deeper mantle by tectonic erosion with time (Maruyama et al., 2013; Maruyama and Ebisuzaki, 2017). As a result, Hadean continents as mother of life must have disappeared from the surface, whereas a number of intra-oceanic island arcs began forming. Primitive life lost the place to live due to disappearance of almost all continent by the end of Hadean at 4.0 Ga. Very limited species could survive on small island arcs. On the other hand, some life is assumed to have adapted to the deep oceanic environment at the spreading ocean.

From such Hadean history based on geological evidence, in addition to phylogenic tree derived from biology, we propose a new tree of life. As stated in a previous section, the key to the origin and evolution of life is the environmental change. In other words, an environment controls both origin and evolution, which is also noted by Charles Darwin; "no environmental change, no evolution". Considering the tree of life based on environmental constraints, tree should reflect the habitat of life in terms of increasing pO_2 through time.

Fig. 14 shows such a new tree of life. First prokaryote, evolved from proto-life was regarded to be born on land centering on nuclear geyser system. With time, they migrated to other sites on the Earth and evolve to adapt different environmental condition. Some of them remained on land, where the situation was significantly tough due to loss of primordial continent and exposed to outer space of the Earth to suffer from the influx of UV and GCR. Such life should have gone through dramatic evolutionary process to survive. On the other hand, some other species migrated into hydrothermal vent which is quite stable and unchanging environment through time. The bottom of ocean is protected from UV, GCR, or environmental changes caused by geologic activities.

However, as we explained, Hadean ocean was too toxic and life could not survive in such environment. If so, how life could come to live in deep sea hydrothermal vent? The key is life cycle of mid-oceanic ridge as schematically shown in Fig. 15. Initially, mid-oceanic ridge appears on land, like African Rift Valley (Fig. 15a and d). In other word, it is not "mid-oceanic ridge", but the rift on the continent. Rift is formed through the upwelling of mantle plumes. Curtain-like upwelling is generated by the connection of two plumes rising from 410 km depth of upper mantle, where decompression melting through mantle upwelling provides magma in divergent region to cause the ridge push force. This is the process to form the rift on the continent (Fig. 15a and d). Continuous uplifting and supply of magma forms larger rift system where a number of normal faults develop, and chasm spreads and expands to both sides of the axis of the rift (Fig. 15b and e). Uplift activity gradually widens and deepens the chasm to fill it with clear water by rainfall where primitive life could migrate from nuclear geyser region along the ridge axis on the same continent. That life could utilize both magmatic heat energy from the Earth's interior and clean water, then adapt to this environment, which should have been different from geyser environment. With time, the chasm becomes much larger and deeper to result in breaking of continent. Finally, toxic ocean starts to fill the chasm, probably it would start with the mixing between toxic ocean and clean water, then filled by full toxic ocean at the end (Fig. 15c, f, g). However, primitive life, migrated from nuclear geyser system, could survive within hydrothermal vent system where boiled clean water is supplied continuously. In this regard, MOR is very unique site, where gushing boiled clean water is continuously supplied. Through boiling of saline water, relatively dense brine sinks down while fresh boiled water is released from MOR. Therefore, immediate vicinity of MOR provides non-toxic environment in spite of the bottom of a toxic ocean. In addition, MOR is a very stable environment since Hadean time, as opposed to the surface environment which underwent dramatic changes through time, e.g. snowball Earth events in Hadean, gradual or rapid increase in density of atmospheric oxygen, amalgamation and dispersion of continents. Therefore, migrant life in hydrothermal vent did not have to evolve or adapt to changing environment, suggesting the oldest type of life could survive there if they had migrated and adapted there during the Hadean.

In Hadean time, the surface environment was more reducing. Through the evolution of the Earth, environment has gotten

