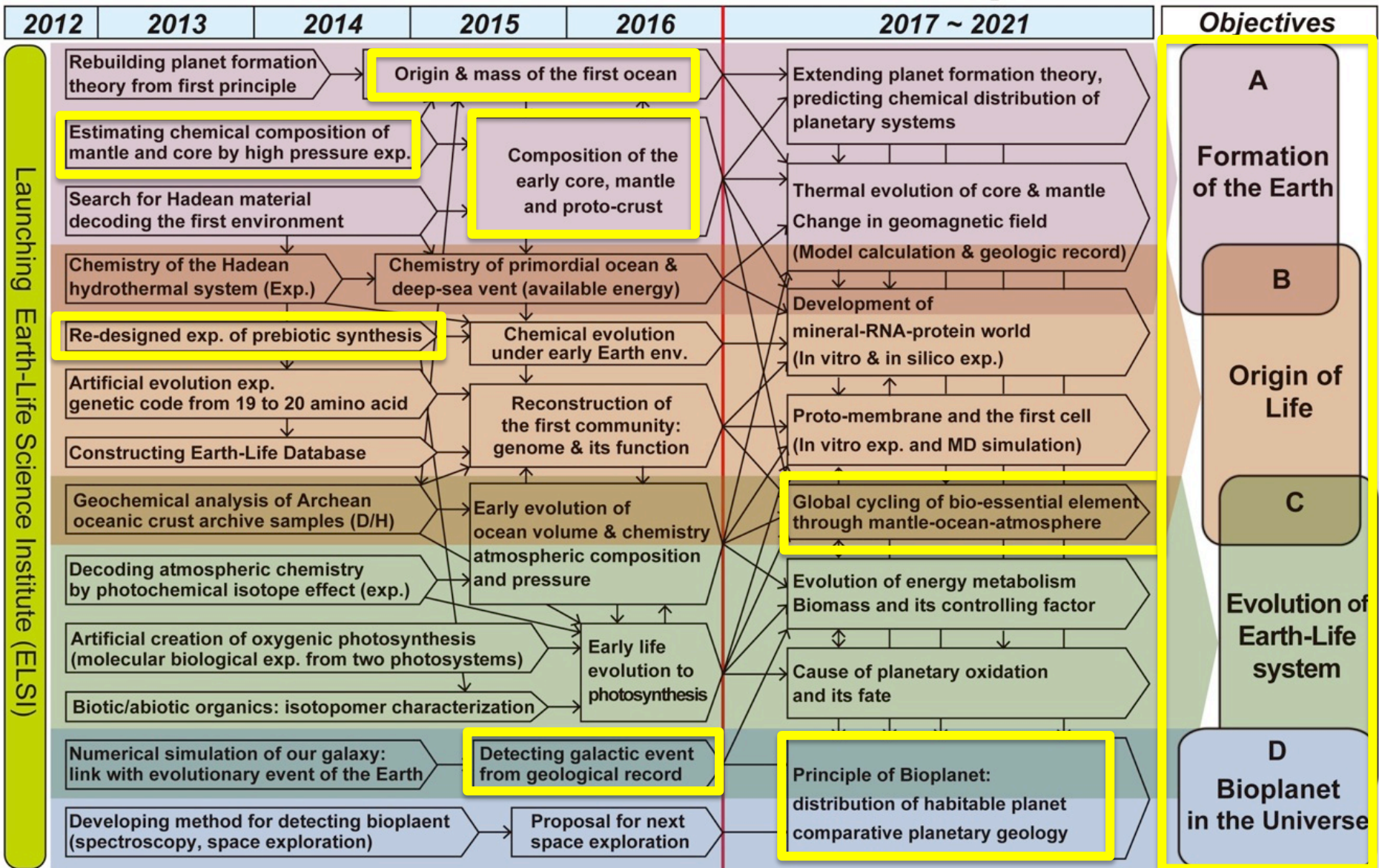


Birth of Astrobiology



Shigenori Maruyama

ELSI Research Roadmap



History of life and Earth < 23 years

Systematization of Astrobiology

Today's Contents

1. Background of Astrobiology

- 1) Cornerstones
- 2) **“World Standard Model” of the Whole Earth History**

2. ELSI's Scheme of Astrobiology

- 1) **“Naked Earth” Hypothesis**
 - > **Water** Supplied Through **Planetary Formation**
- 2) **“Habitable Trinity” Model**
 - > Life Emerged on **Surface Environment** of the Hadean Earth
- 3) Exploring the **Origin of Life**
 - > Bottom-up Approach: Reproducing the **Hadean Chemical Evolution**
 - > Top-down Approach: Decoding the **Genome of Primitive Organisms**

3. “Universal” Life in Space

- 1) Specificity and Universality of the Earth's Life
- 2) Extraterrestrial Life: Exploration of **“Habitable Trinity Zone Planets”**

1. Background of Astrobiology

1) Cornerstones

What is Astrobiology?

Goal: How can life-sustaining planets be formed ? What are the additional conditions for organisms to evolve to intelligent life that eventually produces civilization?

Approach: We conducted intensive research on the Earth, and distinguished the universality and specificity of the Earth's life. We will explore exo-planets to establish Astrobiology (universal biology).

1. Background of Astrobiology

1) Cornerstones

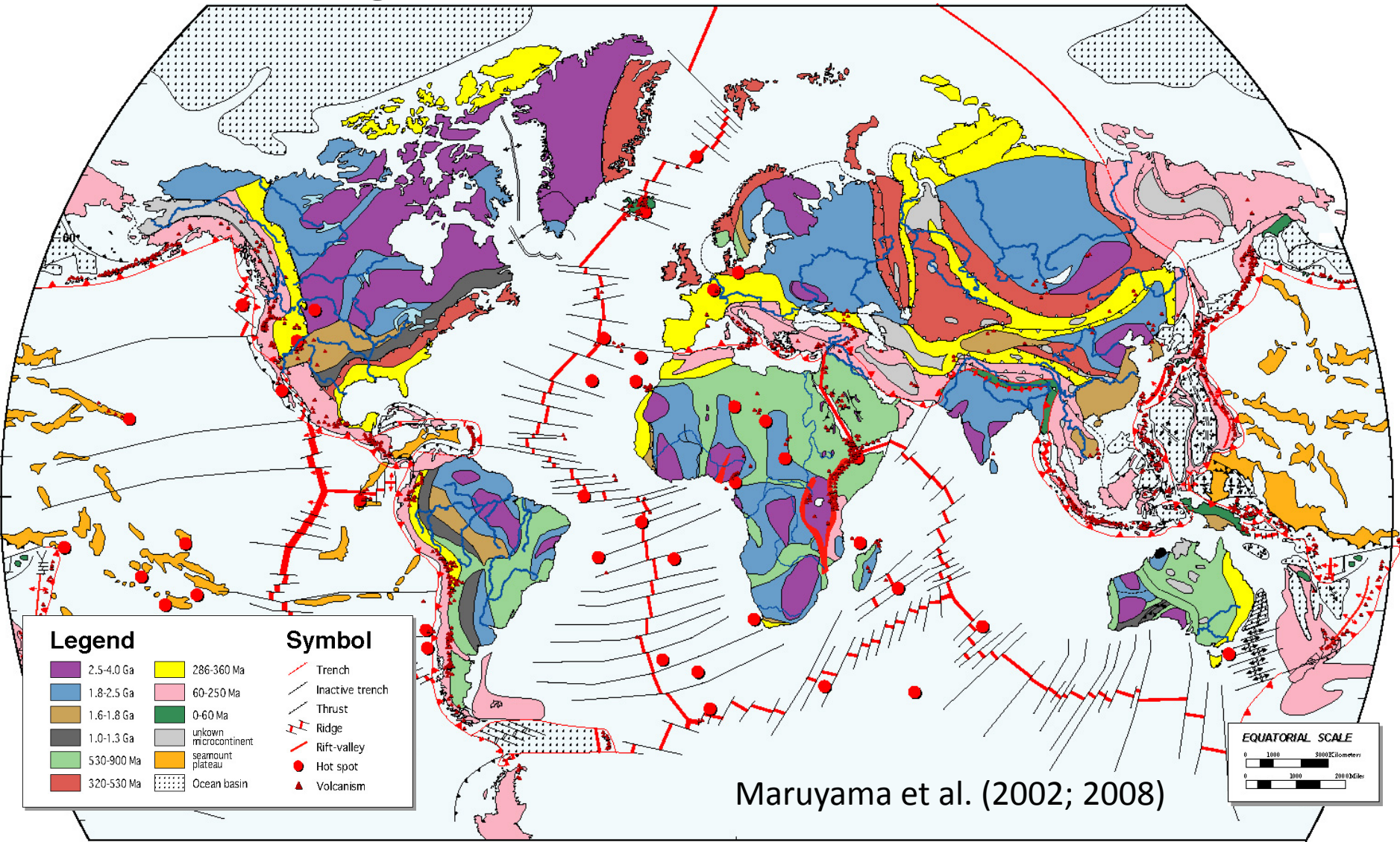
History of Astrobiology

1. Maruyama G has initiated the project of decoding the whole Earth history including life (**Earth Bio-planetology**) since 1990 .
2. NASA has led the **Astrobiology** project since around 1995.
3. Rapid increase in data obtained from the exploration of exoplanets (by Kepler spacecraft) (>1,000 planets) by 2013.
4. The concept of “**Habitable Zone**” was extended to classify the life-sustaining planets (Lammer et al., 2009)← Should be replaced with the concept of “**Habitable Trinity**” (Maruyama G) .

1. Background of Astrobiology

2) "World Standard Model" of the Whole Earth History

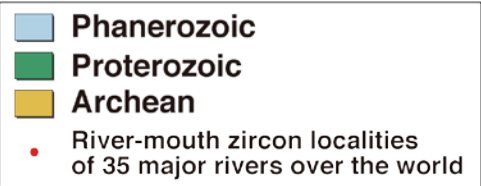
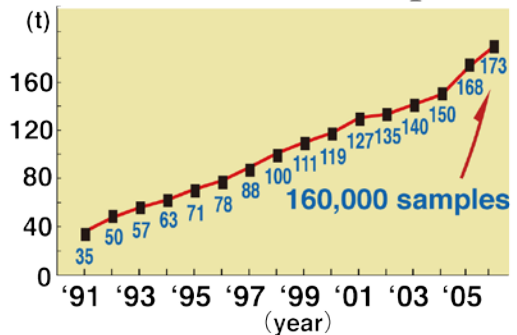
Orogenic Belts of the Earth



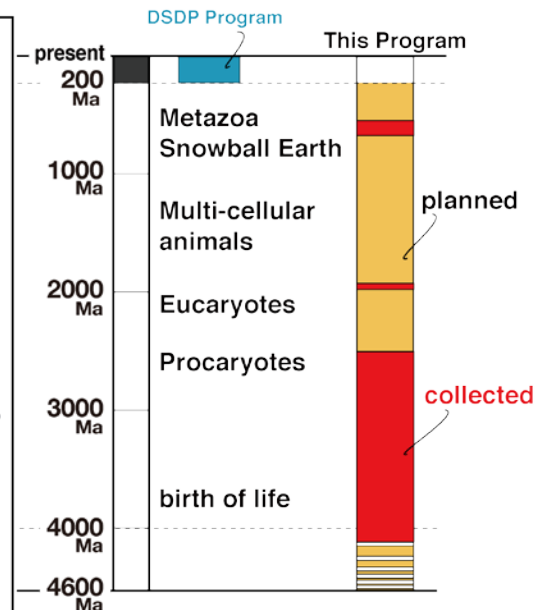
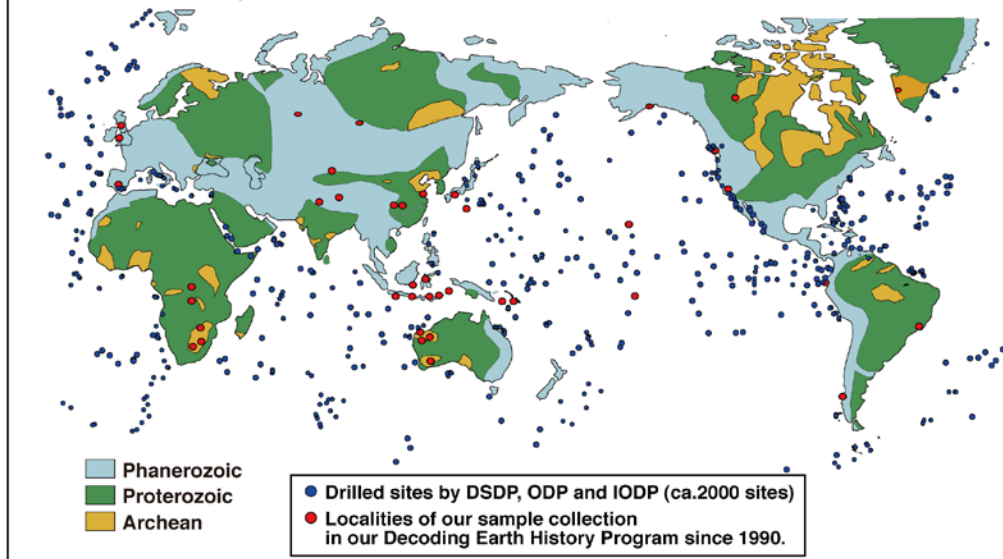
Sample collection for decoding the whole history of the Earth



Total number of samples



Ocean-floor Drilling Program covered ca.2000 sites since 1968, but only younger than 200Ma.



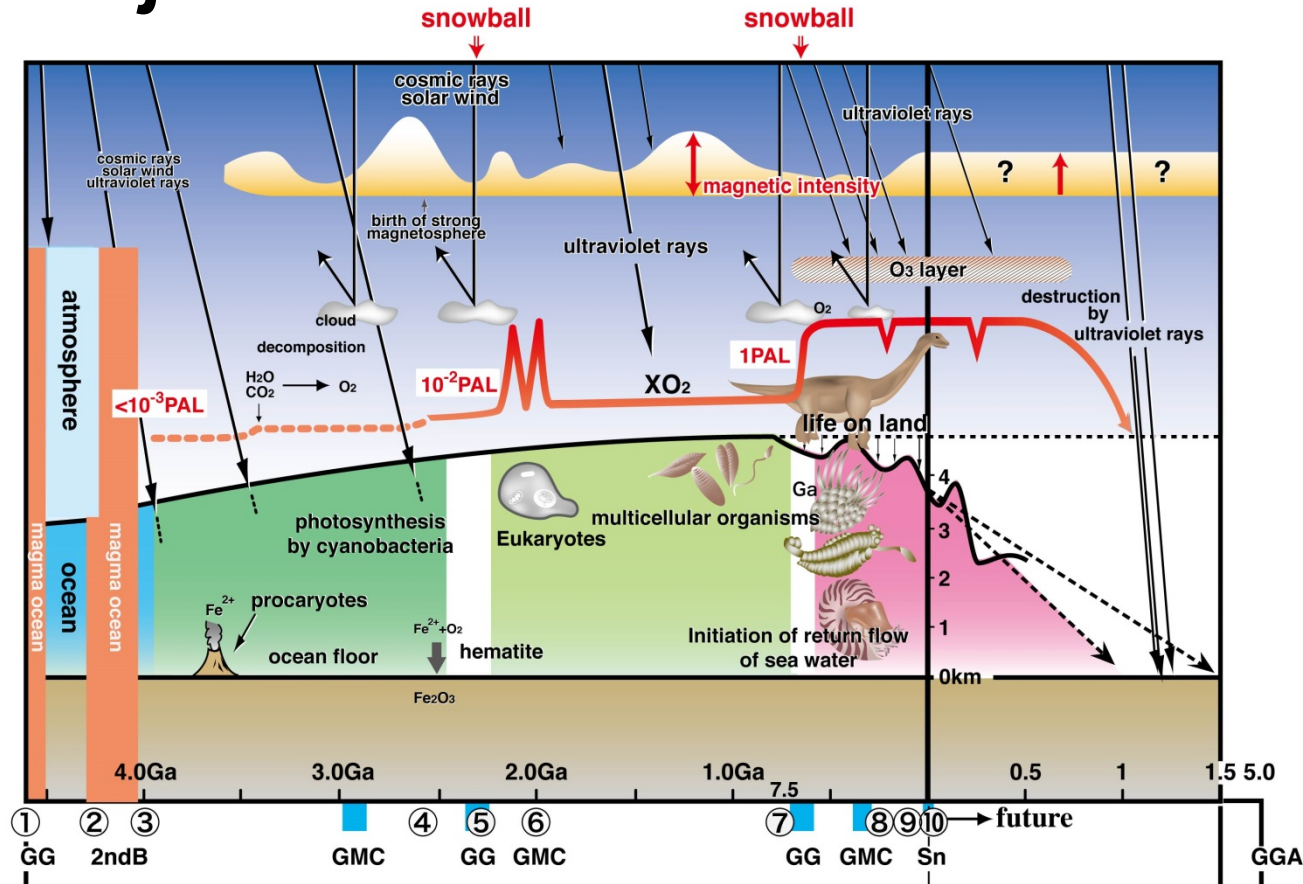
Our Program aims to collect samples older than 200Ma, back to 4.56Ga.

1. Past: Background of Astrobiology

2) "World Standard Model" of the Whole Earth History

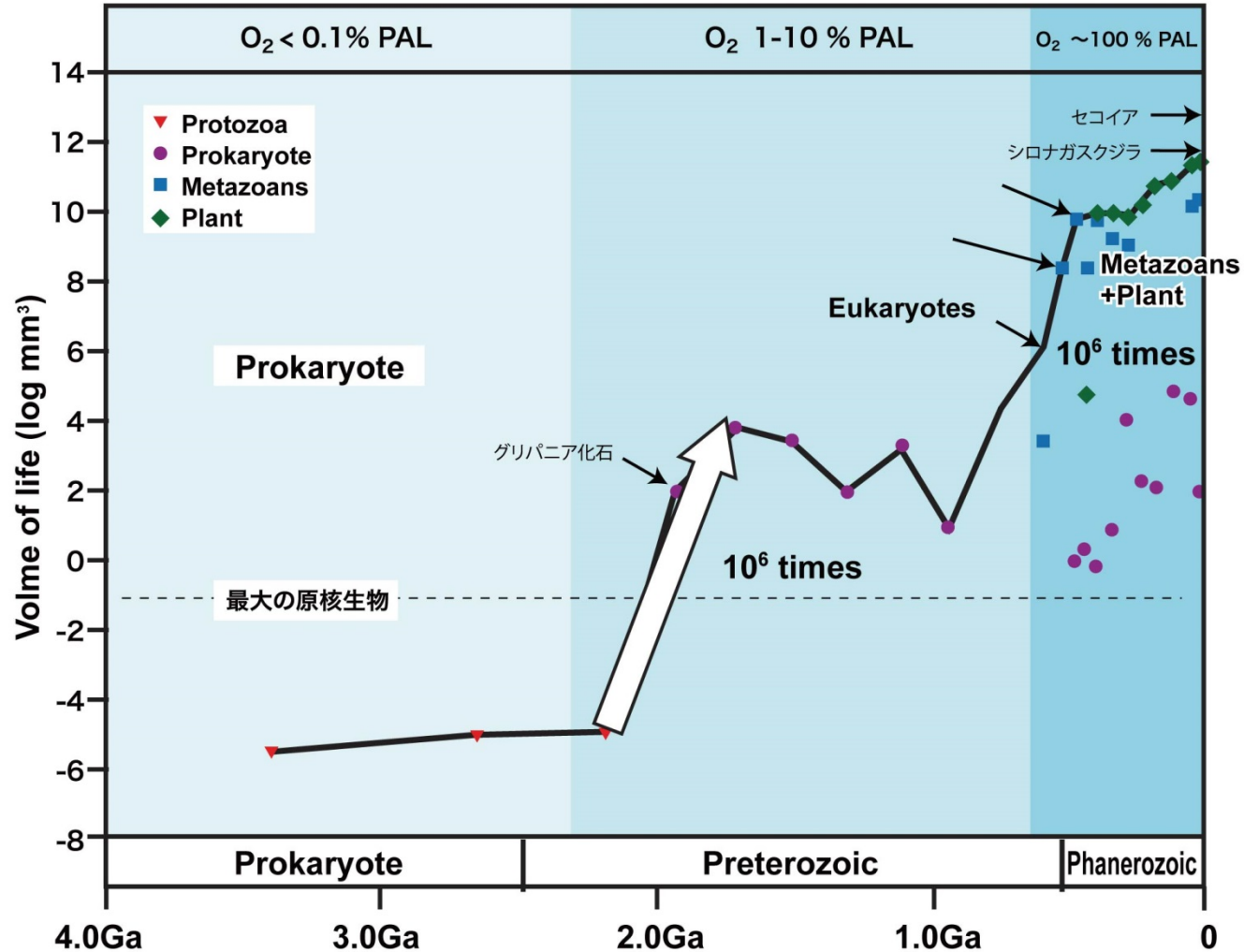
Maruyama et al.,
2002; 2008

10 Major Events in Earth History



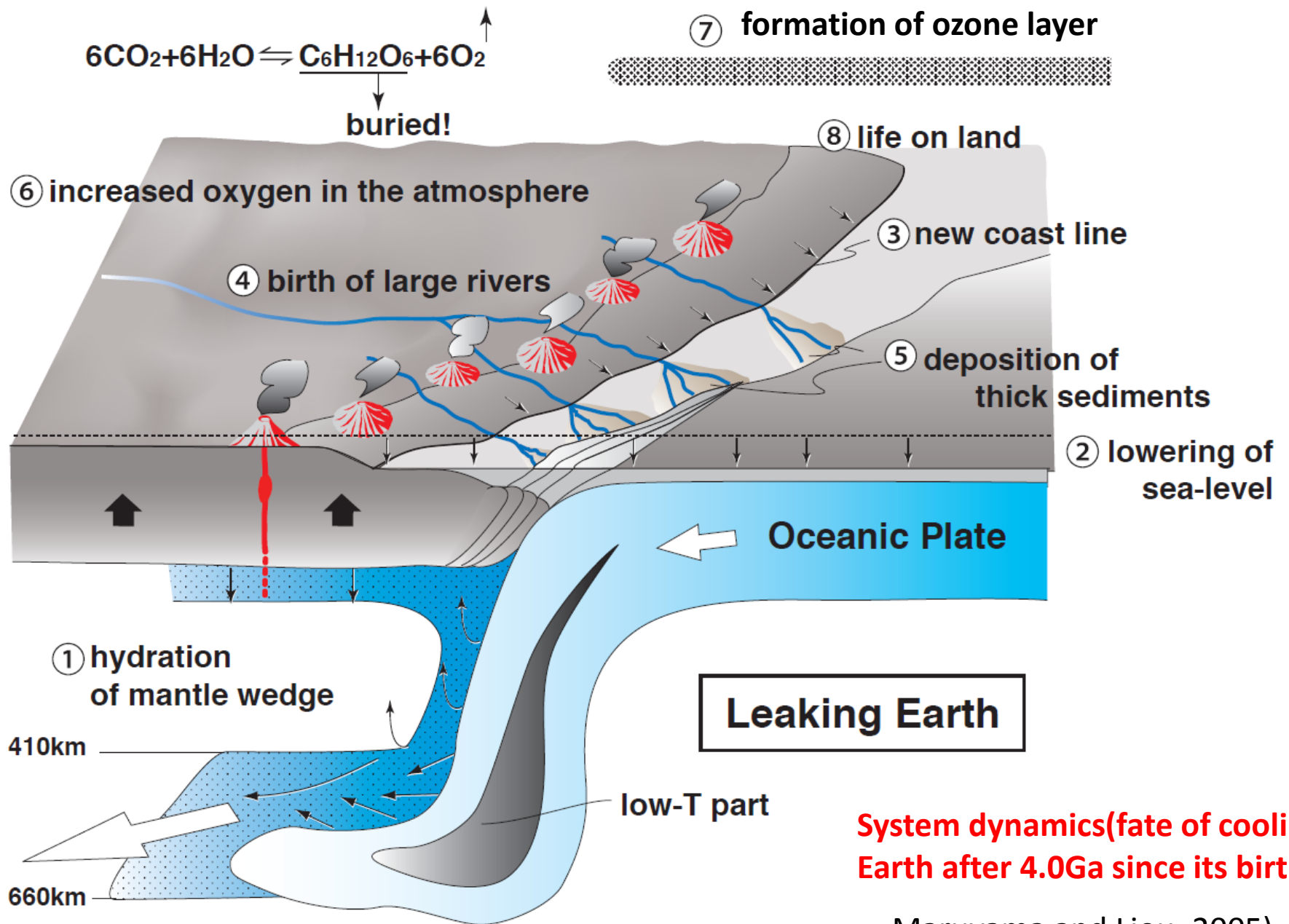
**Irreversible Dynamics of Earth System caused
the Emergence and Evolution of Life.**

Size of life enlarged by two steps, 1 million times bigger than before.



