

Birth place of Life on the Hadean Earth

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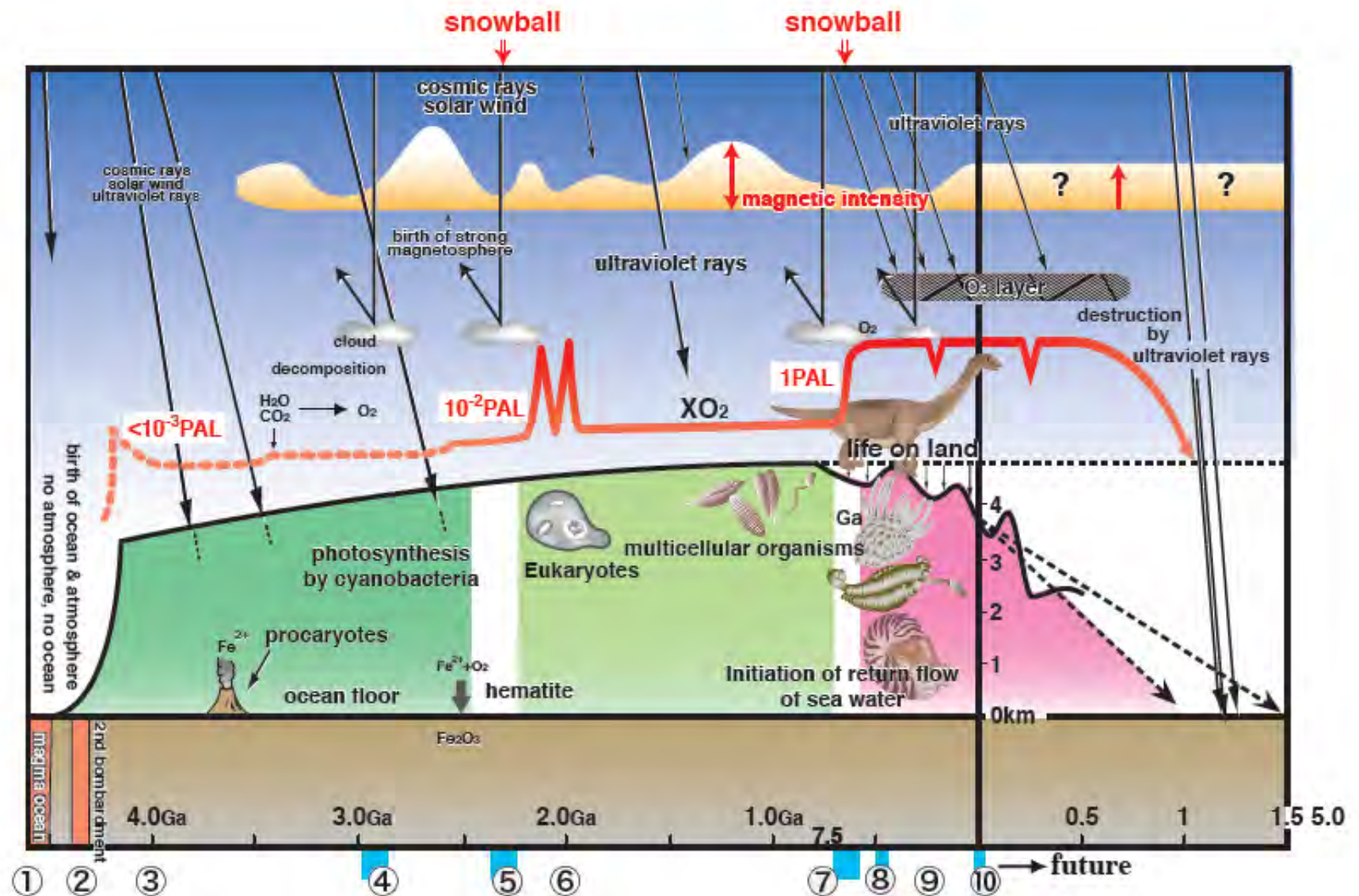
Tokyo Institute of Technology

Contents

- 1 When was life born?
- 2 Hadean surface environment of the Earth
- 3 Habitable Trinity
- 4 Birth place of life on the Hadean Earth
- 5 How to make habitable trinity planet
- 6 Scenario of birth of life
- 7 ELSI program
- 8 Discussion
- 9 Towards Astrobiology

1 When was life born?

ANS:>3.8Ga carbon isotope (Ueno et al., 2013)

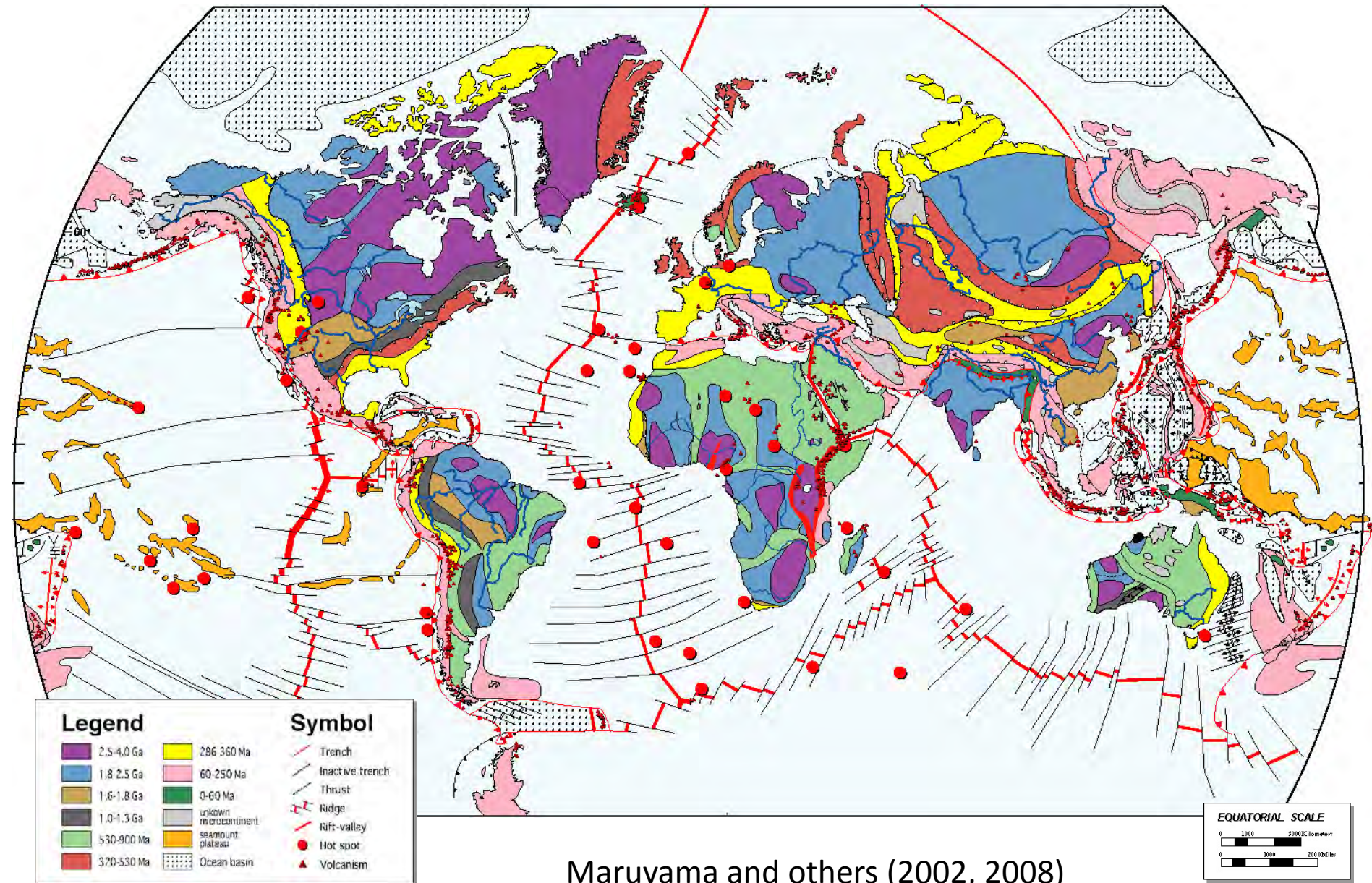


2 Hadean surface environment of the Earth

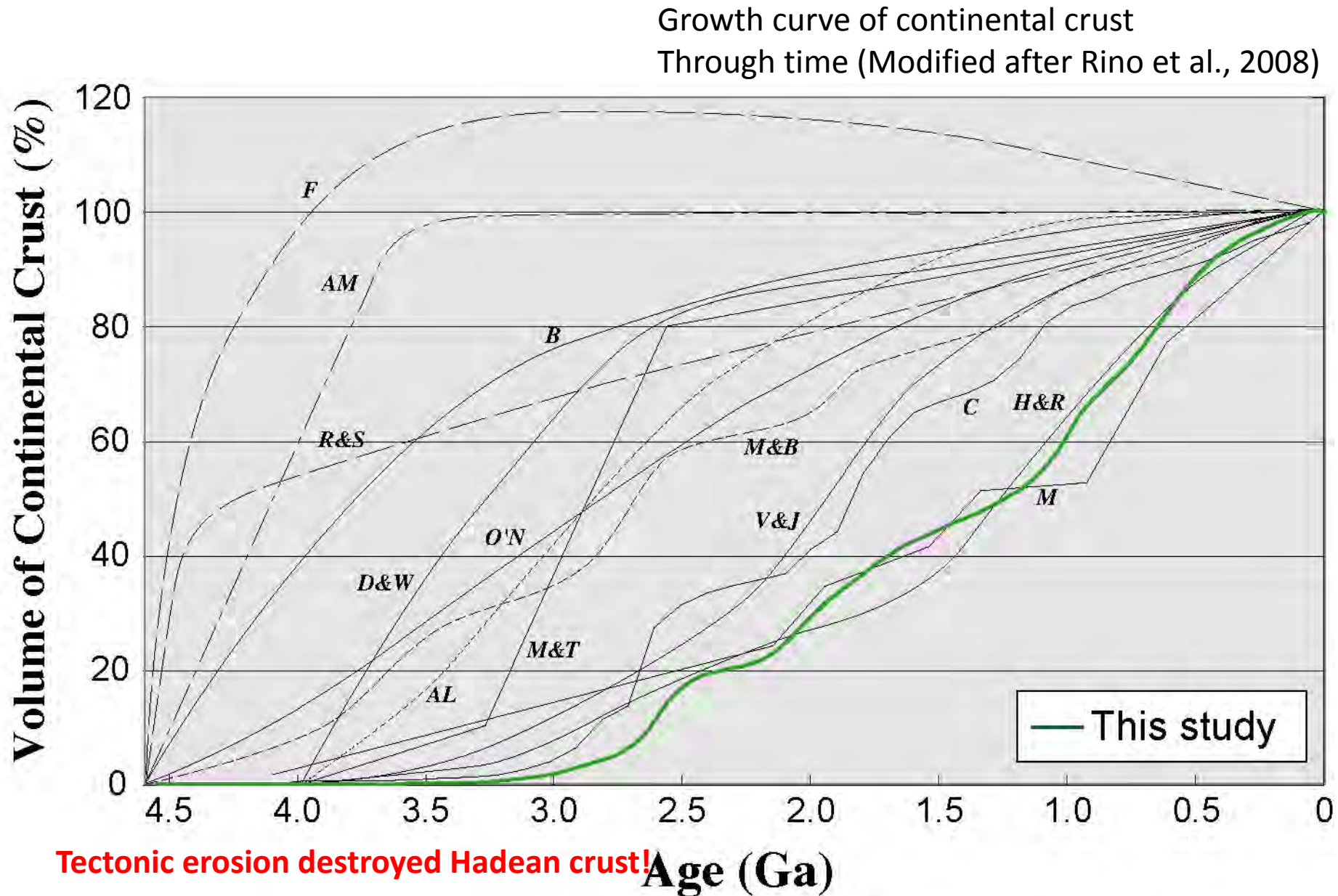


Orogenic belts of the world

No Hadean rocks on the Earth



結果：大陸成長曲線（補正後）River mouth zircons

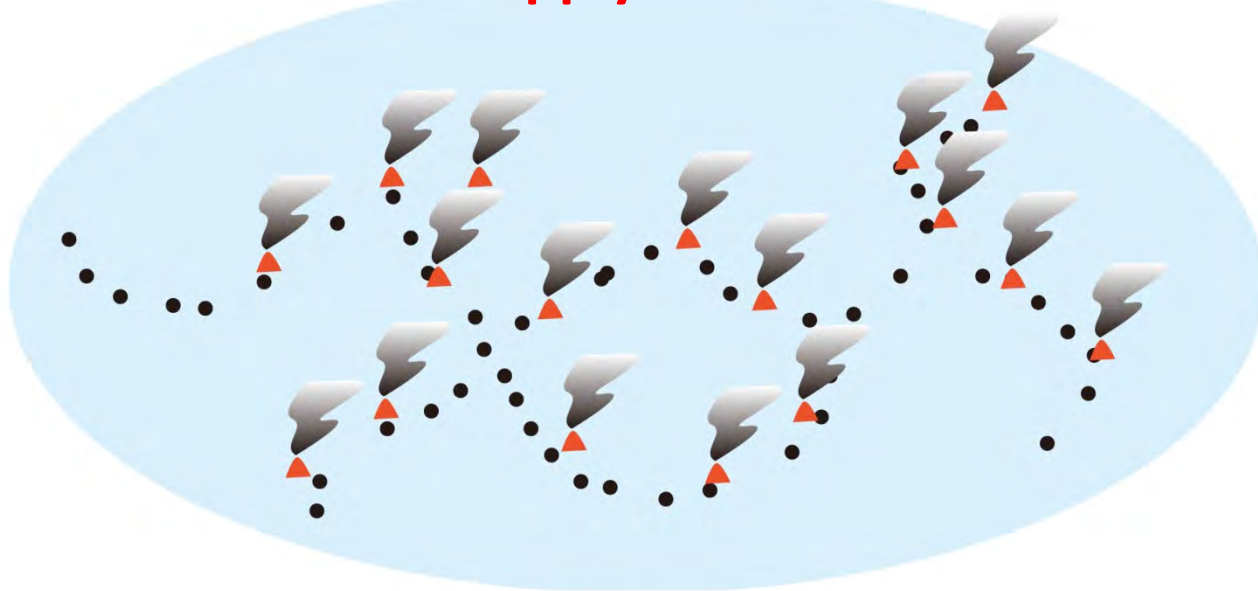


Absence of Hadean rocks, and lesser amounts of TTG crust with increasing geologic age