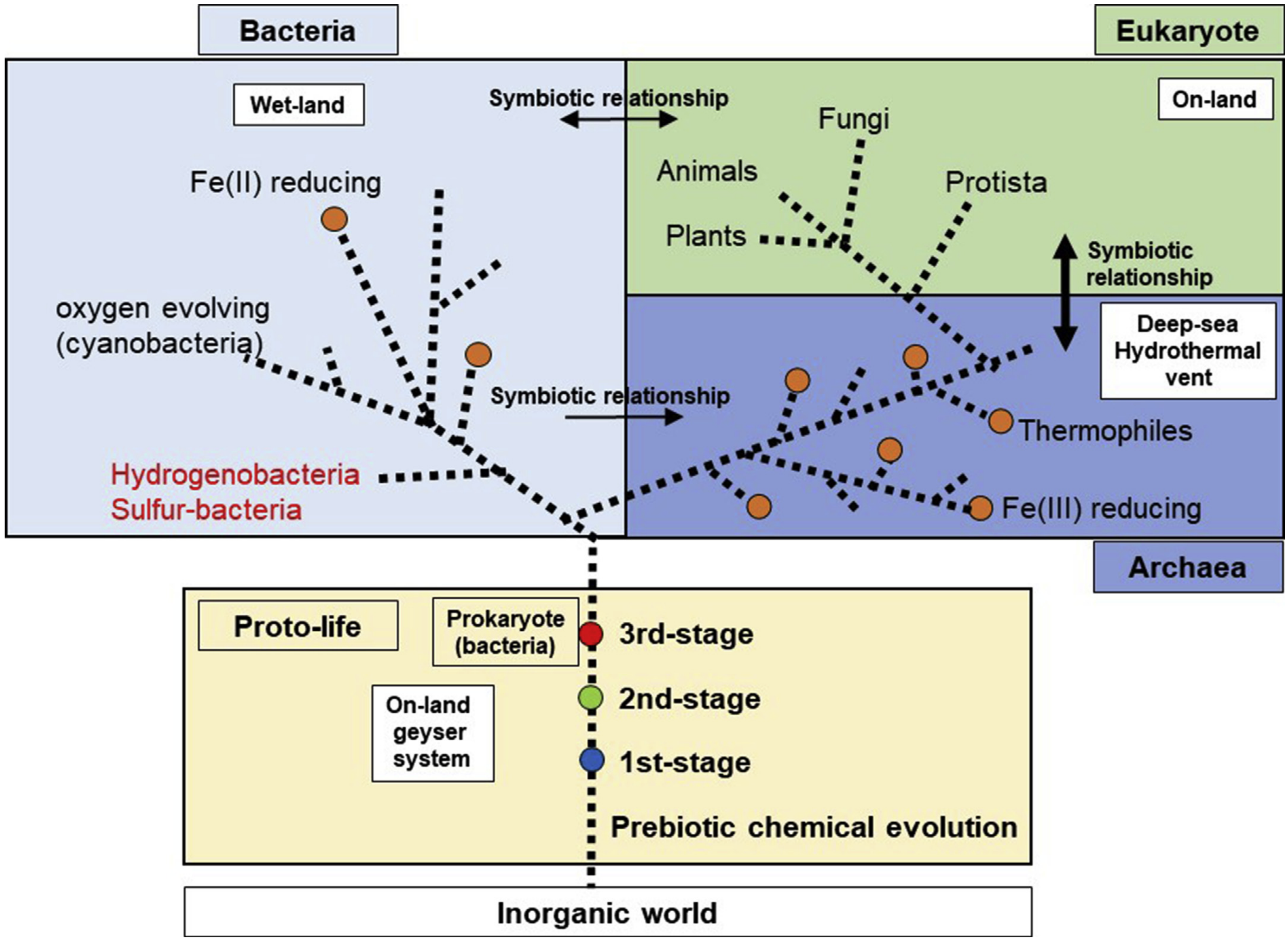

Figure 14. A new tree of life, derived from the combination of geologic perspective and phylogenetic tree of life. First life was born in the nuclear geyser system through three step evolution, and evolved into two domains. One is microbes on-land, the other is microbes in water. On-land microbes were exposed to more severe environment, while microbes in water enjoyed under stable environment.

oxidized, and since 600 Ma, reducing environment has almost lost even in ocean because about 10% of atmospheric oxygen is dissolved into sea water and circulate down to the bottom of the ocean. Therefore, pleasant environment for primitive life do not exist anymore excluding an exception of hydrothermal vents along oceanic transform faults where serpentinization produces H_2 to keep extremely local reducing environment with moderate temperature, like Lost City.

5.4. Role of universe for the origin and evoluton of life on the earth

As another factor to force the environmental change is the change in the outer space, which must be also emphasized here, because birth of life on the Earth may have been strongly influenced by collisions of galaxies. It is already established that snowball events occurred twice in the Earth history which accelerate the evolution of life, e.g. first snowball was at 2.3–2.2 Ga when life evolved from prokaryotes to eukaryotes, and second one was at 0.8–0.5 Ga evolving into metazoas and plants, called the Cambrian explosion. Both events correspond to starburst periods (Fig. 16). Although the records are lost on the Earth, the occurrence of starburst in Hadean time is reported (Rocha-Pinto et al., 2000; de la Fuente Marcos and de la Fuente Marcos, 2004), which suggests snowball state appeared during the birth period of proto-life.

