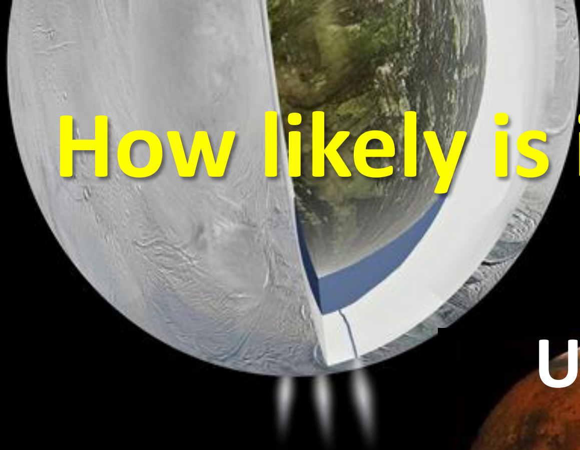
Searching for Life Workshop – Dec. 5-6, 2016

How likely is it that life exists off the Earth?



John Baross

University of Washington

"If you wish to make an apple pie from scratch, you must first invent the universe." Carl Sagan

VPL UW

Outline – issues for discussion

- The focus will be on life resembling Earth life
  - **Carbon-based, requires liquid water, and uses light or chemical energy**
- The requirements for life as we know it **(essential biosignatures – can they be measured?)**
- **The importance of Earth's geophysical and geochemical characteristics in the origin and evolution of life**
- Planets and moons in our solar system that might have or continue to support C-based life
  - Mars, Venus, Europa and **Enceladus**
- Earth-like planets elsewhere in the universe

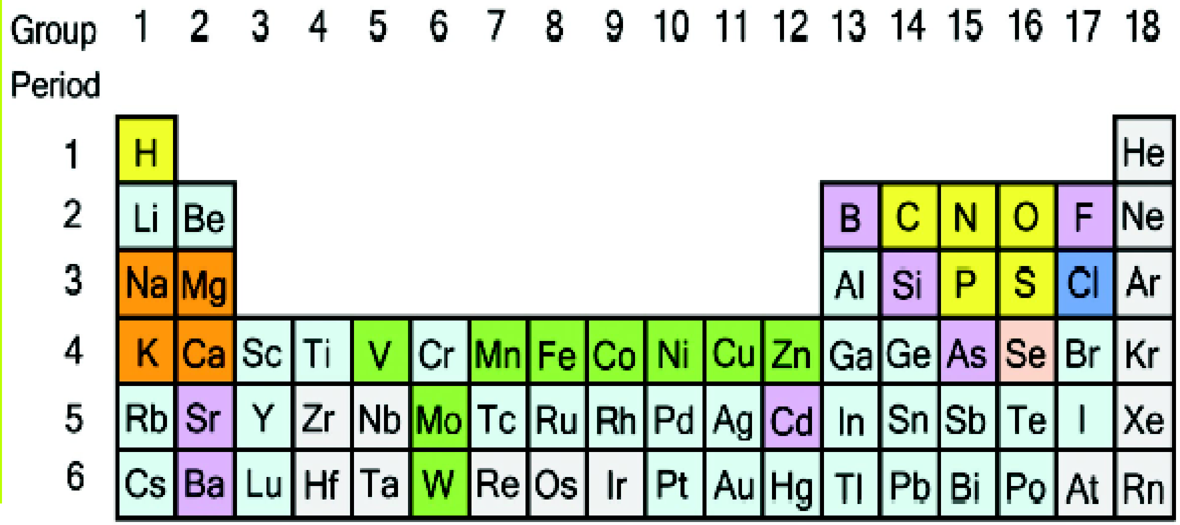
Acquiring life

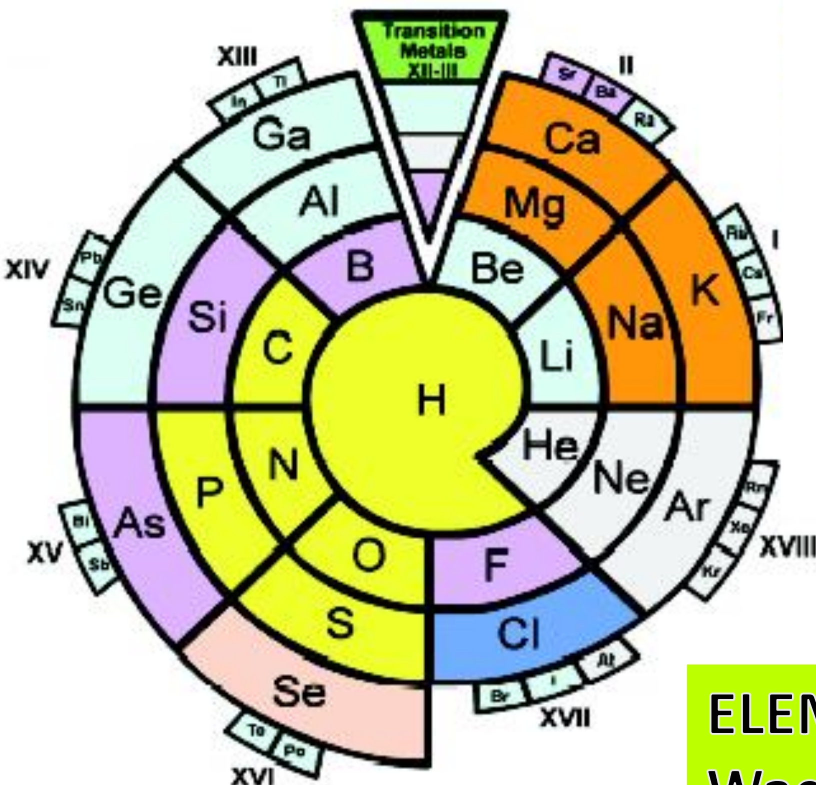
- **Panspermia**
  - What are the "limits" (distance, time, survival characteristics, etc) for microbial space transport?
- ***De novo* origin** (biggest challenge in Science?)
  - Are there essential planetary conditions for *a de novo* origin of life?
  - Can these essential planetary conditions be inferred from signatures/models of planetary bodies that might have life or had life in the past?
  - Are there a subset of essential planetary conditions that can be measured remotely from exoplanets?