Payne et al. (2009) PNAS 106

Fig.12-2

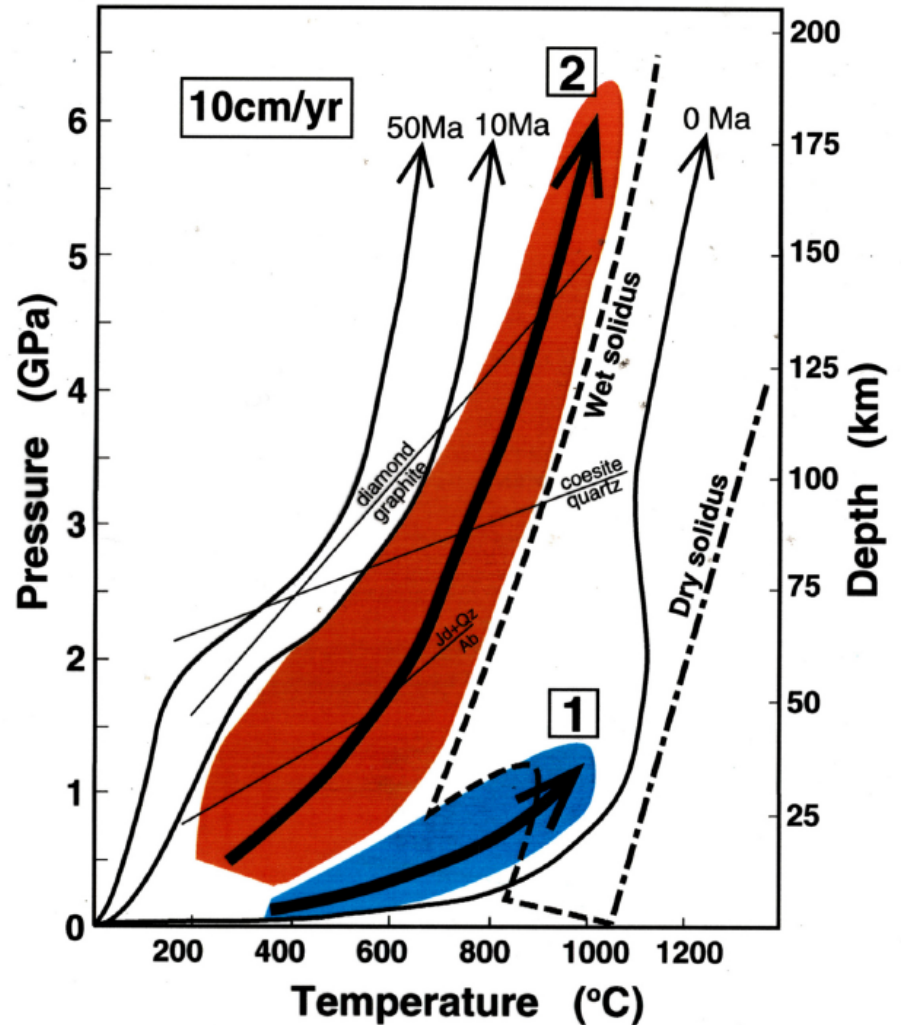
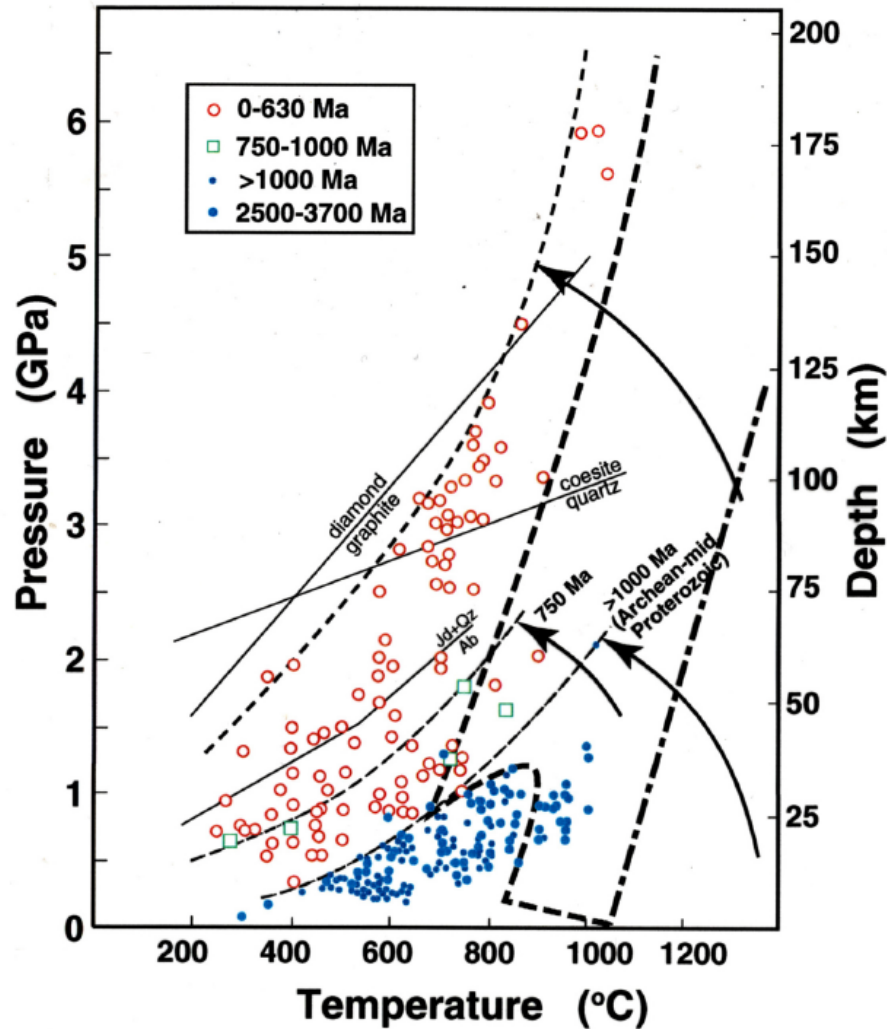


System dynamics(fate of cooling Earth after 4.0Ga since its birth)

Maruyama and Liou, 2005)

Maruyama et al., 2013

Secular variation of P-T conditions of regional metamorphic belts



The subduction zone geothermal gradient has cooled gradually with time. UHP metamorphism has only occurred after the Late Proterozoic.

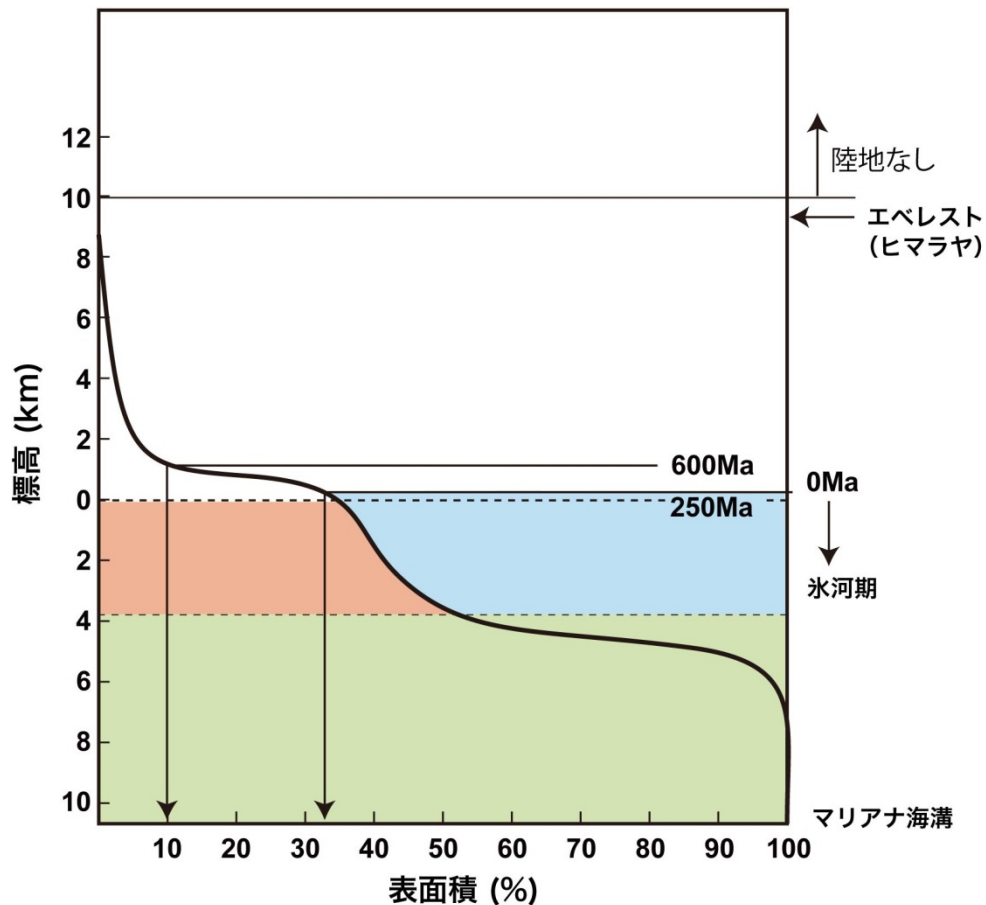
Maruyama et al., 1996; Maruyama and Liou, 2005

Maruyama et al., 2013

Birth of huge landmass: how important same as in the Hadean

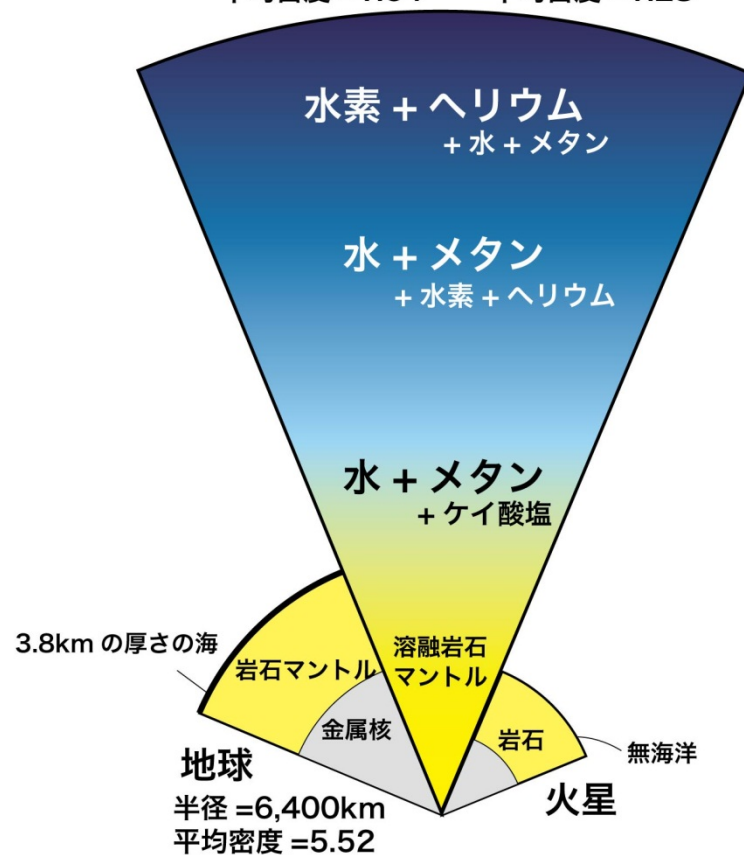
- 1 Diversification of surface environment (Temp. Humidity and other physical conditions, chemical and biological parameters)
- 2 First 600m.y. and last 600 m.y. (Phanerozoic) are the golden age for life. Imagine if the Earth is covered perfectly by ocean, no diversification of surface environment, no life and no evolution.

地球は水が殆どない岩石惑星： どのように創るか？

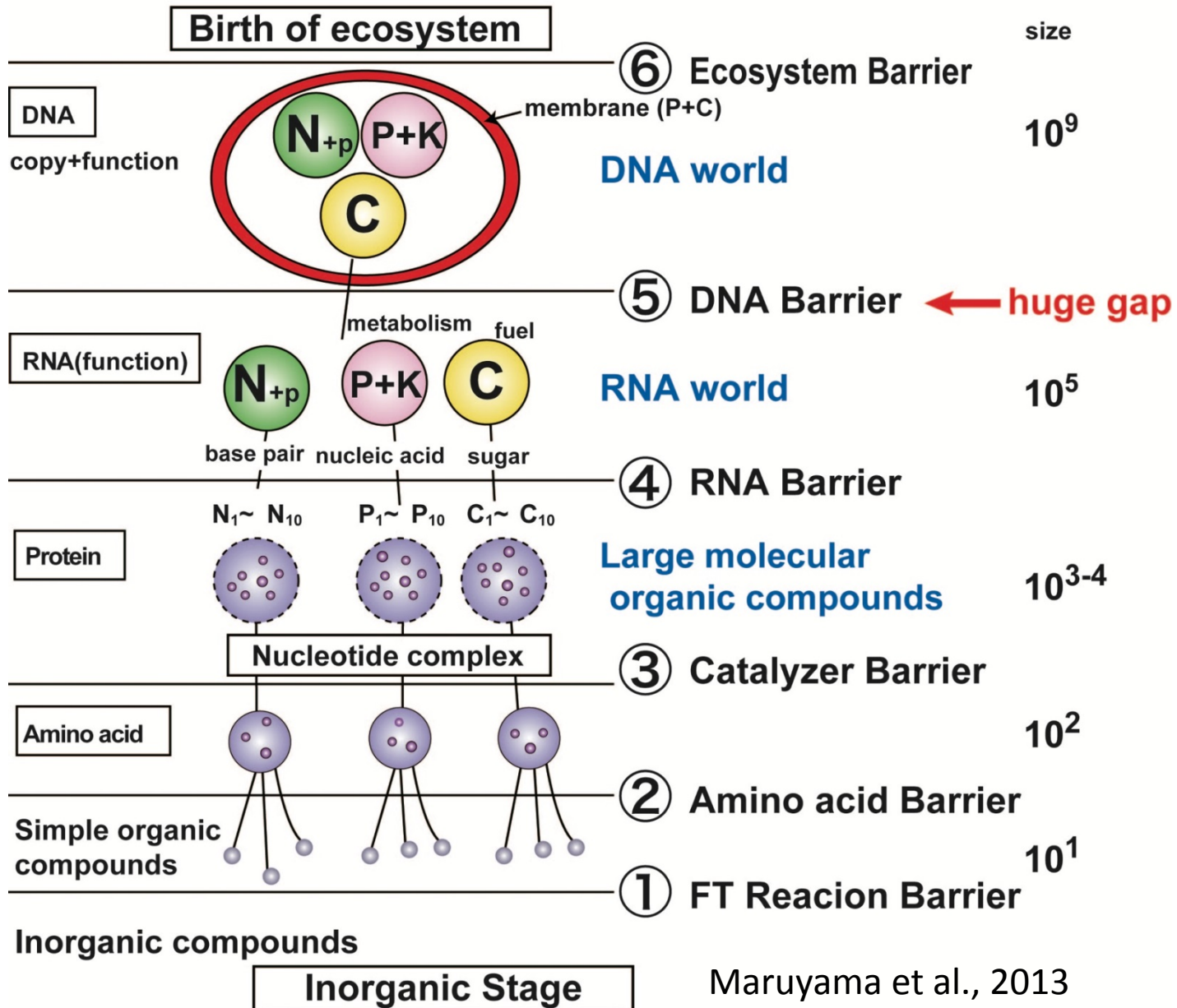


海王星 & 天王星

半径 = 24,764km 半径 = 25,559km
平均密度 = 1.64 平均密度 = 1.28



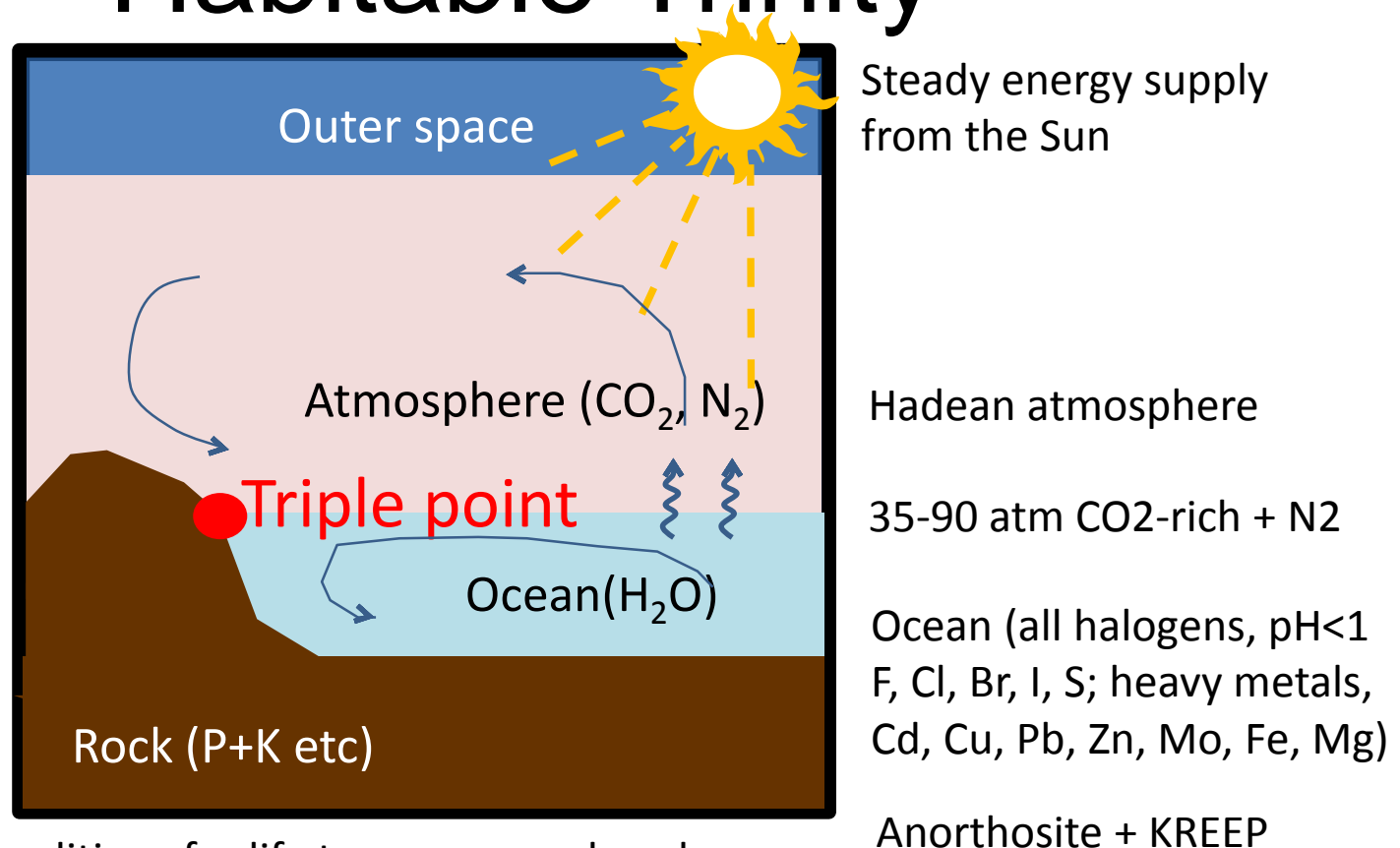
What is life?



