Metals and the Evolution of Life

The interplay between chemical evolution and biological evolution

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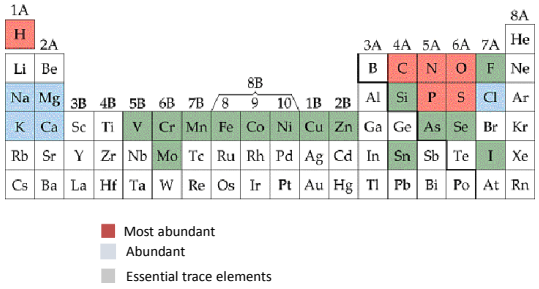
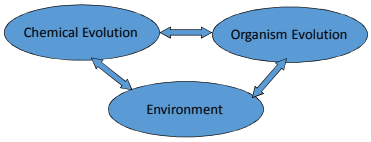
OLLI
February 26, 2016

Biology Periodic Table



Google Images

Overview



- Big bang
- Comic synthesis of elements
- Origin of Life
- GOE
- Change in metal speciation due to environmental pressure
- Cell adaptation
- Environmental change due to life processes
- Application – Trojan Horse therapeutics

Objectives

- Complexity is a useful paradigm from which to investigate siderophore mediated Fe transport in microbial communities
- The evolution of the biogeochemistry of Iron through geological time is a useful example:
  - of the adaptation of single cell organisms to environmental change
  - of chemical and biological evolution leading to emergent behavior

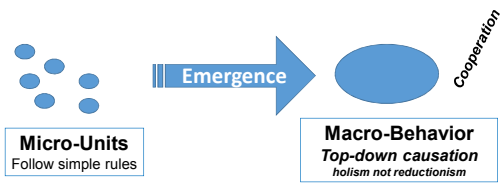
Complexity

Complexity may be defined as a system where large networks of components with no central control and simple rules of operation give rise to:

- complex collective behavior
- sophisticated information processing
- adaptation via learning or evolution

Complexity

Complex systems are sometimes called "self-organizing"



The science of Complexity tries to explain how this emergent macro behavior comes about

Complexity

Individual ant
Random behavior

Ant colony
Predictable behavior

Complexity

Complexity: Core Concepts

"Emergence" as a central concept:
Macroscopic behavior may be considered as emergent if simple rules for microscopic behavior produce complex macroscopic behavior in hard to predict ways.

Information → Computation → Order → Life

Complexity: Core Concepts

Information → Computation → Order → Life

Current state of needs of the cell relfected in concentrations and dynamics of different molecules

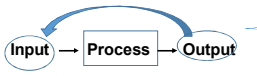
Applied to cellular metabolism

Complexity: Core Concepts

Information → Computation → Order → Life

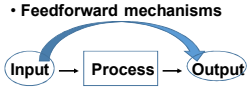
Information processing

- **Feedback mechanisms**



(-) Inhibits input; e.g. Fur box
(+) Stimulates input; e.g. quorum sensing

- **Feedforward mechanisms**



(-) Inhibition of later step
(+) Stimulation of later step

Complexity: Core Concepts

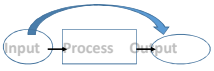
Information → Computation → Order → Life

Current state of needs of the cell relfected in concentrations and dynamics of different molecules

Information processing

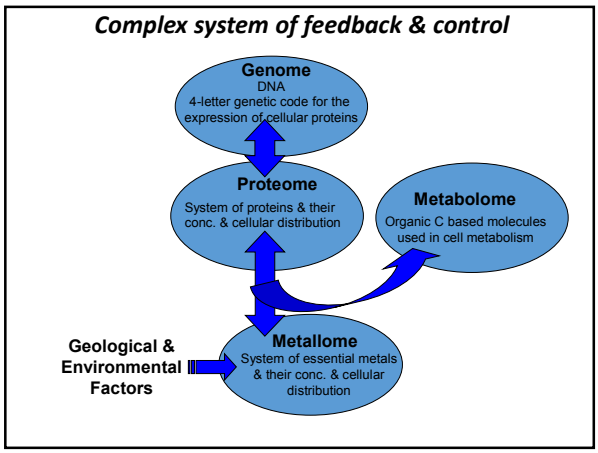
- Feedback mechanisms

- Feedforward mechanisms



Meaning/purpose: Survival and natural selection

- **Catalytic cyclic reactions self sustaining**
- **Self replicating**
- **Heredity – (mutation)**
- **Adaptation through selection**



