# *Hydrothermal systems: the site of the origin and early evolution of life?*

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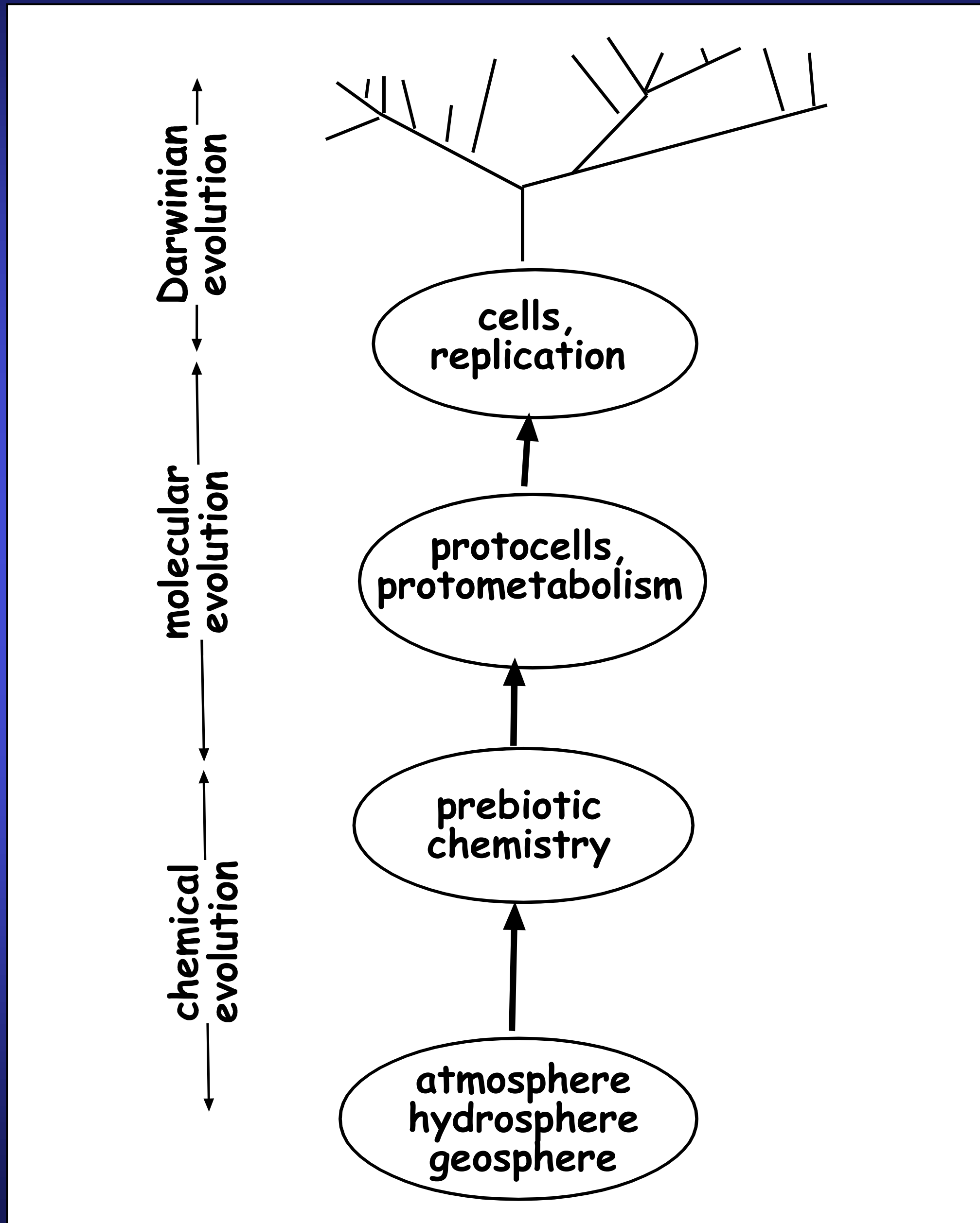
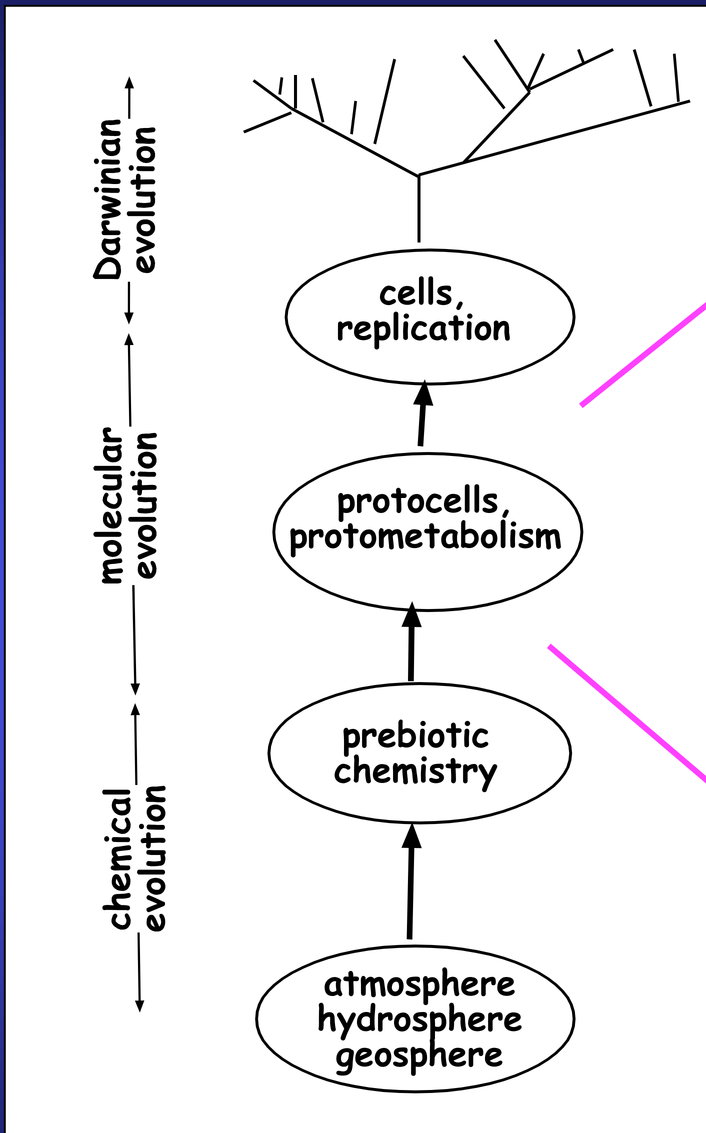
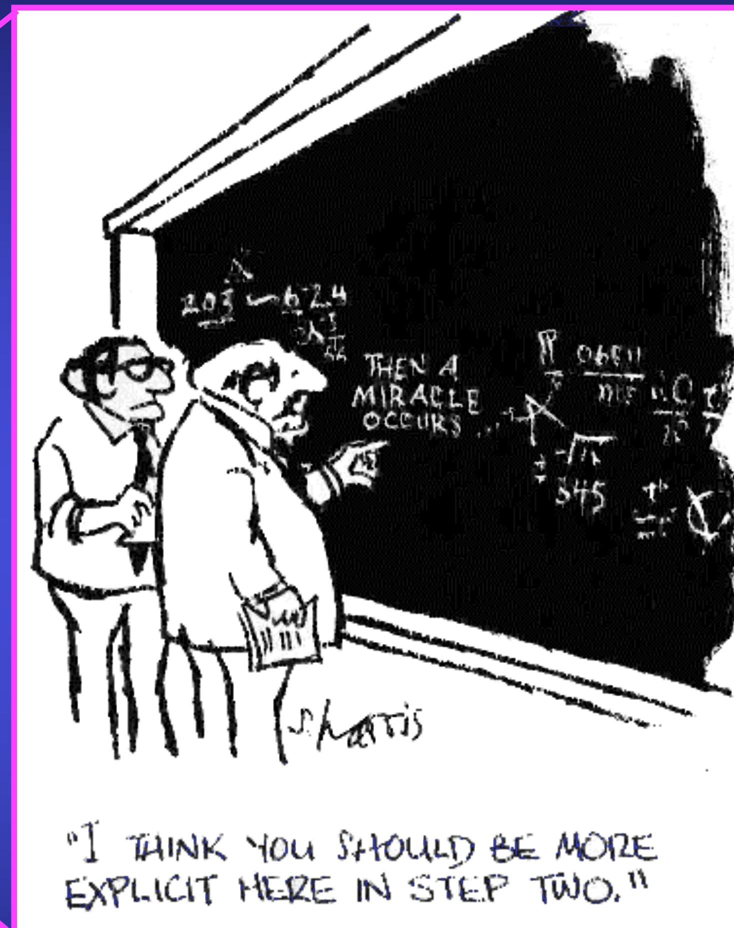
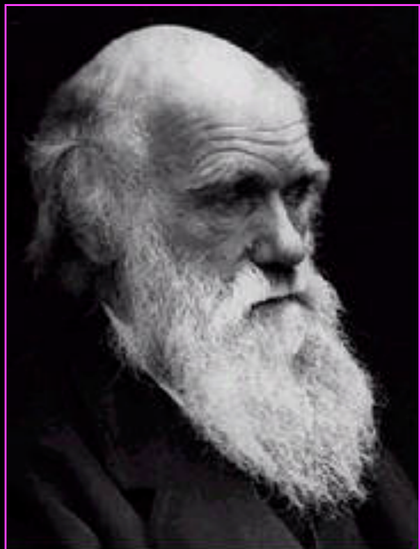
# Origin of life: The grand scheme

