Geoscience Frontiers 4 (2013) 141–165

Contents lists available at SciVerse ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

GSF Focus

The naked planet Earth: Most essential pre-requisite for the origin and evolution of life

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ARTICLE INFO

Article history:
Received 10 July 2012
Received in revised form
2 November 2012
Accepted 7 November 2012
Available online 19 November 2012

Keywords:
Earth
Life
Habitable planet
Initial ocean mass
Metazoan
Nutrients

ABSTRACT

Our blue planet Earth has long been regarded to carry full of nutrients for hosting life since the birth of the planet. Here we speculate the processes that led to the birth of early life on Earth and its aftermath, finally leading to the evolution of metazoans. We evaluate: (1) the source of nutrients, (2) the chemistry of primordial ocean, (3) the initial mass of ocean, and (4) the size of planet. Among the life-building nutrients, phosphorus and potassium play a key role. Only three types of rocks can serve as an adequate source of nutrients: (a) continent-forming TTG (granite), enabling the evolution of primitive life to metazoans; (b) primordial continents carrying anorthosite with KREEP (Potassium, Rare Earth Elements, and Phosphorus) basalts, which is a key to bear life; (c) carbonatite magma, enriched in radiogenic elements such as U and Th, which can cause mutation to speed up evolution and promote the birth of new species in continental rift settings. The second important factor is ocean chemistry. The primordial ocean was extremely acidic (pH = 1–2) and enriched in halogens (Cl, F and others), S, N and metallic elements (Cd, Cu, Zn, and others), inhibiting the birth of life. Plate tectonics cleaned up these elements which interfered with RNA. Blue ocean finally appeared in the Phanerozoic with pH = 7 through extensive interaction with surface continental crust by weathering, erosion and transportation into ocean. The initial ocean mass was also important. The birth of life and aftermath of evolution was possible in the habitable zone with 3–5 km deep ocean which was able to supply sufficient nutrients. Without a huge landmass, nutrients cannot be supplied into the ocean only by ridge-hydrothermal circulation in the Hadean. Finally, the size of the planet plays a crucial role. Cooling of massive planets is less efficient than smaller ones, so that return-flow of seawater into mantle does not occur until central stars finish their main sequence. Due to the suitable size of Earth, the dawn of Phanerozoic witnessed the initiation of return-flow of seawater into the mantle, leading to the emergence of huge landmass above sea-level, and the distribution of nutrients on a global scale. Oxygen pump also played a critical role to keep high-PO_2 in atmosphere since then, leading to the emergence of ozone layer and enabling animals and plants to invade the land.

To satisfy the tight conditions to make the Earth habitable, the formation mechanism of primordial Earth is an important factor. At first, a 'dry Earth' must be made through giant impact, followed by magma ocean to float nutrient-enriched primordial continents (anorthosite + KREEP). Late bombardment from asteroid belt supplied water to make 3–5 km thick ocean, and not from icy meteorites from

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Peer-review under responsibility of China University of Geosciences (Beijing).

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.gsf.2012.11.001

Kuiper belt beyond cool Jupiter. It was essential to meet the above conditions that enabled the Earth as a habitable planet with evolved life forms. The tight constraints that we evaluate for birth and evolution of life on Earth would provide important guidelines for planetary scientists hunting for life in the exo-solar planets.

1. Introduction

The origin of Universe, and the birth and evolution of life on Earth finally leading to the human race constitute important topics in natural science. Since the first successful synthesis of amino acids and related organic compounds by Miller (1953), a number of laboratory experiments have been performed which revealed the importance of catalyzers, role of nutrients, and physical and chemical environments on the primordial Earth to bear life (e.g., Dyson, 1982; Nisbet et al., 1995; Nisbet and Sleep, 2001; Nisbet, 2002; Russell and Arndt, 2005; Russell, 2007).

On the standpoint of planetology, the concept of habitable planet defines it as water-covered, depending on the distance from the central star to the particular planet in the star-planet system. The Earth fits in this framework as only one rocky planet; Mars is frozen, and Venus is too hot for liquid water (Fig. 1). A habitable planet must automatically yield life, which eventually leads into evolved life such as animals in the case of Earth. The hunt for planets outside our solar system (exoplanets), where blue oceans with dense oxygen-bearing atmosphere must be present, is now a frontier area with the speculation that large animals may be surviving on other planets and that such life could be a common phenomenon in the Universe. Our Milky Way Galaxy is composed of 100,000,000,000 stars; among these if 1% of stars acquire planets, presumably more, our Milky Way Galaxy may be full of rocky planets with ocean, and at least more than a few million Earth-like planets can be predicted.

This contribution evaluates the evolution of life on Earth and speculates the scenario of life on other planets, and derives conclusions that contradict the more optimistic views. Our arguments arise from long-term multi-disciplinary research on the origin and history of life on the Earth and the identification of the most critical factors relating to the initial condition of Earth when the planet was born at 4.56 Ga. The most important initial conditions were the size of the planet and a small amount of water contained within only 3–5 km thick ocean; we therefore call the Earth as naked planet in this paper.

2. Nutrients supply: where from?

The key functions for the origin and evolution of life are nutrients and mass of ocean. Life cannot be synthesized under nutrient-free conditions in an atmosphere as shown in the famous experiments of Miller (1953). Life can be considered to comprise three major systems with super-molecules (molecular number as large as 10^9) enclosed by membrane (Fig. 2). These three components are C (carbon)-centered sugar for fuel, P (phosphorous)-centered metabolism, and N (nitrogen)-centered information coding by basic pairs (DNA). For life to function, these three components are critical. Among these, P (negative ion) is a centered nutrient, which, coupled

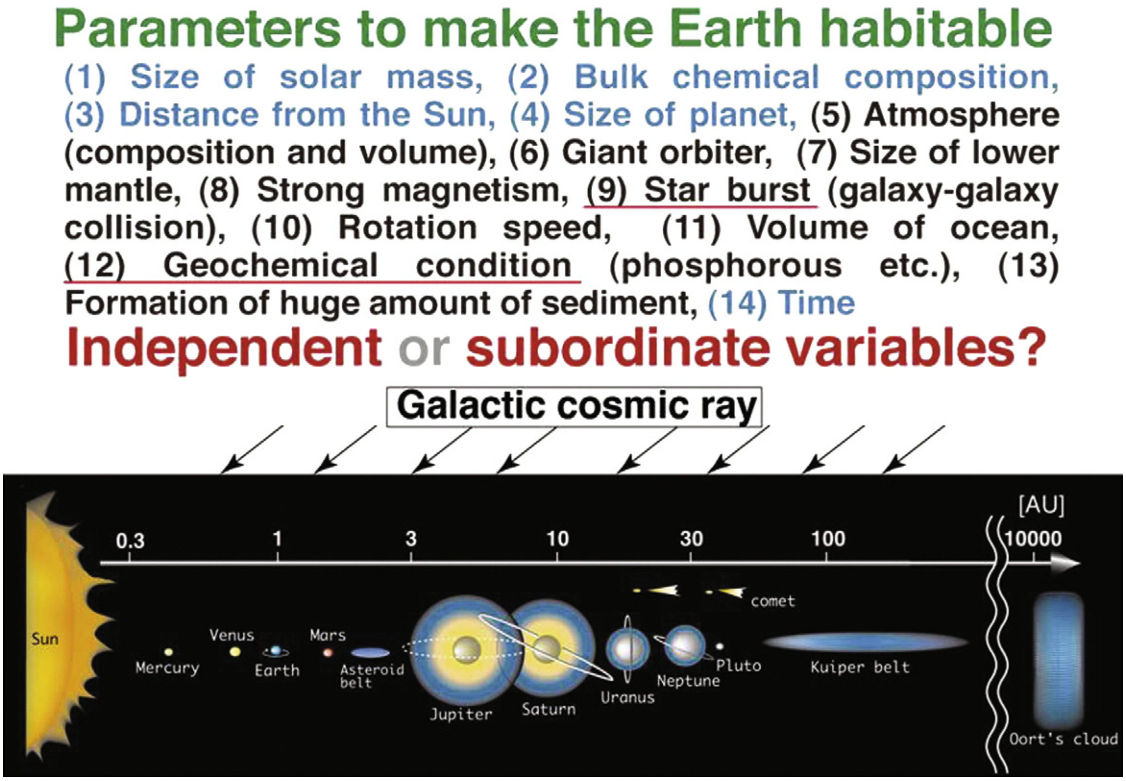

Figure 1. Habitable planets as a function of distance from the central star, Sun, in our solar system. The upper portion shows the parameters to make the Earth habitable. Fourteen major parameters are identified. Note that all of these are not independent functions.

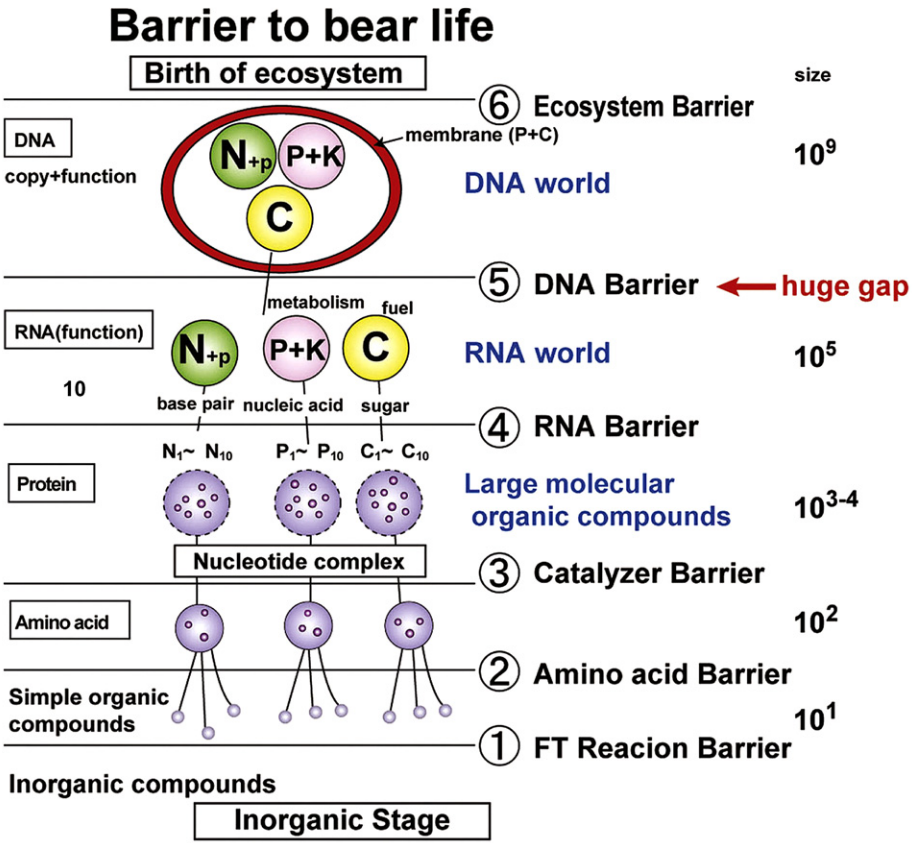

Figure 2. Barrier to bear life. Six barriers are shown in relation to the size of molecule. The largest barrier is No. 5 which is a transition from RNA world to DNA world. The last barrier is the birth of ecosystem.

with K (positive ion), plays a critical role of metabolism, spending sugar. Even in the most primitive cyanobacteria and bachills, P, K and other nutrients are essential components, in addition to C, H, O and N. These nutrients are remarkably different in concentration in different rock species.

3. Source rocks of nutrients

The potential role of nutrients leads to the question of the source of these nutrients. Was there adequate nutrient supply when the primordial ocean was born at 4.5 Ga, and does it continue in the same style even today? The answer is no. Nutrients are continuously supplied from continents by weathering, erosion, and transportation into ocean on the surface of the present Earth, or by the hydrothermal circulation through rock bodies by steady-state supply of magma underneath. Without continuous nutrient supply, life cannot survive at any place on habitable planets. Are these nutrients ubiquitously present, can they be derived from any kinds of rocks on the Earth? Again the answer is no. Life-supporting nutrients are restricted to only three-kinds of rocks: (1) granite, (2) primordial continents (anorthosite with KREEP basalts, dikes and gabbro as lower mafic crust), and (3) carbonatite. Nutrients such as P, K, Ca, Fe and others were derived from final residual liquids after the consolidation of magma ocean at 4.6–4.5 Ga (Table 1) (Anders and Grevesse, 1989; Imai et al., 1995; McDonough and Sun, 1995; Warren, 2003; Workman and Hart, 2005; Keller and Zaitsev, 2006; Kervyn et al., 2008).

3.1. Nutrients: granite

Granite can be formed by two-step extractions of nutrients: first by partial melting of mantle peridotite at mid-oceanic ridge followed by partial melting at subduction zone, either by slab melting, or re-melting of lower mafic crust generated by partial melting of mantle wedge. The major nutrient elements, such as P and K are large ion lithophile elements (LILE) and hence difficult to be bound into major mantle minerals. Plate tectonics increases the volume of calc-alkaline rocks such as TTG (tonalite-trondhjemite-granodiorite) or andesite and dacite at subduction zones through time. TTG crust, the major resource of nutrients on the modern Earth, was nearly absent in the early Earth.

3.2. Nutrients: anorthosite + KREEP

Granitic rock was absent when magma ocean was consolidated at 4.5 Ga on the Moon. Even in the Hadean time (4.6–4.0 Ga) on the Earth, granitic rock was extremely minor, because it takes time to generate granitic magma at the consuming plate boundary and accumulate granitic rocks. Hence, in the Hadean, the major rock unit for nutrient supply was not granitic rock, and was presumably the primordial continents.

Primordial continent is the second candidate for the supply of nutrients. We have no remnants of those continents on the modern Earth (no Hadean rocks are present). Our understanding of the primordial continent is developed from the geology of the Moon, and also from the concept of giant impact. The surface of Moon is covered by 50–70 km thick anorthositic crust with local cover and dikes of KREEP (Potassium, Rare Earth Elements, and Phosphorus) basalt composition, and presumably underplated by KREEP-like rock types beneath the anorthositic continent. Both rock units have been interpreted as the final residue of magma ocean when the Moon was formed by the giant impact that led to the formation of the early Earth (e.g., Canup, 2004), where Mars-sized

Table 1

Chemical composition of CI chondrite, PUM (primitive upper mantle), DMM (depleted mantle peridotite), N-MORB, Japanese andesite and granite (TTG), carbonatite (Oldoinyo Lengai, African rift valley), lunar highland regolith and lunar KREEP. Note the different abundance of nutrients particularly P, K, Mo and U.