In the past, starburst occurred due to collision of a dwarf-galaxy against our galaxy, generated enormous amounts of galactic cosmic rays to form cloud leading snowball event (Kataoka et al., 2013, 2014). This event extensively affected the earliest evolution of proto-life on the Earth. Frequent oscillation of climate between super-cold (−50 °C) and super-hot (+50 °C), should have caused mass extinction repeatedly (Hoffman and Schrag, 2000, 2002). Close relationship between glaciation and space event has been giving a new insight for mass extinction event. For example, mass extinction occurred in the Phanerozoic, e.g., P/T boundary and K/T boundary, in which new data suggests the collision of Dark Cloud against our solar system. This collisional event led similar climate change as well as the case by starburst, although it might be order of magnitude smaller than the snowball state (Nimura et al., 2016).

5.5. Complex science and falsifiability: significance of working hypothesis to understand origin of life

A proposal of hypothesis is a necessary step in the complexity science, especially for the case that a phenomenon cannot be easily expressed by the combination of formulae. Some workers consider

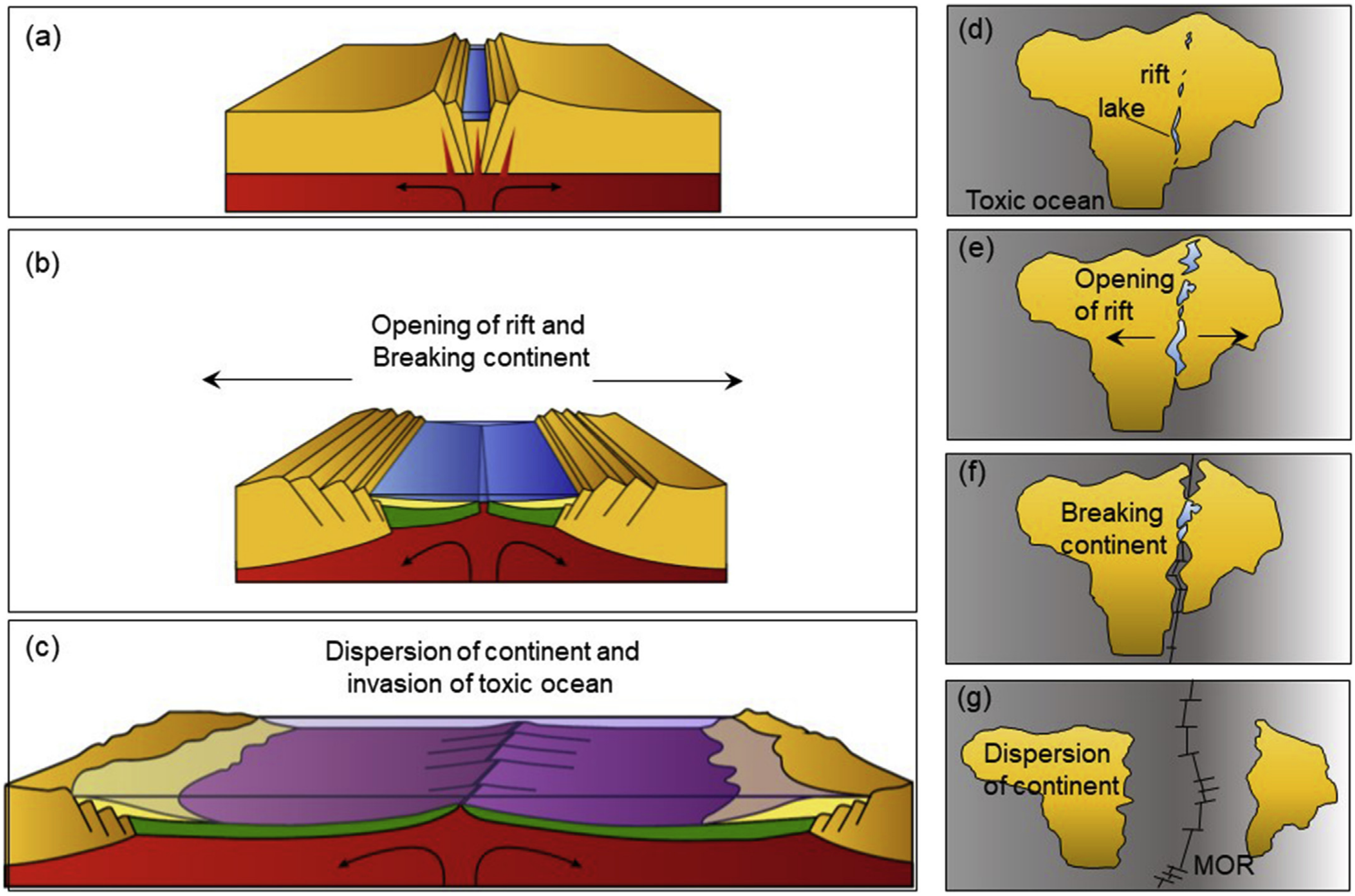

Figure 15. Life cycle of mid-oceanic ridge. (a) A continental rift appears on the land due to the upwelling of mantle plumes. (b) Continuous uplifting and the supply of magma forms larger rift system where a number of normal faults develop. A chasm spreads and expands to both sides of the axis of the rift. (c) Finally a continent breaks off. Hadean toxic ocean fills the chasm. (d) A continental rift appears on the land. Clean water by rainfalls fill the valley. (e) Rift systems widens and water fill in the valley. (f) A continent start to break off. Hadean toxic ocean floods into the valley. (g) A continent completely breaks up. Continental rift turns to mid-oceanic ridge.

that physics can explain all kind of phenomena, however, physics is one of tools to express phenomenon following assumptions. Complexity science represented by biology has numerous parameters, therefore it is impossible to solve a system of equations in biology like in physics or mathematics. To overcome this situation, hypothesis play a critical role to enable us to testify the model. A hypothesis containing rebuttal evidences should be replaced by more reasonable hypothesis, however, this process assists to make the hypothesis more reasonable or get close to the truth.

