Evolutional history of Hadean surface environment and three step model for the emergence of first life

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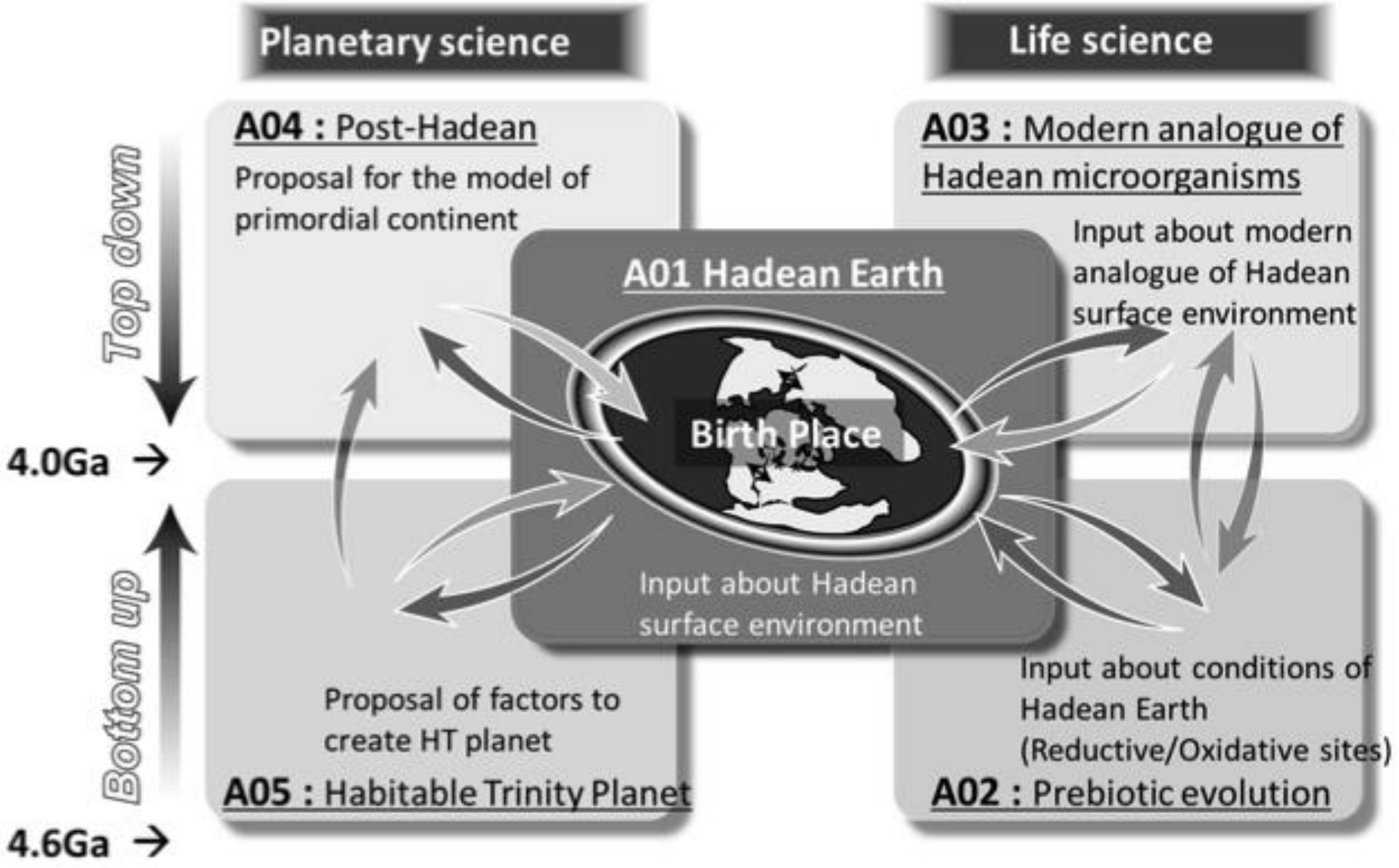
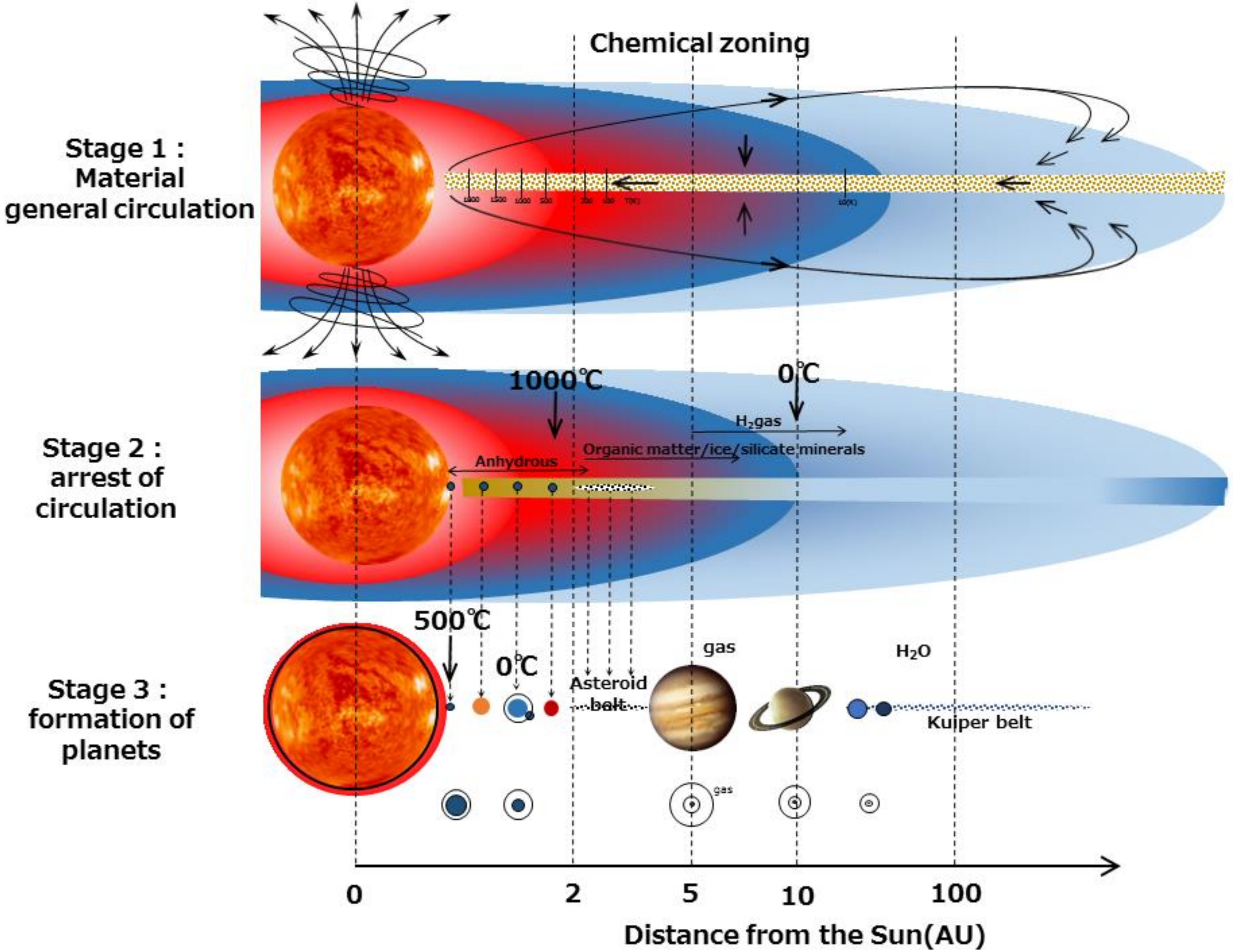
- 1 Introduction
- 2 Hadean Bioscience Project
- 3 Nine Requirements of birth place of life
- 4 Surface environmental change during the Hadean
- 5 Synthesis: Three step evolution of first life
- 6 Discussion

Programmed Research Projects

Cradle of life; Geology, mineralogy and planetary science, combined with biology

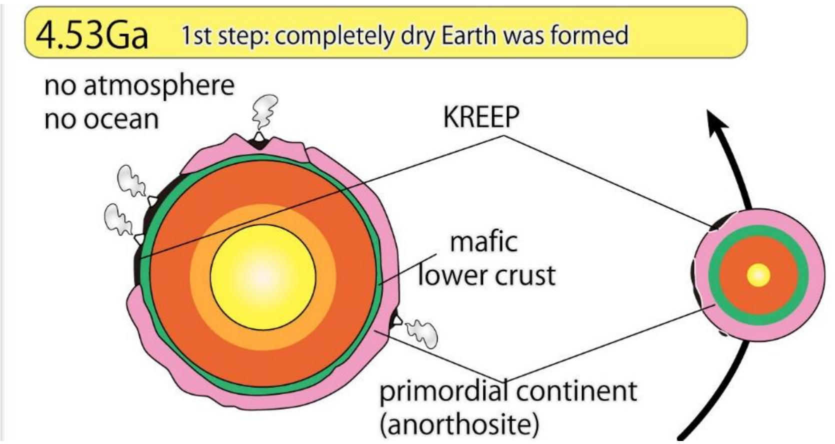


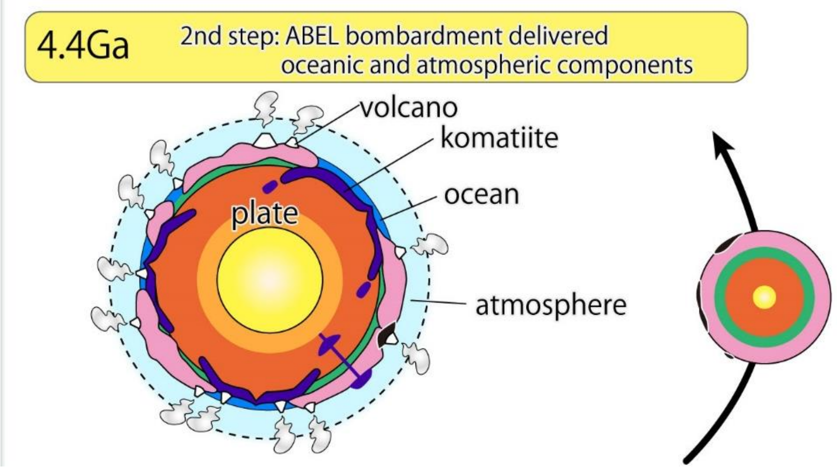
A05


Chemical zoning
Stage 1 : Material general circulation
Stage 2 : arrest of circulation
Stage 3 : formation of planets
1000℃
0℃
H_2gas
Organic matter/ice/silicate minerals
Anhydrous
500℃
0℃
gas
H_2O
Asteroid belt
Kuiper belt
gas
0
2
5
10
100
Distance from the Sun(AU)

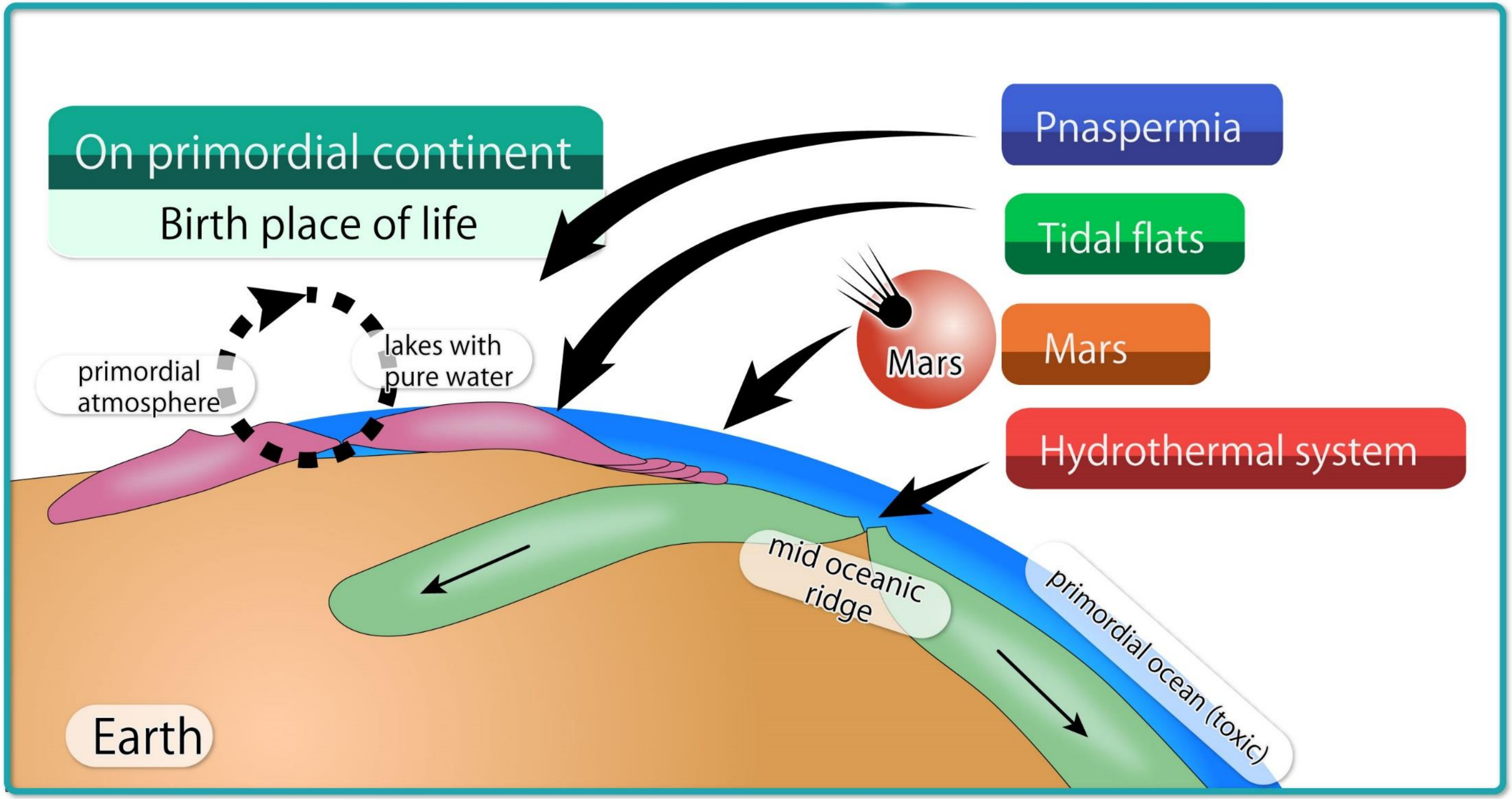
A04+A01

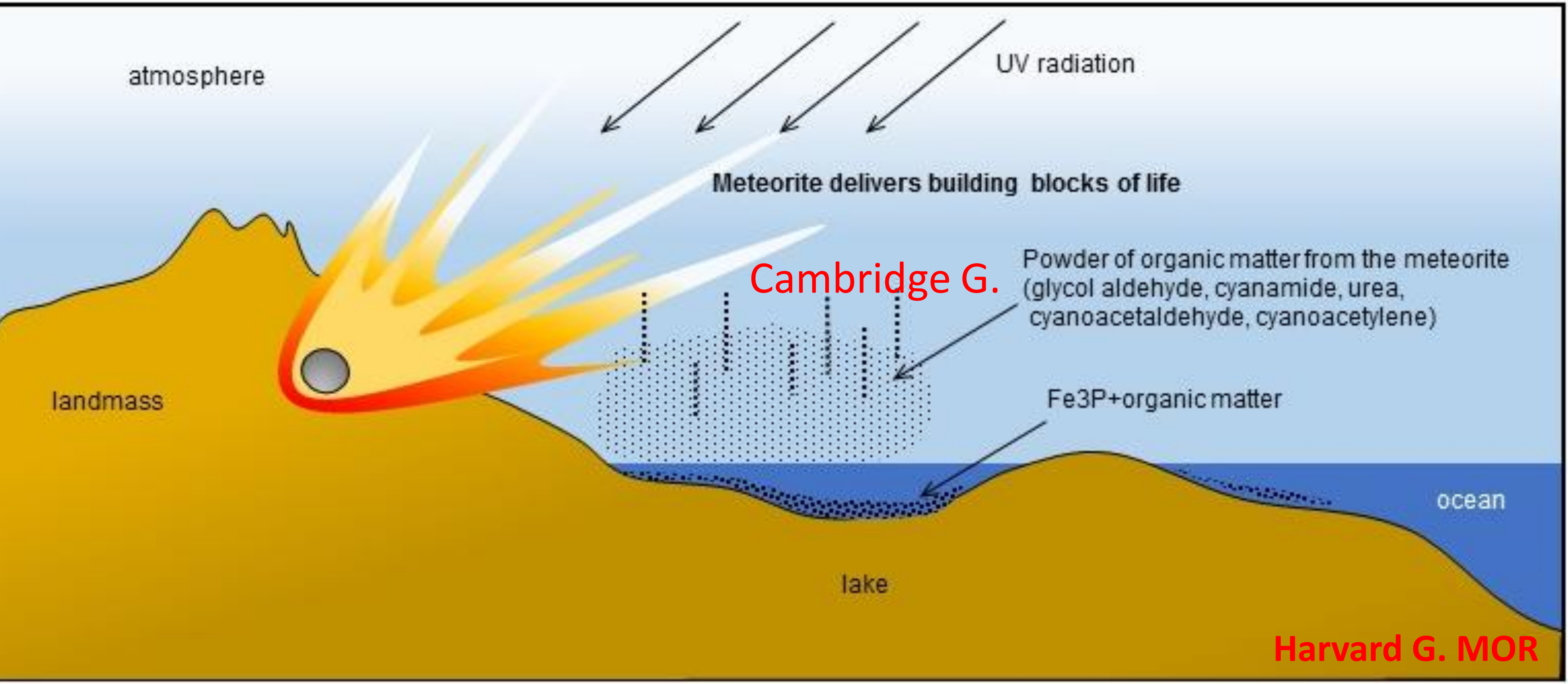
ABEL（Advent of Bio-elements） model
1) Birth of dry Earth at 4.53Ga
2) Accretion of atmosphere and ocean at 4.37-4.20Ga





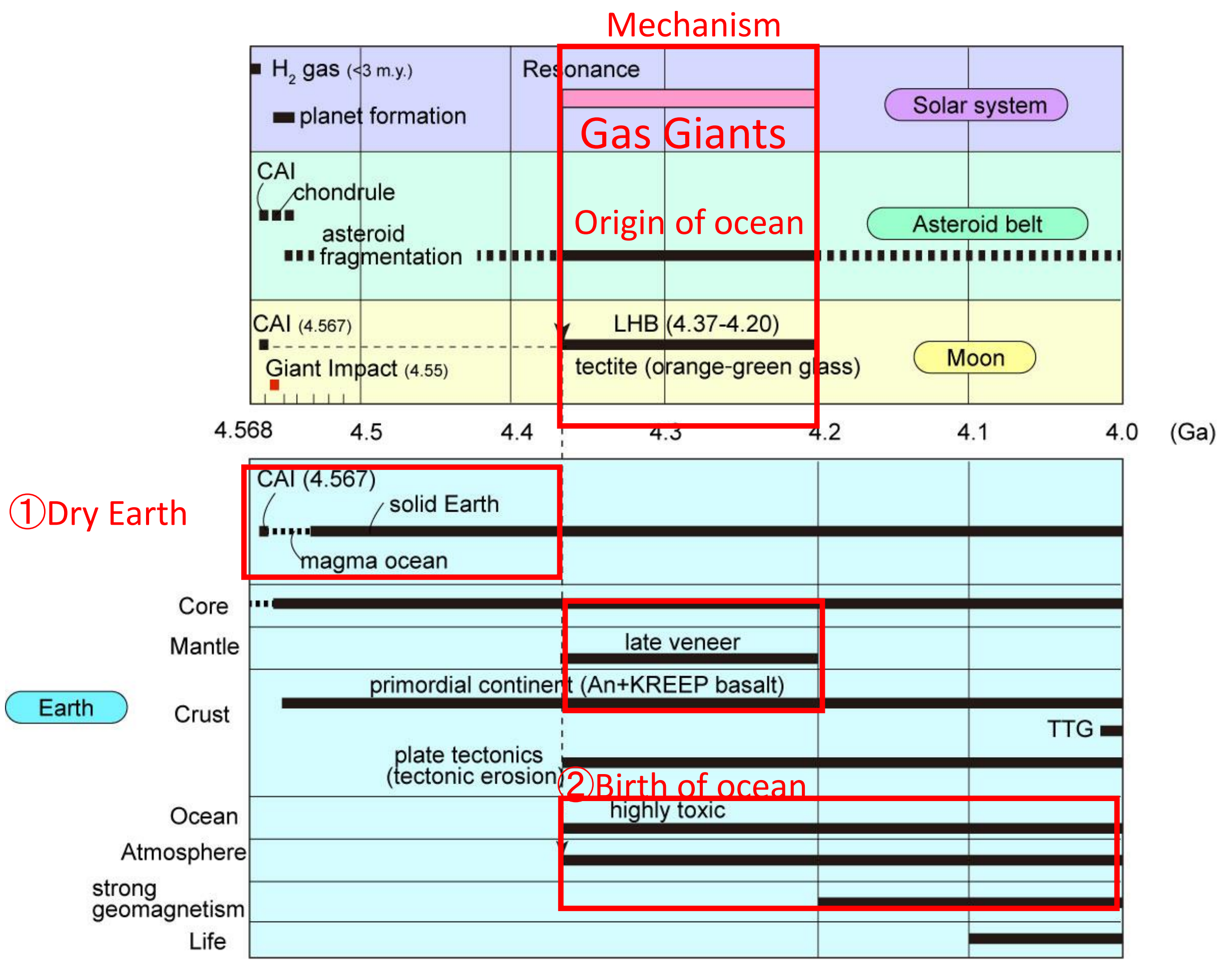
Stroeis about birth place of life




atmosphere
UV radiation
Meteorite delivers building blocks of life
Cambridge G.
Powder of organic matter from the meteorite
(glycol aldehyde, cyanamide, urea,
cyanoacetaldehyde, cyanoacetylene)
landmass
Fe3P+organic matter
ocean
lake
Harvard G. MOR

2 Hadean Bioscience Project

●Hadean chronology



Maruyama and Ebisuzaki (2016)

3 Nine Requirements of birth place of life

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Minimum requirements for the emergence of life

	Environmental factors	Nuclear geyser system	Hydrothermal system	Mars	Univers e
1	Energy source (ionizing radiation+ thermal energy)	YES	No	YES	?
2	Supply of nutrients (P,K, KREEP etc)	YES	No	YES	No
3	Supply of life constituent elements (CHON)	YES	?	YES	YES
4	Concentration of reducing gas	YES	No	?	No
5	Dry/wet cycle	YES	No	?	No
6	Na-poor water	YES	No	YES	No
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9	Cyclic nature	YES	No	No	No

