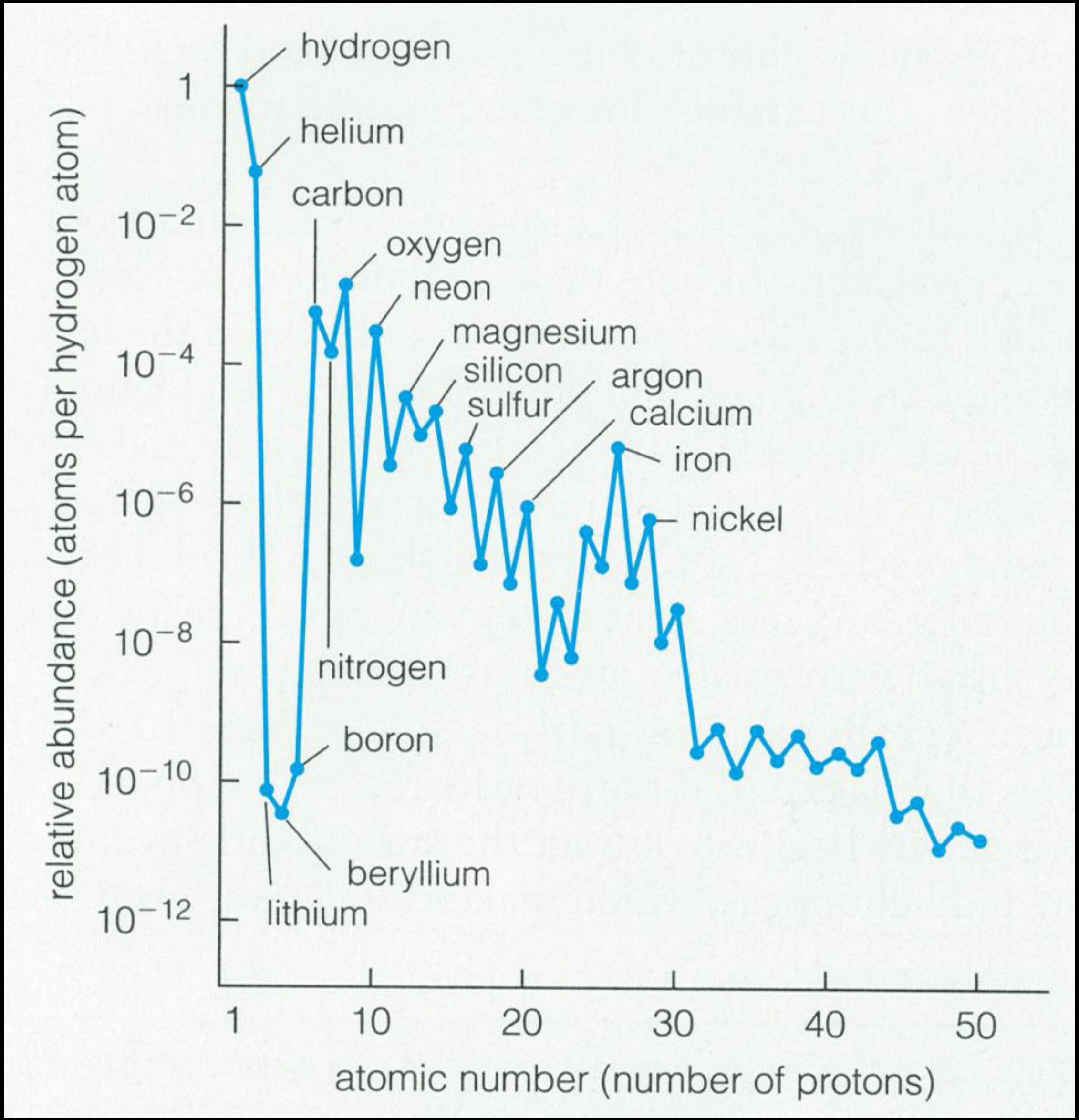
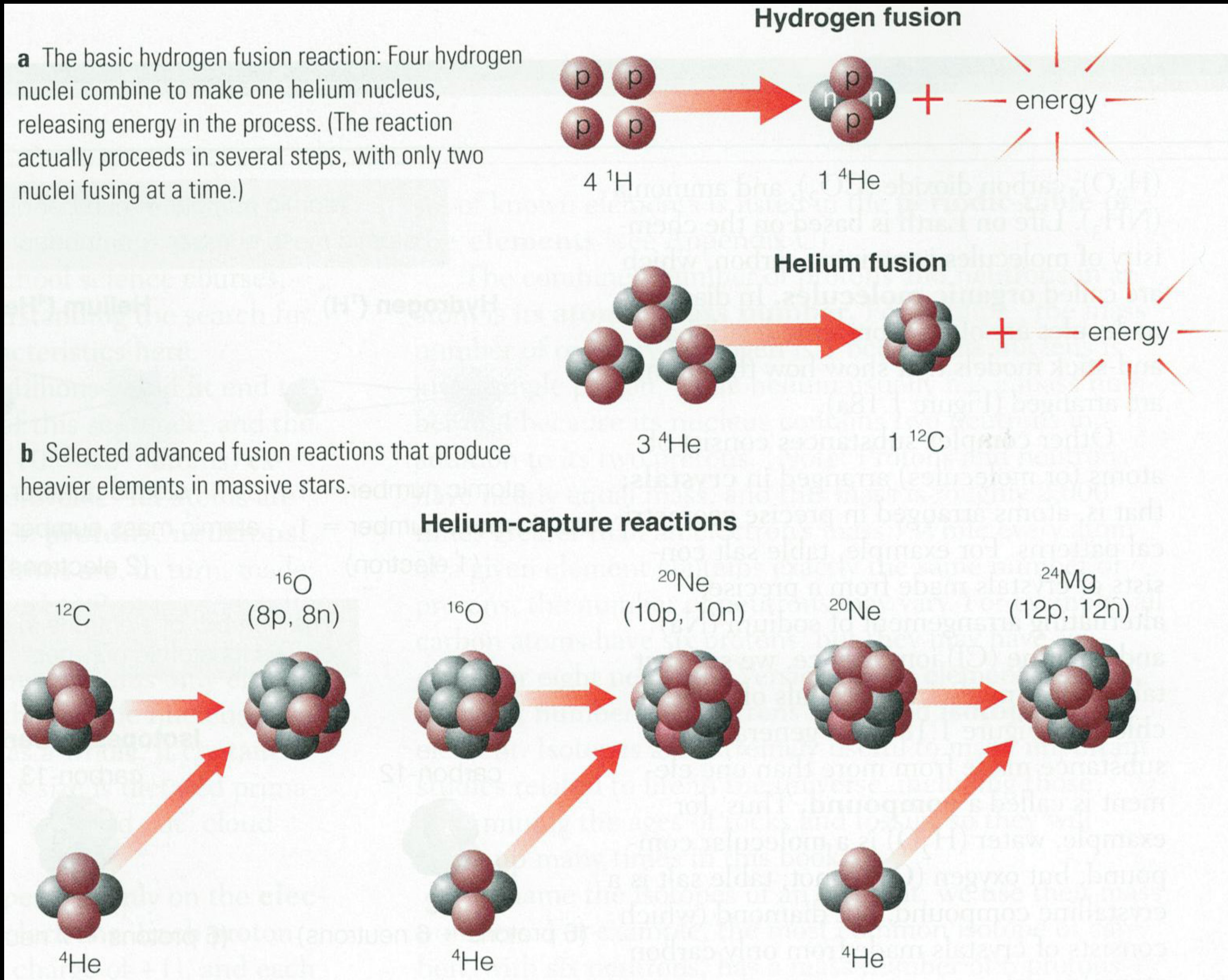
Origins and Evolution of Early Life

- Formation of organic molecules
  - Can occur spontaneously.
- Polymerization to form macromolecules
  - Minerals may have acted as a template
- Protocell formation
  - Can form spontaneously under laboratory conditions.
- Development of a hereditary mechanism
  - RNA as both enzyme and genetic material.

Abundance of atoms in the Universe: We are all made of star-stuff



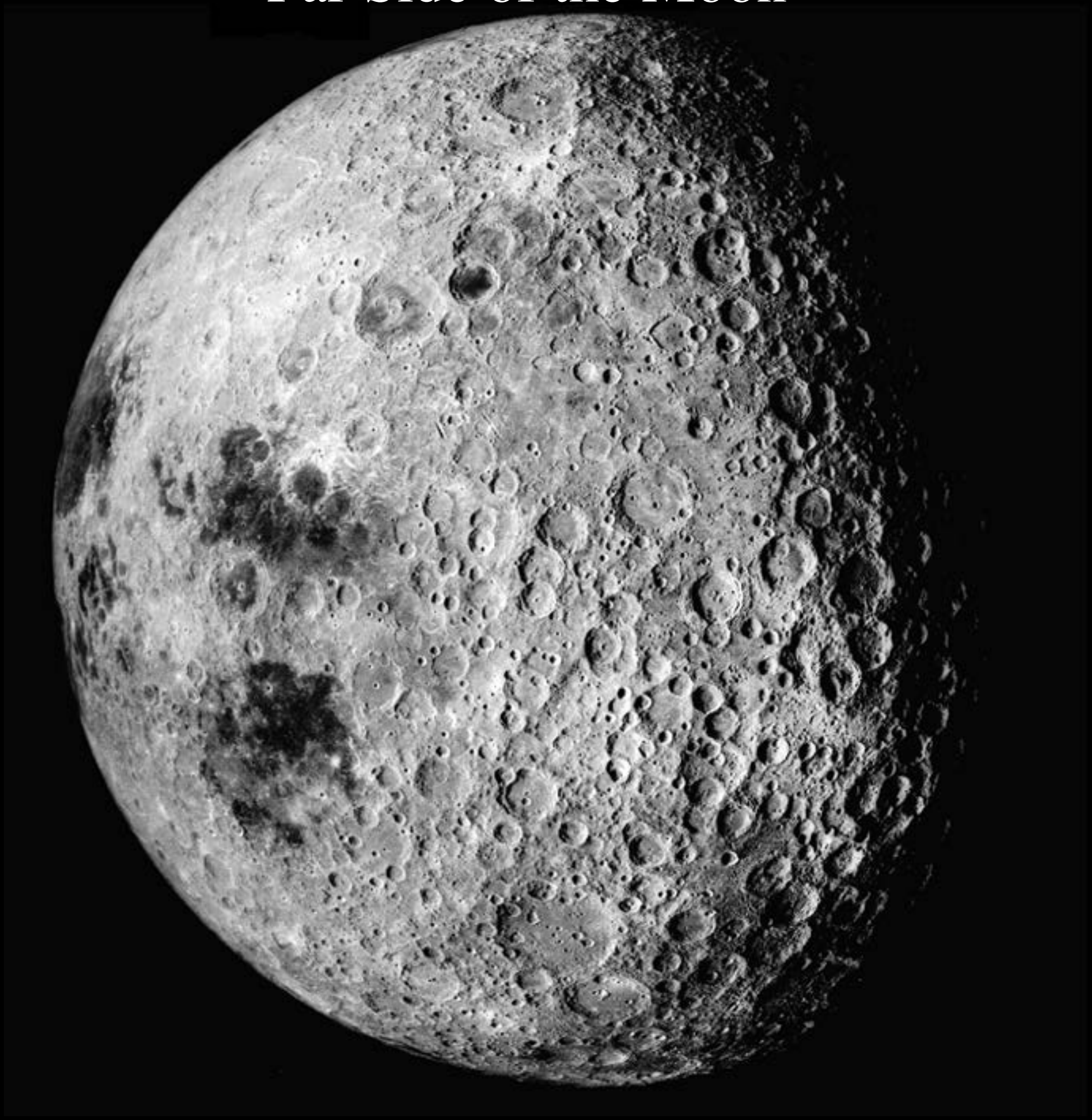


a The basic hydrogen fusion reaction: Four hydrogen nuclei combine to make one helium nucleus, releasing energy in the process. (The reaction actually proceeds in several steps, with only two nuclei fusing at a time.)
Hydrogen fusion
p p p p
p n n p
+ energy
4 ¹H
1 ⁴He
Helium fusion
+ energy
3 ⁴He
1 ¹²C
b Selected advanced fusion reactions that produce heavier elements in massive stars.
Helium-capture reactions
¹²C
¹⁶O (8p, 8n)
¹⁶O
²⁰Ne (10p, 10n)
²⁰Ne
²⁴Mg (12p, 12n)
⁴He
⁴He
⁴He

$E=mc^2$

Did the building blocks of life come from space?

Far Side of the Moon



Confirms Heavy Bombardment

Where did the building blocks of life come from?

From asteroids?