In order to evaluate the birthplace of life, it is essential to understand and base the arguments on scientific philosophy, specifically in the case of complex and interdisciplinary branches of science like biology and geology. Falsifiability, proposed by Austrian-British science philosopher Karl Popper (1902–1994), is particularly important. Most laws in biology are empirical, based on a number of observations. A number of observations cannot verify universal generalization. For example, there is the statement that “all crows are black” as an empirical law or working hypothesis, however it is not possible to demonstrate to be true, because even if 100th crows are black, the 101st crow can be white; similarly, if 1000th crows are black the 1001st crow can be white. Therefore, “all crows are black” cannot be demonstrated. This is a problem of induction, but this statement can be testified by the discovery of white crow. Such testability, e.g. falsifiability, is critical to distinguish scientific from unscientific. Popper stressed the significance of falsifiability (Popper, 1959). What unfalsifiable is regarded unscientific, then practice to explain unfalsifiable statement, hypothesis, or theory to be scientifically true is pseudoscience.

At present, it is known that the color of crows is controlled by a gene anomaly, and white crows are known as Albino. Like this example, elucidation of mechanism lays the principle to explain various phenomena. Biological science is pivoted on several working hypotheses, and has progressed much to understand the different intriguing phenomena through time. To systematize biology, theory or working hypothesis has to be falsifiable or testable as stated above. Even if hypothesis is gained by induction, falsifiability can gives the way to the authentic achievement to unravel the truth, including the mystery of the origin of life and birthplace of life. When the birthplace of life at MOR was proposed, Miller and Bada (1988) opposed the idea of MOR because of no chance of dry/wet cycle. This is one of the typical examples to improve hypothesis with falsifiability. One negative evidence can deny the hypothesis, which is inevitable process for complex science.

As stated in this paper, geological perspective will be more powerful tool to unravel the origin and evolution of life. Life evolved to respond to the environmental changes, and environmental evidence is accessible through world geology. Moreover, geological perspective can be applied to other planetary bodies including exo-planets, which will provide the possibility to discuss Astrobiology more in details.