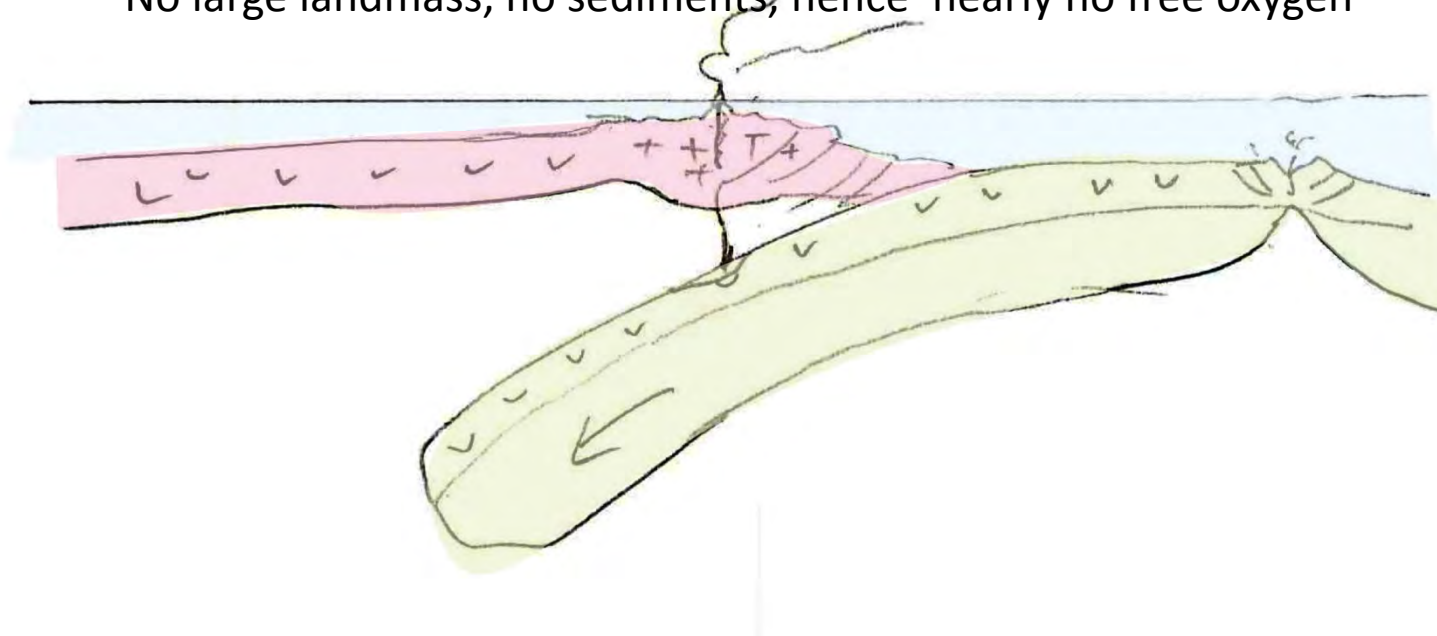
Hadean Earth

ARCHEAN

Few nutrients supply from continents



No large landmass, no sediments, hence nearly no free oxygen

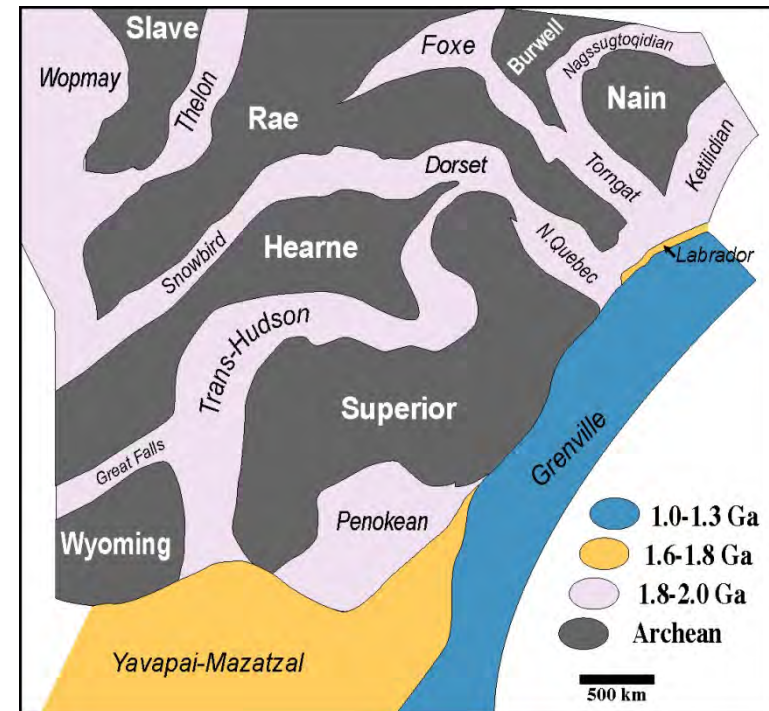
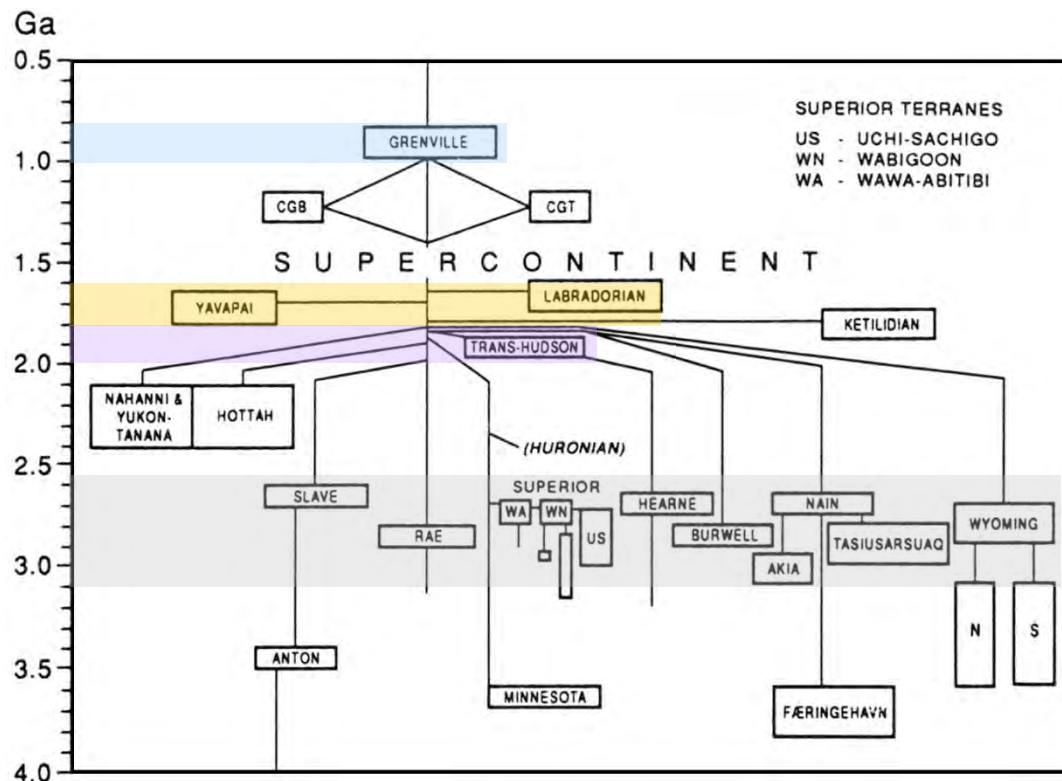
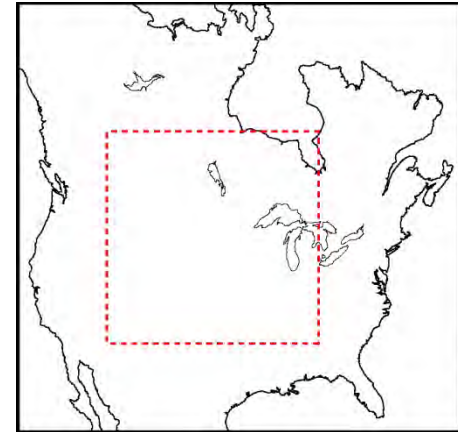


Was a huge landmass present in the Achean?

- Ans: No. Because of no sedimentary rock such as sandstones and mudstones. Only minor mafic sediments and cherts were present.

■ No large continents in the Archean: Geologic evidences

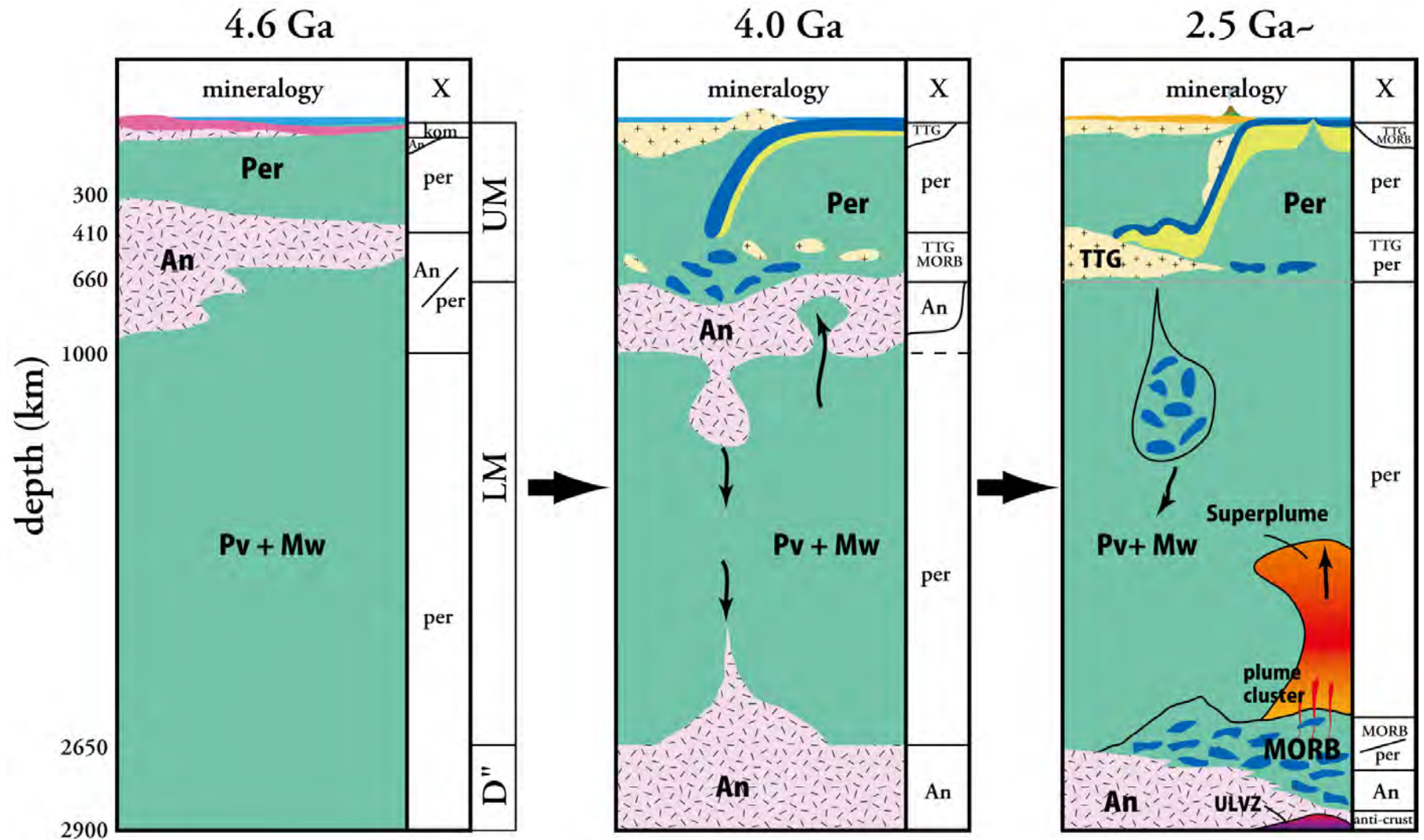
- (1) 島弧-島弧の衝突
- (2) (1)が衝突&間に若い造山帯
- (3) (2)の周りに若い造山帯
- (4) 大きな大陸



Two possibilities of Hadean TTG crust

- 1 Originally absent, by e.g., incomplete fractionation up to gabbro (basalts)
- 2 Present but lost, now in deep mantle
- 3 Look at Moon

Applying First Principle Calculation, we can predict the fate of Primordial Continents
Now at CMB and/or somewhere in lower mantle.



Primordial Earth in the Hadean

- 1 No rocks older than 4.0 Ga. Where the primordial continents had gone?
- 2 Geology of the Moon where 4.6Ga primordial continents remain which is anorthosite + KREEP (fractionated final residue)

Anorthositic continents covered by KREEP basalt with KREEP lower crust

Primordial continents
on which first life was born.

No Na on the
surface!

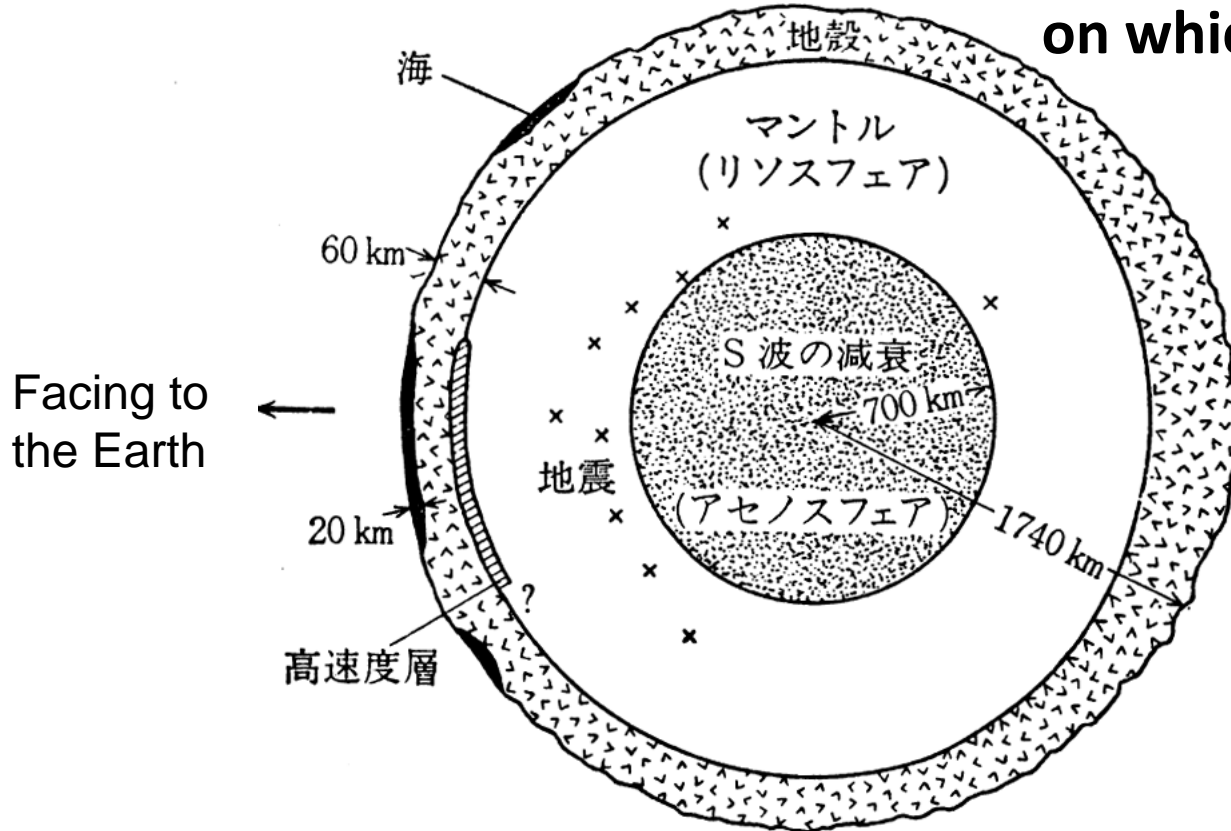


図 5.11 月の内部構造の模式図. 地殻の厚さは実際よりも誇張して書いてある (Toksöz & Johnston, 1974 による).

Anorthositic continents with KREEP are the excellent catalyzer to synthesize amino-acids and much larger organic compounds. Amino acids can be synthesized under the rifted lake on the primordial continents.

Why remained on the Moon?

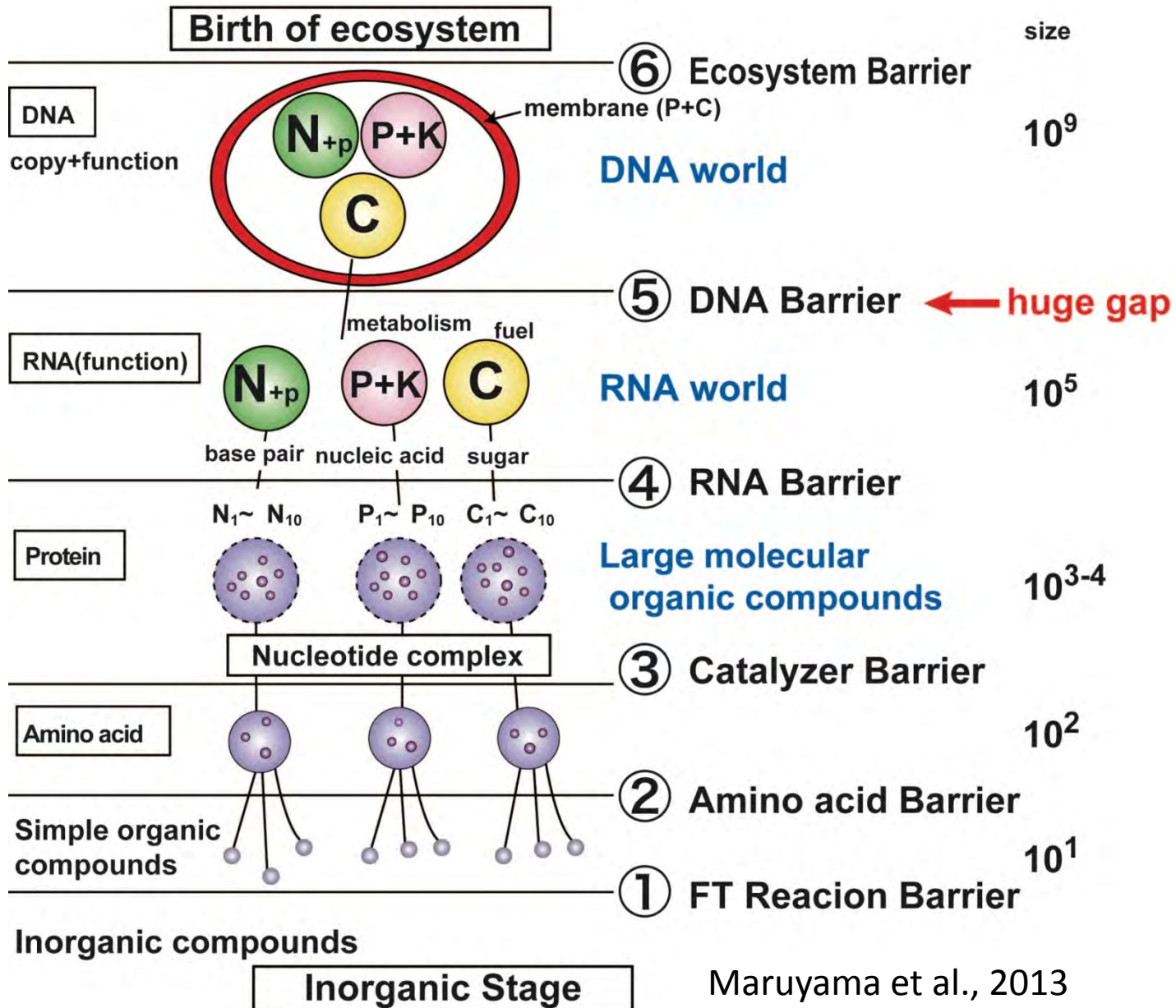
- Size: small hence cooled down quickly $<3.0\text{Ga}$

Habitable trinity

Beyond Habitable Zone concept

Life cannot survive under only water

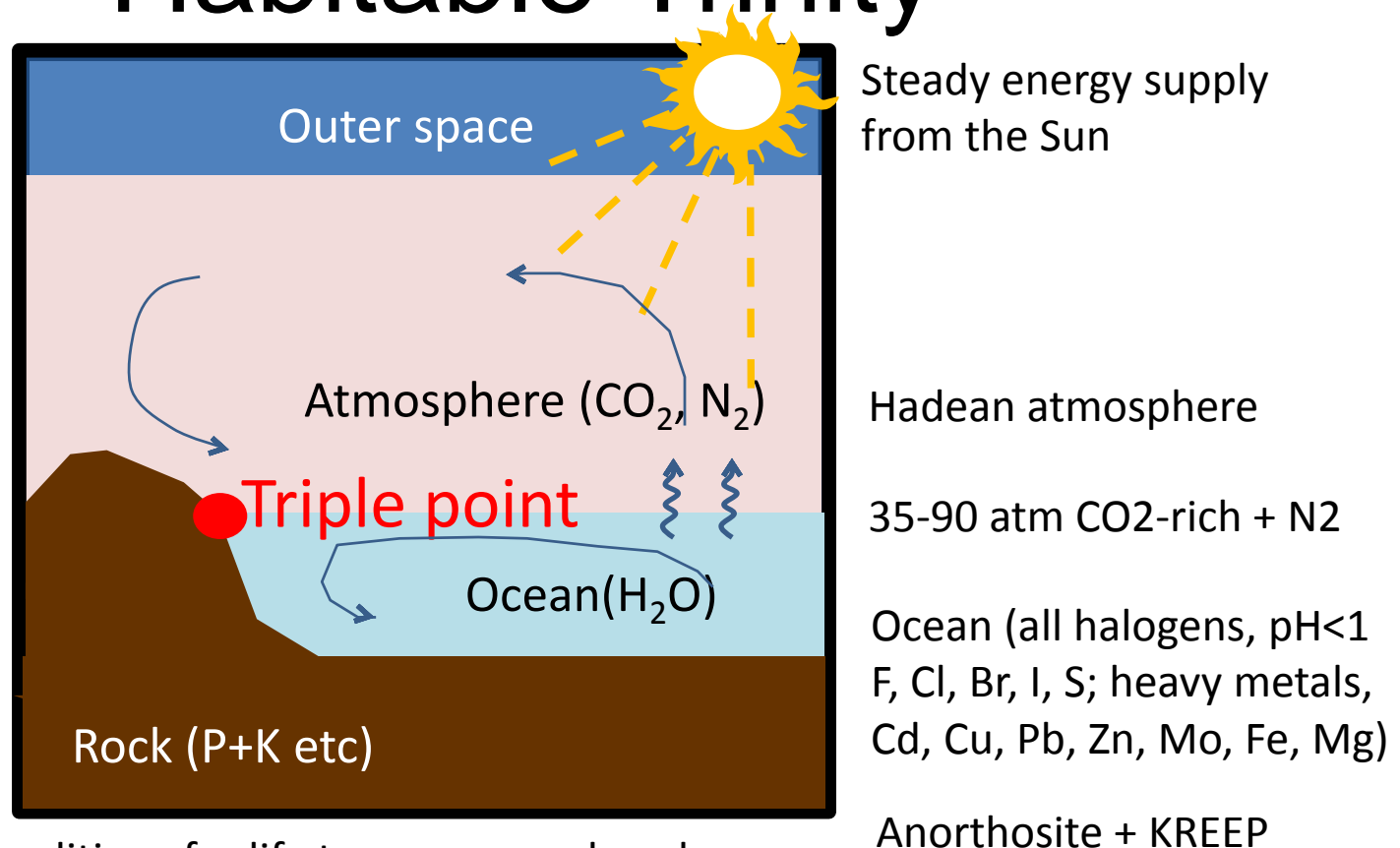
What is life?