Element (ppm)	CI chondrite	Primitive upper mantle	Depleted MORB mantle	N-MORB			Japanese andesites			Japanese granites			Oldoinyo Lengai carbonatites		Lunar highland regolith (avg.)	High-K KREEP (estimated)
				North Atlantic	Pacific	Indian	JA-1	JA-2	JA-3	JG-1	JG-2	JG-3	2006 lava	2000 lava		
Li	1.5	1.6					10.8	27.3	14.5	86.6	42.2	20.9				40
Be	0.025	0.068					0.5	2.05	0.8	3.15	3.26	1.6				
B	0.87	0.3					21	20.7	24.8	6.87	1.78	2.15				
C	34500	120					271	141	61	216	35	120	87709	83345		
N	3180	2														
F	60.7	25					161	223	286	498	972	317	28200	30300		
Na	5000	2670	964	16721	20371	21521	28487	23072	23665	25075	26262	29377	229826	242882	2893	7000
Mg	98900	228000	233571	49488	46196	47746	9468	45834	22434	4463	223	10795	2473	2593	34375	50000
Al	8680	23500	21063	79331	79331	81289	80548	81554	82348	75362	65995	81924	2064	0.00	142362	80000
Si	106400	210000	209004	231956	234621	242054	299038	263744	291091	337978	359154	314558	6918	1075	209892	235000
P	1220	90	82.9	755	694	864	720	637	506	432	8.73	532	4495	3273		3500
S	62500	250					21.6	8.00	214	10.9	7.00	54.7	7009	11215		
Cl	704	17					43.0			58.1		156	17300	41200		
K	558	240	49.8	772	1063	772	6392	15026	11705	33040	39100	21916	56118	68902	700	8000
Ca	9280	25300	22656	83262	83834	81118	40738	44954	44597	15723	5003	26372	126072	107990	111492	70000
Sc	5.82	16.2		41.1	39.9		28.5	19.6	22.0	6.53	2.42	8.76			10	23
Ti	436	1205	779	7522	9781	8019	5094	3956	4195	1558	264	2877	240	120	2218	12000
V	56.5	82		301	324		105	126	169	25.2	3.78	70.1	133	189	23	40
Cr	2660	2625	3900	308	266		7.83	436	66.2	53.2	6.37	22.4			760	1200
Mn	1990	1045	1007	1471	1502	1169	1216	836	805	488	124	550	2943	3640	560	1050
Fe	190400	62600	63584	85815	80297	69134	49450	43435	46163	15248	6785	25809	6575	3078	32423	80000
Co	502	105					12.3	29.5	21.1	4.06	3.62	11.7			20.6	25
Ni	11000	1960	1886	121.2	94.08		3.49	130	32.2	7.47	4.35	14.3			247	
Cu	126	30		87.4	84.35		43	29.7	43.4	2.52	0.49	6.81				
Zn	312	55					90.9	64.7	67.7	41.1	13.6	46.5		80	13	
Ga	10	4					16.7	16.9	16.3	17.8	18.6	17.1			4.8	9
Ge	32.7	1.1					1.33	1.05		1.44	1.7	1.06				
As	1.86	0.05					2.78	0.85	4.68	0.33	0.68	0.37				
Se	18.6	0.075					0.0088			0.003						
Br	3.57	0.05								0.068						120
Rb	2.3	0.6	0.05	1.325	3.765	0.86	12.3	72.9	36.7	182	301	67.3	143	195		22
Sr	7.8	19.9	7.664	97.65	124.8	116.1	263	248	287	184	17.9	379	10650	12346	149	200
Y	1.56	4.3	3.328	30.68	36.72	29.9	30.6	18.3	21.2	30.6	86.5	17.3	11	8		400
Zr	3.94	10.5	5.082	83.51	111.9	86.5	88.3	116	118	111	97.6	144	0	1.3	113	1400
Nb	0.246	0.658	0.1485		4.181	1.711	1.85	9.47	3.41	12.4	14.7	5.88	70	30		100
Mo	0.928	0.05	0.0096				1.59	0.6	1.89	1.75	0.37	0.45				
Ru	0.712	0.005														
Rh	0.134	0.0009														
Pd	0.56	0.0039					0.0002	0.0005	0.001	0.0002	0.0002	0.0002				
Ag	0.199	0.008					0.033	0.043	0.084	0.034	0.019	0.029				
Cd	0.686	0.04					0.11	0.078	0.089	0.04	0.004	0.054				
In	0.08	0.011					0.0494			0.044	0.021					
Sn	1.72	0.13					1.16	1.68	0.95	3.6	3	1.4				
Sb	0.142	0.0055					0.22	0.14	0.32	0.13	0.057	0.08				
Te	2.32	0.012														
I	0.433	0.01					0.015	0.005		0.012						
Cs	0.187	0.021		0.017	0.06	0.01	0.62	4.63	2.08	10.1	6.79	1.78		4.5	123	1000
Ba	2.34	6.6	0.563	12.61	18.3	10.16	311	321	323	466	81	466	8845	13793	100	1300
La	0.2347	0.648	0.192	3.284	2.886	2.667	5.24	15.8	9.33	22.4	19.9	20.6	418	646	7.87	110
Ce	0.6032	1.675	0.55	7.371	10.4	8.367	13.3	32.7	22.8	45.8	48.3	40.3	769	790	19.9	280
Pr	0.0891	0.254	0.107			1.456	1.71	3.84	2.4	4.83	6.2	4.7		51.1		37
Nd	0.4524	1.25	0.581	6.589	9.118	7.967	10.9	13.9	12.3	19.3	26.4	17.2	122	122	12.2	178

Sm	0.1471	0.406	0.239	2.755	3.21	2.733	3.52	3.11	3.05	4.62	7.78	3.39		7.65	3.34	48
Eu	0.056	0.154	0.096	1.025	1.208	1.021	1.2	0.93	0.82	0.73	0.1	0.9		2.98	0.97	3.3
Gd	0.1966	0.544	0.358	2.858	4.564	3.944	4.36	3.06	2.96	4.28	8.01	2.92		4.86		58
Tb	0.0363	0.099	0.07	0.689	0.736	0.711	0.75	0.44	0.52	0.78	1.62	0.46		0.53	0.71	10
Dy	0.2427	0.674	0.505	3.941	6.566		4.55	2.8	3.01	4.14	10.5	2.59		2.13	4.54	65
Ho	0.0556	0.149	0.115			1.033	0.95	0.5	0.51	0.81	1.67	0.38		0.16		14
Er	0.1589	0.438	0.348	2.657	4.028	3.011	3.04	1.48	1.57	2.16	6.04	1.52		0.49		40
Tm	0.0242	0.068		0.652		0.431	0.47	0.28	0.28	0.41	1.16	0.24		0.04		5.7
Yb	0.1625	0.441	0.365	2.899	3.006	2.811	3.03	1.62	2.16	2.47	6.85	1.77		0.21	2.51	36
Lu	0.0243	0.0675	0.058	0.44	0.411	0.407	0.47	0.27	0.32	0.39	1.22	0.26		0.03	0.37	5
Hf	0.104	0.283	0.157		4.186		2.42	2.86	3.42	3.56	4.73	4.29			2.56	38
Ta	0.0142	0.037			0.077		0.13	0.8	0.27	1.79	2.76	0.7			0.31	5
W	0.0926	0.029					0.34	0.99	8.07	1.58	23	14.1				3
Re	0.0365	0.00028					0.00045	0.000063	0.00065	0.000098	0.000016	0.000033				
Os	0.486	0.0034													11.3	
Ir	0.481	0.0032					0.0000028	0.000013	0.000014		0.000004	0.0000016			10.1	
Pt	0.99	0.0071					0.0005	0.0013	0.0017	0.0005	0.0005	0.0005				
Au	0.14	0.001					0.00016	0.00026	0.00095	0.00011	0.000059	0.00017			5.2	
Hg	0.258	0.01					0.0117	0.0018	0.0019	0.0165	0.0033	0.0024				
Tl	0.142	0.0035					0.13	0.32	0.23	1.03	1.55	0.4				
Pb	2.47	0.15	0.018		1.879	0.397	6.55	19.2	7.7	25.4	31.5	11.7	92	69.3		
Bi	0.114	0.0025					0.0091	0.07	0.05	0.5	0.64	0.05				
Th	0.0294	0.0795	0.0079		0.18	0.168	0.82	5.03	3.25	13.2	31.6	8.28	6	5.62	1.27	22
U	0.0081	0.0203	0.0032		0.165	0.039	0.34	2.21	1.18	3.47	11.3	2.21	10	13.6	0.4	6.1
Data source	[a]	[b]	[c]	[d]	[d]	[d]	[e]	[e]	[e]	[e]	[e]	[e]	[f]	[g]	[h]	[h]

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[a] Anders and Grevesse, 1989.

[b] McDonough and Sun, 1995.

[c] Workman and Hart, 2005.

[d] The website for Earth Science reference data and models (http://earthref.org/).

[e] Imai et al., 1995.

[f] Kervyn et al., 2008.

[g] Keller and Zaitsev, 2006.

[h] Warren, 2003.

protoplanets collided with each other (e.g., Chambers and Wetherill, 1998; Genda et al., 2012). If the giant impact theory is correct, the Earth must have been completely molten even up to the core (Tonks and Melosh, 1992). During the gradual cooling of the Moon and the Earth, the final liquid remained near the surface forming the buoyant anorthositic crust, covered or underplated by KREEP magma similar to that observed on the Moon. If this scenario is correct, the Earth must have produced primordial continents that are similar in composition, and presumably similar in ratio as in the case of Moon. However, there is no direct evidence on the modern Earth for the presence of primordial continents on the surface at present. It should therefore be inferred that the primordial continents must have subducted and sunk into deep mantle during the Hadean time. If the primordial continent was present on the Hadean Earth, nutrients could be supplied to the site of the birthplace of life.

3.3. Nutrients: carbonatite

Host rocks of nutrients must have exerted a significant control on the evolution of life. Only specific rock type can contribute adequate nutrients required to feed life. Nutrients which are critical to generate and sustain life on the Earth are highly concentrated only in the final residue of the total melting of the Earth. In case of primordial continents, these were formed in a short time during the consolidation of magma ocean at 4.6–4.5 Ga. However, granite formation took a long time in geological scale, through the operation of plate tectonics. Successive concentration of nutrients by two-step processes involving the partial melting of mantle peridotite followed by basalt melting are necessary for the formation of granite. It took over 4.0 Ga to generate the modern size of continental crust.

However, in case of carbonatite, there is only a single step fractional melting of mantle peridotites under the cratons with extremely small degree of melting. The selective removal of melt to form considerable amounts of nutrients under the sub-cratonic mantle creates carbonatite magma enriched in nutrients (Table 1) with highly volatile incompatible elements such as H_2O and CO_2 (more than 80% are volatiles) (Kervyn et al., 2008). Nutrients concentrate into melt, depending on the degree of melting. Peridotite contains $P = 50$ and $K = 240$ (all values in ppm hereafter), but 100 times concentration of $P = 3273–4495$ and 200–300 times of $K = 56118–68902$ are seen in carbonatite. In general, the nutrient abundance is ideal for carbonatite, except for the U abundance. Compared to $U = 0.0203$ in peridotite, carbonatite contains 500 times ($U = 10–13.6$ ppm; Table 1). Carbonatite plays the role of milk-like materials to grow life. However, it may also function like atomic bomb magma to cause local mass extinction, and resultant promotion of genome mutation by internal radiation through food chains.

The examples are current hotspots of on-going speciation of Cichlids (fish) in the Lake Victoria of Tanzania along African Rift Valley, and presumably on Galapagos islands where nutrients are brought by strongly alkaline rocks by hotspot magmas. At 7–6 Ma, our ancestor of human-being was born in African Rift Valley, and evolved there rapidly, presumably due to genome instability through radiation as suggested by Dubrova (2006). Gene diversity among our *Homo sapiens* has been measured by Mitochondrial, Autosomal and Y-Chromosome data, and the result indicates the highest variance ratio in Africa in the world (Jorde et al., 2000). This could be well-interpreted by radiation derived from strongly alkaline magma along the rift valley.

In the Archean, due to higher degree of partial melting of mantle peridotite, the formation of carbonatite magmas was not possible, and these rocks appeared only after 2.6 Ga (Woolley, 1987, 1989, 2001). Peridotite and basalt cannot supply all necessary nutrients. Specifically P and K are extremely poor in peridotite. Small amount of $P + K$ is present in mid-oceanic ridge basalt, but not sufficient to yield life at initial stage when $P + K$ must have been saturated in circulating hydrothermal fluids (see Table 1).

3.4. Nutrient-enriched landmass

Even though nutrient-enriched rocks are available on the planet, the nutrients cannot be adequately delivered everywhere. The delivery system of nutrients into the ocean occurs through weathering and erosion, and transportation by rivers. If the ocean was much thicker (e.g., 10 km) than today (3.8 km), no landmass is exposed on the Earth, and hence no nutrient supplies into oceans (Fig. 3). This situation is similar to the case of all “habitable exoplanets” reported so far, with the majority covered by thick hydrosphere, sometimes exceeding 30,000 km. The scenario is similar to Uranus and Neptune which contain a thick ocean (as thick as 19,000 km, Guillot, 1999), covered by ice on the top (Fig. 3). In such a case, it seems impossible to supply nutrients on the surface because of no landmass, and presumably not even at the bottom of the ocean.

3.5. Distribution mechanism of nutrients into ocean

Here we discuss the mechanism of derivation of nutrients from the rocks and their distribution into the ocean, where water–rock interaction is the key. A well-known example is the mid-oceanic ridge-hydrothermal system where seawater penetrates into MORB crust along the cracks at the spreading center. Continuous supply of seawater occurs up to a depth of ca. 2 km; below this depth the temperature rises up leading to the boiling of water and its return to the surface. The down-going seawater extracts nutrients from MORB crust, although here P is nearly absent (e.g., Wheat et al., 2002; Fantle and DePaolo, 2004). Deeply penetrated water returns upwards by boiling at temperatures of about 150 °C transporting nutrients to the surface. The surface manifestation of this hydrothermal system is called black or white smoker (depending on the temperature) and microbial communities have long been described from such environments, and characterized as hyperthermophile archea/bacteria (Stetter, 1996). These microbial ecosystems use chemical energy and not solar radiation.

Another system of nutrient distribution is on the surface of the Earth. If landmass is present, the rock surface would be weathered, eroded, and transported finally into the ocean. This is controlled by climate system through the circulation of water vapor from the equatorial ocean to the polar regions. Through water vapor circulation, the wind erosion of mountain belts leads to the disintegration of rocks; weathering, erosion and transportation results in fine-grained particles of rocks to be transferred to rivers.

The effectiveness of extraction of nutrients from rocks depends on the size of water–rock interface. The net surface of fine-grained particles in sediments must be exponentially large, compared to the hydrothermal ridge system (Fig. 4). Exponentially increasing effectiveness of nutrient extraction by weathering, erosion and transportation into the ocean is critical. A rough estimate of effectiveness, as compared to hydrothermal fracturing system, is 1 million times more effective extraction of nutrients, particularly well balanced nutrient concentration in the case of the surface of the Earth, because granite is the major rock component of continental crust.