The requirements for life as we know it

- Life uses the most abundant elements in the universe **(CHONPS) + Fe**
- Life uses light or chemical energy sources (H_2 was probably the first energy source used by the earliest microbial ecosystems - e.g. methanogenesis and photosynthesis)
- Life requires oxidants. CO_2, S°, Fe(III) are most important in dark ecosystems (O_2 important the last two billion years)
- Life builds catalytic and energy-transfer organic macromolecules around metals and metal-sulfur clusters
- Life requires trace elements such as boron, vanadium, tungsten, nickel, etc (>30 elements)

The elements used by living organisms either in structural macromolecules (proteins, lipids), energy trans-formation, electron transfer chains, energy sources, and as oxidants or reductants





Needed for mineral catalysis and metal-S enzymes

ELEMENTS REQUIRED FOR LIFE (From: Wackett et al., AEM 70:647-655, 2004)

Metal co-factor usage in the six major categories of enzymes *(Stüeken et al., Geobiology 2013)*

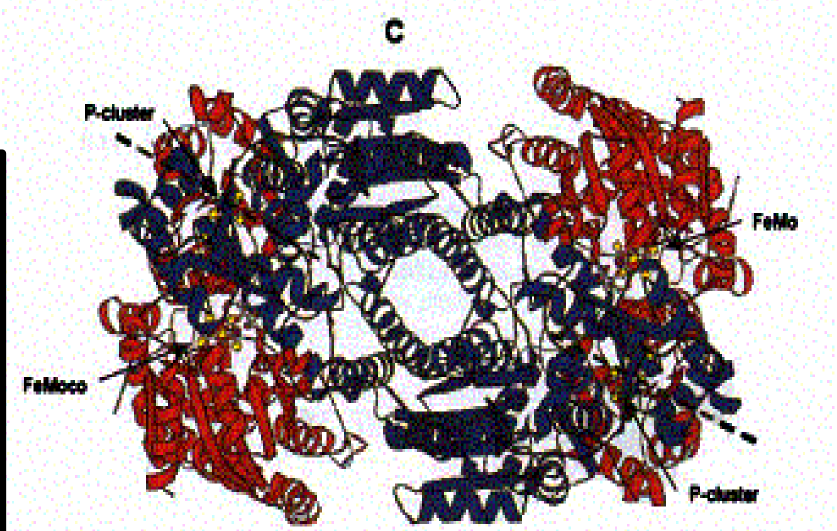
	Cd	Ca	Co	Cu	Fe	Fe-S	Mn	Mg	Mo	Ni	K	Se	W	Zn
oxidoreductases		x	x	x	x	x	x	x	x	x	x	x	x	x
$A^- + B \rightarrow A + B^-$														
Transferases	x	x	x		x	x	x	x			x			x
$A\text{-}X + B \rightarrow A\text{-}B + X$														

There is evidence that almost 50% of metalloproteins in *Pyrococcus furiosus* are uncharacterized and include metals not observed in characterized proteins from *P. furiosus* or any other organism including Pb and U(Cvetkovic et al., Nature 2010).

There are 22 subclasses of oxidoreductases that include hydrogenases ($H_2 + A_{ox} \rightarrow 2H^+ + A_{red}$) and other enzymes involved in the oxidation/reduction of metals, sulfur, nitrogen etc

Metal-Sulfur Cluster Enzymes lead to the hypothesis: Mineral catalysts preceded protein catalysts and furthermore "were the backbone of prebiotic reaction networks that led to modern metabolism" *(Stüeken et al., Geobiology 2013*

What minerals have catalytic activity and how, where and when did they originate on Earth?

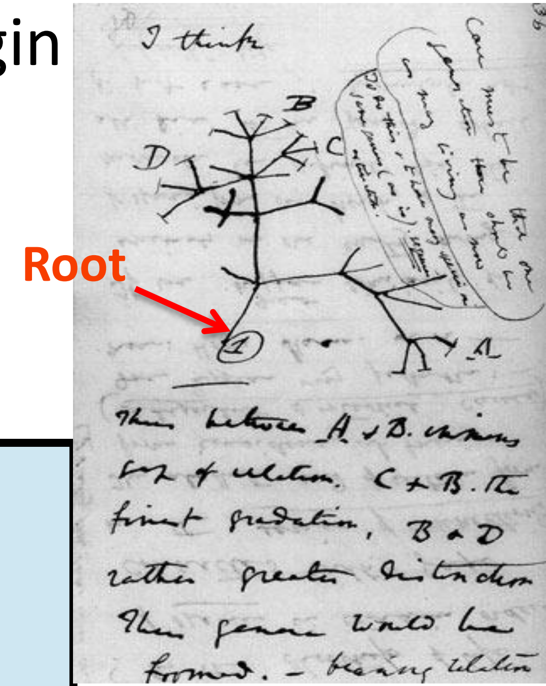


Nitrogenase

Also, Earth life has a “common ancestor”

- The “common ancestor” concept has its origin in what is referred to as the “unity of biochemistry”, that is, all extant organisms share the same biochemical and molecular characteristics:
  - Same nucleotide bases

Would we expect to see a “unity of biochemistry” on other planetary bodies harboring life? Do the best fit genes win out in Darwinian selection fashion?



The first tree of life (Darwin, Origin of Species, 1859) A common ancestor to all life.