Establishing a molecular relationship between chondritic and cometary organic solids

George D. Cody[a,1], Emily Heying[a], Conel M. O. Alexander[b], Larry R. Nittler[b], A. L. David Kilcoyne[c], Scott A. Sandford[d], and Rhonda M. Stroud[e]

[a]Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington, DC 20015; [b]Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington, DC 20015; [c]Advanced Light Source, Lawrence Berkeley Laboratory, Berkeley, CA 94720; [d]Astrophyiscs Branch, Mail Stop 245-6, National Aeronautics and Space Administration Ames Research Center, Moffet Field, CA 94035; and [e]Naval Research Laboratory, Washington, DC 20015

www.pnas.org/cgi/doi/10.1073/pnas.1015913108

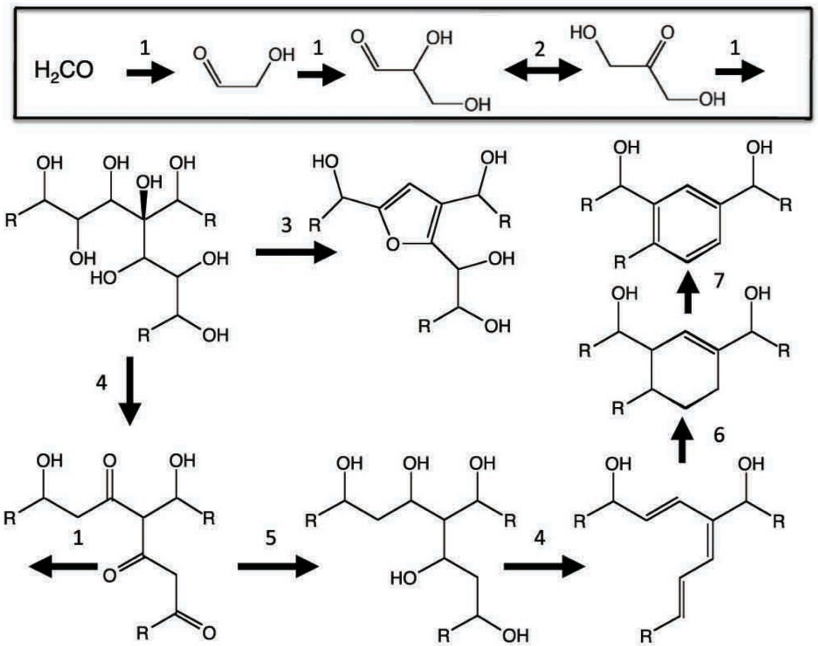


Fig. 3. Schematic representation of reactions that lead from formaldehyde to formaldehyde polymer. Hydrogen atoms bonded to carbon are excluded for clarity. Single and double bonds are designated with single and double lines, respectively. Formaldehyde condenses with itself (reaction 1) to form glycoaldehyde. Sequential Aldol condensations yield polyalcohols. Intramolecular hydride transfer (reaction 2) intraconverts glyceraldehdye to dihydroxy acetone. Aldol condensation (reaction 1) with dihydroxyacetone lead to branched polyalcohols. Polyalcohols may eliminate H_2O and cyclize forming furan moieties (reaction 3). Dehydration of branched polyalcohol (reaction 4) yields polyketone that may condense further via Aldol condensation (reaction 1) or through successive reduction and elimination reactions (reactions 5 and 4) yield poly-olefin that may undergo either inter- or intramolecular cycloaddition reactions to form cyclohexene moieties via reaction 6. Dehydrogenation (reaction 7) yields highly substituted aromatic moieties.

Space material has lots and lots of formaldehyde and some material (asteroids) has highly substituted aromatic structures

Formose Reaction

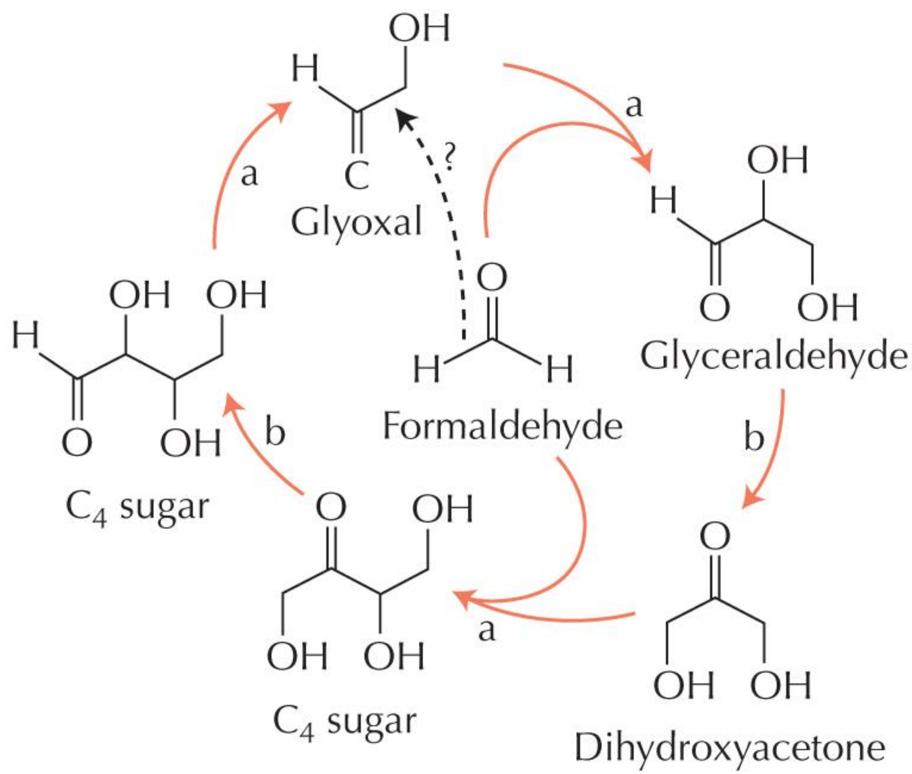
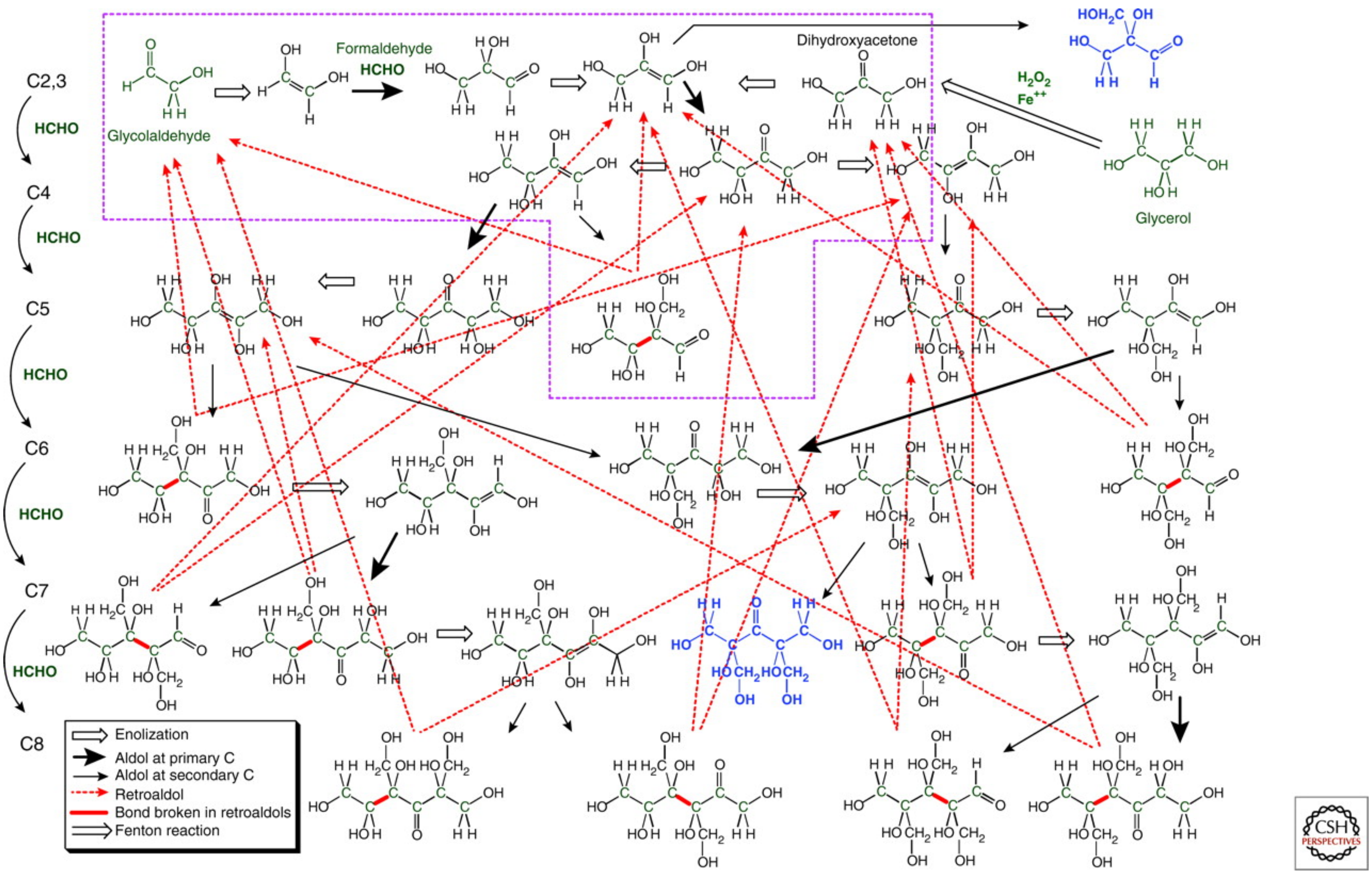


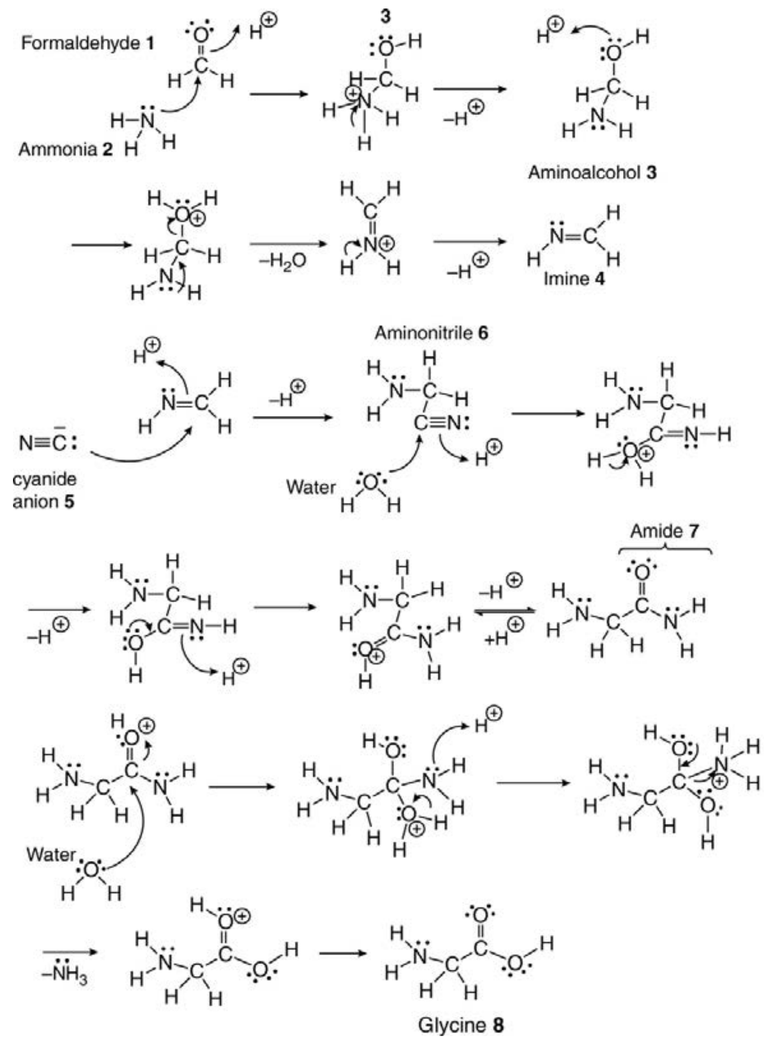
FIGURE 4.7. The chemical pathways that make up the formose reaction. In this reaction, formaldehyde can be polymerized to produce longer-chain sugar molecules. The reaction products (e.g., the C_4 sugar) can be readily converted to ribose. *Arrows* labeled with b represent ketone-alcohol isomerizations. *Arrows* labeled with a represent aldol/retroaldol reactions.

This figure shows the complexity that is possible simply by repeating the two reactions shown in the previous slide.