3.6. Only two sites of nutrient supply on the modern Earth

The mid-oceanic ridge runs over our globe extending ca. 40,000 km long and ca. 2.5 km below sea-level. The hydrothermal

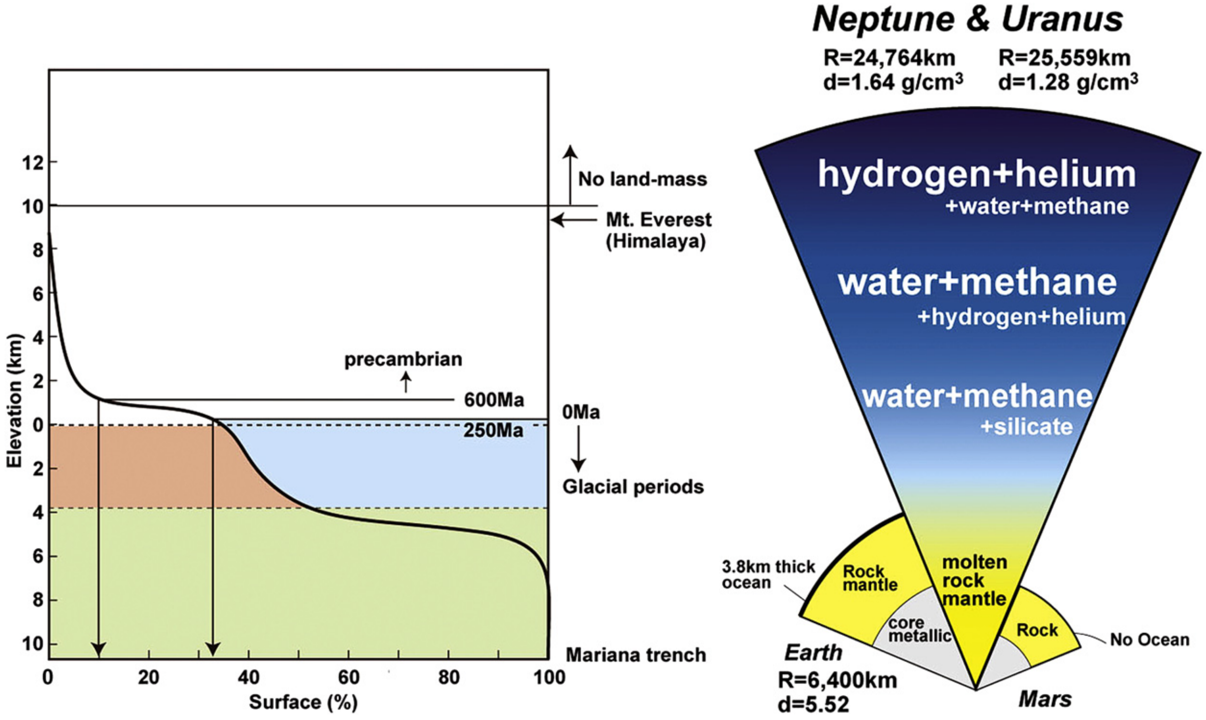


Figure 3. Earth's average topography and mass of ocean (e.g., Maruyama and Liou, 2005). Note the thin film-like nature of Earth's ocean (ca. 3.8 km thick), in comparison with thick oceans in Neptune and Uranus exceeding over 25,000 km with variable phases of ice in superionic state.

system at mid-oceanic ridge is a crucial site of continuous nutrient supply into oceans, and hence characterized by microbial community. The system is stable through the continuous supply of MORB magma underneath. Although minor, an equivalent nutrient supply system is present in hotspots such as Hawaii. The Loihi seamount, the easternmost active submarine volcano in Hawaii, stands immediately above an active hotspot, and shows the presence of microbial community (Glazer and Rouxel, 2009) – in this case, it is not the MORB type. Also, subduction zone volcanoes under the sea such as those in the Mariana arc are alternate candidates. In general, any region where there is circulating water, like cold seep (active hydrothermal circulation) in the fore-arc, is also a possible candidate, but the amount of microbial system is very small.

Compared to the mid-oceanic ridge-hydrothermal system, the surface landmass system is huge in terms of its potential for

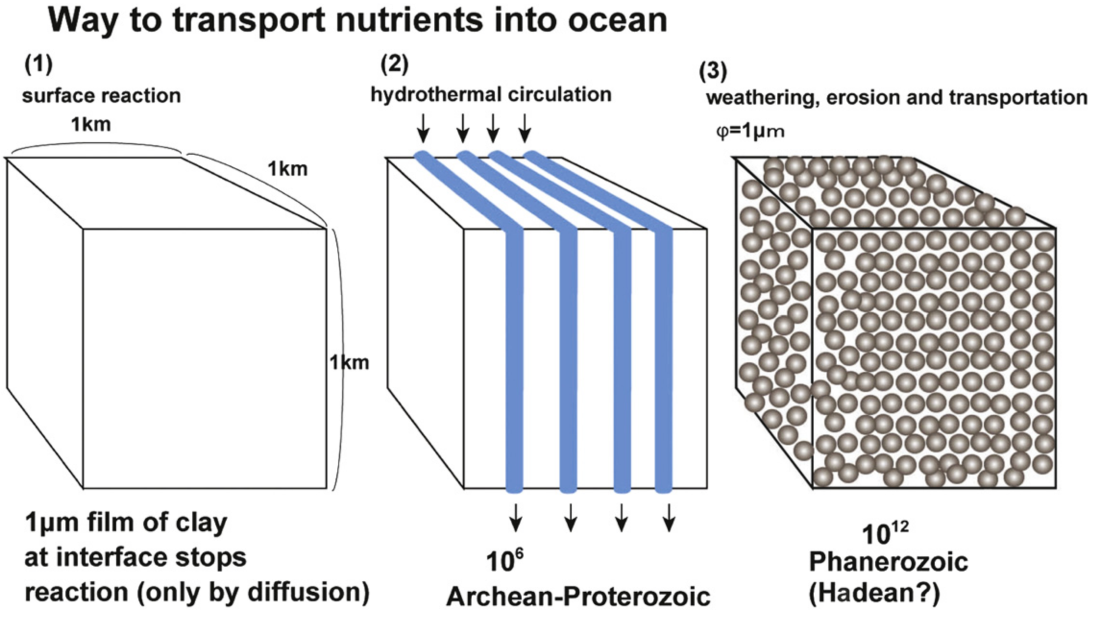


Figure 4. Mechanisms of supply of nutrients into ocean. (1) Surface reaction with rock. (2) Hydrothermal water circulation. (3) Weathering, erosion and transportation into river. A rough comparison of the effectiveness among these is also indicated.

nutrient supply. The driving force of nutrient supply is Sun; if the Sun dies, the surface nutrient delivery system stops, leading to the termination of life (Fig. 5). Considering the stability of nutrient supply in terms of life community survival, the concept of subsurface microbial community does not hold good, because of the absence of steady-state nutrient circulation. The subsurface microbial community at mid-oceanic ridge, hotspot, or arc volcano belongs to the hydrothermal nutrient supply system.

4. Landmass: present in the Hadean, nearly absent in the Archean, minor in the Proterozoic and huge in the Phanerozoic

4.1. Hadean Earth

The presence or absence of landmass can be estimated back to Archean, by the records of sedimentary rocks, particularly the ratio of sandstone and mudstones in a given orogenic belt (Fig. 6). Orogenic belts back to 4.0 Ga have been documented on the Earth (Bowring and Williams, 1999; Wilde et al., 2001; Whitehouse and Kamber, 2002; Iizuka et al., 2007, 2009, 2010). As seen in Fig. 6, thick successions of sedimentary rocks are absent in the Archean (until about 2.5 Ga), with only minor deep-sea hydrothermal cherts as shown by the Archean orogenic belts. A steady increase is recorded toward 2.7 Ga when minor arkosic sandstone started to appear around the embryonic continents (Maruyama et al., 2001, 2007). At the same time, a number of stromatolitic carbonates appeared on the Earth, on all fragmental continents, at least in more than 35 regions over the globe (Windley, 1977, 1984, 1995). This corresponds to the timing of oxygen level increase from $<10^{-3}$ to ca. 10^{-1} PAL (Fig. 7). The final increase up to 1 PAL occurred during the onset of Phanerozoic at 600 Ma.

In the Archean, landmass (which appeared above the sea-level and does not mean whole continental crust) with TTG composition was nearly absent, except for some intra-oceanic arcs such as the 3.8 Ga Isua, West Greenland (Komiya et al., 1999; Nutman et al., 1989, 1993, 1996, 2001), Pilbara, W. Australia (Ohta et al., 1996; Kitajima et al., 2001, 2008; Komiya et al., 2002b), South Africa and other cratons (Maruyama et al., 2007; de Wit et al., 2011). Local unconformity began to appear, accompanying basal conglomerates with TTG crust after 2.7 Ga (Sakurai et al., 2005), and on a much larger scale since 2.1 Ga (e.g., Hoffman, 1988), and thereafter on a global scale in the Phanerozoic (Windley, 1984; Condie et al., 2009).

We have no direct information on the Hadean, because no Hadean rocks remain on the Earth, except 4.4–4.0 Ga zircons <1 mm long in some Proterozoic sedimentary rocks (Bowring and Williams, 1999; Wilde et al., 2001; Whitehouse and Kamber, 2002; Iizuka et al., 2007, 2009, 2010). These Hadean zircons have chemical characteristics (mineral inclusions in zircon and oxygen isotopes) suggesting derivation from TTG magma which provides strong evidence for the operation of plate tectonics back to 4.4 Ga, with the speculation that "No water, no granite, and no plate tectonics" by Campbell and Taylor (1983).

On the other hand, the theoretical concept on the formation of the Moon through giant impact of Mars-sized protoplanet onto Earth-sized planet indicates a total melting of the primordial Earth at 4.5 Ga (Tonks and Melosh, 1992; Ida et al., 1997). During cooling after the giant impact, the primordial continents must have formed presumably in the same style as the 50–70 km thick anorthosite covered Moon's crust, penetrated, or underplated by KREEP basalts

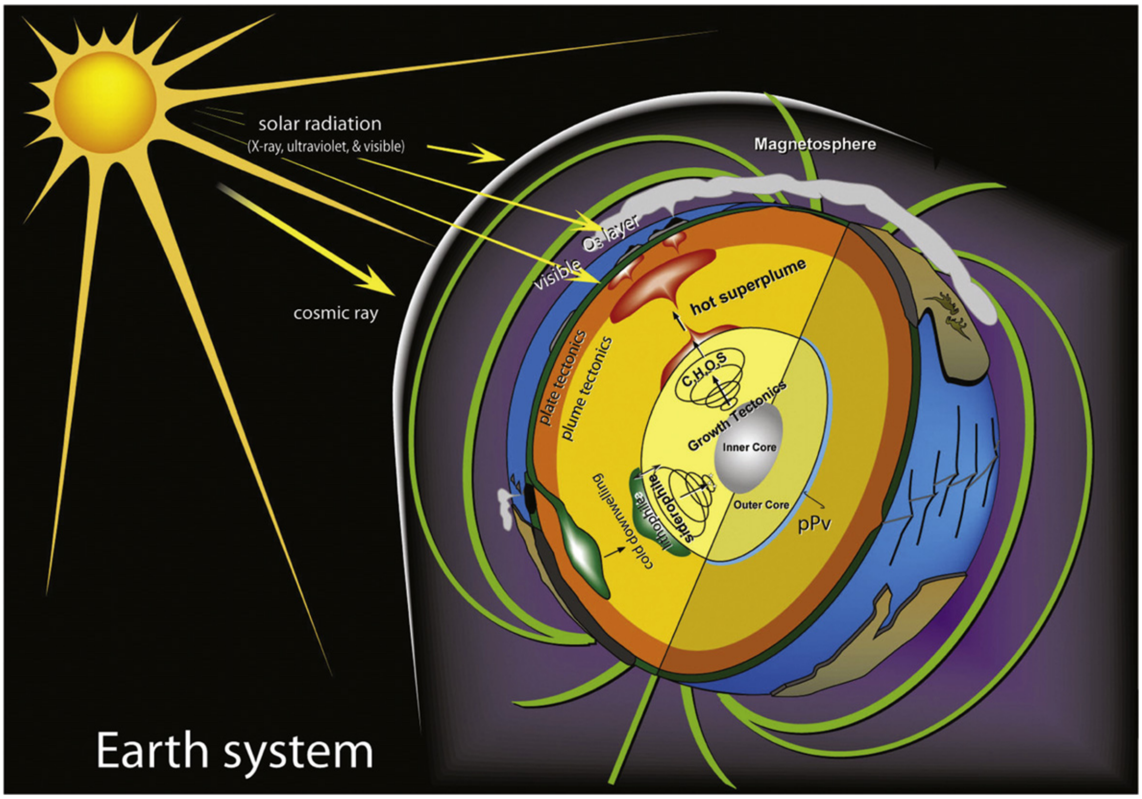


Figure 5. Only two sites of life-survival on the Earth, deep-sea hydrothermal system and the Earth's surface. Note the driving force of circulation, steady-state magma supply underneath mid-oceanic ridge, and Sun's radiation on the surface. Also note that the concept of subsurface microbial community is wrong, because of no steady-state supply of nutrients with water.

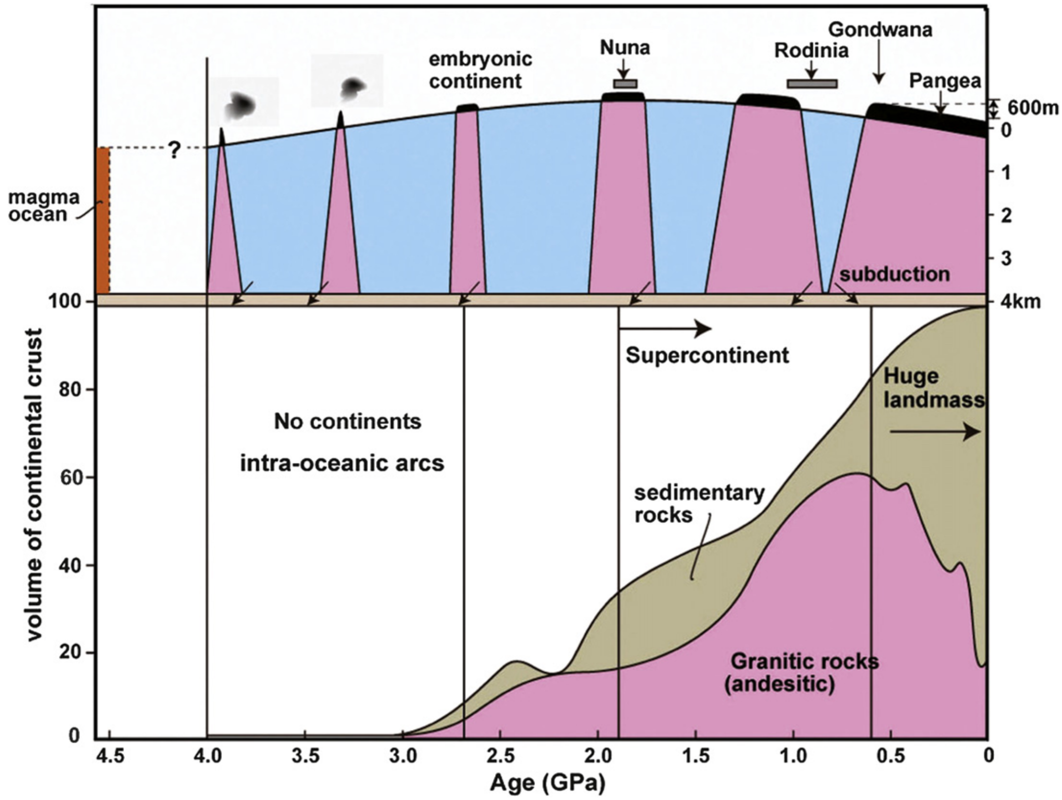


Figure 6. Sedimentary rocks through time (bottom). Growth curve of TTG crust through time is after Rino et al. (2008). The amount of sediments occupying specific orogens is divided based on the ratio of sediments/TTG + greenstone. Top figure shows schematically the relationship between ocean vs arc (Archean), embryonal continents (Proterozoic) and huge continents (Phanerozoic). Sedimentary rocks appeared in abundance predominantly in the Phanerozoic. They were nearly absent in the early 2.0 Ga, when TTG and greenstone with minor deep-sea chert dominated.

which are enriched in nutrients such as P, K, Fe, Ca, Mg and others (Table 1).

For the Earth to bear life in the Hadean, we speculate the presence of primordial continents compositionally same as those on the Moon. Moreover, as suggested by the geological records in Earth since Archean, the ocean volume must be similar to that of today, allowing the landmass to rise above sea-level. For life to appear in the Hadean Earth, it would be necessary to clean-up the poisoned ocean water (2–5 times more saline than today, strongly acidic $\mathrm{pH} = 1–2$, and enriched in heavy metals) by evaporation and rainfall on landmass, aiding in the distribution of nutrients in lakes with clean water (Fig. 8a). We speculate that during Hadean plate tectonics, ridge propagation into primordial continents rifted the KREEP crust, to generate H_2-producing hydrothermal system at depths where komatiitic crust turned to serpentinite by hydration. The formation of magnetite caused hydrogen production and brucite leading to highly alkalic pH (around 12). The birthplace of life could be in a lake hydrothermal system saturated in P and other nutrients (Fig. 8b). The successive ridge propagation would have finally evolved the rifted lake into ocean where the primordial life must have survived to evolve under the severe geochemical environments. Plate tectonics functioned as a geochemical cleaner, transporting the metallic ores generated at the ride to the trench, and dumping them into the mantle by subduction. The growing TTG crust promoted the geochemical filtering of the Hadean ocean.