* Mars kept ocean for the first 400million years after the formation.
**Universe does not have liquid water in the matrix

Maruyama et al 2016 Birth place of early life on Earth

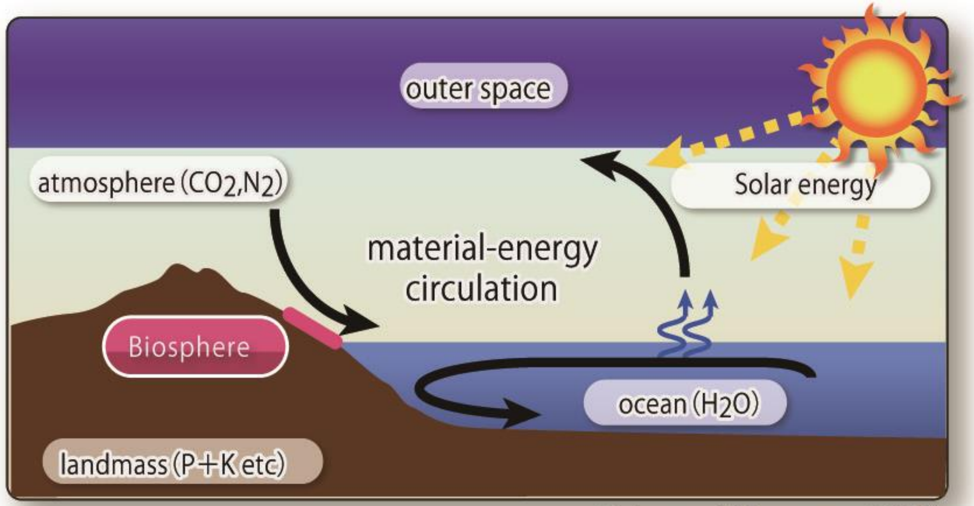
1 Energy source; thermal and ionizing radiation

Habitable Trinity environment

present day vs Hadean Earth

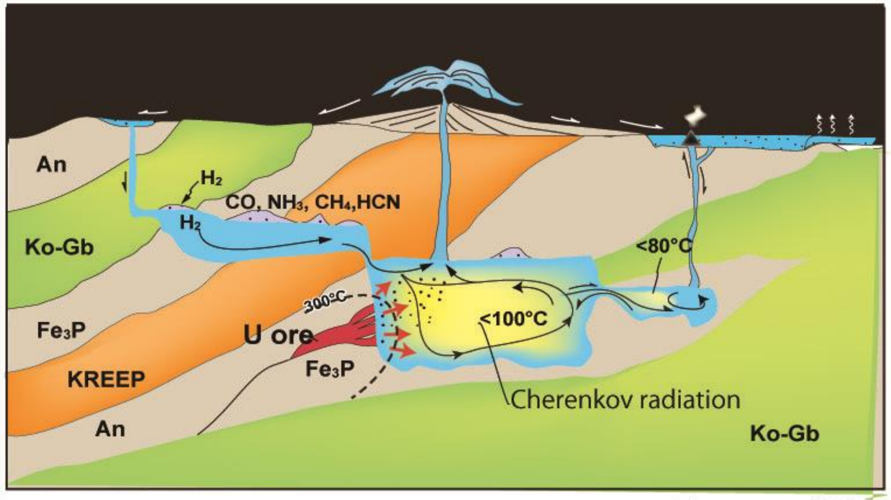
Life: A phenomenon of biosphere as sub-system on Earth which is driven by the Sun

Hadean Earth: Due to unavailability of the Sun, natural nuclear reactor functioned as “small Sun”



Dohm and Maruyama (2014)

present day Earth



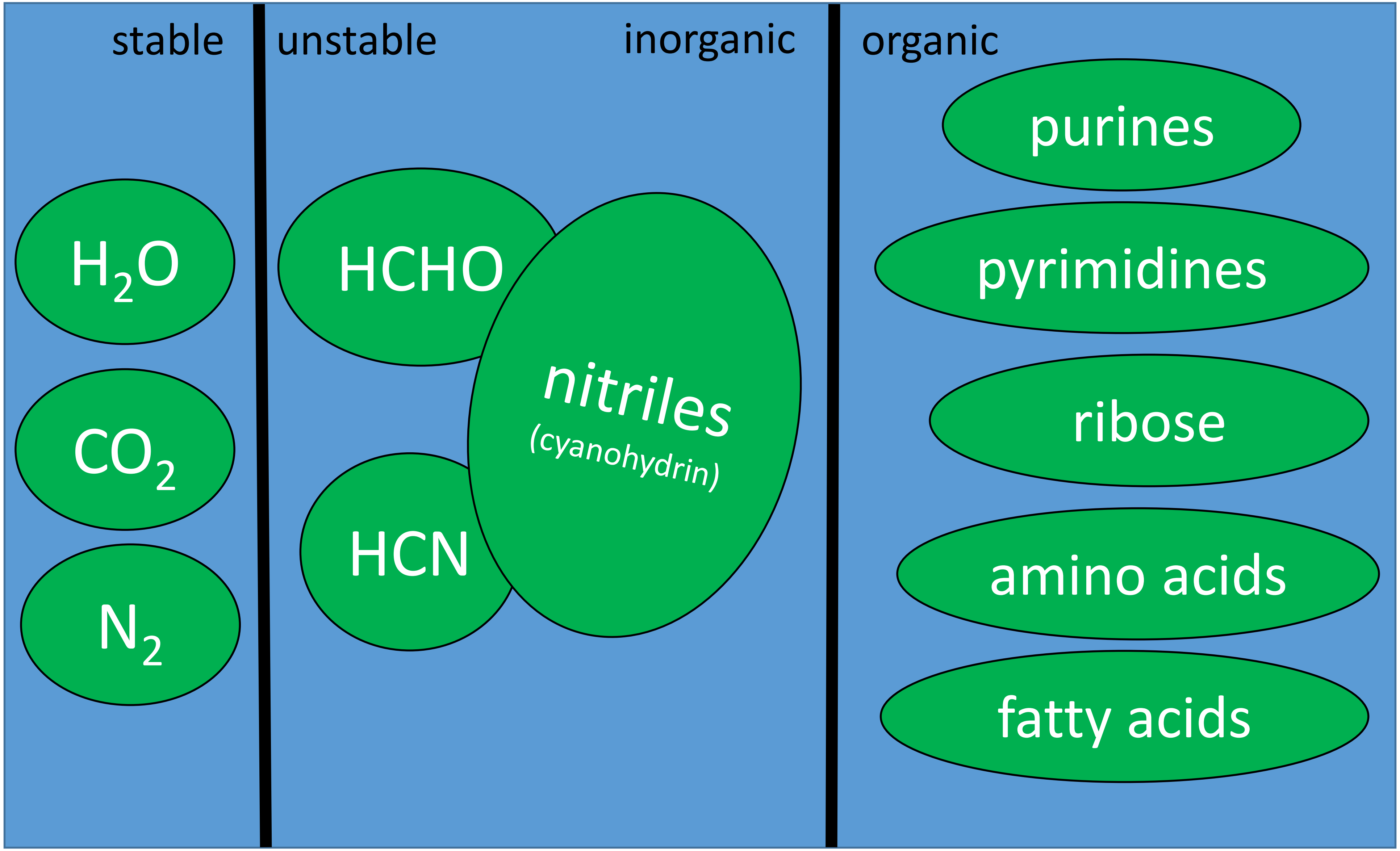
Hadean Earth

Maruyama (2016)

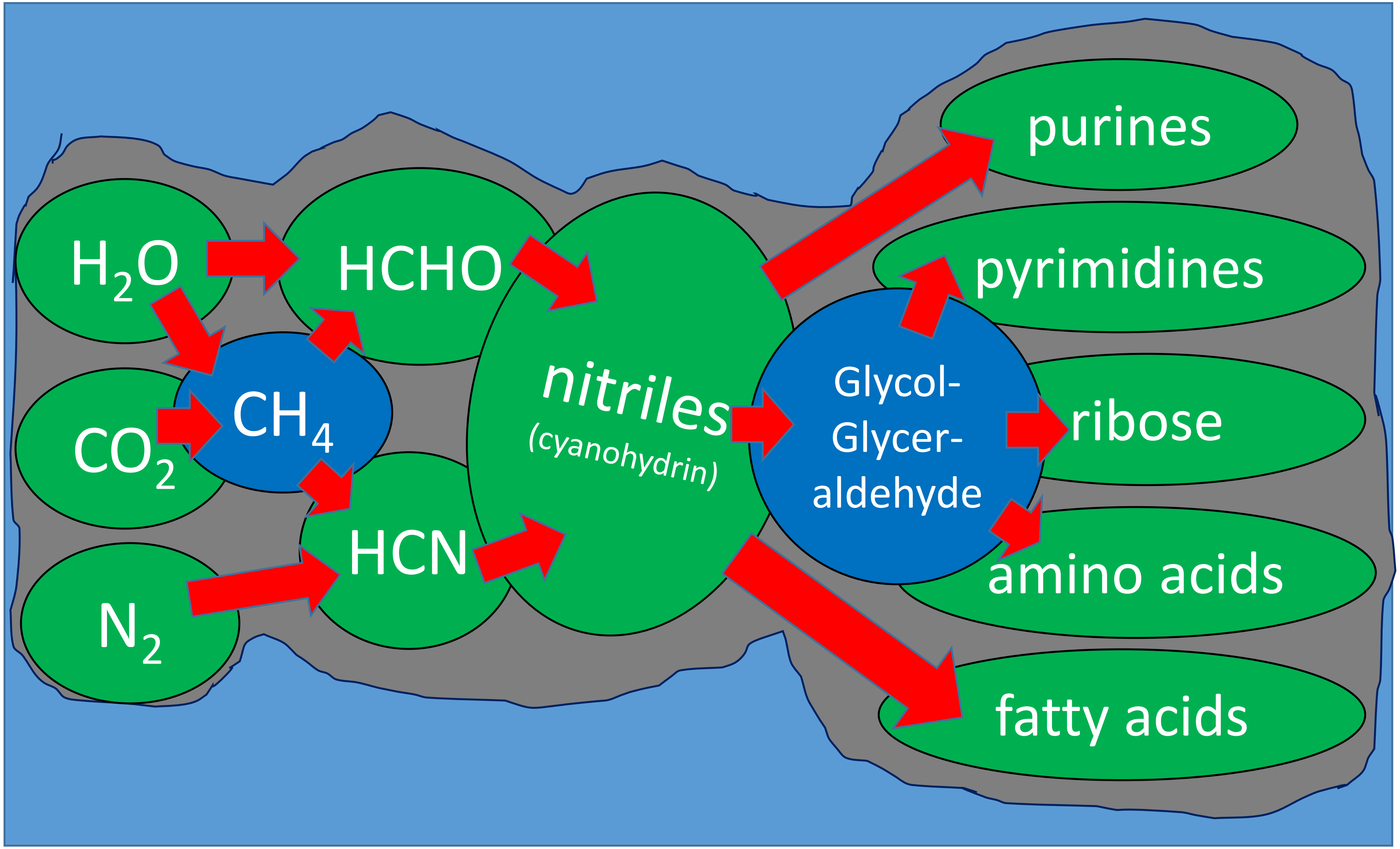
Habitable trinity concept (Dohm and Maruyama, 2014): Why important ?

Initial ocean mass ca. 4± 1km, extremely tight initial condition for the habitable planet to bear life.

High activation energy is necessary, e.g.,NH_3 from N_2



Continuous radiation(aqua-electron jet): Life is a chemical phenomenon of continuous electron flow



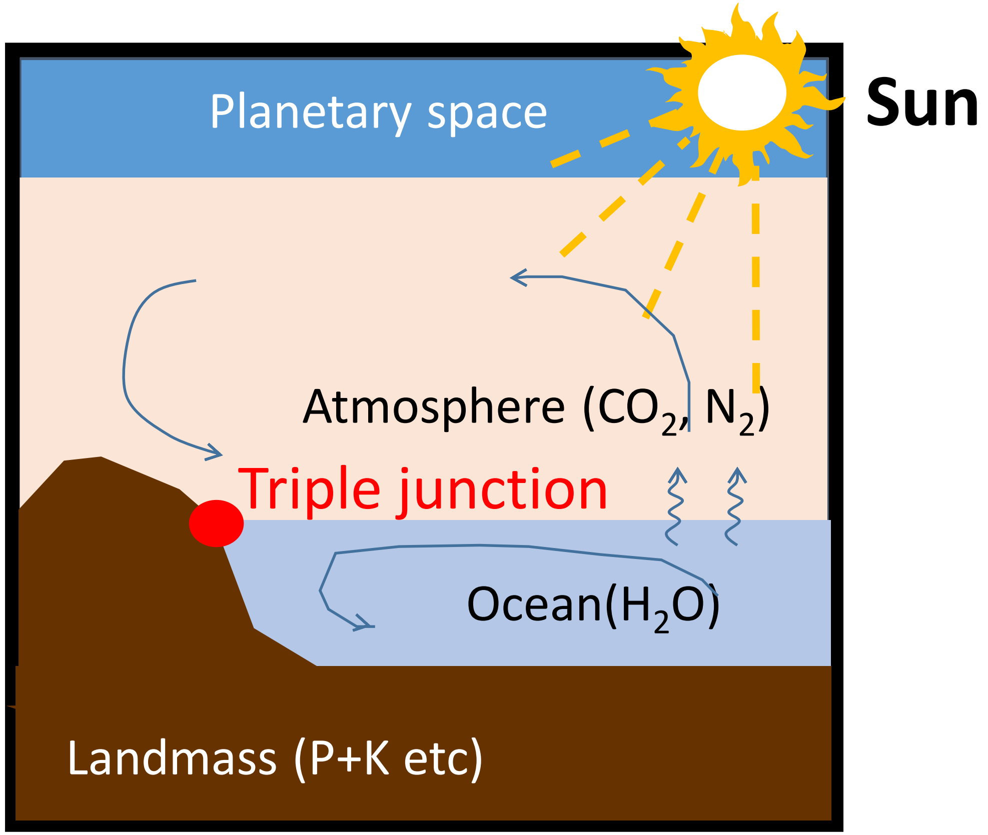
2 Supply of nutrients

2 Supply of nutrients

"Habitable Trinity" model

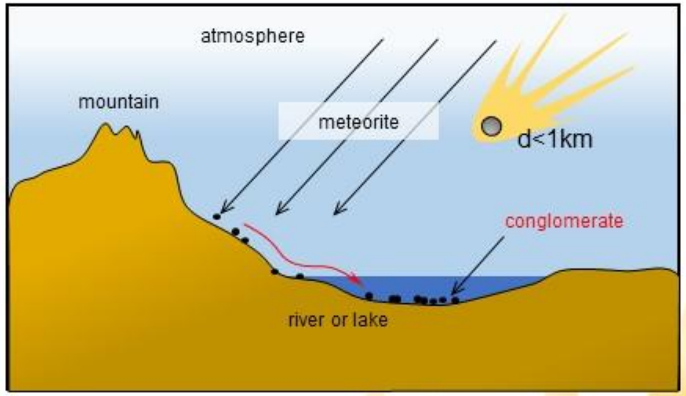
(Dohm and Maruyama, 2014)

CN (atmosphere) + HO (ocean) + Nutrients (P,K,Ca,Mg,Fe, S etc. from Rock) coexist circulating continuously by driving force by Sun



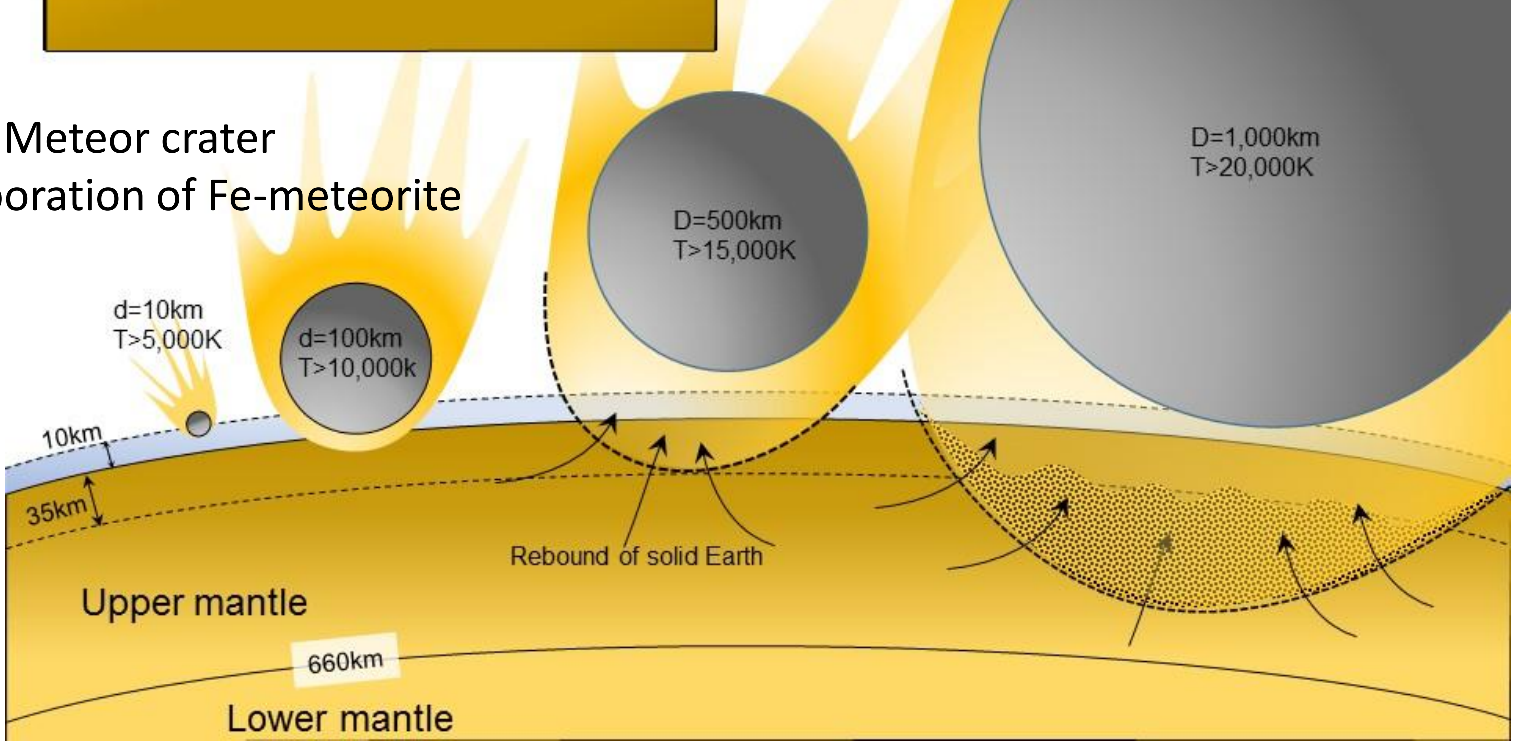
3 Supply of major life components

Any organic compounds from volatile-rich asteroids instantaneously evaporate during collision on the ground, even in a small planetesimal with D=1km. In much smaller meteorites 1-5m across, when on-landed, floated, weathered and buried in sediments; no escape of organic compounds outside the meteorites forever.



Meteorite margin Is burned
bur inside Is protected to
be remained as amino-acids, yet
Never being outside.

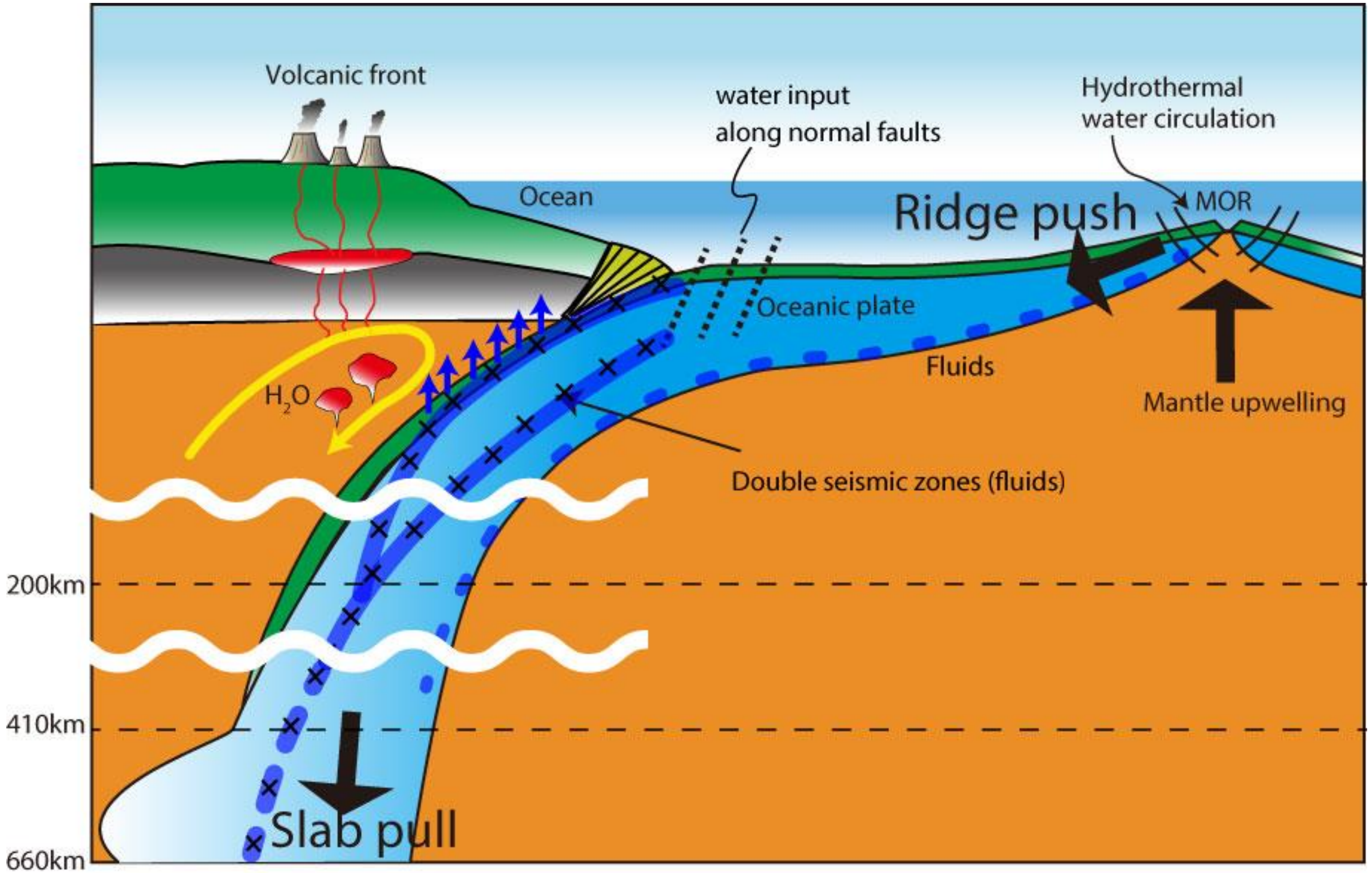
D=0.1km like Meteor crater
Arizona, evaporation of Fe-meteorite



Huge hole by asteroid impact can creates an ocean such as Pacific Ocean, a trigger if Plate Tectonics.