2. ELSI's Scheme of Astrobiology

- 2) “**Habitable Trinity**” Model (Dohm and Maruyama, 2014)
> Life Emerged on **Surface Environment** of the Hadean Earth

“Habitable Trinity”



Three necessary conditions for life to emerge and evolve:

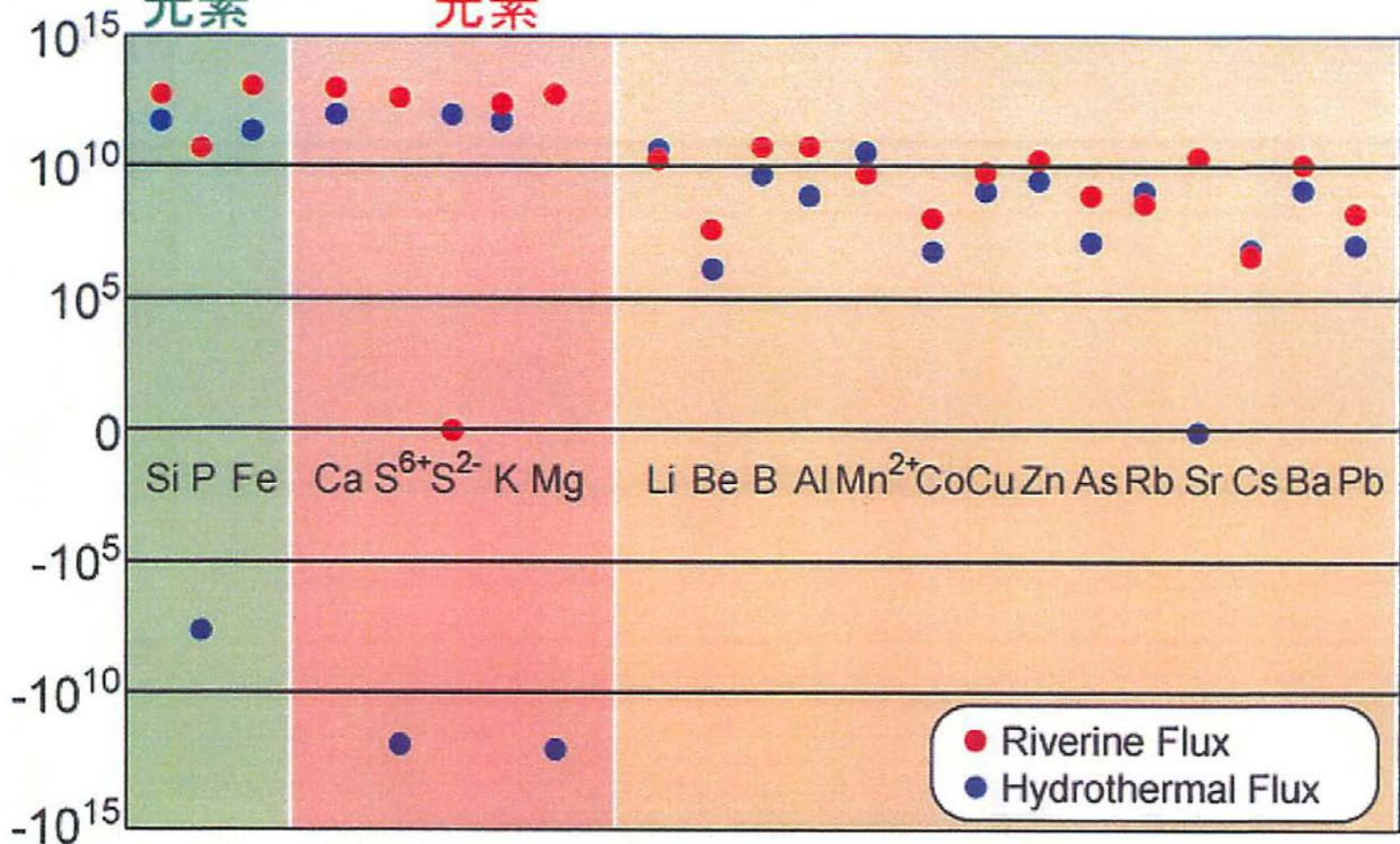
- (1) **Landmass** (oversaturated P for membrane),
- (2) **Lakes** (primordial ocean is **toxic**; ultra-acidic, high salinity, ultra-rich in heavy metals),
- (3) **Nutrients** (P-ore etc) continuously supplied

Birth place of life on the Hadean
Earth

Basalts and komatiites cannot provide nutrients such as P and K

- Origin of birth place of life at deep hydrothermal system (Takai et al., 2005; Sleep et al., 2007 and others) is wrong!

生物制限 生体構成主要
元素 元素



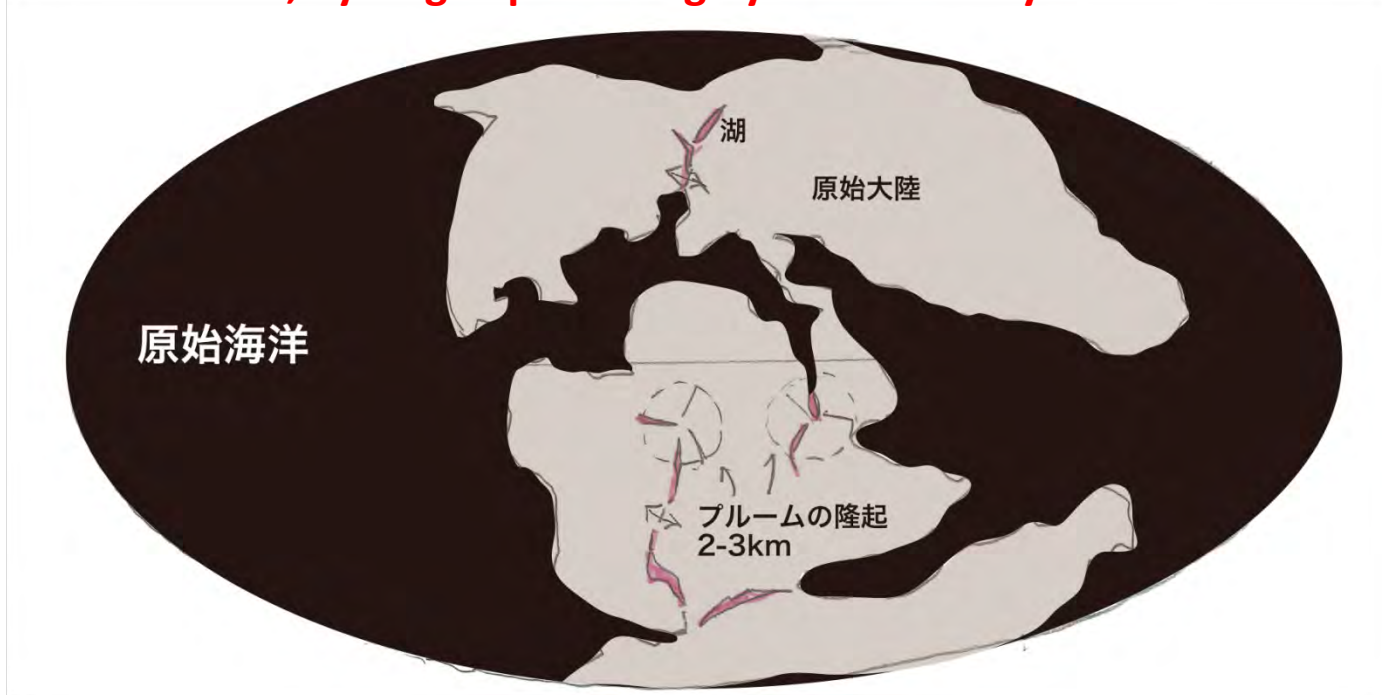
(mol/year)

(modified after Wheat et al., 2002; Klinkhammer et al., 1994b; German et al., 1990; Nozaki et al., 1997; Sholkovits, 1993; Sholkovits, 1992; Elderfield et al., 1990; Fantle and DePaolo, 2004)

Surface environment of the Hadean Earth right after the consolidation of magma ocean(4.4Ga)

原始生命誕生の場（湖）：水素 + 栄養塩 + 熱水 + 降雨

Birth place of life: Lake, hydrogen producing hydrothermal system with nutrient supply

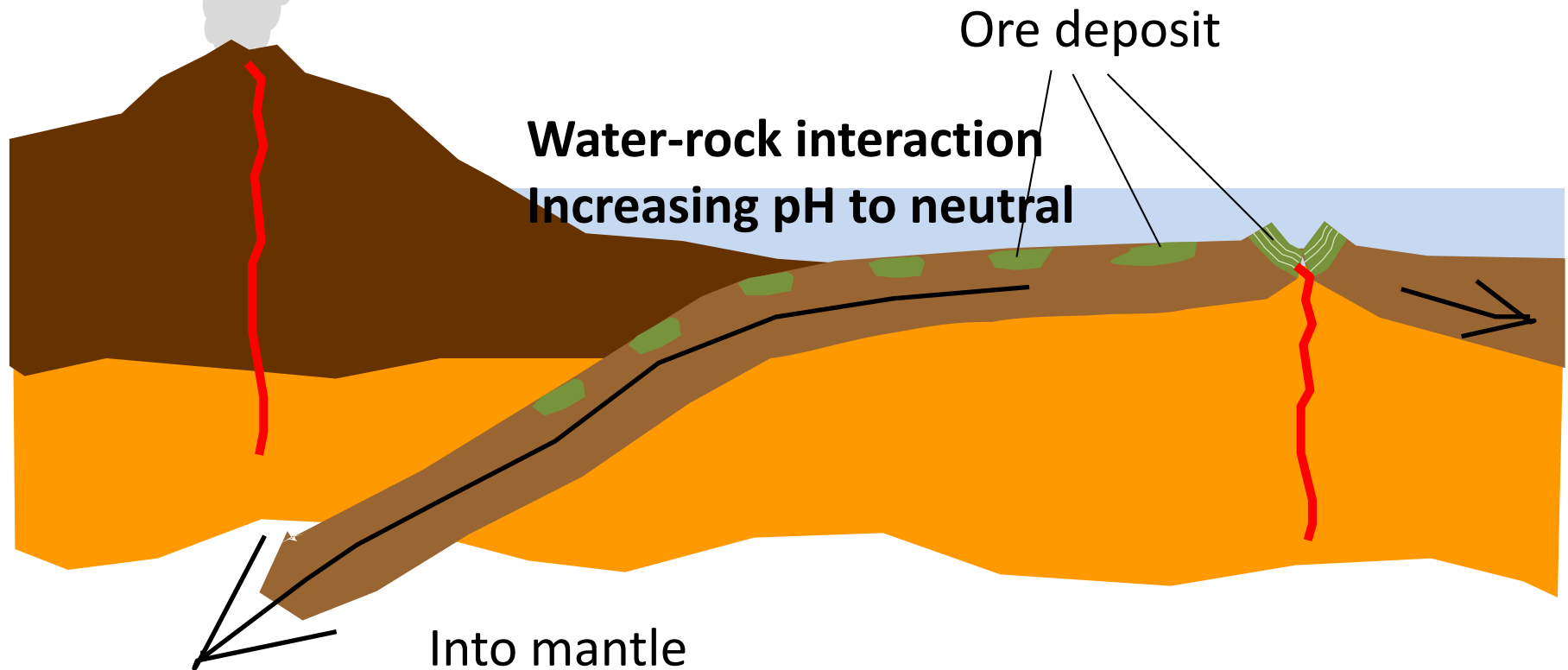


Primordial ocean was not the birth site of life because of super acidic (pH 1-2), super saline, high concentration of interfering metals

(1) Clean water was generated by evaporation of sea water and rainfall in the lake, (2) catalyzer (Li and B) concentration, (3) Hydrogen-producing hydrothermal system can be possible on the bottom of the Rift by serpentinization, (4) Large Oxidation-reduction Potential was born in the hydrothermal system with P-bearing ore at pH12 where first life was born.

Plate tectonics as a cleaner

Primordial ocean is (1) Ultra-acidic, (2) High salinity, (3) Ultra-enriched in heavy metals

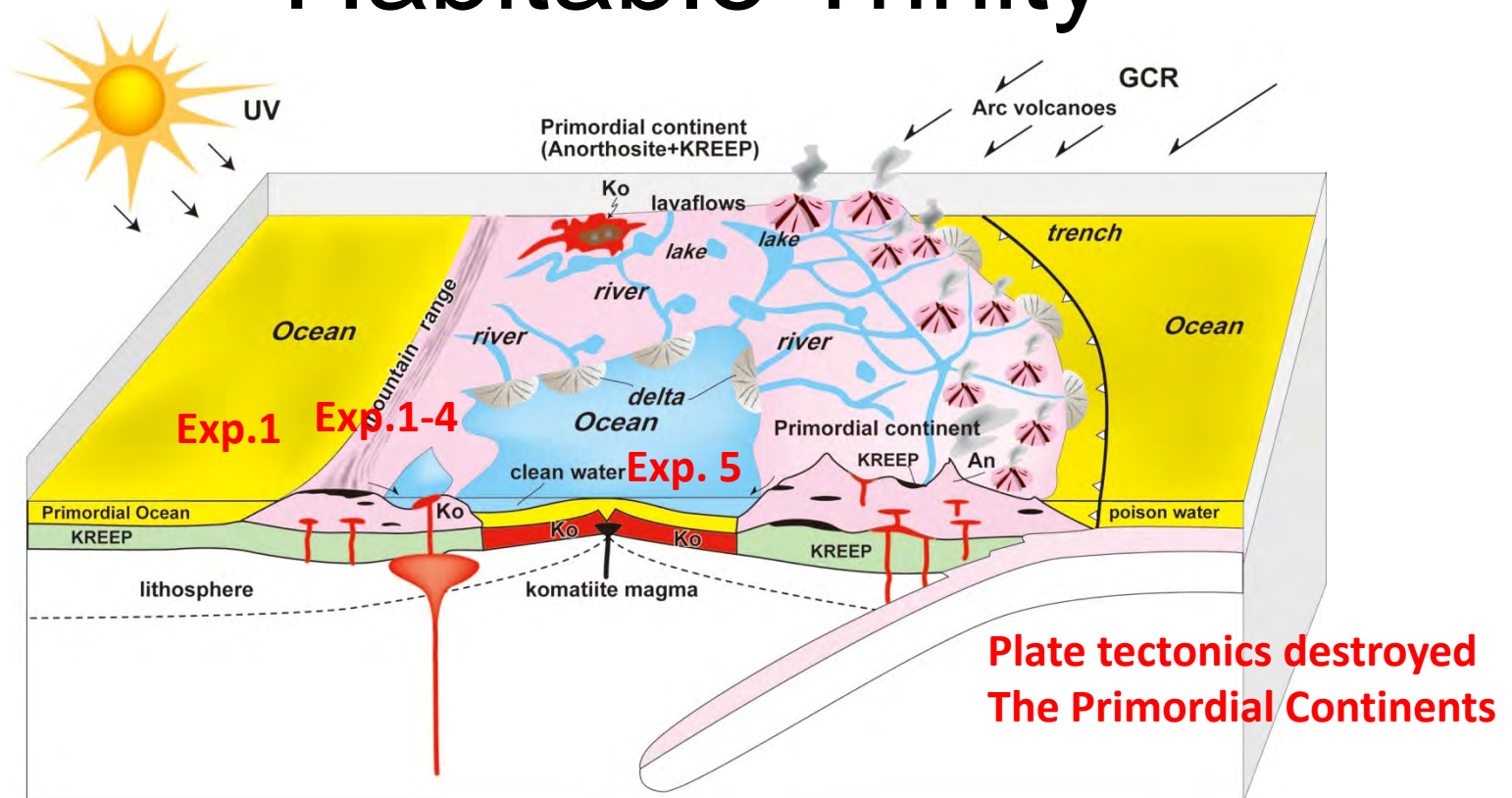


2. ELSI's Scheme of Astrobiology

2) "Habitable Trinity" Model

> Life Emerged on **Surface Environment** of the Hadean Earth

"Habitable Trinity"