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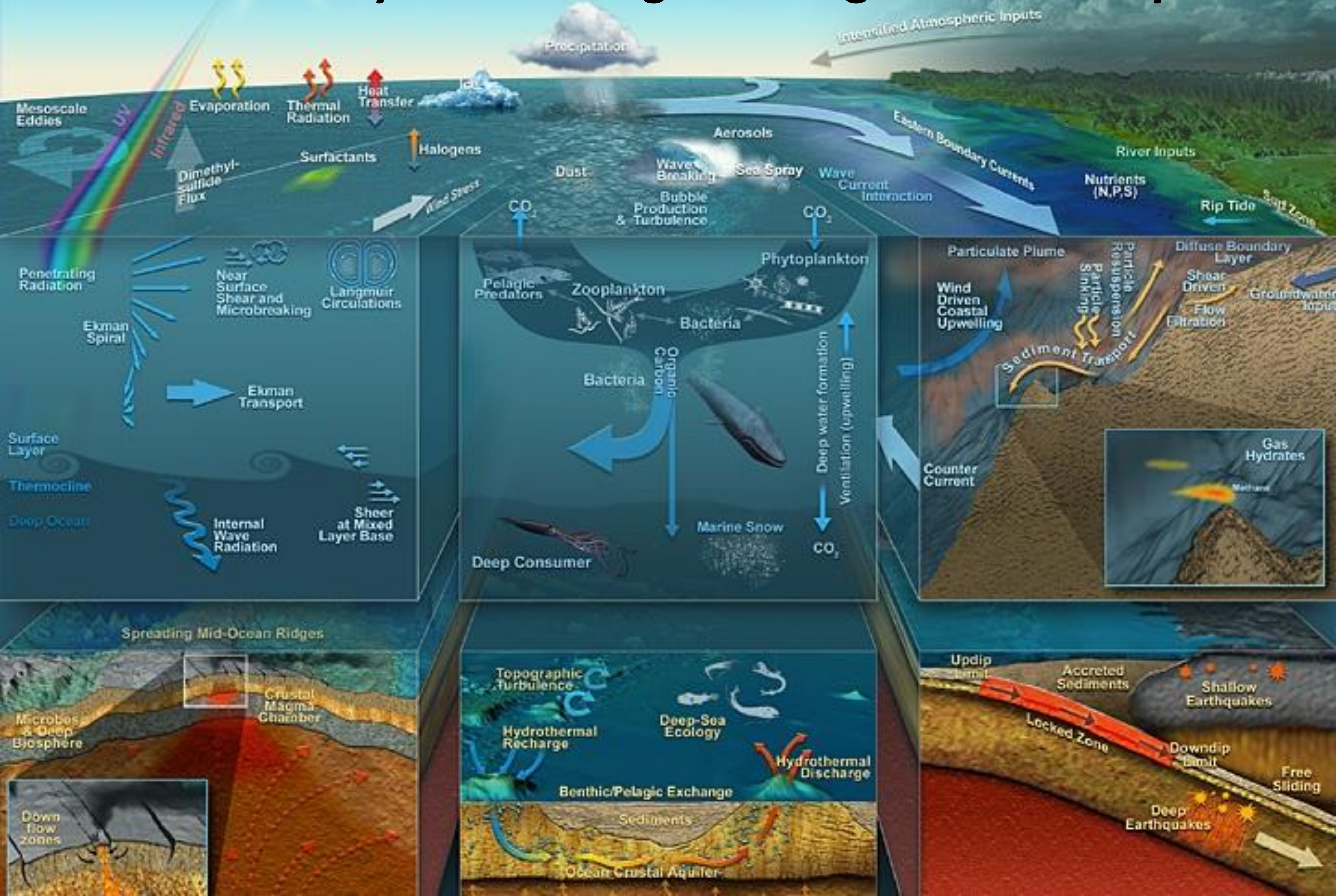
evolutionary relationship between all life - referred to as the “Global Phylogenetic Tree”

The importance of Earth's geophysical and geochemical characteristics in the origin and evolution of life

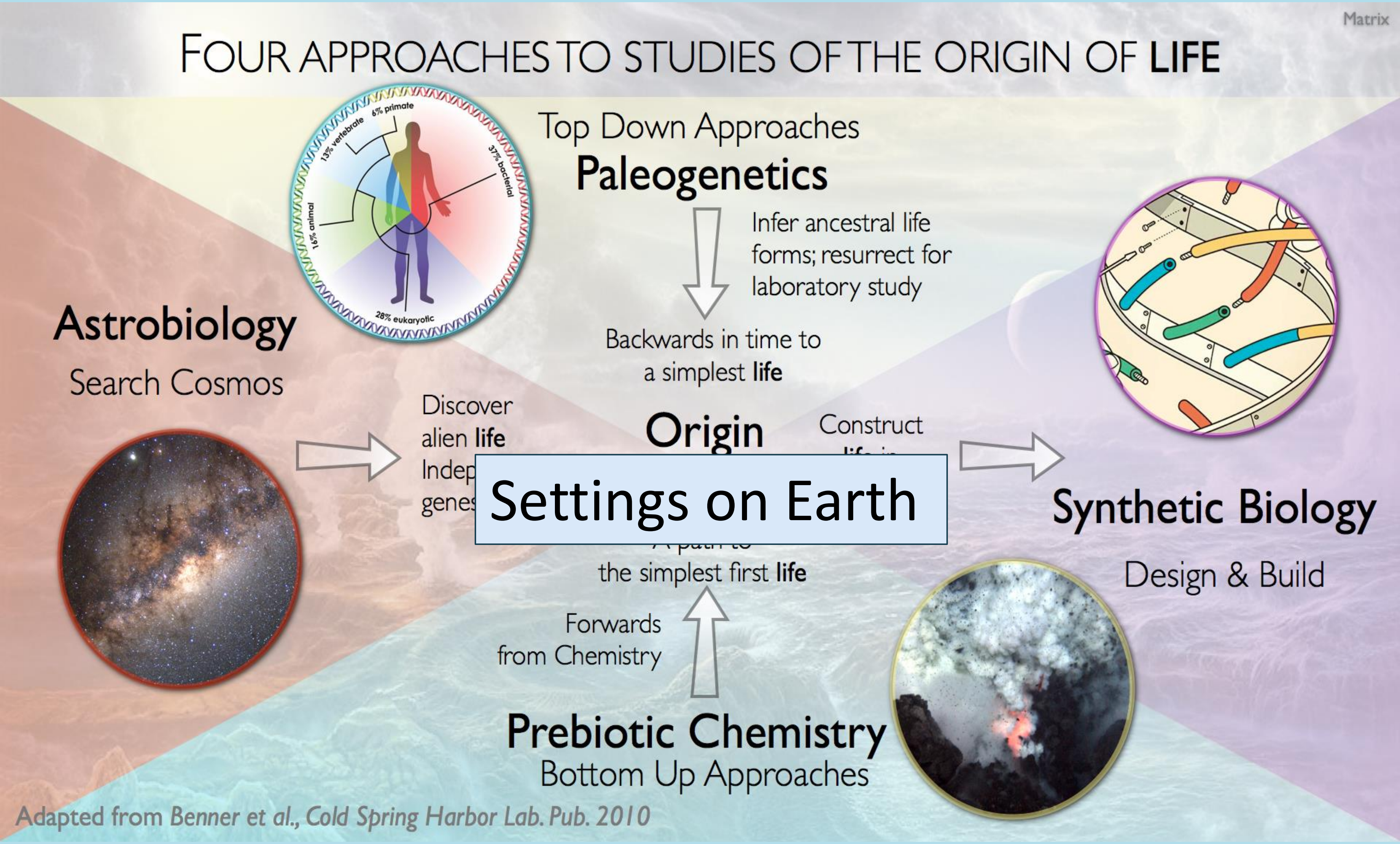
- What are the sources of the essential elements and minerals used by life and likely to have been essential for a *de novo* origin of life
  - Are plate tectonics and hydrothermal systems essential?