CO_2: How to remove it into mantle ? Presence of huge landmass.
Keep XCO_2<10 bar, spending long time ca. 170m.y. Ocean planet

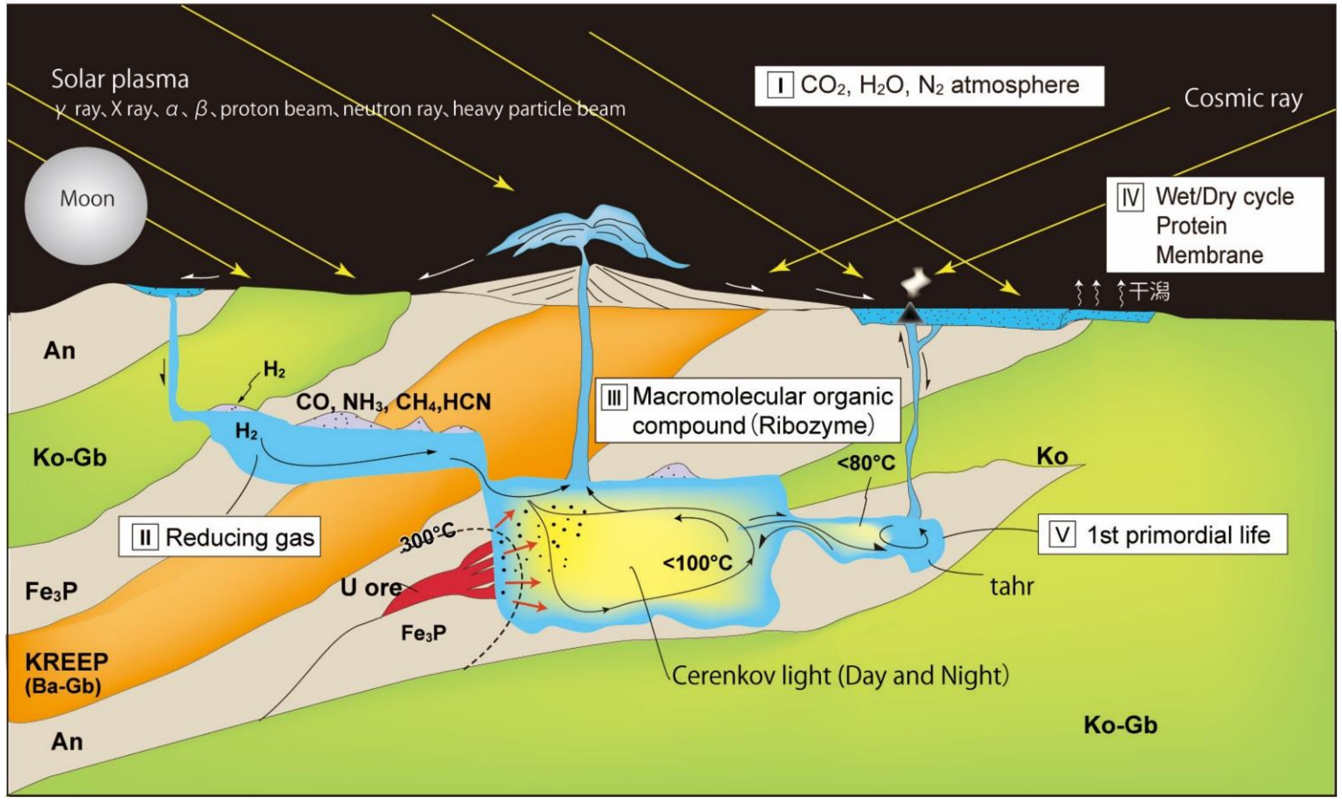
H_2O: Small amount making primordial continents above sea-level



Otherwise Habitable Trinity Planet cannot be born.

4 Concentration of reduced gas
5 Dry/wet cycle

Material circulation at 4.37-4.20Ga between surface environment and geyser



Surface was impossible for life to survive → Underground HT + 1 (natural rector)

Explain from 1,2,3,4, to 5

- Reaction of organic materials is accelerated through material circulation between surface environment and inside of geyser.
- Building blocks of life can be produced in geyser main room. Surface was oxidized, inside was reduced through water-rock interaction, and concentrated on the wall.
- Due to closer Moon, strong tidal force create wet/dry to polymerize amino acids and membrane by evaporation, those of which are transported to the small room for the birth place of life

6 Na-poor water

P concentration in cell cytoplasm is **extremely high**, 10 $^{-2}$ vs 10^{-5-9} (seawater)
To make it possible, we need highly reduced state of P, i.e., Fe_3P is a key mineral.
Under such highly reduced condition, solubility of P in water is 10^4 **higher**.
Valence of P must be -5, and P of schreibersite is -6, an ideal state on the Hadean Earth.
Life hates Na and prefer K; **K/Na ratio** is an index for the birth place of life.

Table 1. Approximate concentrations of key ions in various environments

Ion, mol/L	Modern sea water	Anoxic water of primordial ocean	Cell cytoplasm
Na^+	0.4	>0.4	0.01
● K^+	0.01	~0.01	0.1
Ca^{2+}	0.01	~0.01	0.001
Mg^{2+}	0.05	~0.01	0.01
Fe	10^{-8} (mostly Fe^{3+})	10^{-5}	10^{-3} to 10^{-4}
Mn^{2+}	10^{-8}	10^{-6} to 10^{-8}	10^{-6}
Zn^{2+}	10^{-9}	$<10^{-12}$	10^{-3} to 10^{-4}
Cu	10^{-9} (Cu^{2+})	$<10^{-20}$ (Cu^{1+})	10^{-5}
Cl^-	0.5	>0.1	0.1
● PO_4^{3-}	10^{-6} to 10^{-9}	$<10^{-5}$	$\sim10^{-2}$ (mostly bound)

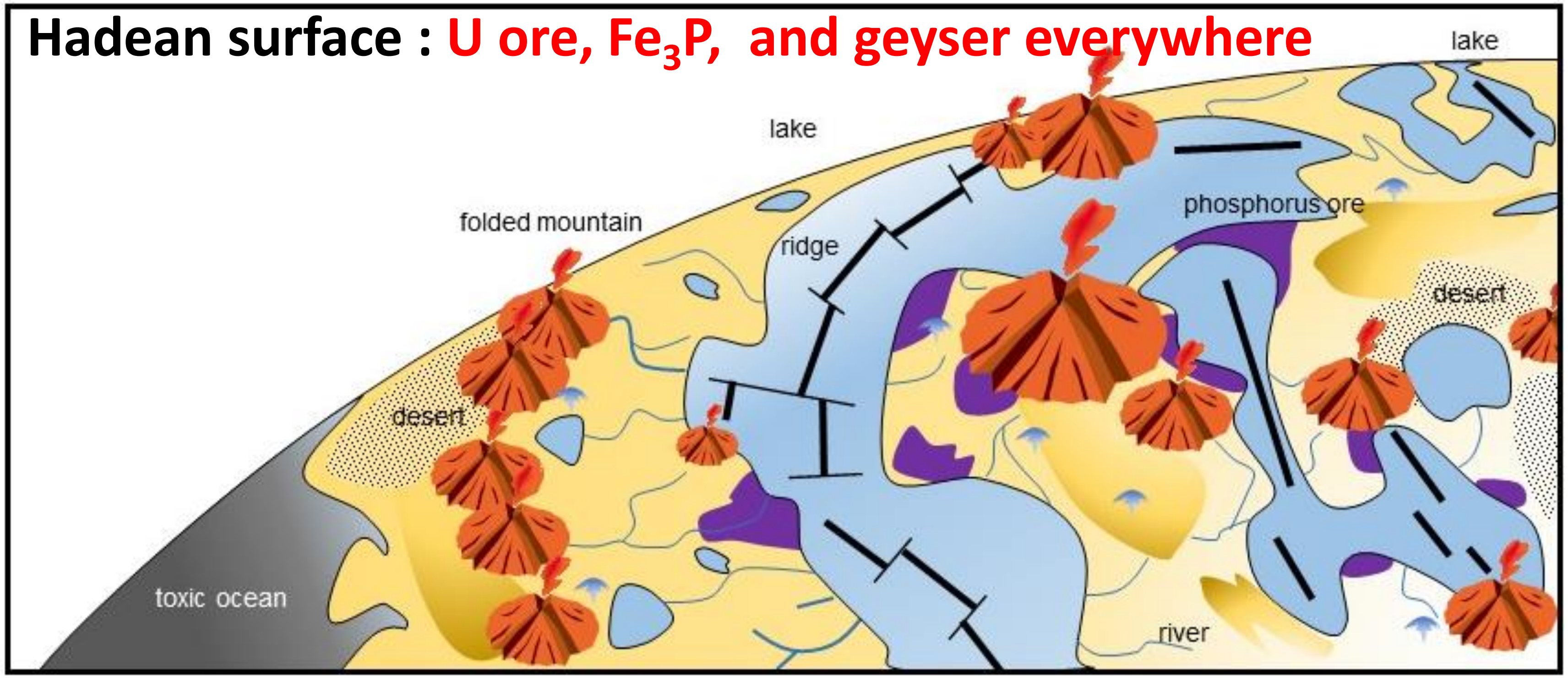
The intracellular concentration is defined here as the total content of a particular element divided by the cell volume and should be discriminated from the much lower free ion concentration, which does not account for the ions that are bound to biological molecules. The reconstructed chemical composition of the anoxic ocean includes data from refs. 14, 15, 58, 141. The data on intracellular concentrations of different chemical elements are based on refs. 14, 142–145.

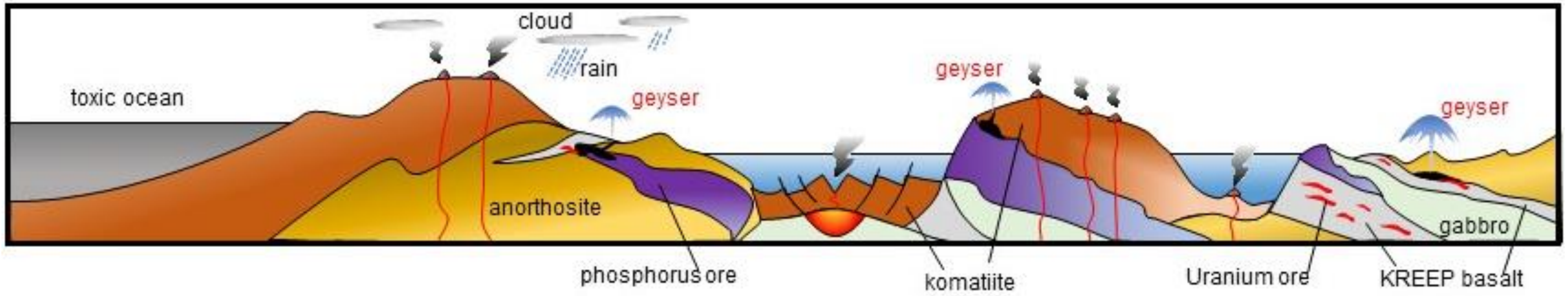
Mulkidjanian, A. Y. et al.,（2012）

7 Non-toxic water environment

- Highly toxic ocean; need a huge landmass to improve by hydrological circulation (weathering, erosion and transportation of primordial landmass), otherwise the solid planet turns to Venus-type ocean-free planet

Rocks on the Hadean Earth was remarkably different from the modern Earth.

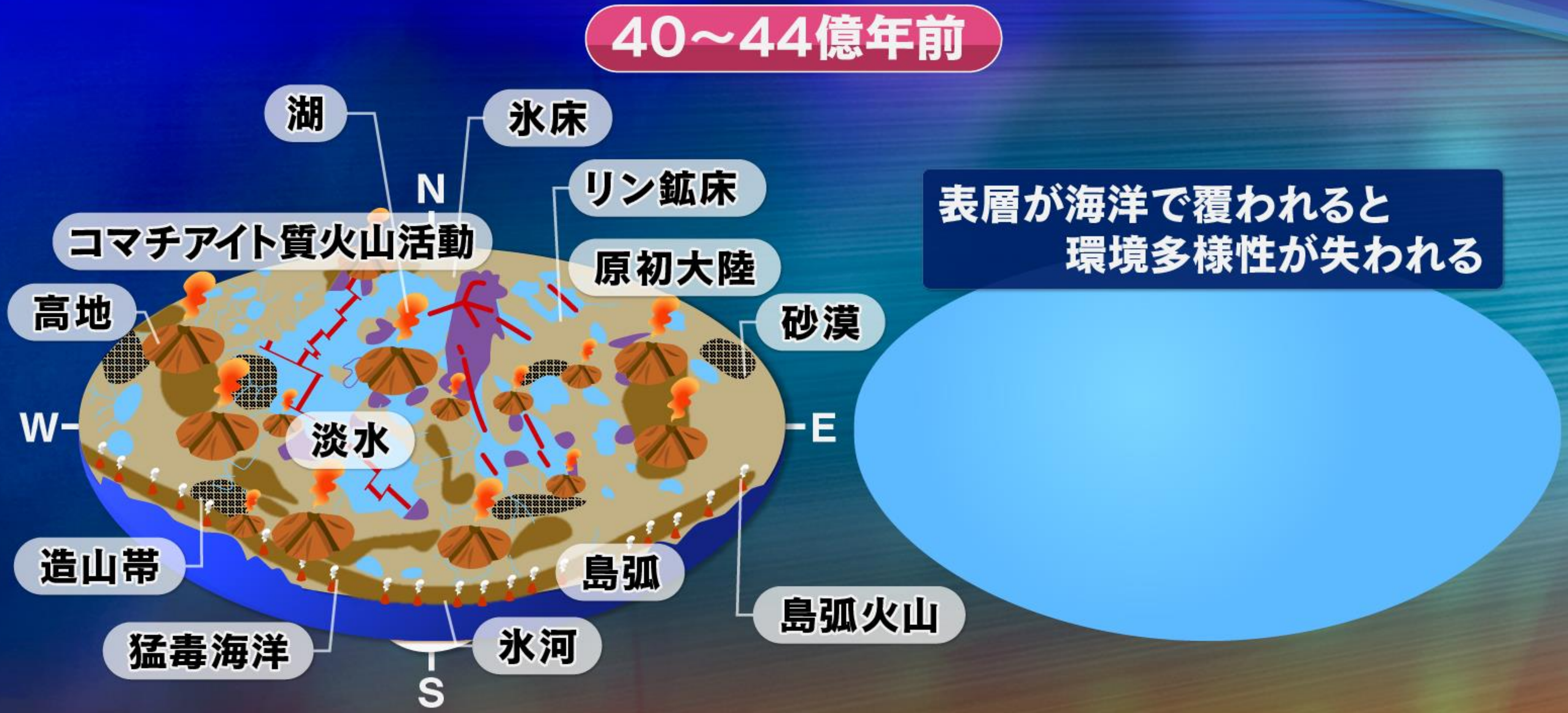




8 Diversified surface environments

Highly diversified surface environment is the most important condition

多様な表層環境１：自然地理と表層地質



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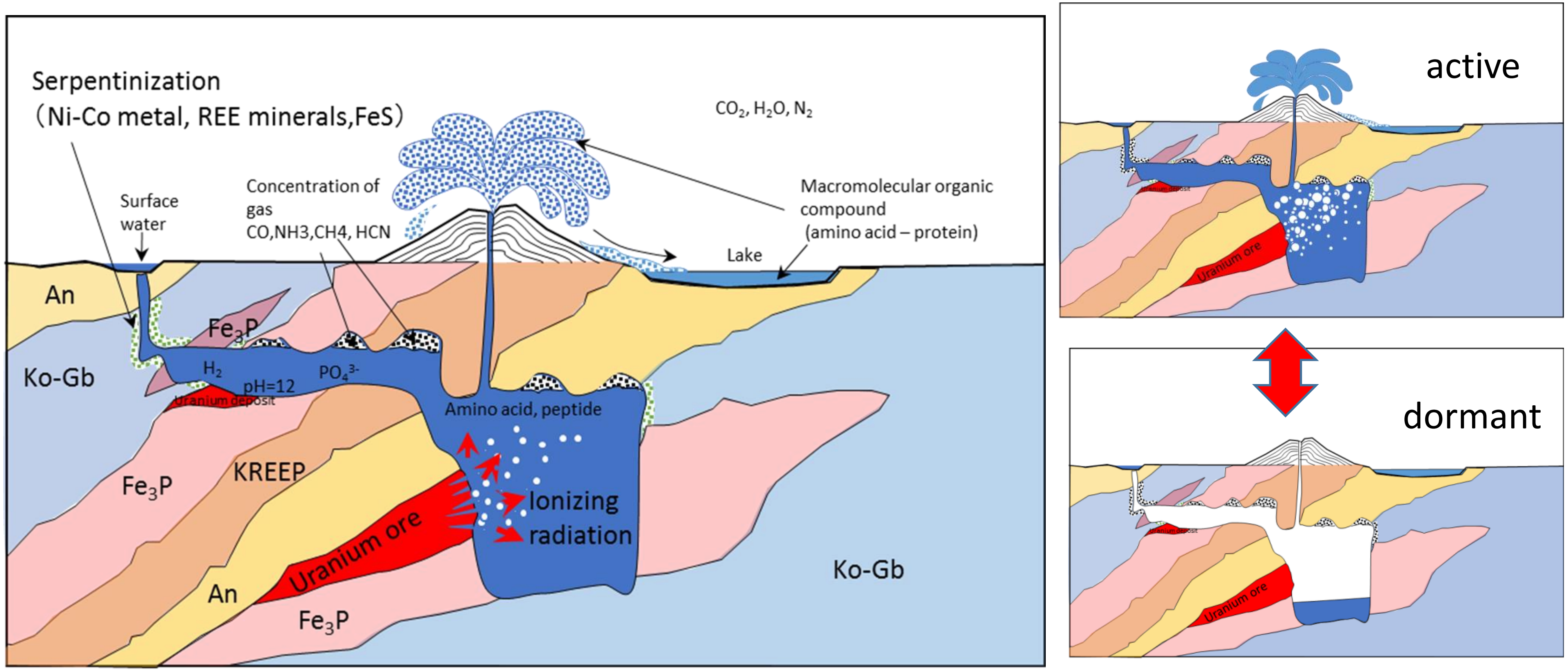
Maruyama et al 2016 Birth place of early life on Earth

Nuclear geyser model

Non-thermal energy (ionizing radiation) is necessary to facilitate the reaction

非熱的エネルギー（電離放射線）源が必要（ただの温泉や中央海嶺では不可）

CO_2, H_2O and N_2 are very stable materials thermodynamically on the Earth's surface.



Natural reactor can destroy those into elementary particles in the broad sense, i.e., proton, neutron and numbers of electrons near the reactor, but those were react to form complex organic compounds away from the reactor. T<100℃ to nearly 0℃, repeats cyclic and erupts organic compounds To the surface.

4 Surface environmental change during the Hadean

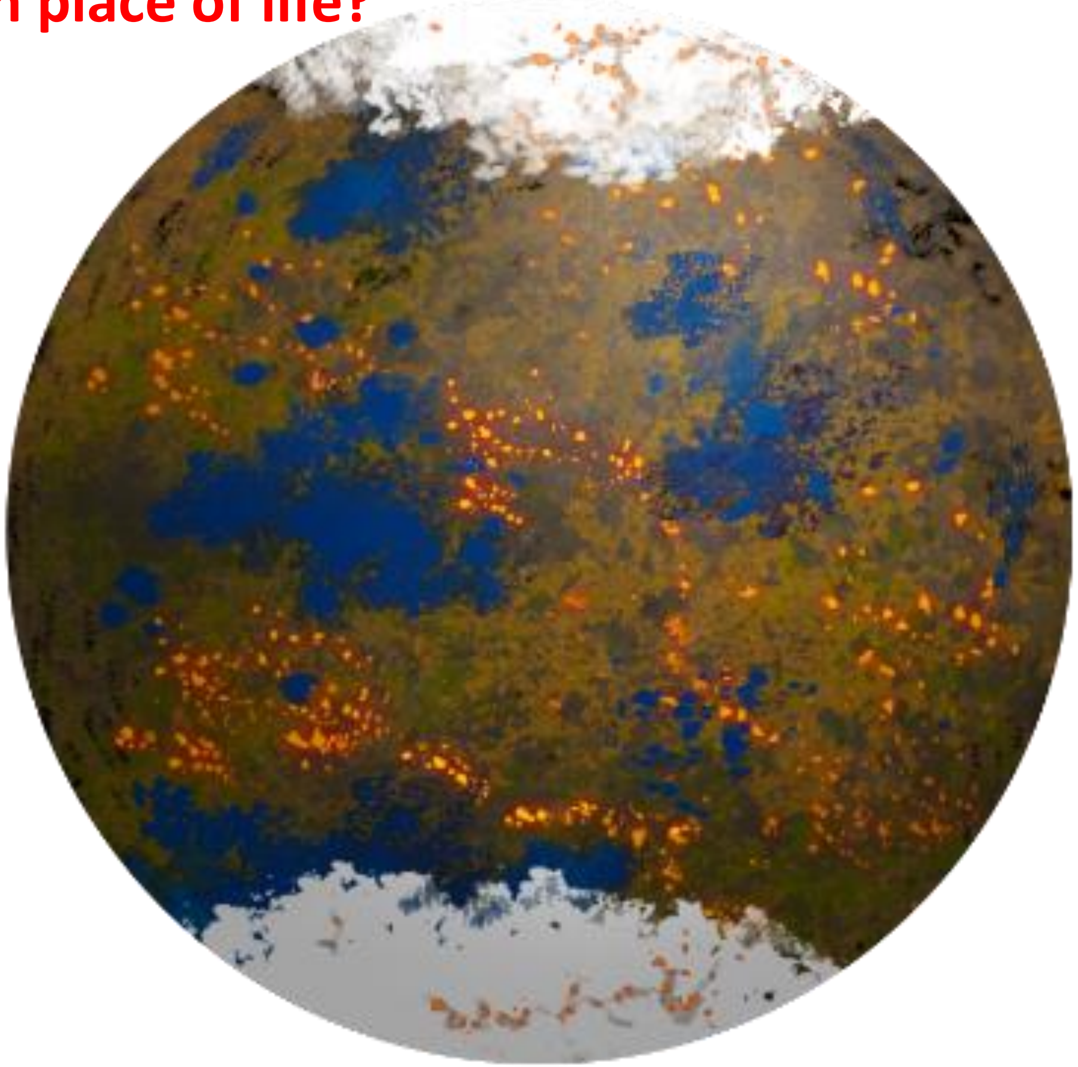
ABEL Model(Maruyama and Ebisuzaki, 2017)

Paleogeography of the Earth since 4.567Ga

4.56-4.53Ga

4.37-4.20Ga : ABEL event

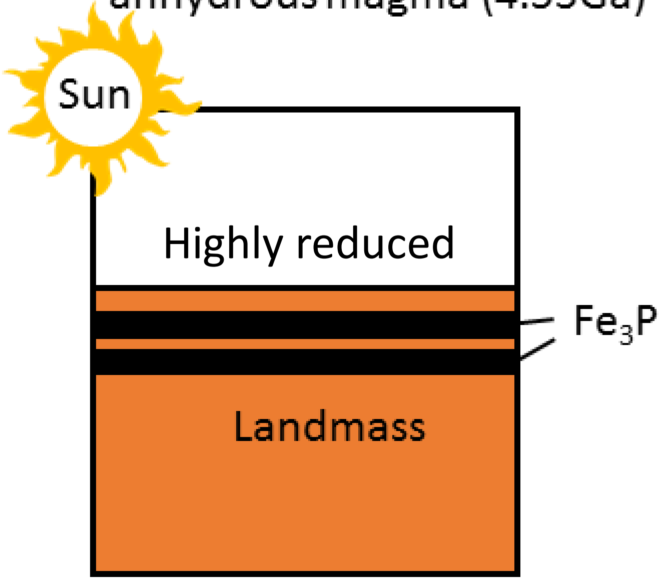
Where was the birth place of life?