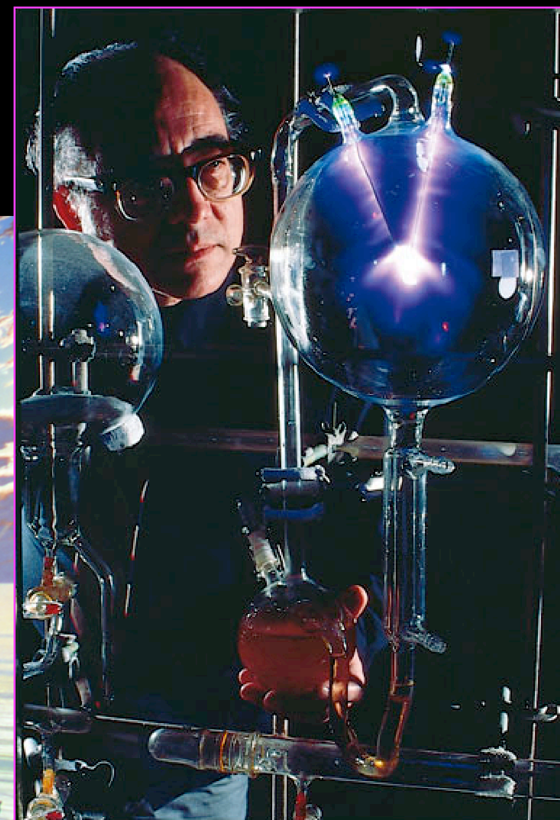



Darwinian evolution
molecular evolution
chemical evolution
cells, replication
protocells, protometabolism
prebiotic chemistry
atmosphere hydrosphere geosphere


THEN A MIRACLE OCCURS
S. Harris
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

# The origin of life:
# A primordial soup in a "warm little pond"?





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# The origin of life:
# … or maybe in a hydrothermal system?

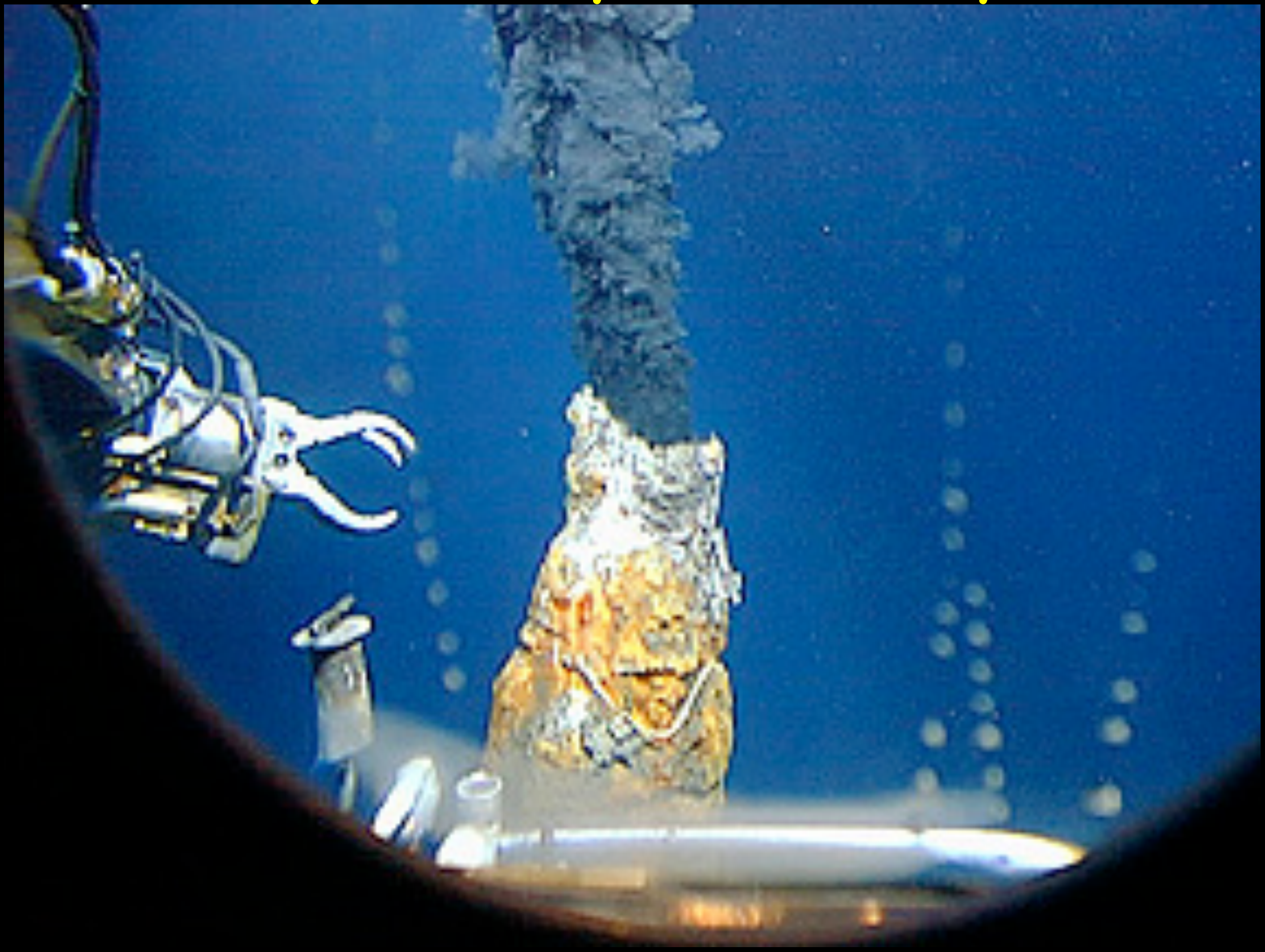


Photo by Patrick Hickey

# A basic dichotomy in theories of the origin of life:

***Heterotrophic origin*** – first organisms consumed organic compounds present in their milieu (the "primordial soup)

***Autotrophic origin*** – first organisms derived energy from chemical reactions and produced their own biomass

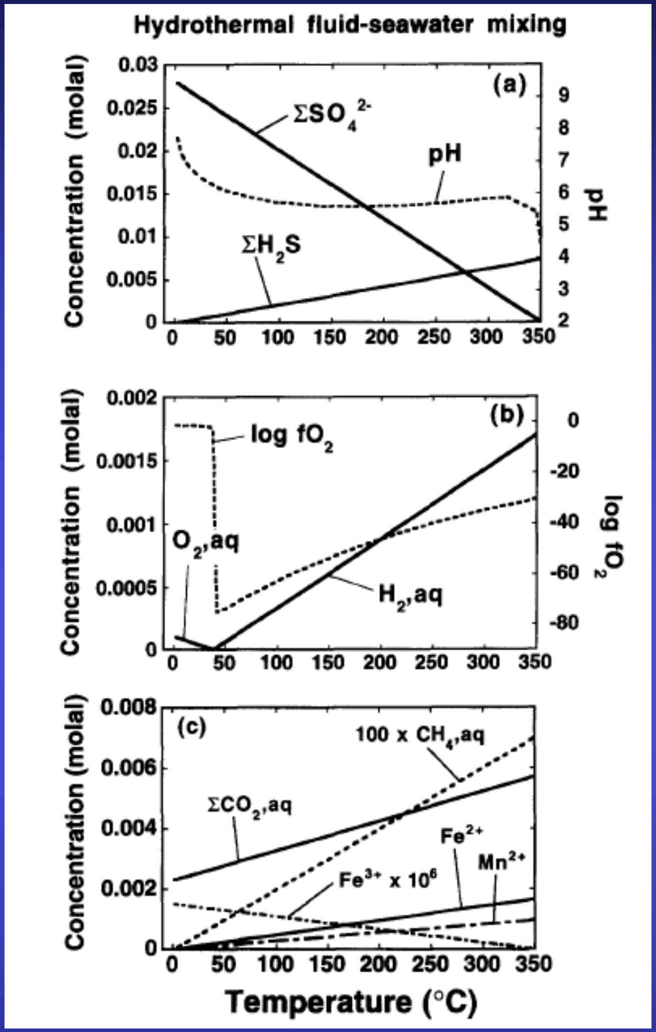
Many features of hydrothermal systems would have been conducive to the origin & early evolution of life:

- Chemical & temperature gradients favorable for chemical evolution
- Conditions favorable for abiotic synthesis of prebiotic organic compounds
- Mineral surfaces promote organic synthesis & chemical evolution

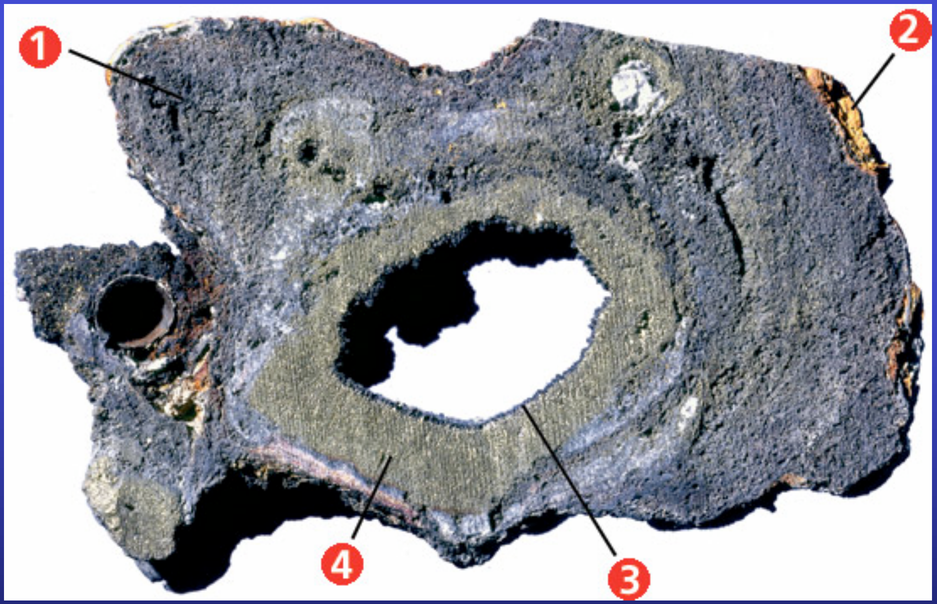
## Hydrothermal systems create steep chemical and physical gradients and chemical disequilibria