4.2. Annihilation of host rock body of primordial continents

The earliest life (Ueno, 2011) born on the primordial continents must have lost the mother rock body mostly in the Hadean, although minor remnants were preserved in the Archean. Therefore, the Earth's life survived as an orphan in the Hadean–Archean time. The host primordial continents must have subducted into deep mantle together with oceanic lithosphere in a manner similar to the mechanism of tectonic erosion of hanging wall of the overriding continental plate and/or direct subduction of thin (<20 km) primordial continent defined by the stability field of plagioclase (Kushiro and Fujii, 1977).

If this speculation is valid, then a question arises as to the fate of those primordial continents in the modern mantle on the Earth. Kawai et al. (2009) calculated the density of anorthosite, MORB, harzburgite, pyrolite and TTG along the whole mantle depth, and concluded that anorthosite turns to the densest among all rock types near the bottom of mantle, i.e., in the D" layer, indicating that the anorthosite layer is gravitationally stable in the D" layer if subducted into the bottom mantle. Through the successive phase changes of anorthoclase to high-pressure phases such as grossular garnet, coesite-stishovite in the deep upper mantle, and Ca-perovskite, high-pressure SiO_2 phases and Al_2O_3 phases in the lower mantle, primordial continents would easily subduct into deep mantle, and finally settle down at the bottom of lower mantle (Kawai et al., 2009).

4.3. Archean Earth and thickness of ocean

The thickness of ocean in the past back to Archean cannot be directly measured. However, there are several indirect evidences to constrain the thickness. One of these is the presence of unconformity with basal conglomerate with rounded pebbles of granitic and other rocks derived from on-land exposures. If the unconformity is

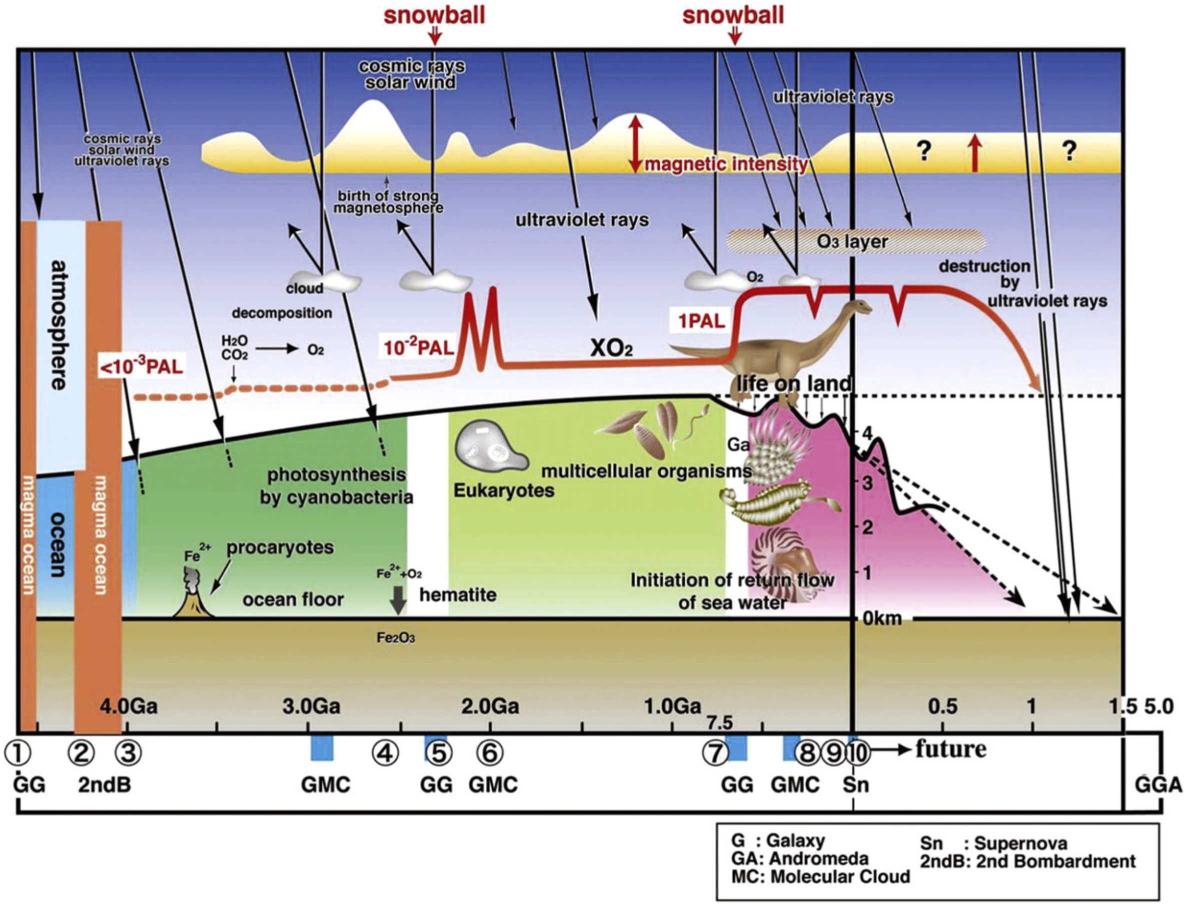


Figure 7. Comprehensive schematic diagram showing secular variations in geological, biological and environmental factors through the history of Earth (modified after Maruyama et al., 2001, 2007).

present over all continents such as in the Phanerozoic Earth at given geologic ages, it provides a strong constraint to estimate a continuous fluctuation of sea-level through time. This is an essential base for the proposed Phanerozoic sea-level change curve (Hallam, 1992). The second aspect is the presence of conglomerate layer even though it occurs within a trench-turbidite unit resting on the top of ocean-plate stratigraphy such as in the 3.8 Ga Isua accretionary complex, West Greenland (Komiya et al., 1999). This indicates the presence of landmass above sea-level, because andesitic volcaniclastic gravels were rounded by erosion during the transportation through river systems. This is also true in the 3.5 Ga Pilbara craton, Western Australia, where a huge oceanic plateau similar to the modern Ontong-Java plateau in the western Pacific (formed during Cretaceous time, Ishikawa et al., 2011; Utsunomiya et al., 2011) accreted to be preserved as fragments in the 3.5 Ga accretionary complex (Kitajima et al., 2008). Within the huge fragment, an excellent unconformity is present with basal conglomerate layers having rocks derived from on-land above sea-level in the 3.5 Ga Earth. These are all volcaniclastic rocks with bimodal affinities of komatiite and related rocks and rhyo-dacites with REE signatures suggesting the presence of an unusually thick oceanic crust with abundant modal content of garnet underneath. Similar evidences are available from Barberton Greenstone belt, S. Africa, suggesting that the thickness of early Archean ocean was similar to that of the modern Earth (ca. 3.5 km), and does not compare with the unusually thick ocean in other planets, such as in Neptune.

Another important constraint comes from ocean-plate stratigraphy in the Archean accretionary complex over the world (Kimura et al., 1993; Ohta et al., 1996; Komiya et al., 1999; Kitajima et al., 2001, 2008; de Wit et al., 2011). The most representative examples are from 3.8 Ga Isua, Greenland (Komiya et al., 1999; Maruyama and Komiya, 2011), 3.0 Ga Cleaverville complex, Pilbara craton (Ohta et al., 1996; Shibuya et al., 2007, 2010, 2012) and 3.5 Ga North Pole region (Kitajima et al., 2001, 2008; Ueno et al., 2006), and South Africa (Komiya, 1999; de Wit et al., 2011). The reconstructed ocean-plate stratigraphy clearly demonstrates that the rock suites were formed in the intra-oceanic environments where no huge continents were present; instead they were all formed in an oceanic realm such as the present western Pacific domain. The Mariana arc-trench system is a modern analog (Maruyama et al., 2001, 2007). Thus, major parts of primordial continents must have gone into deep mantle by the end of Hadean.

The style of formation of sedimentary rocks has changed through time, reflecting the change in size of landmass through time (Fig. 6). In the first 2.0 b.y., sedimentary rocks were nearly absent except in minor localities. Moreover, they were formed in intra-oceanic environments as mentioned above. At the end of Archean, presumably since 2.7 Ga, embryonic continents appeared, and caused oxygen increase in the atmosphere (Fig. 7) (Maruyama et al., 2001, 2007). The first supercontinent appeared at 1.9–1.8 Ga (Hoffman, 1988), although the size was only 40% compared to the Phanerozoic supercontinent Pangea. The size was insufficient to deliver nutrients over the entire globe, as seen from the volume ratio of sedimentary rocks among all the rock units formed at given geologic ages (Fig. 6). The predominance of sedimentary rocks in orogens began since 600 Ma and continues up to now with

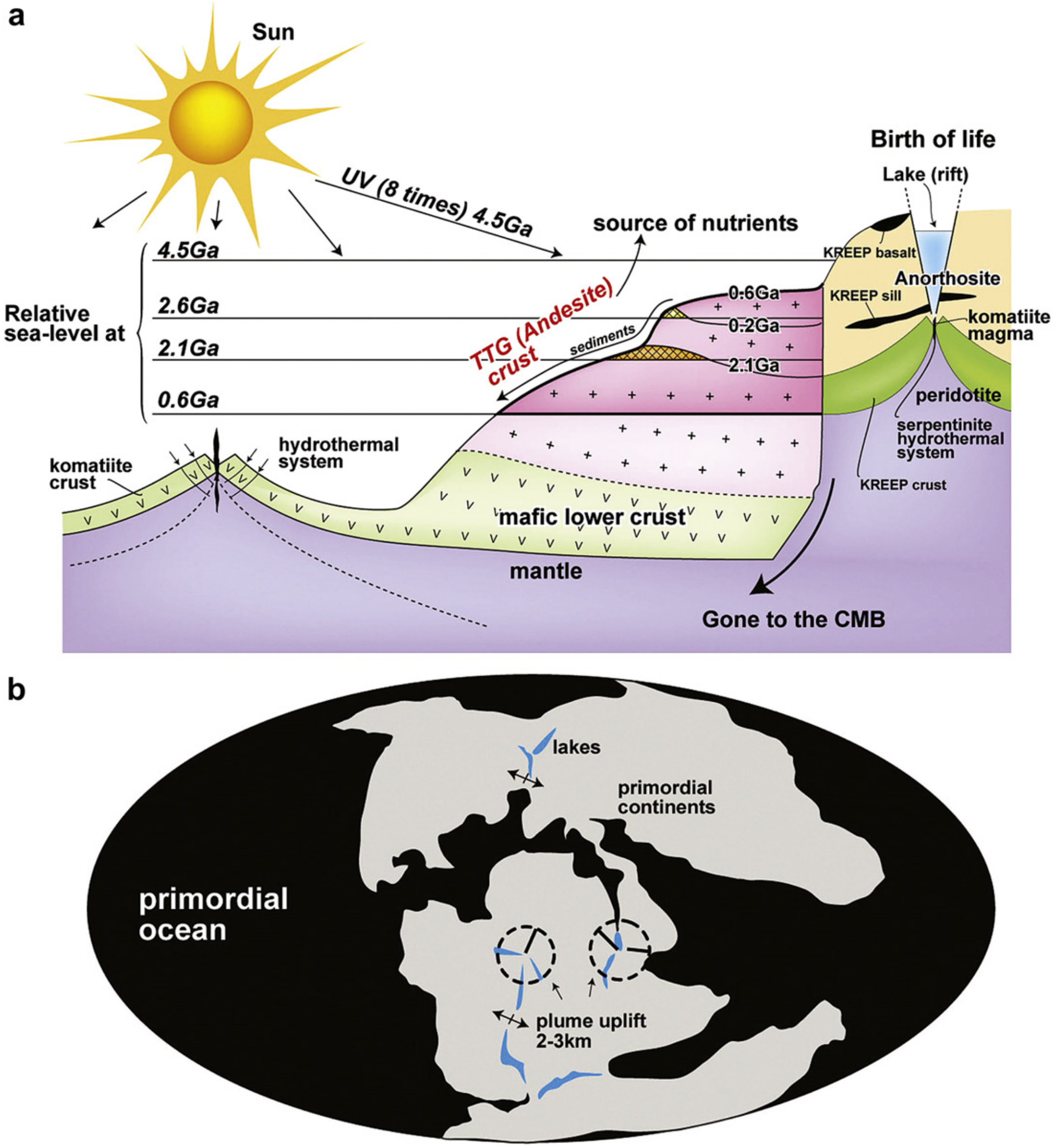


Figure 8. (a) Most probable birth site of life in the Hadean. The first life could have been born in a lake on the rifted primordial continents with sufficient nutrients and clean water. On the bottom of rifted continents, H_2-producing hydrothermal system dominated with localized ultra-alkalic environments (pH = 12). (b) Map view of Hadean Earth with landmass of primordial continents carrying abundant nutrients. The Hadean ocean was highly toxic, suggesting that evaporation was necessary to make clean water in a lake.

considerable fluctuations (Figs. 6 and 7). This sudden increase was due to rapid emergence of huge landmass that reflects the physical fate of cooling planet Earth as discussed later.

Chemical composition of granitic rocks has gradually changed from Na-rich in the Archean to K-rich in the Phanerozoic.

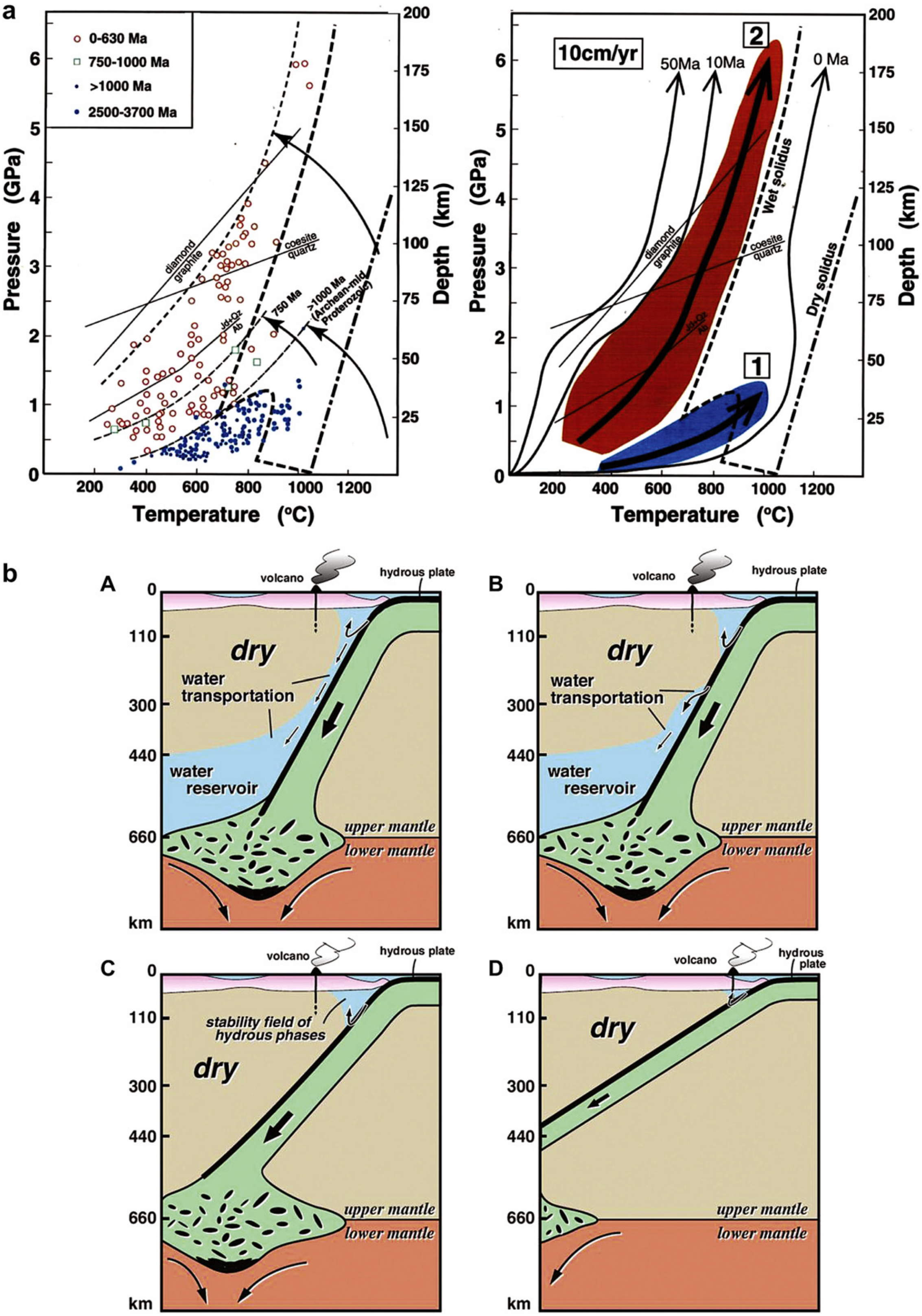
4.4. *Change of ocean thickness through time*