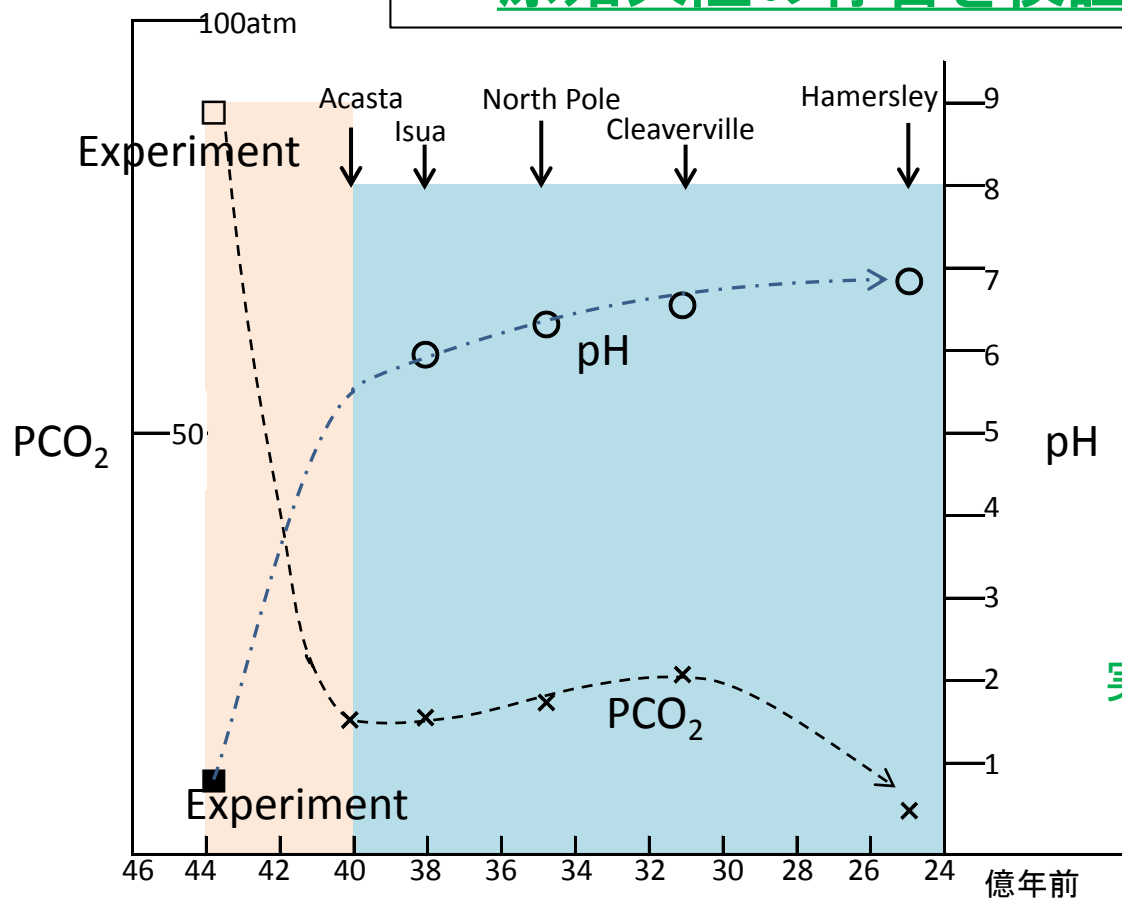
Why is Landmass necessary for Life to emerge and evolve? → Continuous Nutrient Supply

(1) Primordial continents (An+KREEP)

(2) Cytoplasm ($K/Na > 40$), but Archean TTG is Na-rich.

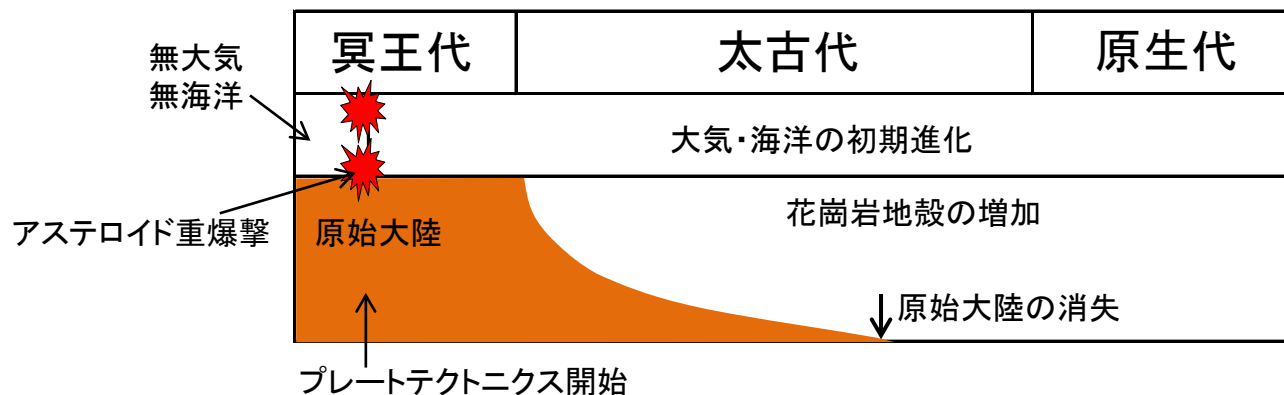
Maruyama et al., submitted to GR; Surface environment of first life on the Hadean Earth

原始大陸の存否を検証



- ・重金属元素
- ・Salinity
- ・ PO_2 など

実験G3(澤木)



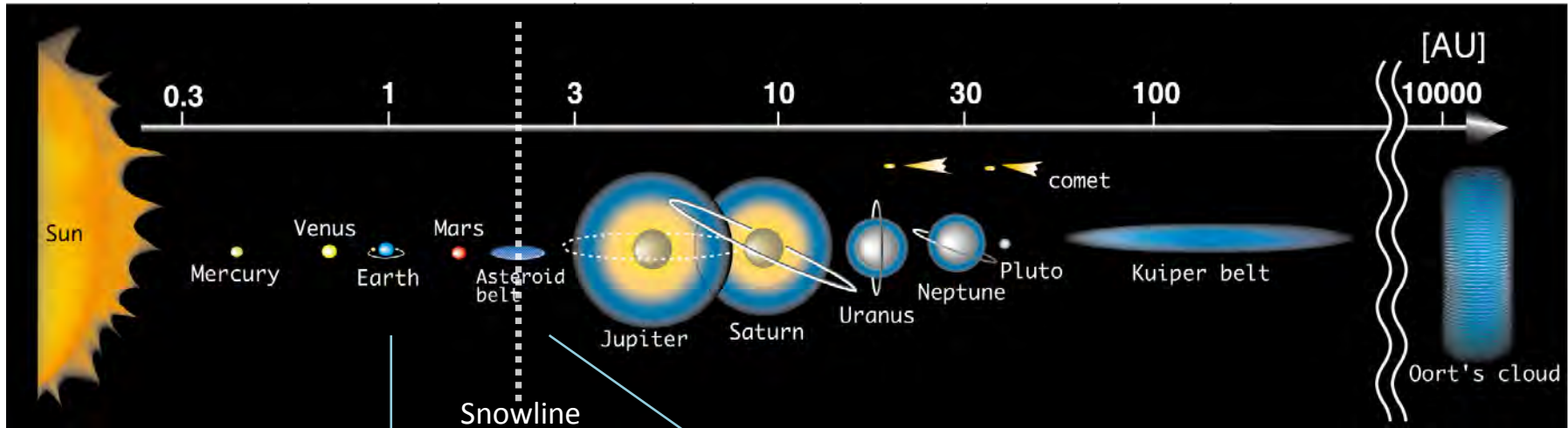
How to make a naked rocky planet

Habitable trinity planets

2. ELSI's Scheme of Astrobiology

1) "Naked Earth" Hypothesis (Maruyama et al., 2013)

> Water Supplied Through **Planetary Formation**



"Naked" = extremely thin
ocean and atmosphere

Earth → Landmass → Life



Ocean: 4km thick
(0.023H₂O%)

Another Earth



Ocean: 400km thick

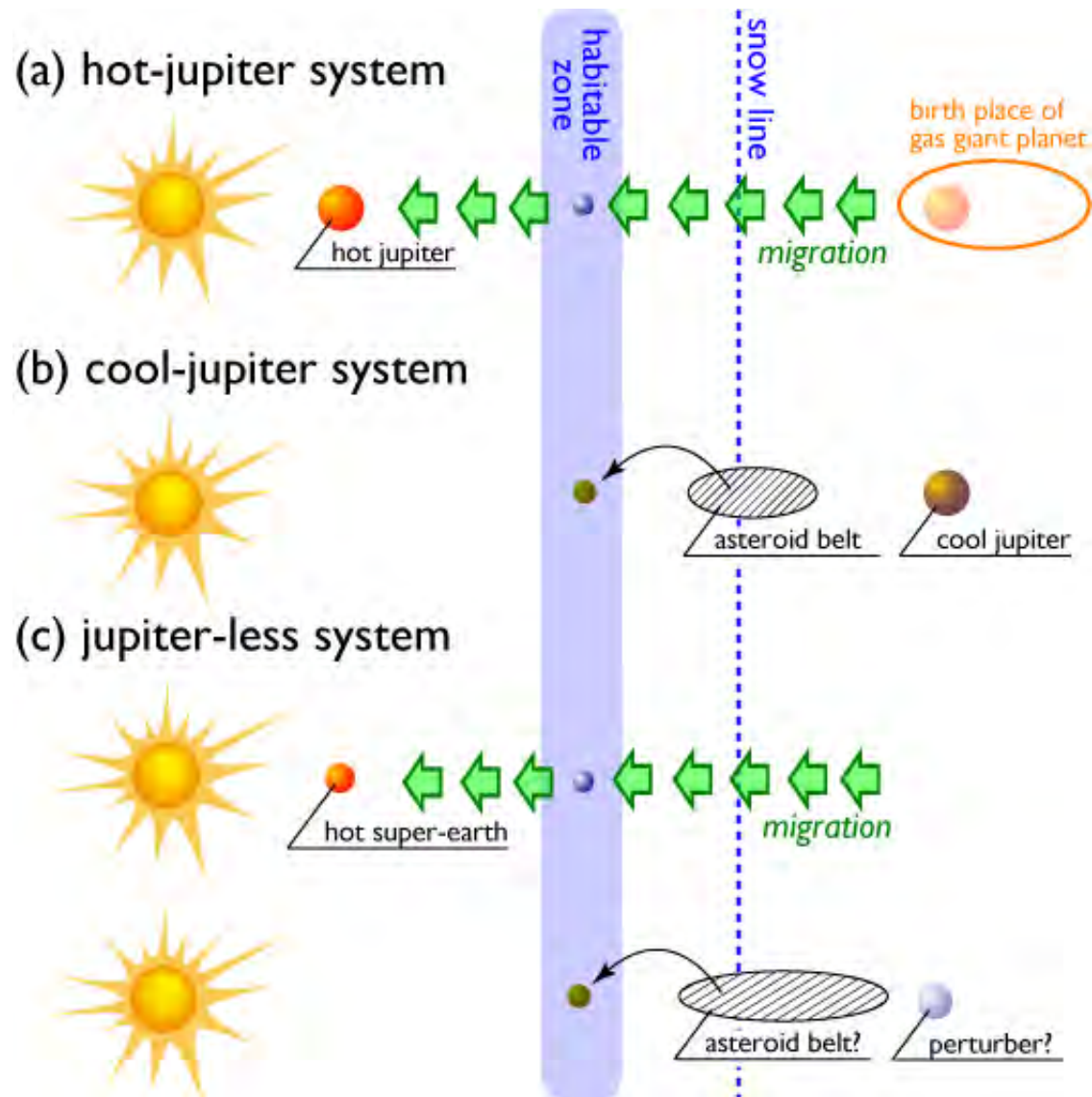
Made from 3H₂O%
chondrite

No Landmass → No Life

2. ELSI's Scheme of Astrobiology

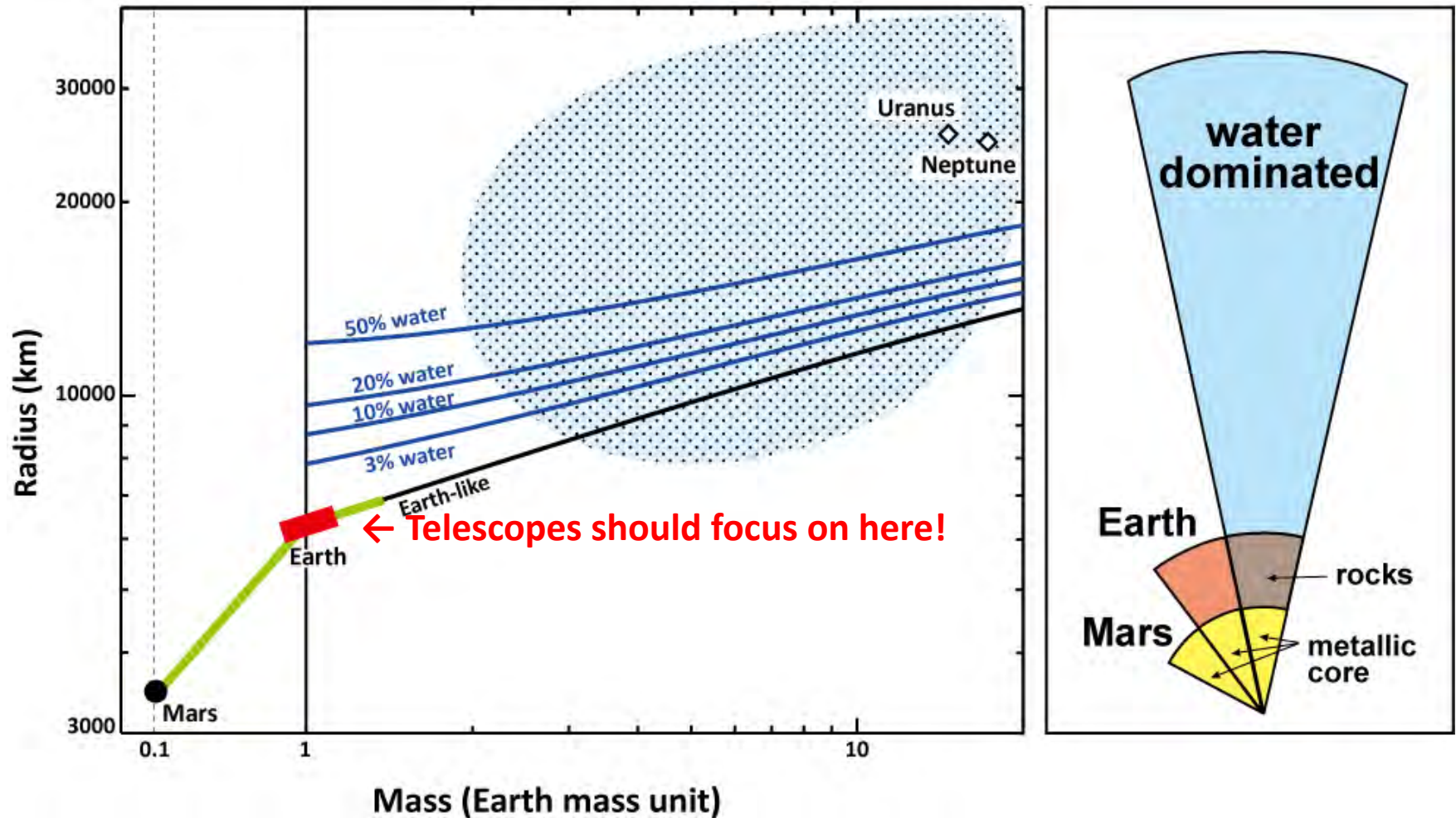
1) "Naked Earth" Hypothesis

> Water Supplied Through **Planetary Formation**



3. “Universal” Life in Space

2) Extraterrestrial Life: Exploration of “Habitable Trinity Zone Planets”



To harbor large multicellular life: the size of planet must be not too big, not too small

Maruyama, Ikoma, Genda, Hirose, Yokoyama, 2013

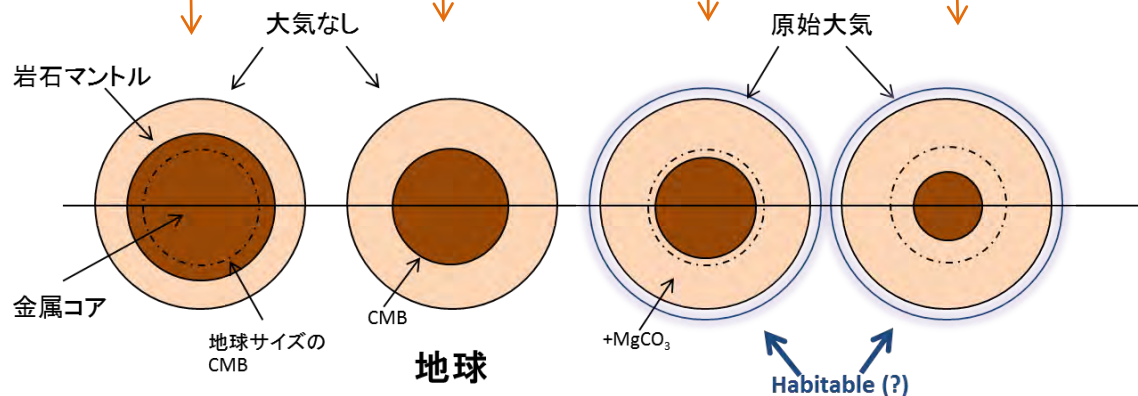
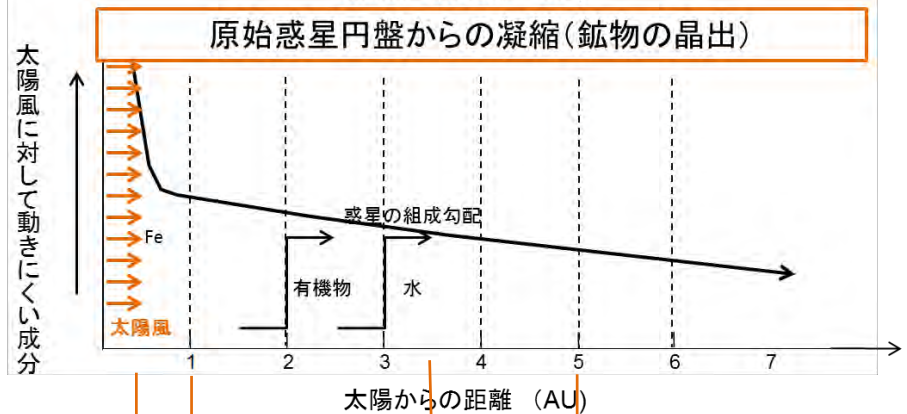
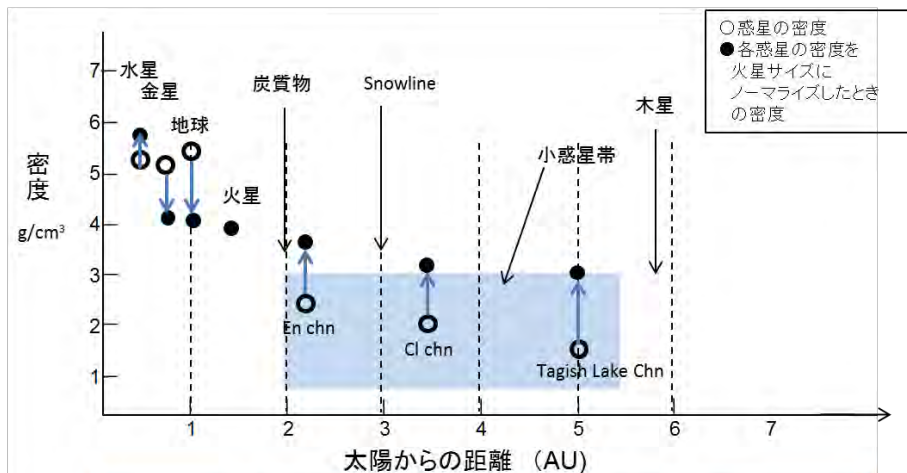
太陽系岩石惑星の化学組成の推定