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”



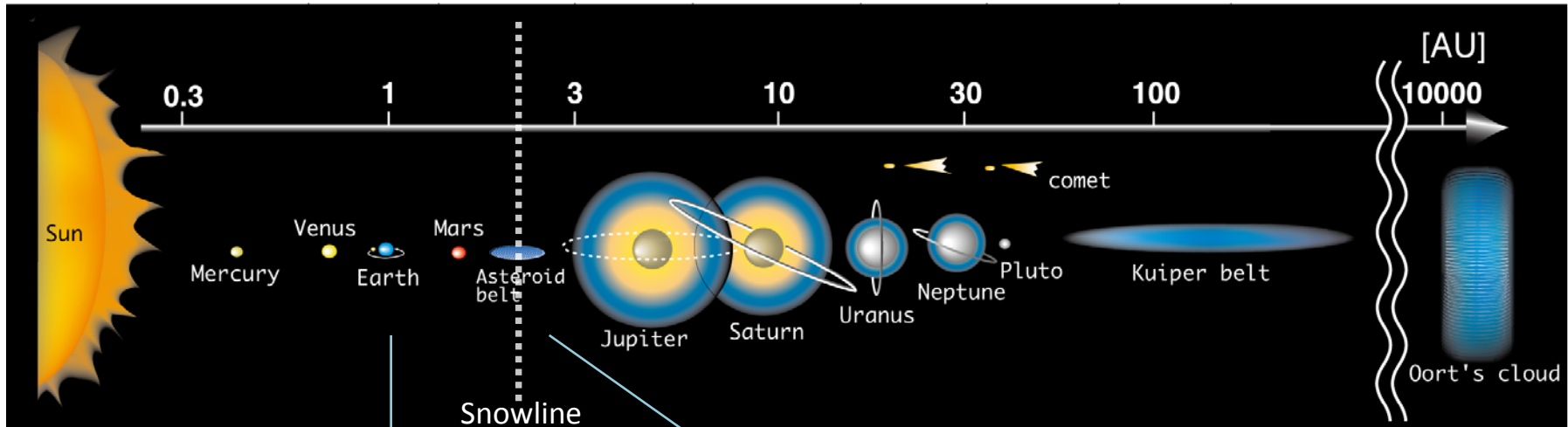
Three necessary conditions for life to emerge and evolve:

- (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

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

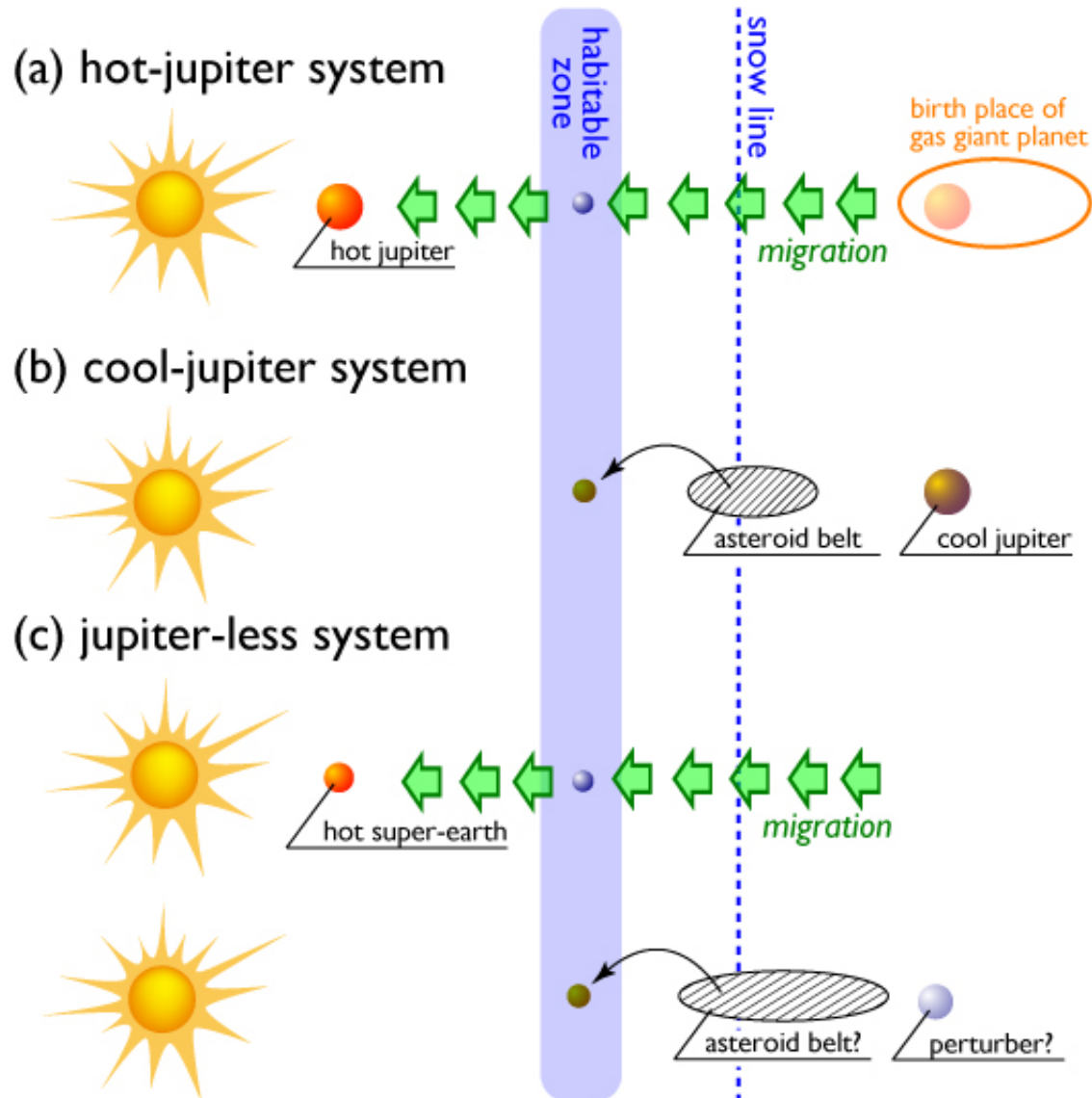
Made from 3H₂O%
chondrite

No Landmass → No Life

2. ELSI's Scheme of Astrobiology

1) "Naked Earth" Hypothesis

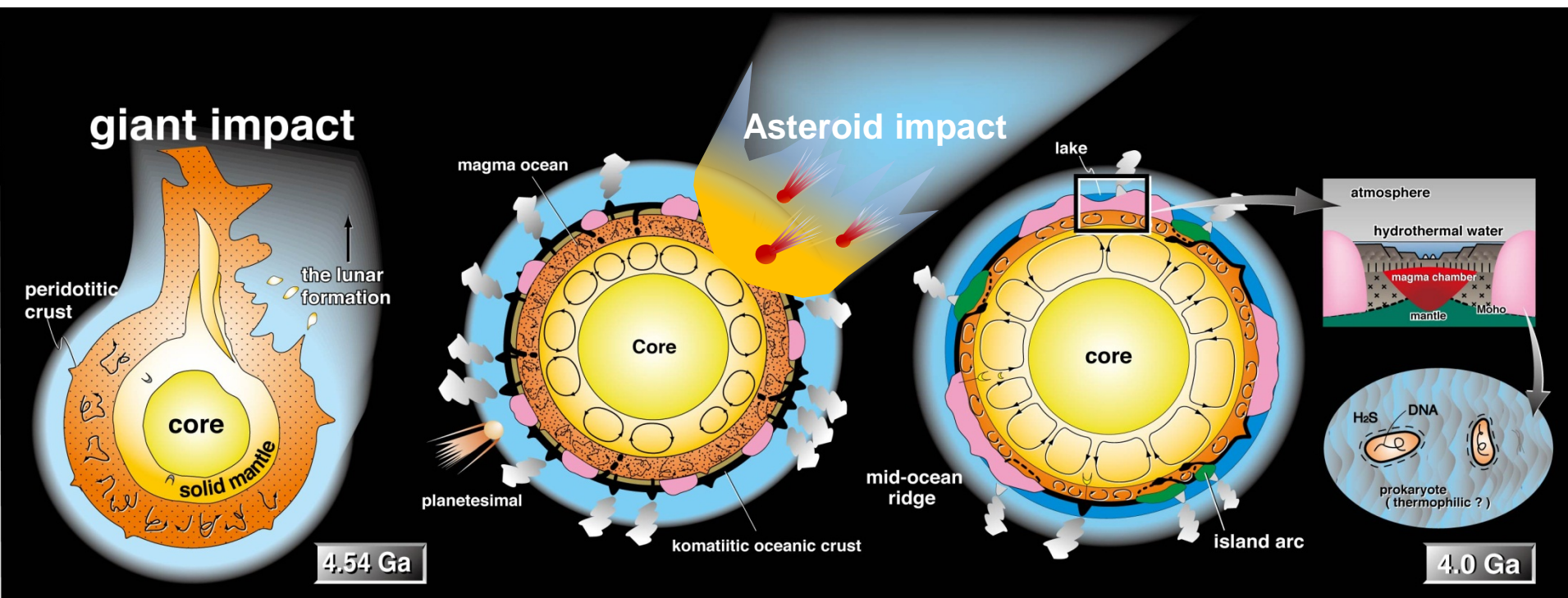
> Water Supplied Through **Planetary Formation**



Two step formation of the Earth-Moon system

4.56Ga: Dry Earth-Moon system : No ocean and no atmosphere

4.4Ga: 4km thick thin skin of ocean and atmosphere



Birth of life on the
primordial continents
Anorthosite + KREEP

Anorthositic continents covered by KREEP basalt with KREEP lower crust . No Na.

Primordial continents on which first life was born.

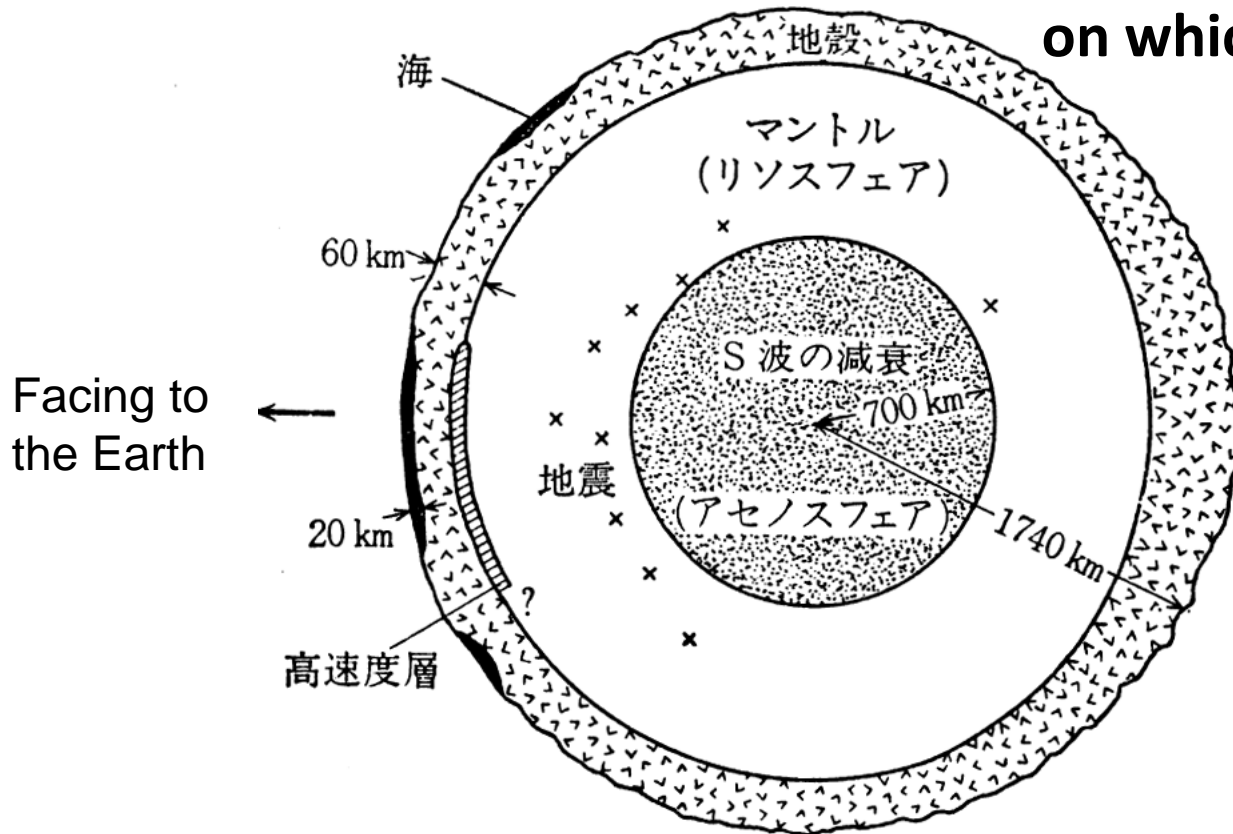
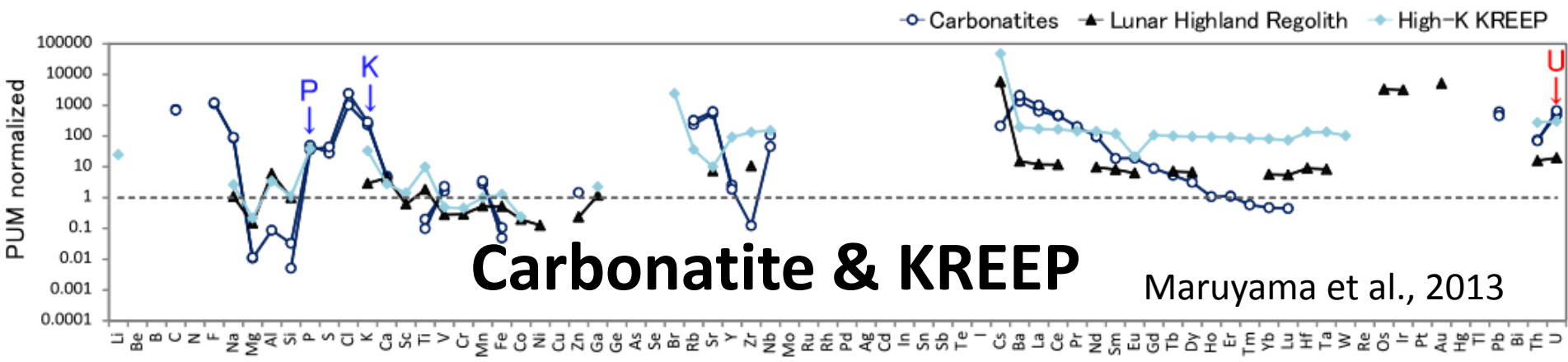
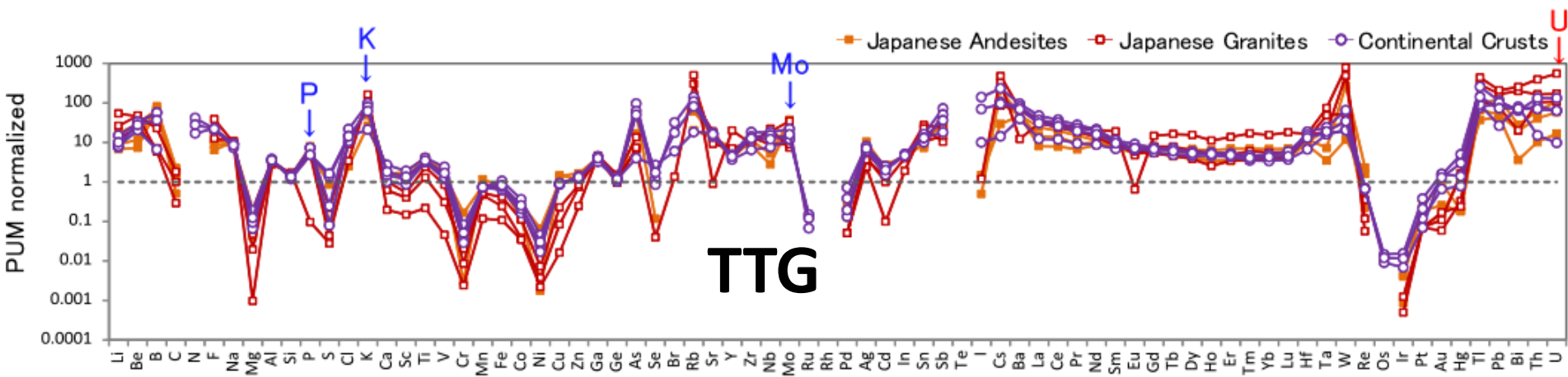
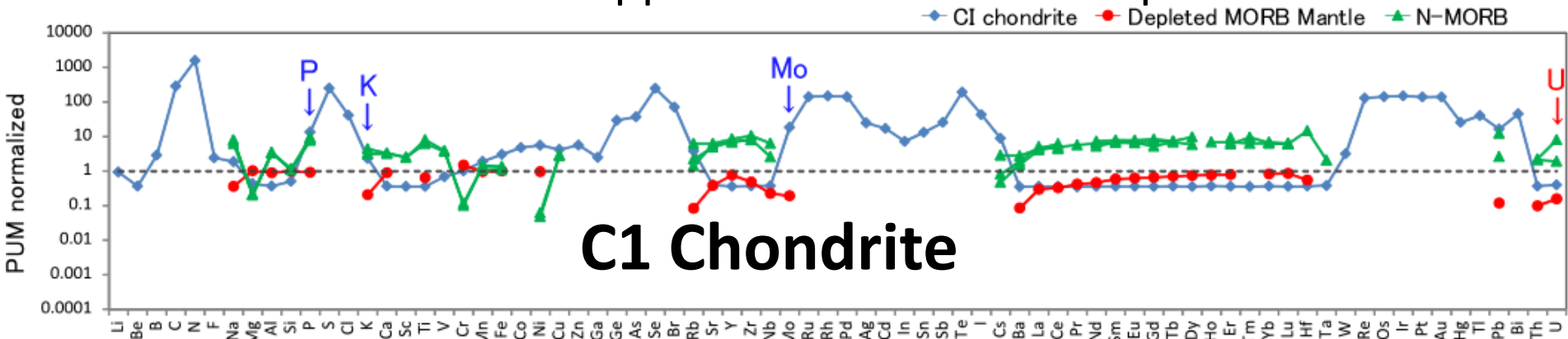


図 5.11 月の内部構造の模式図. 地殻の厚さは実際よりも誇張して書いてある (Toksöz & Johnston, 1974 による).

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.

Primitive upper mantle normalized pattern

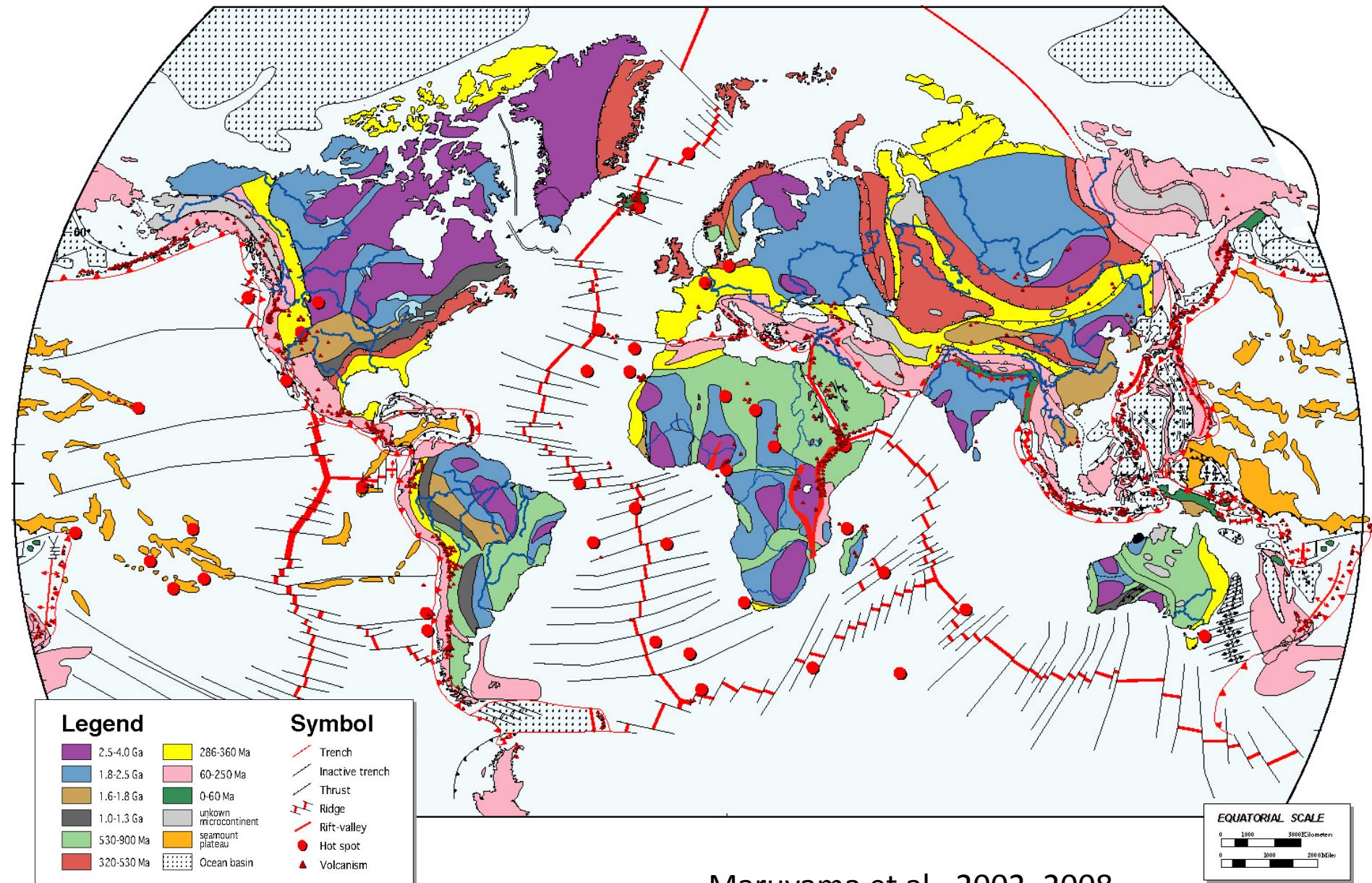


Maruyama et al., 2013

Elements for origin of life

- 1 Extremely fractionated melt is necessary (K, no Na, P and others)= KREEP and no Na.
- 2 Also large ion lithophile elements such as U is concentrated for the primordial continents (promoted mutation). Role of U and radioactive elements may have played a critical role for birth of life.
- 3 Atomic bomb magma played a critical role for evolution afterward the birth of life, specifically in the Phanerozoic. See a recent model by Ebisuzaki and Maruyama (2013).