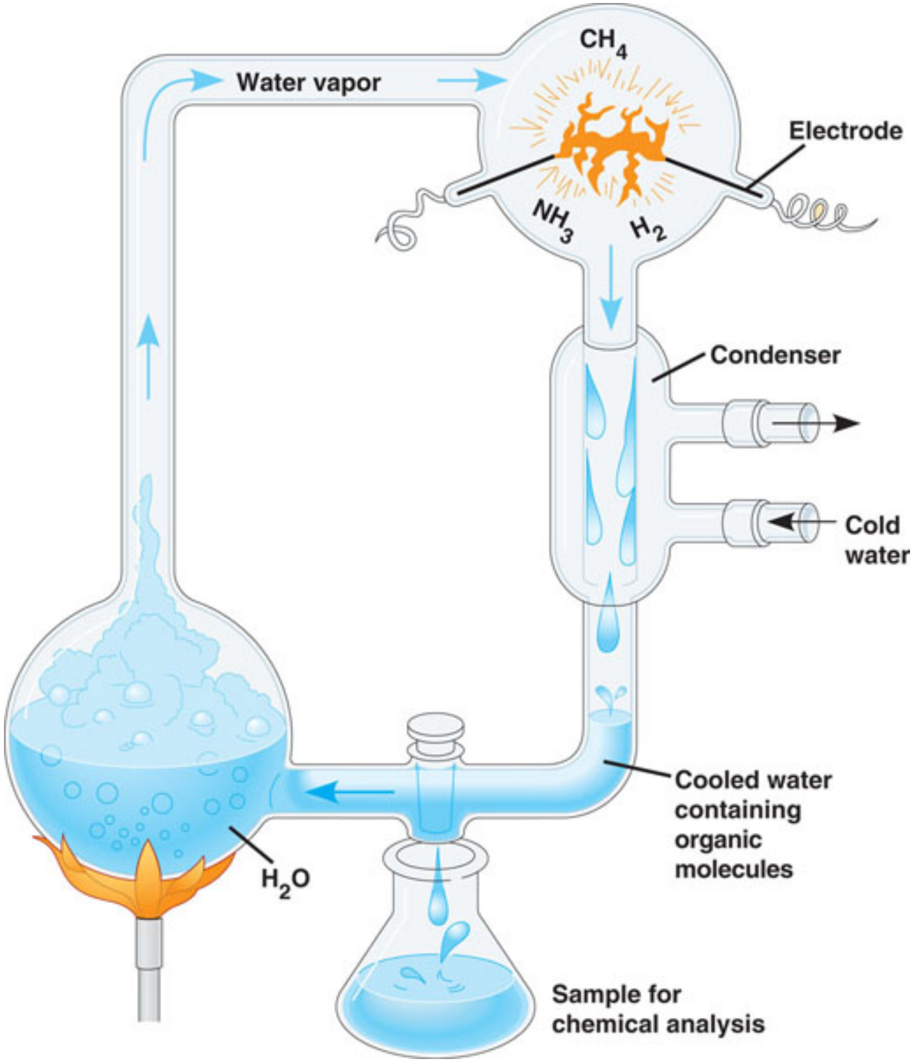
Benner S A et al. Cold Spring Harb Perspect Biol 2010;2:a003467

The Strecker synthesis of glycine, an amino acid.



Benner S A et al. Cold Spring Harb Perspect Biol 2010;2:a003467

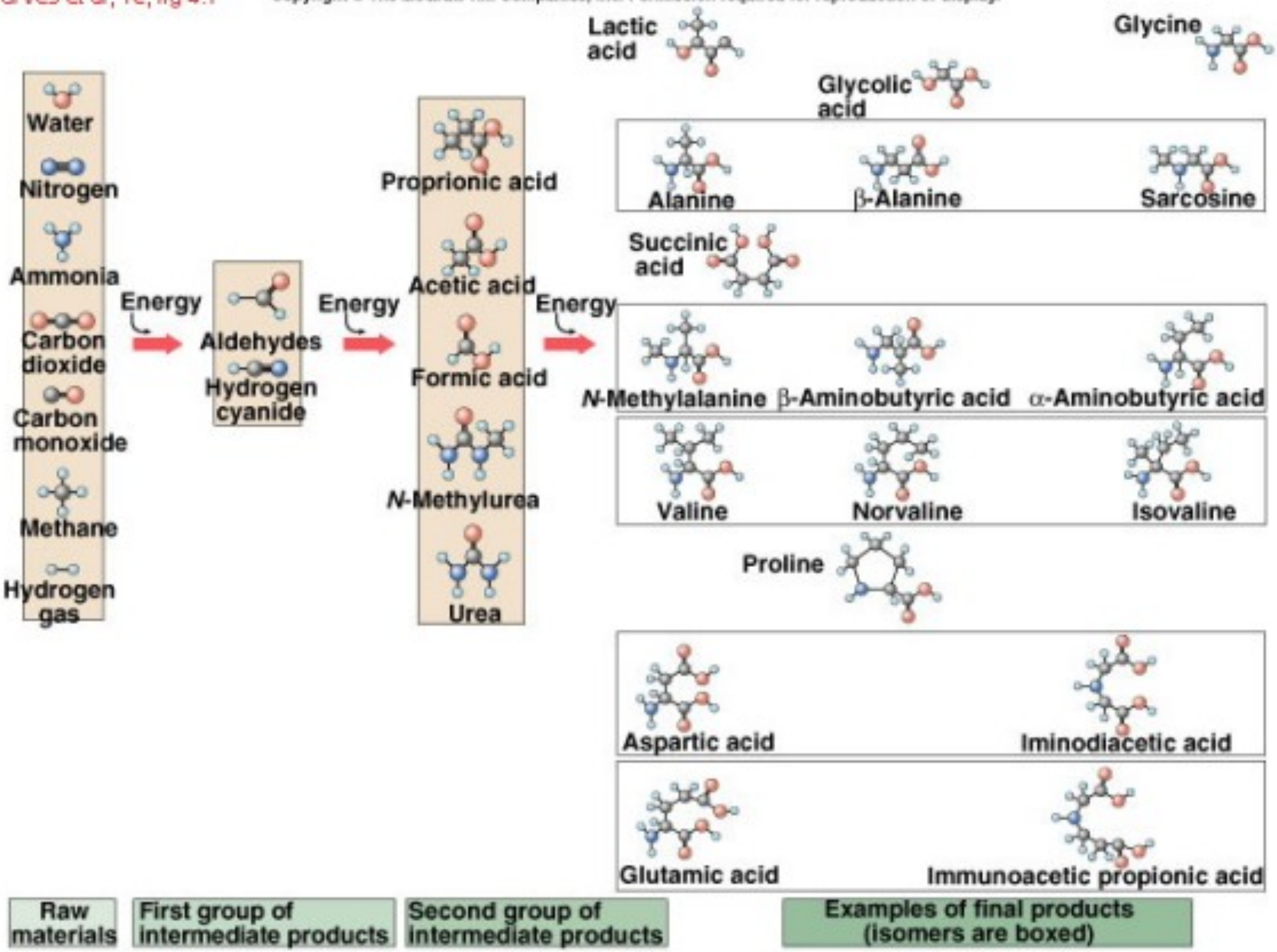
Miller & Urey Experiment

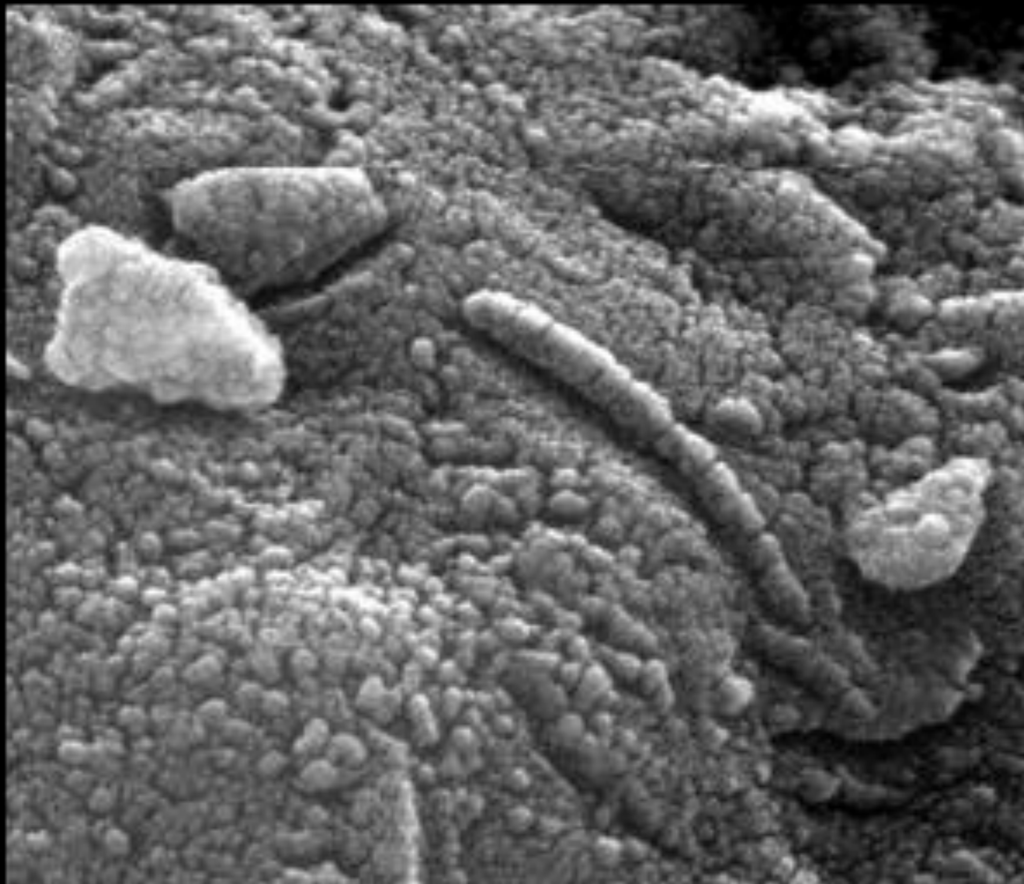


- Simulated early earth with a strongly reducing atmosphere, an ocean, and a hydrologic cycle.
  - Energy inputs via heating & an electrical discharge.
  - Inorganic reactants CH_4, NH_3, and H_2
- Amino acids and other organic molecules formed spontaneously under these conditions.
- The building blocks of living organisms can form spontaneously on short time scales.

Campbell & Reece 7th Edition, Fig. 26.02

Purves et al, 7e, fig 4.7





ALH84001
McKay et al. Science
August 16, 1996

Is this evidence for life on Mars?

President Clinton briefs Nation on ALH84001
August 7, 1996

Structure	Diameter Size
ALH84001	~50 nm
E. coli	660-990 nm
Ancient life?	~500 nm
Nanoarchaeum	400 nm
Mycoplasma	200-300 nm
Nanobes (controversial)	20 nm
Viruses	10-100 nm
Cell membrane	8 nm
Ribosome	15-30 nm
Average Protein	5 nm
Double-helix	2 nm

Size limits of cells having modern biochemical complexity

Mycoplasma: smallest genome of “free-living” organism (parasite)
482 genes: only 382 are essential
[Glass et al. PNAS, 2006]

Assuming this many genes + 10 copies of each protein + 1 ribosome + 1 tRNA set, + 1 mRNA/gene = ~270 nm

1000 copies of each protein = 300 nm

Doubling time would be extremely long, as average cell has between 3,000 and 30,000 ribosomes!

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50 nm appears to be unrealistic

Size limits of cells having ancient biochemical complexity

Modern metabolism consists of a two-biopolymer system

Information storage

Stable, linear molecules

Catalytic behavior

Chemical diverse,
dynamic structures

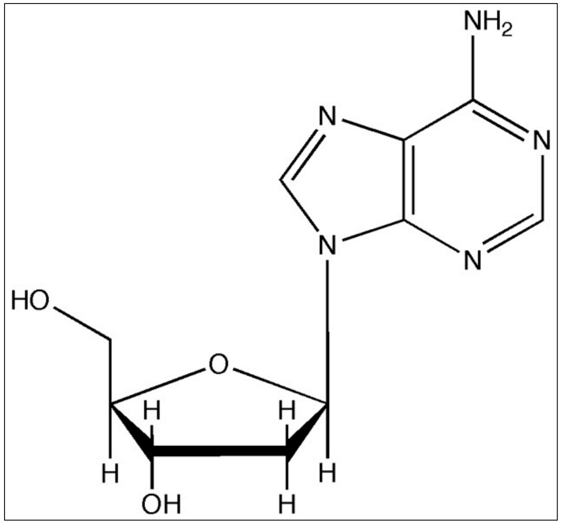
Single-biopolymer system?