- favorable environments for chemical reactions (particularly oxidation-reduction reactions)
- provides sources of chemical energy for metabolism

# Example: mixing of hydrothermal fluids with seawater at a deep-sea hydrothermal vent chimney

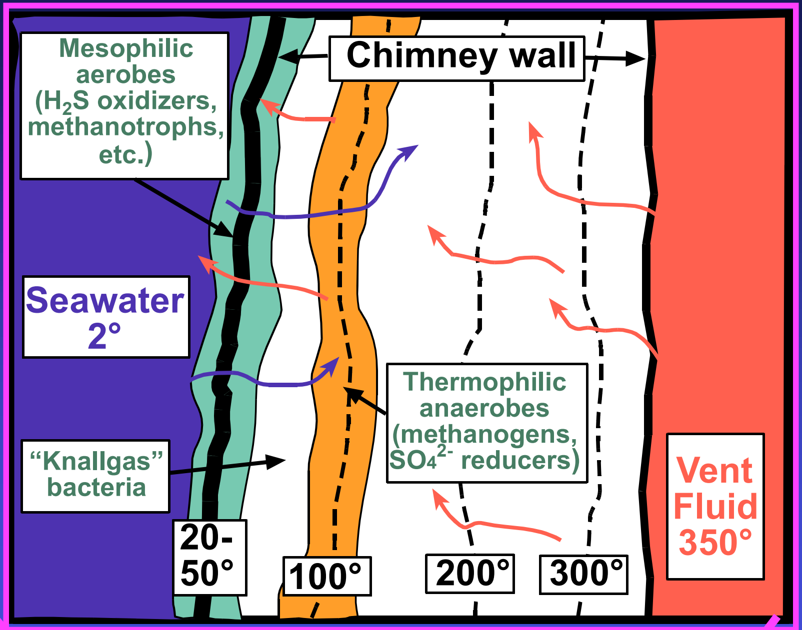



Modeled fluid composition for mixing of hydrothermal fluid & seawater across chimney

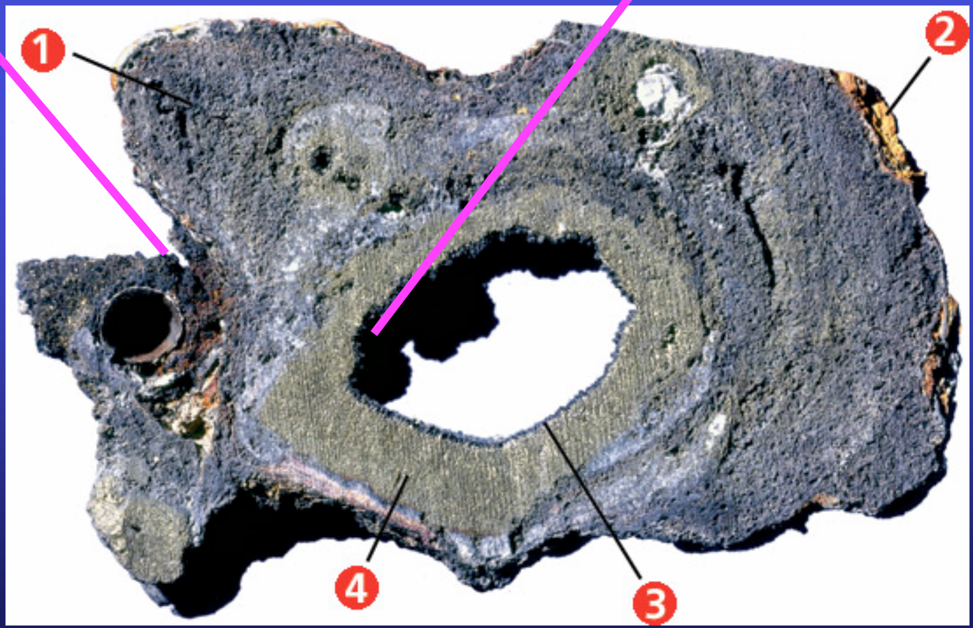



Cross section of deep-sea hydrothermal chimney

(Cross-section image courtesy Meg Tivey, Woods Hole Oceanographic Inst.)




Chemical & thermal gradients provide a variety of chemical energy sources leading to multiple microbial niches in chimney walls



Chemically reducing conditions in hydrothermal environments conducive to conversion of inorganic compounds (or simple organics) to prebiotic organic compounds:

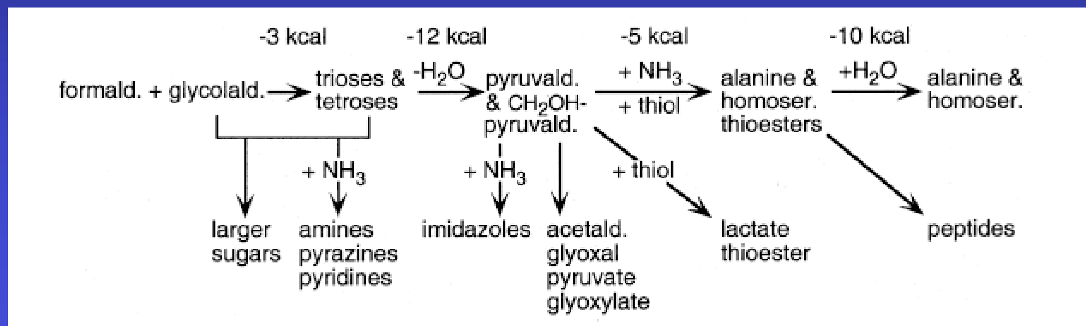
$$CO_2 + H_2 + NH_4^{+} + H_2S + HPO_4^{-2}$$

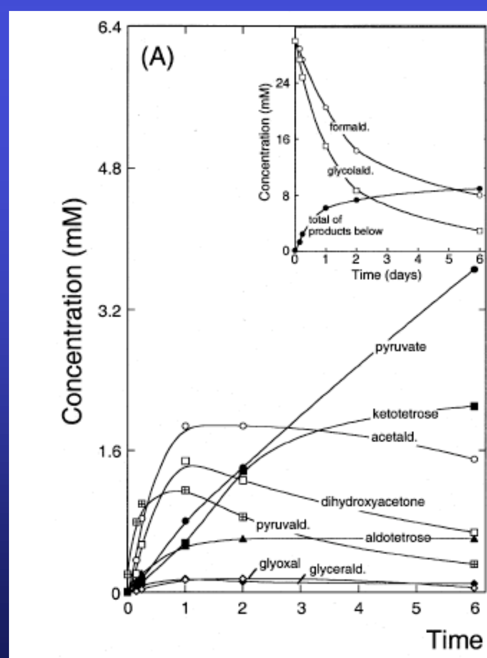
$$\downarrow$$

Lipids, amino acids, sugars, nucleotides(?), etc.