Orogenic belts of the world

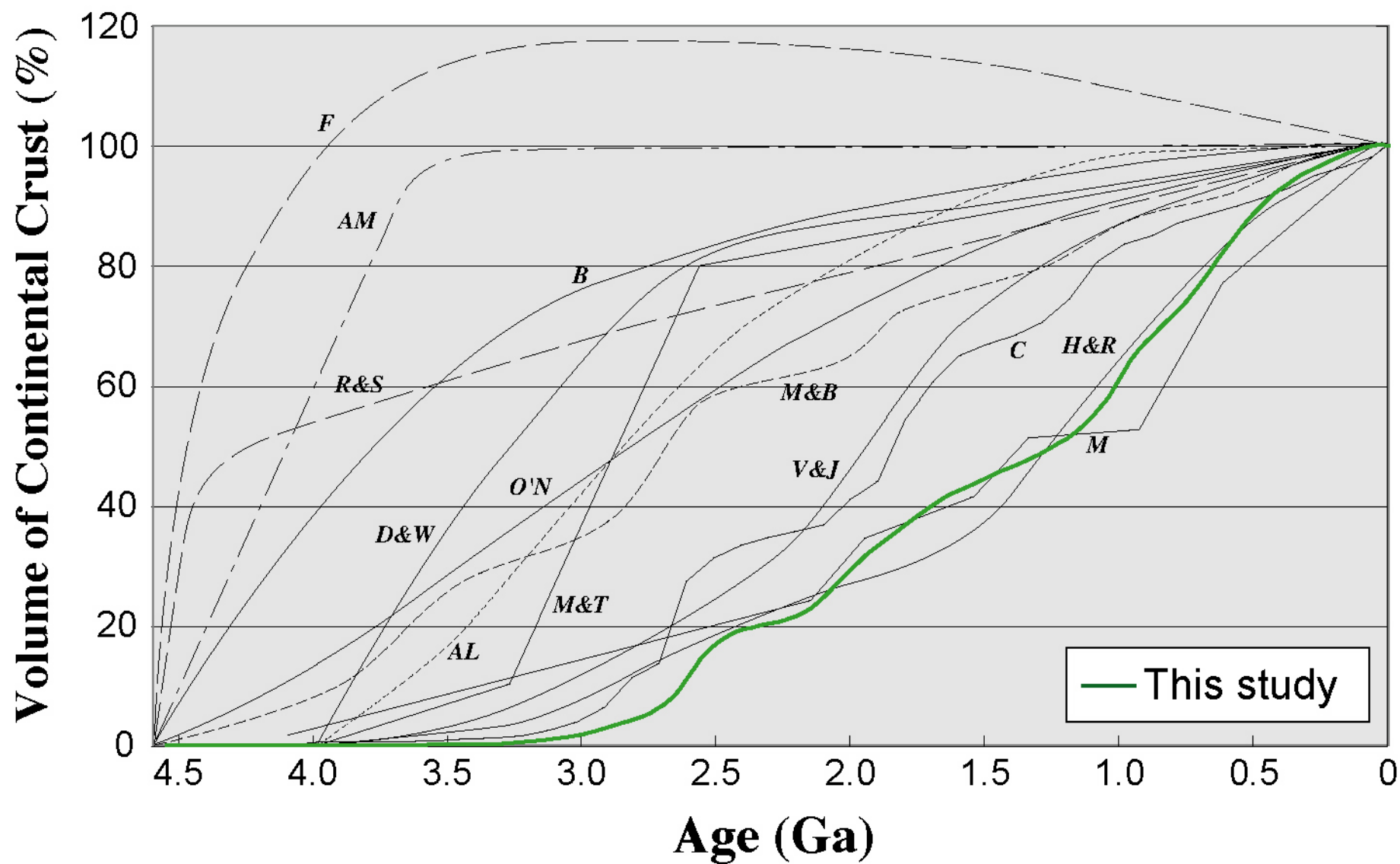


Maruyama et al., 2002, 2008

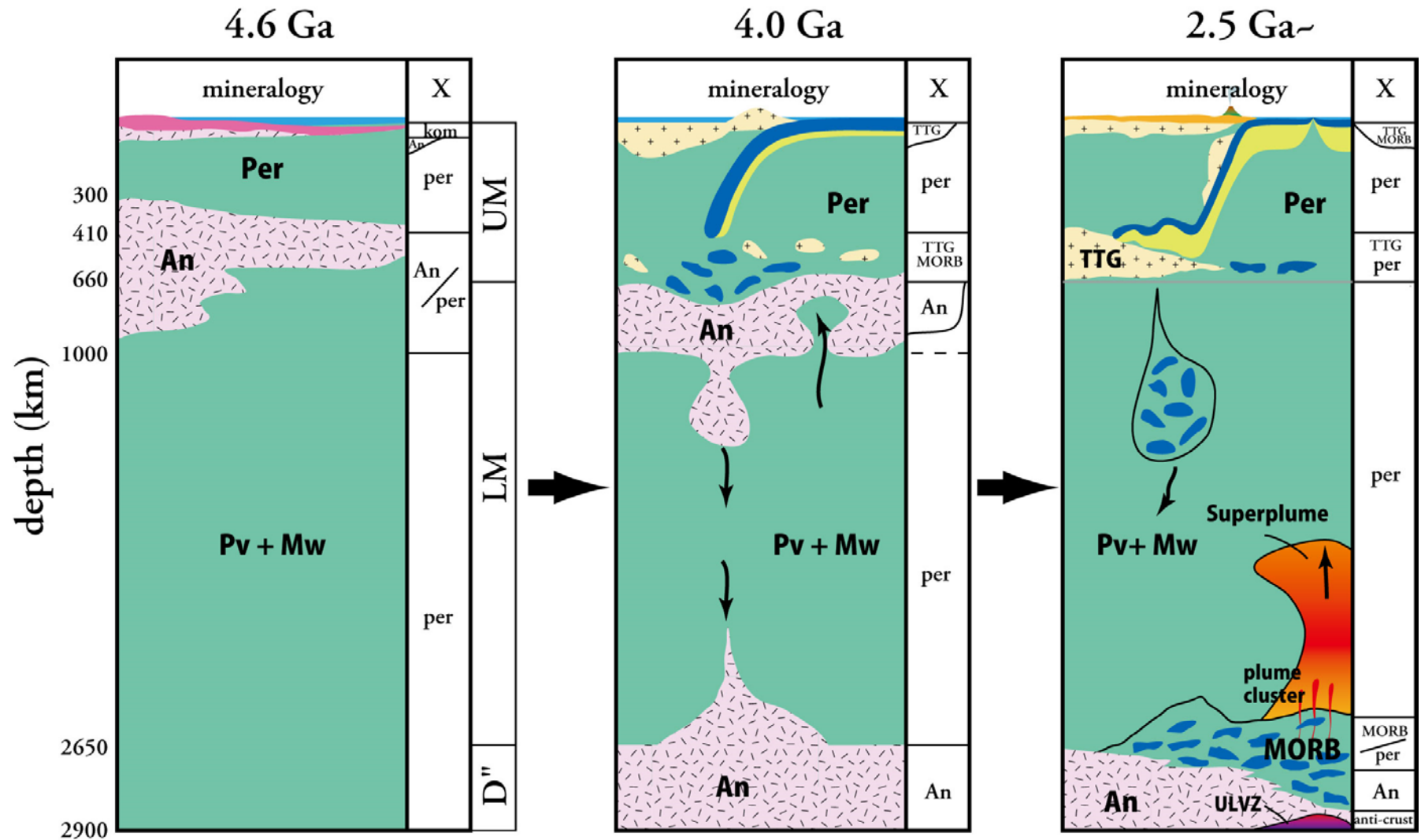
Absence of Hadean rocks on the Earth

- 1. Originally absent by less extensive fractionation up to gabbro
- 2. Present but annihilated afterward
- 3. 2 may be correct, because of two reasons
(1) Nutrients source (HTP) and (2) $K/Na=40/1$ ratio of cell cytoplasm
- 4. Mechanism=Tectonic erosion

結果：大陸成長曲線（補正後）



Primordial Continents now in deep Earth to be identified seismologically above on the CMB



To expose landmass as nutrients-source, primordial ocean must be extremely small in amount.

How to make a naked planet Earth: a key is **origin of asteroid belt**.

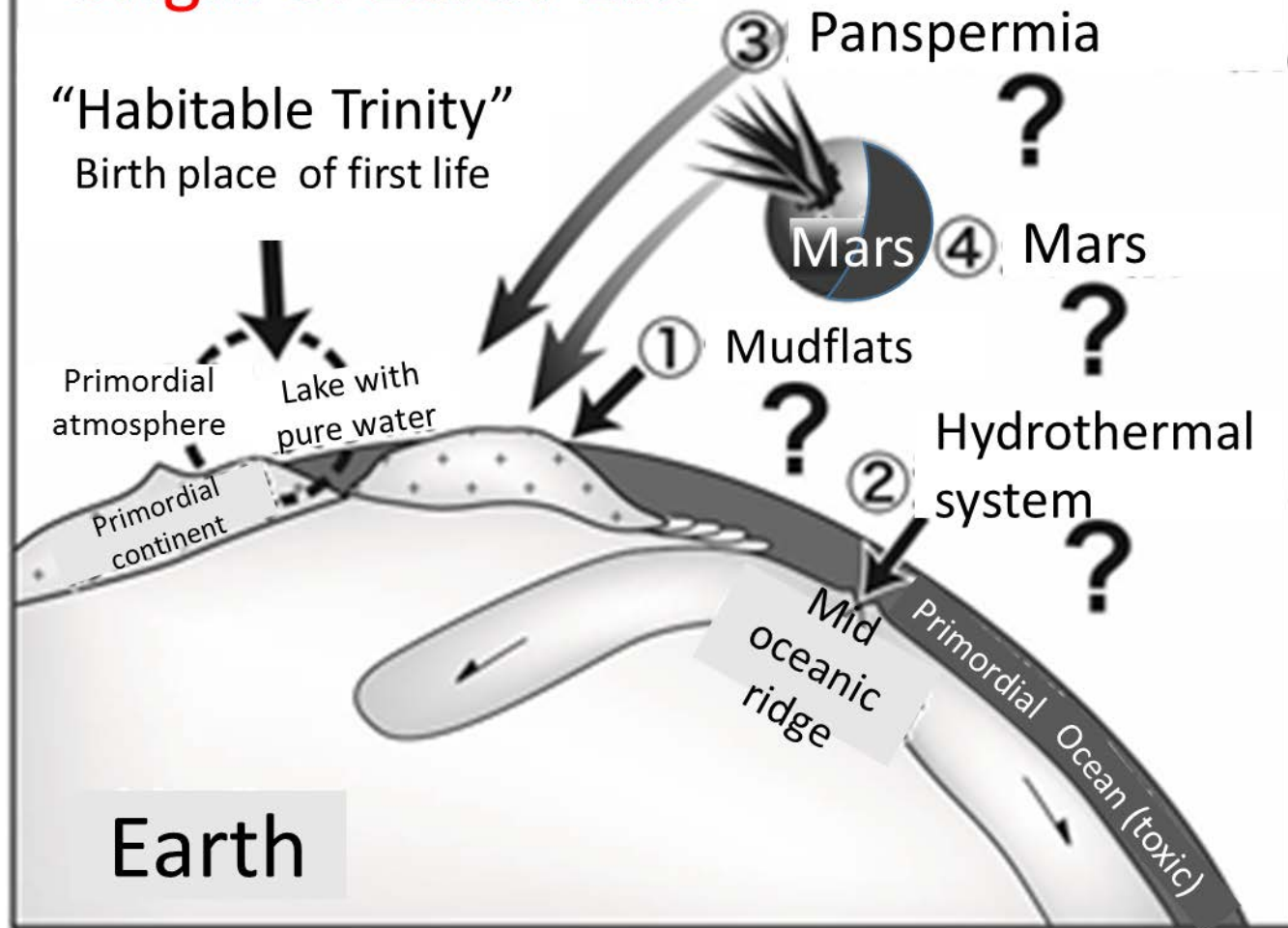
See more in appendix

History of Earth and Life

Origin of Earth-Life

“Habitable Trinity”

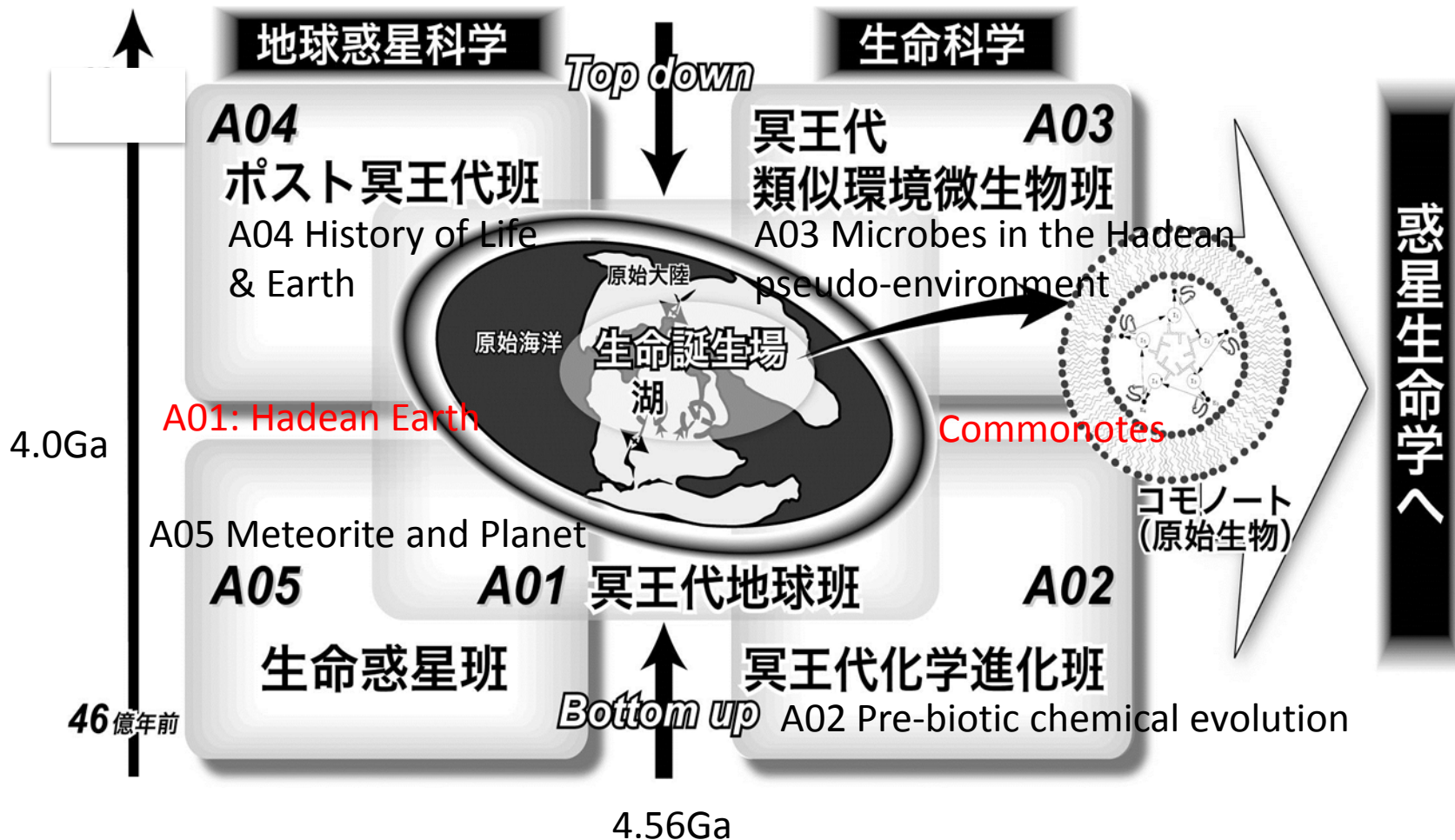
Birth place of first life



Earth & Planetary Sciences

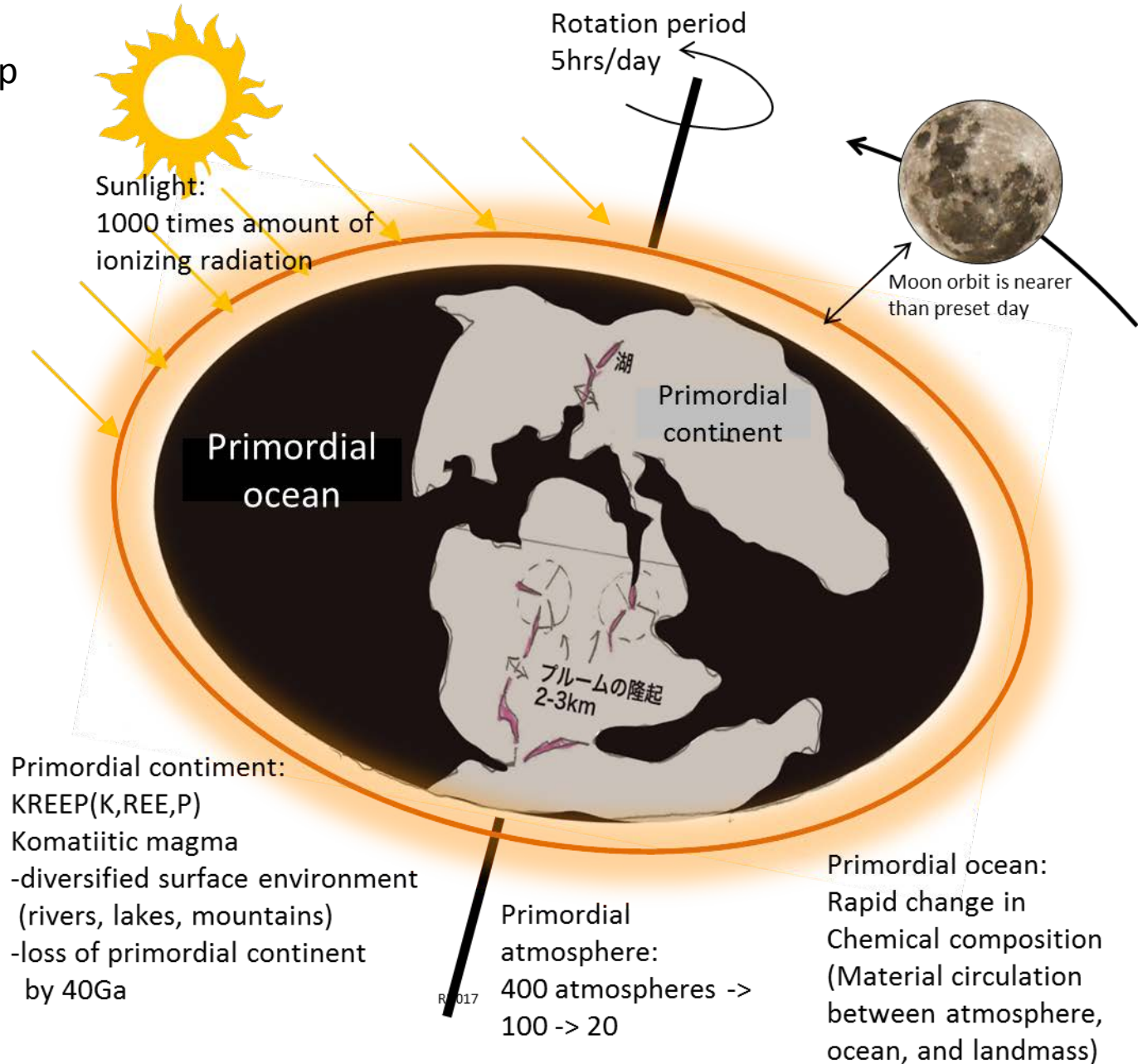
Life Science

Astrobiology



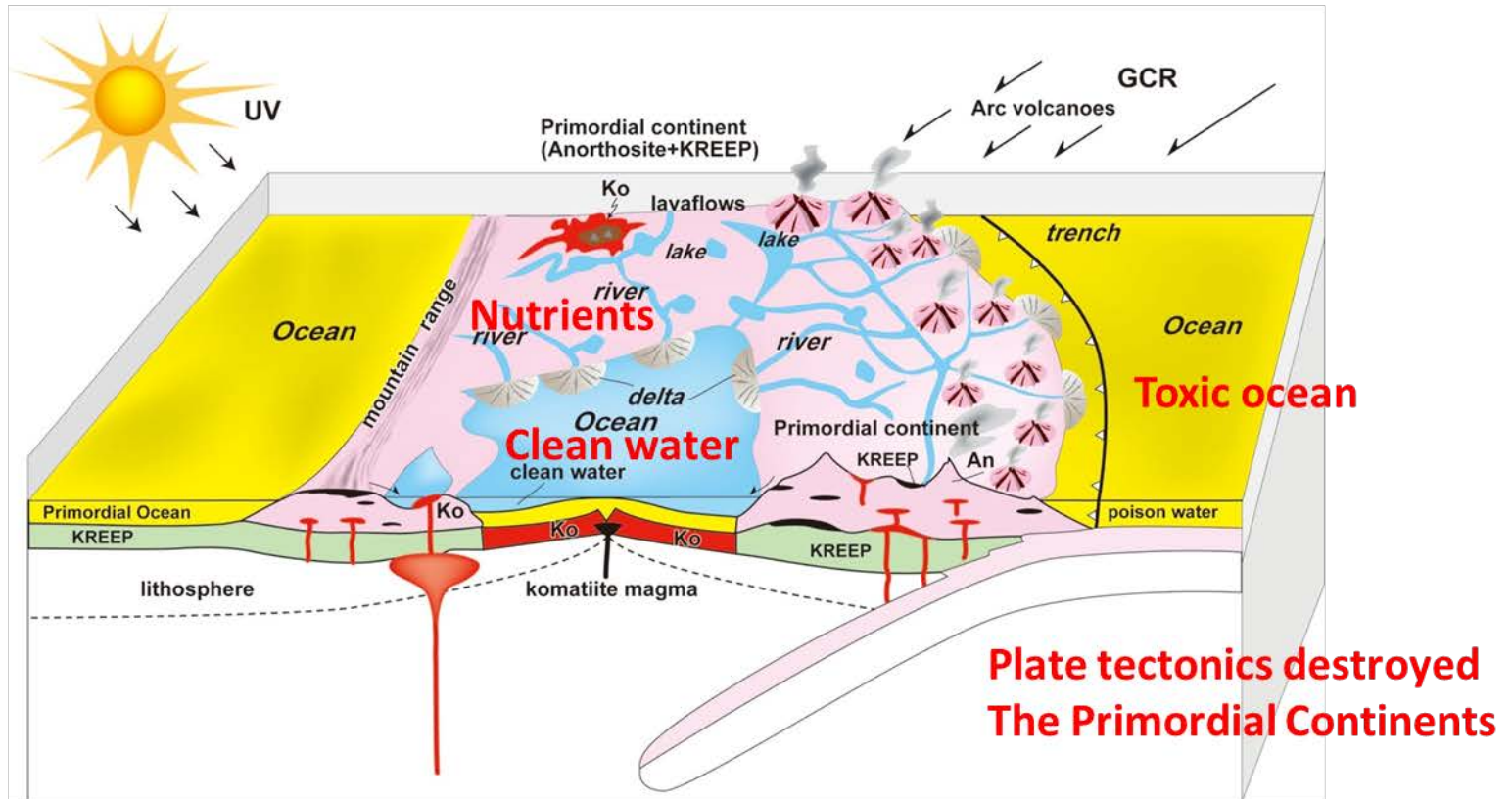
Surface environment on Hadean Earth (4.4-4.0Ga)