ABEL model

Advent of Bio-element

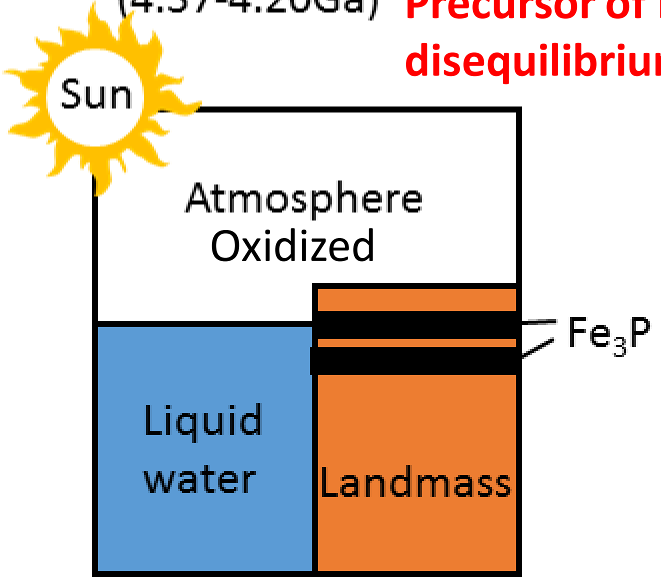
① Primordial continent was formed from final residue of anhydrous magma (4.53Ga)



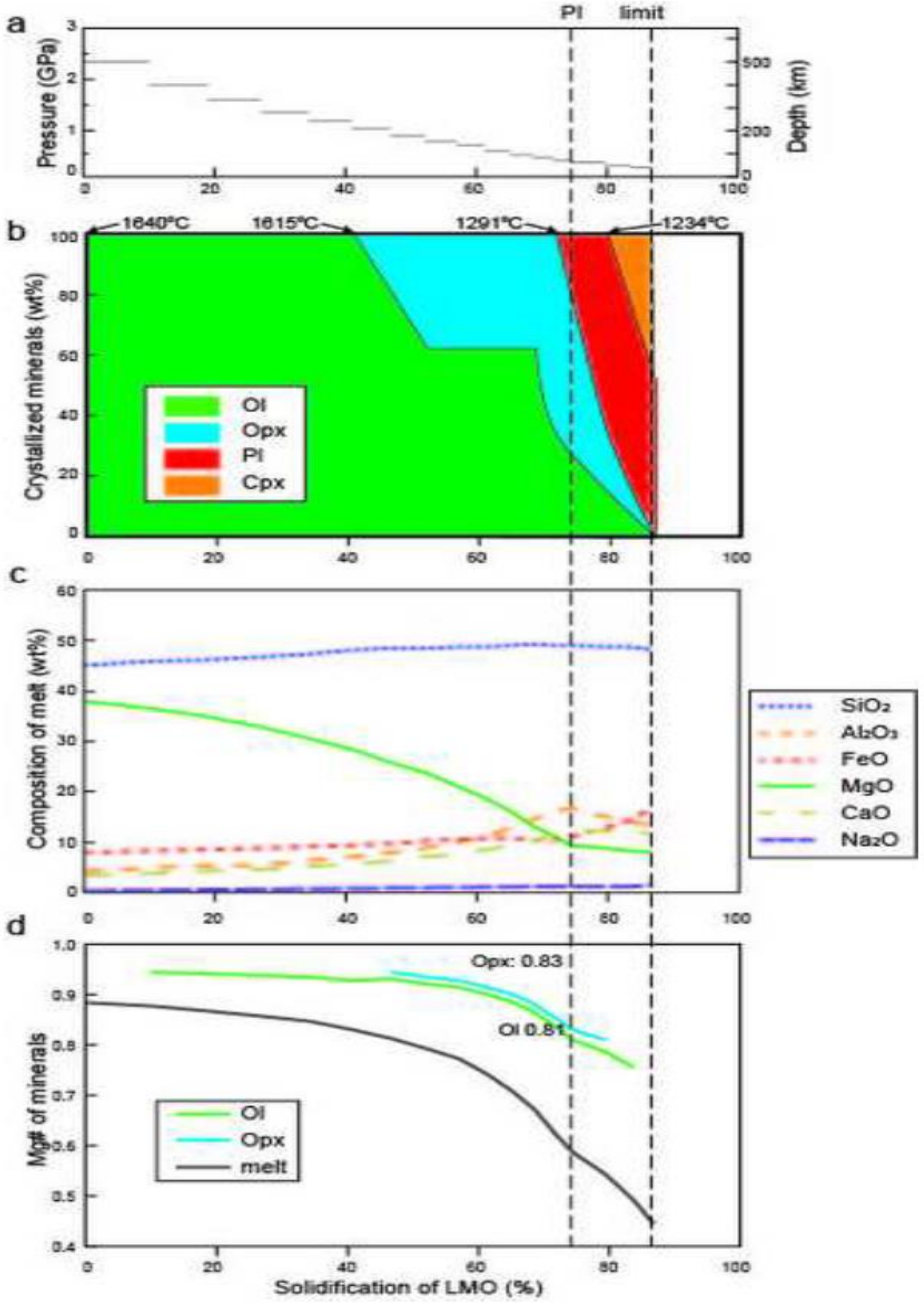
No atmosphere, no ocean

② Ocean/Atmosphere components were delivered from asteroid belt (4.37-4.20Ga)

Precursor of metabolism: Beginning th
disequilibrium reaction of $Fe_3P + H_2O$



Solidification of lunar magma ocean by MELTS program



Arai et al., 2016

Mantle minerals cannot contain U,Th and K, remaining those in the residual liquids which finally consolidate as lower mafic crust composed of KRREP

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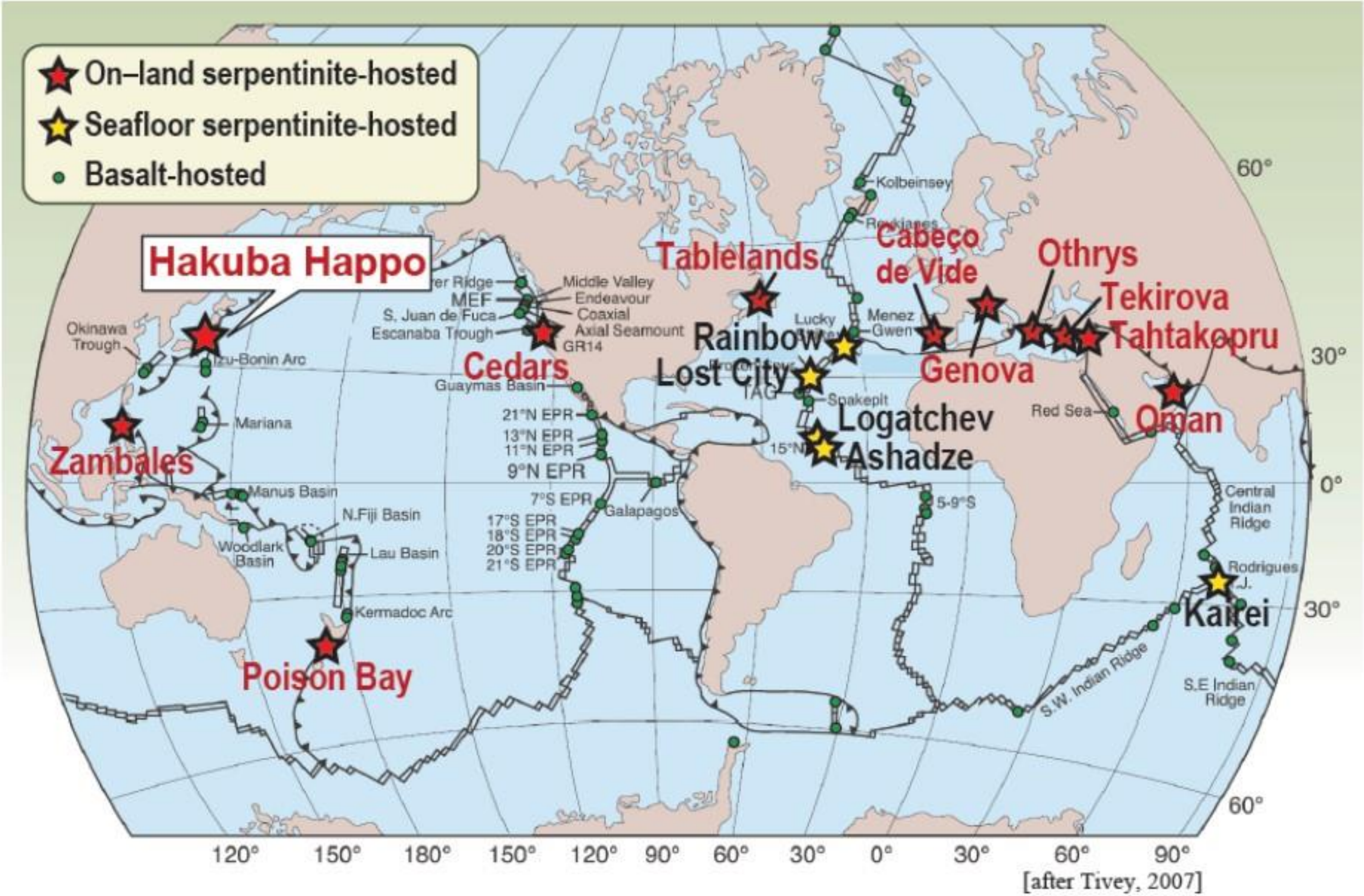
Maruyama et al 2016 Birth place of early life on Earth

●Cyclic natures; key to RNA-DNA world

Next target of Hadean Bioscience

Hadean mid-oceanic ridge is not the birth place of life

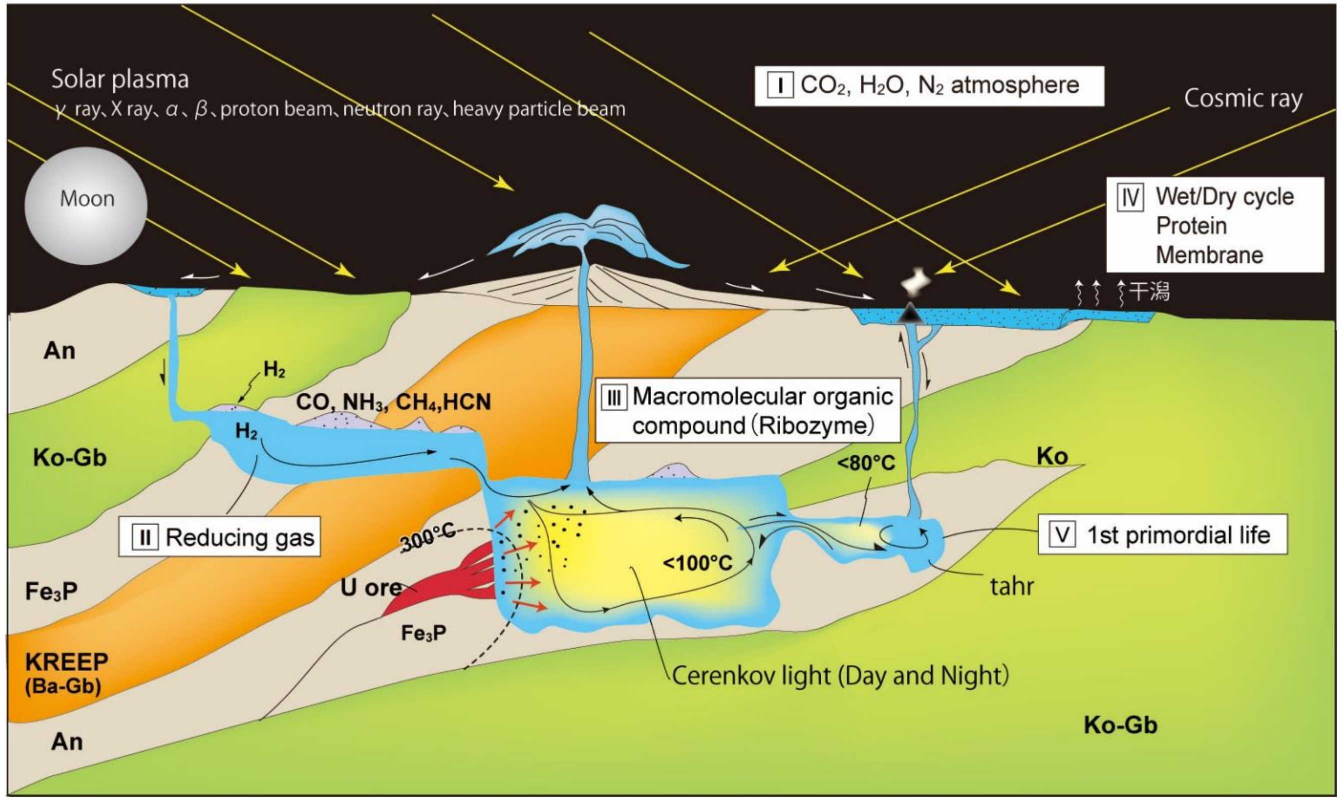
Mid-oceanic ridge was not birth place of life



Serpentinite hydrothermal system at deep-seafloor and onland. pH=10-12, H_2-producing, no magmatic flux

5 Synthesis: Three step evolution of first life

Material circulation at 4.37-4.20Ga between surface environment and geyser



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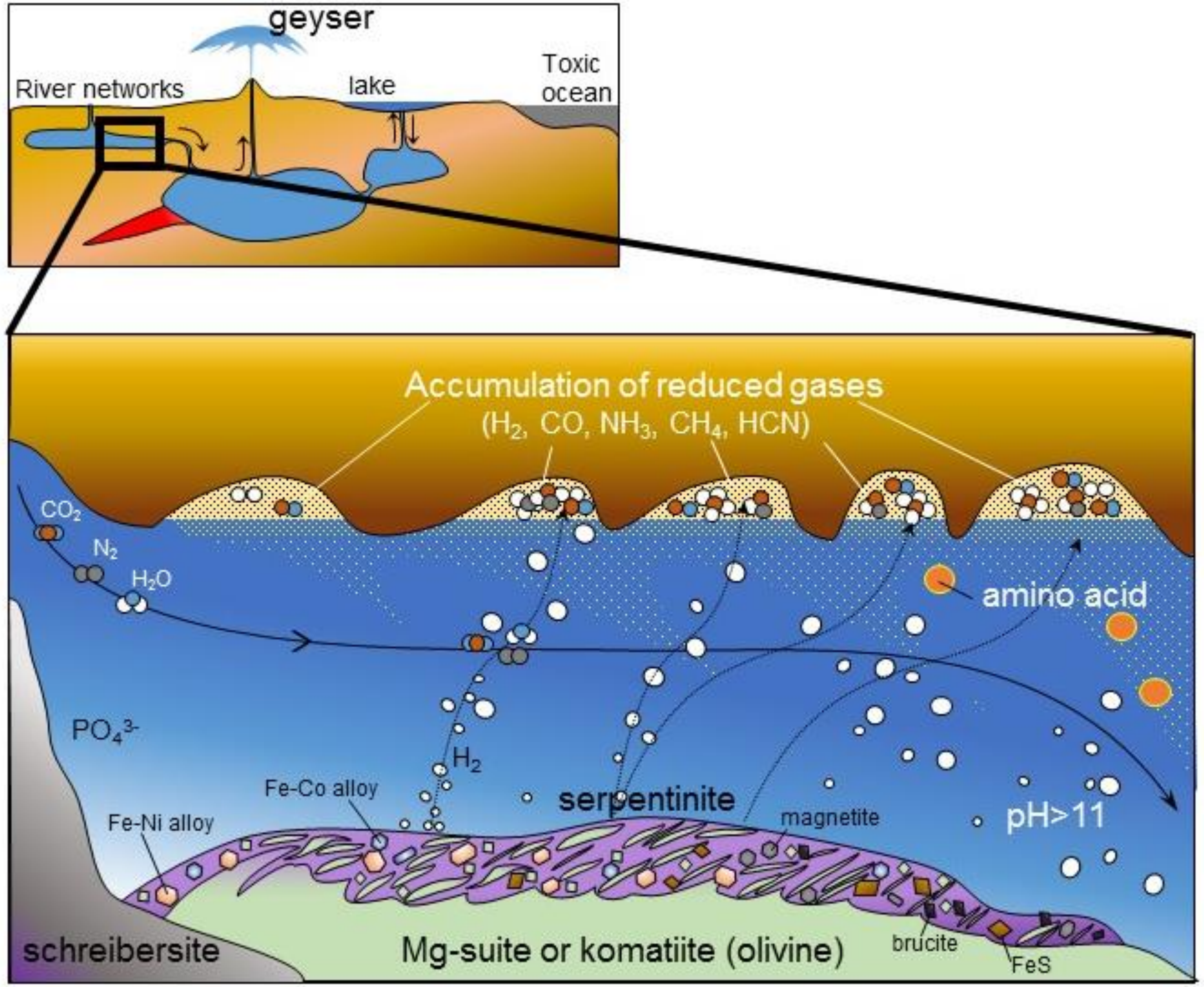
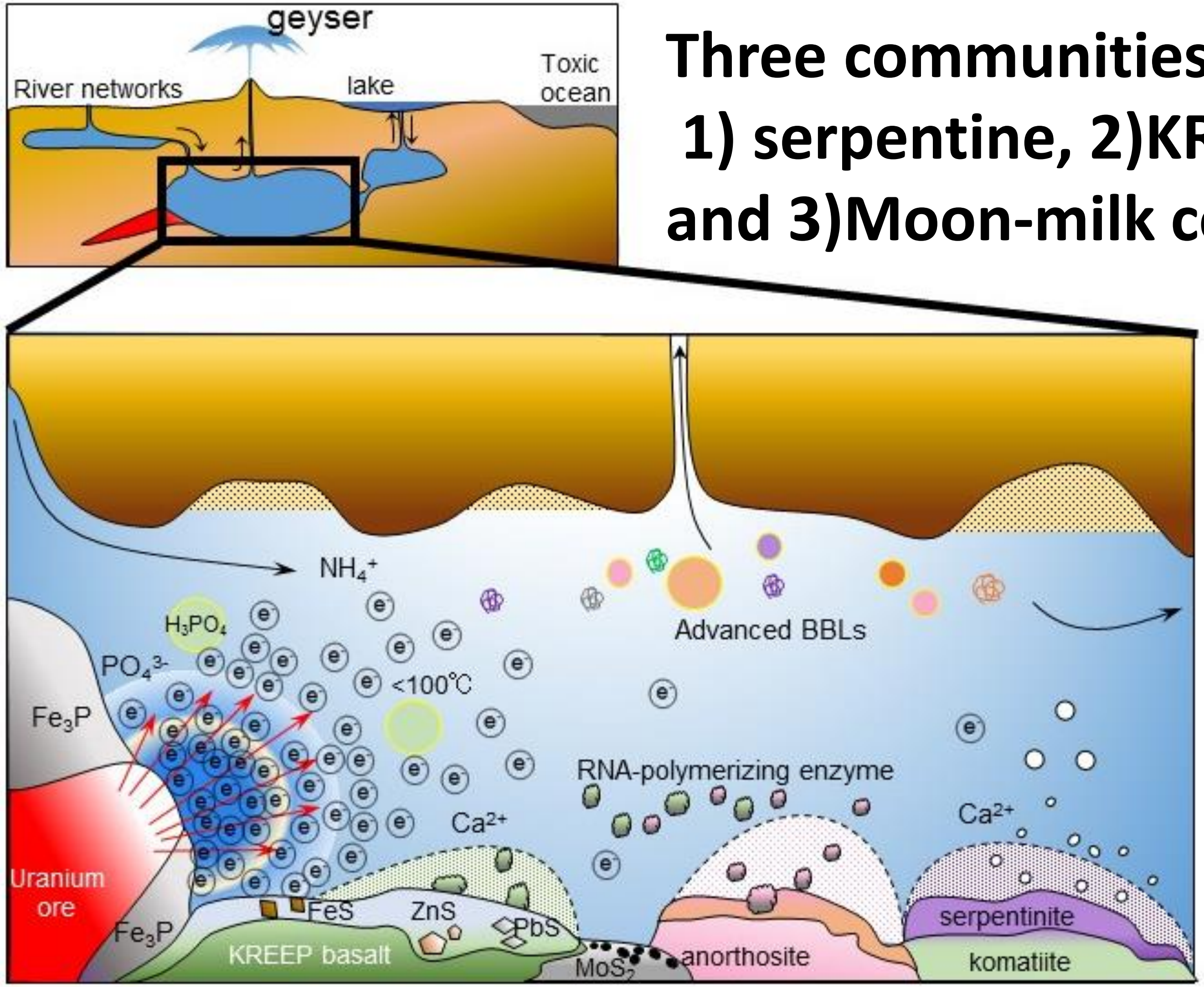
- ●Due to closer Moon, strong tidal force create wet/dry to polymerize amino acids and membrane by evaporation, those of which are transported to the small room for the birth place of life.