# E.g., formation of simple sugars and amino acids from formaldehyde

## (Weber, Origins of Life & evolution of the Biosphere, 2001)




82 ARTHUR L. WEBER

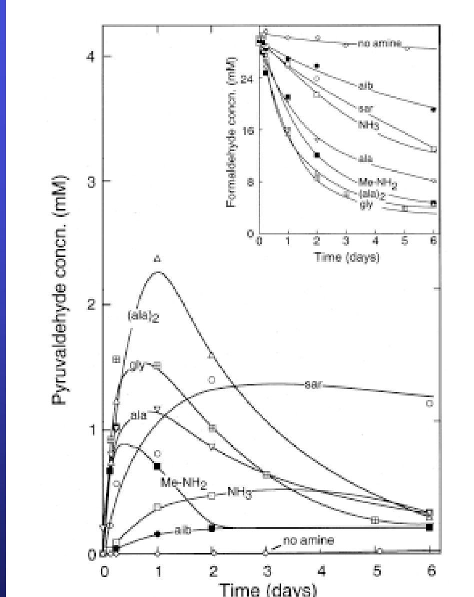
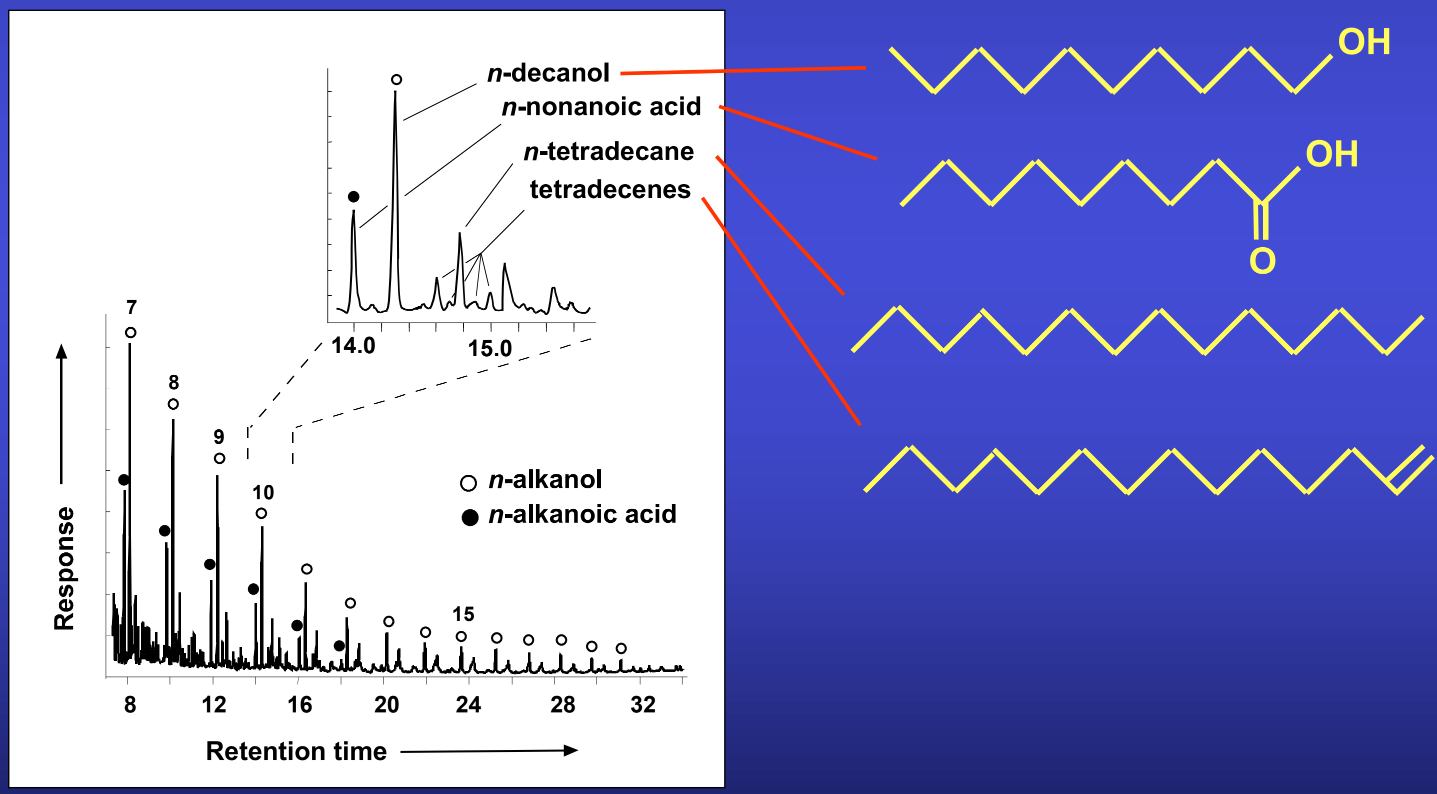



*Figure 3.* Time course of the amine-catalyzed formation of pyruvaldehyde from 30 mM formaldehyde and 30 mM glycolaldehyde in 200 mM sodium acetate (pH 5.5) in the dark under anaerobic conditions at 50°C. The reactions used 15 mM $\alpha$-aminoisobutyric acid (aib), sarcosine (sar), ammonia ($NH_3$), alanine (ala), methylamine ($Me-NH_2$), alanylalanine $(ala)_2$, and glycine (gly). The plot inserted in the upper right of the figure shows the formaldehyde and glycolaldehyde concentrations during the reaction.

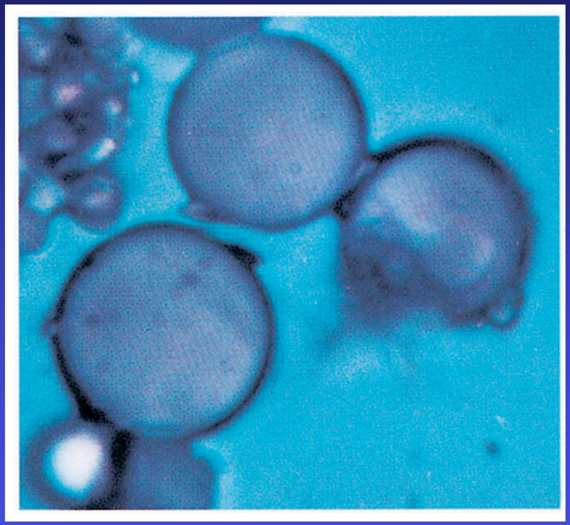
# E.g., lipid synthesis under hydrothermal conditions

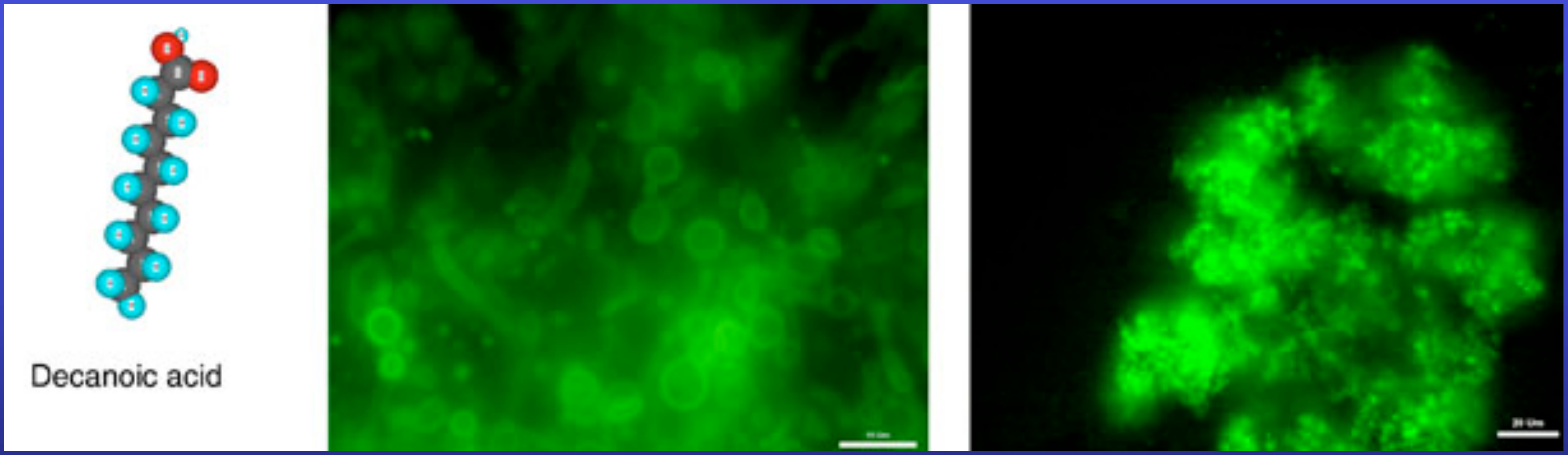
Fischer-Tropsch reaction products
(Formic acid in $H_2O$, 72 hours @ 175°C)




(McCollom et al., 1999)

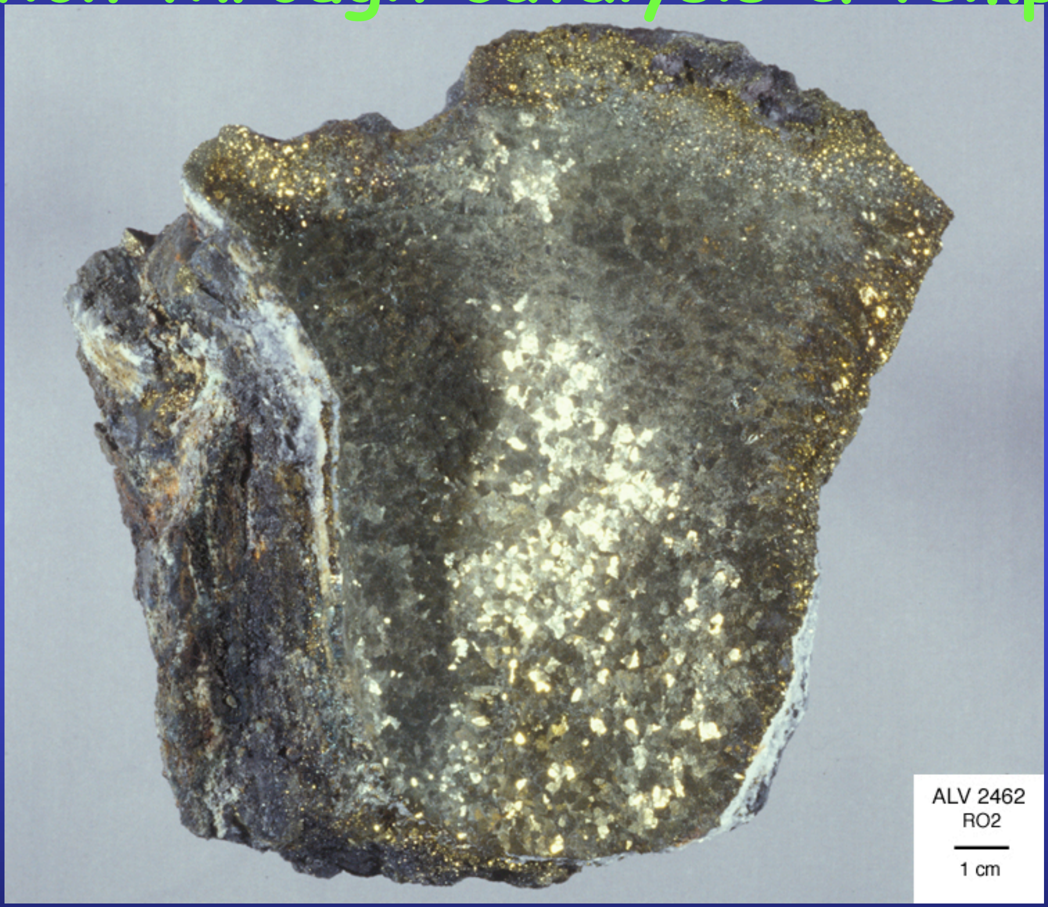
Lipids spontaneously form micelles (lipid-bound cells) during cooling of hydrothermal solutions:
The first cellular membrane??