A01 Group



時間変化図

Birth place of life on Hadean Earth

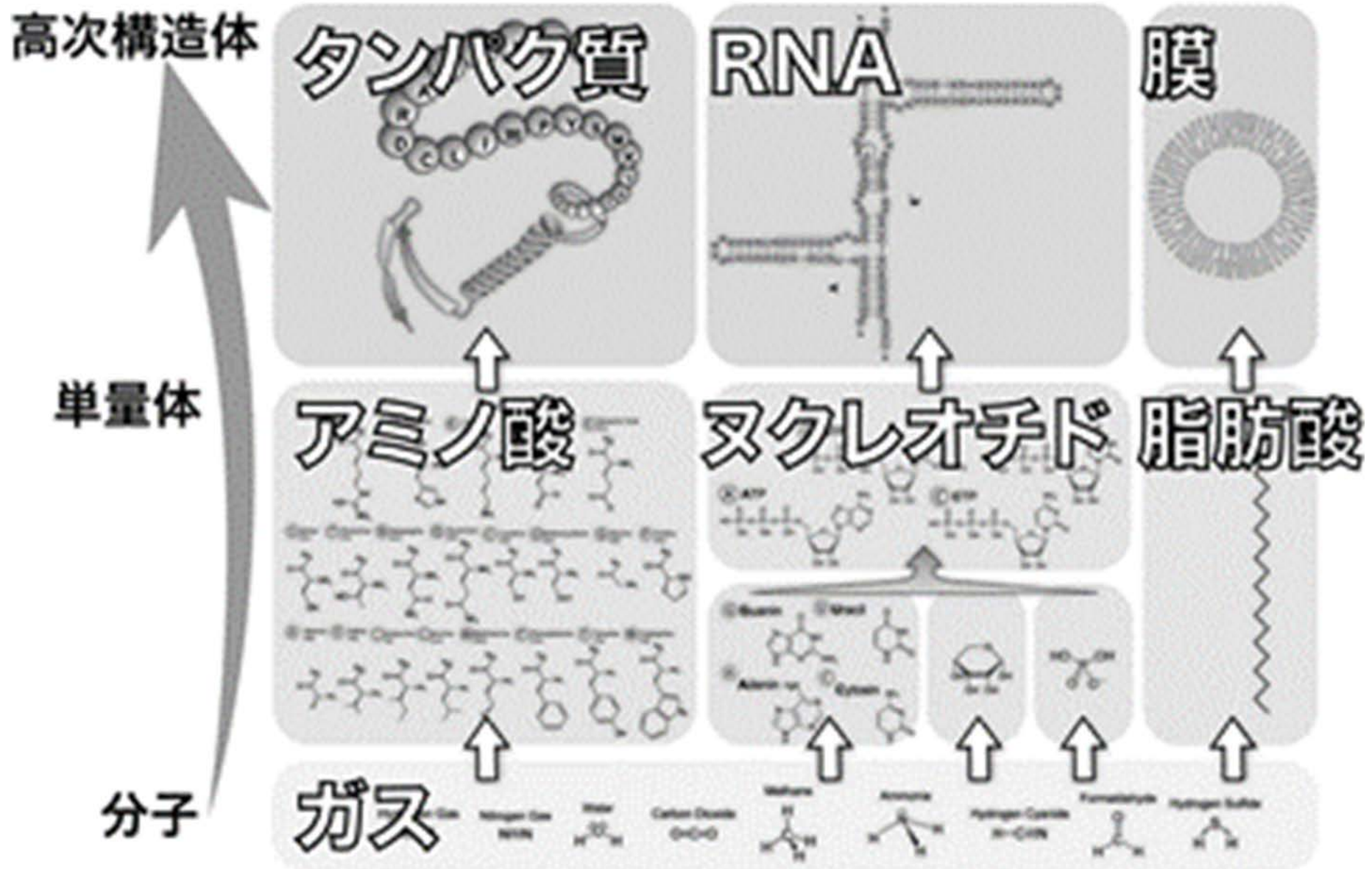


Why is Landmass necessary for Life to emerge and evolve? → Continuous Nutrient Supply

(1) Primordial continents (An+KREEP)

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

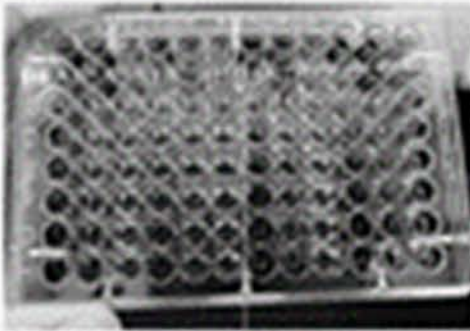
A02 Pre-biotic chemical Evolution



A03 Pre-biotic chemical Evolution

培養法の確立

Establishment of cultivation

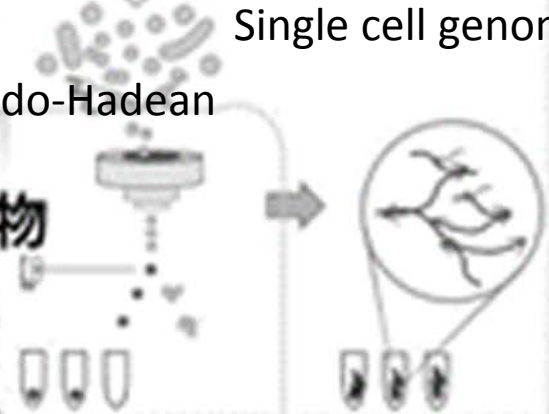


Microbes living in the pseudo-Hadean environment

冥王代類似環境微生物

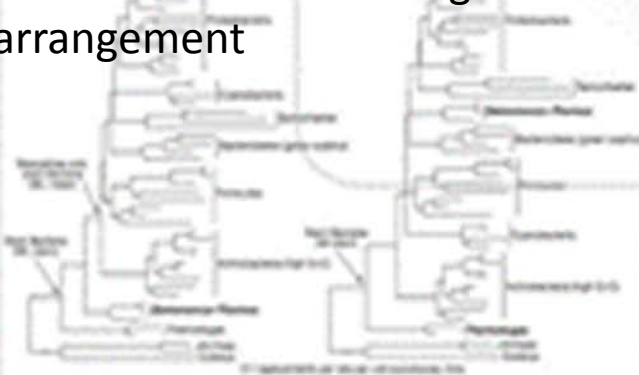
シングルセルゲノミクス

Single cell genomics



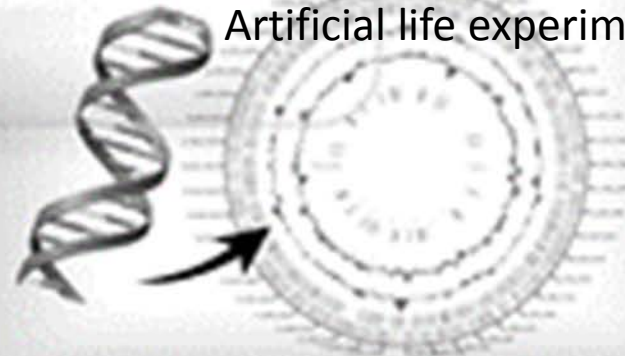
祖先型ゲノム配列の推定

Estimation of ancestral genome arrangement



半人工生命実験 (合成生物実験)

Artificial life experiments



2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

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

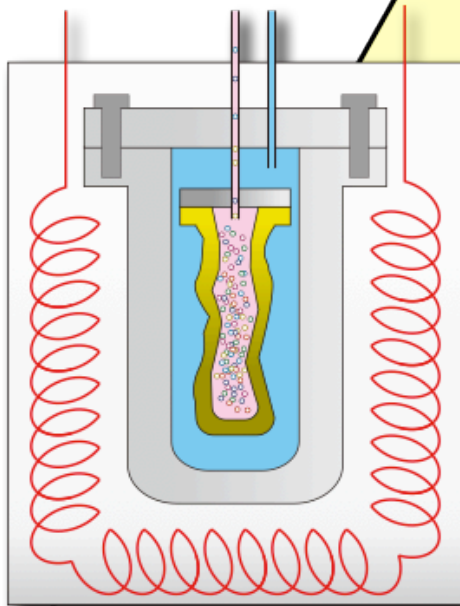
ELSI's Identities

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

1st Phase (~March, 2017)

1) Primordial Ocean

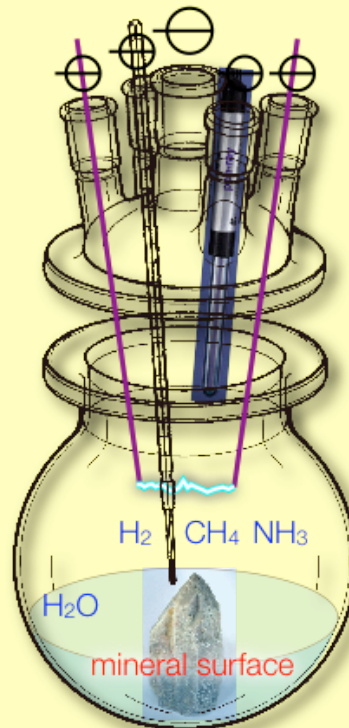
chemical compositions



Hydrothermal Reactors

2) Prebiotic Chemistry

chemical evolutions



Multi-Stage Miller-Urey Experiments

3) Primitive Microbes

resurrection database

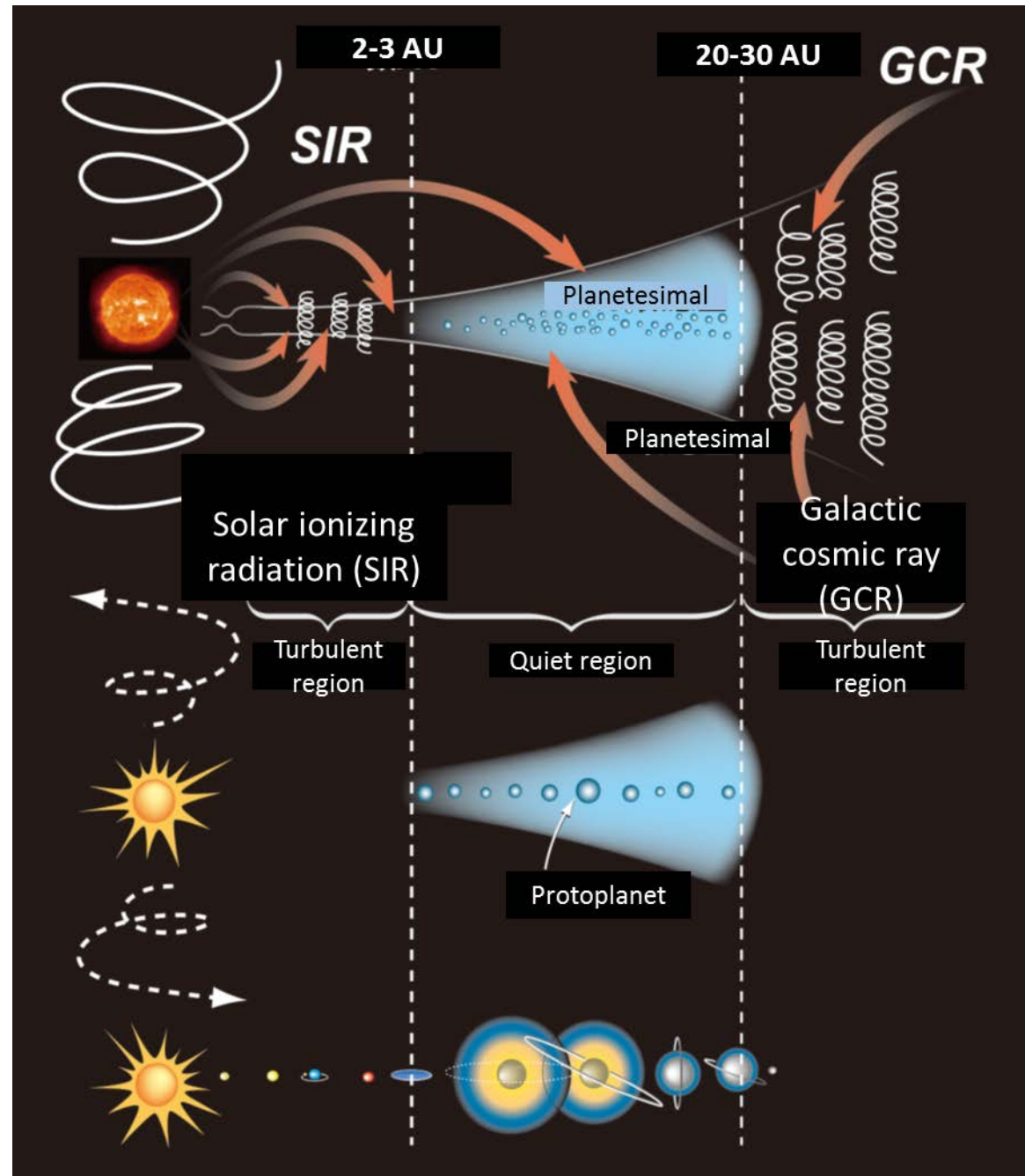


Hakuba Hotspa

Genome Analysis of
Thermophilic Microorganisms

A05 Meteorite and Planet

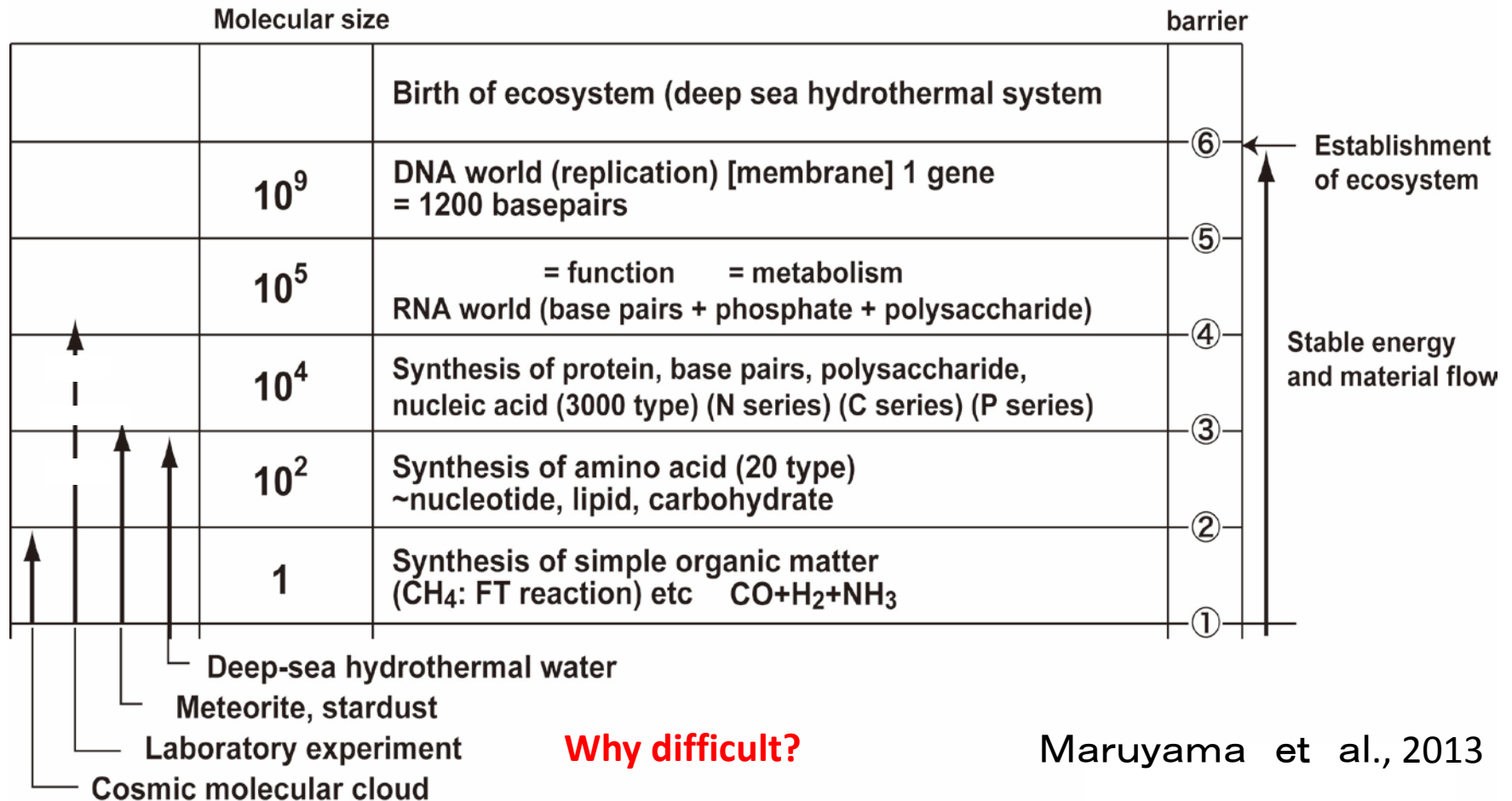
How to make HT planets



地球史解説試料の充足



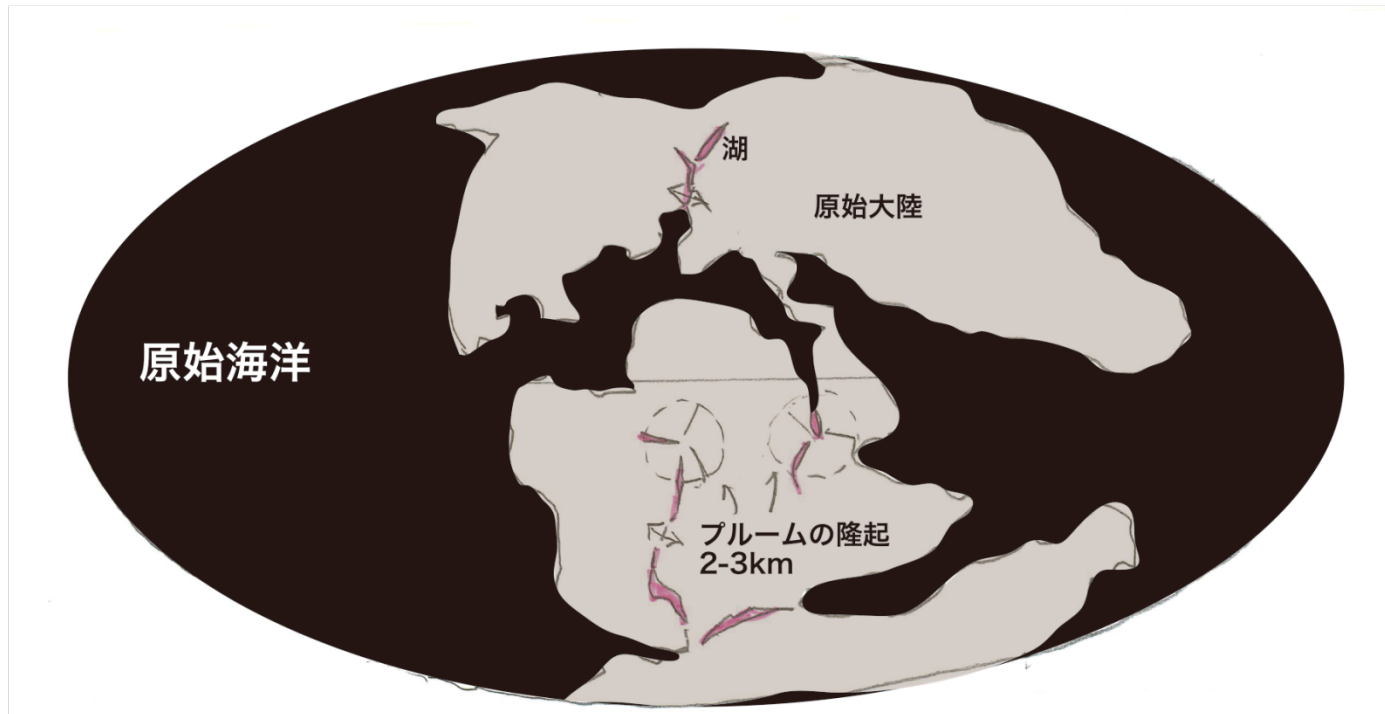
Difficulty of synthesis of huge organic compounds



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.

Surface environment of the 4.4Ga Earth

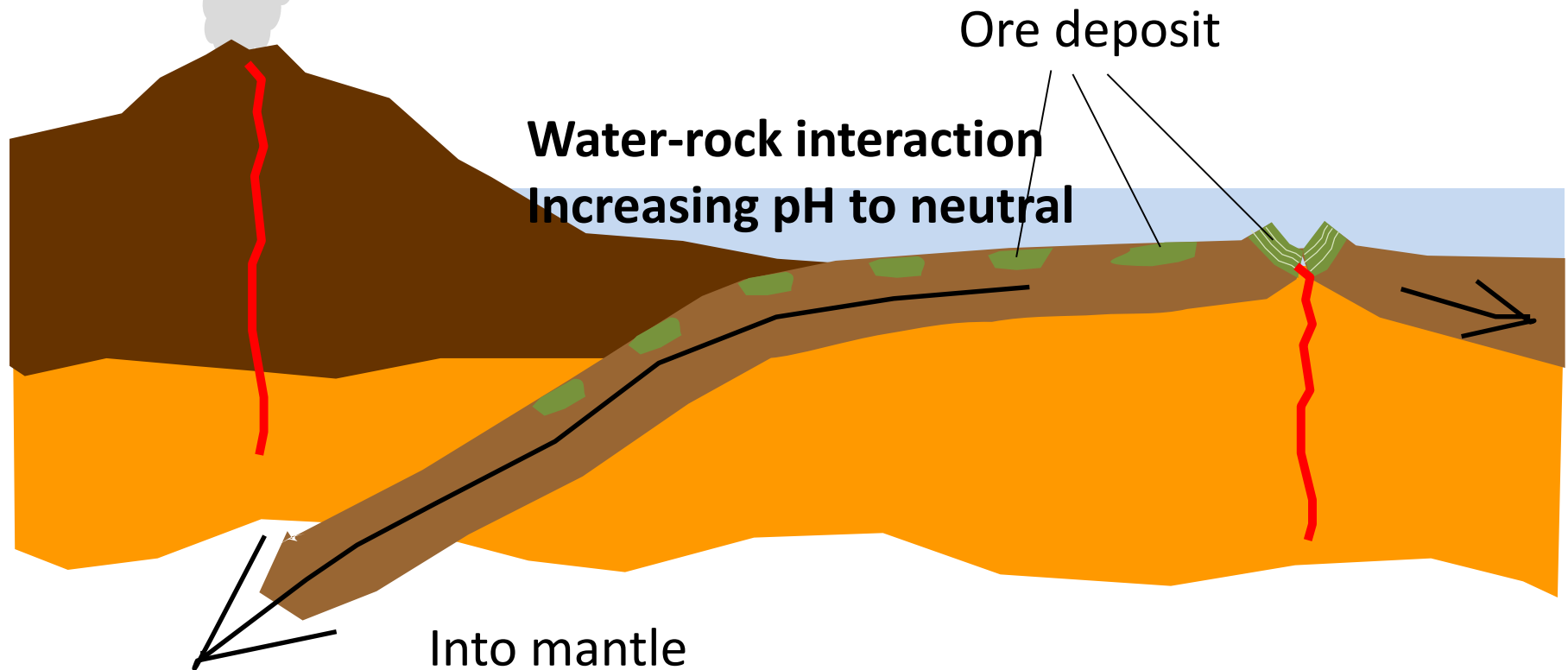
Birth place of life: only one to satisfy numbers of conditions=Lake