Role of Metals in Biology

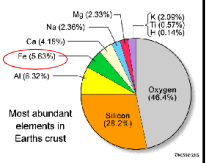
- Catalysts
- Signaling agents
- Energy transduction
- Regulation
- Transport of small molecules
- Storage of small molecules

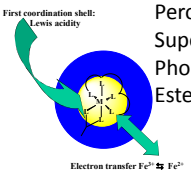
- Reactive: Good and Bad

Role of Iron in Biology

Essential for all cells

- Electron transport
- Small molecule transport
- Small molecule storage
- Enzymes
  - Hydroxylases
  - Peroxidases
  - Superoxide dismutases
  - Phosphatases
  - Esterases





Iron Paradox

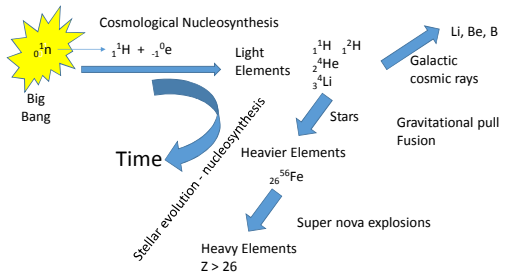
- Fe is essential to almost all living cells
  - e^- transport; small molecule transport & storage; enzymes
- Fe is toxic (location & environment must be controlled)

Too little iron
Iron deficiency

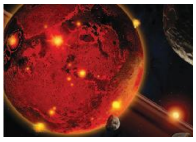
Too much iron
Iron overload

Biological iron needs to be balanced and well controlled
-Iron Homeostasis-

Formation of the Elements: Stellar Nucleosynthesis



Environmental Pressure = Gravitational Pull → Adaptation → Fusion Result → Heavy elements