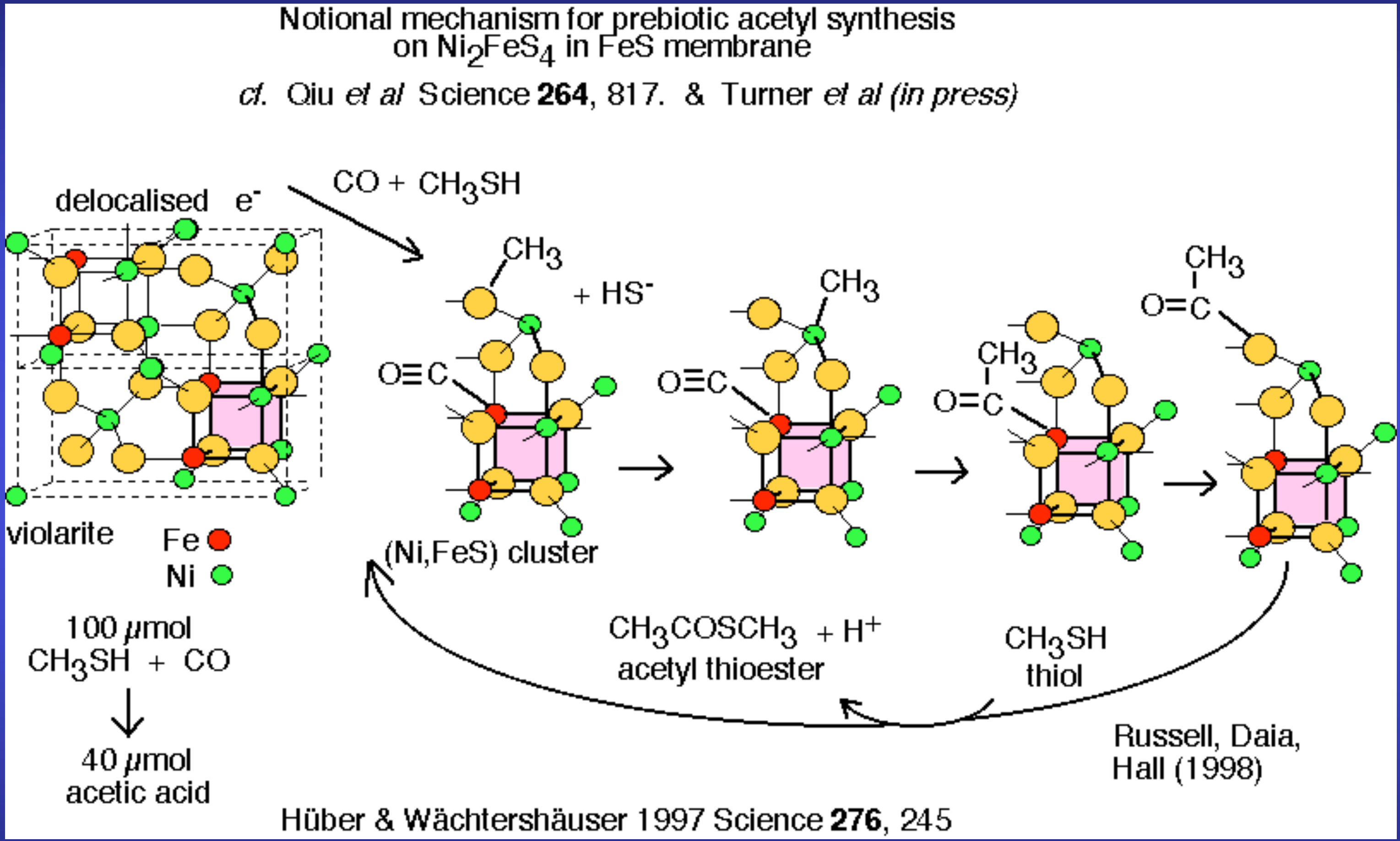

(Monnard et al. Astrobiology, 2004;
http://www.chemistry.ucsc.edu/deamer_d.html)

# Minerals precipitated from hydrothermal solutions (sulfides, clays) promote chemical evolution through catalysis & templating



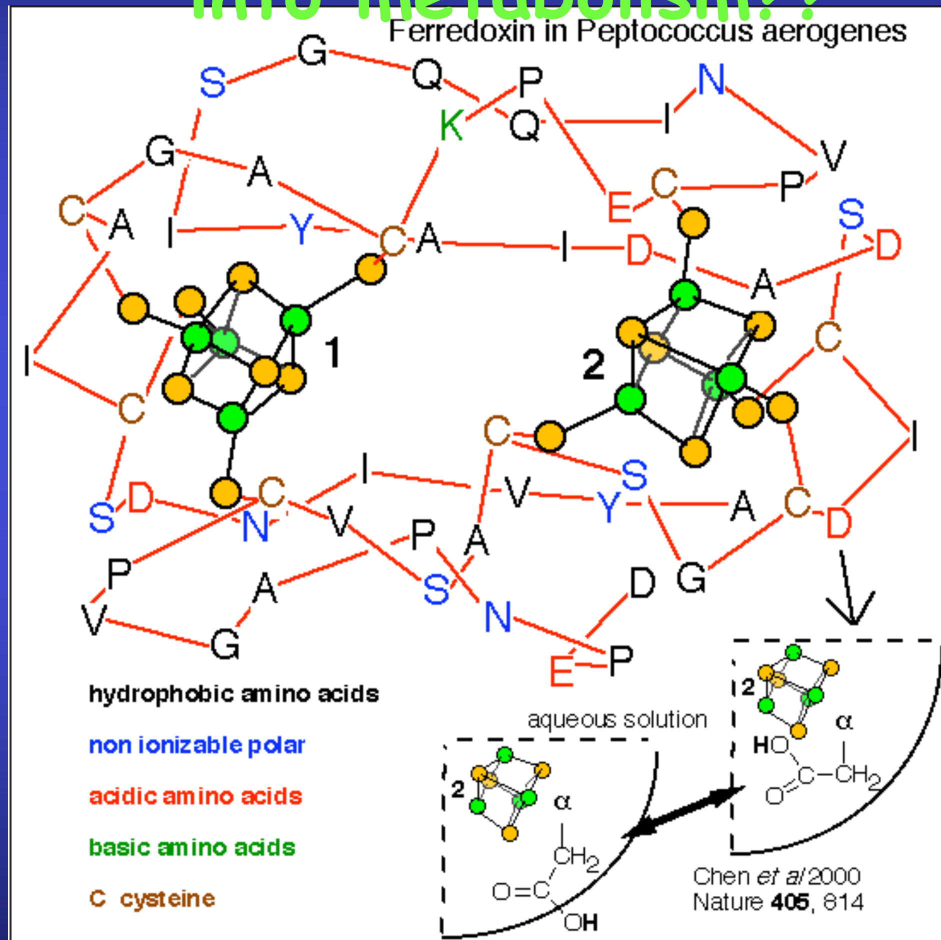

(image courtesy Meg Tivey, Woods Hole Oceanographic Institution)

# E.g., sulfide mineral catalysis of acetic acid:



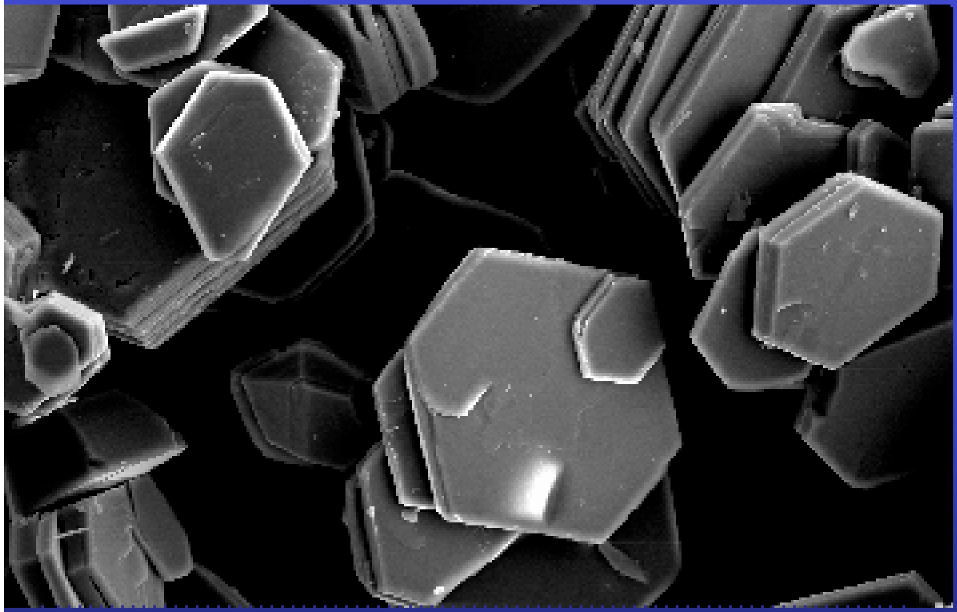

(image courtesy Mike Russell;
http://www.gla.ac.uk/projects/originoflife/)

# Transition from prebiotic chemistry to early life: did mineral-catalyzed processes transform into metabolism??




(image courtesy Mike Russell; http://www.gla.ac.uk/projects/originoflife/)