- Toxic Primordial Ocean (Ultra-acidic, high salinity, and super-enriched heavy elements). Imagine an ore solution in a blast furnace. Impossible for life to bear in the toxic primordial ocean. Highly different from the modern Ocean.
- Constraints: Geology of Moon, Earth , Mars and meteorites

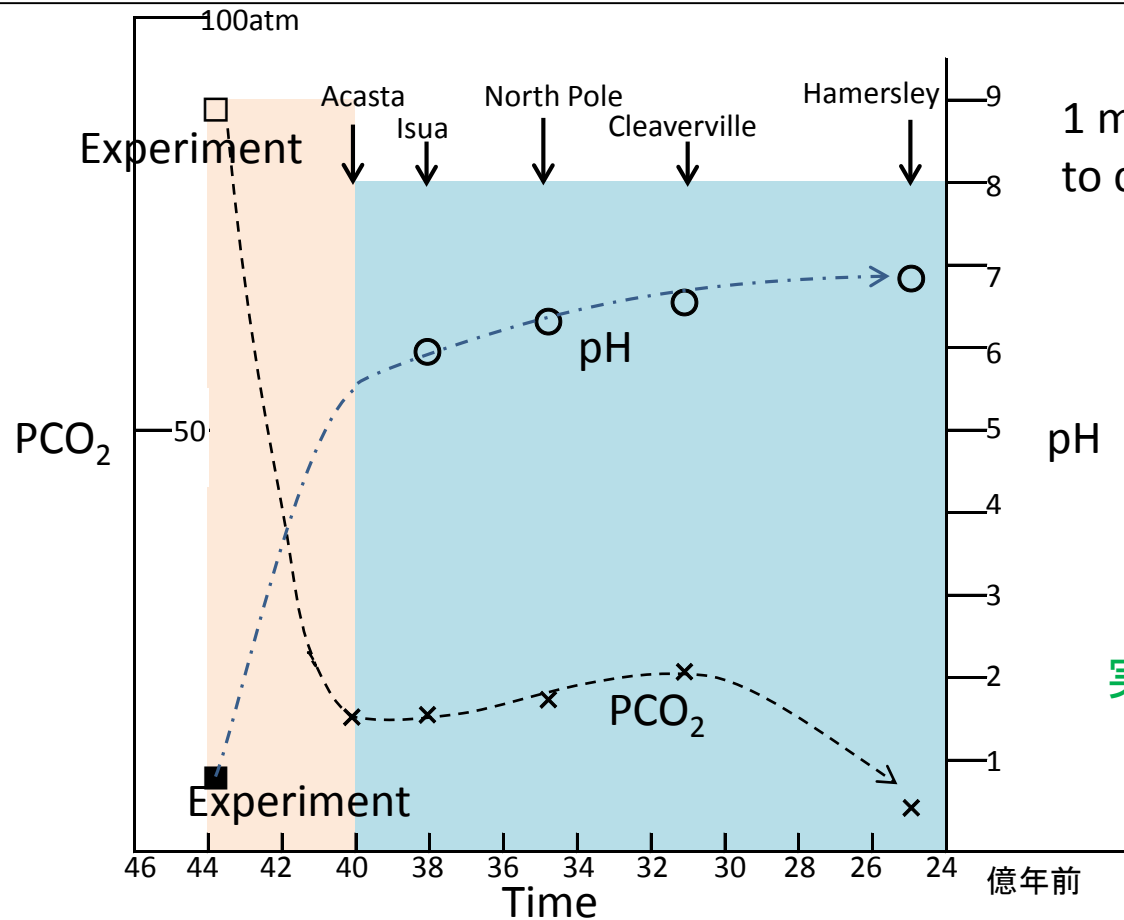
Plate tectonics as a cleaner

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



The Earth has lost primordial
continents by tectonic erosion

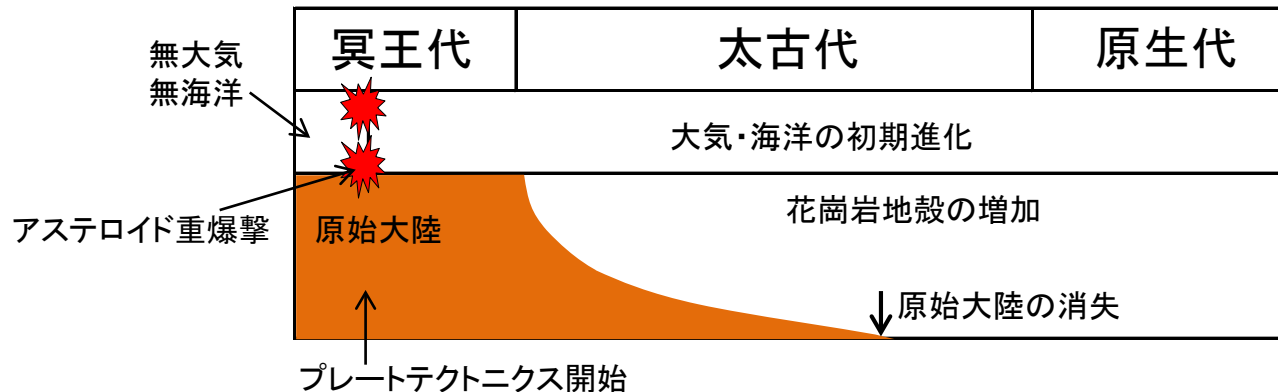
How to demonstrate the presence of Primordial Continents



1 million times more efficient to change seawater chemistry

- 重金属元素
- Salinity
- PO_2 など

実験G3(澤木)



2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

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

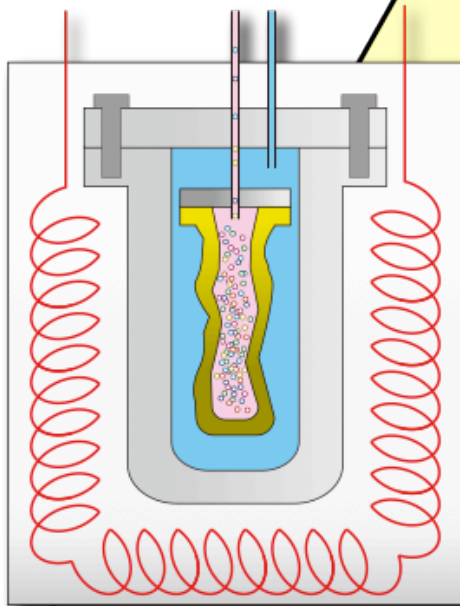
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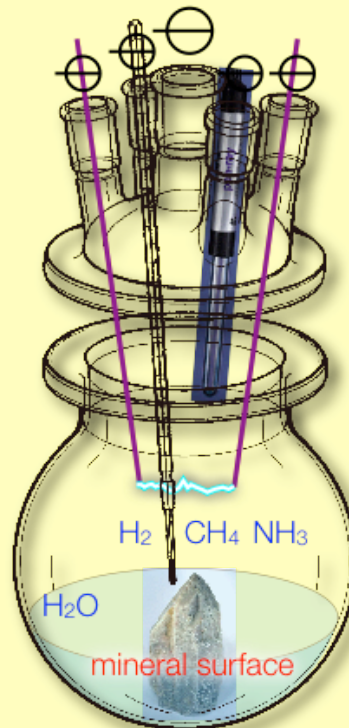
chemical compositions



Hydrothermal Reactors

2) Prebiotic Chemistry

chemical evolutions



Multi-Stage Miller-Urey Experiments

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resurrection database



Hakuba Hotspa

Genome Analysis of
Thermophilic Microorganisms

2. ELSI's Scheme of Astrobiology

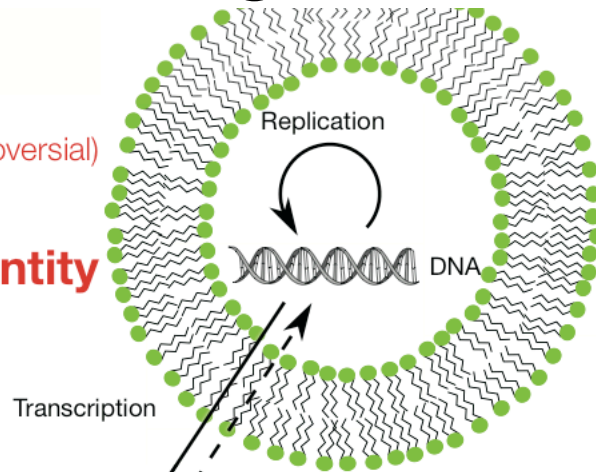
3) Exploring the **Origin of Life**

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

Origin of Life

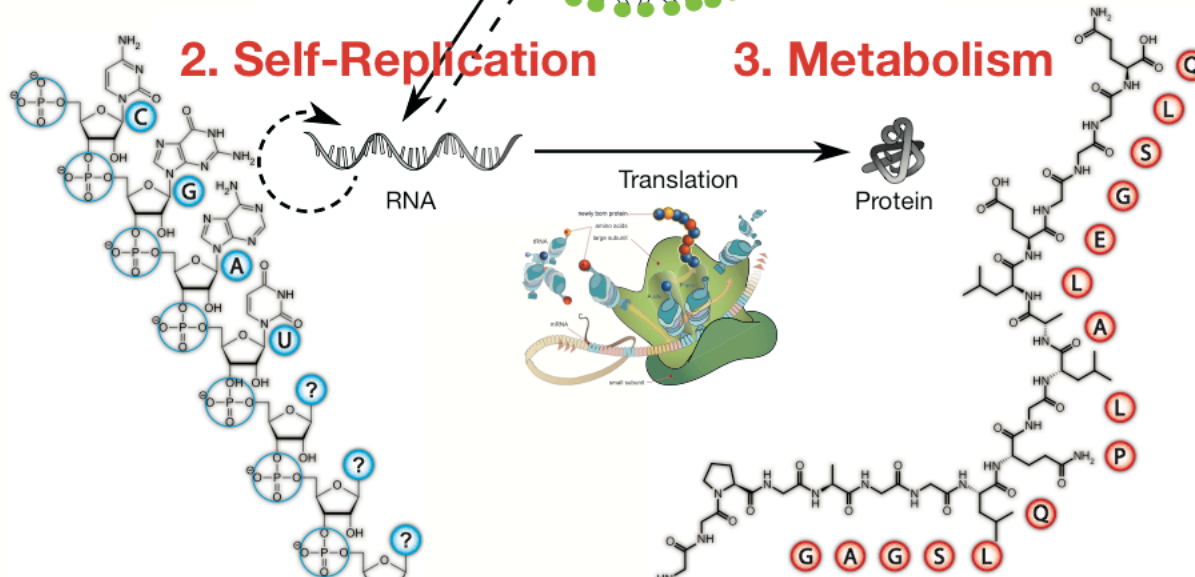
Def) Life (controversial)

1. Identity



2. Self-Replication

3. Metabolism



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

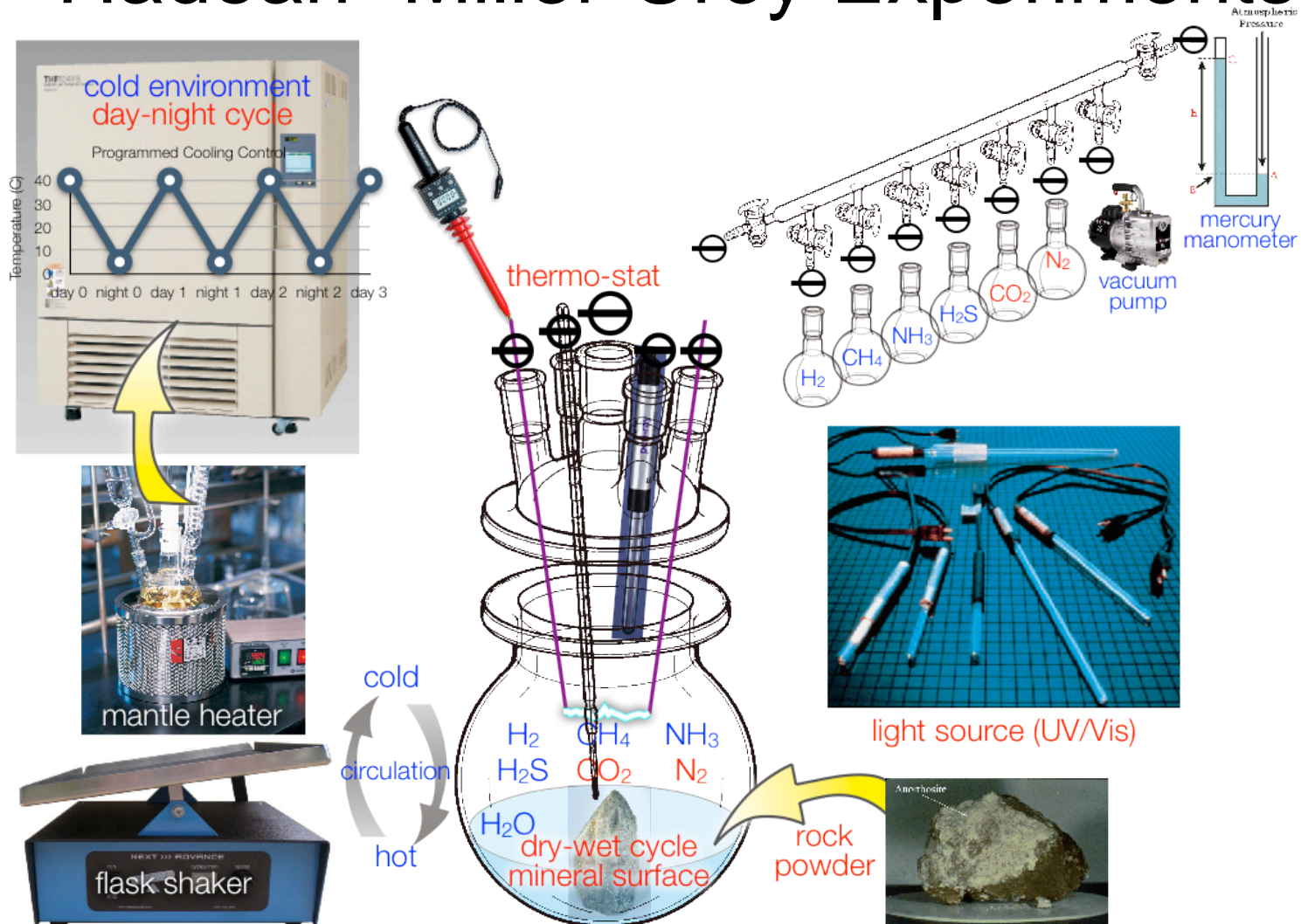
3rd row: membrane

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3) Exploring the **Origin of Life**

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

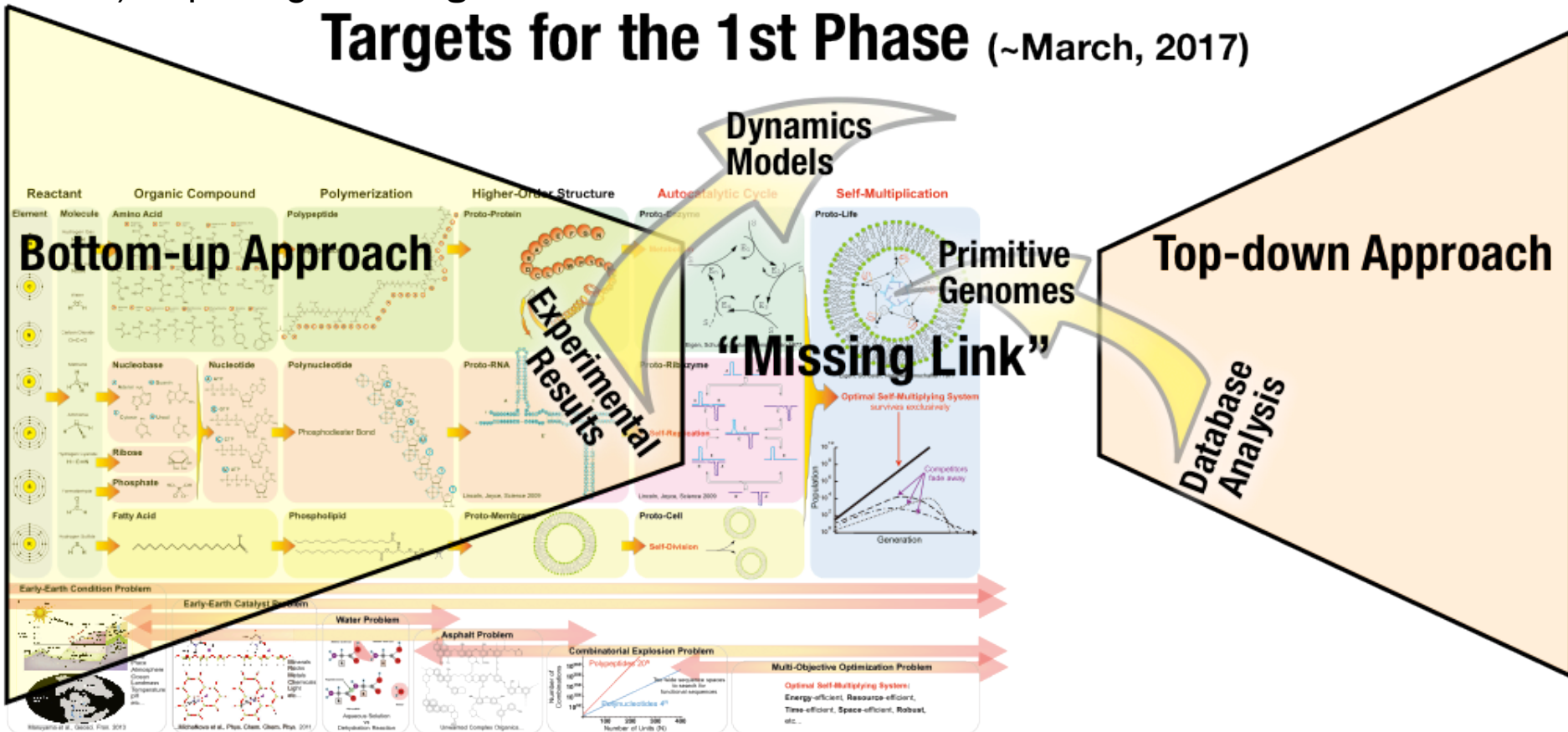
“Hadean” Miller-Urey Experiments



2. ELSI's Scheme of Astrobiology

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

Life=Organic radical reactions

1. What is radical reaction? Analogy: Nucleids radiation reactions making continuously unstable nucleids.
2. Organic radical reactions continue over 4.4 Ga
(e.g., **Fertile egg**→**Baby chick**→adult chicken,
Reactions occur in a restricted T range ca. 37°C)
3. Self-organizations
(Coordinate bond & organic compound:
Frontier of new material industry)
4. Nearly infinite number of organic radical reactions which are possible only by C,H,N,O with metallic elements from rocks, and impossible by silicates only.

2. ELSI's Scheme of Astrobiology

3) Exploring the **Origin of Life**

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

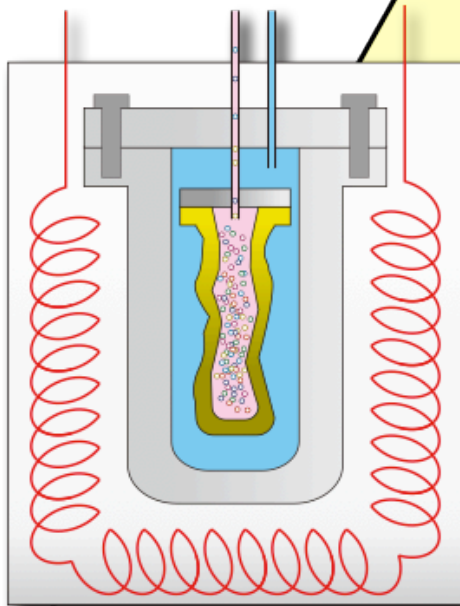
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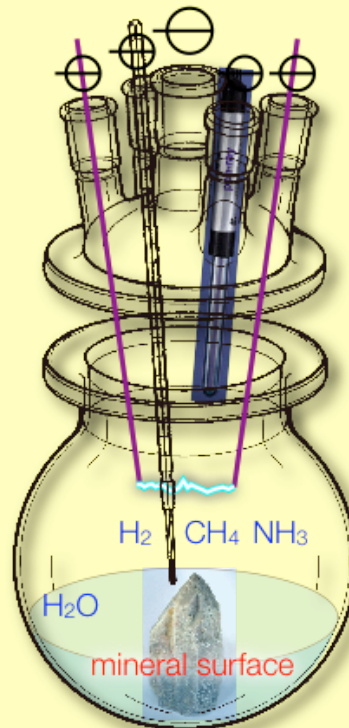
chemical compositions



Hydrothermal Reactors

2) Prebiotic Chemistry

chemical evolutions



Multi-Stage Miller-Urey Experiments

3) Primitive Microbes

resurrection database



Hakuba Hotspa

Genome Analysis of
Thermophilic Microorganisms

Towards Astrobiology

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)

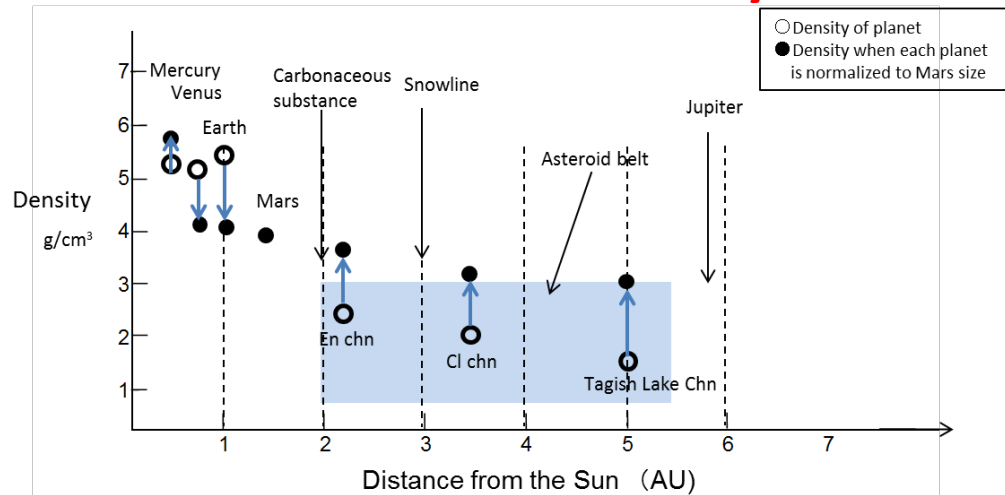
Universality and specificity of biology
applied to the **Earth, Solar System, and Milky Way Galaxy**