Formation of reduced gasses and their concentration in the geyser cave through water-rock interaction (serpentinization), also pH>10



Birth place of life in the geyser system



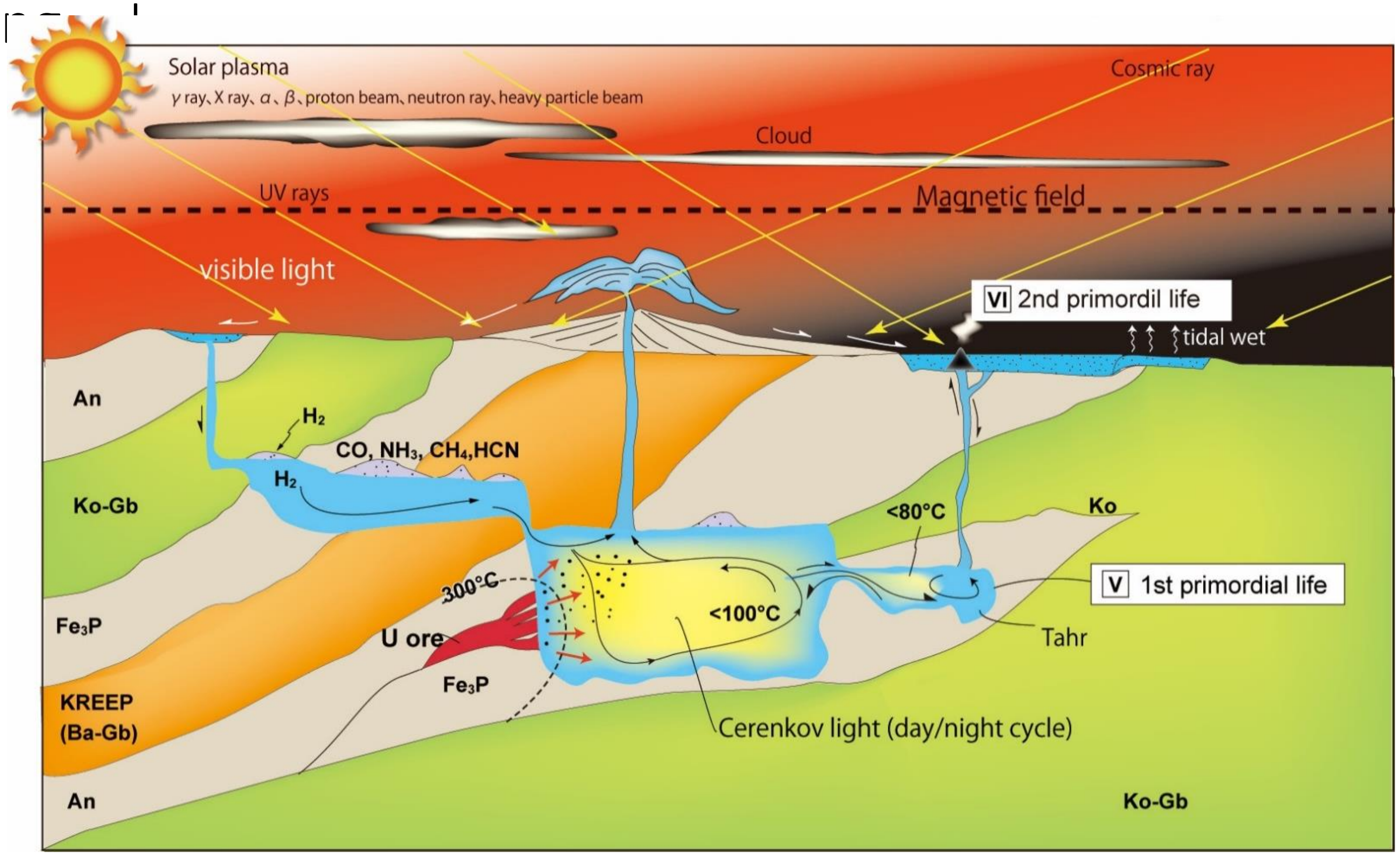
Three communities of microbes,
1) serpentine, 2)KREEP
and 3)Moon-milk communities

Rooms III and V

Altered portions, a series of secondary minerals including
FeS, MoS, ZnS, PbS, Clay, CaAl silicate and other minerals

2nd primordial life under the Sun at 4.3Ga

utilizin…



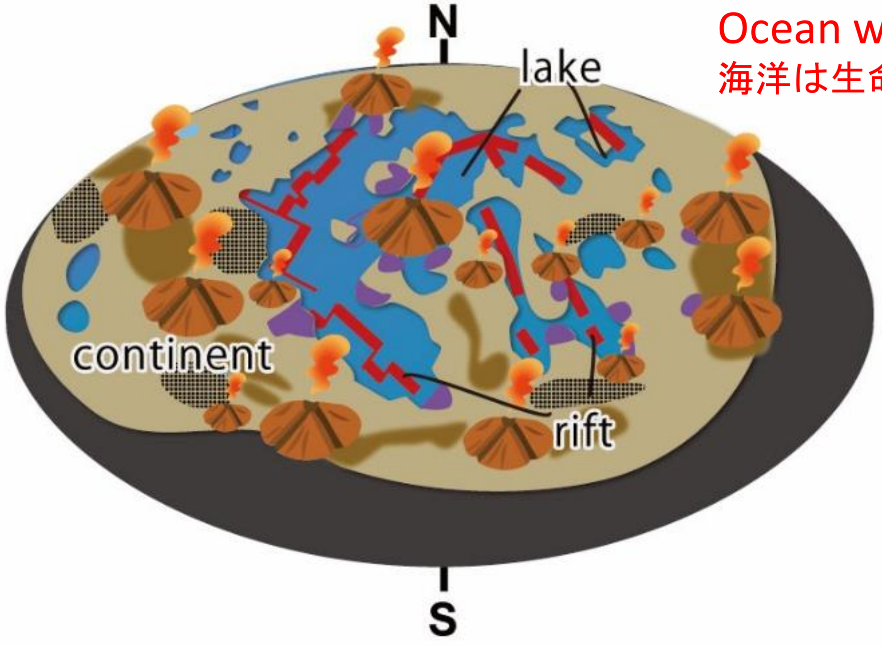
- First stage life was transported to the surface periodically through geyser explosion.
- Transition period from 1st primordial life to 2nd primordial life which can utilized solar energy by application of principle of semiconductor (electron bank). Night has come to use ATP stock in daytime.
- Still in the stage of ext.-symbiosis with others.

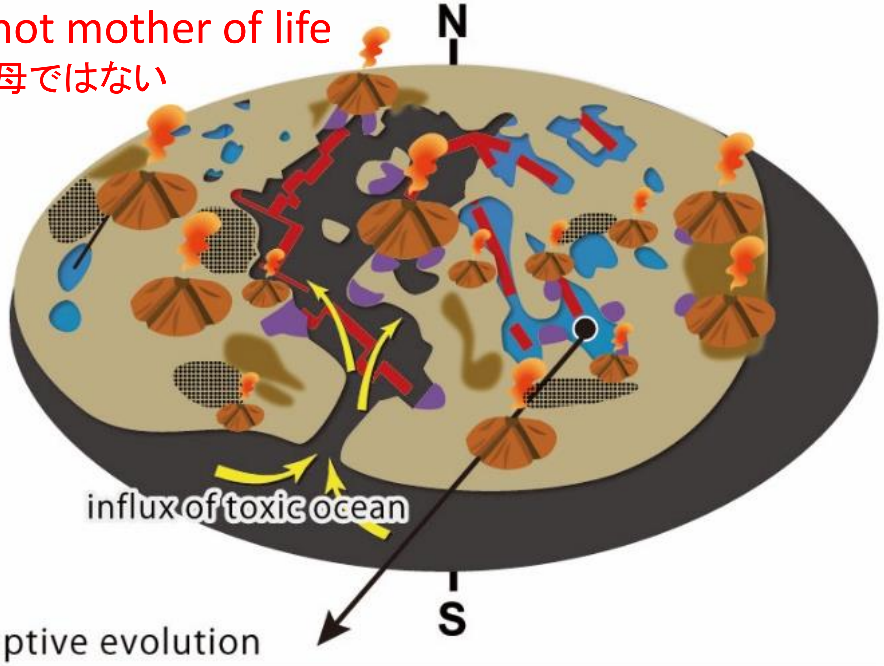
4.2Ga Birth of 3rd primordial life (Prokaryote)

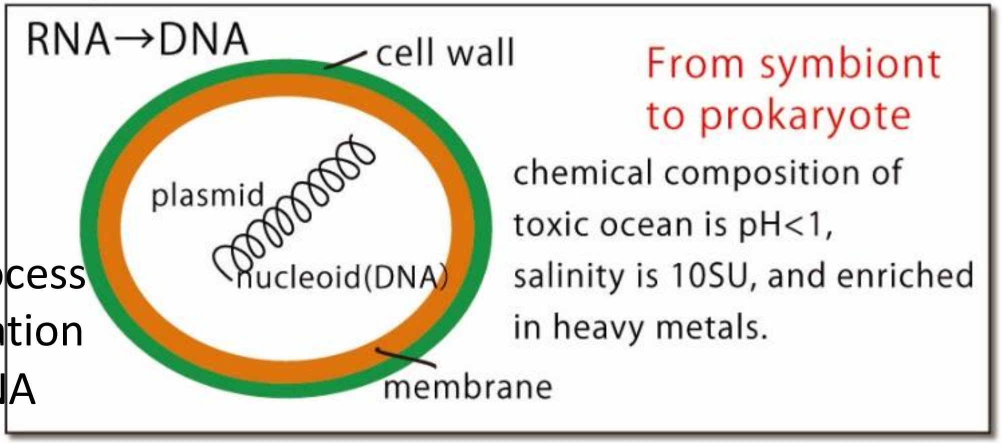
2nd primordial life move in rift valley (with non-toxic water) from lucstrine environment

Influx of toxic ocean and mass extinction

Ocean was not mother of life
海洋は生命の母ではない







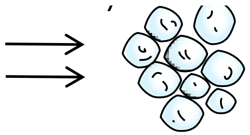
- To prevent from entering toxic elements such as Na inside the cell, Na-pump was invented, as well as cell wall.
- Multiple mass extinction and severe
- environmental change made a series of process spiral DNA shape and process of self-replication
- Minimum gene ca. 100-200 entered into DNA

3 step model to be first life

Extracellular symbiosis to intracellular symbiosis

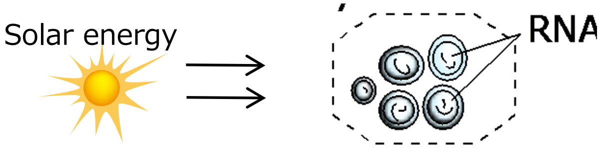
First proto-life : Extracellular symbiosis within the energy-material circulation system driven by natural nuclear geyser

Ionizing radiation from nuclear geyser



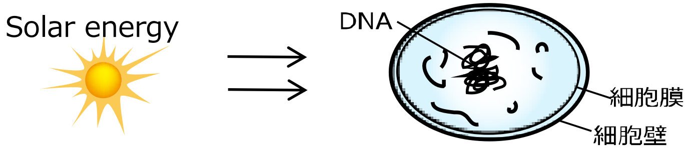
Ectosymbionts

Second proto-life : Sun energy drives the system. More evolved extracellular symbiosis (RNA)



Ectosymbionts

Third proto-life (prokaryote) : Due to repeated mass extinction, functions were evolved to have DNA, cell wall, and Na pump. Intracellular symbiosis.



Endosymbionts

Photomicroscope picture of bacillus coli, x a few hundred times (Goodsell, 1992)

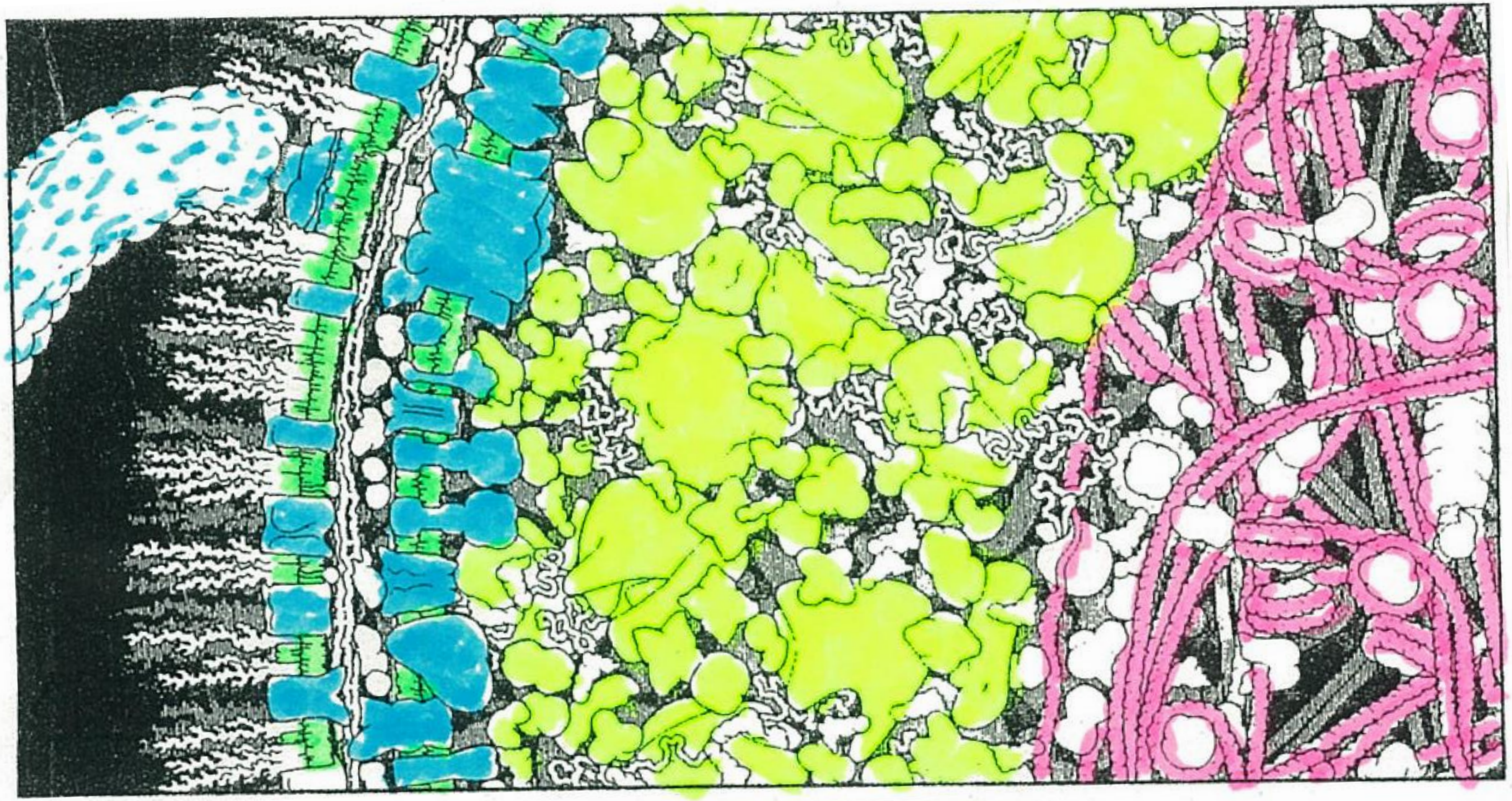


図 2.10 数百倍に拡大した大腸菌の断面の模式図（Goodsell 1992）

Extremely dense inside the cell, where even one molecule of H_2O is difficult to pass among the protein factories. Suddenly numbers of necessary functions increased during the third stage of evolution. Key functions were Increased number of kinds of pumps.

三段階進化を分かりやすく説明する

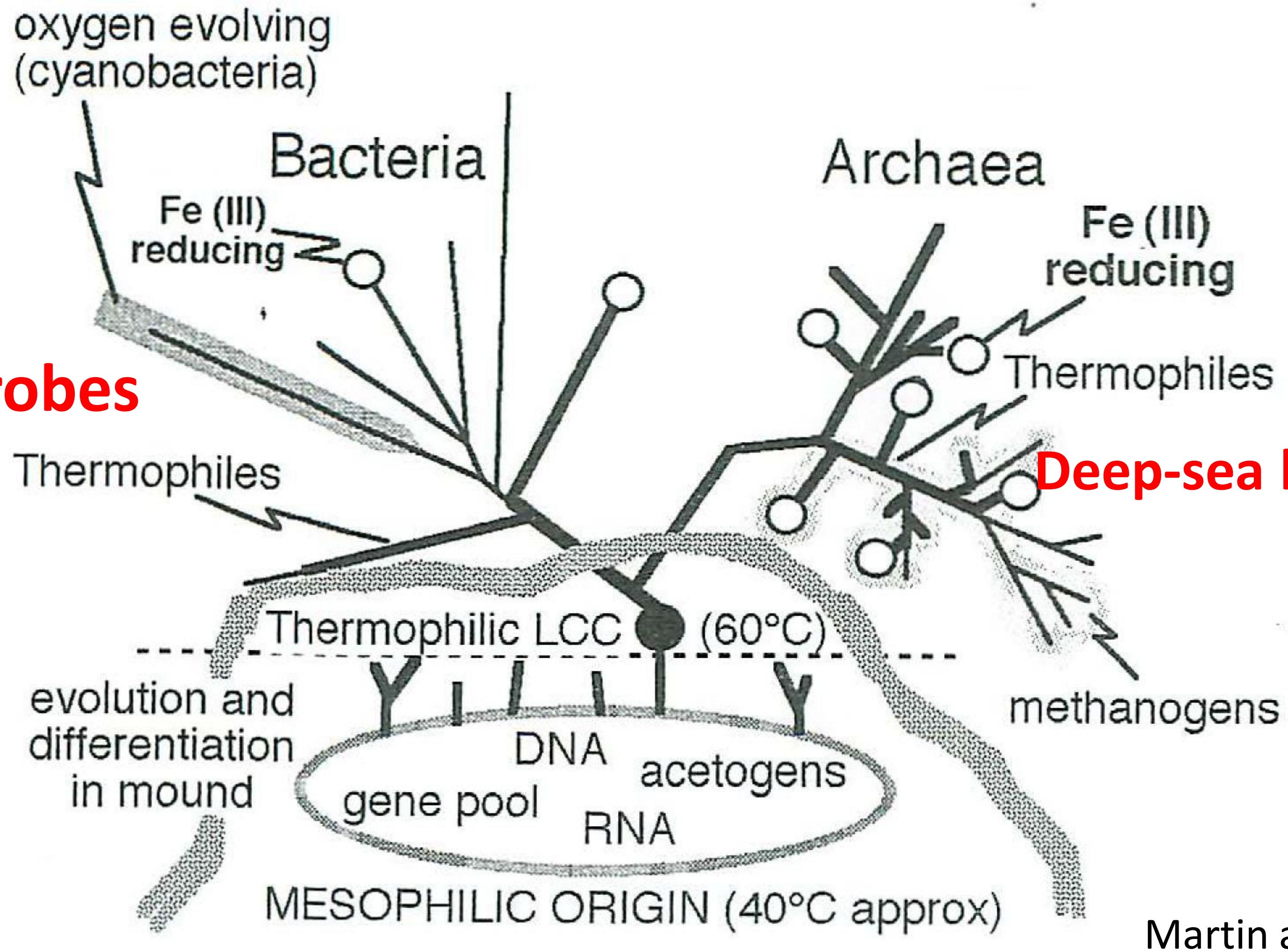
- 要領よく順番に、１）生命とは何か、２）必要な要素のまとめ、３）環境とその変動（全体の物質・エネルギー循環のしステムの概要、その中の各部の役割、合成場）、生命構成単位の段階的進化：各場所で、４）多量絶滅の役割、５）全体の進化、６）総まとめ

Discussion

We proposed a new model of birth place of life, different from any previous models including MOR. Moreover and implication to the phylogenic tree of life is discussed below.

Archaea dominated by thermophiles and live under highly reduced environments
Different from bacteria, which must be secondary microbes after Bacteria.

Land-living microbes



Deep-sea hydrothermal at MOR

Martin and Russel (2008)

Origin : On-land geyser system

Geology can give time-sequence of environment not only in the Hadean bust also all the way to the present which would contribute to solving the phylogenic tree of life.