NASA’s definition of Life

“Life is a self-sustained chemical system capable of undergoing Darwinian evolution”

1. “Darwinian”: Reproduction (replication), mutation, natural selection

2. “Self-sustained”: contains all genetic information necessary for its own metabolism



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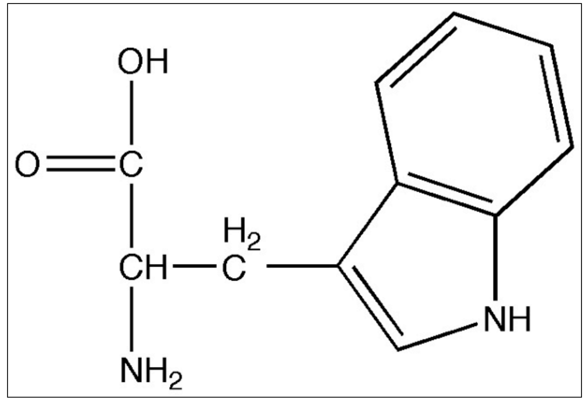

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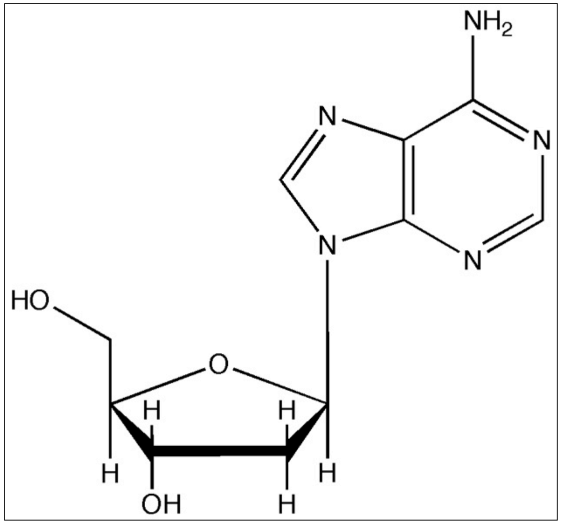

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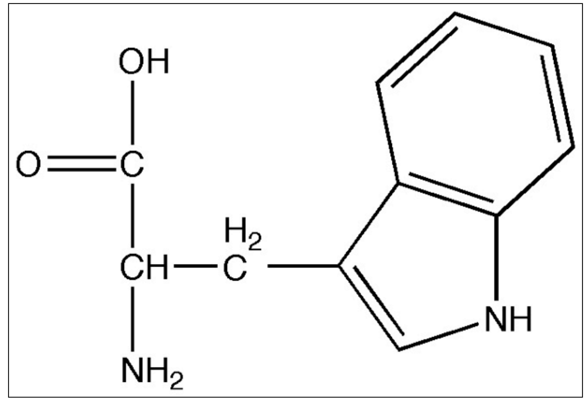

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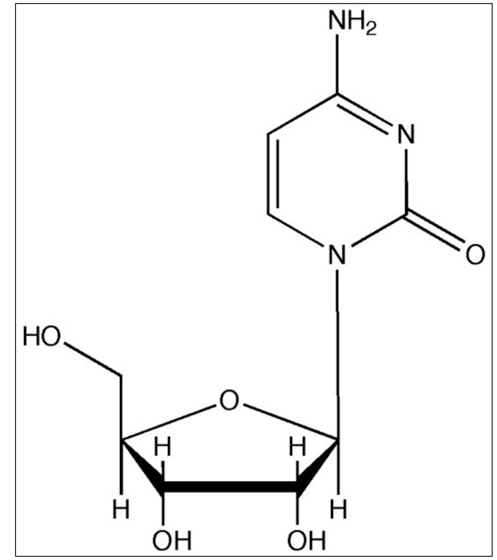
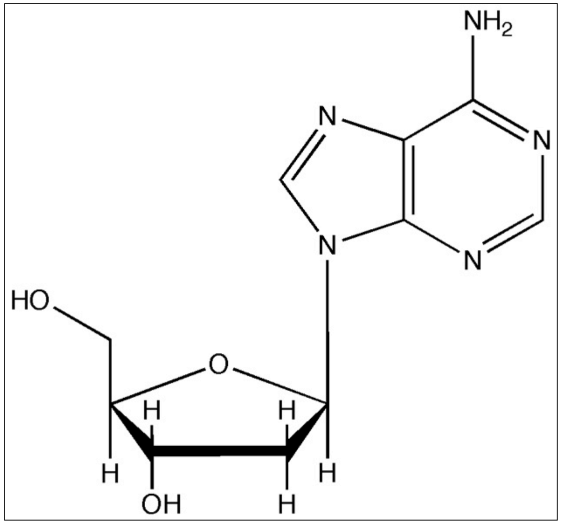


C



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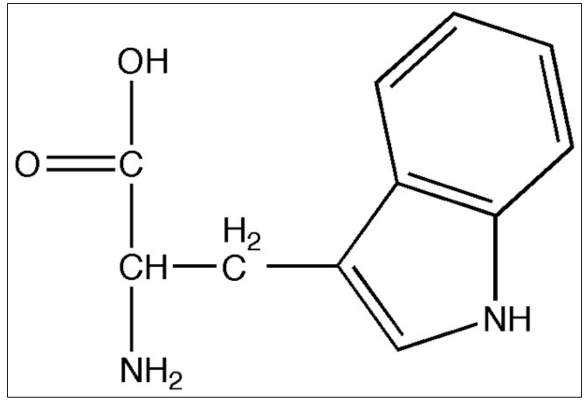

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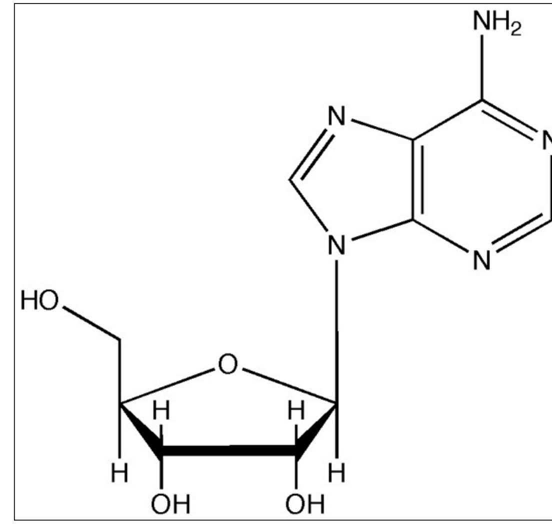

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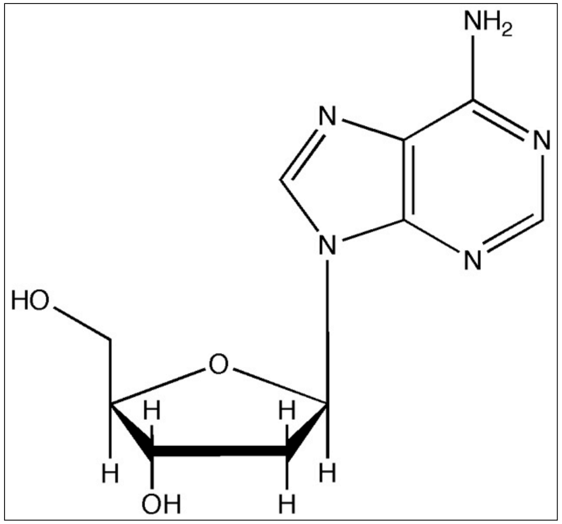

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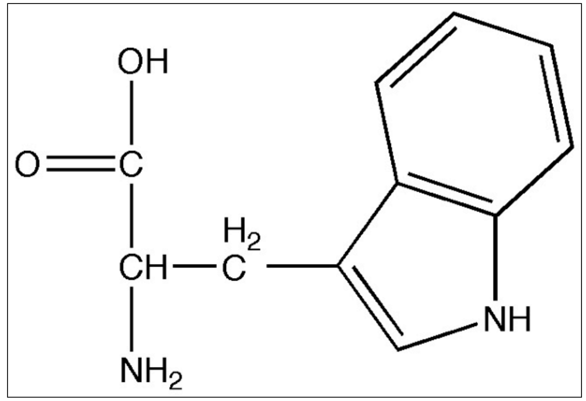

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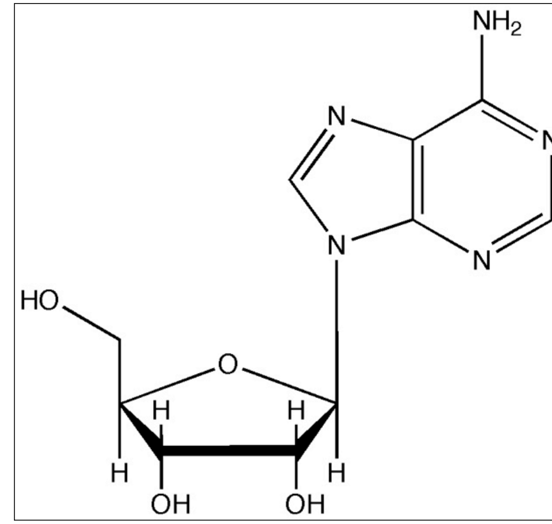
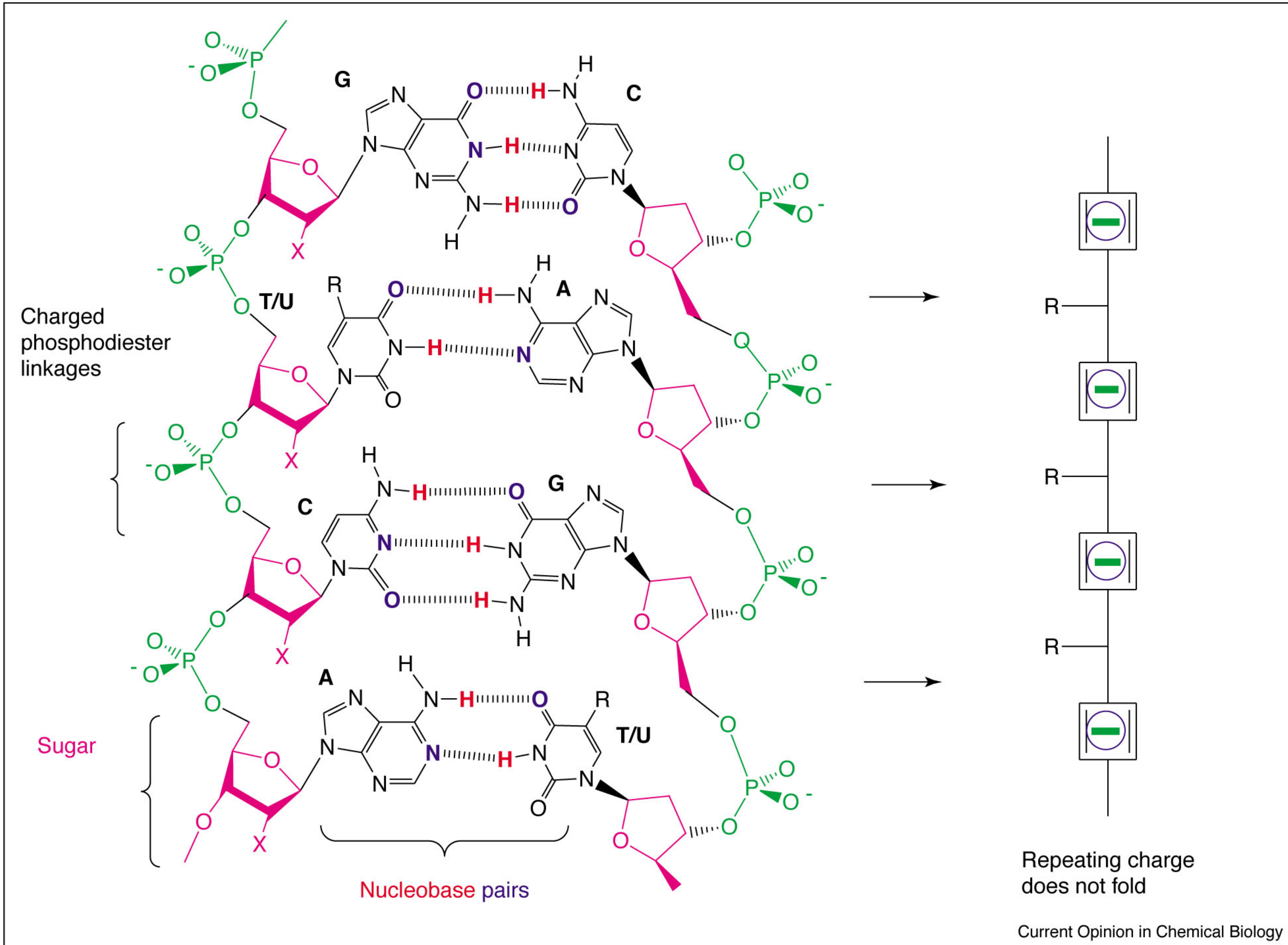
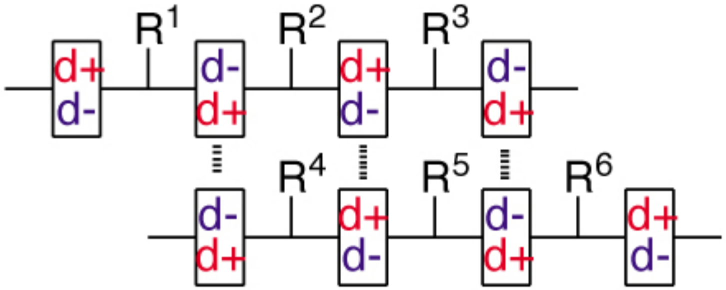