Geochemical cycles evolving into biogeochemical cycles?

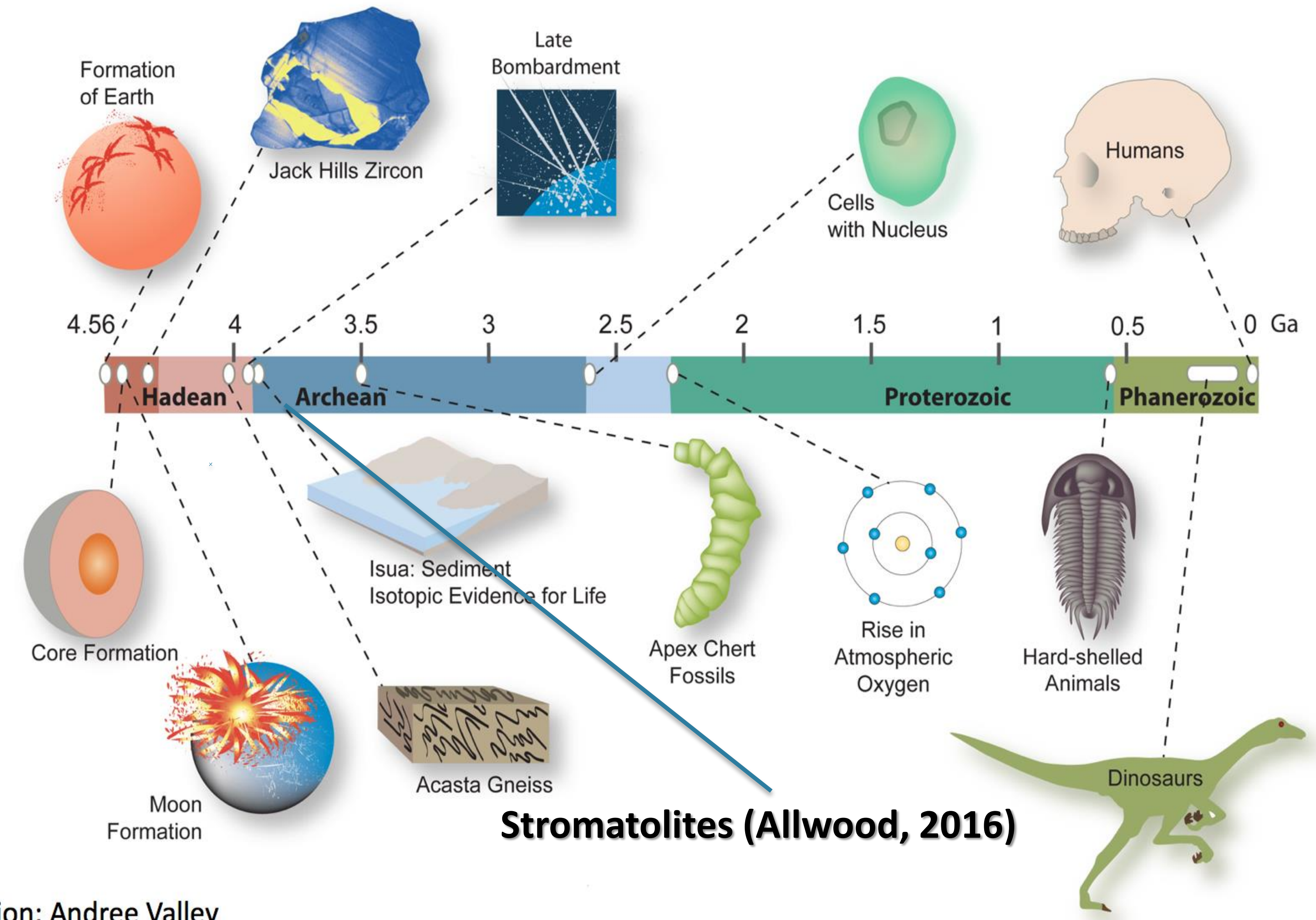


The convergence of geology and biology: Paleogenetics

Paleogenetics and Prebiotic chenistry converge on ***settings on Earth*** for the origin of life



Time line of Earth history over 4.5 billion years (GA)



Stromatolites (Allwood, 2016)

Illustration: Andree Valley

The settings and metabolism of the earliest microbial communities

- All evidence points to **hydrogen** as the earliest source of chemical energy (both non-photosynthetic and photosynthetic organisms)
- Methanogens appear to be ancient and the root of the Archaea tree
- Evidence for stromatolites at >3.7 Ga
- Hydrothermal vent environments would have provided the hydrogen, other volatiles (CO_2, sulfur compounds, nitrogen, etc), key elements to support life, and physical, chemical and spatial gradients