第1段階:
太陽系岩石惑星の
全岩化学組成を知る

第2段階:
中心星(サイズと組成)と
中心星からの距離の関数
として、惑星のタイプが求まる

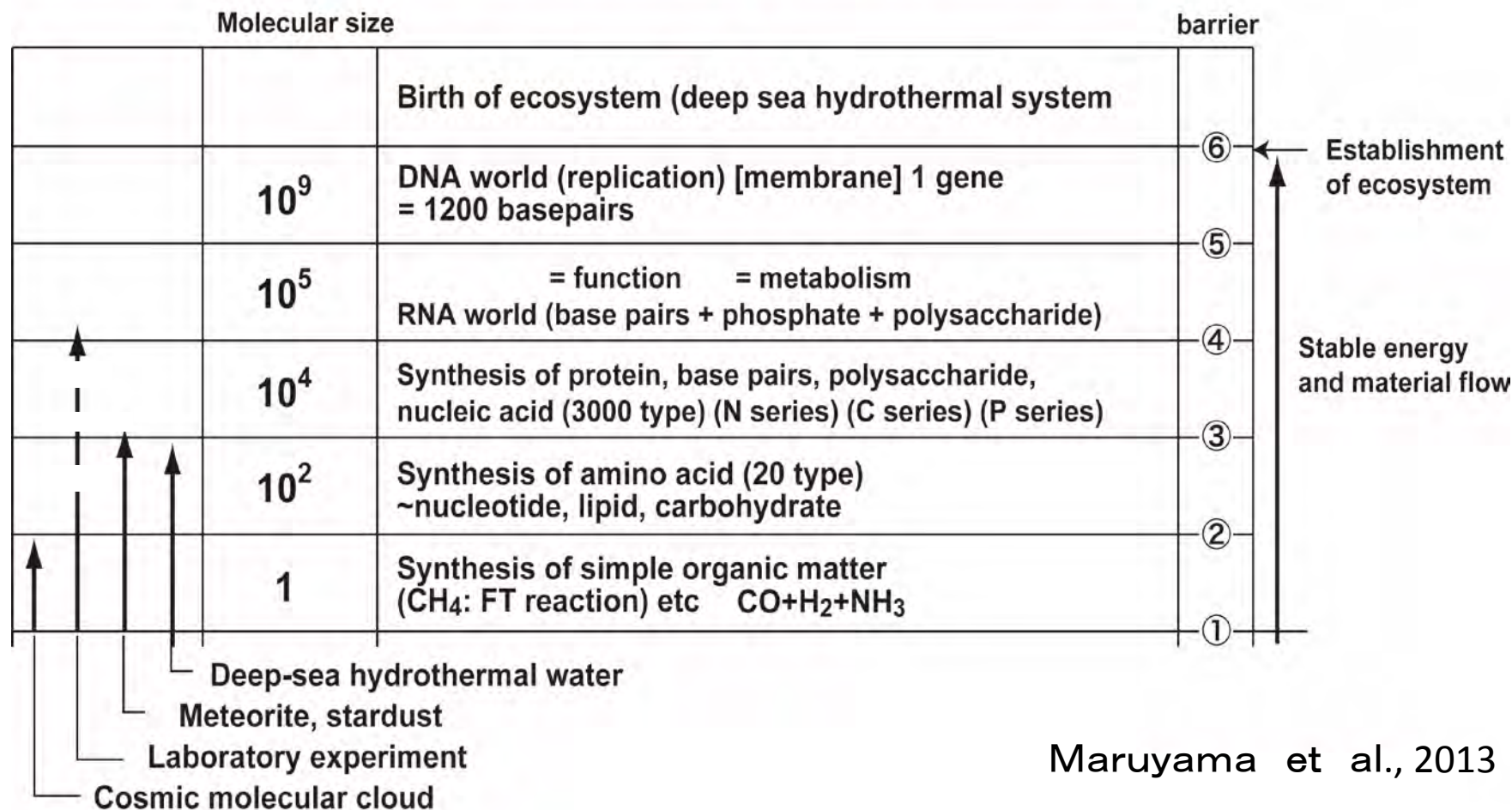
第3段階:
生命惑星の誕生と進化
は固体惑星内部の
ダイナミクスが決める

●実験室で岩石惑星を創る



Birth of life

Difficulty of synthesis of huge organic compounds



Maruyama et al., 2013

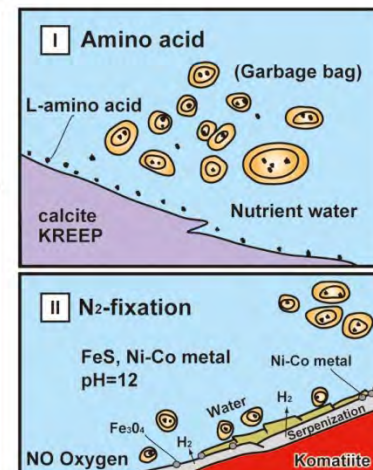
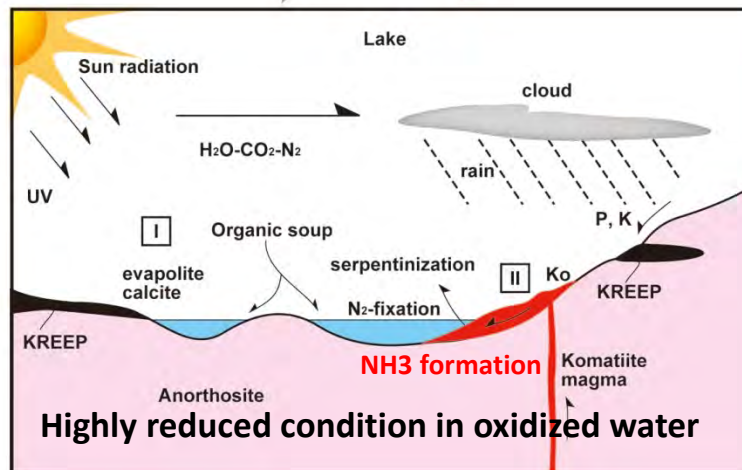
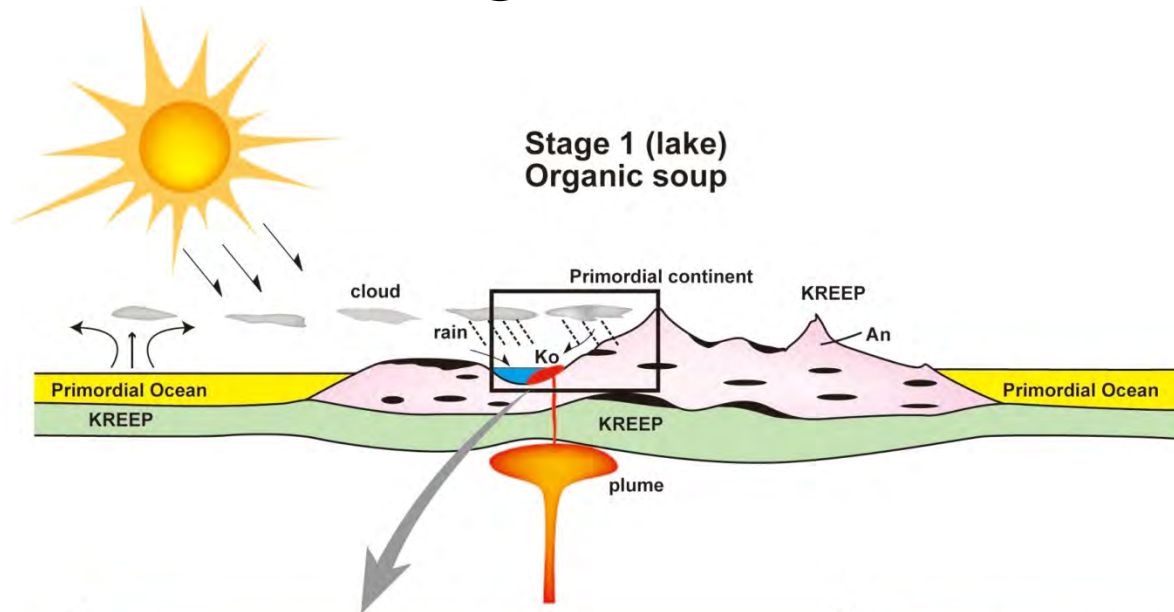
Difficulty of synthesis of life in laboratory. Barrier 4, 5 and 6 are extremely difficult because of stabilization of huge organic molecules. Natural processes more than several thousands of reactions were coded finally into Genome finally to pass over the Barrier 5 to become life.

2. ELSI's Scheme of Astrobiology

2) "Habitable Trinity" Model

> Life Emerged on **Surface Environment** of the Hadean Earth

Formation of Organics and Membrane

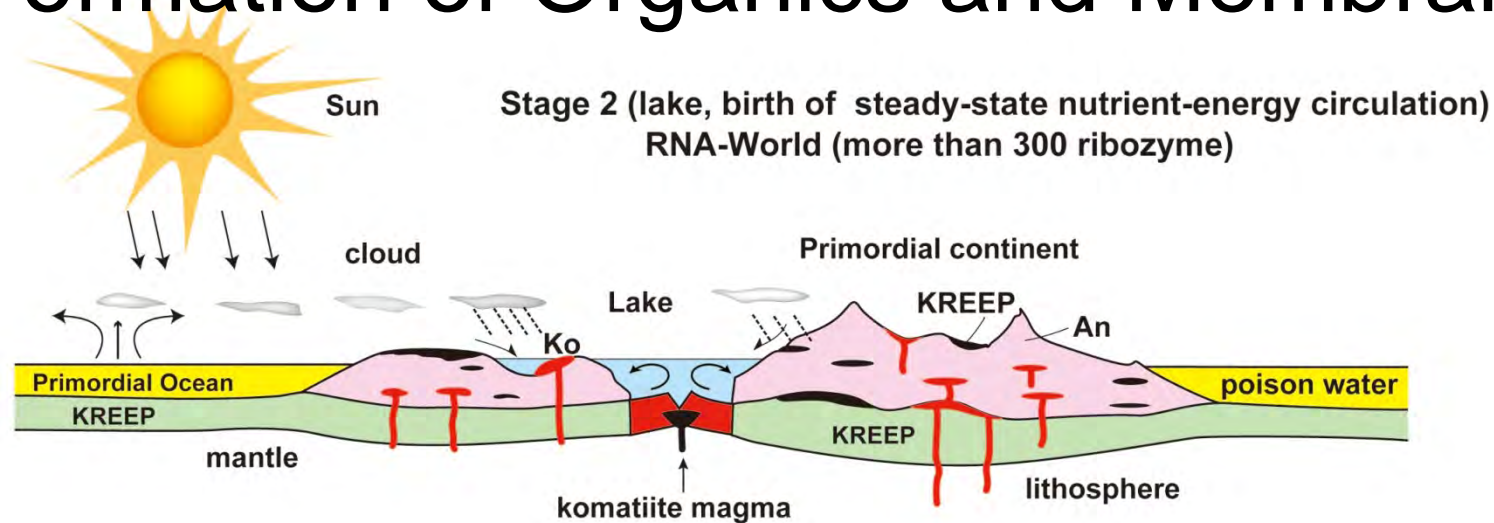


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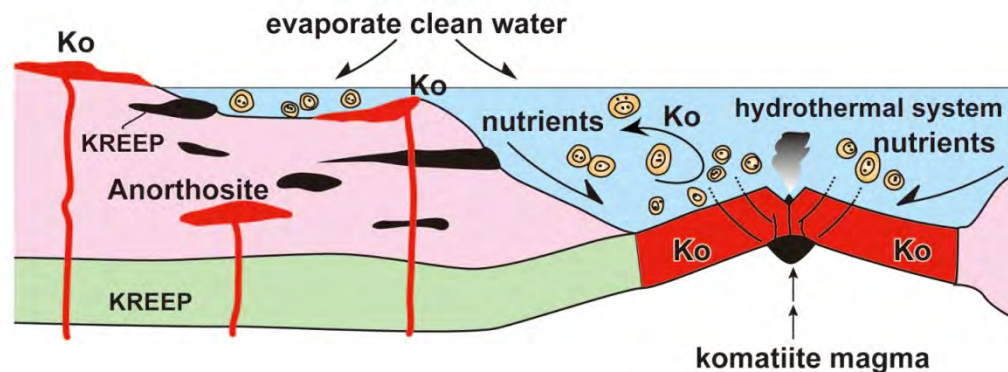
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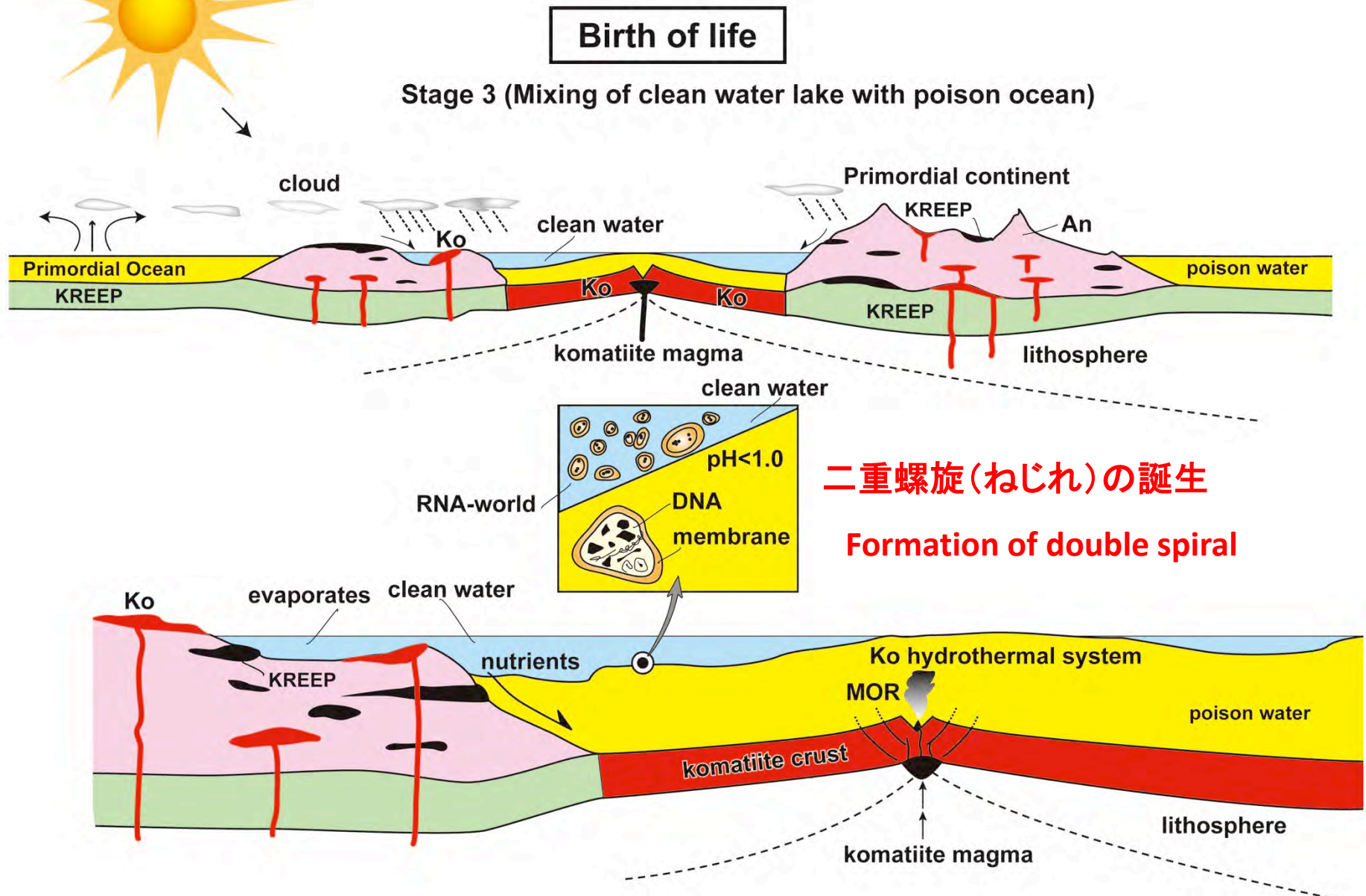
Formation of Organics and Membrane



Diversified and evolved ribozymes (replication by steady-state nutrients circulation)