C

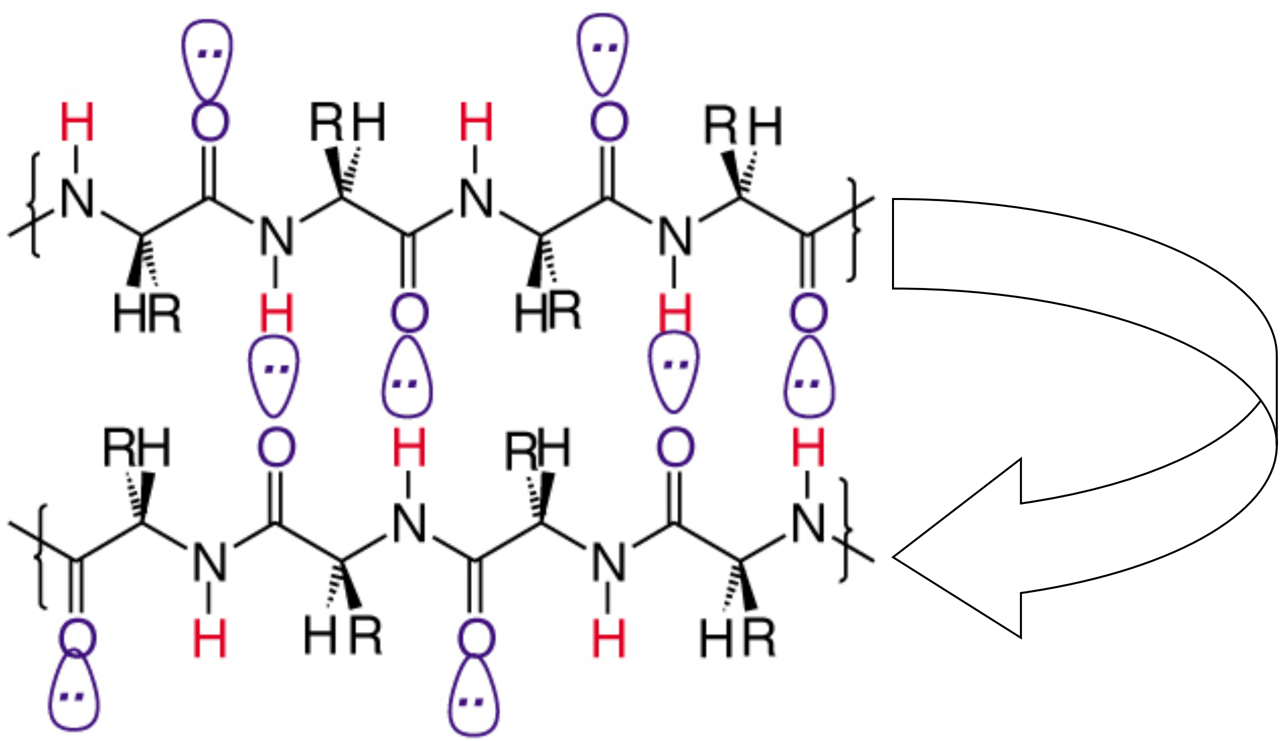
Why do these molecules differ in their information/catalytic capacities?

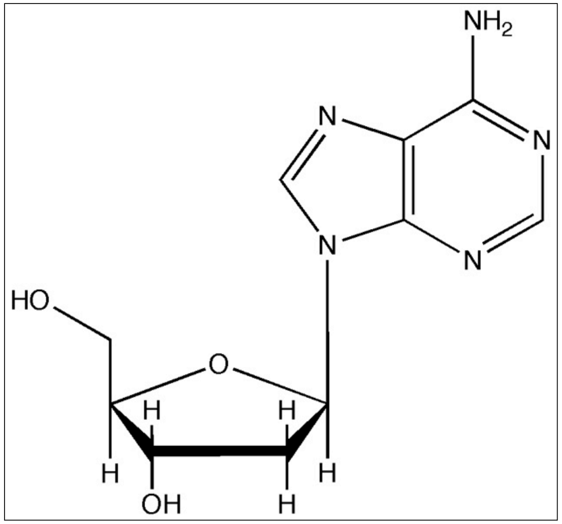

G
C
T/U
A
Charged phosphodiester linkages
Sugar
Nucleobase pairs
Repeating charge does not fold
Current Opinion in Chemical Biology

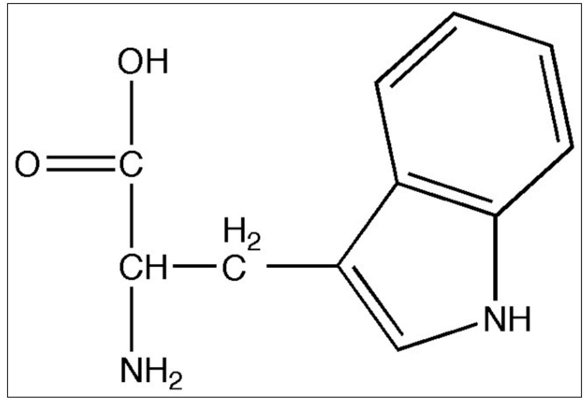


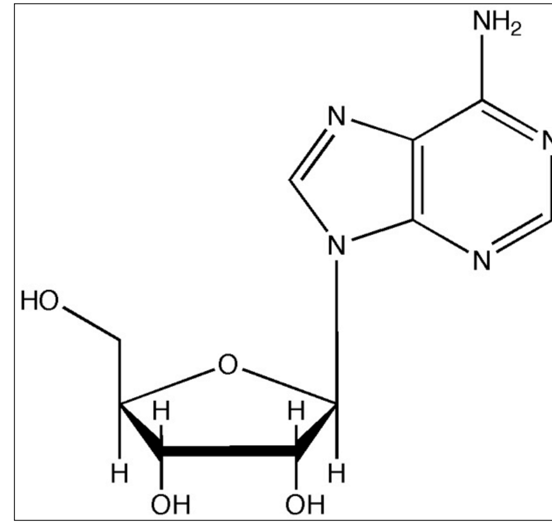
Repeating dipole can fold = conformation

Hydrogen bonds holding strands together
R = aminoacids




NH2
N
N
N
N
HO
O
H
H
H
H
OH
H

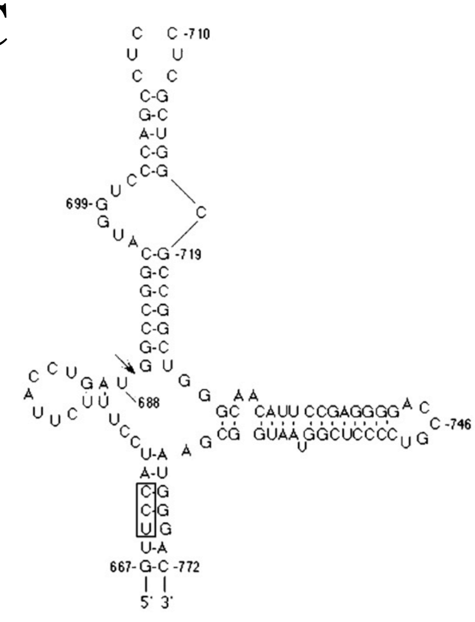

OH
O
C
H2
CH
C
NH
NH2


NH2
N
N
N
N
HO
O
H
H
H
H
OH
OH

A

B

C

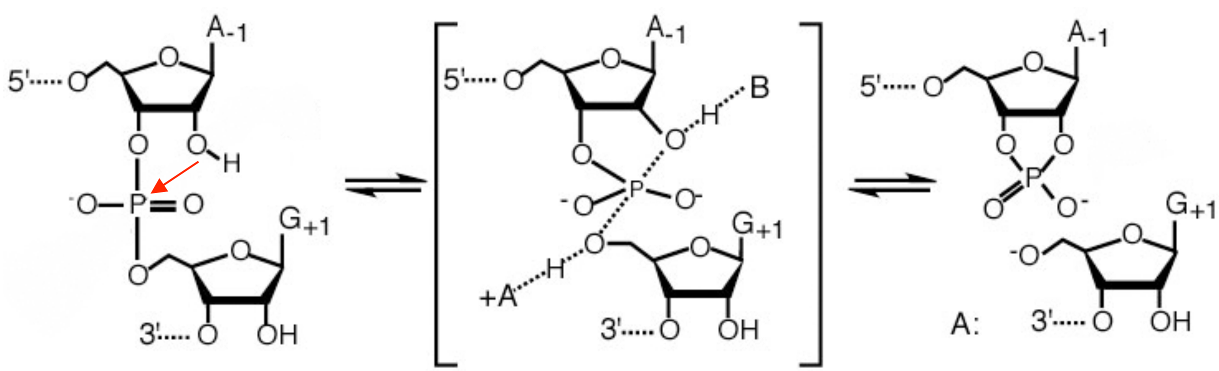

-710
699-
-719
688
-746
667-
-772
5'
3'

The story of the ancient molecule (Goldilocks) and the 3 biopolymers (Bears)

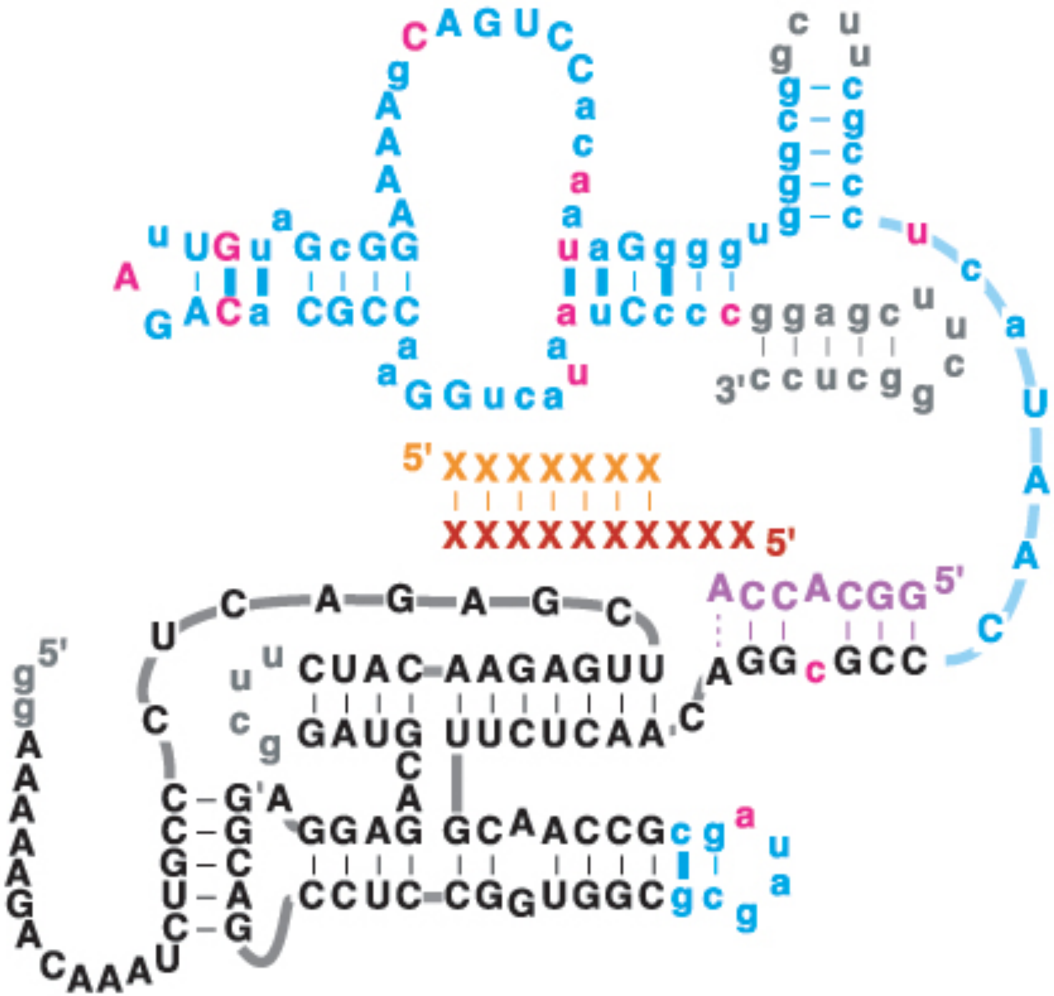
DNA: Too stable and rigid for catalysis

Protein: Too dynamic for a hereditary molecule

RNA: Just right, neither too rigid nor too dynamic



RNA-based RNA polymerase (self-replicator)