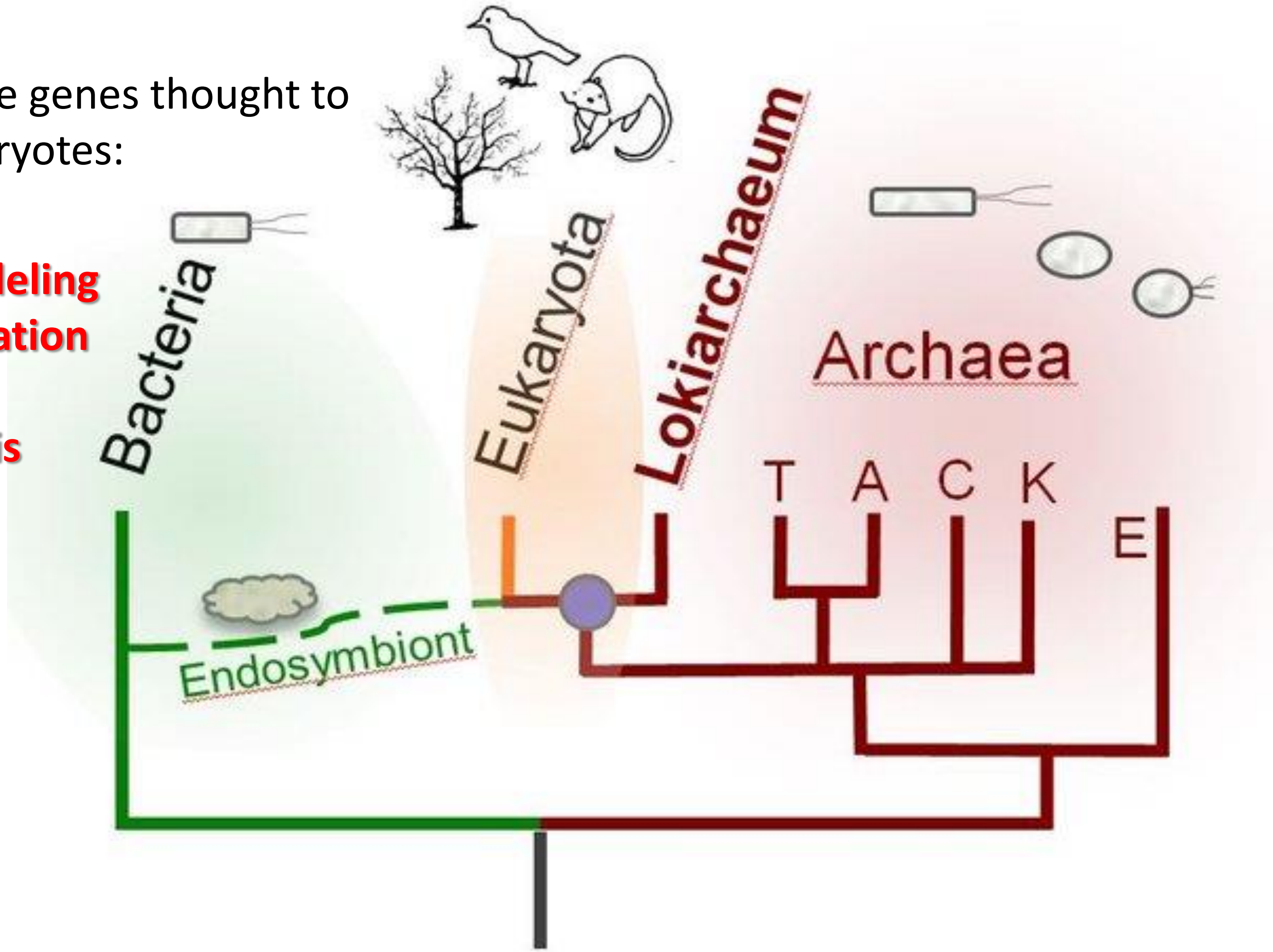
New discoveries of hydrothermal vent microbes lead to potential changes in the phylogenetic tree of life – Two domains with the Eukarya imbedded with the Archaea

New Advances in Molecular Phylogeny and Evolution

- New stuff on Archaea, the three domain phylogenetic tree and the origin of eukaryotes
  - Evidence for a two domain tree of life
  - Evidence that the root of the archaea tree were methanogens
- Loki microbiology
  - Microbial diversity associated with barite chimneys
  - New archaea discovered from phylogenetic data – Lokarchaeota group (Spang et al., Nature 2015)
  - Implications for the origin of eukaryotes and support for the two domain tree of life

Lokarchaeota have genes thought to be unique to eukaryotes:

Cyroskeleton
Membrane remodeling
Ubiquitin modification
Endosymbiosis
an/or phagacytosis



The Lokiarchaea are surprisingly similar to modern eukaryotes, suggesting they share a relatively recent common ancestor. The divergence of Lokiarchaeota and Eukaryota may have coincided with a merger between this common ancestor and a bacteria. Image credit: Christa Schleper, University of Vienna.

Paleogenetic approaches point to hydrothermal systems as providing the carbon, energy sources (mostly H_2) essential elements for early life on Earth, including possibly the source organisms that led to modern-day eukaryotes

Looking for geophysical processes (water/rock reactions) on other planets and moons

- Europa, Enceladus and Titan
- Exoplanets (what signatures of geophysical processes (plate tectonics, hydrothermal and other volcanic activity, etc) can be measured remotely?

Looking for geophysical processes (water/rock reactions) on other planets and moons

Enceladus is an example of a icy moon that may have (or have had) active water/rock interactions related to serpentinization systems similar to those on Earth that support life

Hydrothermal systems: serpentinization-driven

Lost City (*Brazelton et al. 2010*)

Fischer-Tropsch synthesis of organic carbon molecules:

$$CO_2 + H_2 \rightarrow CH_4 + C_2H_6 + C_3H_8 + C_nH_{n+2} \ldots + H_2O$$

pH 9-11

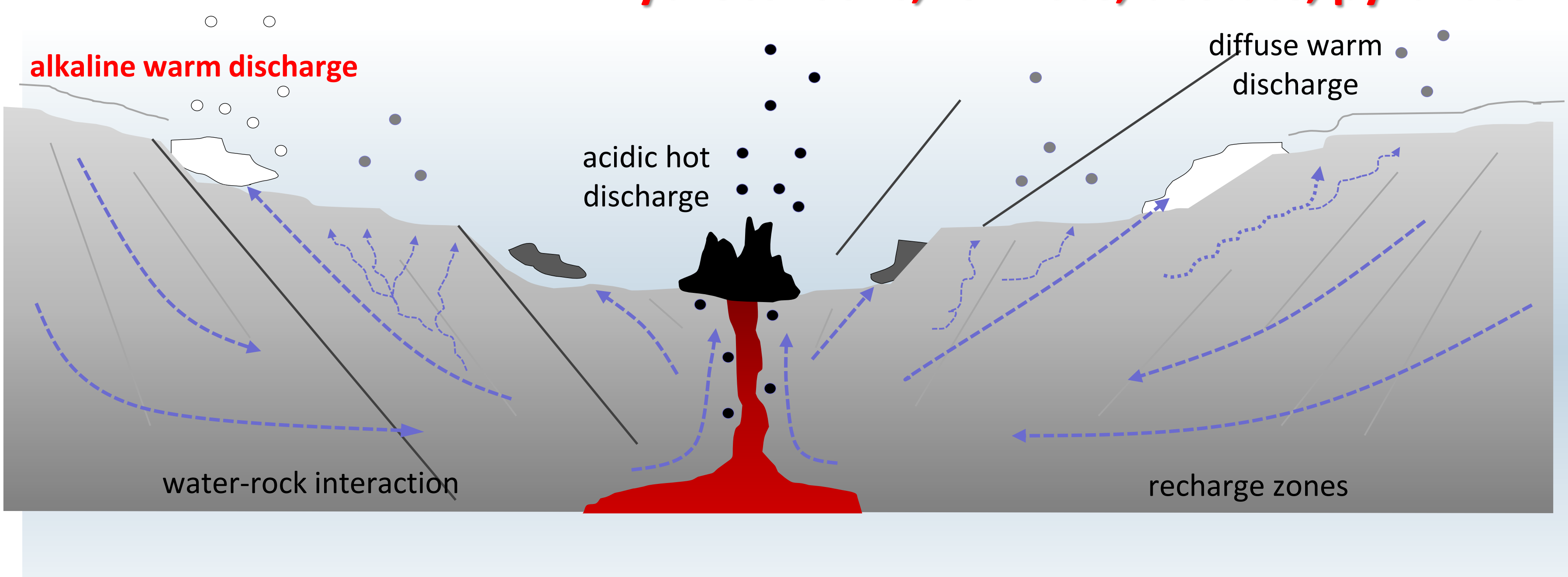
T° >250C

+ hydration and volume increase

$$\underset{\text{Olivine}}{(Mg, Fe^{2+})_2SiO_4} + H_2O \pm C = \underset{\text{Serpentine}}{Mg_3Si_2O_5(OH)_4} \pm \underset{\text{brucite}}{Mg(OH)_2} + \underset{\text{Magnitite}}{(Fe^{3+}{}_2\, Fe^{2+})O_4} +$$

$H_2 \pm CH_4 \pm C_2$-C_5

hydrocarbons, formate, acetate, pyruvate



Summary of characteristics of serpentinization reactions

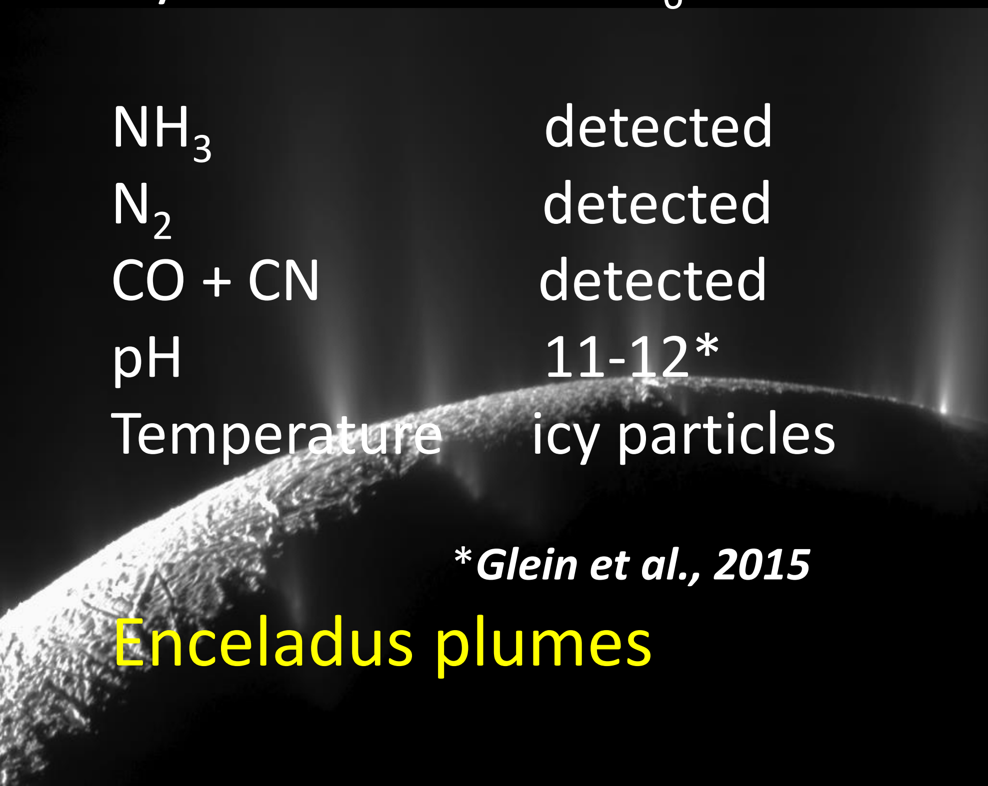
Serpentinization—does two things: it **produces heat** (possibly as high as 268°C at the reaction site) and it **expands the rock by roughly one-third**. Because of serpentinization, oceanic plates take up a great deal of water: a cubic meter of rock can gain as much as 300 kg of water. When oceanic plates undergo subduction, the heat and pressure reverse the serpentinization reaction and release the water into the deep lithosphere, where it gives rise to volcanoes. **So the mechanism building Lost City is one that carries huge amounts of water down into the mantle, part of the vast and complex cycles that keep the Earth running**.