In the early 2 Ga after the birth of ocean, the ocean thickness increased through the degassing of water-rich magma generated from primordial mantle and this water was added into the ocean (Fig. 7). This is a speculation based on the geologic constraints mentioned above, and has also a theoretical base. In the Archean to Proterozoic Earth, mantle potential temperature was 200–150 K higher than that of today (Komiya et al., 2002a,b, 2004; Komiya, 2004, 2007). The subduction zone geotherm as documented by P-T conditions of regional metamorphic belts (Maruyama et al., 1996; Maruyama and Liou, 1998; Hayashi et al., 2000) prohibits water transportation into mantle by the subduction of hydrated slabs. Water subduction began at the onset of Phanerozoic as discussed below. On the other hand, OIBs since Archean, such as komatiites and picrites, are enriched in H_2O and CO_2 (see Shimizu et al., 2005), as well as MORBs with minor water and CO_2, all of which tend to increase the ocean volume through time. However, the volume of ocean never exceeds so as to bury all continents through time in the Precambrian time. Presumably the maximum thickness of ocean would have been less than 5 km (Fig. 7).

About 700–600 Ma ago, the ocean thickness started to decrease, and about 600 m has been reduced until now through the fluctuations in the balance between output vs input of water into the mantle. An overall decrease has been estimated from sea-level change through time in the Phanerozoic (Maruyama and Liou, 2005).

4.5. *Rapid decrease of sea-level during the Neoproterozoic*

As shown in Fig. 7, rapid increase of oxygen in atmosphere, emergence of metazoans and decrease of sea-level occurred all


a
0-630 Ma
750-1000 Ma
>1000 Ma
2500-3700 Ma
Pressure (GPa)
Depth (km)
Temperature (°C)
diamond
graphite
coesite
quartz
Jd+Qz
Ab
750 Ma
>1000 Ma (Archean-mid Proterozoic)
10cm/yr
50Ma
10Ma
0 Ma
2
1
Wet solidus
Dry solidus
b
A
B
C
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0
110
300
440
660
km

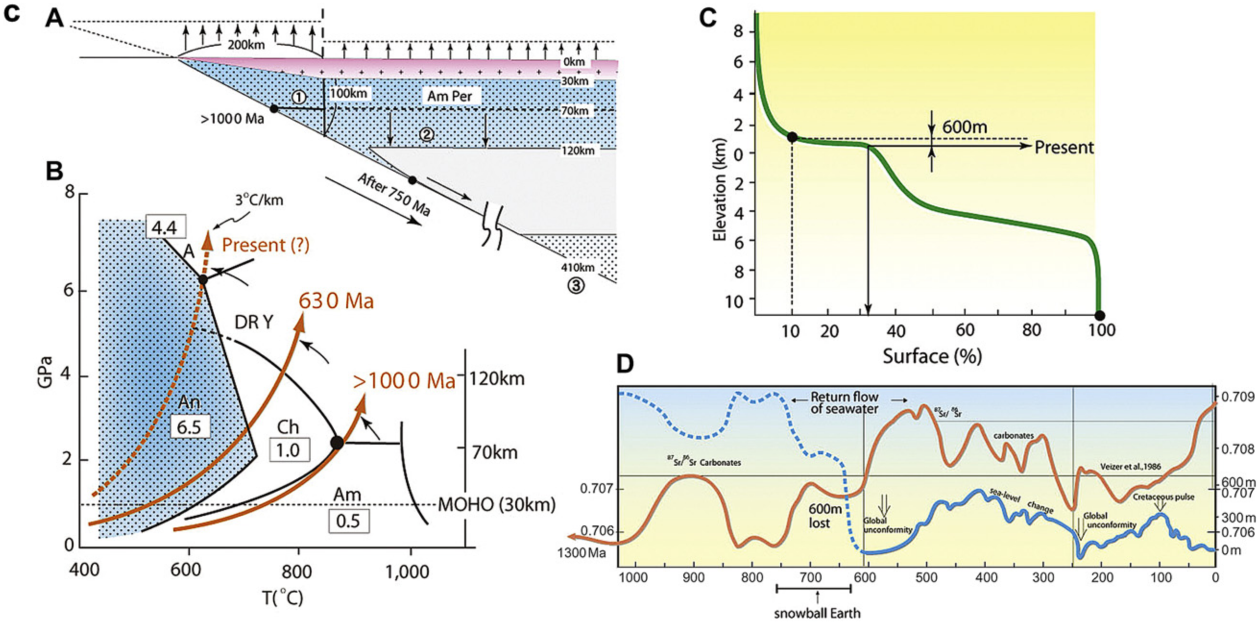

Figure 9. (*continued*).

together at the onset of Phanerozoic. Here we will discuss the ultimate cause to explain the golden time of the evolution of life in our planet.

Phase diagrams of MORB + H_2O and peridotite + H_2O indicate that the ocean level would decrease though subduction of hydrated oceanic slabs if the top of the descending slab changes to temperatures lower than 600 °C at Moho depth of 30 km through time from hot Archean mantle to the present (Maruyama and Liou, 2005). The subduction zone geotherm along the surface of descending slab turns to generate blueschist facies rocks if it crosses the high-temperature corner of blueschist facies in a P-T space defining the subduction zone geotherm and passing to the point at 10 kb, 600 °C (Maruyama et al., 1996; Maruyama and Liou, 2005). A plot of the P-T conditions of regional metamorphic belts over the world since the Archean shows that the first appearance of blueschist was ca. 700 Ma (Nakajima et al., 1990), and subduction zone rapidly changed cooler at the onset of Phanerozoic (Fig. 9a; Maruyama et al., 1996; Maruyama and Liou, 1998). The temperature of Moho depth was higher than 600 °C before 700 Ma, but rapidly changed to cooler than 600 °C thereafter, and down to 200 °C at present (Fig. 9a). This suggests that the initiation of return-flow of seawater into mantle began in the latest Proterozoic, as estimated by the phase diagrams, and the mechanism is schematically shown in Fig. 9b (Maruyama and Okamoto, 2007) and Fig. 9c (Maruyama and Liou, 2005). The observed sea-level drop clearly supports the idea, and the proposed sea-level change curve (Fig. 7c) shows that ca. 600 m thick ocean has been removed from surface into mantle, at the 410–660 km depth transition zone, which has a capability to store about 5 times the total mass of water in the surface oceans (Maruyama and Liou, 2005).

The sea-level fluctuation of ±300 m in the Phanerozoic could be explained by the glacial and non-glacial periods, and partial mantle overturn when high-temperature and fertile lower mantle materials replaced the upper mantle catastrophically such as during the Cretaceous (120–85 Ma) pulse period (Larson, 1991; Utsunomiya et al., 2007). Another pulse period was mid-Paleozoic when huge batholith belts were formed similar to the Cretaceous pulse. If the rate of decreasing volume of ocean will continue over 1.0–1.5 b.y. toward the future, the Earth will finally dry up, which will mark the end of life (Fig. 7).

Independently from the work of Maruyama and Liou (2005), Wallmann (2001) had already reached a similar conclusion by analyzing the secular decrease of $\delta^{18}O$ of carbonate. The systematic decrease of oxygen isotope ratio in the Phanerozoic reflects the subduction of hydrated oceanic slabs into mantle. If hydrated slabs are transported into mantle, the present value of oxygen isotope of seawater can be explained in the case that ca. 400 m thick ocean mass was removed into mantle during the last 600 Ma (Wallmann, 2001).

4.6. *Phanerozoic time: why is it a golden time for life?*

Cambrian explosion was firstly pointed out by Cloud (1948, 1968) and later, its uniqueness was speculated by Gould (1995) who pointed out that the birth of metazoan community and subsequent Cambrian explosion were the beginning of unrelated mass extinctions that occurred frequently in the Phanerozoic, and caused accelerated evolution of life such as in the P/T and K/T boundaries (Sepkoski, 1986; Keller, 2005; Bambach, 2006). Recent detailed studies on Cambrian explosion, mainly from rock records in South

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Figure 9. (a) P-T conditions of regional metamorphic belts over the world (left). Regional metamorphic belts are formed at consuming plate boundary, indicating subduction zone geotherm. Precambrian metamorphic rocks show low-P/T conditions, whereas Phanerozoic ones show high-P/T conditions. Subduction zone geotherms were calculated by a speed of 10 cm/year for the different slabs with different ages. Rapid change of subduction zone geotherm from 1 to 2 suggests the initiation of return-flow of seawater into mantle at the onset of Phanerozoic. (b) Water transportation into mantle along cold geotherms of (A and B) (Phanerozoic), and (C and D) (Precambrian). See also Fig. 9a for details. (c) The processes to show rapid decrease of sea-level around 600 Ma, by the initiation of return-flow of seawater into mantle. (A): shows hydration of mantle wedge by serpentinization to push up the continental margin. (B): shows 6.5 times more incorporation of water as antigorite serpentinite dominated after 630 Ma from chlorite peridotite before 1000 Ma at subduction zone. (C): shows the sensitivity of landmass size against sea-level. Only 600 m above sea-level make 20% decrease of landmass. (D): shows sea-level change curve as defined by Hallam (1992) for the last 600 Ma, and extension (broken line) estimated by Sr isotope curve of carbonate (modified after Maruyama and Liou, 2005).

China, has led to the idea that the more frequent mass extinctions during the time span of Cambrian explosion from 635 Ma to early Cambrian at 520 Ma is a key, and that 8 times of mass extinction occurred by the end of Cambrian at 488 Ma (Zhu et al., 2007). Therefore, the idea of Gould (1989) became invalid. Inversely, a rapid evolution of metazoans could be the result of accelerated evolution caused by frequent mass extinctions.

The Phanerozoic time began from Cambrian explosion. Most of the ancestral life forms, more than at least 20 Phylum-level, appeared in a short time from 540 to 520 Ma. Up to 35 Phylum-level metazoans appeared by the end of Cambrian at 488 Ma. Since then, diversification of animals and plants proceeded extensively on account of environmental and geochemical diversifications (Fig. 10). This is due to the global scattering of nutrients by the emergence of huge landmass similar to that of the present. Note the comparison of available amount of phosphorous in the Phanerozoic and the Precambrian time, as documented by systematic difference of sedimentary rocks between Precambrian and Phanerozoic time. An abrupt increase of nutrient supply began by the emergence of huge landmass, because the amount of water in the mantle wedge must have increased from 1.0 to 6.5 wt% (Fig. 9c), if subduction zone geotherm began to cut the boundary of the stability field between clinochlore peridotite and antigorite peridotite during the cooling (Fig. 9c). This is due to the initiation of return-flow of seawater into mantle during the Neoproterozoic.

We envisage the following processes for the dawn of Phanerozoic (Fig. 11). First, initiation of return-flow of seawater into mantle caused hydration of mantle wedge, leading to the lowering of sea-level. Subsequently, the coast line moved oceanward to increase the size of landmass, with the resultant birth of huge rivers to transport large volumes of sediments leading to the burial of organic matter synthesized by photosynthesis by algae and cyanobacteria. The burial of organic matter kept the high oxygen content in atmosphere by preventing from back reaction to consume the stock of free oxygen. The increased oxygen in atmosphere finally diffused upwards to create the ozone layer. The birth of ozone layer shielded the

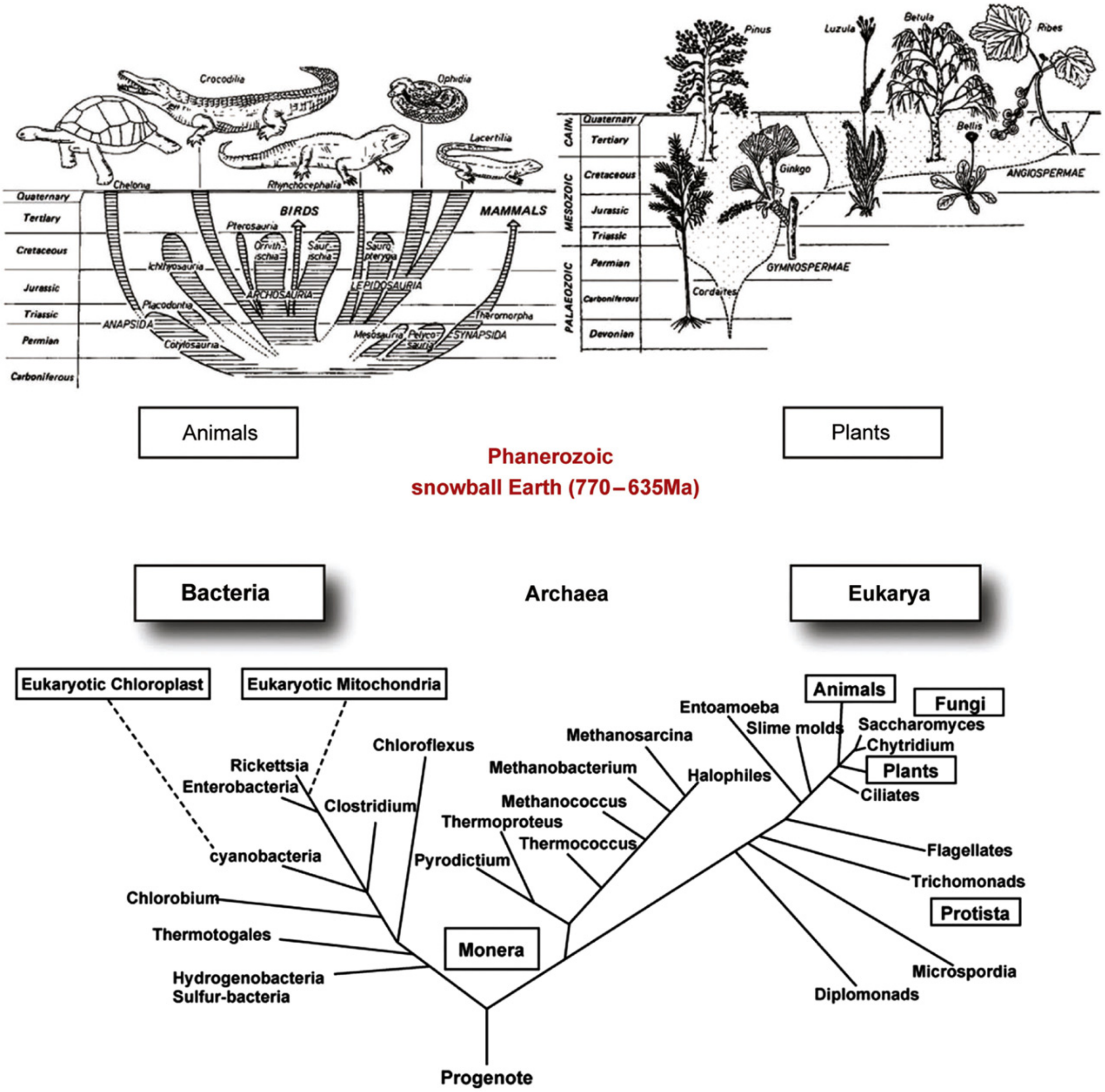


Figure 10. Diversified animals and plants in the Phanerozoic (after Condie and Sloan, 1998). Phylogenetic tree of life (below, Woese et al., 1990) and explosive evolution of animals and plants in the Phanerozoic (Condie and Sloan, 1998).