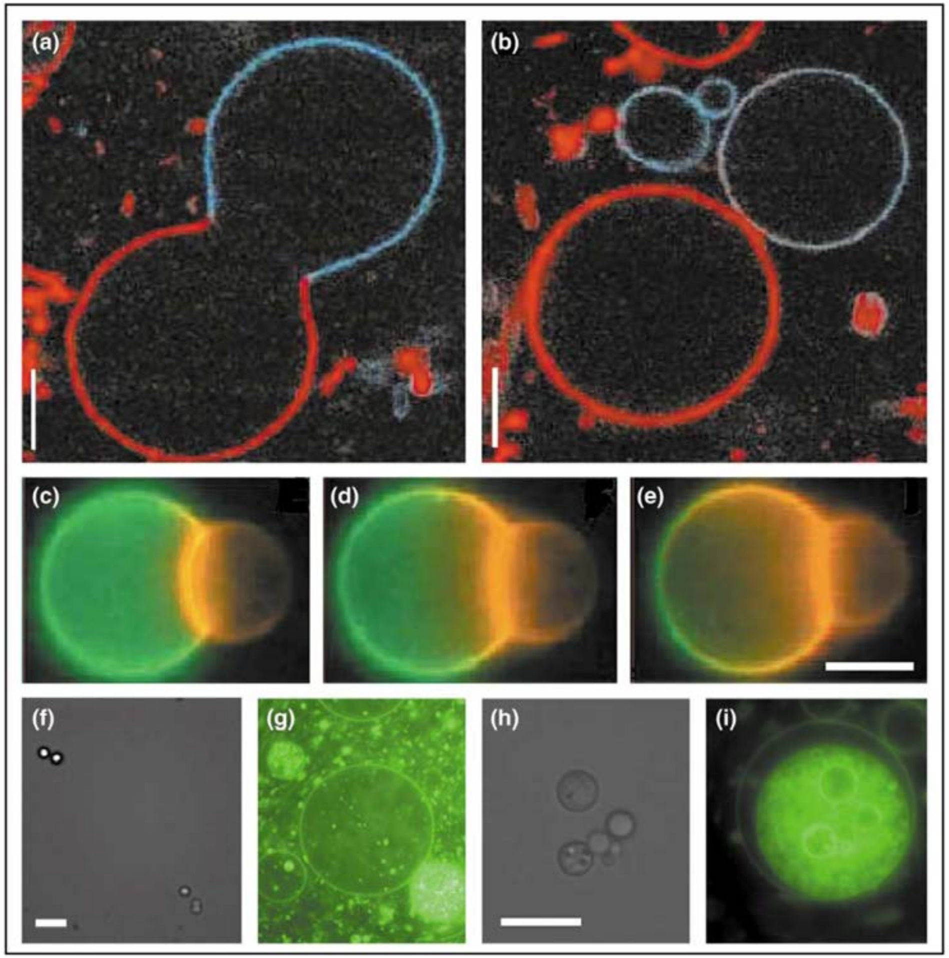


David Bartel et al.

Ribozymes: RNA molecules capable of catalysis

1. phosphoester transfer
2. phosphoester hydrolysis
3. polynucleotide ligation
4. polynucleotide phosphorylation
5. **mononucleotide polymerization (analogous to protein polymerase)**
6. aminoacyl transfer (analogous to aminoacylation of a transfer RNA)
7. amide bond cleavage
8. amide bond formation
9. peptide bond formation (analogous to the ribosome)
10. N-alkylation and S-alkylation,
11. porphyrin metallation,
12. Diels-Alder reaction
13. oxidative DNA cleavage (DNA damage)

Primitive Artificial Cells (Jack Szostak et al.)



Phospholipid bilayer encapsulating Hammerhead ribozyme
Capable of growth (modification) and competition -
chemical evolution

Size limits of cells having ancient biochemical complexity

Single biopolymer system: Thousands of different RNA species could be encapsulated within a stable membrane having a total diameter less than 50 nm.

Photosynthesis

Non-chlorophyll (green & purple sulfur bacteria):

$$CO_2 + 2H_2S \longrightarrow (CH_2O) + S_2 + H_2O$$

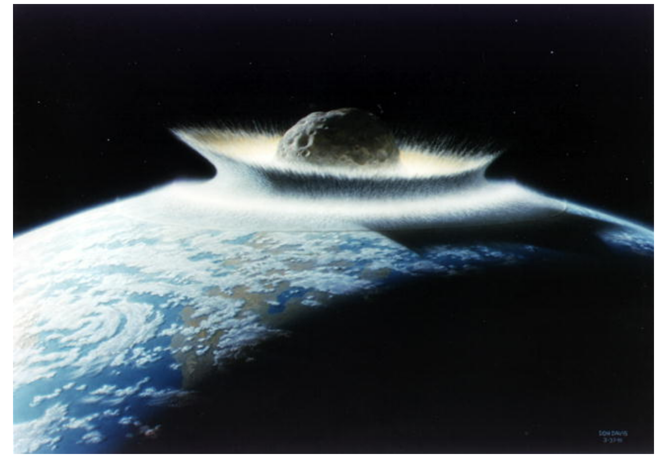
Hydrogen sulfide – volcanoes (abiotic)
swamps, flatulence, rotten eggs (biotic)

Chlorophyll (cyanobacteria):

$$CO_2 + H_2O \longrightarrow (CH_2O) + O_2 + H_2O$$

Very Brief History of Early Earth

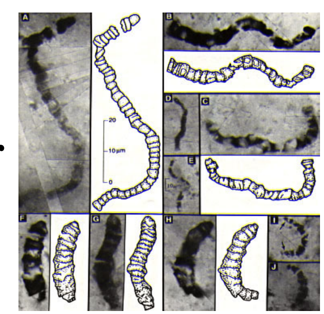
4.6 Ga Earth forms



3.9 Ga Bombardment of Earth by planetesimals stops

3.9 Ga Earth's crust solidifies (oldest sedimentary rocks) and Oceans form

3.8-3.2 Ga Microbial signatures & cellular organisms



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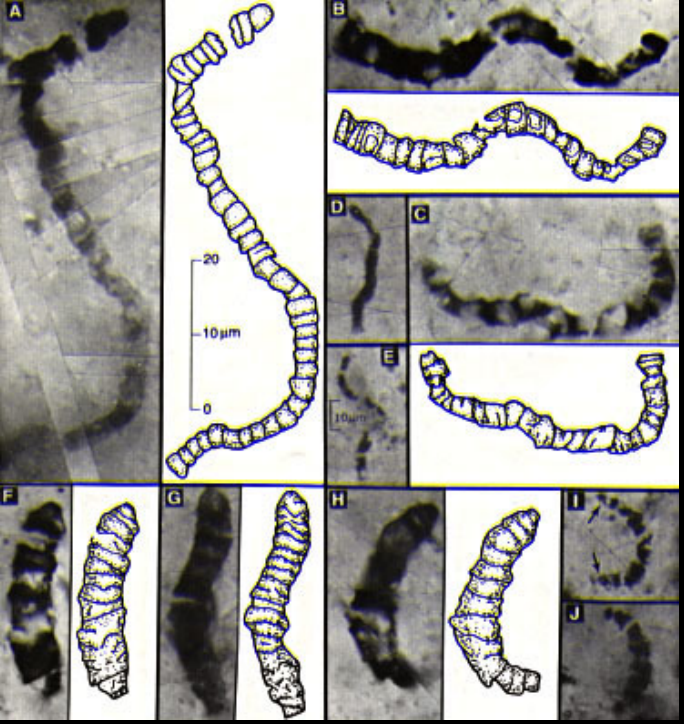

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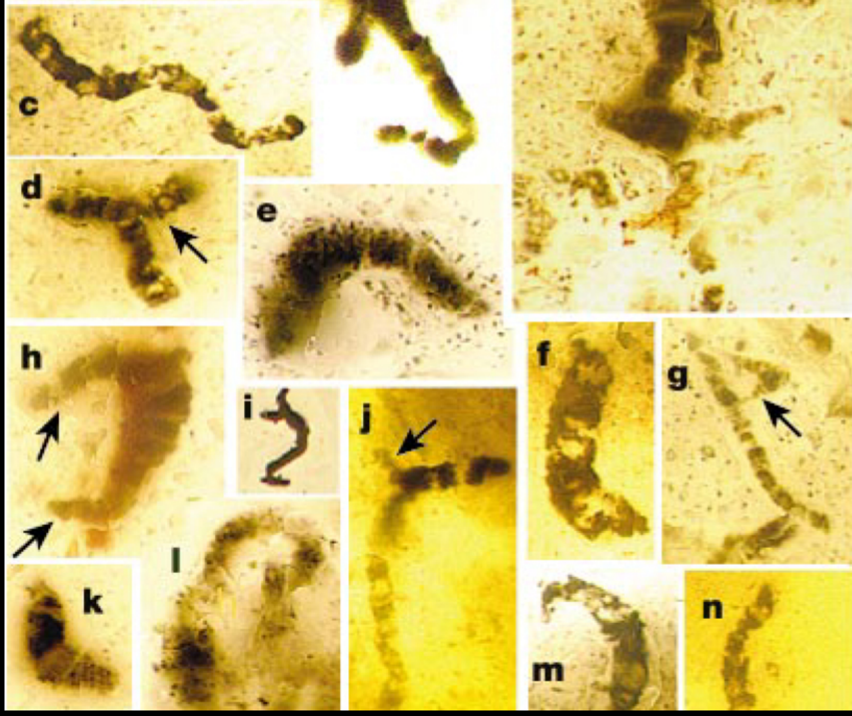

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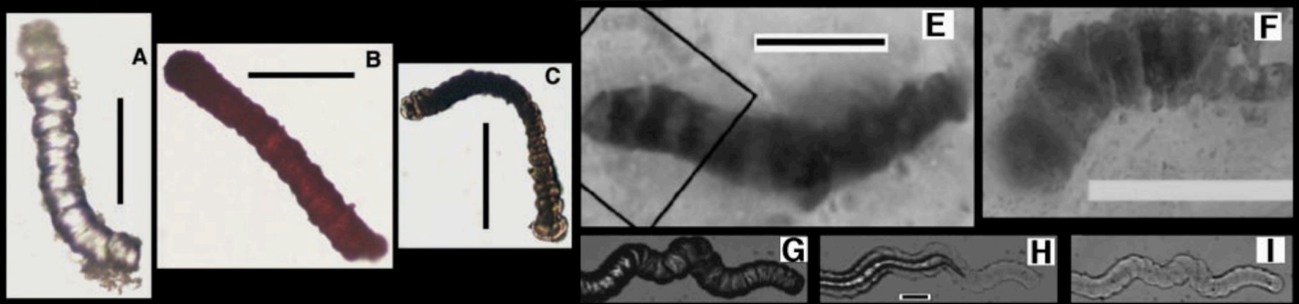
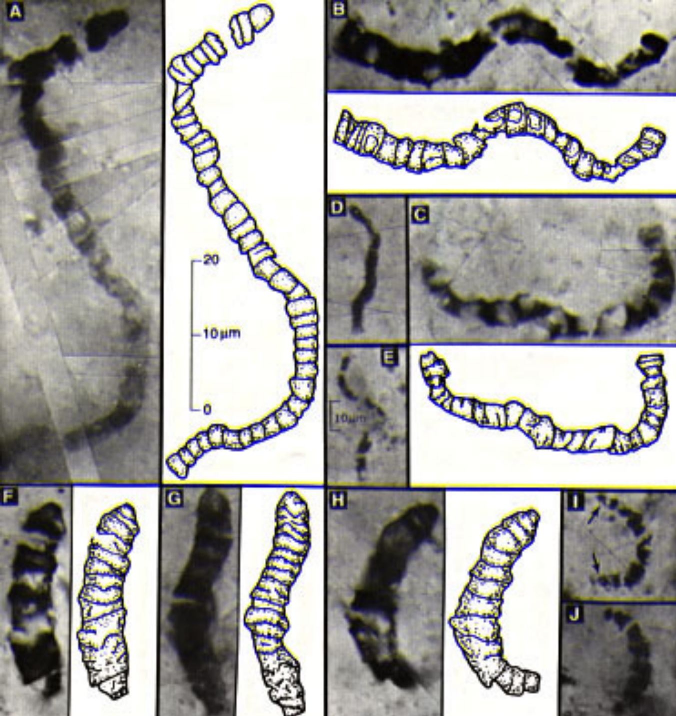