Structure of ribosome RNA from simple inside to outwards

-Bacteria is older than Archea？-

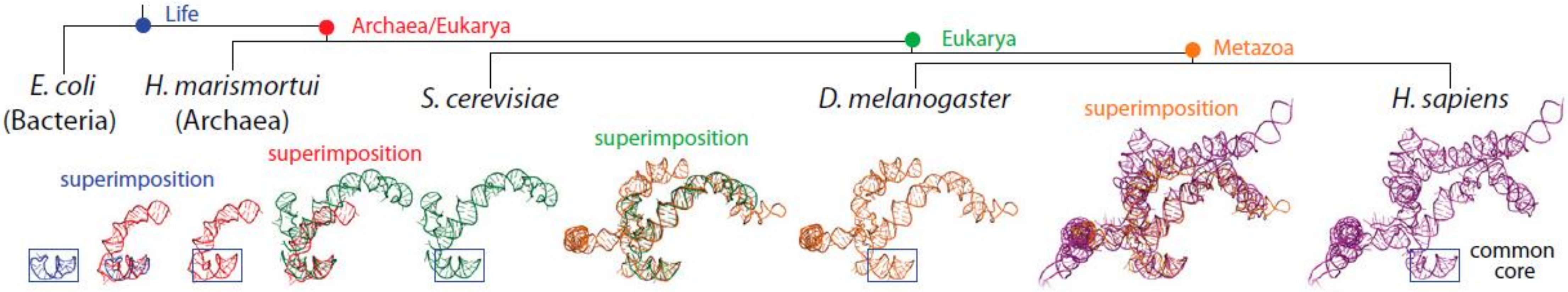
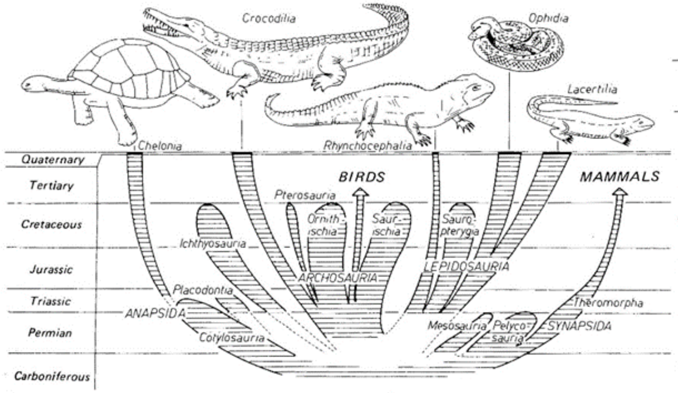
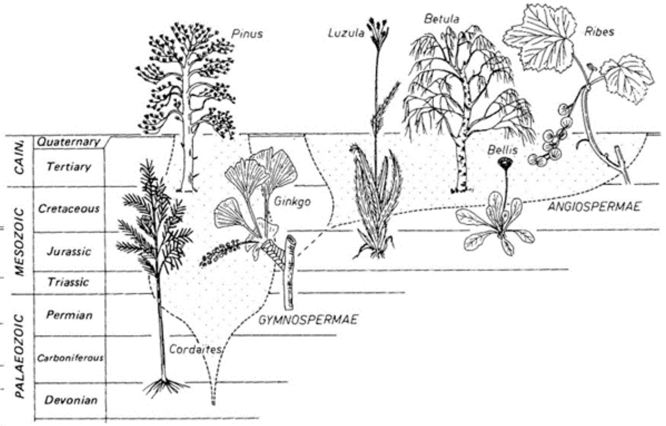
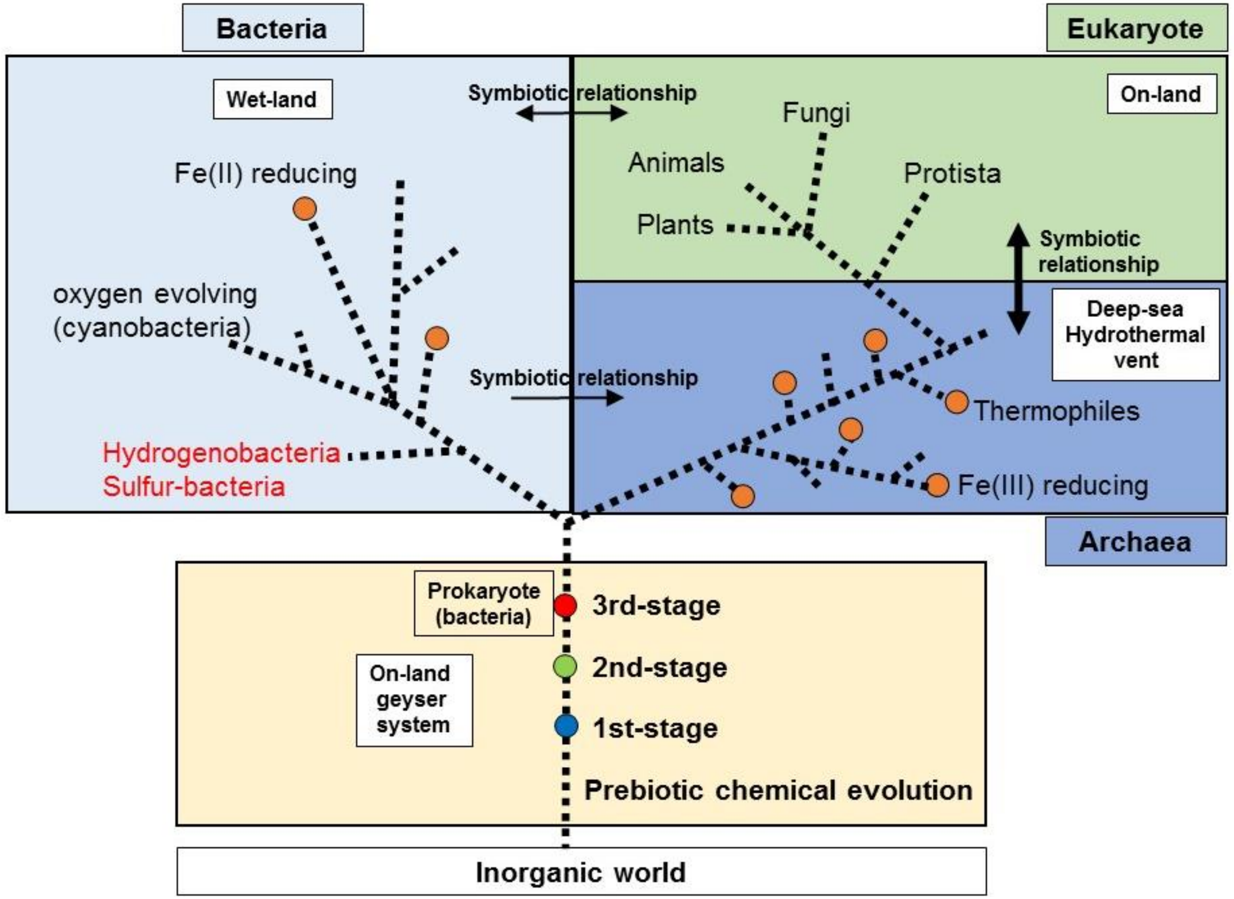


Fig. 3. The evolution of helix 25/ES 7 shows serial accretion of rRNA onto a frozen core. This image illustrates at the atomic level how helix 25 of the LSU rRNA grew from a small stem loop in the common core into a large rRNA domain in metazoans. Each accretion step adds to the previous rRNA core but leaves the core unaltered. Common ancestors, as defined in Fig. 1, are indicated. Pairs of structures are superimposed to illustrate the differences and to demonstrate how new rRNA accretes with preservation of the ancestral core rRNA. Each structure is experimentally determined by X-ray diffraction or Cryo-EM.

Petrov et al (2014)


Crocodilia
Ophidia
Chelonia
Rhynchocephalia
Lacertilia
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
BIRDS
MAMMALS
Pterosauria
Ornithischia
Saurischia
Sauropterygia
Ichthyosauria
ARCHOSAURIA
LEPIDOSAURIA
Placodontia
ANAPSIDA
Cotylosauria
Theromorpha
Mesosauria
Pelycosauria
SYNAPSIDA

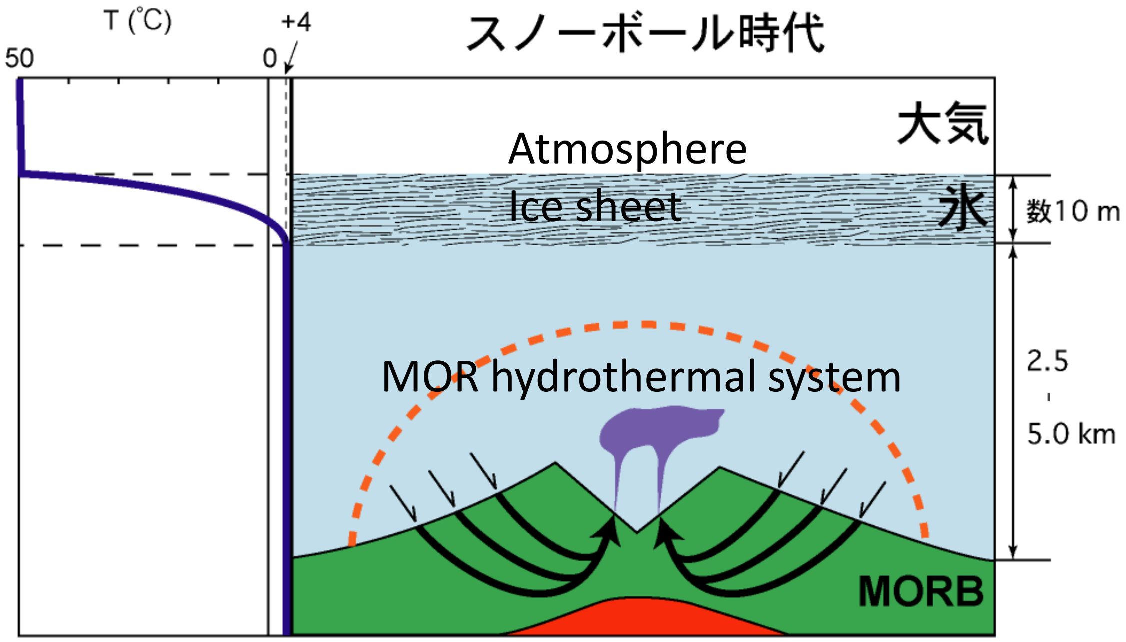

Pinus
Luzula
Betula
Ribes
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
CAIN.
MESOZOIC
PALAEOZOIC
Ginkgo
Bellis
ANGIOSPERMAE
GYMNOSPERMAE
Cordaites

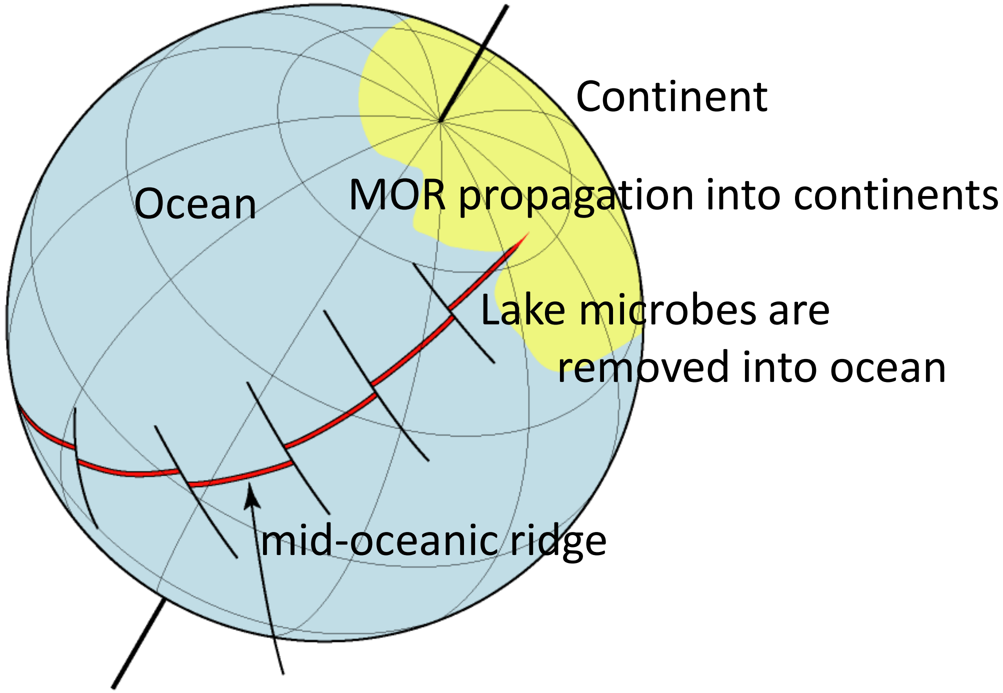

Bacteria
Eukaryote
Wet-land
Symbiotic relationship
On-land
Fungi
Animals
Protista
Plants
Fe(II) reducing
Symbiotic relationship
oxygen evolving
(cyanobacteria)
Deep-sea
Hydrothermal
vent
Symbiotic relationship
Thermophiles
Hydrogenobacteria
Sulfur-bacteria
Fe(III) reducing
Archaea
Prokaryote
(bacteria)
3rd-stage
2nd-stage
On-land
geyser
system
1st-stage
Prebiotic chemical evolution
Inorganic world

Structural evolution of rRNA from bottom (highly reduced environment) to the top (oxidized environment) for both Bacteria and Archaea, to judge which was first?

中央海嶺熱水系は強固な温室

Mid-oceanic ridge is a stable greenhouse; microbes never evolve





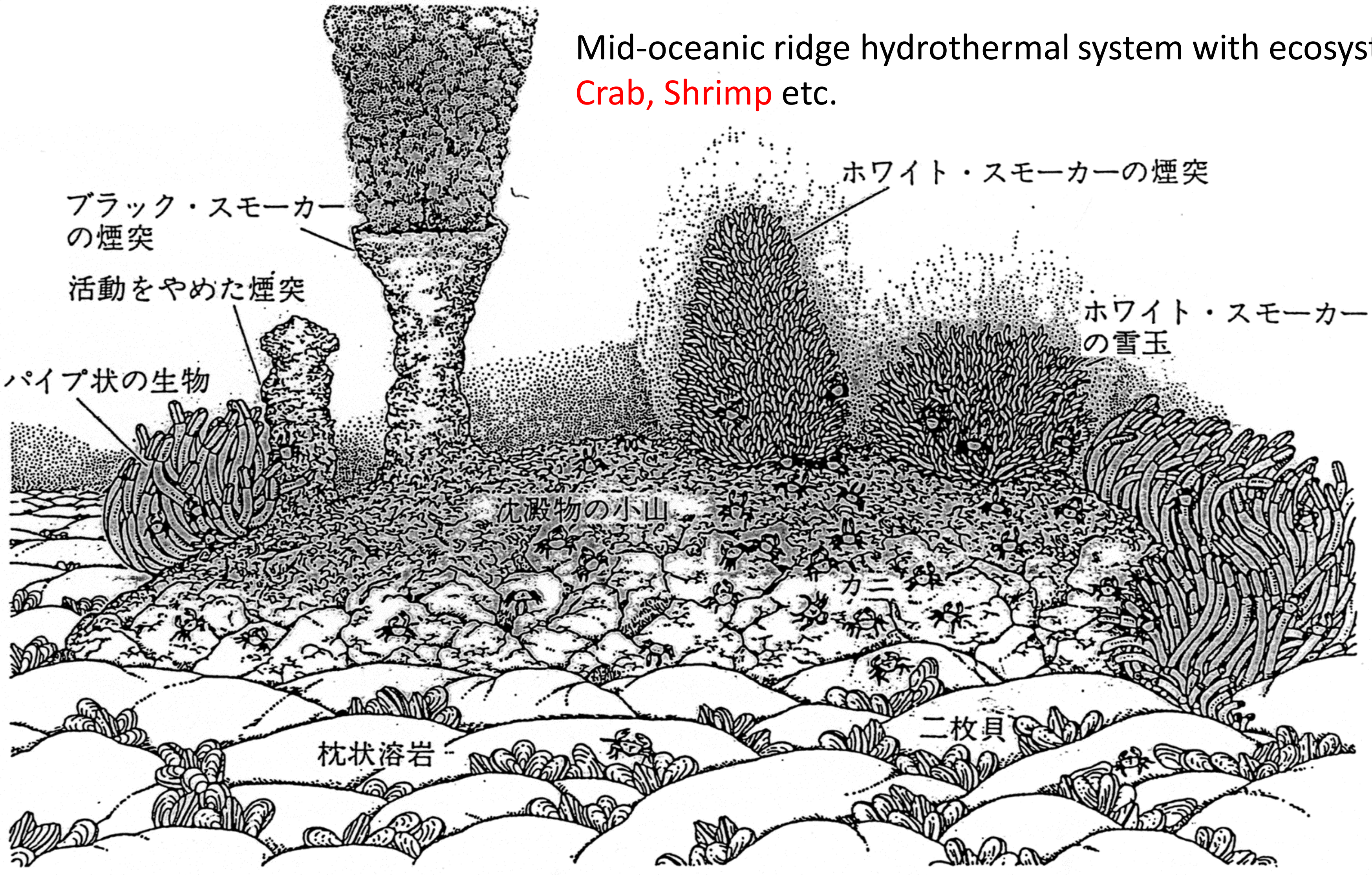
水: Clapeyron slopeが負

40億年前以降安定に存在
（プレート運動の継続と連動）

低温化に対する防御システム

Metazoans: Retrograde evolution, presumably microorganisms as well

Mid-oceanic ridge hydrothermal system with ecosystem including Crab, Shrimp etc.



超大陸と中央海嶺による分裂；その結果としての生態系の変化を分かりやすく説明する

Removal speed of organisms (extremely fast) vs plate movements (extremely slow, cm per year)

- 1 Bacteria was born first, then removed into MOR, remaining wet on-land bacteria which has evolved quickly because of exposures against Universe (GCR, UV, changing intensity of geomagnetism), whereas Bacteria at MOR changed to Archaea and afterward unchanged until now, even in the case of oil-field Archaea, through 40 times rotation of ridge propagations, because under constant environments unchanged. Explain using a series of figures.
- 2 Since 2.3Ga, Eukaryote appeared on land, and removed to MOR as a fate of continental rifting from lake to ocean, where Eukaryote evolved backward, as well as Metazoans since 700Ma.
- 3 To demonstrate the scenarios herein proposed, the genome, ribosomal RNA, and proteins for all microorganisms, Eukaryote and metazoans analyzed to reconstruct the faunal provinces in Atlantic, Indian and Pacific ridges.
-

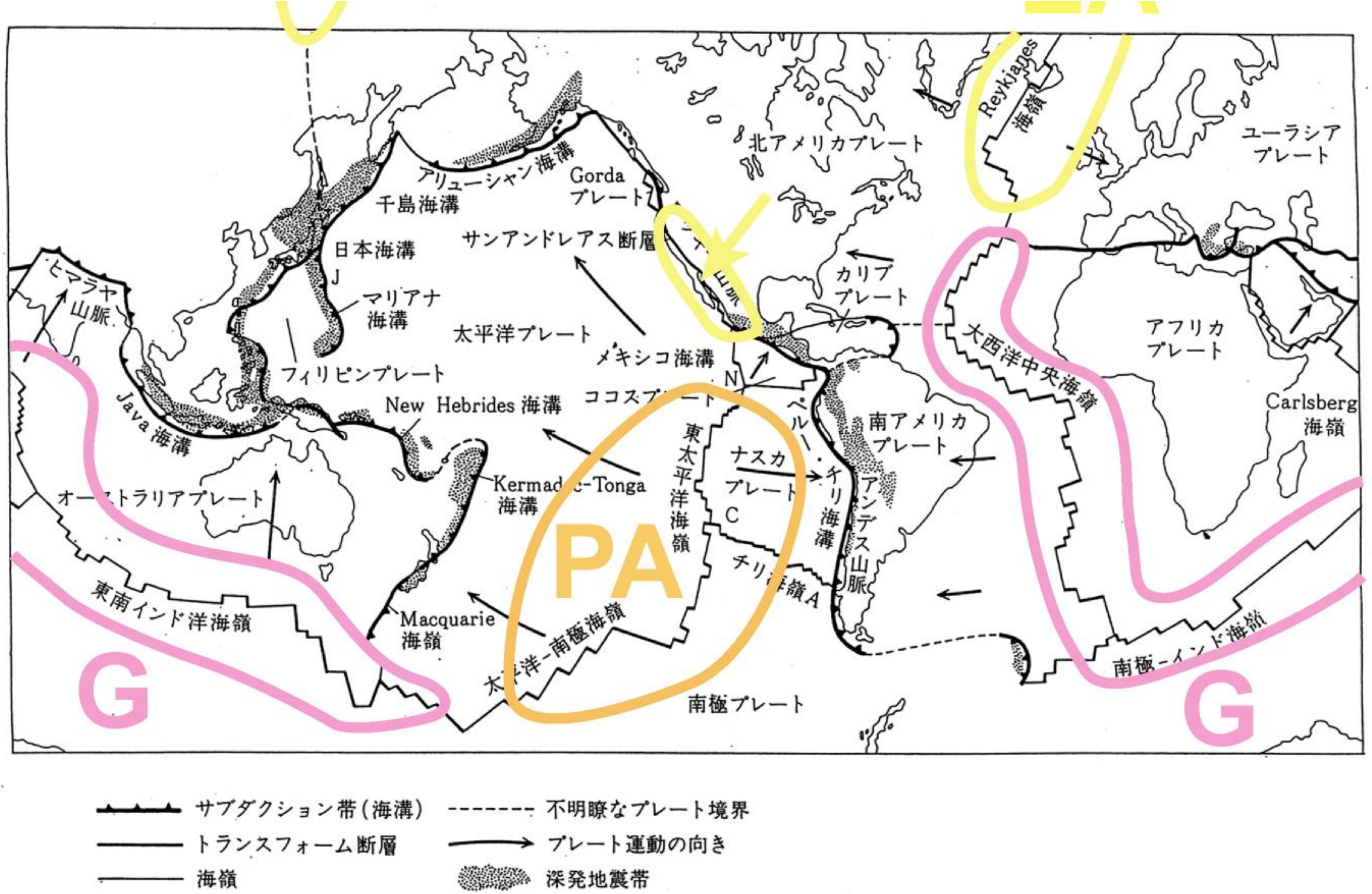
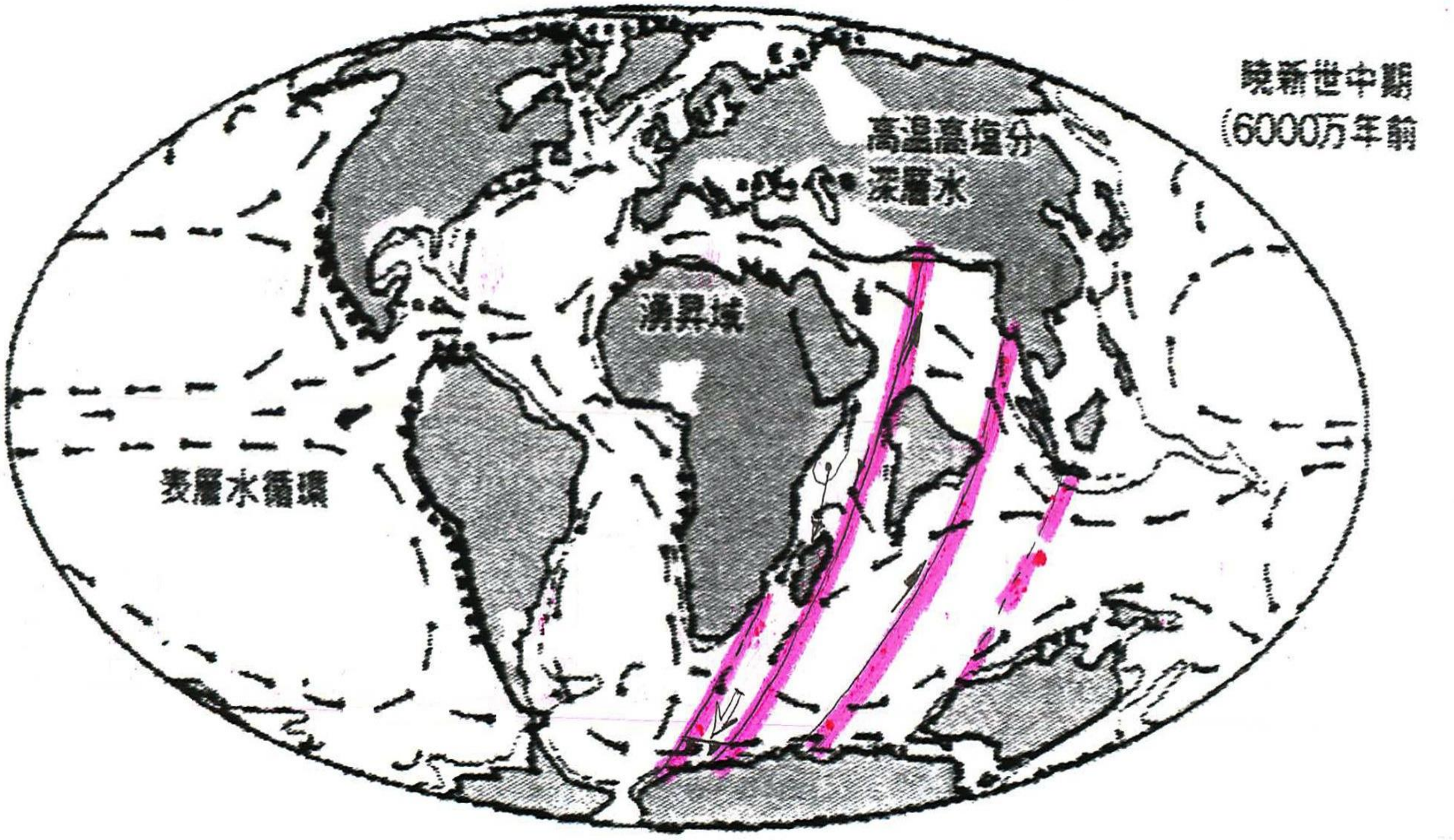
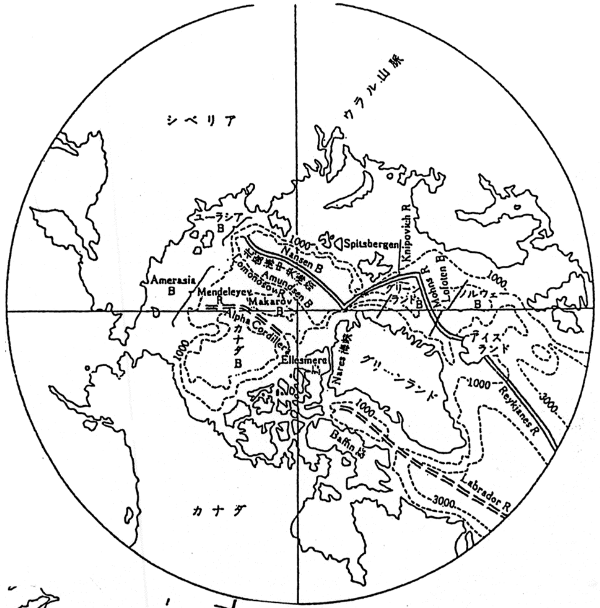