Towards the establishment of Astrobiology

→ Universal Formation Model of Habitable Trinity Planets

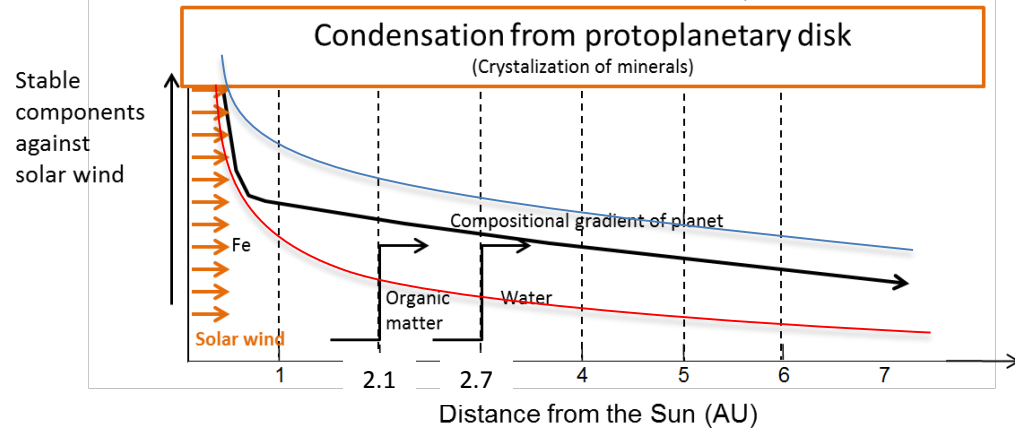
1st Step:

Bulk chemical composition of Solar Rocky Planets



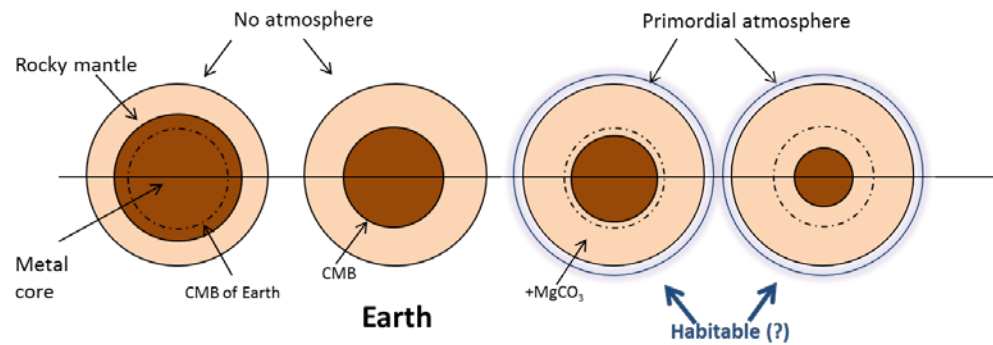
2nd Step:

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

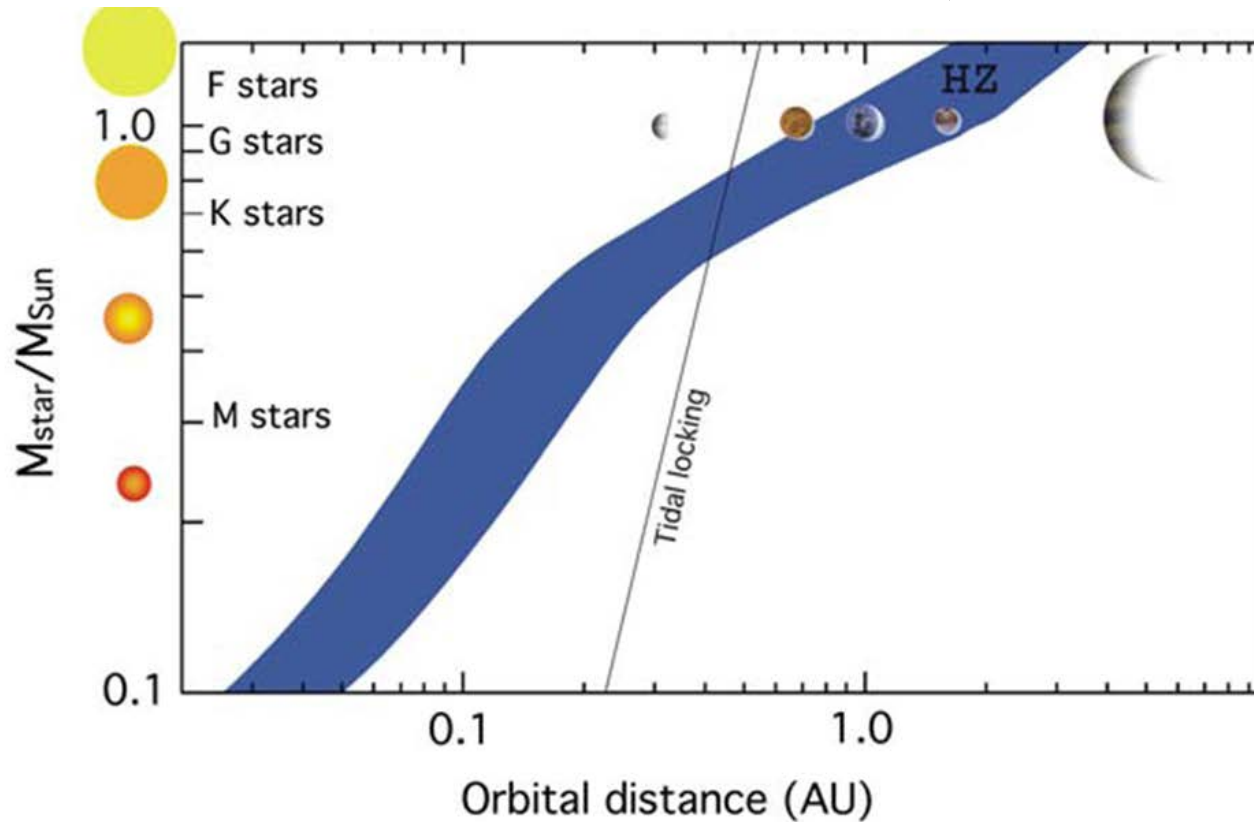


3rd Step:

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



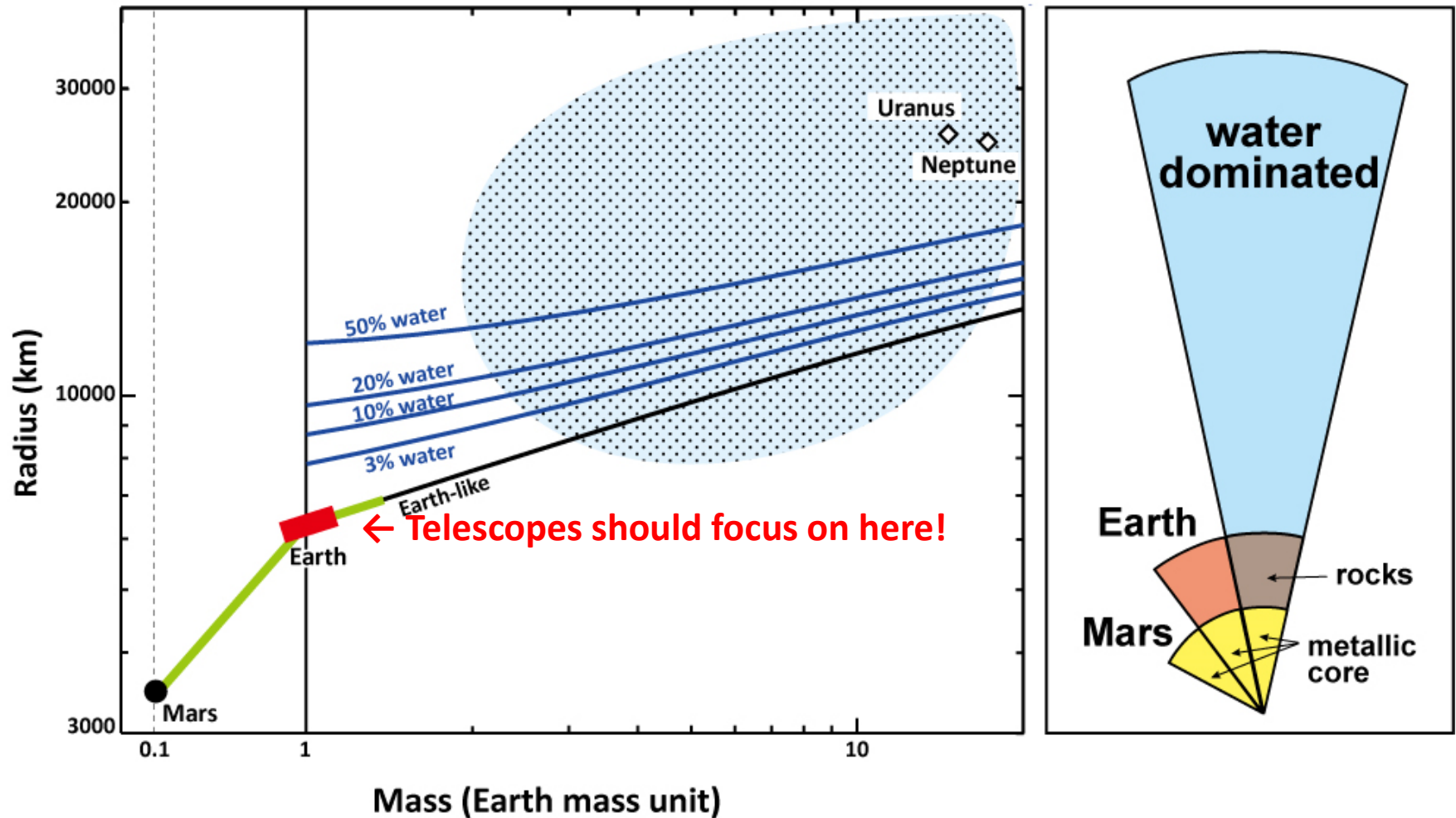
Habitable Zone as functions of not only by distance from CS but also
greenhouse gas (X and amount), X of CS, and time
中心星からの距離だけでは定義できない



Lammer et al., 2009

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

Expected results

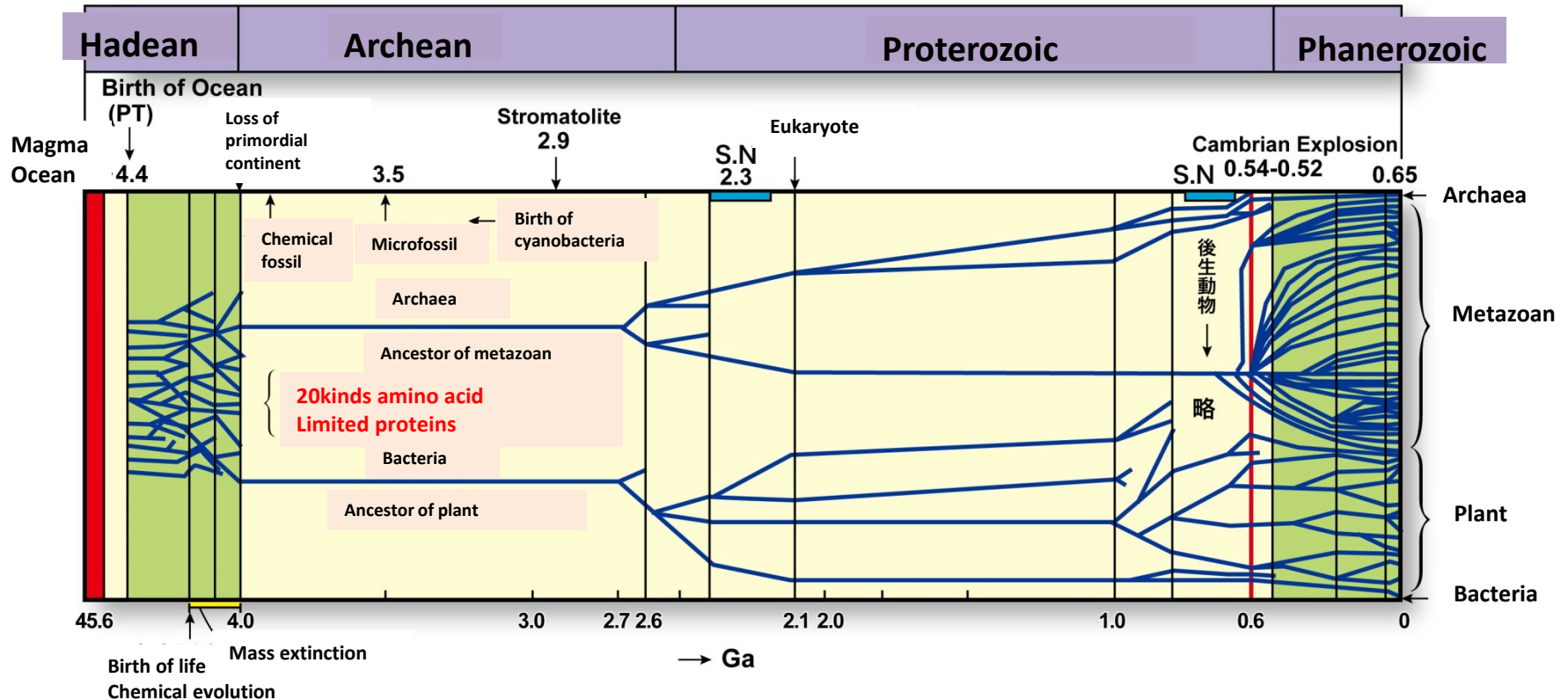
1 Birth of life

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

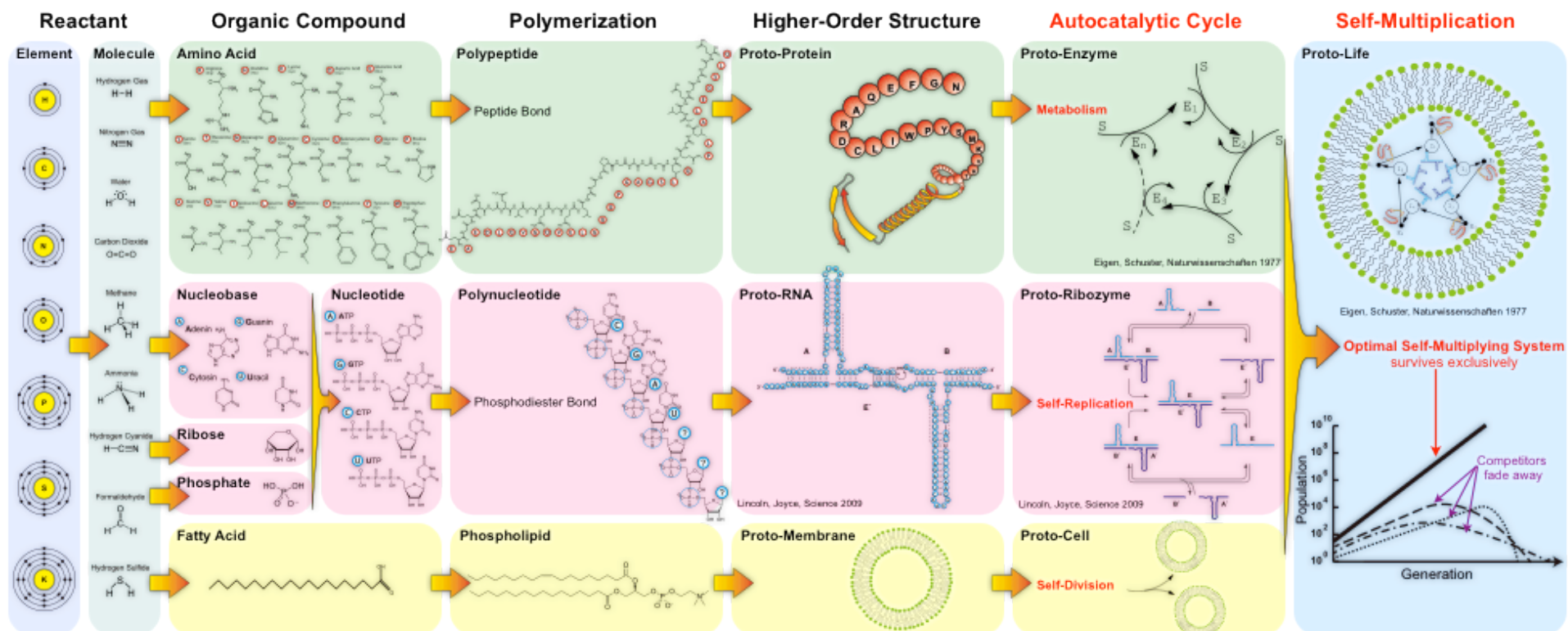
- Diversified microorganisms
- Extinction & evolution during 400 m.y.
- Finally, Archaea & eubacteria
- Loss of primordial continent

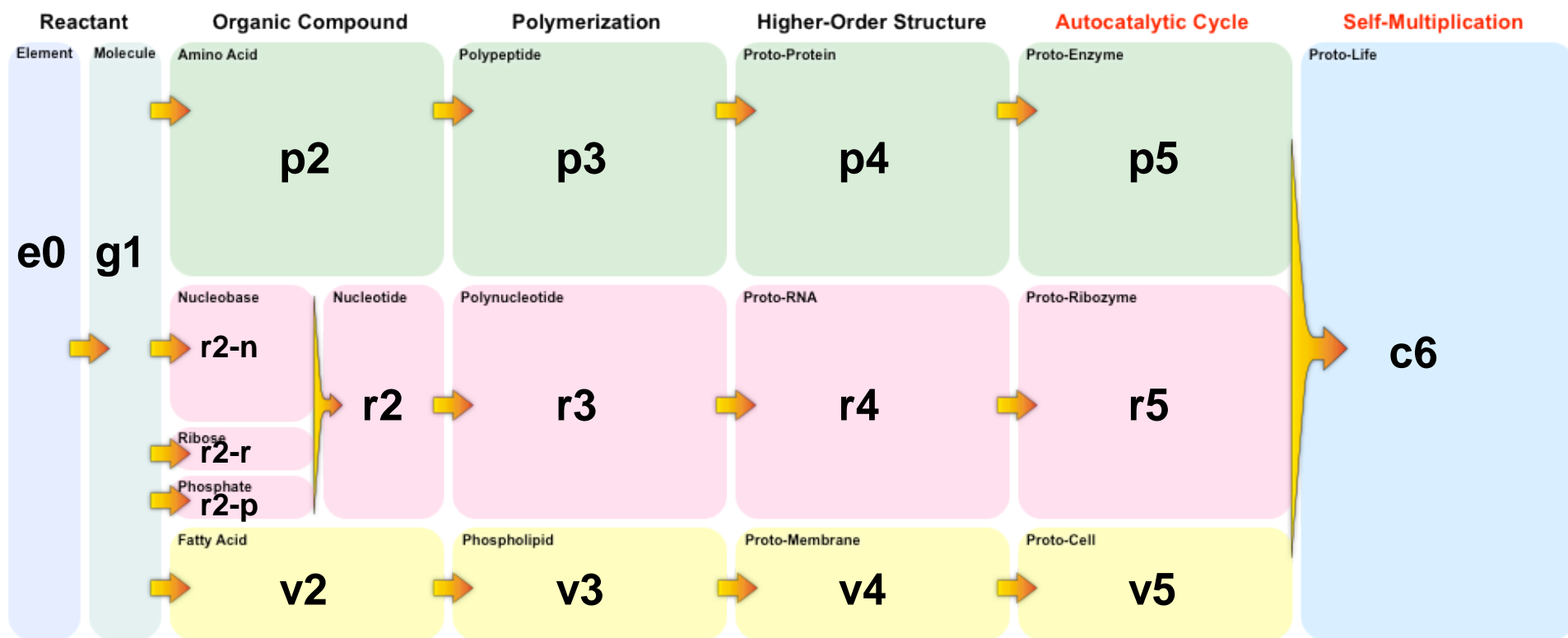
第2段階はtop-downを組み合わせる

Phanerozoic

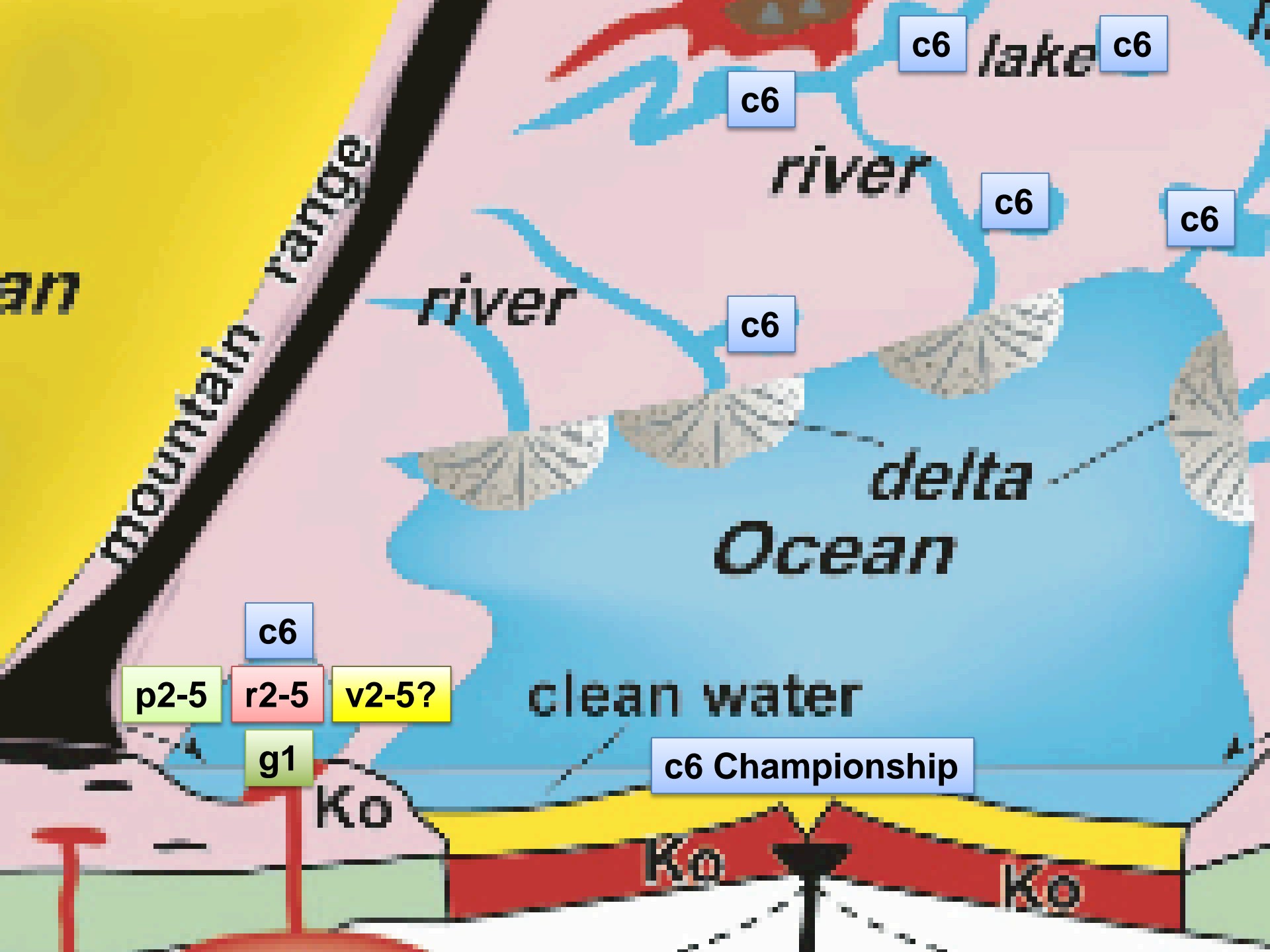
- Golden age for plants and metazoan
- Occupying on-land environment (increase in oxygen content)
- Emergence of huge landmass

How to do experiments





E=elements, g=gas, p=protein, r=RNA, v=vesicle (membrane), c=cell



c6

c6

lake

c6

river

c6

c6

river

c6

delta

Ocean

c6

p2-5

r2-5

v2-5?

clean water

g1

c6 Championship

Ko

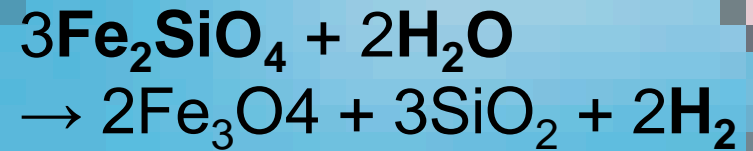
Ko

Ko

Birth Place of Proto-Life

g1: H₂

Catalysts=magnetite, Ni-Co a



H₂O@Lake

Fe₂SiO₄@Magma

Birth Place of Proto-Life

N_2 @ Atmosphere

g1: NH_3 @ Low Temp. $< 150^\circ\text{C}$



H_2 @ Lake

H_2O @ Lake

Anorthite + H_2O

→ Cements

(Ca-Zeolites, Carbonates, CaAl-silicates)

Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) @ Continental Crust

Birth Place of Proto-Life

CO_2 @Atmosphere

g1: CH_4

$\text{Komatiite} + \text{H}_2\text{O} + \text{H}_2 + \text{CO}_2$
 $\rightarrow \text{CH}_4$

H_2O @Lake

H_2 @Lake

Komatiite@Magma

Birth Place of Proto-Life

UV, VIS, X-ray, Gamma-ray (energy) @Atmosphere

Electric Discharge (energy) @Atmosphere

p2: Amino Acids (MU Exp.)