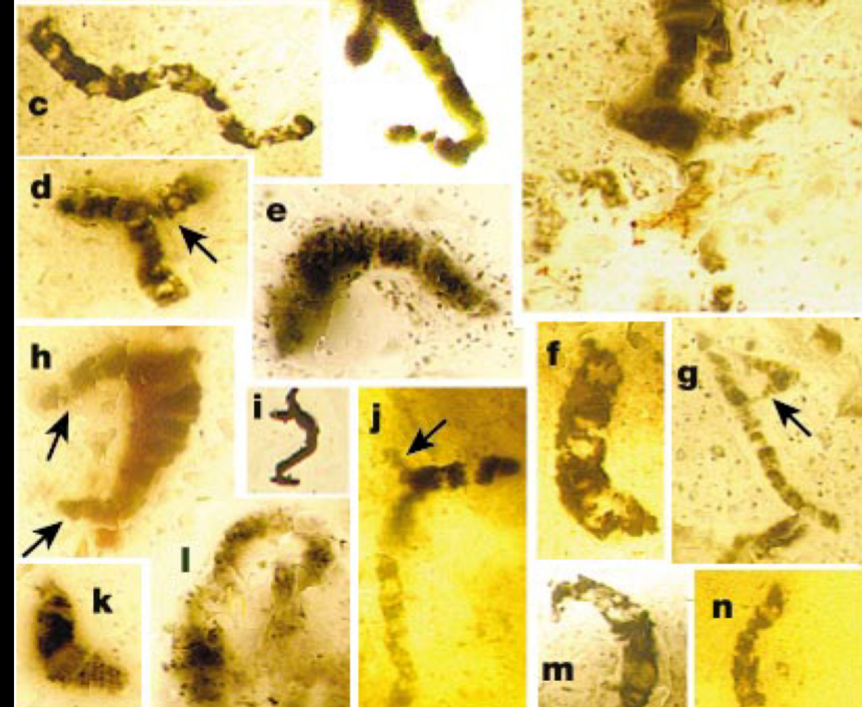
Secondary artifacts

Abiotic organic synthesis

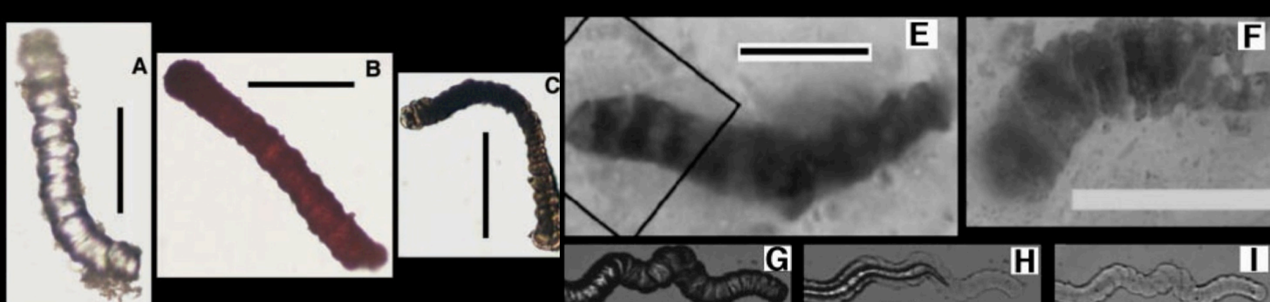
3.5 Billion year old
Microfossils



3.5 Billion year old Microfossils of cyanobacteria?
(W. Schopf 1993)



Secondary artifacts formed from amorphous graphite?
(M. Brasier *et al*. 2002)



silica, carbonate, and barium in an alkaline medium with a dash of simple organics.
(Garcia-Ruiz *et al*. 2003)

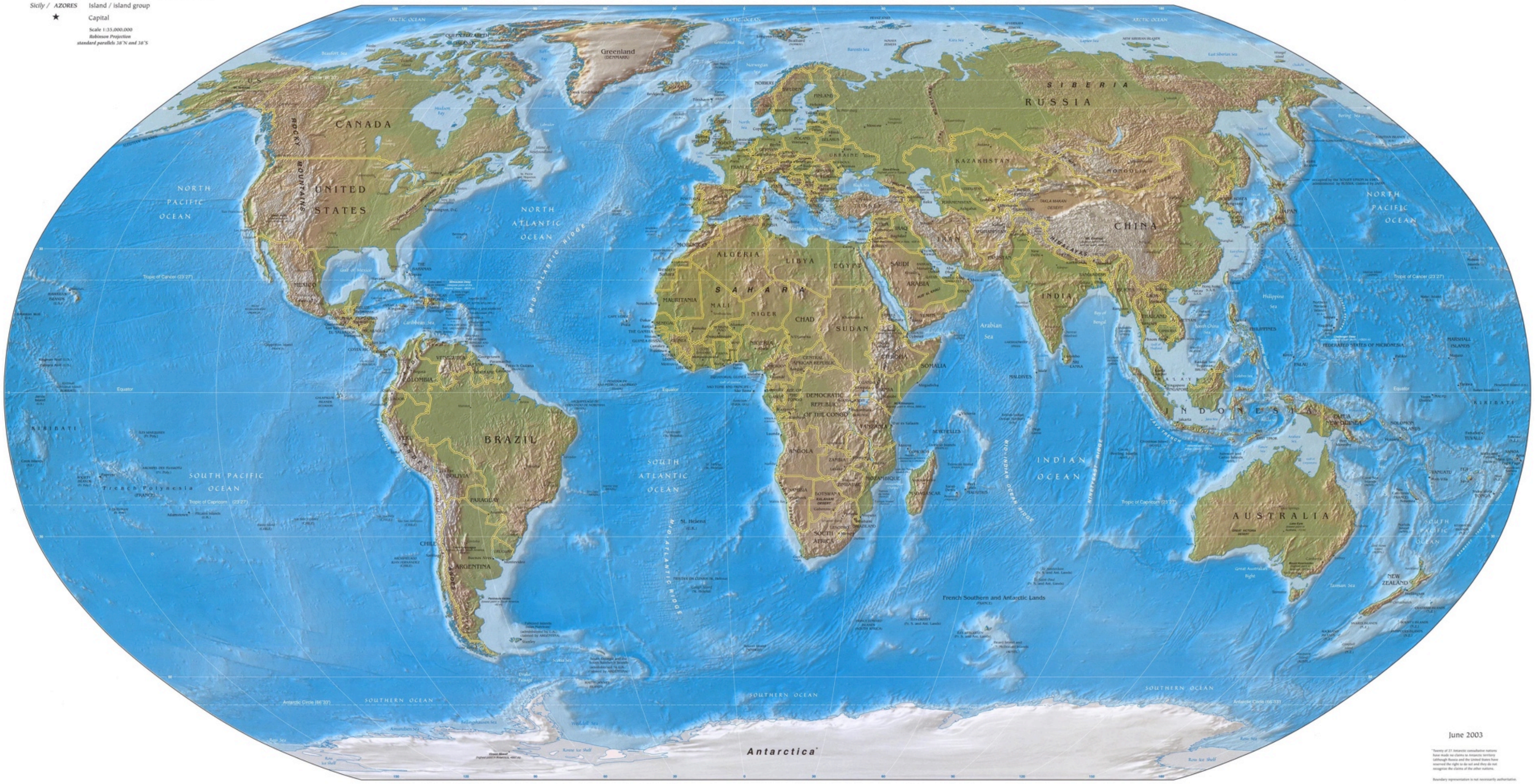
3.45 Billion year old rock from Western Australia
Consensus=biotic

Fossil record shows that stromatolites were highly abundant on early Earth. They are not so abundant on today's Earth.

Physical Map of the World, June 2003

AUSTRALIA	Independent state
Bermuda	Dependency or area of special sovereignty
Sicily / *AZORES*	Island / island group
★	Capital

Scale 1:35,000,000
Robinson Projection
standard parallels 38°N and 38°S

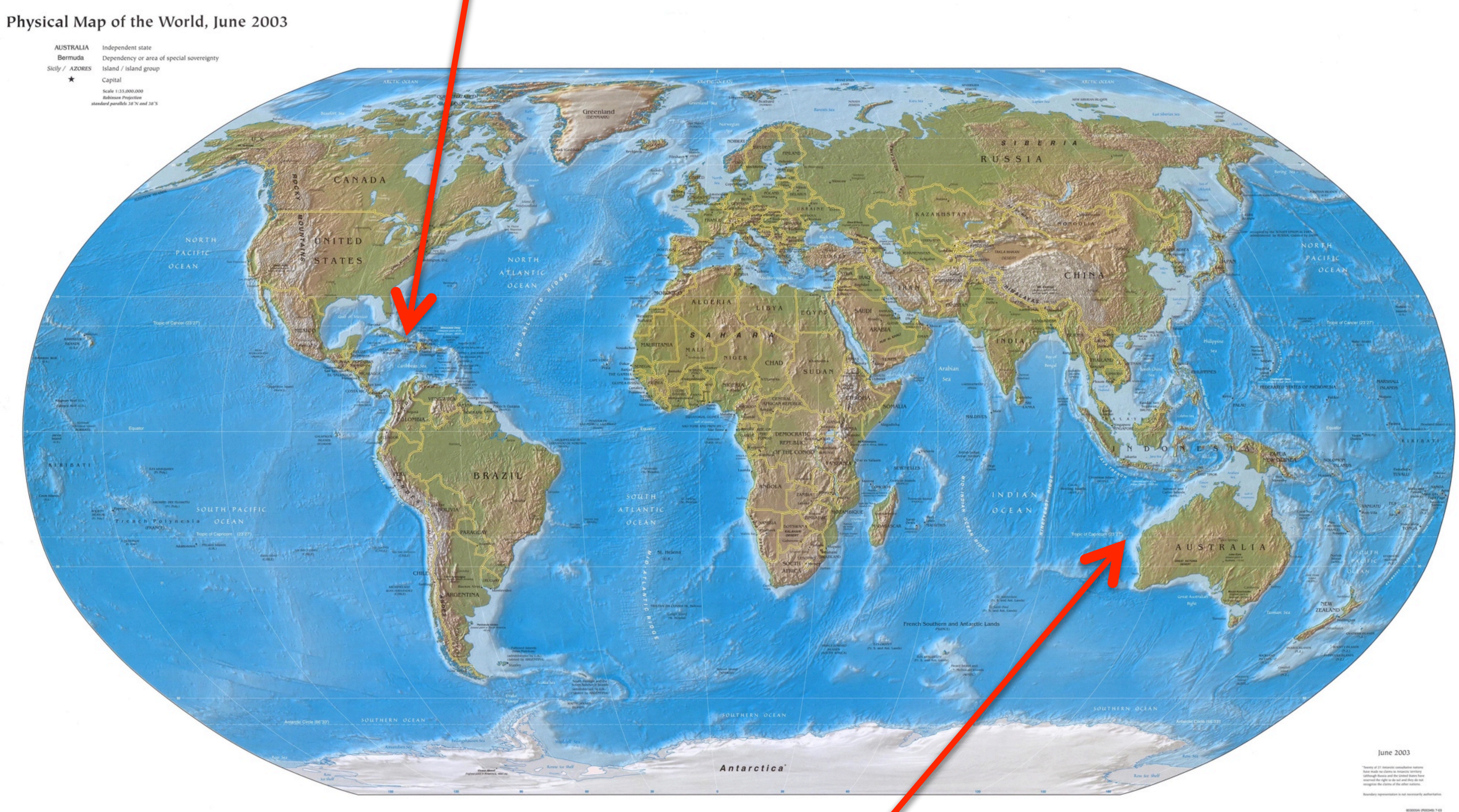


June 2003

*Twenty of 27 Antarctic consultative nations have made no claims to Antarctic territory (although Russia and the United States have reserved the right to do so) and they do not recognize the claims of the other nations.

Boundary representation is not necessarily authoritative.

Bahamas



Shark Bay, Australia




Very diverse, hundreds and hundreds of different species

Big!

Interesting Fact:
These are gigantic stromatolites in the 2.74 billion-year-old Pilbara region of Western Australia. These indicate that oxygen-producing cyanobacteria were already flourishing in the Archaean era

Stromatolites represent some of Earth's earliest life forms. They have been on the planet for billions of years. Cyanobacteria living inside stromatolites shaped life on Earth because they produce oxygen (O_2)

Earth 3.5 Billion Years Ago

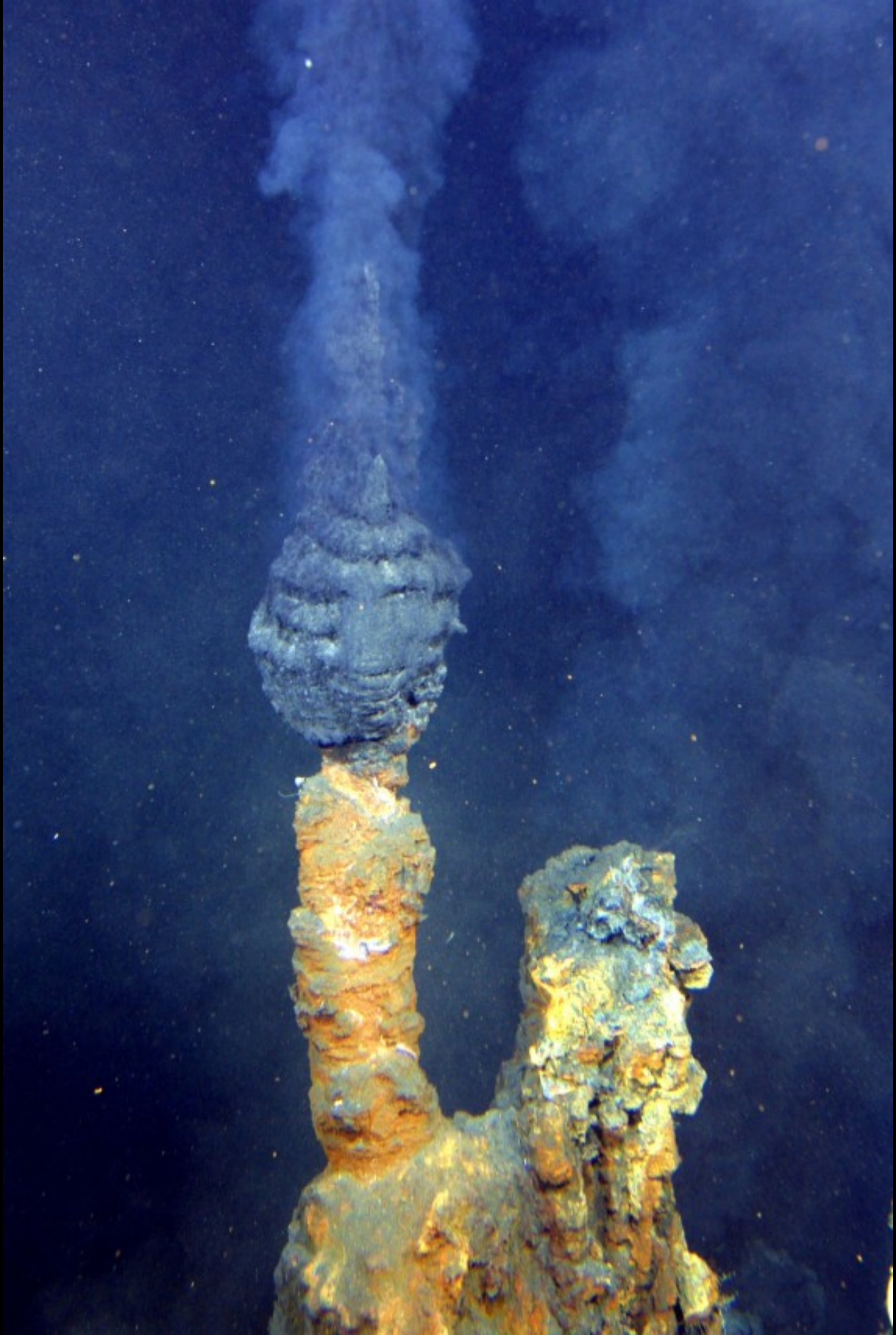
Campbell & Reece 7th Edition, Fig. 26.01