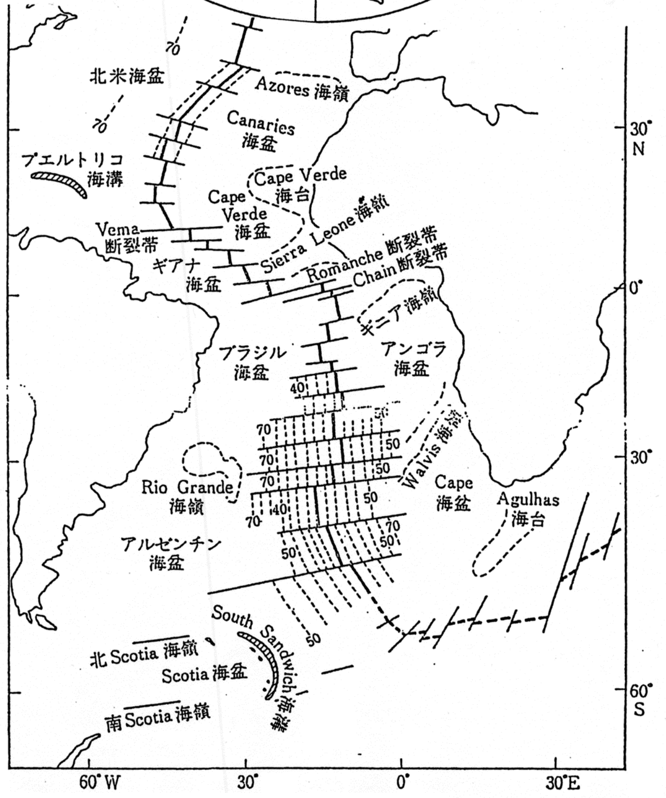
図 1.1 世界のプレート分布．アフリカ・プレートを不動としたときの各プレートの運動の概略を矢印で示してある．J, N, C は 3 重会合点の例(§1.3(g)参照)．

インド洋の構造発達史は大西洋と太平洋とは違う



南北走向の大トランスフォーム断層で３－４区域に分割される。
マダガスカル島の固有哺乳類の起源論争





大西洋の発達史

1　中央部で分裂開始（2億年前）
2　南部が拡大→北部へ、
3　現在は北極海から南下し、将来は北海道へ

問題：なぜ大西洋中央部から拡大が始まったのか？

太平洋の発達史

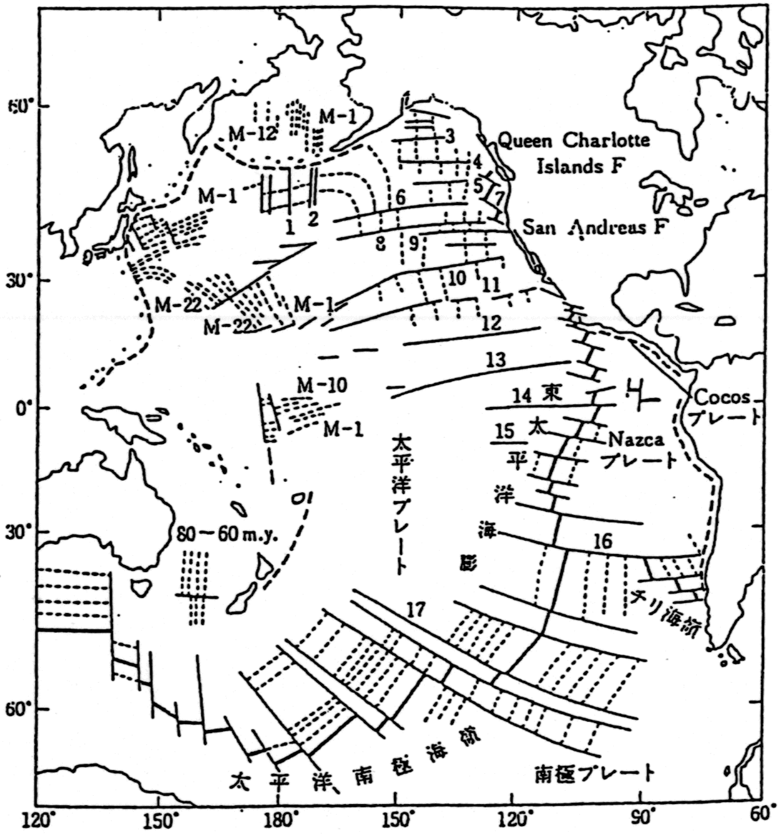
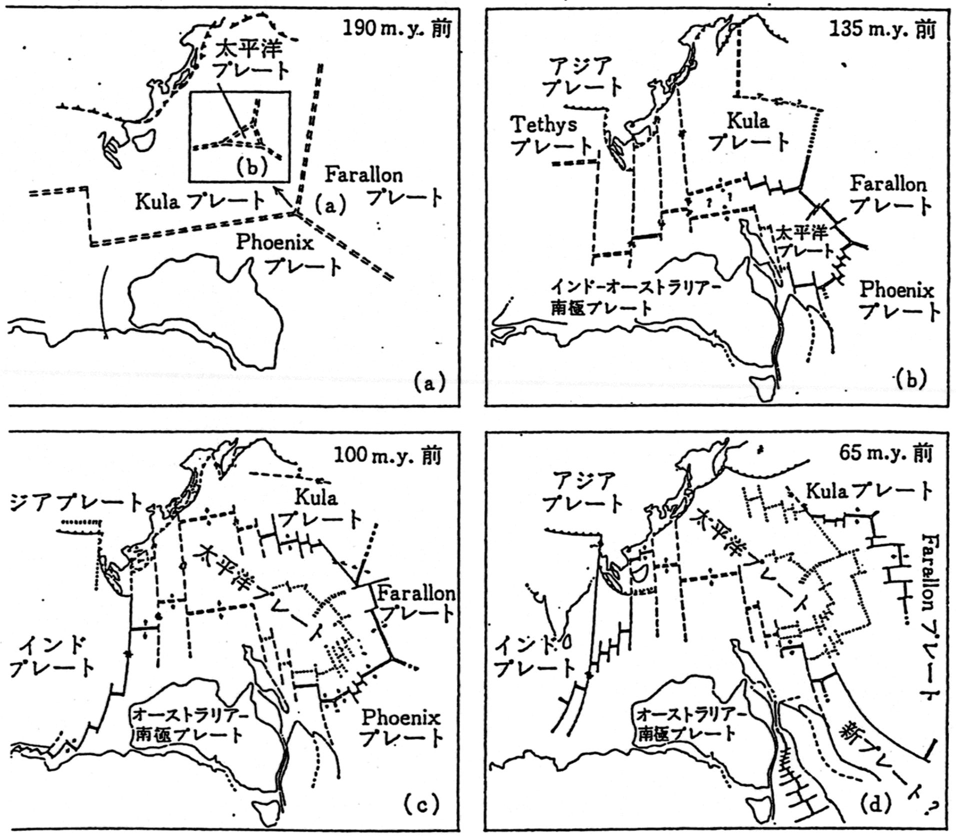


図3.10　太平洋の中央海嶺と断裂帯．数字は断裂帯を示す．1: Adak, 2: Amlia, 3: Aja, 4: Sila, 5: Sedna, 6: Surveyor, 7: Blanco, 8 :Mendocino, 9: Pioneer, 10: Murray, 11: Molokai, 12: Clarion, 13: Clipperton, 14: Galapagos, 15: Marquesas, 16: Easter, 17: Eltanin



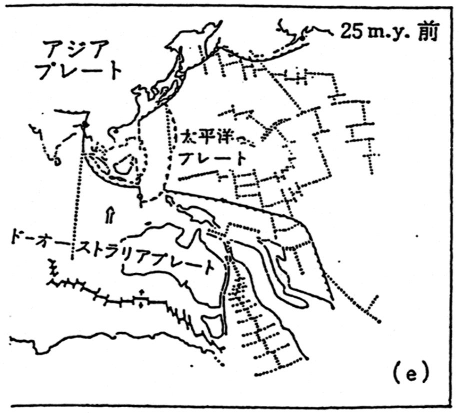
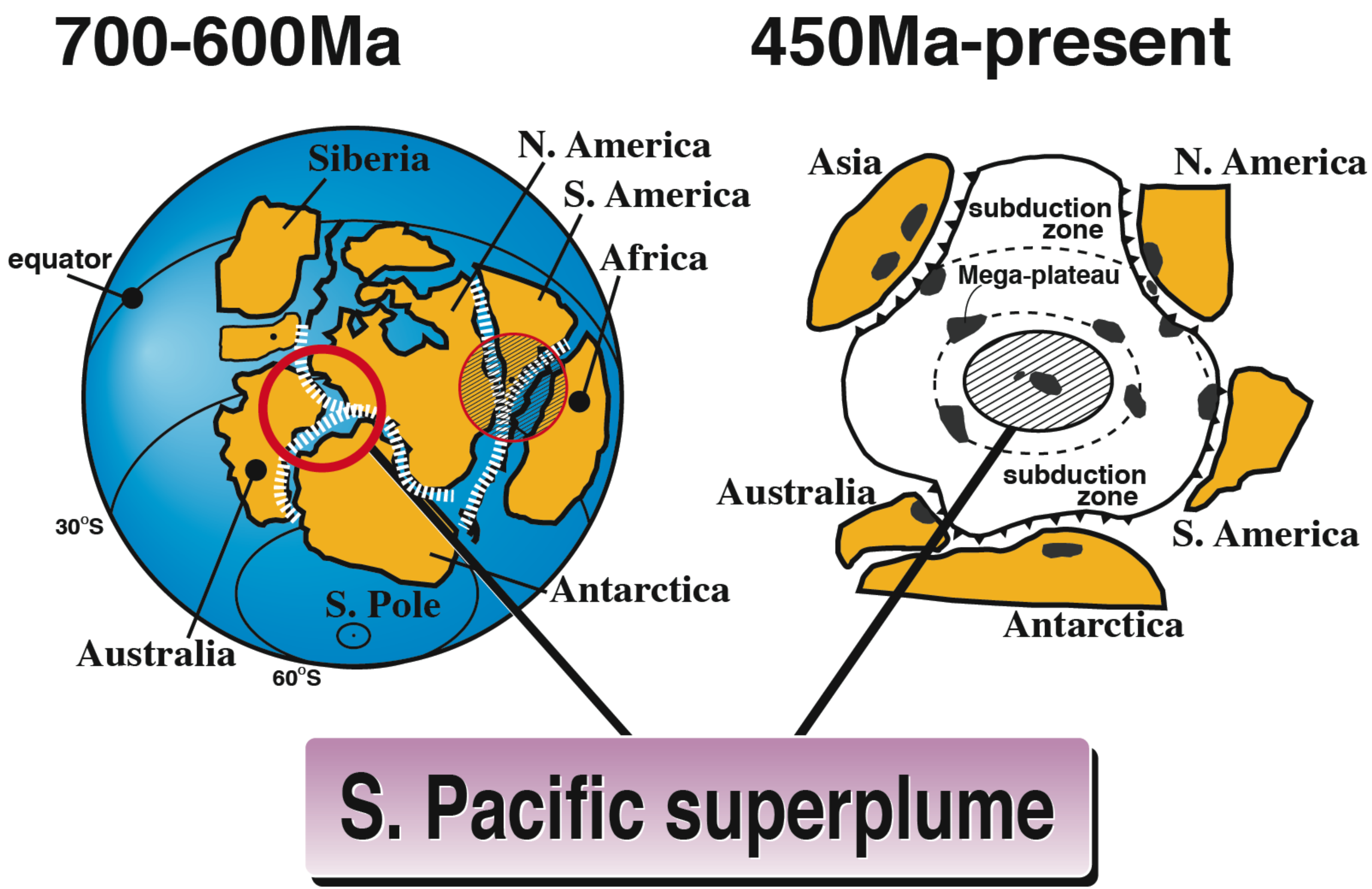


図2.36　西太平洋発達史のモデル (Hilde *et al*., 1977*による).
(a)190 m.y. 前, (b)135 m.y. 前, (c) 100 m.y. 前, (d)65 m.y. 前, (e) 25 m.y. 前. 実線は縞模様データにもとづくもの, 点線は前の時代についてのもの(データにもとづいている), 破線は推論されたもの(データなし)

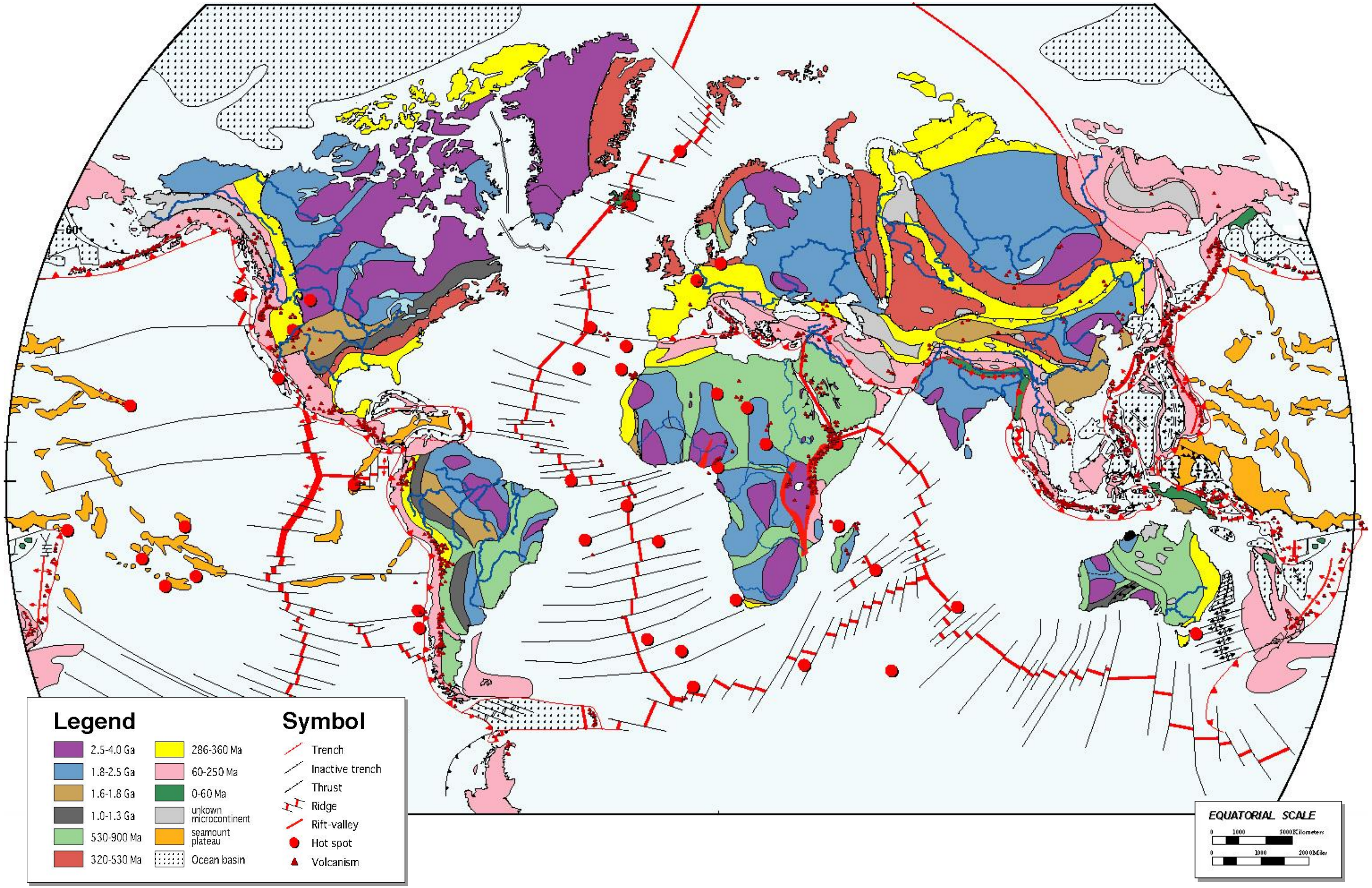


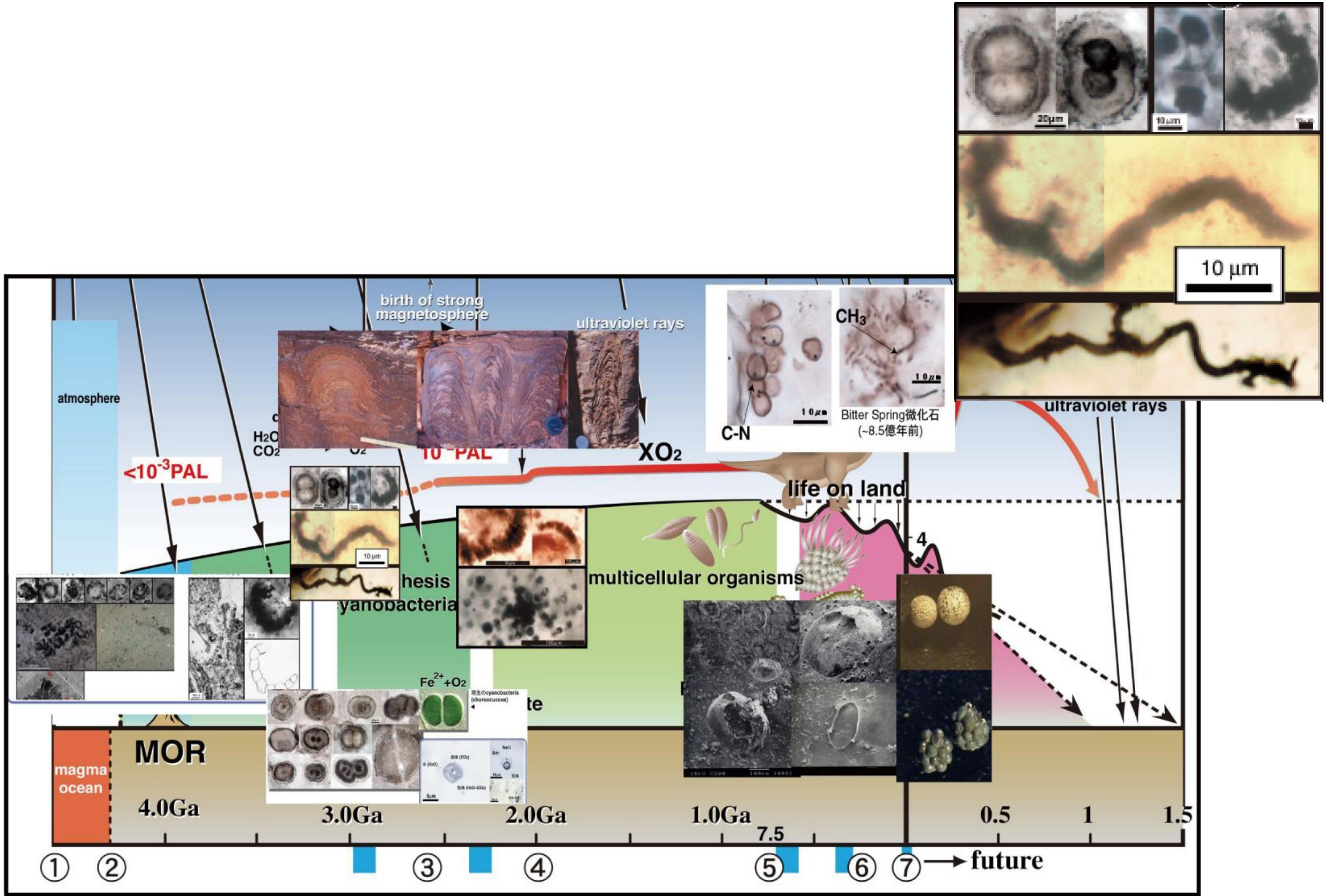
700-600Ma
450Ma-present
Siberia
N. America
S. America
Africa
equator
30°S
60°S
S. Pole
Australia
Antarctica
Asia
N. America
subduction zone
Mega-plateau
subduction zone
Australia
S. America
Antarctica
S. Pacific superplume

Topics for the next works

- 1 Metallic proteins
- 2 RNA-DNA world (Pumps, membranes, spiral structure, self-replication vs environmental change cyclic etc) demonstrate in laboratory, cf. environmental change during Hadean, as three-steps.
- 3 Earth history, evolution of life, environmental change, and System evolution (+ phylogenetic tree of life)