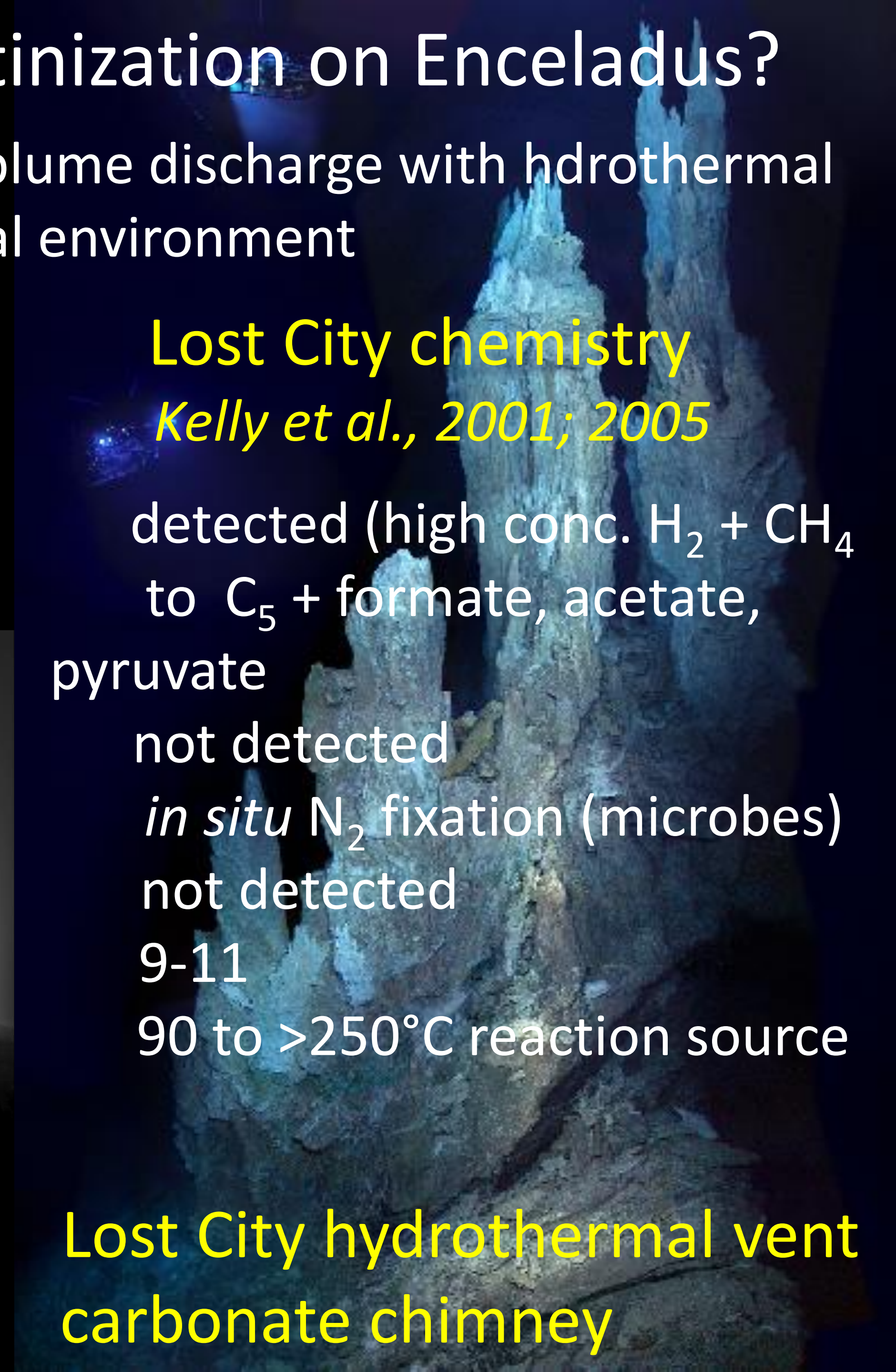
Is there active serpentinization on Enceladus?

Comparing the chemistry and pH of plume discharge with hdrothermal fluids from the Lost City hydrothermal environment

Enceladus chemistry *Waite et al., 2009*		Lost City chemistry *Kelly et al., 2001; 2005*
CO_2, H_2, CH_4	detected	detected (high conc. H_2 + CH_4
Hydrocarbons	to C_6	to C_5 + formate, acetate, pyruvate
NH_3	detected	not detected
N_2	detected	*in situ* N_2 fixation (microbes)
CO + CN	detected	not detected
pH	11-12*	9-11
Temperature	icy particles	90 to >250°C reaction source