Cosmic nucleosynthesis

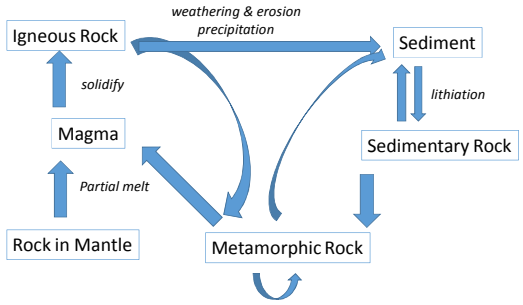
Earth Forms

Big bang

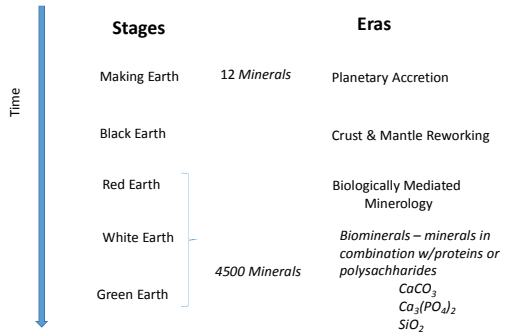
15 — 5 — 4 — 0 Ga

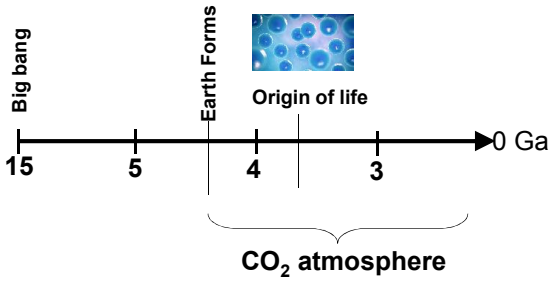
CO_2 atmosphere

Rock Cycle



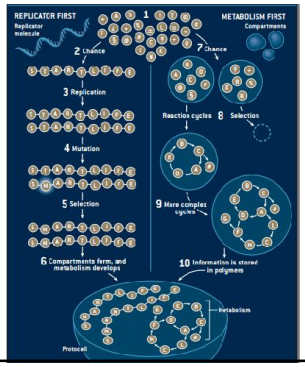
Mineral Evolution





Origin of Life

Two hypotheses: Replicator first & Metabolism first



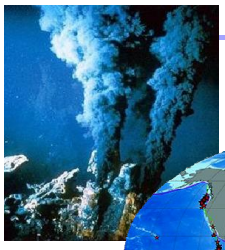
LIFE

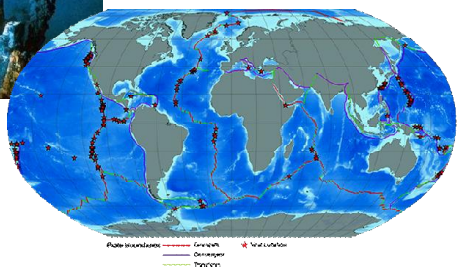
Meaning/purpose:
Survival and natural selection

Catalytic cyclic reactions self sustaining
Self replicating
Heredity – (mutation)
Adaptation through selection

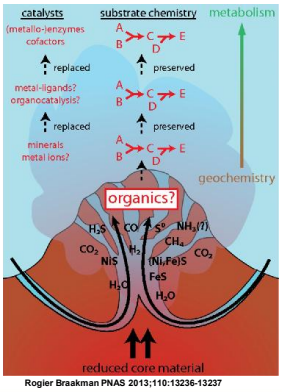
R. Shapiro, *Scientific American*, June 2007, pp 46 – 53.

Hydrothermal Vents





Hypothesis: emergence of metabolism at hydrothermal vents.

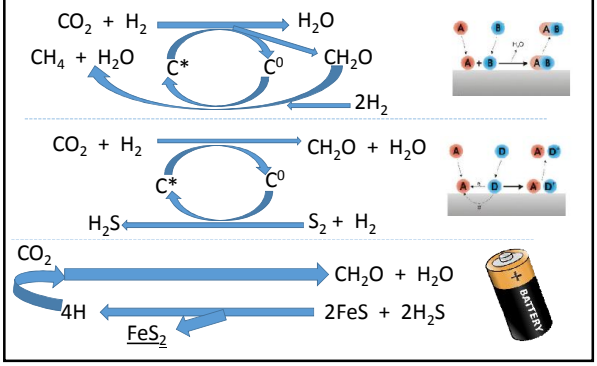


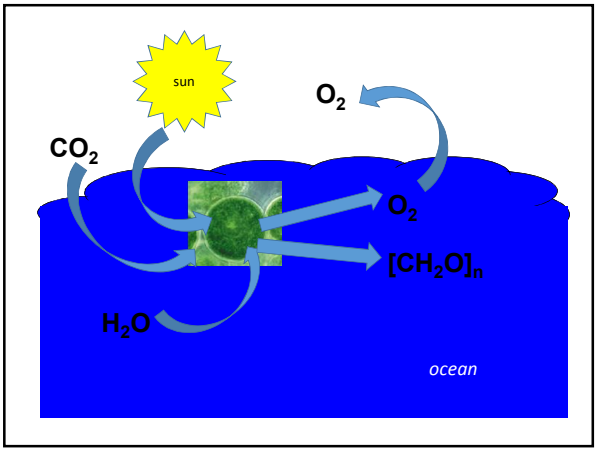
Rogier Braakman PNAS 2013;110:13236-13237