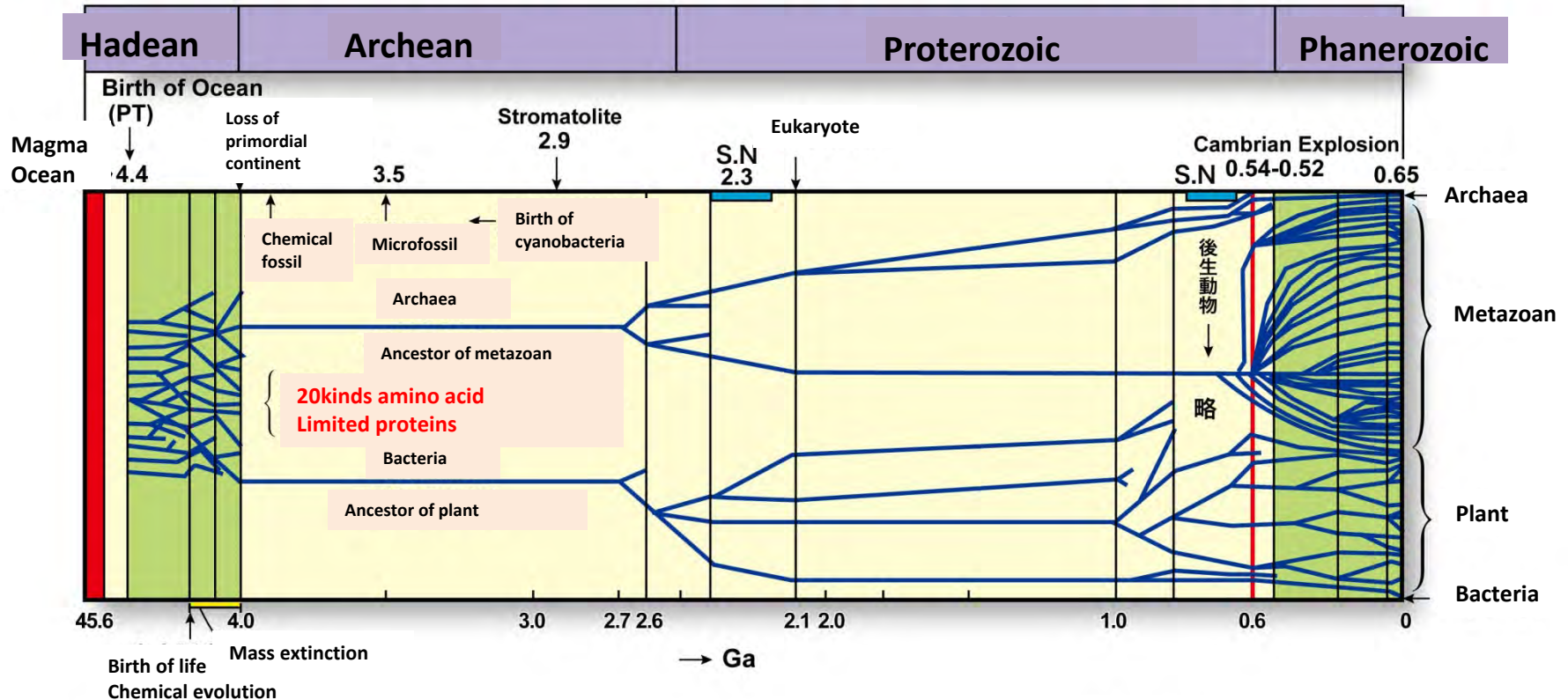
Birth of DNA: Taking time over 300m.y. by repeated mixture of farming proto-cells in lakes with toxic ocean. This is a try-and-error process to bundle several hundred organic radical reactions.



Golden age for life:

生命の合成実験: 第一段階まではOK
第2段階(RNA→DNA)は困難

First and Last 600 million years (Repetition of extinction)



Hadean

- Diversified microorganisms
- Extinction & evolution during 400 m.y.
- Finally, Archaea & eubacteria
- Loss of primordial continent

第2段階はtop-downを組み合わせる

Phanerozoic

- Golden age for plants and metazoan
- Occupying on-land environment (increase in oxygen content)
- Emergence of huge landmass

5 ELSI program

> Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**

3rd row: membrane

2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

> Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**

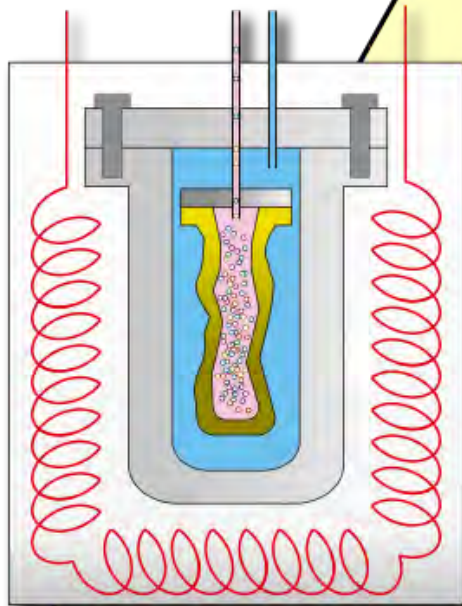
ELSI's Identities

1. Early Earth's Surface Environments 2. Extreme Environments Microbes (GCOE)

1st Phase (~March, 2017)

1) Primordial Ocean

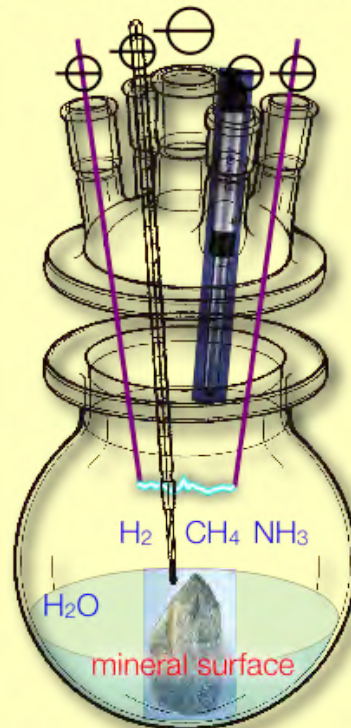
chemical compositions



Hydrothermal Reactors

2) Prebiotic Chemistry

chemical evolutions



Multi-Stage Miller-Urey Experiments

3) Primitive Microbes

resurrection database



Hakuba Hotspa

Genome Analysis of
Thermophilic Microorganisms

Experiments for pre-biotic evolution of life

2. ELSI's Scheme of Astrobiology

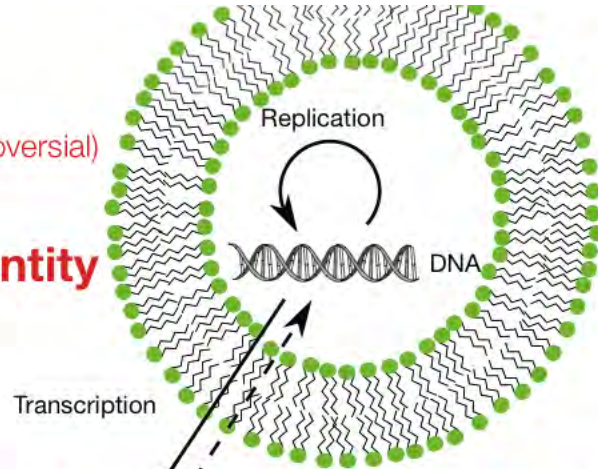
3) Exploring the **Origin of Life**

> Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**

Origin of Life

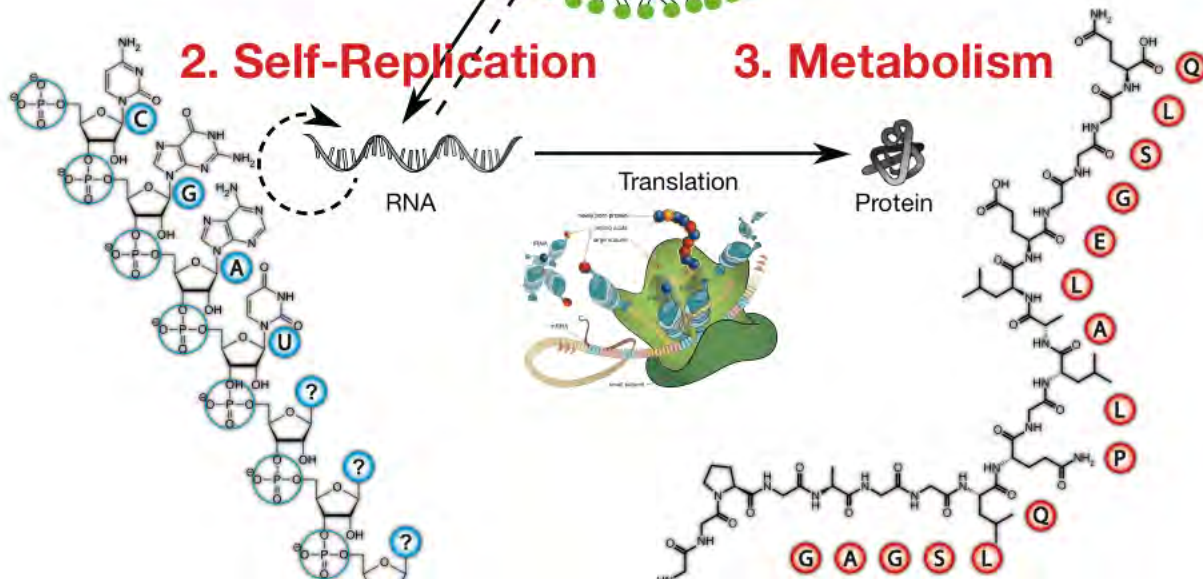
Def) Life (controversial)

1. Identity



2. Self-Replication

3. Metabolism

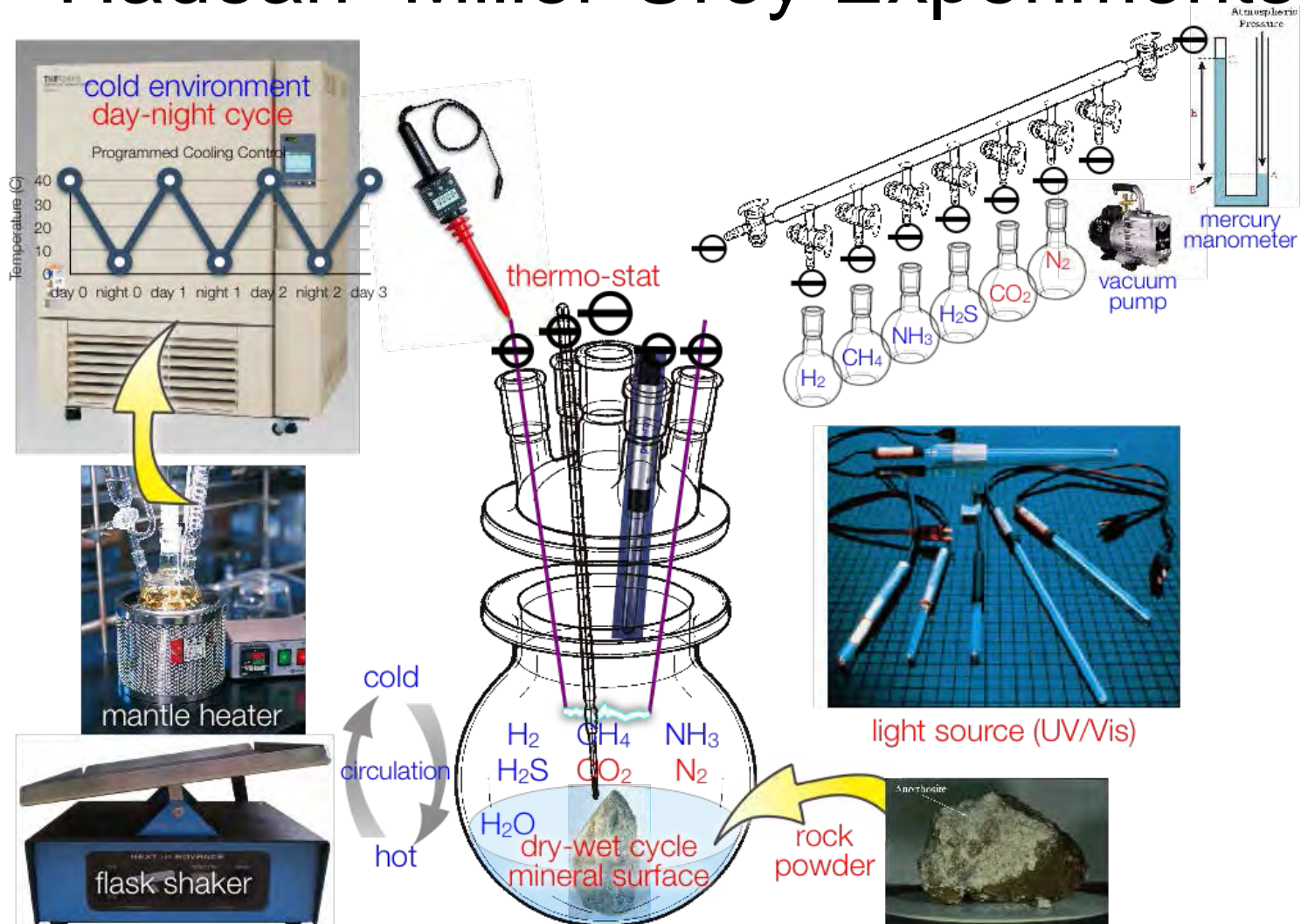


2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

> Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**

“Hadean” Miller-Urey Experiments

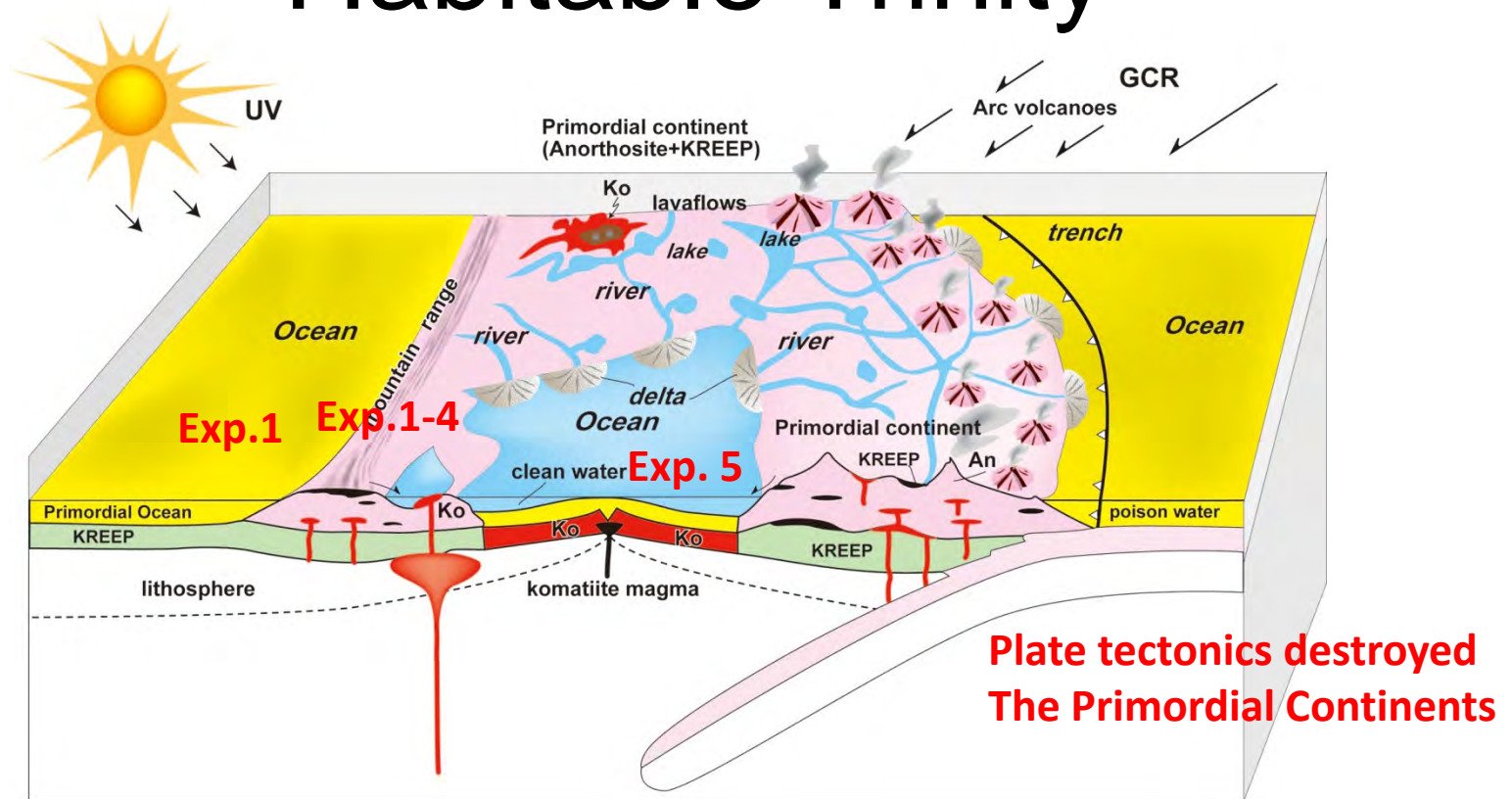


2. ELSI's Scheme of Astrobiology

2) "Habitable Trinity" Model

> Life Emerged on **Surface Environment** of the Hadean Earth

"Habitable Trinity"



Why is Landmass necessary for Life to emerge and evolve? → Continuous Nutrient Supply