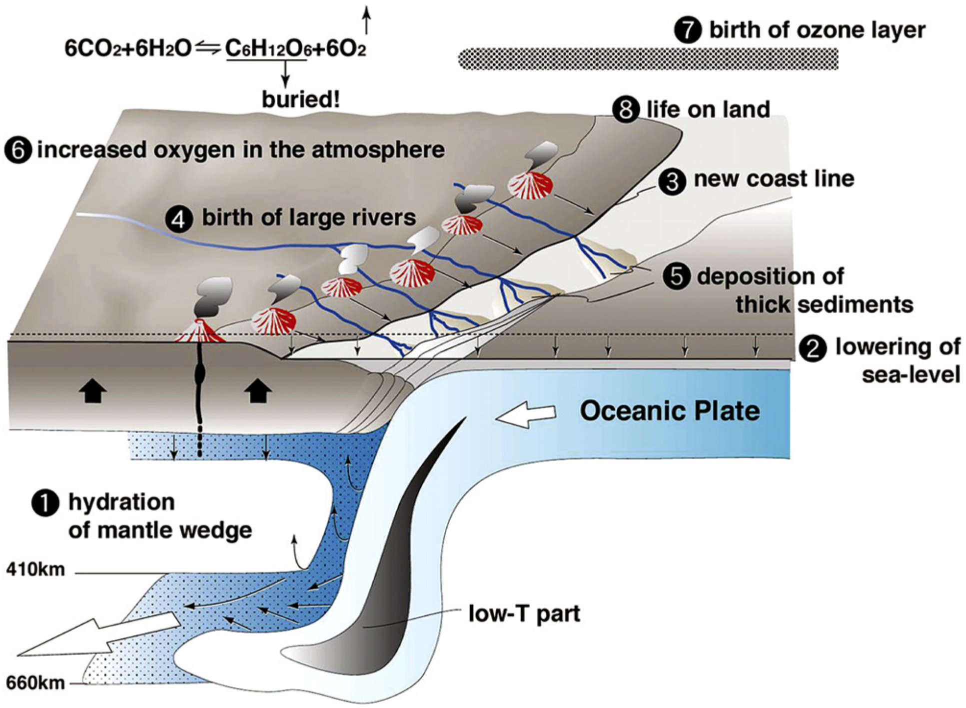


Figure 11. Process to make the golden period of life evolution on the Phanerozoic Earth, by initiation of return-flow of seawater into mantle. Numbers indicate the order of genetic link from 1 to 8. Also shown are the essential mechanisms to increase free oxygen in atmosphere.

ultraviolet radiation from Sun, thereby enabling plants and animals to invade the land. Firstly, cyanobacteria invaded in the swamp along the river to lake (Gray, 1993). It gradually evolved to algae, bryophytes and to tracheophytes by late Devonian (Scheckler, 2001).

After the termination of Cambrian explosion, periodic mass extinctions also occurred less frequently after the end of Cambrian. The top of ecosystem was collapsed during the mass extinction, and replaced by a new niche afterward. Frequent mass extinctions termed the “Big Five” promoted the rapid evolution of life. Moreover, the on-land life faced dangers for animals and plants more severely than before, because of the exposure to Universe. The nearby supernovae, collision against dark cloud and starburst in our Milky Way Galaxy all caused mass extinctions to accelerate the speed of mutation (Maruyama and Santosh, 2008). Nevertheless, life evolved widespread by diversification and through adjusting with the diversified surface environments.

Thus, initiation of return-flow of seawater into mantle brought a golden time of life, by the continuous and global-scale distribution of nutrients, thereby enabling flourishing and diversified life on this globe. The initiation of return-flow was the fate of cooling Earth covered by ocean. It began 4.0 b.y. after the birth of planet with R (radius) $=$ 6400 km and only 3–5 km thick ocean. If the ocean was even only 1 km thicker than today, the metazoans could not have appeared yet. If the thickness of primordial ocean was 2 km thinner than today, plate tectonics would not have operated because of mid-oceanic ridge rising above sea-level. The lack of hydration of oceanic slabs at mid-oceanic ridge prevents plate tectonics, hence no ways to clean-up ocean, and no accumulation of TTG materials through time.

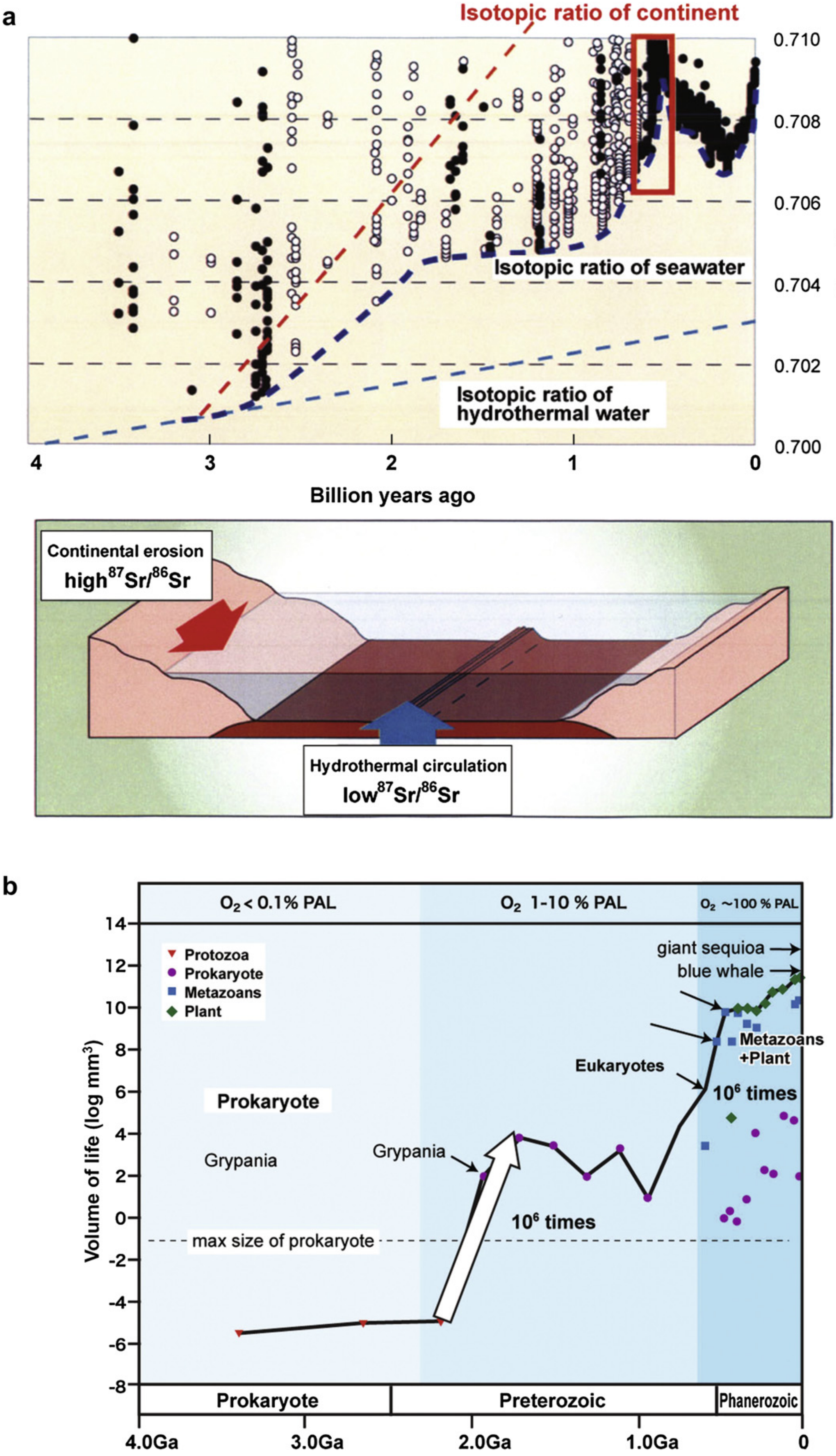
4.7. *Nutrient supply, oxygen increase and Cambrian explosion: why coincidental?*

The major reason for Cambrian explosion has long been traditionally ascribed to the increased oxygen content in atmosphere (Rye and Holland, 1998; Holland, 2006; Knoll et al., 2006), from less than 10^{-2} to 1 PAL, because high oxygen pressure is necessary to keep the reaction to produce collagen that paste plural cells together (Towe, 1970). The birth of large multi-cellular animals became possible only after the increased oxygen partial pressure (Runnegar, 1991).

However, we consider that this scenario is not correct, because various kinds of nutrients such as P, K, Ca, Fe and other trace metals were more essential factors to be prepared for life to evolve. For example, Mo is a key element to fix N by Prokaryotes to make protein. Mo is hyper-enriched in granite and nearly absent in peridotite and basalts (Table 1). Even if oxygen pressure turned to be high, metazoans cannot be synthesized if the above elements that make up the metazoans were not supplied.

The dramatic and rapid increase of nutrients occurred at the onset of Cambrian time, as clearly shown by $^{87}Sr/^{86}Sr$ ratio of carbonate (Fig. 12a) (Veizer et al., 1999; Shields and Veizer, 2002). The rapid oxygen increase in atmosphere is also estimated to have occurred at this period (Fig. 12b). The paleontological evidence of appearance of Ediacaran fossils after 580 Ma, SSFs (small shelly fossils), and first fish (Shu et al., 2003; Shu, 2008) coincide with increased oxygen level in the crude sense. The volume of animals increased to 1 million times larger than that of Eukaryotes (Fig. 12b). Thus, the increased amount of landmass, supply of large amount of nutrients in the platform, and high oxygen level in atmosphere all coincide in time, and hence must be related in process among one another.

The mechanism for this coincidence is proposed as follows. The emergence of huge landmass due to drop of sea-level caused global scattering of nutrients into the ocean through river drainage, presumably also by wind as aeolian dusts from the desert regions which fed the planktons in the surface of open oceans. Enormous amounts of nutrient supply caused an accelerated burst of photosynthesis to increase free oxygen in atmosphere. This resulted in a rapid increase in organic matter, which was buried in the


a
Isotopic ratio of continent
Isotopic ratio of seawater
Isotopic ratio of hydrothermal water
0.710
0.708
0.706
0.704
0.702
0.700
$^{87}Sr/^{86}Sr$
4
3
2
1
0
Billion years ago
Continental erosion
high $^{87}Sr/^{86}Sr$
Hydrothermal circulation
low $^{87}Sr/^{86}Sr$
b
O_2 < 0.1% PAL
O_2 1-10 % PAL
O_2 ~100 % PAL
Protozoa
Prokaryote
Metazoans
Plant
giant sequioa
blue whale
Metazoans +Plant
Eukaryotes
10^6 times
Prokaryote
Grypania
Grypania
10^6 times
max size of prokaryote
Volume of life (log mm^3)
14
12
10
8
6
4
2
0
-2
-4
-6
-8
Prokaryote
Preterozoic
Phanerozoic
4.0Ga
3.0Ga
2.0Ga
1.0Ga
0

sediments, preventing back reaction to reduce the amounts of free oxygen in atmosphere, maintaining a steady-stage oxygen pump. Since then a golden time of life has come. Huge expense of CO_2, H_2O, N_2 and nutrients has continued up to now, and the Earth now faces poverty of CO_2 in the atmosphere (only 400 ppm).

4.8. A brief summary of the history of life: what controlled the evolving life, and the importance of volume of ocean and size of planet

Summarizing the various factors that made the Earth habitable where metazoans appeared to evolve to a super-size, ca. 10^{12} times bigger than that of Prokaryotes (Fig. 12a), several critical points emerge. The underlying assumptions are 1 AU distance from the Sun, strong geomagnetism, presence of giant orbiter, rotation speed, and size of central star and its chemical composition (Fig. 1). The critical aspects are: (1) the essential requirement of 3–5 km thick ocean; if above or below this value, the birth and evolution of metazoans will not take place; and (2) the size of planet, both super-Earth and Mars-size cannot bear metazoans within a lifetime of the central star. The appropriate size of the planet is a critical factor. In case of Earth, it took 4.0 Ga to decrease the ocean by water transportation into mantle through the subduction of hydrated slabs. The initiation of return-flow of seawater into mantle was the most important factor to emerge huge landmass and resultant global supply of nutrients to oceans, i.e., the birth of second ecosystem on the planetary surface.

5. How to make ‘naked planets’

As discussed above, the appropriate range of the amount of seawater on a rocky planet for the emergence and evolution of life is quite narrow. For example, the range is approximately 0.3–3 M_{oce} for planets of 1 Earth mass (6.0×10^{24} kg), where M_{oce} is the present total mass of the Earth’s oceans (1.4×10^{21} kg). This corresponds to as small as 0.007–0.07% of the Earth mass. On planets richer in water, continents would be globally and permanently covered with oceans. In such a circumstance, weathering never operates to supply nutrients continuously from continents, so that life would be hard to emerge and evolve.

Recently, more massive planets called super-Earths have been identified beyond the solar system. Provided the maximum depth of oceans allowed for continents to appear above the sea-level is the same irrespective of planetary mass M_{p}, the permissible amount of seawater itself increases with M_{p}, because of increase in the planetary surface area A_{p}. However, the corresponding mass fraction of seawater relative to M_{p} decreases, as M_{p} increases, because it scales with $M_{\mathrm{p}}^{-1/3}$ (A_{p} being proportional to $M_{\mathrm{p}}^{2/3}$). The permissible amount of seawater is, for example, about 0.003–0.03% of M_{p} for a super-Earth of 10 Earth masses.

A question arises whether such ocean masses are large or small, from the viewpoint of planet formation. To answer this, we first provide a brief review of the popular theories of solar-system formation, followed by what have been recently revealed as to planets beyond the solar system (i.e., exoplanets). Then, we describe how rocky planets in the habitable zone obtain appropriate amounts of water, and predict what kind of planetary system harbors rocky planets with oceans and continents on their surfaces, which are potentially habitable.

5.1. Birth of the Earth

Theories suggest that planet formation consists of several processes. First, a molecular cloud core, which is a relatively dense part of the interstellar medium, collapses to form a proto-star (Hayashi and Nakano, 1965; Larson, 1969). Because of the angular momentum that the molecular cloud core initially had, a disc-shaped nebula is inevitably formed around the proto-star as a remnant of star formation. Such a nebula is usually called the solar nebula when the origin of the solar system being discussed, and is called a protoplanetary disc (or simply a disc) in general cases. The protoplanetary disc is thought to be the birthplace of planets (Safronov, 1969; Hayashi, 1981). A self-consistent scenario of the solar-system formation was proposed by C. Hayashi, K. Nakazawa, and their students, and is often called the Kyoto model (Hayashi et al., 1985). The outline of the Kyoto model is illustrated in Fig. 13.