PNAS

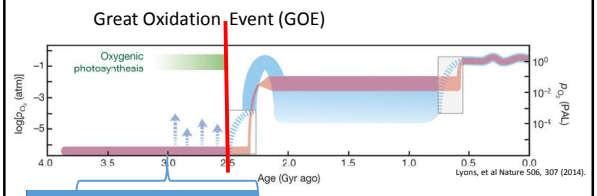
Origin of Life

Small molecule hypothesis





Evolution of Earth's atmospheric oxygen content through time



Energy + H_2O + CO_2 → $(CHO)_n$ + O_2

$CuS + O_2 \rightarrow Cu^{2+}_{aq} + SO_4^{2-}{}_{aq}$

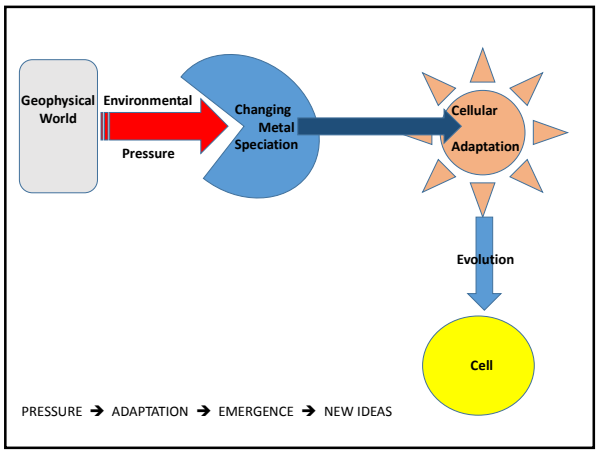
$ZnS + O_2 \rightarrow Zn^{2+}_{aq} + SO_4^{2-}{}_{aq}$

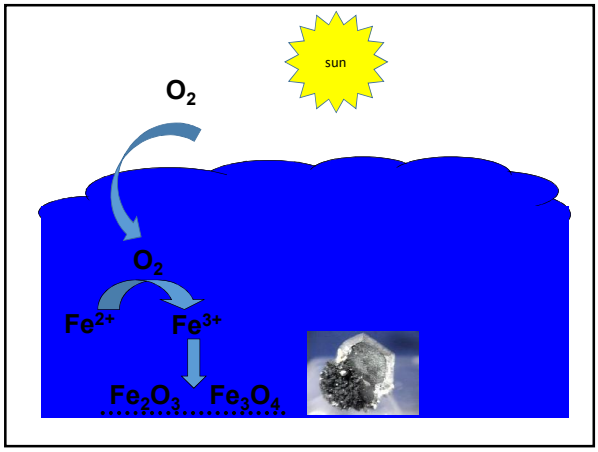
Change in metal solubility

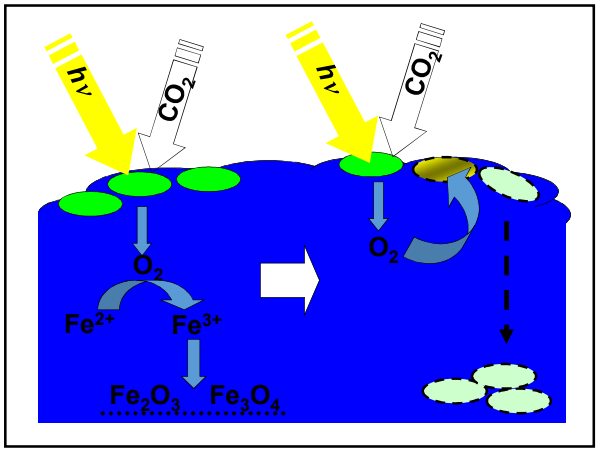
$WS_2 + 4H_2O \rightarrow WO_4^{2-}{}_{aq} + 2H_2S + 4H^+ + 2\varepsilon^-$

$MoS_2 + H_2O \rightarrow$ *Insoluble*

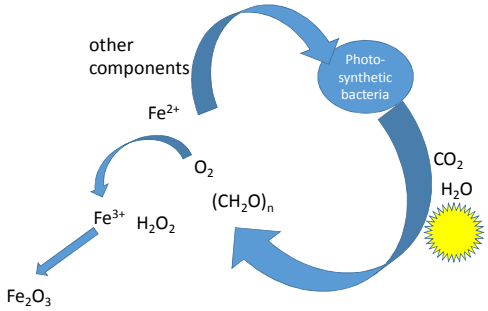
$MoS_2 + O_2 + H_2O \rightarrow MoO_4^{2-}{}_{aq} + SO_4^{2-}{}_{aq}$