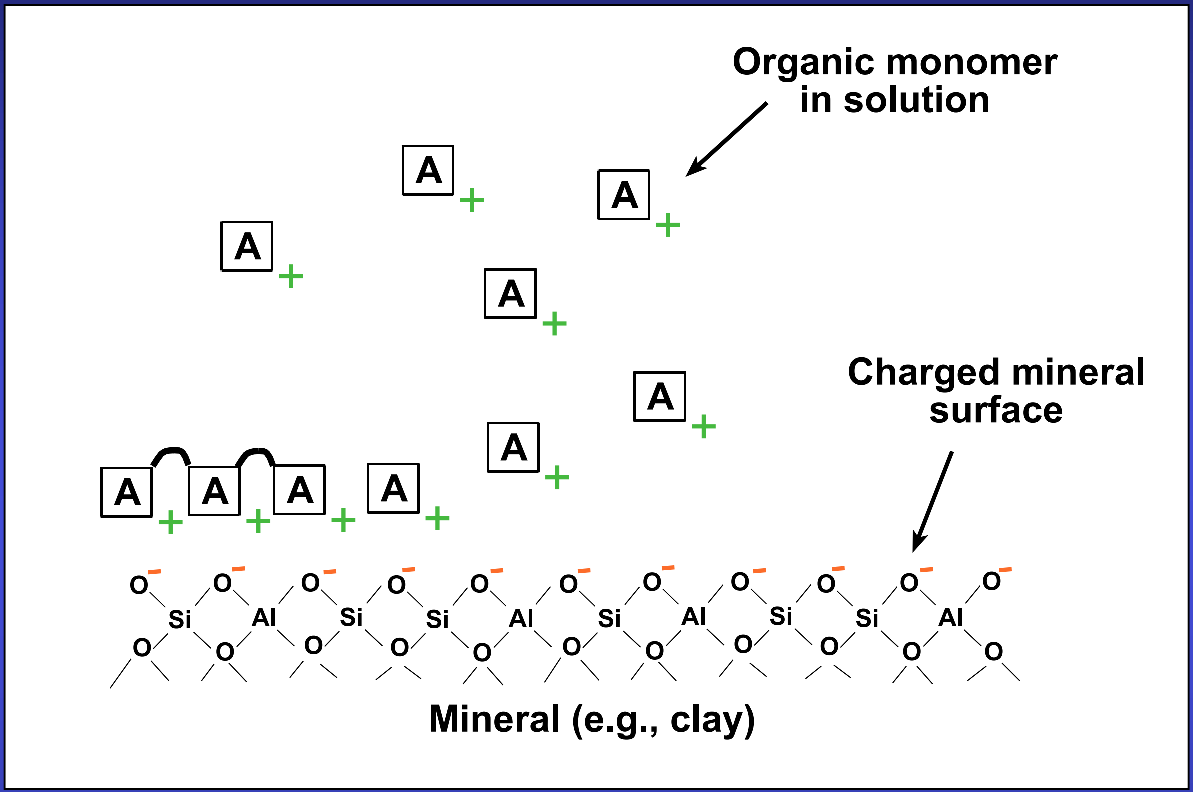
# Minerals may have also served as templates for formation of polymers (peptides, nucleic acids) on the prebiotic Earth



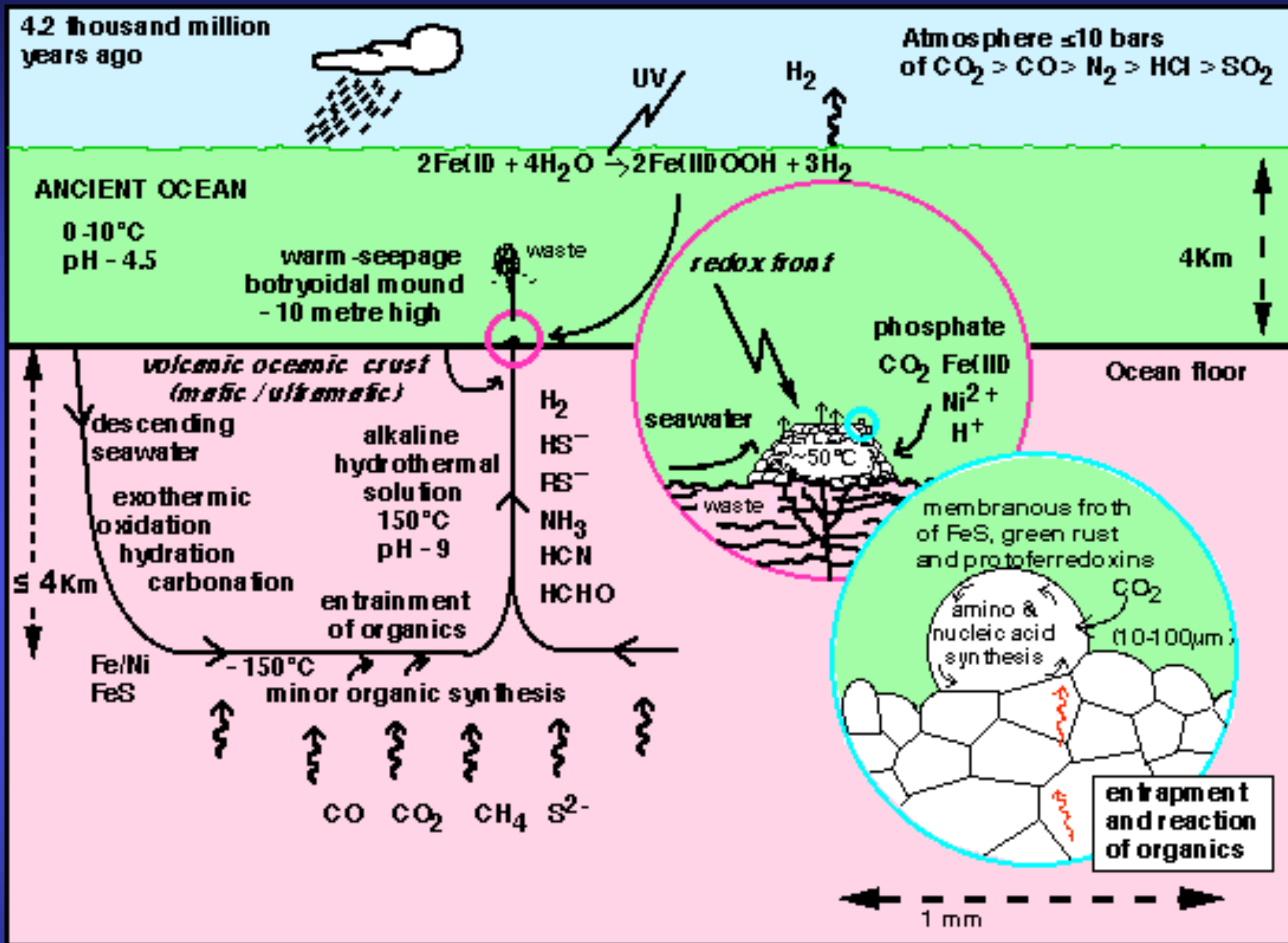
clay (microscopic image)

Pyrite (iron sulfide)

# Minerals surfaces as templates:




Monomers in solution (amino acids, nucleotides) adhere to charged surface and polymerize, possibly forming precursors to proteins and RNA




(image courtesy Mike Russell;
http://www.gla.ac.uk/projects/originoflife/)

# The early Earth

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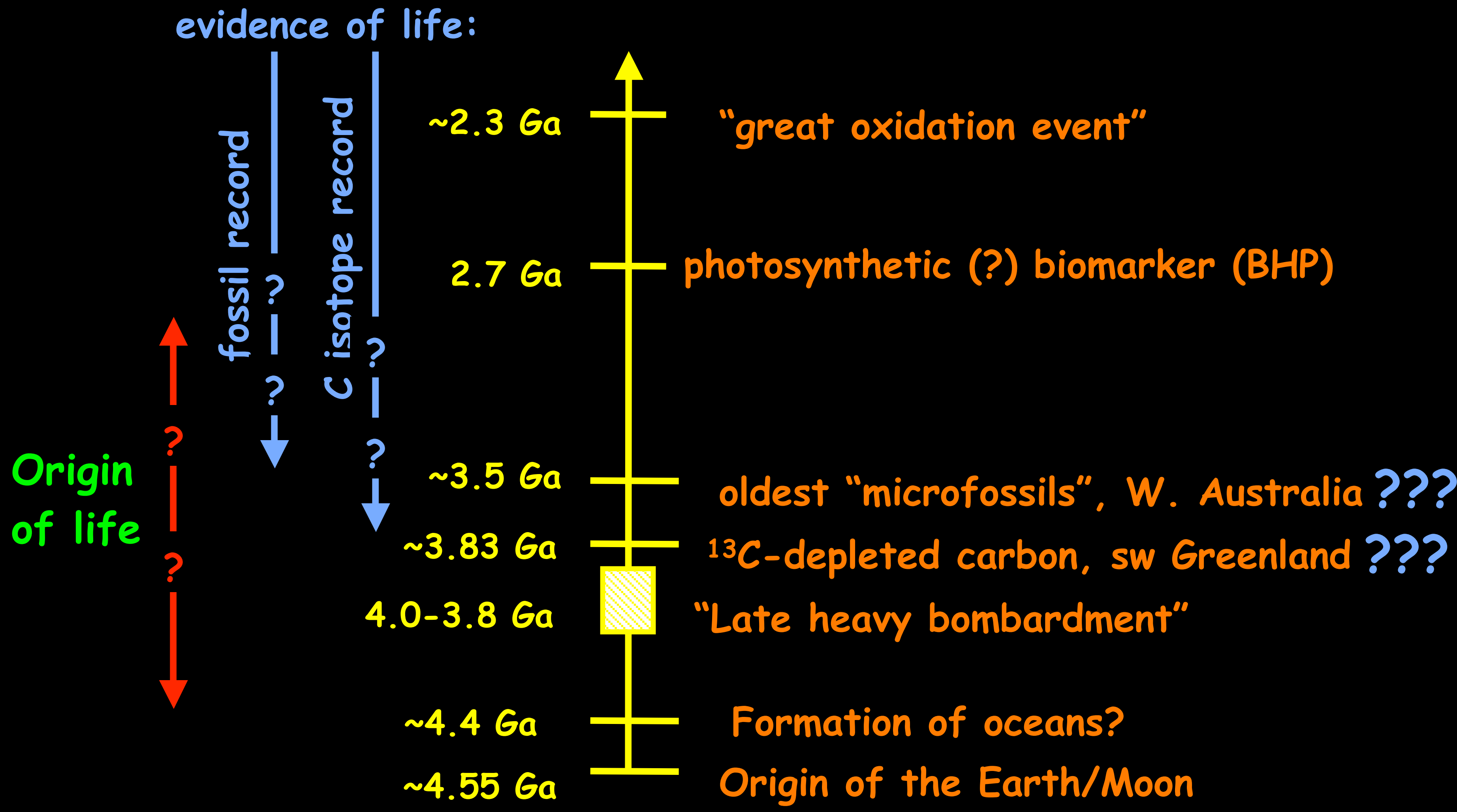
Oldest rocks on Earth <4 billion years old