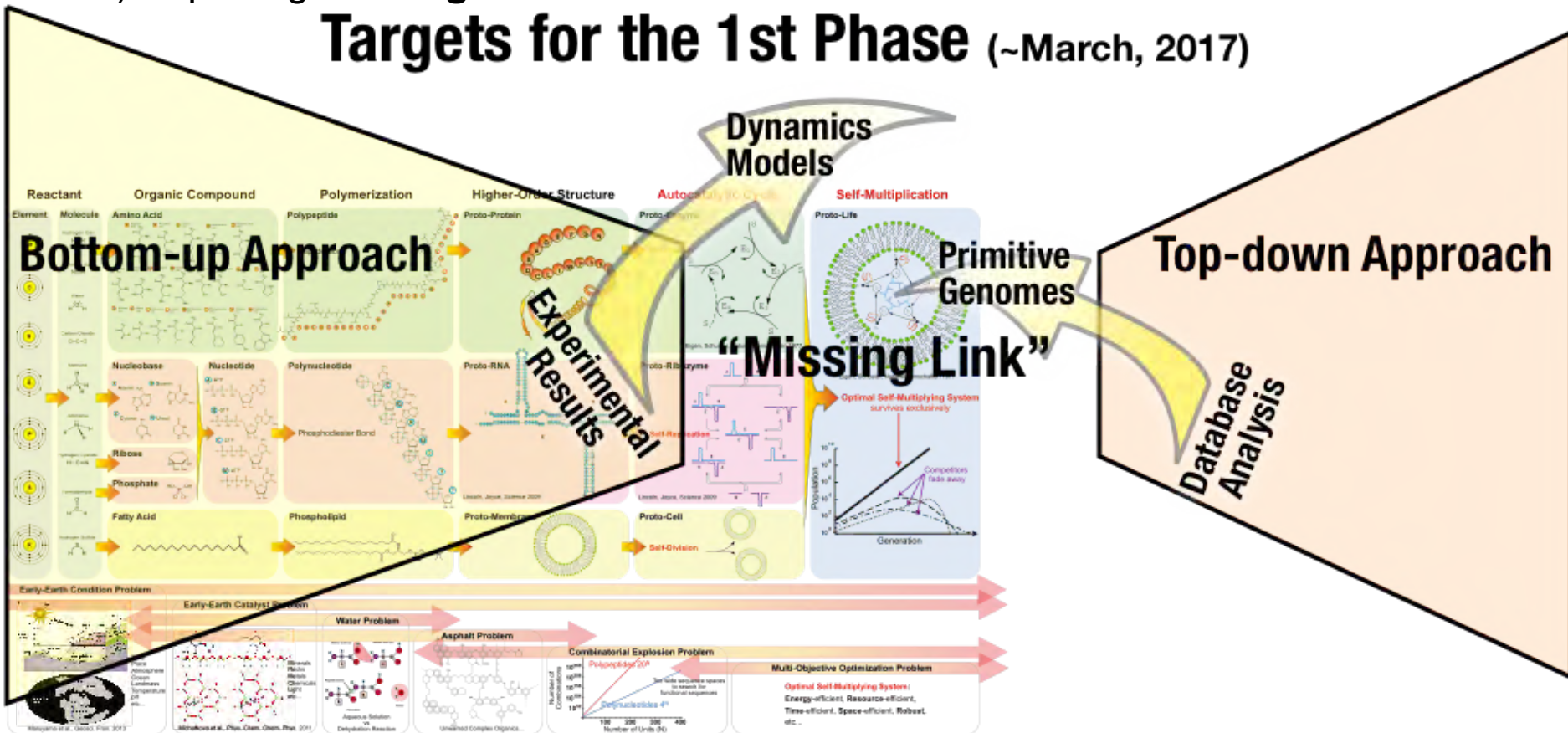
(1) Primordial continents (An+KREEP)

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Maruyama et al., submitted to GR; Surface environment of first life on the Hadean Earth

3) Exploring the **Origin of Life**

Targets for the 1st Phase (~March, 2017)



Chemical Evolution Experiments

- 1) Discovery of New Self-Organizing Phenomena: **Multi-Stage Synthesis of “Functional” Polypeptides and Polynucleotides**
- 2) Discovery of **Optimal Catalysts** (Minerals, Rocks, Interfaces, Wavelength, etc)
- 3) Comprehensive **Parameter-vs-Product Database**

Genome Database Analysis

- 1) Primitive Metabolism
- 2) Primitive Self-Replication
- 3) Primitive Membrane

How to bridge missing link

2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

> Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**

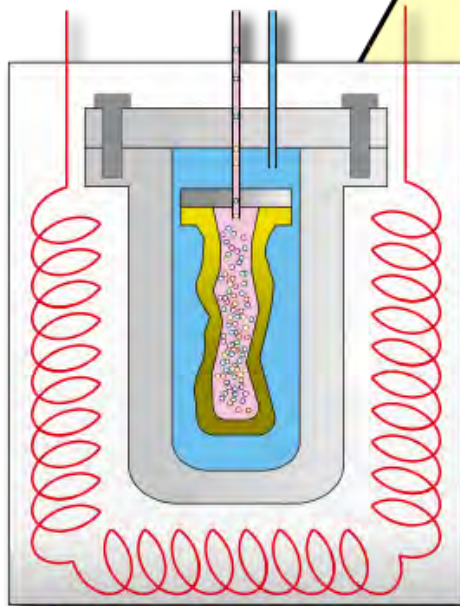
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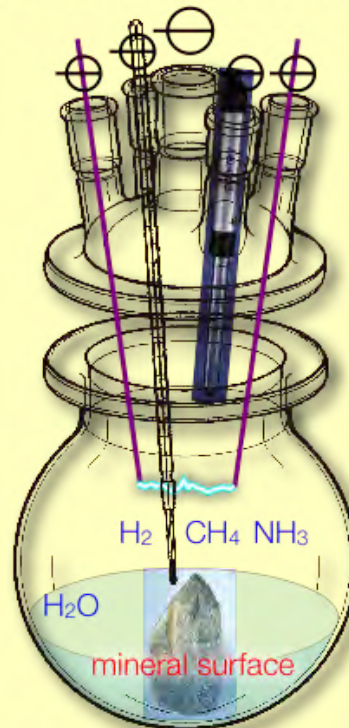
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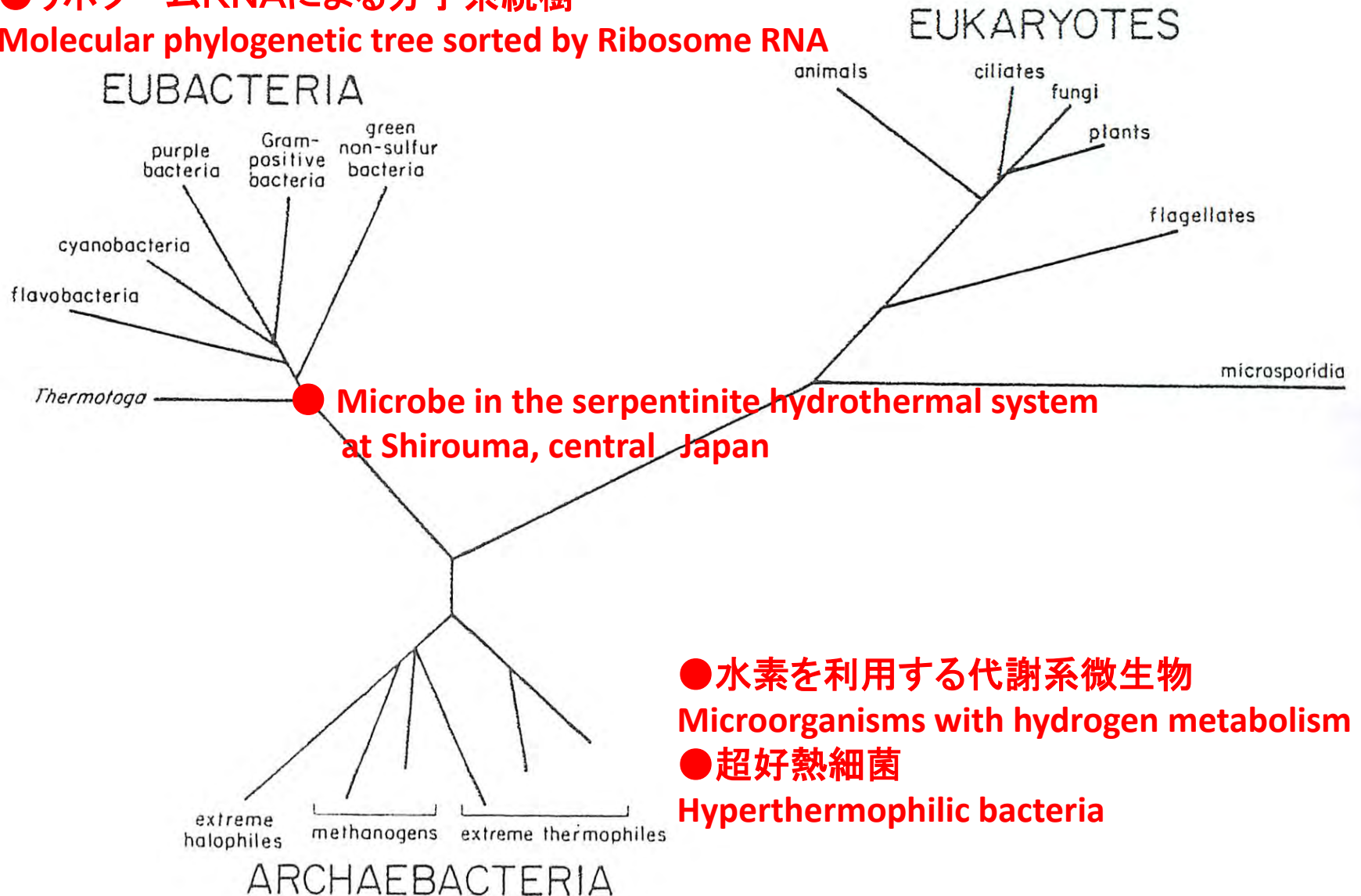
2. Present: ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

Top-down Approach: Decoding the **Genome of Primitive Organisms**

● リボソームRNAによる分子系統樹

Molecular phylogenetic tree sorted by Ribosome RNA



Discussion

- 1 Previous works
- 2 Oparin-Miller-Urey Hypothesis
- 3 Deep-sea hydrothermal system (basalt)
- 4 Deep-sea hydrothermal system (komatiite)
- 5 Primordial Continents (our model)

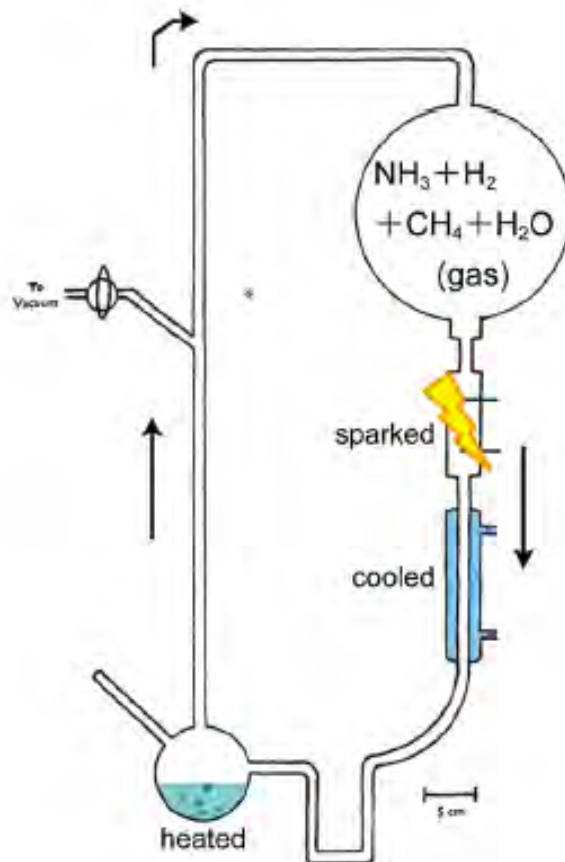


FIG. 1.



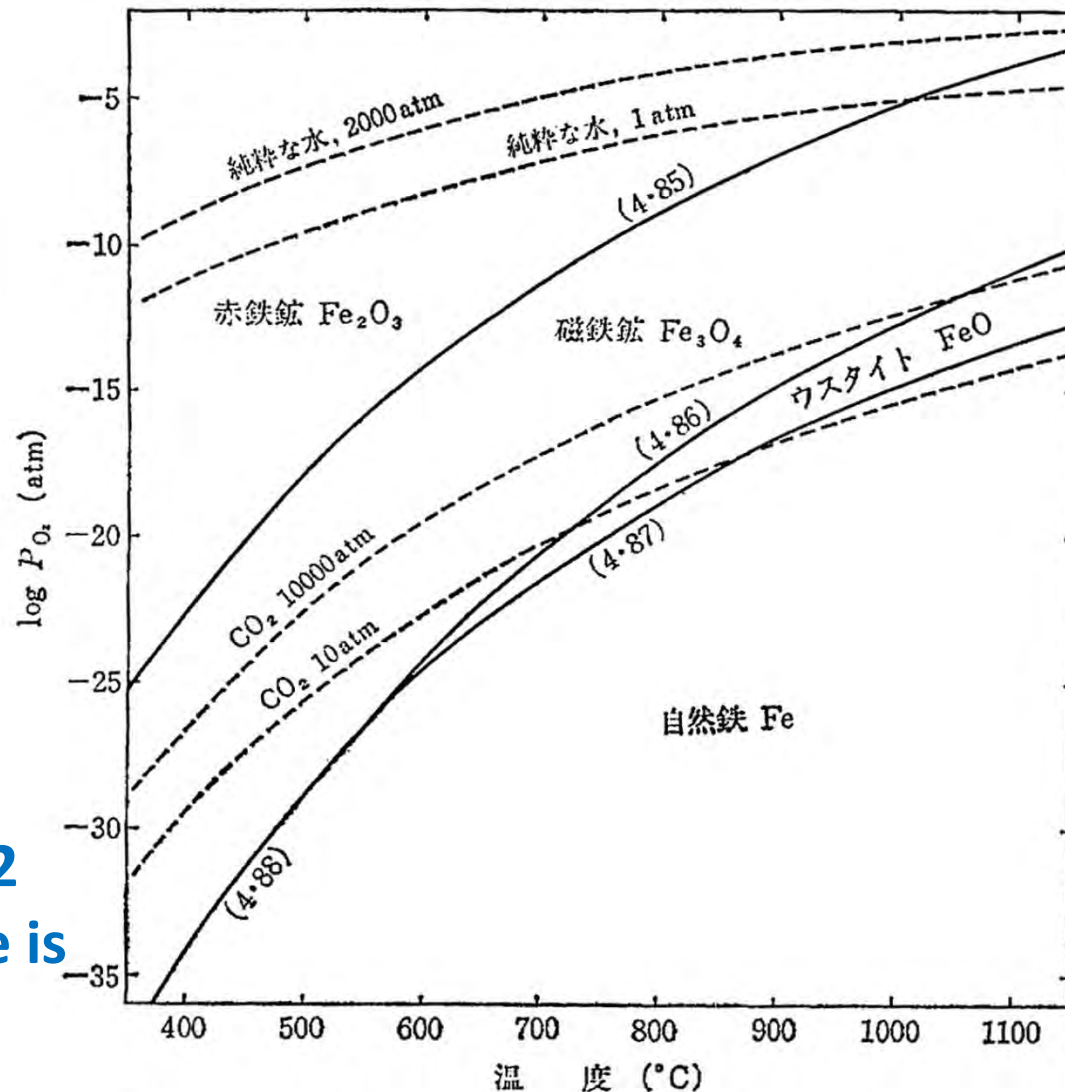
(<http://universe-review.ca/F11-monocell.htm>)

Fig. I-1. The design of the Urey-Miller experiment (Miller, 1953), which included the use of flasks, a pair of electrodes, liquid water, methane, ammonia, and hydrogen, all of which were connected into a loop by a glass tube, is shown. The liquid water was heated to induce evaporation, sparks were fired between the electrode to simulate lightening through the atmosphere and water vapor, and then atmosphere was cooled again so that the water could condense and trickle back into the first flask in a continuous cycle.

Yoshizaki (2013)

Stability of water Under high PO₂

Stability field of H₂ Under low-PO₂: Fe is stable



第 46 図 酸化鉄および自然鉄の安定関係. 曲線 (4.85), (4.86), (4.87) および (4.88) は, それぞれ反応 (4.85), (4.86), (4.87), (4.88) の平衡曲線を示す. 純粋な水の解離によって生ずる酸素の圧力の曲線を, $P_{\text{H}_2\text{O}}=1\text{ atm}$ および $P_{\text{H}_2\text{O}}=2000\text{ atm}$ の場合につき示す. また, グラファイトと平衡する酸素の圧力の曲線を, $P_{\text{CO}_2}=10\text{ atm}$ および $P_{\text{CO}_2}=10000\text{ atm}$ の場合につき示す(都城, 1964).

Towards Astrobiology

To establish Astrobiology

- 1 How to make habitable trinity planets in our solar system and more general in the Universe
- 2 What are the initial conditions for habitable trinity? ANS= Ocean mass and size of rocky planet.
- 3 Additional constraints for the birth of metazoans and the fourth life of human-being and birth of civilization?
-

3. “Universal” Life in the Universe(Astrobiology)

1) Distinction between Specificity and Universality of the Earth’s Life

What is Life in space?

1. Never-ending organic radical reactions (since its birth up to the present)
2. Programming for millions of reactions (genome-controlled)
3. Impossibility of silicate life (Si over C)
 - (1) Number of Chemical Reactions
Organics vs. **Clay and zeolite minerals**
over millions vs. <hundreds (within water-stable region)
 - (2) Speed of Chemical Reactions
Organic materials vs. **Clay** (silicate minerals)
Fast vs. Slow
4. Universality of Astrobiology
C,H,O and N will always be major players

3. “Universal” Life in the Universe

1) Specificity and Universality of the Earth’s Life

What is Life?

1) What is life?

It is a system that is composed mainly of **C, H, O, and N**, involving **never-ending organic radical reactions** (= universality). Life cannot be made by clays (silicate minerals) but allows small amounts of various nutrients to bear specificity.