$\text{H}_2\text{O} + \text{H}_2 + \text{CH}_4 + \text{NH}_3 (+ \text{Energy})$
 $\rightarrow \text{Amino Acids}$

$\text{H}_2\text{O} @ \text{Lake}$

$\text{NH}_3 @ \text{Lake}$

$\text{H}_2 @ \text{Lake}$

$\text{CH}_4 @ \text{Lake}$

Amino Acids (precipitation)

Birth Place of Proto-Life

UV, VIS, X-ray, Gamma-ray (energy) @Atmosphere

Electric Discharge (energy) @Atmosphere

r2: Nucleotide Precursors (MU Exp.)

$\text{H}_2\text{O} + \text{H}_2 + \text{CH}_4 + \text{NH}_3 (+ \text{Energy})$
 $\rightarrow \text{Amino Acids}$

$\text{H}_2\text{O} @ \text{Lake}$

$\text{NH}_3 @ \text{Lake}$

$\text{H}_2 @ \text{Lake}$

$\text{CH}_4 @ \text{Lake}$

Nucleotides (precipitation)

Nutrients from KREEP
Catalysts: B and Li

Birth Place of Proto-Life

Catalyst: = B & Li

v2: Fatty Acids?

CH_4 @Lake

H_2O @Lake

NO

Birth Place of Proto-Life

Nutrients from KREEP, no Na

p3-4: Polypeptides

**Amino Acids + Mineral Surface
+ Dry-Wet Cycle (Tide) → Polypeptides**

Amino Acids (precipitation)

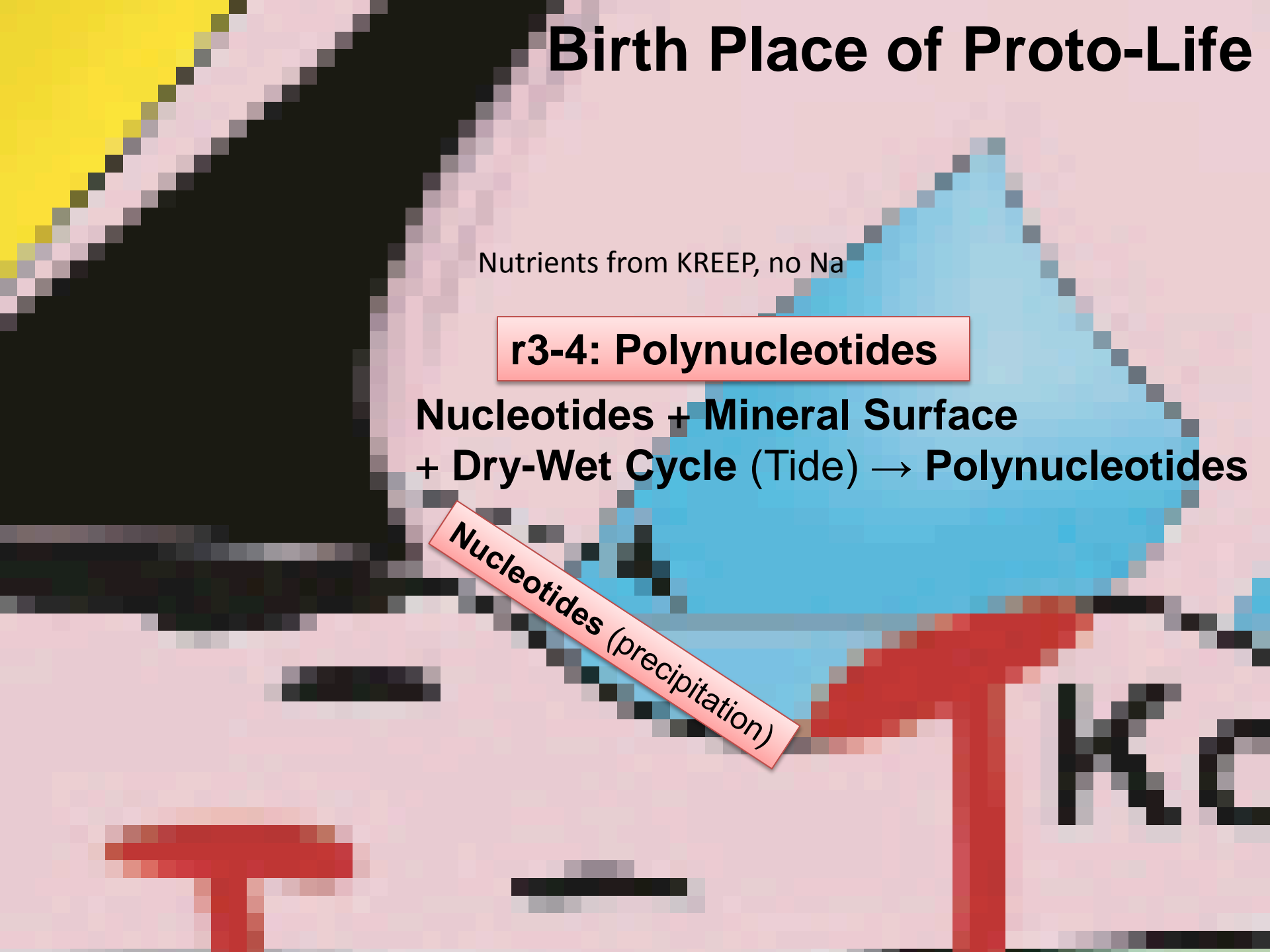
Birth Place of Proto-Life

Nutrients from KREEP, no Na

r3-4: Polynucleotides

**Nucleotides + Mineral Surface
+ Dry-Wet Cycle (Tide) → Polynucleotides**

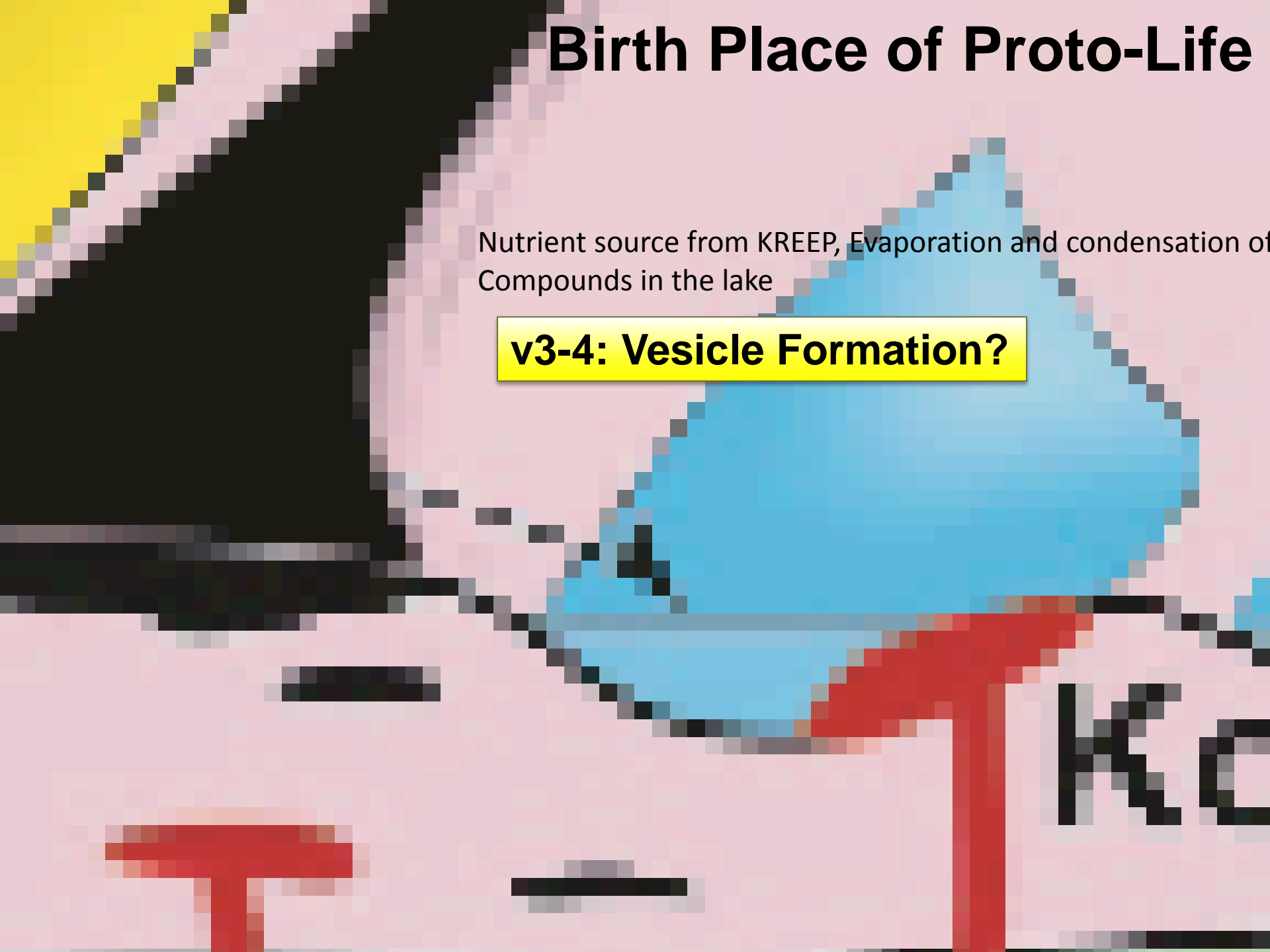
Nucleotides (precipitation)



Birth Place of Proto-Life

Nutrient source from KREEP, Evaporation and condensation of
Compounds in the lake

v3-4: Vesicle Formation?



Carbonate Minerals
(unstable@Toxic Ocean)

Birth Place of Proto-Life

p5: Enzyme-like Polypeptides

+

r5: Ribozyme-like Polynucleotides

+

v5: Membrane-like Vesicle

↓

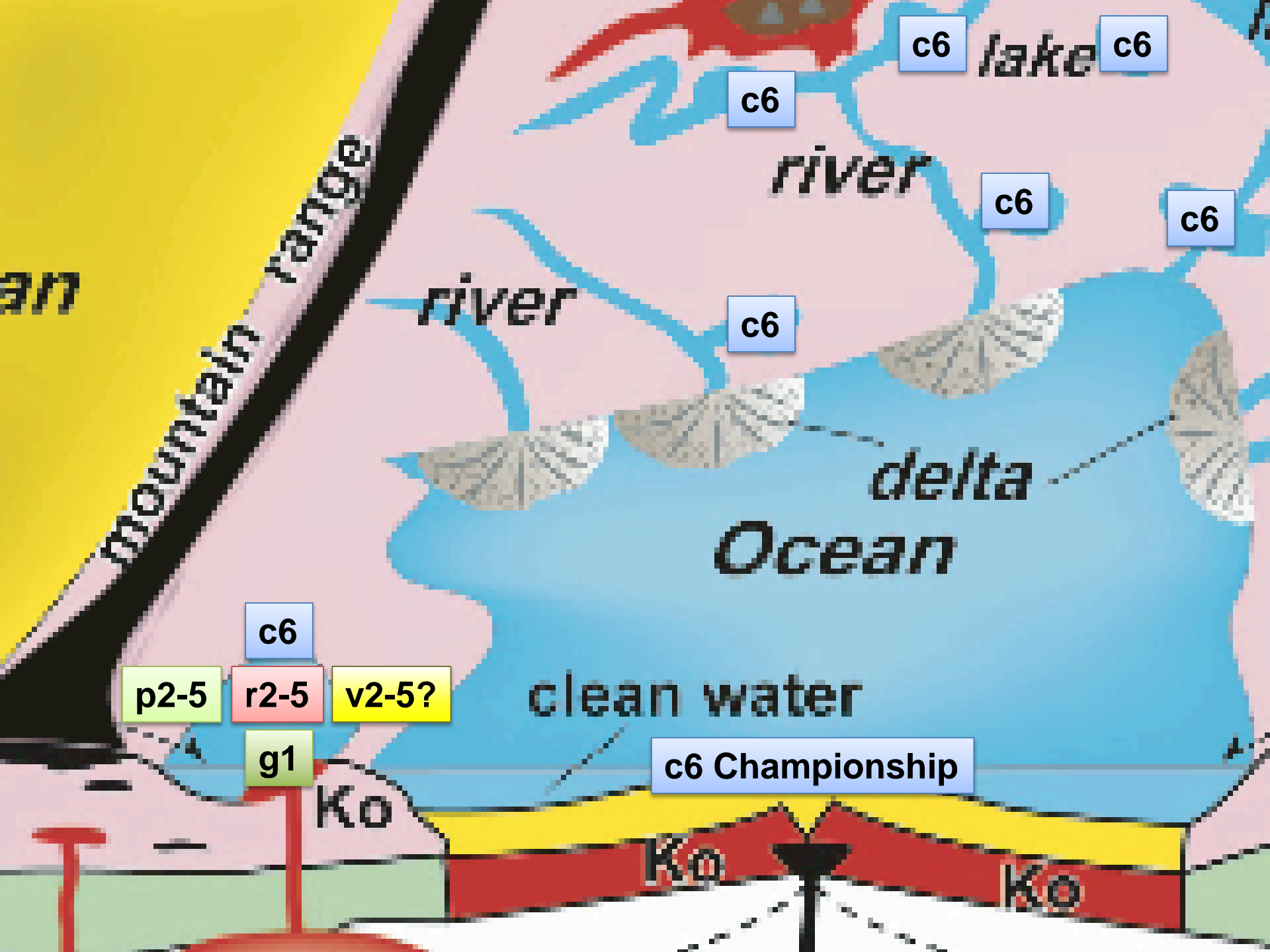
c6: Proto-Life

Carbonate Minerals
(stable@pH7 Lake):
Calcite, Dolomite, Ankerite, etc.

KREEP@Basalt
(K, Rare Earth, P)

Concentration of
K, P, and nutrients
by evaporation

NO



c6

c6

lake

c6

river

c6

c6

river

c6

delta

Ocean

c6

p2-5

r2-5

v2-5?

clean water

g1

c6 Championship

Ko

Ko

Ko

c6 Championship: Survival of Optimal Proto-Life

Natural Selection@Toxic-Clean Water Interface

lean water

Clean Water@Lake

c6

c6

c6

c6

c6

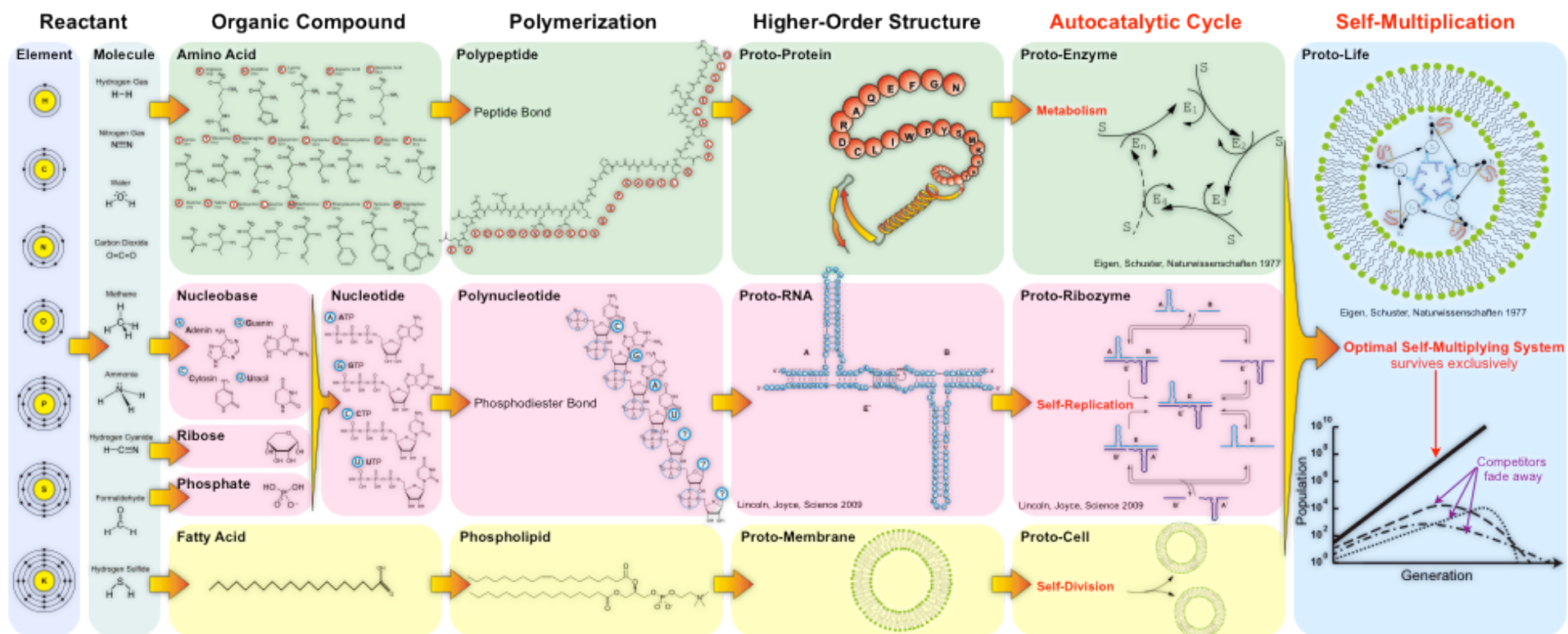
Toxic Ocean Water@Continental Lift

c6

c6

Ko

K



1) Atmosphere

2) Ocean

3) Continent

4) A-O-C Interaction

5) Self-Rotation Freq.

6) Tide Freq.

7) Magnetic Intensity

resulted in

Unidirectional Chemical Evolution

Philosophical background: How to
proceed multi-disciplinary works

戦略(革新的研究の一般側)

Rule: How to create new science

- 1 世界を独走する独自性: 生命の誕生場
- Geoscience to bear life on the Hadean Earth
- 2 冥王代類似環境微生物(未記載)の確保
- Discovered bacteria (new species) under Hadean Earth analog of hydrothermal system
- 3 人工生命実験に利用(世界へ開放)
- Use for artificial life synthesis
- 4 学際研究を加速する法則
- How to proceed multi-disciplinary works

Difficulties to do interdisciplinary research

1) It is nonsense to think interdisciplinary research will progress by conversation in common room (where free soft drink and alcohol provided!)

2) It is wrong that directors expect that younger researchers should provide the excellent achievement on behalf of them.

3) Every researcher have to be prepared and make tremendous effort to do interdisciplinary research. Directors must perform it first. Planetary scientist have to write papers of biology, geology and astronomy, and vice versa, which is interdisciplinary science. Interdisciplinary scientist must be brave and perform by himself.

4) Internal assessment panel should annually evaluate staff performance including both researchers and admin staff with application of praise and blame. Familiarize all staff with necessity to deliver the result.

Implementation of internal assessment panel

1) Conduct **annual performance review** for all researchers and administrative staff.

Evaluate result and set goal, which is evaluated by the panel member.

2) Application of **praise and blame**

Praise: bonus, base up of salary, more funding

Blame: commitment to deliver the result and set a clear target to make a progress

3) 4 Directors are evaluated by all staff in ELSI

(15 items; from +5 to -5)

4) Performance review spend 3 days. Invite appraisers (3-5 person) from outside of ELSI.

5) English is preferred language. But presentation material include both English and Japanese to make it more understandable for appraisers from various fields.

Appraisal items

● For researchers

- 1) performance for interdisciplinary research
- 2) publication (or achievement)
- 3) care for others
- 4) quality of research (by 3 rank; only description, establishment of concept, systematization)
- 5) and others (+10 items)

● Admin staff

- 1) Endeavor for administrative organization
- 2) quality/accuracy
- 3) care for others

Organization Theory

- Fatal disease of organization
 Functionive (Organization to strive for the goal) shifts to Community (Pursue happiness of members)

Once member is fixed after the organization is established, biological urge appears in the organization to pursue happiness of members, regardless of the goal of the organization.

Organization Theory

1) Shift from funcrive to community

- Feel like chosen people,
- Non-intervention each other
- Bureaucratization
- Power game
- Stability orientation
- Keeping information secret within the organization
 - > Remember the importance of mutual criticism

2) Successful experience

3) Over-adapted to the circumstances

- Sectionalism
- Specialty

Organization Theory

Characteristics of Community

- 1) avoid appraisal
- 2) dislike a person of high ability
- 3) like a person of noble character

Check points

- 1) Seniority-based system
- 2) Keep things confidential (no disclosure of information)
- 3) A please-everyone policy
- 4) Anti- Shigenori Maruyama