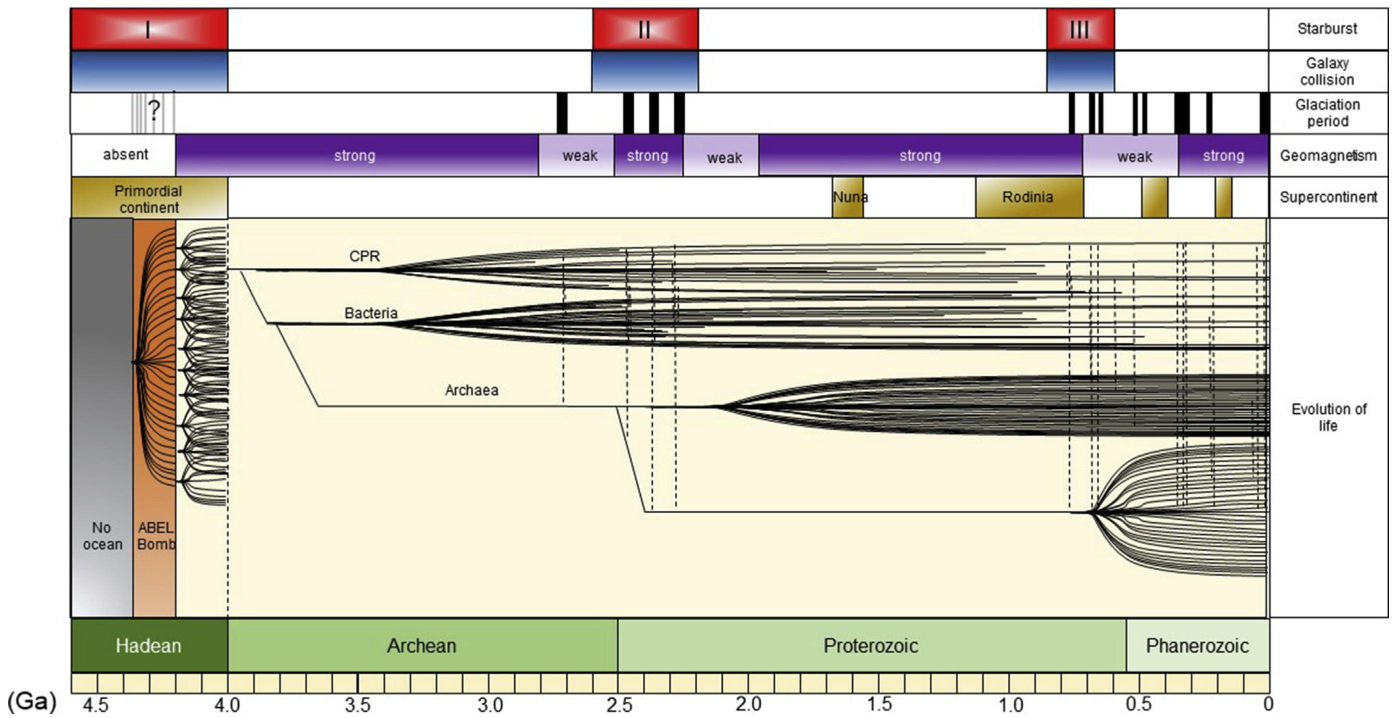

Figure 16. Relationship between events in the universe and the life's origin and evolution. At the top of the chart, three starburst periods caused by galaxy collisions are shown: (I) middle Hadean, (II) 2.3–2.2 Ga, and (III) 0.8–0.5 Ga in our Milky-Way Galaxy. Starburst causes Snowball periods to cause rapid evolution of life through extensive mass extinction. Another critical event for life is the state of geomagnetism. Strong geomagnetism protects the surface environment for life. If weak geomagnetism and universal event is combined, Earth's life is severely affected.

6. Conclusion

From a comprehensive review of previous research on the origin of life and birthplace of life, we picked up nine requirements to be fulfilled for the birthplace of life: (1) an energy source (ionizing radiation and thermal energy); (2) a supply of nutrients (P, K, REE, etc.); (3) a supply of life-constituting major elements; (4) a high concentration of reduced gases such as CH_4, HCN and NH_3; (5) dry-wet cycles to create membranes and polymerize RNA; (6) a non-toxic aqueous environment; (7) Na-poor water; (8) highly diversified environments, and (9) cyclic conditions, such as day-to-night, hot-to-cold etc.

Based on these nine requirements, we evaluated previously proposed hypotheses for the birth place of life such as a deep-sea hydrothermal system, Neo-panspermia model, and others. We propose that Nuclear Geyser model is the most plausible scenario as a birthplace of first life. Geyser system combined with uranium ore as a natural nuclear reactor could produce necessary material to form life through ionizing radiation and material circulation.

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