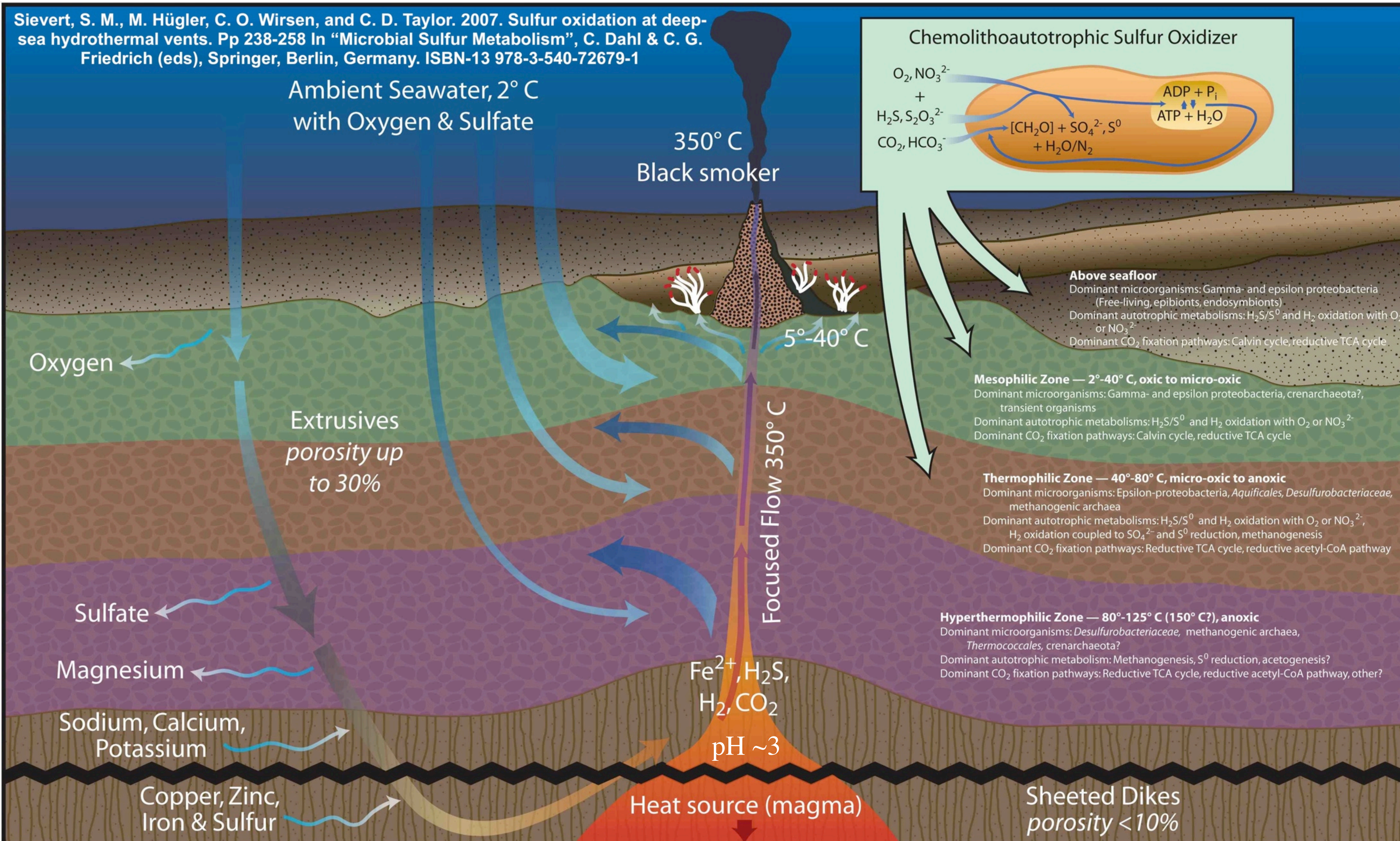
What of a Less Reducing Atmosphere?

- Simple organic molecules are much harder to generate in a less reducing atmosphere.
  - Marine environments out of direct contact with the atmosphere may have provided a critical site for organic material synthesis.
  - Hydrothermal vents are an excellent environment for synthesis of organic molecules.
  - Genomic studies imply a high-temperature origin of life.

Campbell & Reece, Fig. 25.02

Hydrothermal System

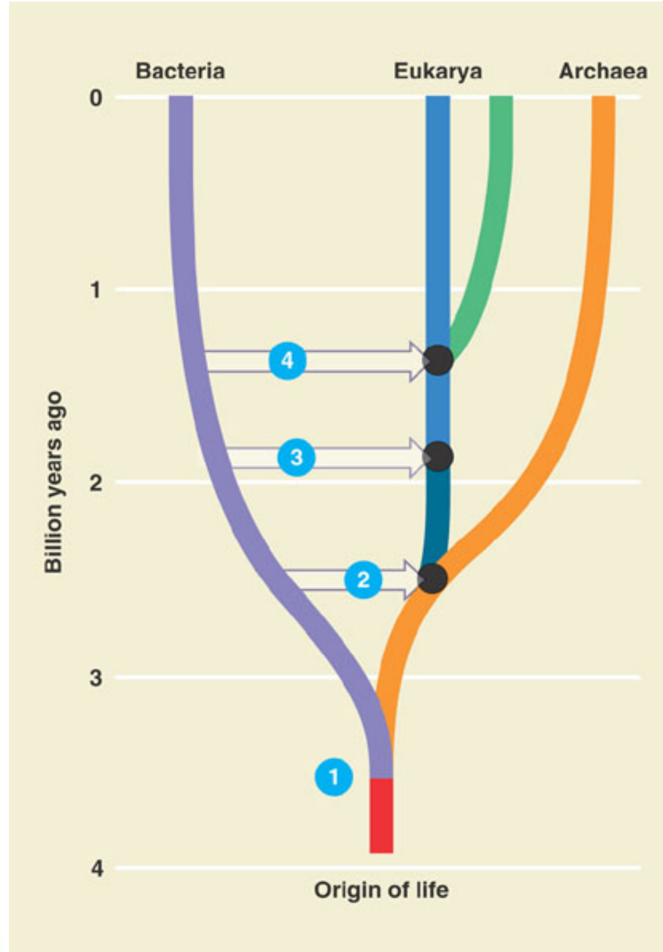




Sievert, S. M., M. Hügler, C. O. Wirsen, and C. D. Taylor. 2007. Sulfur oxidation at deep-sea hydrothermal vents. Pp 238-258 In "Microbial Sulfur Metabolism", C. Dahl & C. G. Friedrich (eds), Springer, Berlin, Germany. ISBN-13 978-3-540-72679-1
Ambient Seawater, 2° C with Oxygen & Sulfate
350° C Black smoker
Chemolithoautotrophic Sulfur Oxidizer
O_2, NO_3^{2-} + H_2S, $S_2O_3^{2-}$
CO_2, HCO_3^-
$[CH_2O] + SO_4^{2-}, S^0 + H_2O/N_2$
$ADP + P_i$
$ATP + H_2O$
Oxygen
5°-40° C
Above seafloor
Dominant microorganisms: Gamma- and epsilon proteobacteria (Free-living, epibionts, endosymbionts)
Dominant autotrophic metabolisms: H_2S/S^0 and H_2 oxidation with O_2 or NO_3^{2-}
Dominant CO_2 fixation pathways: Calvin cycle, reductive TCA cycle
Mesophilic Zone — 2°-40° C, oxic to micro-oxic
Dominant microorganisms: Gamma- and epsilon proteobacteria, crenarchaeota?, transient organisms
Dominant autotrophic metabolisms: H_2S/S^0 and H_2 oxidation with O_2 or NO_3^{2-}
Dominant CO_2 fixation pathways: Calvin cycle, reductive TCA cycle
Extrusives *porosity up to 30%*
Focused Flow 350° C
Thermophilic Zone — 40°-80° C, micro-oxic to anoxic
Dominant microorganisms: Epsilon-proteobacteria, *Aquificales*, *Desulfurobacteriaceae*, methanogenic archaea
Dominant autotrophic metabolisms: H_2S/S^0 and H_2 oxidation with O_2 or NO_3^{2-}, H_2 oxidation coupled to SO_4^{2-} and S^0 reduction, methanogenesis
Dominant CO_2 fixation pathways: Reductive TCA cycle, reductive acetyl-CoA pathway
Sulfate
Hyperthermophilic Zone — 80°-125° C (150° C?), anoxic
Dominant microorganisms: *Desulfurobacteriaceae*, methanogenic archaea, *Thermococcales*, crenarchaeota?
Dominant autotrophic metabolism: Methanogenesis, S^0 reduction, acetogenesis?
Dominant CO_2 fixation pathways: Reductive TCA cycle, reductive acetyl-CoA pathway, other?
Magnesium
Fe^{2+}, H_2S, H_2, CO_2
Sodium, Calcium, Potassium
pH ~3
Copper, Zinc, Iron & Sulfur
Heat source (magma)
Sheeted Dikes *porosity <10%*

Three Domains of Life

- All organisms we know of on Earth today are descended from a common ancestor that lived about 4 billion years ago.



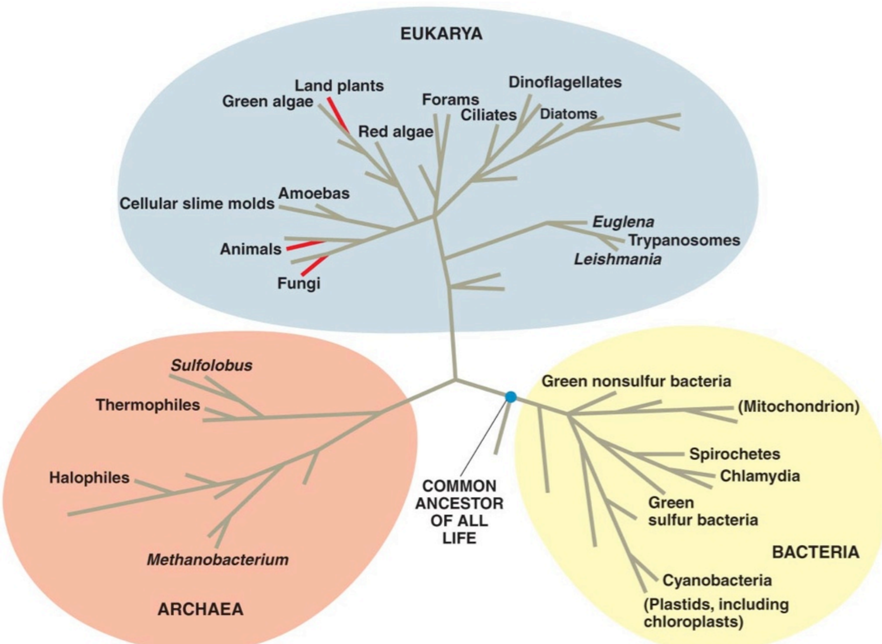
4 Symbiosis of chloroplast ancestor with ancestor of green plants

3 Symbiosis of mitochondrial ancestor with ancestor of eukaryotes

2 Possible fusion of bacterium and archaean, yielding ancestor of eukaryotic cells

1 Last common ancestor of all living things (LUCA)

Campbell & Reece 7th Edition, Fig. 25.18



Campbell & Reece, Fig. 26.21

Evolutionary Milestones

- Life arose from nonlife
- The first organisms were single cells
- Speciation has generated the diversity of life
- Eukaryotes are "cells within cells"
- Photosynthesis and sex changed the course of evolution - and the planet
- Multicellular organisms developed relatively late in Earth history.