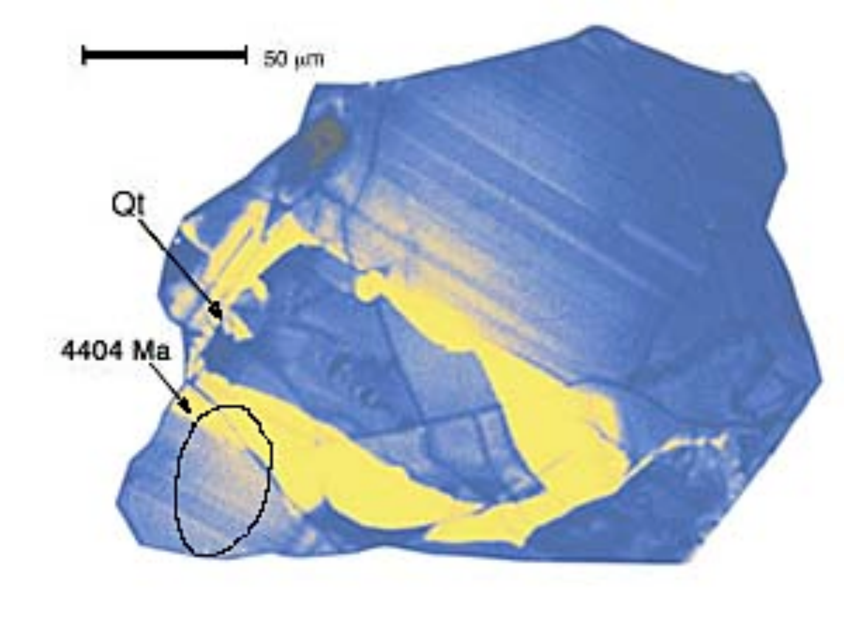
$\Rightarrow\Rightarrow$ *(almost) no geologic record of the very Earth!!*

# *Timeline of the early Earth*



Oldest rocks on Earth <4 billion years old. *But…* older zircon minerals in younger rocks provide some information on the first 500 million years.

Occurrence and isotopic composition of oldest zircons indicates continents and oceans were present within a ~150 million years after Earth




(from website of Dr. John Valley, Univ. of Wisconsin)

# What can we infer about hydrothermal environments on the very early Earth?

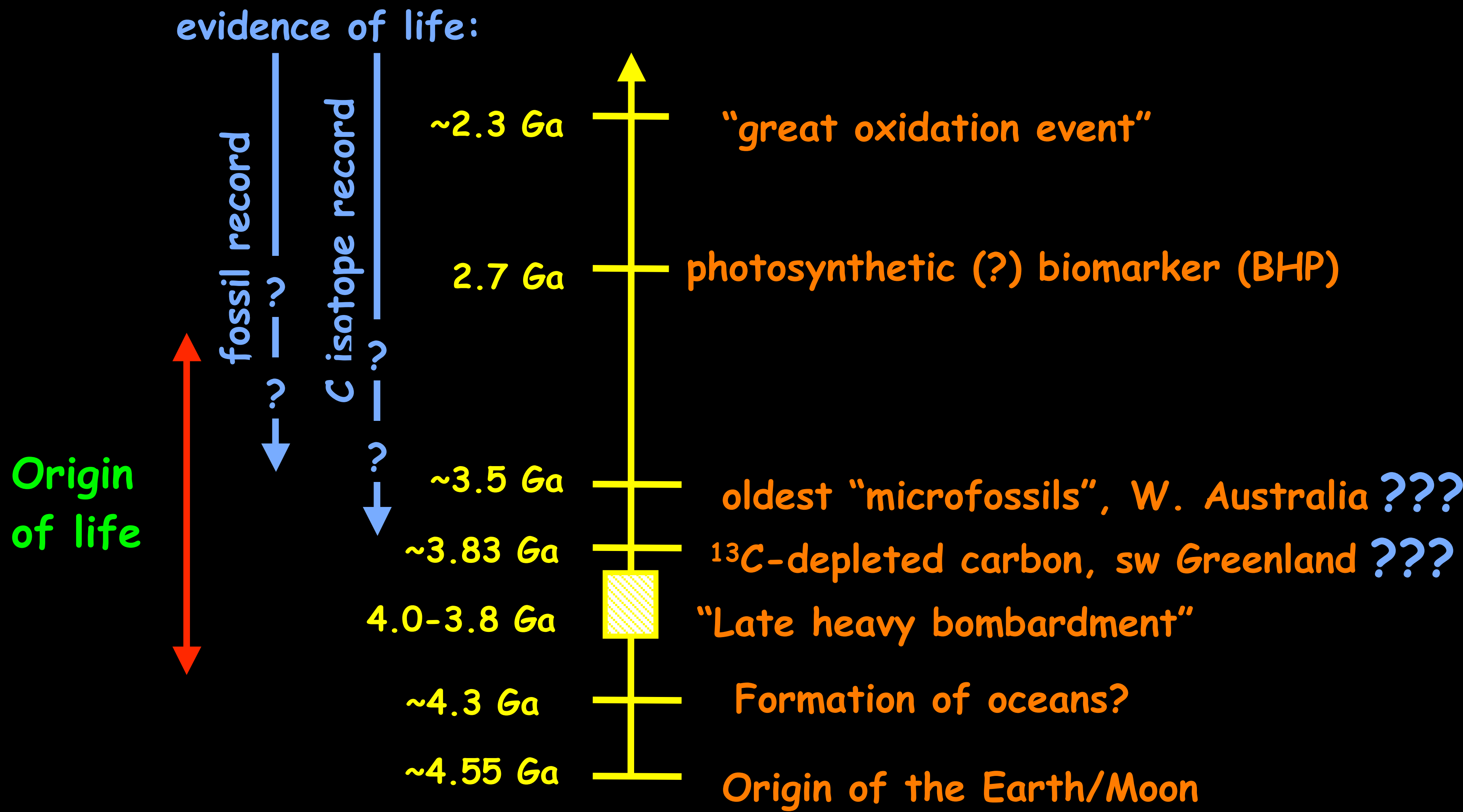
- Heat flow much greater, therefore hydrothermal environments were likely much more abundant (both submarine and continental)
- Atmosphere/oceans much less oxidizing
  ⇒ electron acceptors for metabolic energy sources much *less* abundant
- Chemically reducing volcanic rocks more prevalent
  ⇒ electron donors for metabolic energy sources much *more* abundant

# Peridotite-hosted hydrothermal systems were more prevalent on the early Earth

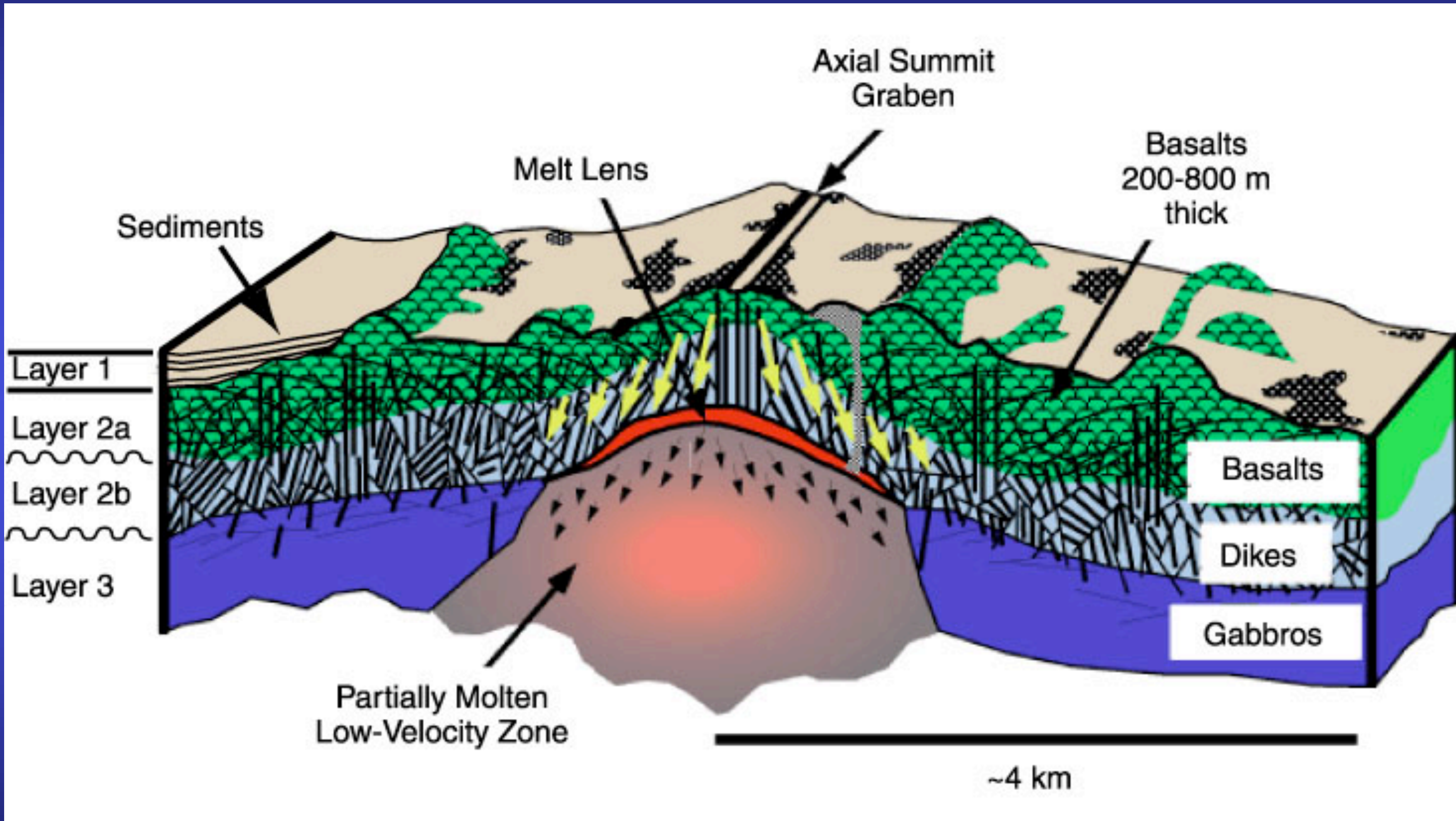
Produce alkaline fluids highly enriched in $H_2$ and methane.