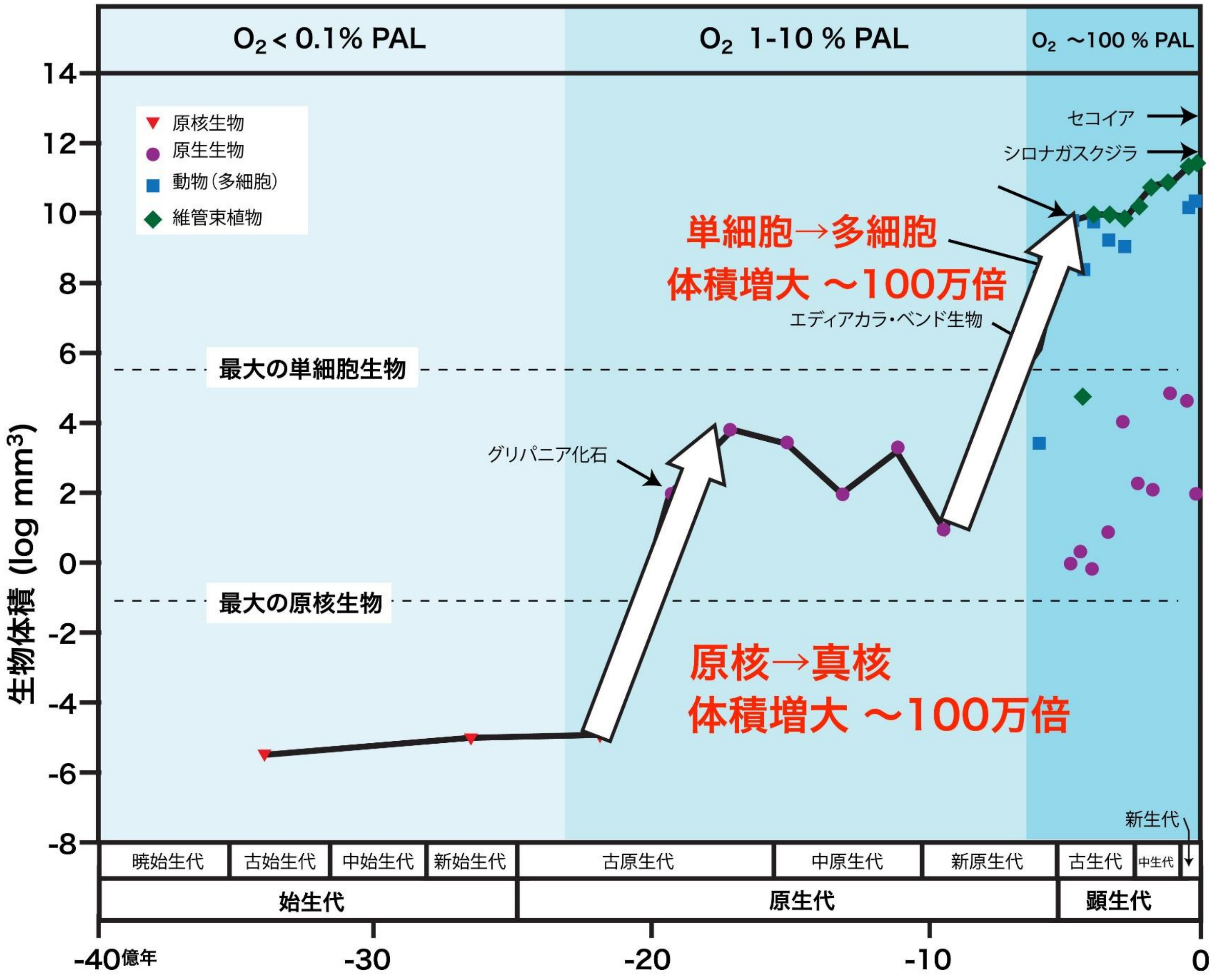
Orogenic belts of the world



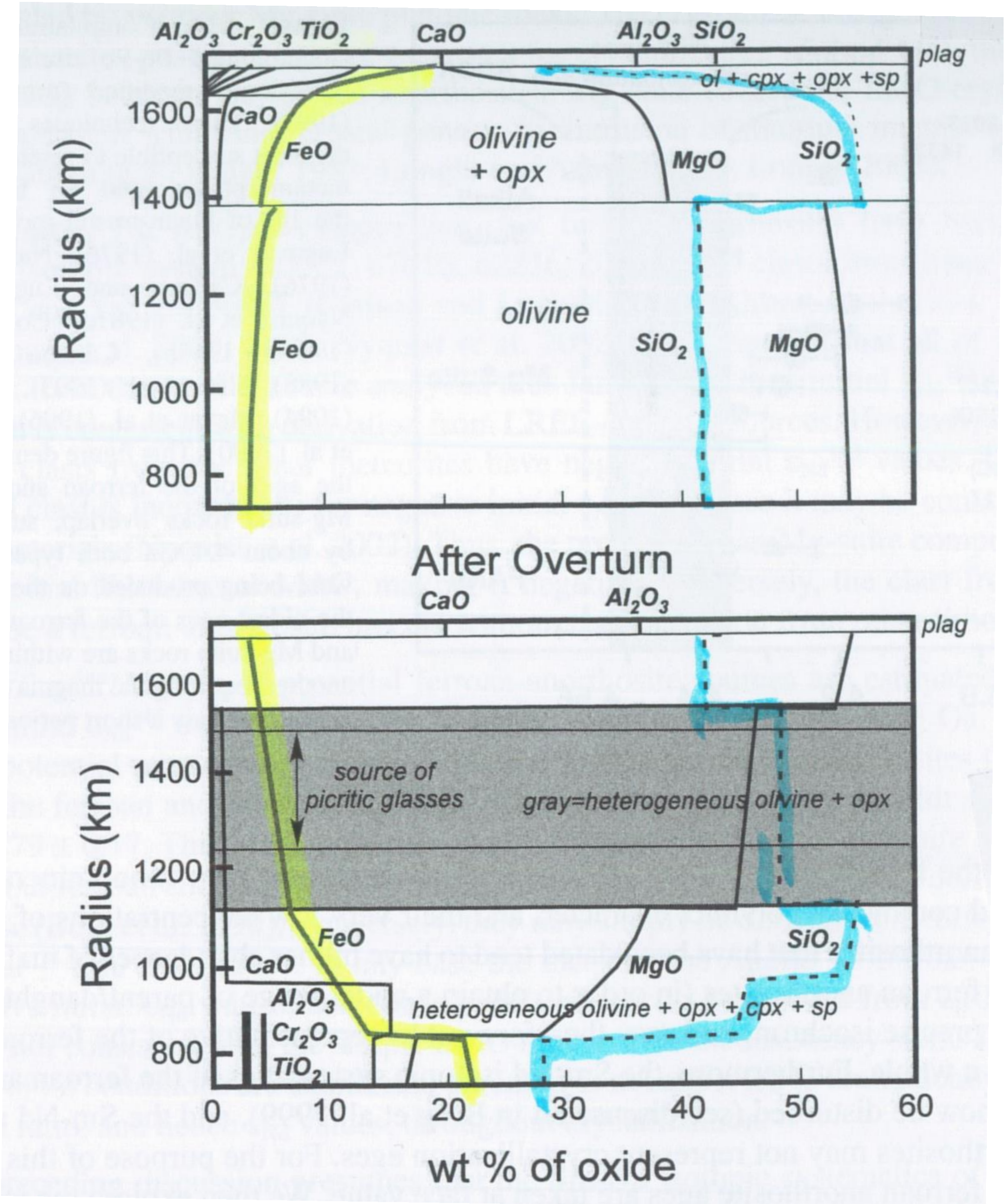


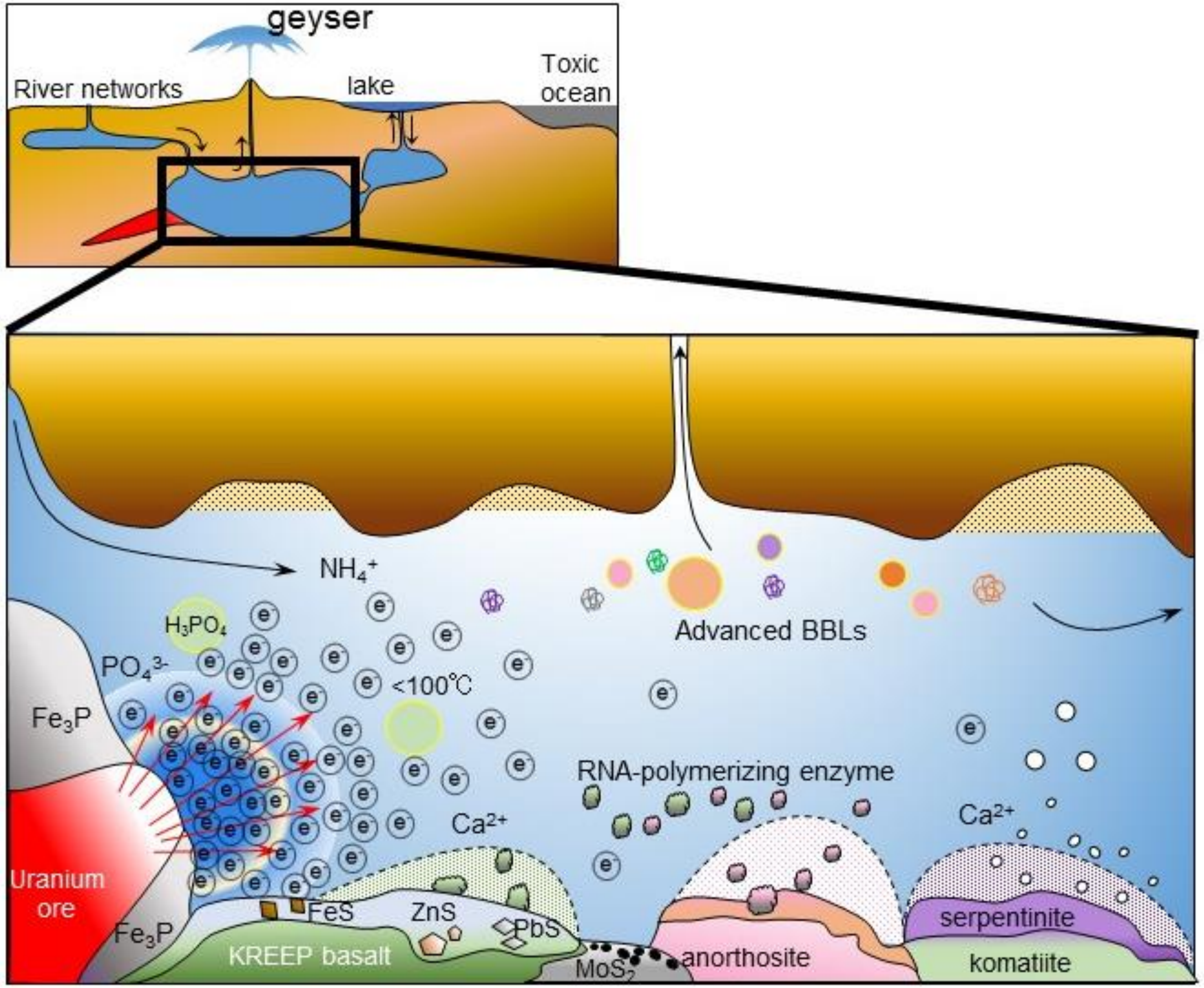
生命と地球の進化の模式図。申請者のグループが発見記載した化石・微化石群を示す。

原核細胞と多細胞生物は、生物量で1兆倍の差がある



Before Overturn

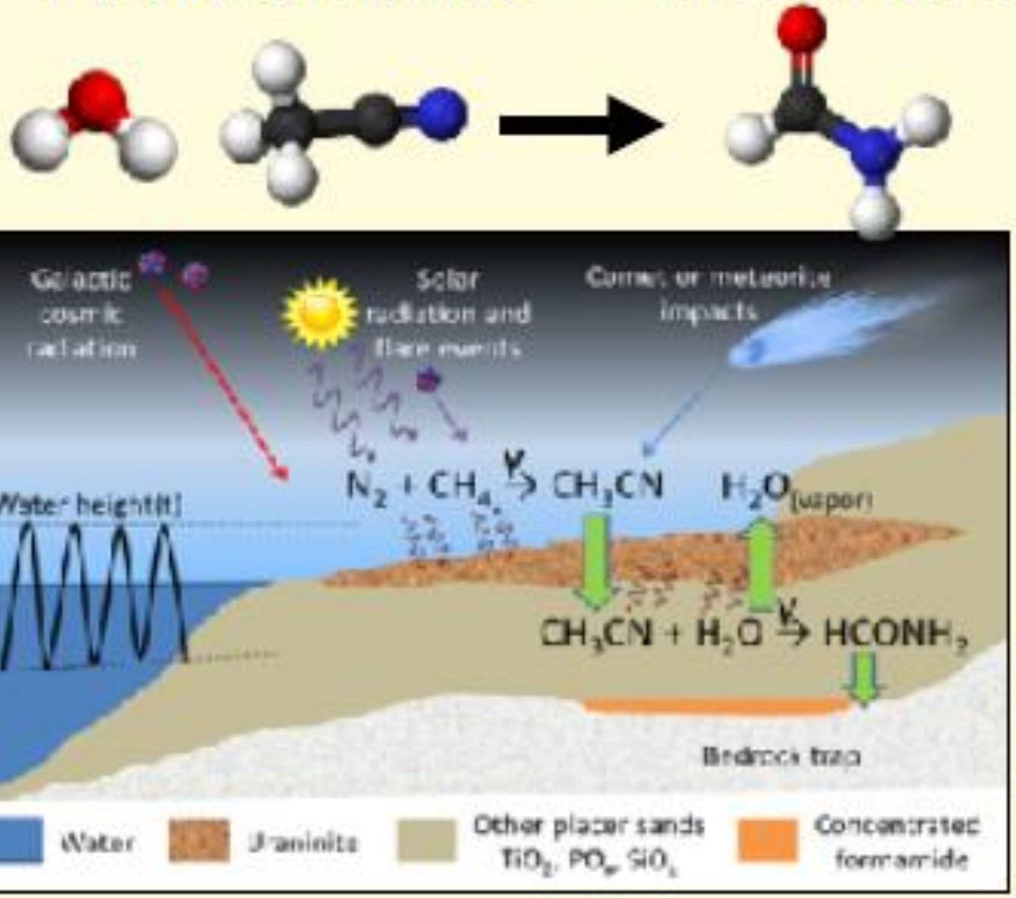



geyser
River networks
lake
Toxic
ocean
NH₄⁺
H₃PO₄
PO₄³⁻
Fe₃P
<100℃
Advanced BBLs
RNA-polymerizing enzyme
Ca²⁺
Uranium
ore
Fe₃P
FeS
ZnS
PbS
KREEP basalt
MoS₂
anorthosite
Ca²⁺
serpentinite
komatiite

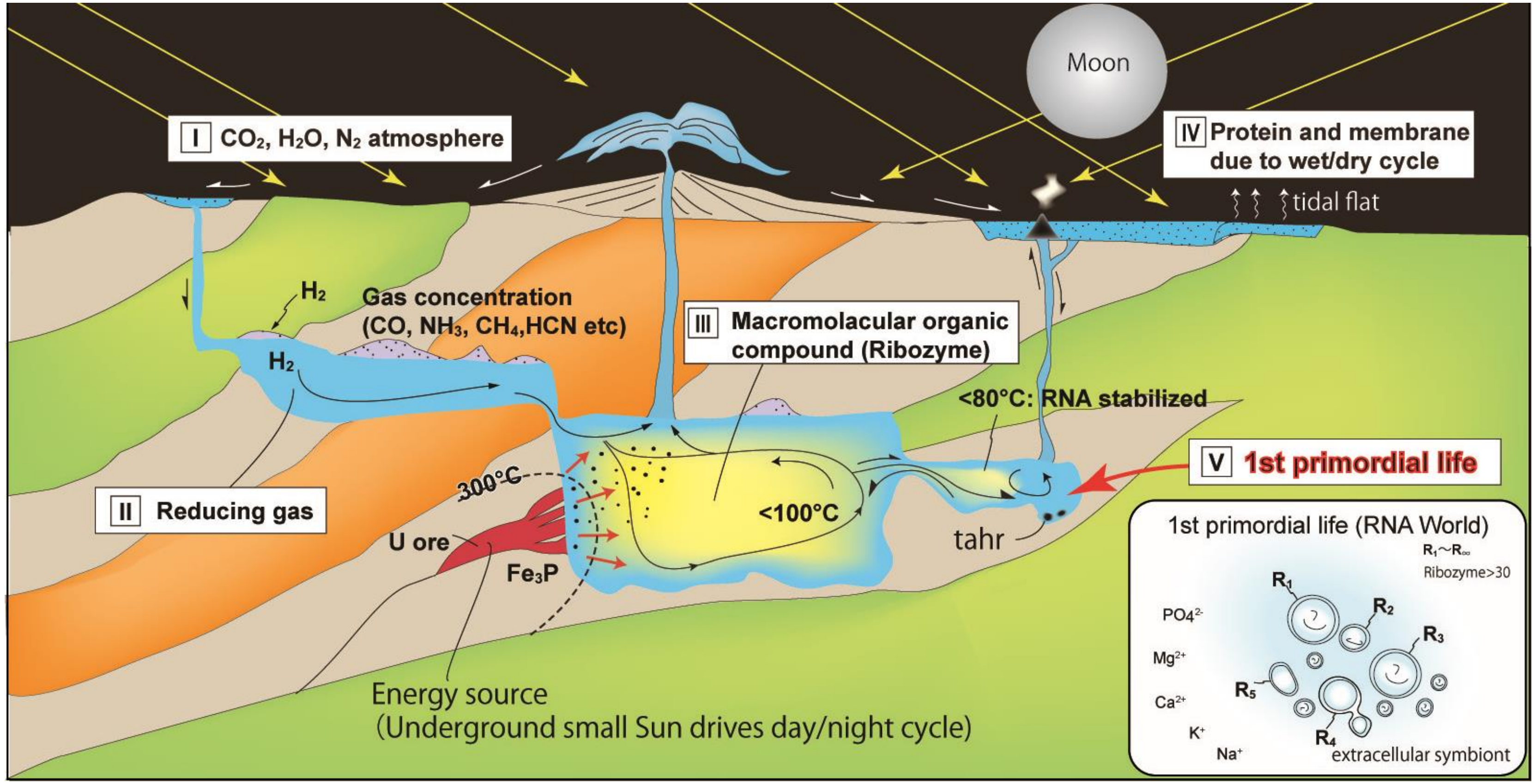
① Formamide Formation

H_2O + Acetonitrile → Formamide (FA)

A02

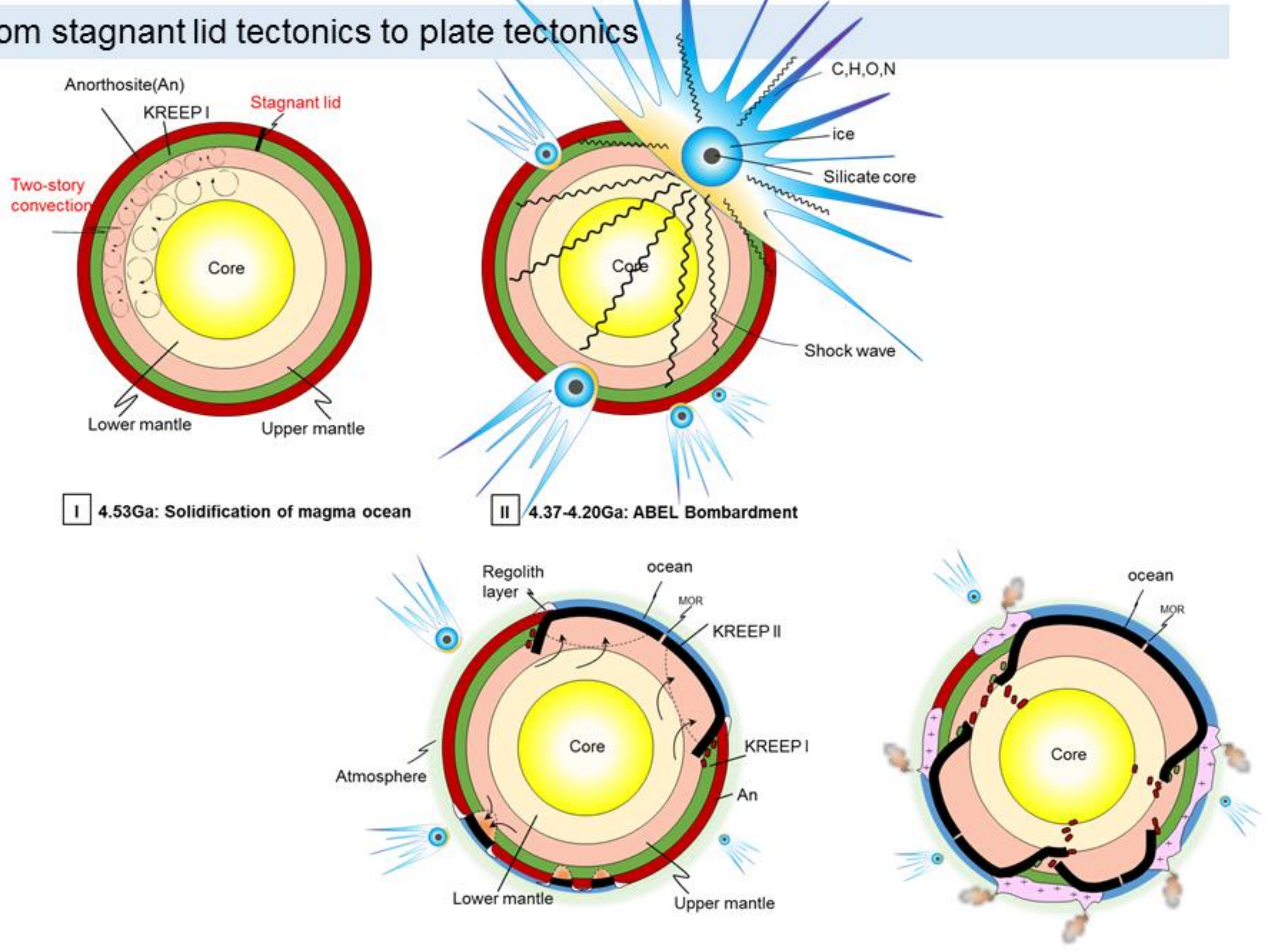


1st primordial life in nuclear geyser at 4.4Ga



- Necessary 20 ribozymes should have been produced at this stage in this small room (temperature less than 80 ℃). Metabolism-oriented ext-symbionts deduced from Minimum gene ca. 120 (Ohshima & Kurokawa)
- Primordial life created extracellular symbiont to survive (symbiosis like virus)
- 1st primordial life was periodically transported to the surface by the geyser to die.

From stagnant lid tectonics to plate tectonics



I 4.53Ga: Solidification of magma ocean

II 4.37-4.20Ga: ABEL Bombardment

III 4.20Ga: Formation of bimodal lithosphere

IV since 4.20Ga: Initiation of plate tectonics