The element abundance in a protoplanetary disc should be almost the same as that in its host star: namely, hydrogen and helium constitute more than about 90% of the disc’s mass, while the rest (<10%) includes carbon, oxygen, silicon, iron, magnesium etc., which are often lumped together as “heavy elements” in the astronomical community. Those heavy elements first make dust grains of micrometer size. They are composed of rocky minerals in the inner disc, while they are mixtures of ice and rock in the outer disc. The boundary between the inner and outer discs is called the snowline, which is defined as the location where the gas temperature is equal to the sublimation temperature of water (~170 K). Since oxygen is most abundant among the heavy elements in the solar nebula, main component of dust grains in the outer disc is H_2O ice, and the mass ratio of ice and rock is thought to be 2–4. In the inner disc, water exists in the vapor form and is never incorporated in solid dust grains.

The dust grains aggregate to form km-size solid bodies called planetesimals, building blocks of solid planets. Meteorite parent bodies in the asteroid belt and comets are believed to be the remnants of planetesimals. Planetesimals grow via mutual collisions. It is, thus, natural that rocky planets like the Earth, Venus, Mars, and Mercury are formed interior to the snowline, while icy planets (or water-dominated planets) like Uranus and Neptune are formed beyond the snowline.

For Jupiter and Saturn to form, the disc gas has to be collected, in addition to solid. Because of abundant materials available beyond the snowline, icy planets grow massive enough to capture the surrounding disc gas gravitationally, resulting in the formation of hydrogen-dominated gas giant planets like Jupiter and Saturn. Observations suggest that protoplanetary discs dissipate in a few million years (e.g., Haisch et al., 2001). In the solar system, Jupiter and Saturn were formed before disc dispersal, while Uranus and Neptune are likely to have formed in a significantly depleted disc.

While the Kyoto model does not tell anything directly about the origin of seawater on the Earth, it follows from the model’s assumptions that the terrestrial planets were born dry, because their building blocks interior to the snowline contained no water. While the terrestrial planets were, in principle, able to gain water in

Figure 12. (a) $^{87}Sr/^{86}Sr$ ratio of carbonate through time. Because the ratio is sensitive to secondary alteration, the minimum value is believed to show the original Sr isotopic ratio at given geologic age. Red broken line shows the evolution line of TTG through time, whereas the bottom broken line shows the evolution line of hydrothermal Sr isotope derived from MORB. The observed Sr isotope curve is in between. The result indicates two sharp bends, one at 2.5–2.1 Ga and another at 600 Ma. The bottom shows the genetic relationship of Sr isotope value of seawater, as a binary system. Data are from Shields and Veizer (2002). (b) Size (volume) evolution of life through time. Prokaryotes evolved to 1 million times bigger Eukaryotes at around 2.3 Ga, which in turn evolved to another 1 million times bigger Metazoans at 600 Ma. These timings are same as those for rapid oxygen increase (top column) and rapid increase of Sr isotopic ratio in Fig. 12a. Data are from Payne et al. (2009).

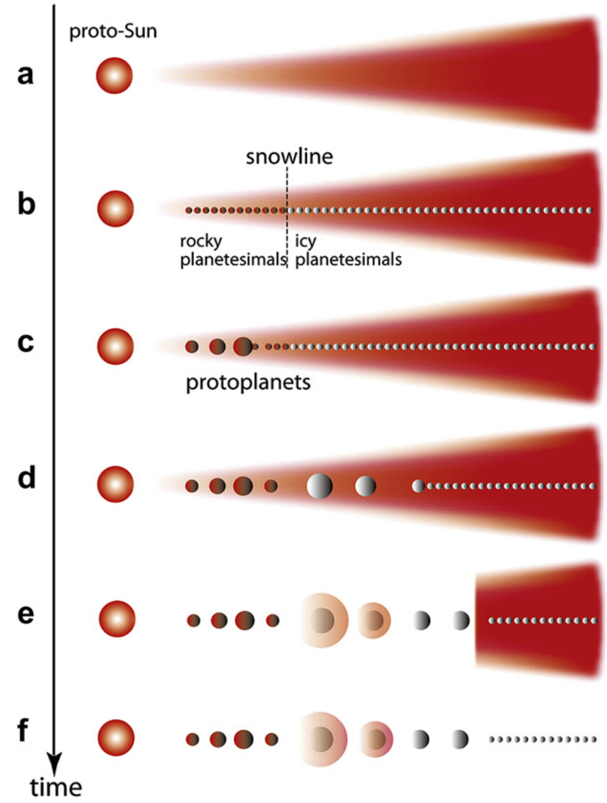


Figure 13. Schematic representation of the Kyoto model. (a) A disc-shaped nebula called the solar nebula is formed around the proto-Sun, which is the birthplace of planets. The solar nebula is composed mostly of hydrogen and helium with a small fraction of heavy elements. (b) There are many km-size building blocks of solid planets called planetesimals. There is a snowline inside which planetesimals are rocky and outside which planetesimals are mixtures of rock and ice. (c) Planetesimal growth occurs via their mutual collisions to form massive bodies with size of ~1000 km called protoplanets. (d) Beyond the snowline, more massive protoplanets form, because of contribution of ice. (e) Such massive protoplanets capture surrounding disc gas gravitationally to form gas giant planets such as Jupiter and Saturn. At the same time, disc dissipation occurs. The formation of Uranus and Neptune were probably formed after disc dispersal. (f) The present solar system.

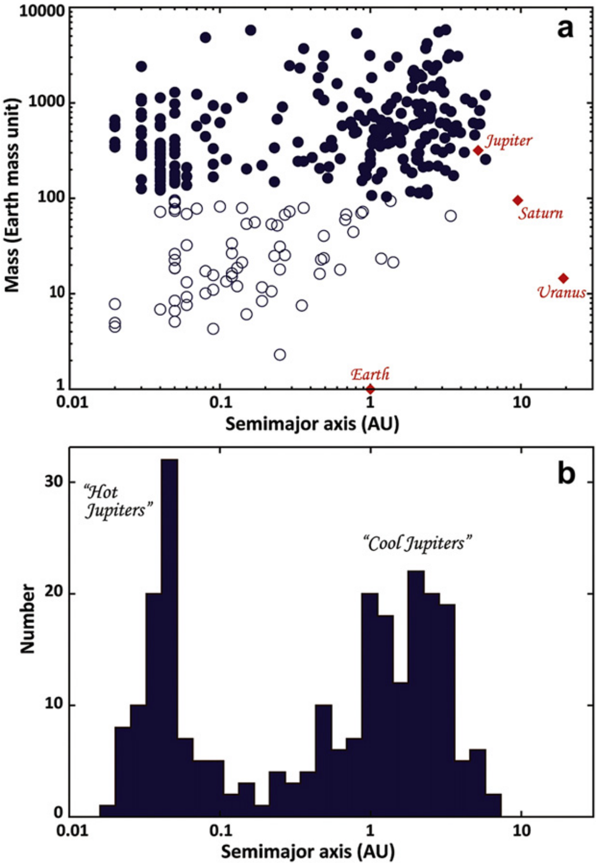


Figure 14. Statistics of population of exoplanets that orbit stars with masses of 0.8–1.2 solar masses (i.e., G-type stars). (a) The distribution of lower limits to planetary masses and semi-major axes are shown. Filled and open blue circles represent exoplanets with masses of >100 and <100 Earth masses, respectively. Red diamonds represent planets in the Solar system. (b) Histogram of semi-major axes of exoplanets of >100 Earth masses. Data were taken from http://exoplanets.org/ (as of 29th June 2012).

the vapor form from the disc gas, the amount is tiny compared to the present mass of the Earth's oceans, unless a significant amount of oxygen was supplied by the magma ocean (Ikoma and Genda, 2006). The crucial assumptions in the Kyoto model are that the snowline was located at about 3 astronomical unit (AU), which was far out from the current Earth's orbit (i.e., 1 AU), and that all the planets were formed via in-situ accretion of planetesimals. Both assumptions are currently matters of debate. Modern theories suggest that discs are cooler than previously thought (Min et al., 2011; Oka et al., 2011) and planets tend to migrate toward their host stars (Ward, 1986 and other studies). In particular, the latter has been confirmed by discoveries of planets with short orbital periods beyond the solar system, as described below.

5.2. How common are "Earth-like" planets in the Universe?

Recent investigations have revealed many planets beyond the solar system (about 800 planets, as of June 2012; www.exoplanet.eu). The discovery of exoplanets showed that the architecture of the solar system is not the only one in the Universe. Fig. 14a shows the distribution of exoplanets detected so far on a diagram with horizontal axis of the averaged distance to the central star (more precisely, the semi-major axis) and vertical axis of the lower limit to planet mass. Only the lower limits to planetary masses are usually determined by observation, because their orbital inclinations toward the observer are unknown. However, from the statistical point of view, the averaged value of exoplanet's true mass differs only by a factor of $4/\pi$ (~ 1.3) relative to the lower limit.

As shown in Fig. 14a, there are a great number of gas giant planets that orbit extremely close to their central stars (typically, <0.1 AU), in contrast to the gas giant planets, Jupiter (5.2 AU) and Saturn (9.5 AU), orbiting far from the Sun. In the solar system, even the innermost planet, Mercury, orbits at 0.4 AU. Because such extrasolar gas giant planets are in hot environments, they are often called hot Jupiters. On the other hand, gas giant planets orbiting far from host stars like Jupiter and Saturn are called cool Jupiters in this paper.

Fig. 14b shows a histogram of semi-major axes of exoplanets of more than 100 Earth masses (i.e., gas giant planets). The distribution of the gas giant planets seems to be a bimodal one. This means that extra-solar planetary systems that contain gas giant planets are not randomly diverse; otherwise, there are three major types of planetary system, namely, hot-Jupiter systems, cool-Jupiter systems, and Jupiter-less systems. Obviously, the solar system is a cool-Jupiter system.

The Jupiter-less systems contain small, low-mass planets. Thanks to recent progresses in observation techniques for exoplanets, especially the operation of space telescopes (CoRoT from ESA and Kepler from NASA), small exoplanets are also being detected. Furthermore, in addition to masses, radii of exoplanets are measured. Small exoplanets with radii of 1 to ∼4 Earth radii and/or with masses of 1 to ∼20 Earth masses are often called super-Earths. A recent, noticeable finding is that there are a significant number of low-density super-Earths that are less dense than naked (i.e., atmosphere-free) rocky bodies.

Fig. 15 shows the masses and radii of super-Earths detected thus far. Also, the radii of Earth-like rocky planets with water vapor theoretically calculated are shown as functions of masses (modified after Valencia et al., 2010). It is realized that most of the super-Earths contain water that accounts for more than 1% of the planetary total masses. Whereas such large radii may be accounted for by the presence of hydrogen-rich atmospheres instead of water, the masses of the hydrogen-rich atmospheres seem to be incompatible with recent formation theories (Ikoma and Hori, 2012). The amounts of water may be tiny relative to the planet mass, but huge compared to the total mass of Earth's oceans, which is only 0.023 wt% of the Earth's mass. Furthermore, bulk densities of some of the super-Earths are so low that they should be made mostly of water like Uranus and Neptune.

5.3. *How to bring tiny amounts of water to rocky planets*

The issue of interest in this paper is how rocky planets obtain the appropriate amounts of water for the emergence and evolution of life, which are tiny (on the order of 0.001–0.01%) relative to planetary masses, as described above. Once a rocky planet in the habitable zone acquires a large amount of water, it is difficult for the planet to lose the water to space (e.g., Kasting et al., 1993). Therefore, the best way for a planet to get such a tiny amount of water (0.3–3 M_{oce}) is to be born dry, followed by subsequent accretion of a small number of water-bearing objects from beyond the snowline (asteroid and/or comets in the solar system). Here, we discuss possible pathways toward making such potentially habitable planets.

As mentioned earlier, the planetary systems are divided into three systems; hot-Jupiter systems, cool-Jupiter systems, and Jupiter-less systems (Fig. 16). Some of the Jupiter-less systems have super-Earths orbiting close to their central stars (called hot super-Earths). The presence of hot-Jupiter systems indicate that gas giant planets migrate from beyond the snowline after solid protoplanets become massive enough by accretion of icy planetesimals to collect the surround disc gas gravitationally. In contrast, in the solar system, such significant migration of gas giant planets never occurred. Furthermore, the presence of super-Earths with large radii (see Fig. 15) indicates that super-Earths also come over to the inner regions from the outer regions of protoplanetary discs. This fact offers quite important suggestion: it is rather easy for planets to obtain abundant water.

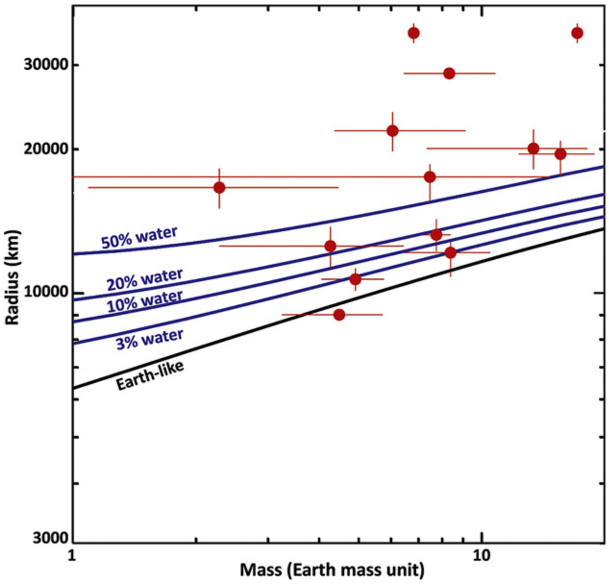


Figure 15. Relationship between masses and radii of transiting exoplanets (red circles; data from http://exoplanets.org/). Also shown are theoretical curves for Earth-like rocky planets with water vapor atmospheres whose percentages are indicated by attached numbers (modified after Valencia et al., 2010).

In hot-Jupiter systems and Jupiter-less systems with hot super-Earths, dry rocky planets would not remain in the habitable zone, because significant migration of planets and planetesimals occurs in these systems (Fig. 16a, c). Even if Earth-sized planets in the habitable zone are found in these systems, those planets should contain large amounts of water (more than 10% compared to the planetary masses). Therefore, systems with dry rocky planets are limited to systems where no planetary migration occurs, that is, cool-Jupiter systems and Jupiter-less systems without hot super-Earth.

In the solar system, the Earth was born as a dry rocky planet, because the planetesimals around the habitable zone do not contain water. After the formation of the dry planet Earth, water-bearing objects in the asteroid belt fell on the Earth. The asteroid belt is the region located between the orbits of Mars and Jupiter, and some asteroids contain water (up to ∼5 wt%). The total mass of the asteroids in the present asteroid belt is significantly depleted. A large fraction of the asteroids has been lost by the gravitational perturbation of Jupiter. Some fraction of perturbed asteroids is thought to fall onto the Earth. The total mass of the asteroids falling onto the Earth depends on several factors such as the initial surface density in the asteroid belt, and the timing of Jupiter formation. Additionally, accretion event of asteroids seems to be stochastic event (e.g., Morbidelli et al., 2000; Petit et al., 2001). For example, if only one large object that grows up to Mars-sized protoplanet in the asteroid belt hits onto the Earth, a large amount of water much larger than M_{oce} is supplied to the Earth. Therefore, total amount of water supplied to the Earth seems to have large variety. In the solar system, there is no inevitability to 1 M_{oce} on the Earth.

In the extra-solar system, many cool-Jupiters have been discovered. The existence of cool-Jupiters indicates that large-scale migration of planets and their building blocks has not occurred in the protoplanetary disk. Therefore, a dry rocky planet can form in the habitable zone. As the analog of the solar system, asteroid-like belt located between habitable zone and cool-Jupiter would be perturbed by a cool-Jupiter (Fig. 16b). The dry rocky planet becomes wet through the bombardment of water-bearing objects. It is possible that cool-Jupiter systems harbor habitable Earth-like planets with ∼1 M_{oce}. However, as discussed before, the appropriate range of the seawater for the emergence and evolution of life is quite narrow, and the total amount of water supplied to a dry planet vary widely, as discussed in the case of solar system.