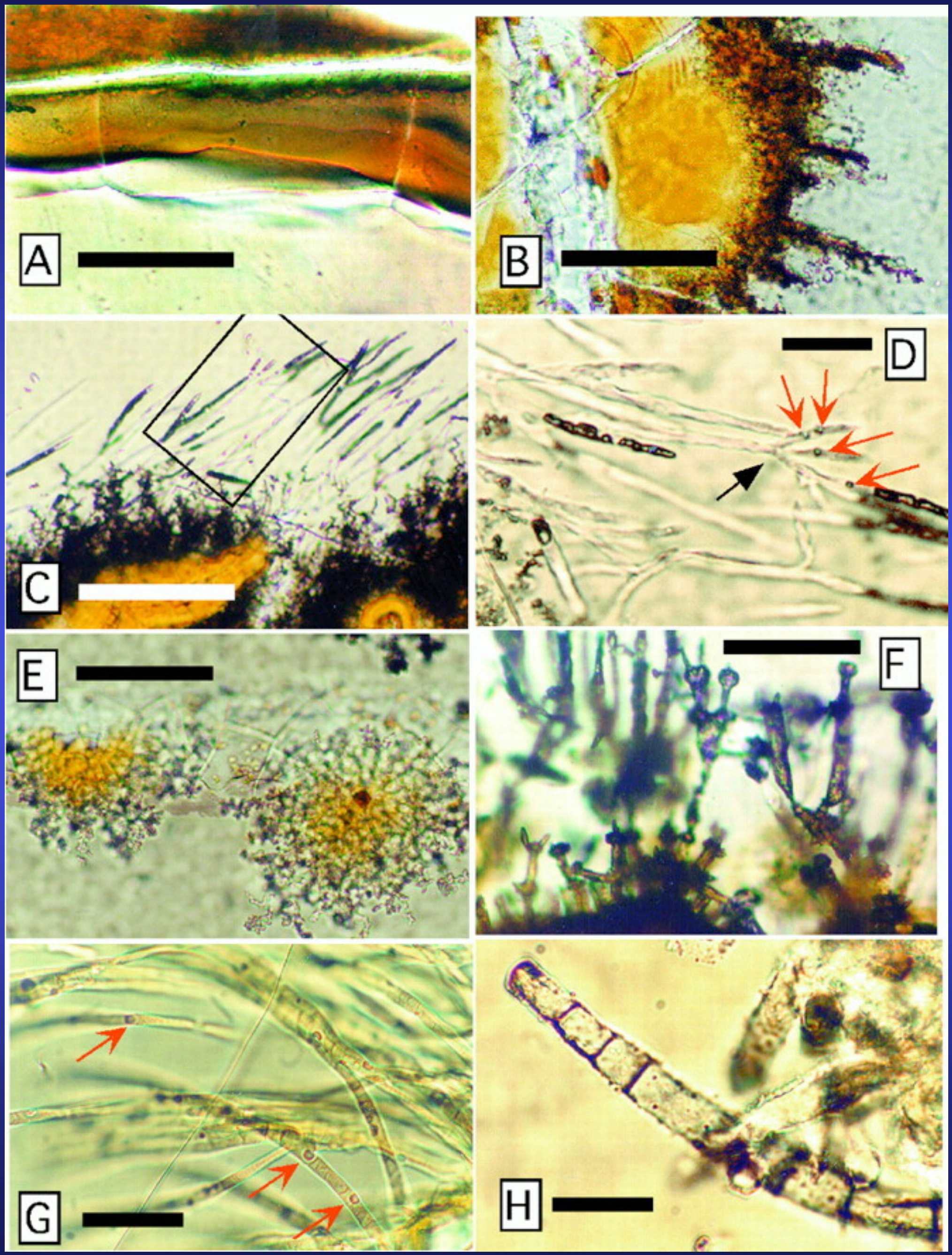
Chimney structures from Lost City, a modern peridotite-hosted system (Kelley et al., Science, 2005)

# Timeline of the early Earth



# Cross-section of the ocean crust at mid-ocean ridge

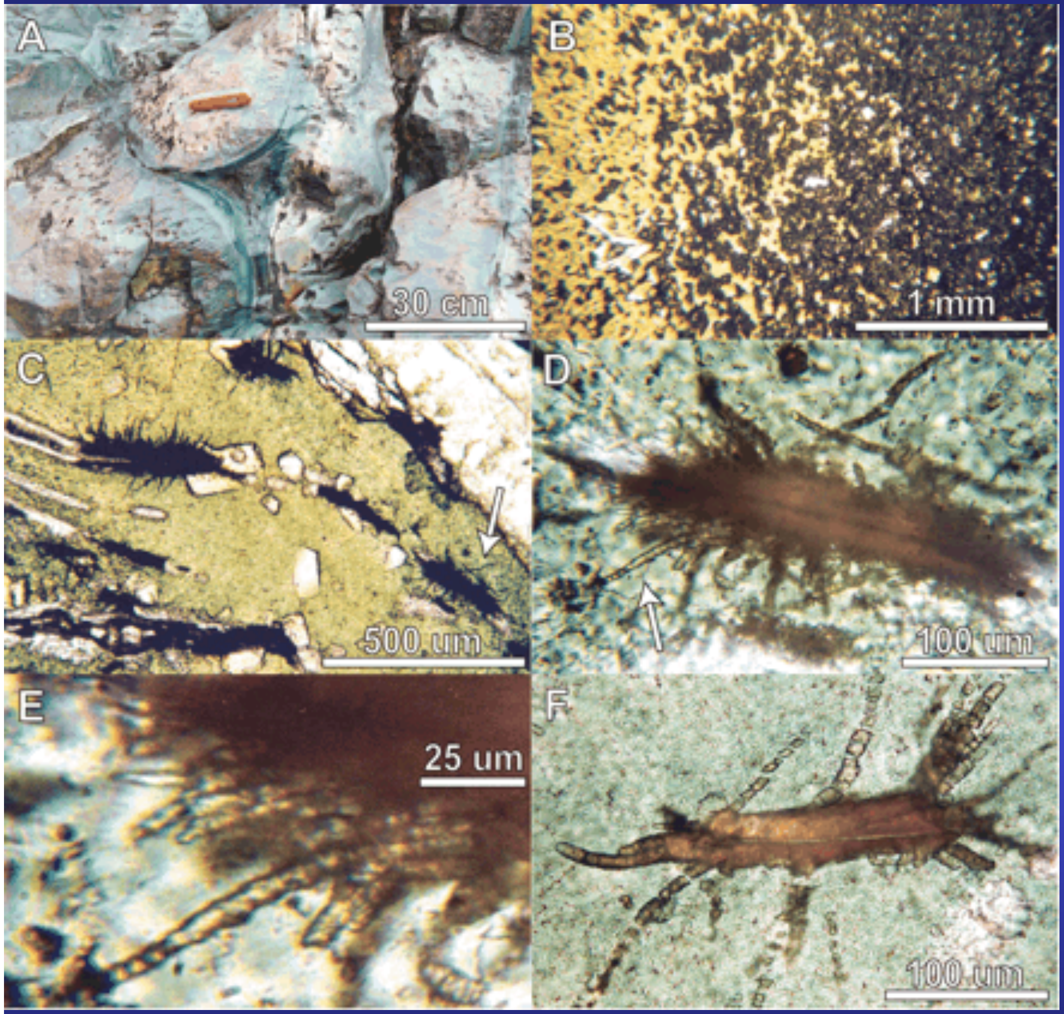





## Subsurface life in the ocean crust

**Morphological & chemical evidence for active microorganisms 100's of meters beneath seafloor**

(Fisk et al., *Science*, 1998)




Microbial(?) textures in ~3.5 billion year old rocks,
Barberton Greenstone Belt

(Furnes et al., *Science*, 2004)

Chemolithoautotrophic iron-oxidizing bacteria growing on the mineral pyrite as an energy source (also grows very well on basalt)