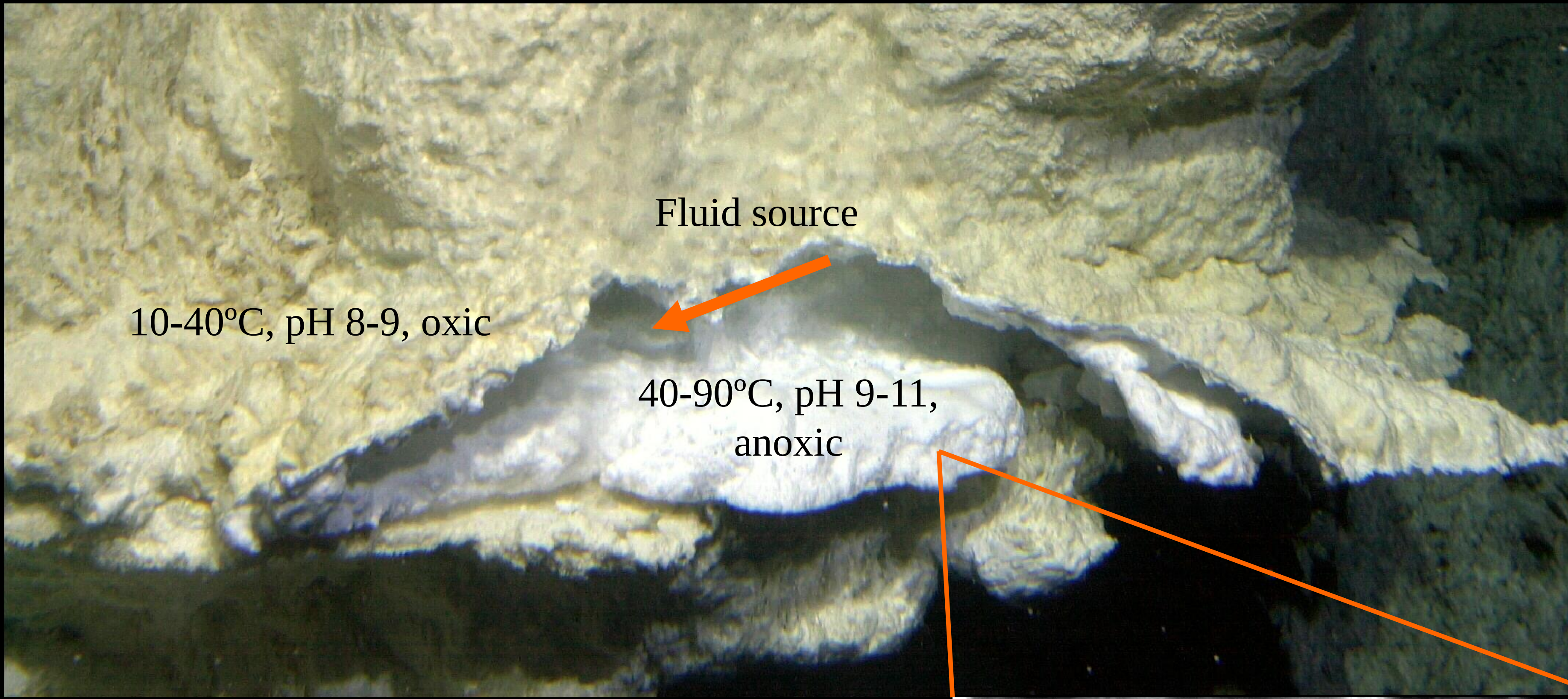
***Glein et al., 2015**


Enceladus plumes


Lost City hydrothermal vent carbonate chimney

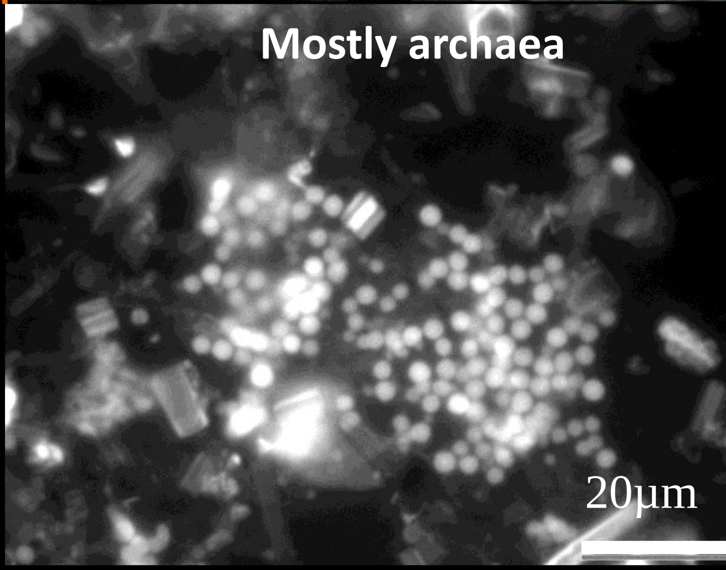
Enceladus: Some issues related to life

- **Are all the chemical and physical conditions that are known to support life present on Enceladus?**
  - No data on key metals and particularly those that are known to be important to microbes in serpentinization environments (metals extracted from rock at high temperature?)
  - Assume a liquid ocean (Less et al, 2014 and other papers) – what is the source of heat?



A single ‘species’ biofilm – belongs to the

- Methanosarcinales group of CH_4-cycling archaea.
- Capable of both producing and consuming CH_4 anaerobically



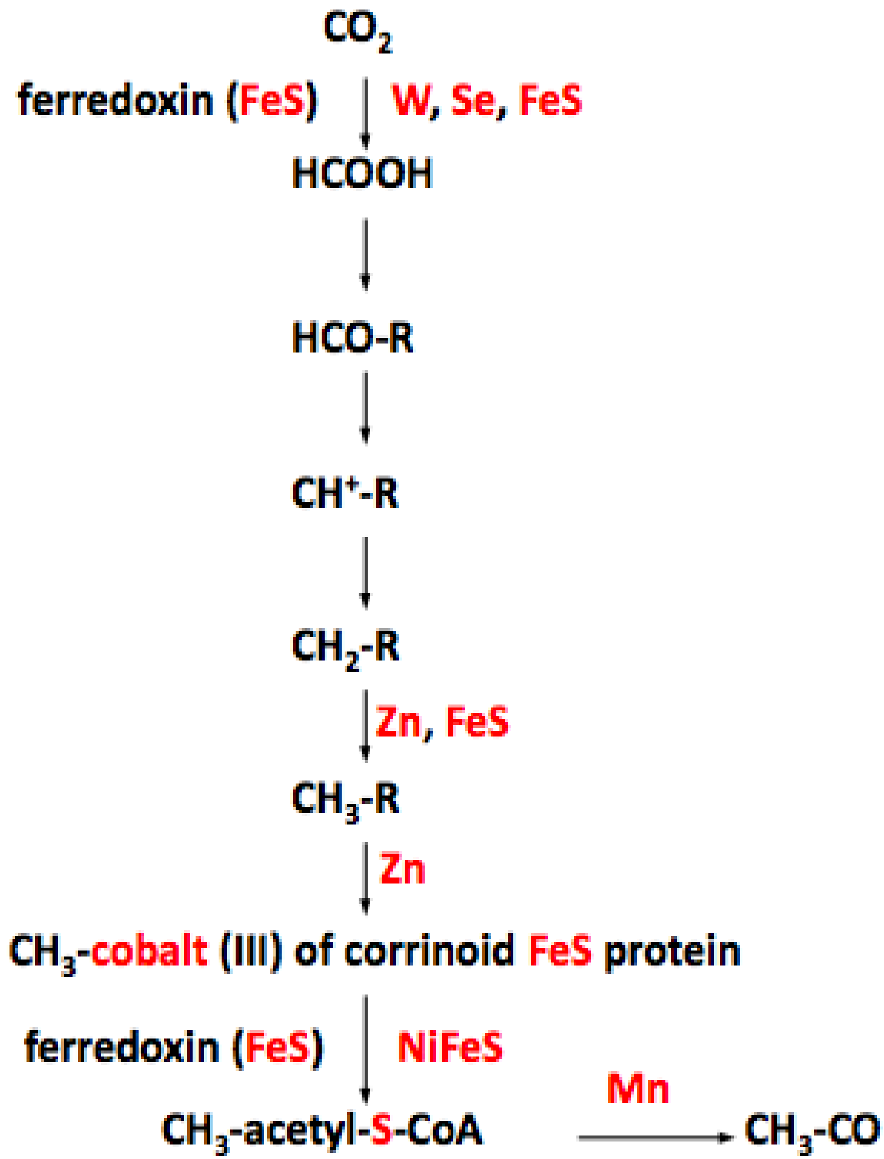
Lost City Biofilm

The metabolic pathway of the Lost City Archaea: A living vestige of mineral catalysis

modern CO_2-fixation via acetyl-CoA pathway

Methanogens and acetogens: both use H_2 to reduce CO_2

Recent reports point to Mo and W enzymes to be the most ancient



Enceladus: Some issues related to life

- **Are all the chemical and physical conditions that are known to support life present on**

If Enceladus is capable of supporting life as we know it, how did it acquire life?
Back to the issue of panspermia or a *de novo* origin
Can tidal heating mimic subduction? (hydration and dehydration)

Concluding thoughts

- We don’t understand how life got started on Earth but we can assume that if earth-like life exists elsewhere it was acquired either by panspermia or a *de novo* origin
- There may be many planets and moons that have conditions to support life as we know it if they could acquire the appropriate organisms
- A *de novo* origin of Earth-like life requires a tectonically active, rocky planet as the source of minerals, elements, carbon and energy sources
- Inferring from paleogenetics: The earliest group of microbes, including possibly the source organisms that led to modern-day eukaryotes, were associated with hydrothermal systems