In the case of Jupiter-less system without hot super-earth, a dry rocky planet can form in the habitable zone. However, if there is no gravitational perturber such as Neptune-sized planet beyond the snowline, water-bearing objects cannot be supplied onto a dry rocky planet in the habitable zone. We do not know the best or better configuration of planetary system among Jupiter-less systems to form a rocky planet with a tiny amount of water (∼1 M_{oce}) in the habitable zone, which should be systematically investigated.

6. Lessons from the Earth: hunting habitable planets form exo-solar planets

Since the first finding of exo-solar planet in 1995 (Mayor and Queloz, 1995), the number of exo-solar planets discovered so far

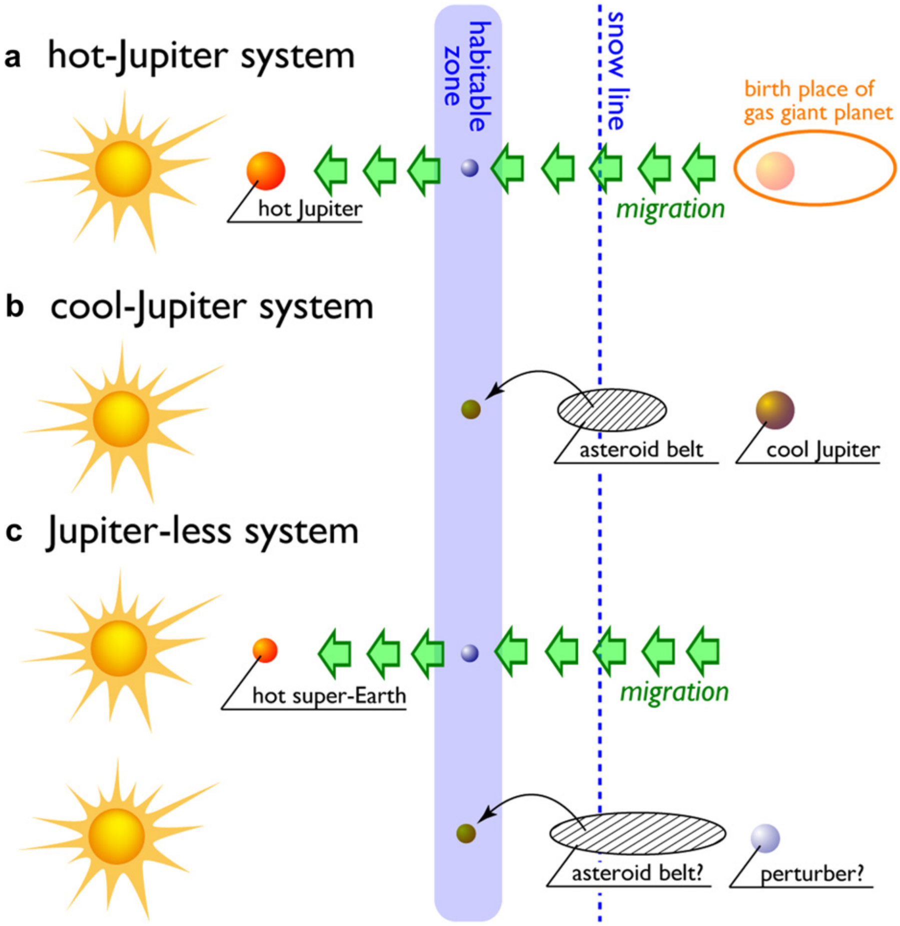


Figure 16. Three types of extra-solar systems and water supply on planets within habitable zone. (a) A hot-Jupiter formed beyond the snowline, and then migrated into the current location, which predict that the Earth-sized planet is composed mainly of water. (b) In cool-Jupiter system, no migration of planets occurred. Dry rocky planet can form in the habitable zone. Some fraction of asteroids might supply tiny amount of water to the dry rocky planet. (c) In Jupiter-less system with a hot super-Earth, dry rocky planets cannot form in the habitable zone, because significant migration of planets and planetesimals occur. On the other hand, Jupiter-less system without a hot super-Earth may harbor a rocky planet with tiny amount of water.

has increased rapidly to over 800 in 2012. The research direction is shifting toward life-bearing habitable planets now. The first target is ocean-covered planet and a few have been listed up already as possible candidates. We will discuss the method of finding life-bearing planets in more detail, based on the research experience on the Earth's life as summarized above.

In the following, we consider the planets which satisfy all the necessary conditions listed up in Fig. 1. Although most previous workers do not consider well the importance of nutrients, we consider that nutrients play a key role, as emphasized in this work.

6.1. Lesson I: summary of parameters

6.1.1. Importance of nutrients

Nutrients (Ca, Fe, P, K, Mg, Mn, Ni, Co, Mo and others) are the most essential for the birth and evolution of life, in addition to liquid water, together with CO_2 and N_2 in atmosphere. The host rocks carrying balanced nutrients are restricted to three: primordial continents, TTG and carbonatite. Primordial continents which are the products of consolidation of magma ocean are not stable on the planet, in spite of their buoyancy. For example, much more buoyant TTG crust (density $= 2.8$ g/cm^3) floating on mantle (density $= 3.5$ g/cm^3), than anorthositic primordial continent, that has subducted into mantle over 4.0 Ga. The volume of subducted TTG materials has been measured geophysically to be 10 times larger than that of surface continents. The subducted TTG materials are present in the mantle transition zone (Kawai et al., 2010). Only 10% of the total amount of TTG crust formed during the history of Earth remains on the Earth (Maruyama et al., 2011). This clearly indicates that even the ca. 30–35 km thick TTG crust easily subducts, hence primordial anorthositic continents must have gone into mantle.

6.1.2. Nutrient-bearing host rock survival: production vs destruction

Habitable planets must therefore produce continuously nutrient-bearing rocks through plate tectonics by subduction of oceanic plates to overcome tectonic erosion and arc subduction. The Earth has accumulated TTG crust, covering ca. 1/3 of the present solid Earth over 4.6 Ga. It has taken time to increase the volume of continental crust, and to overcome the subduction and destruction of continental crust either by arc subduction or tectonic erosion (von Huene and Scholl, 1991).

6.1.3. Tightly constrained initial mass of ocean, 3–5 km

To supply nutrients effectively, the presence of host landmass composed of adequate nutrients is crucial. Because the hydrothermal system is highly restricted in space ($<$10 km wide and $<$2 km deep, although extending over thousands km), the surface system of the Earth driven by Sun is the best as the most effective way to distribute nutrients into ocean. Oxygen concentration in ocean is restricted, usually less than 1/10 in atmosphere. Therefore, evolution to large multi-cellular animals would be restricted.

6.1.4. *Time*

It takes time to increase TTG materials on the surface of the Earth, only 5 km^3/year is generated at present on the Earth (Reymer and Schubert, 1984), whereas the erosion rate of TTG by subduction is nearly equal (von Huene and Scholl, 1991), hence no net continental growth at present, and will be opposite in future and different from the geologic past (Yamamoto et al., 2009; Maruyama et al., 2011). Considering the difficulty of TTG survival to overcome erosion and transportation into deep mantle, and absence of primordial continents on the present-day Earth, the availability of nutrient-host rock bodies on surface is also a function of time.

6.1.5. *Timing of emergence of huge landmass*

The timing of emergence of huge landmass above sea-level is a function of the size of ocean-covered planet. The size is crucial to initiate return-flow of seawater into mantle. If the size of rocky planet is huge such as super-Earth, 10–20 times bigger volume than the Earth, the cooling rate of solid planet by plate tectonics must be slower than that of the Earth. Sea-level would never decrease down enough to expose landmass after 4.0 Ga past since the birth date in case of Earth. The life-time of central star is another factor to compete the initiation timing of return-flow of seawater into mantle.

6.2. *Lesson II: index of life-sustaining planet*

To satisfy the conditions above for bearing life on planets, it is crucial that there are relatively shallow oceans with thickness of $<$3–5 km. Beyond the solar system, for the time being, measurement of only planetary masses and sizes is available, in addition to the distances to the central stars. Among planets with measured masses and sizes, the candidates for the search for life would be the dense ones with densities of $>$5.5 g/cm^3 (i.e., Earth-like) and with masses close to Earth's mass (Fig. 17). The range of planetary mass is also restricted for sustaining life, because it is difficult for return-flow of seawater to proceed on super-Earths even though the ages of central stars are favorable.

For the search of life-sustaining planets, the presence of landmasses would be the next hurdle to be cleared. Astrobiology would advance extensively if the composition of landmasses is known, the presence or absence of plants on land is identified, and oxygen partial pressure is measured. To the end, measuring reflection and/or emission spectra of exoplanets are more feasible in the near future (Fujii et al., 2010, 2011; Kawahara and Fujii, 2010, 2011). Like light-curve observations of asteroids in the solar system, the surface environments of exoplanets such as the presence of lands, plants, snow, and so on are characterized via periodic changes in the reflection spectra. A problem is, then, target selection. Based on our prediction above, rocky planets with appropriate amounts of water are found in cool-Jupiter systems. Therefore, it is suggested that search for life-sustaining planets should focus on exoplanetary systems that have been already known to harbor cool-Jupiters.

6.3. *Lesson III: civilization-bearing planet; are we alone or not in the Universe?*

This is the most interesting question, and astronomers had proposed SETI (Search for Extraterrestrial Intelligence) Project since the 1960s to detect artificial radio wave like TV. From the Earth to Universe, we human-beings sent radio waves about 60–70 years ago. We have not yet received similar radio waves from anywhere in the Universe. If we confirm the presence of civilization on exosolar planets in the Universe, our philosophy of human-being centered would undergo revolutionary change.

In 1961, Frank Drake proposed an equation to estimate the number of detectable extraterrestrial civilizations in our Milky Way Galaxy, which has been widely referred to as "The Drake equation". The Drake equation is formally composed of several factors:

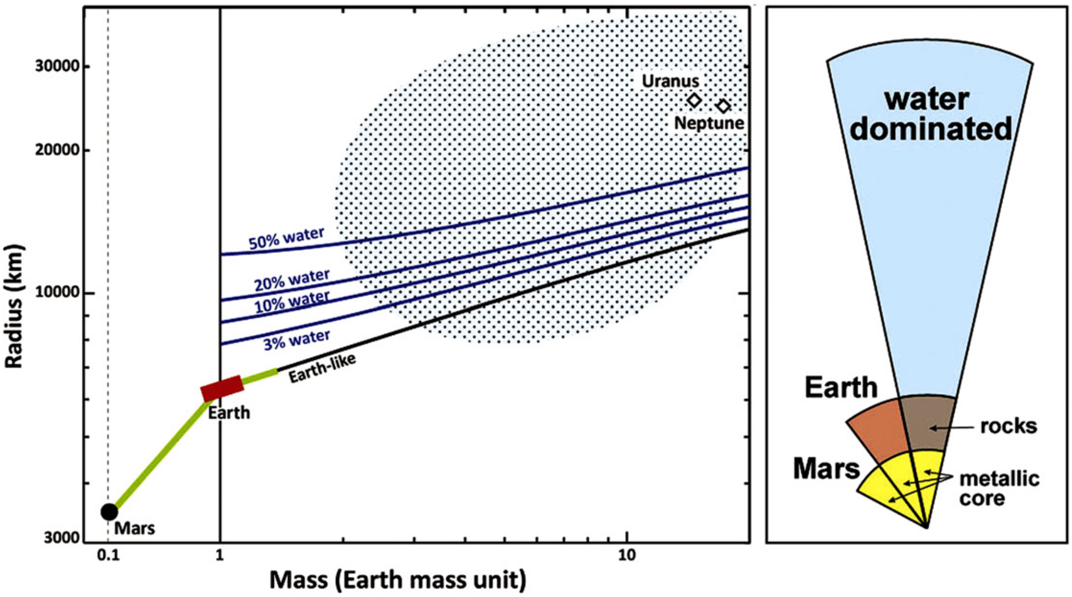


Figure 17. Mass (Earth mass unit) vs radius (km) diagram with different density of exoplanets to focus the location of life-sustaining planets (modified Fig. 15). Left-hand below close to Earth-Mars line is the most probable planet with life. Red bar mean the planet with potential to evolve Metazoans. Green bar regions may have bacteria with microscopic scale. Note the planet with only 3–5 km thick ocean is plotted right above the solid line of Moon-Mars-Earth-super-Earth.

$$N = R^{*} \cdot f_{\mathrm{p}} \cdot n_{\mathrm{e}} \cdot f_{\mathrm{l}} \cdot f_{\mathrm{i}} \cdot f_{\mathrm{c}} \cdot L$$

where N is the number of detectable extraterrestrial civilizations in our galaxy, R^{*} is the birth rate of suitable stars in our galaxy, f_{p} is the fraction of those stars that have planets, n_{e} is the average number of habitable planets per a planet-hosting star, f_{l} is the fraction of the habitable planets where life actually emerges, f_{i} is the fraction of planets from f_{l} with intelligent life, f_{c} is the fraction of planets from f_{i} where technology that releases detectable signs of their existence into space develops, L is the life-time of communicating civilizations. Nowadays, the values of R^{*} and f_{p} are derivable observationally, and estimated to be ∼7/year and ∼0.5 (e.g., Borucki, 2011), respectively. Recent space telescope Kepler mission tells us information about n_{e}. According to Traub (2012), the frequency of terrestrial planets in the habitable zones around solar-type stars is about 0.3; therefore, n_{e} has been thought to be ∼0.3. Although the other factors relevant to the birth and evolution of life are highly uncertain, many researchers attempted to estimate them so far and concluded that N was more than 1.

We give a warning against such optimistic estimation in this paper. Not all terrestrial planets in the habitable zones are habitable. As discussed above, continuous supply of nutrients is an essential pre-requisite for the birth and evolution of life. The ocean mass and the planetary size are the key factors, because sufficient nutrient supply is possible in restricted, narrow ranges of both factors. Furthermore, our argument based on recent planet formation theories predicts that rocky planets with tiny amounts of water are found in specific systems (i.e., cool-Jupiter systems), which is consistent with statistical properties of exoplanets detected so far. While such cool-Jupiter systems are not minority, water delivery to the habitable zone in those systems is a very stochastic process, so that the frequency of such suitable rocky planets may not be high. The planetary size is also restricted to around the Earth size. Therefore, n_{e} should be much less than 0.3, if supply of nutrients is taken into account as a pre-requisite for the birth and evolution of life.

What about the possibility of another planet with civilization? If we find perfectly same rocky planet as our Earth with entirely same age 4.6 Ga, then will there be a civilized world? The human-beings were born 7–6 Ma in the African Rift Valley, migrated outward from Africa since 2–1 Ma several times, and became finally successful at 0.4 Ma, conquering all creatures and sitting on the top of niche. Human population was less than 400,000 before 0.4 Ma, but exponentially expanded to over 7 billion in 2011.

Three hundred years ago, industrial revolution began, and radio waves emanated from the Earth to Universe about 60–70 years ago. This was the timing 4.56 Ga after the birth of Earth. Therefore, the probability of civilization-bearing planets must be 60–70/ 4,560,000,000 years, for the Earth-like planets in exo-solar planets. Furthermore, the extremely tight initial condition of 3–5 km thick ocean is another highly pessimistic hurdle.

Acknowledgments

We extend our sincere thanks to the two referees from *Geoscience Frontiers* whose detailed comments and suggestions were helpful in improving our paper. We appreciate fruitful and stimulate discussions with Drs. T. Ebisuzaki, Y. Isozaki, and J. Makino. K. Nakazawa, professor Emeritus at Tokyo Institute of Technology, guided us to explore the research combining origin and evolution of life with planetary formation, to whom we are sincerely thankful.

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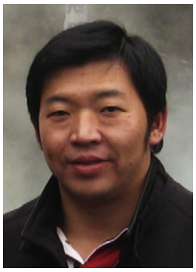

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