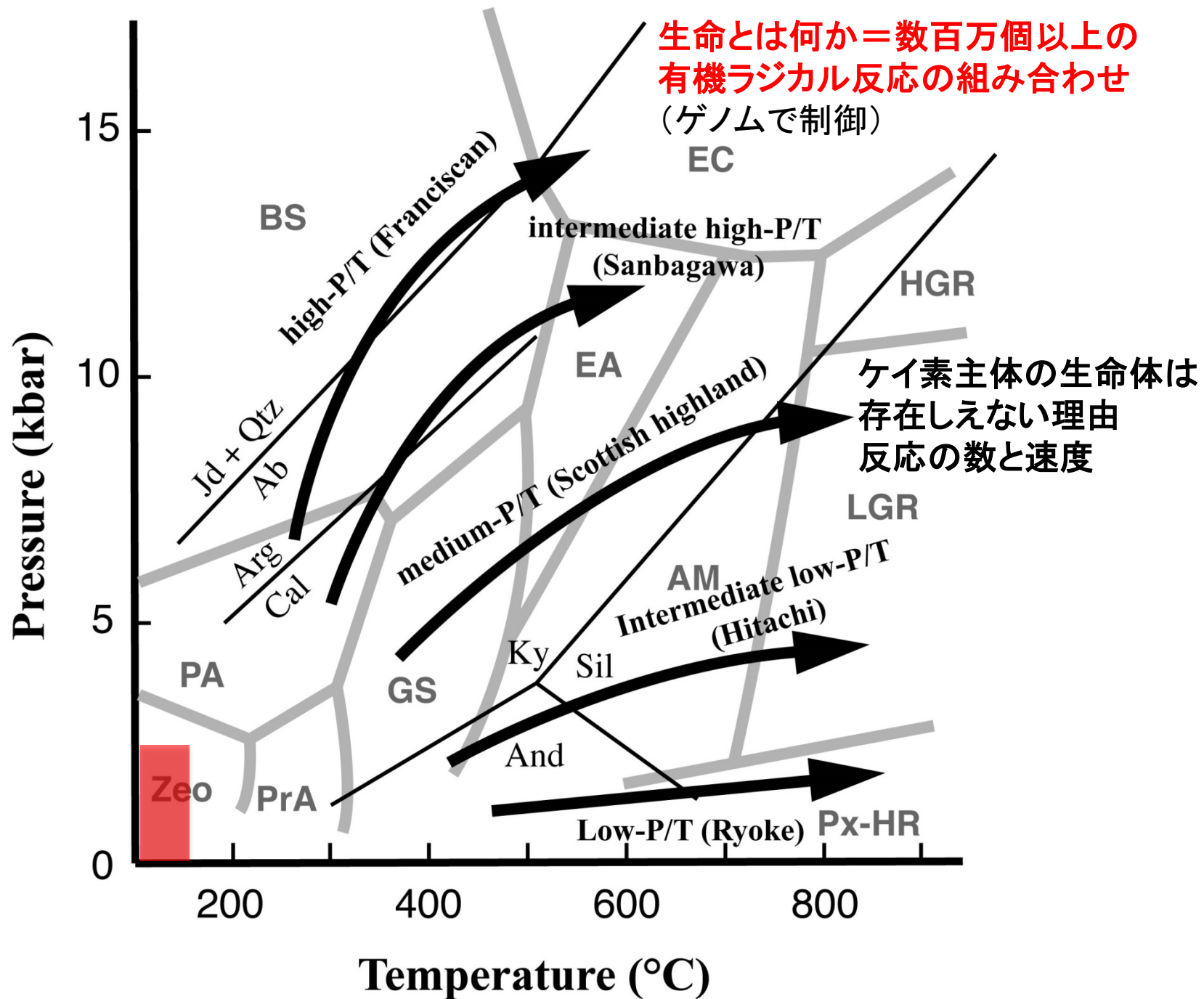
2) Life sustaining planet:

Only planets within **habitable trinity** zone can bear life (= universality). The diversity in chemical compositions of central star produces the diversity in planets (= specificity)

3) **Habitable trinity zone** is determined by strength of solar wind (universality), but the diversity in chemical composition for each rocky planet produces the individuality of each planet (= specificity).

4) Others key issues (about 30) → Springer (Book, 2014-2015)

Universality and specificity of biology
applied to the **Earth, Solar System, and Milky Way Galaxy**

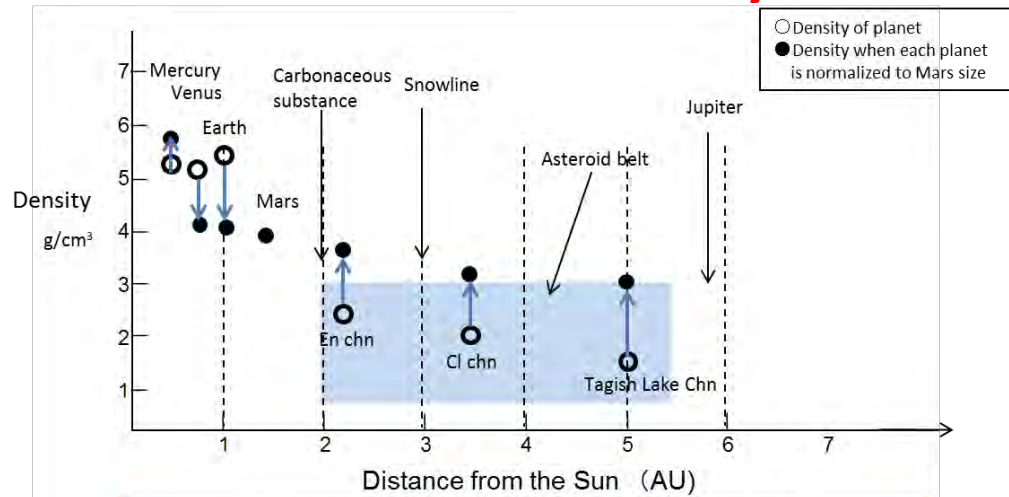


Towards the establishment of Astrobiology

→ Universal Formation Model of Habitable Trinity Planets

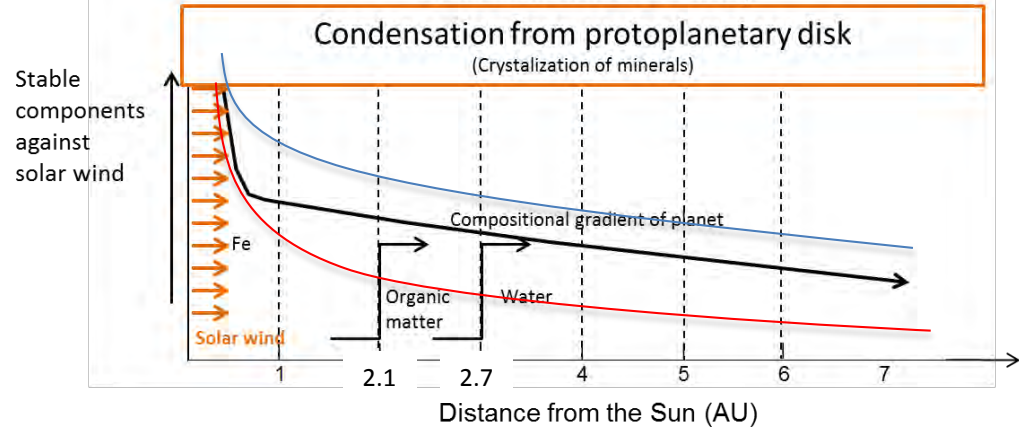
1st Step:

Bulk chemical composition of Solar Rocky Planets



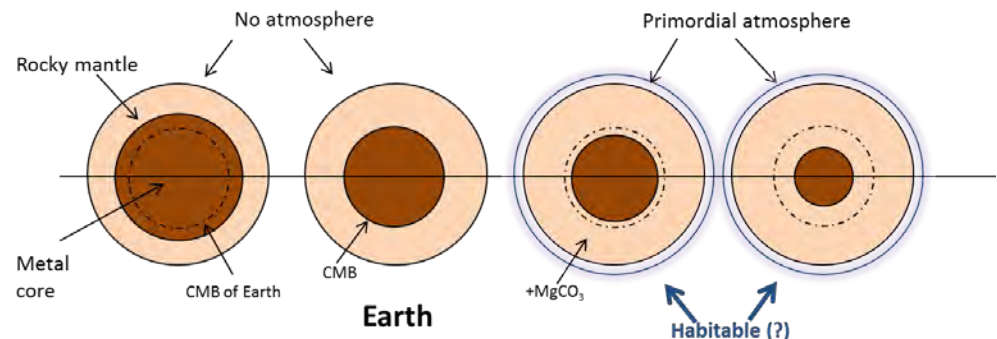
2nd Step:

Bulk chemical composition of Universal Rocky Planets determined as a function of Central Star (chemistry and size) and distance (from CS)

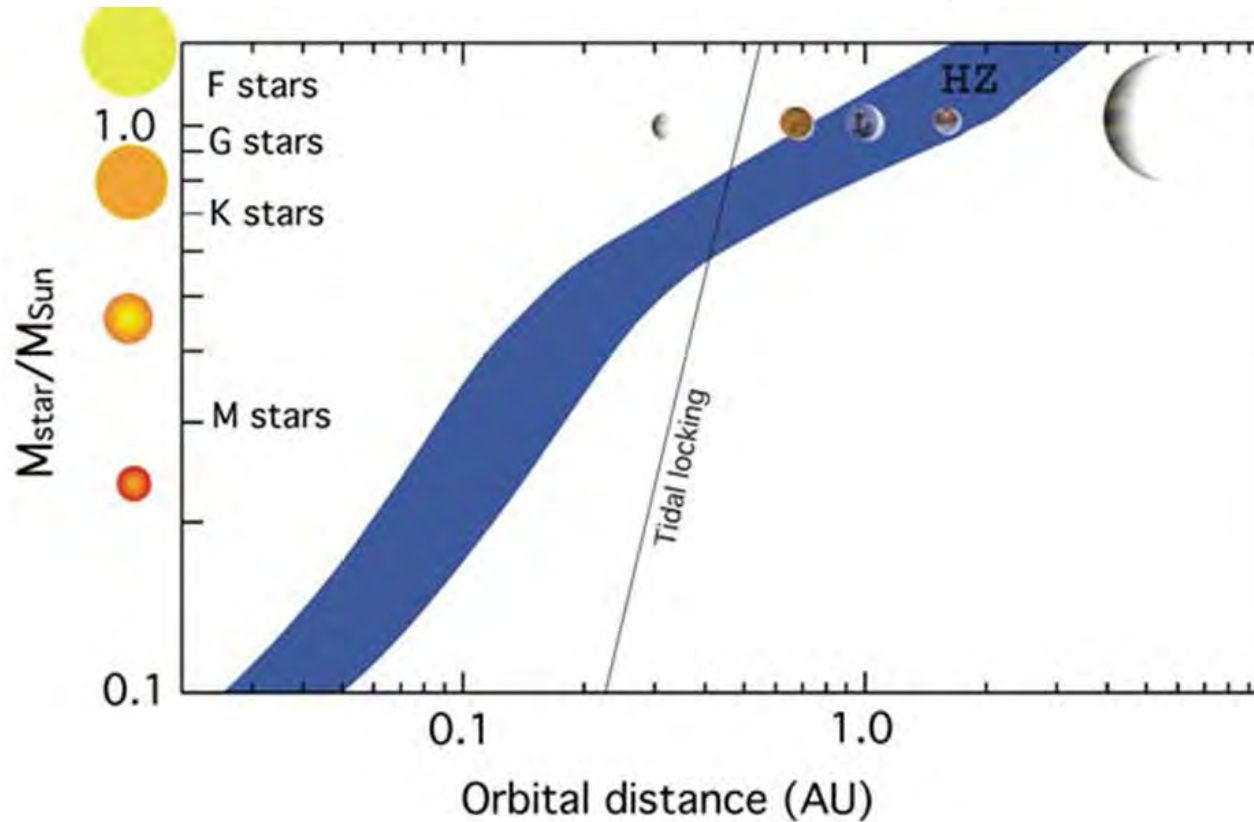


3rd Step:

The birth and evolution of Habitable Trinity Planet are determined by internal dynamics of solid planet



Habitable Zone as functions of not only by distance from CS but also
greenhouse gas (X and amount), X of CS, and time
中心星からの距離だけでは定義できない



Lammer et al., 2009

Appendix

History of Life and Earth

玄田の鉄の雨（ジャイアントインパクト）は月がない地球に降らなかったか、少なくとも1億年も浮遊したこ

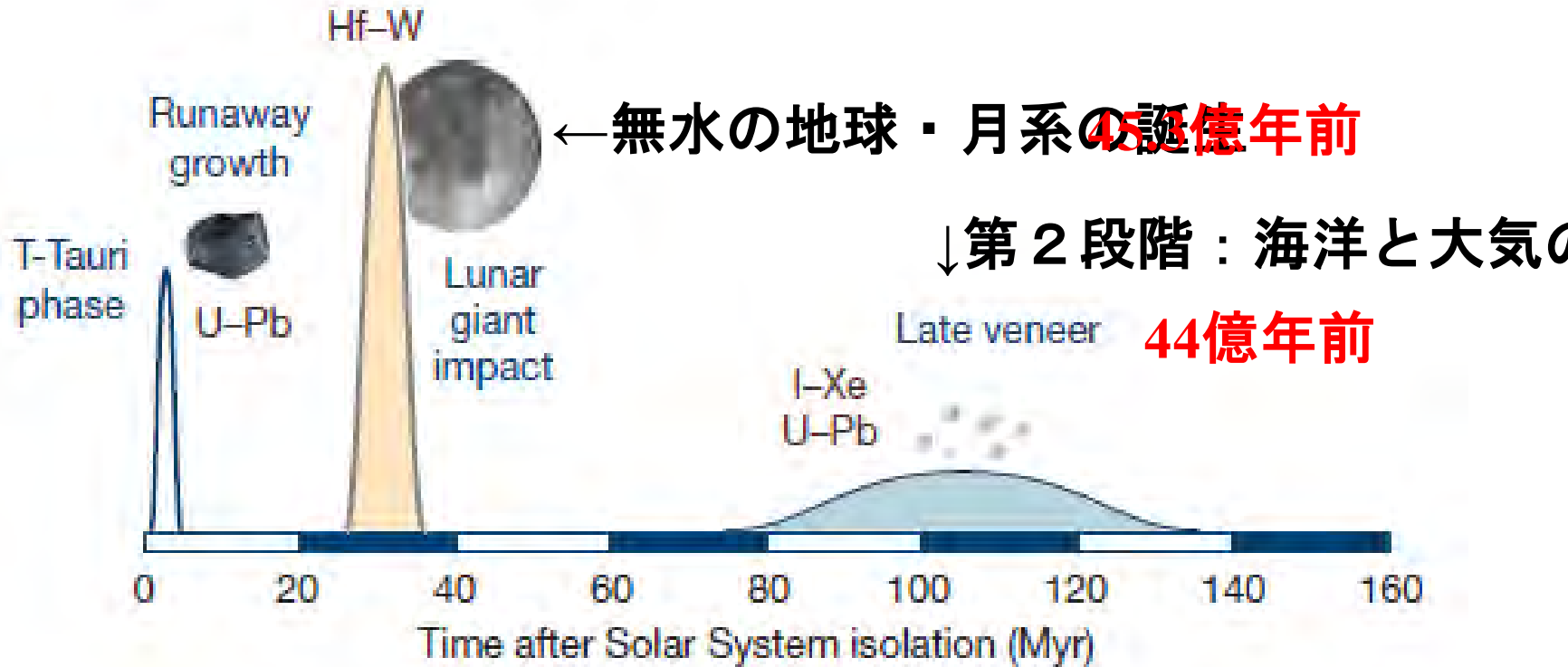


Fig. x: A tentative chronology of the Earth's accretion
Albarede (2009)

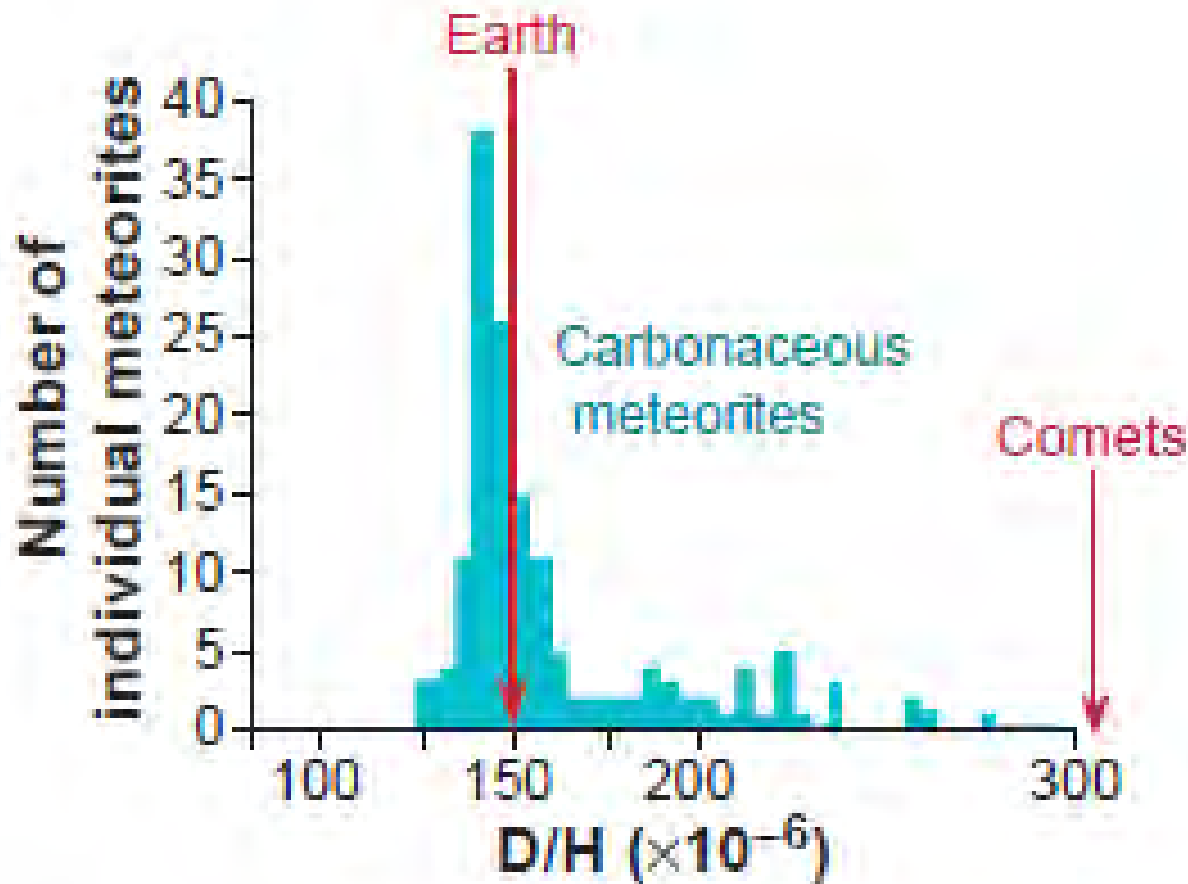


Fig. xxx : Water from meteors. Distribution of the hydrogen isotopic ratio in carbonaceous meteorites compared with Earth and comets. According to this distribution, water on Earth seems mostly derived from a meteoritic source.

Robert, F. (2001)

Conclusions

- 1 Origin: It takes time, and impossible to synthesize it in the Laboratory.
- 2 Birth place: On the primordial continents with KREEP (nutrients), and presumably in the Rift hydrothermal system on the 4.4Ga primordial continents under phosphorite-ore, lake, and H₂-producing (pH=12) shallow water environments. This would help some experiments for the synthesis of super-molecule.