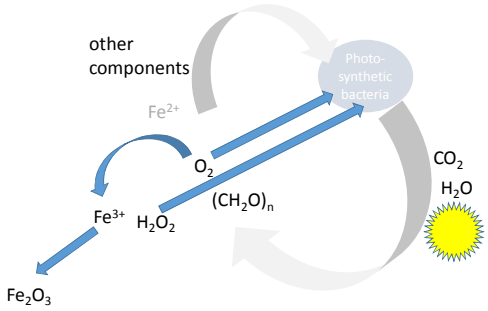

Geophysical World
Environmental Pressure
Changing Metal Speciation
Cellular Adaptation
Evolution
Cell
PRESSURE → ADAPTATION → EMERGENCE → NEW IDEAS

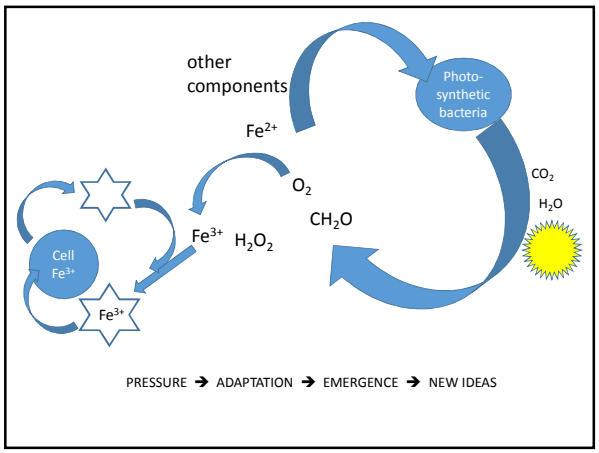

sun
O_2
O_2
Fe^{2+}
Fe^{3+}
Fe_2O_3
Fe_3O_4


hν
CO_2
hν
CO_2
O_2
O_2
Fe^{2+}
Fe^{3+}
Fe_2O_3
Fe_3O_4

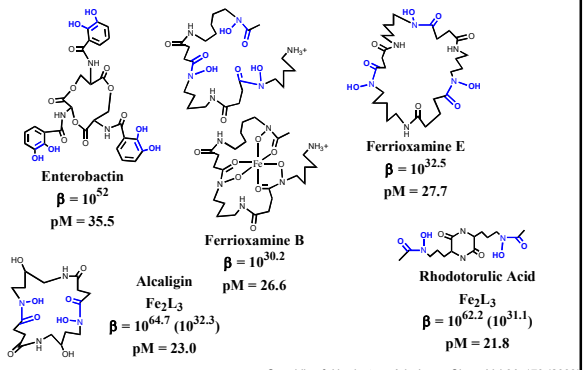
Banded Iron Formation (BIF)







Siderophore Structures

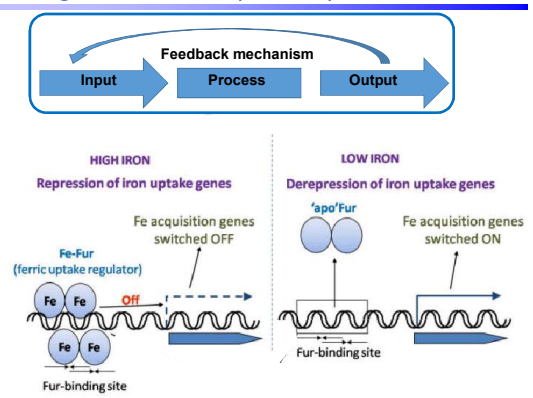


Crumbliss & Harrington, *Adv. Inorg. Chem.*, Vol **61**, 179 (2009)

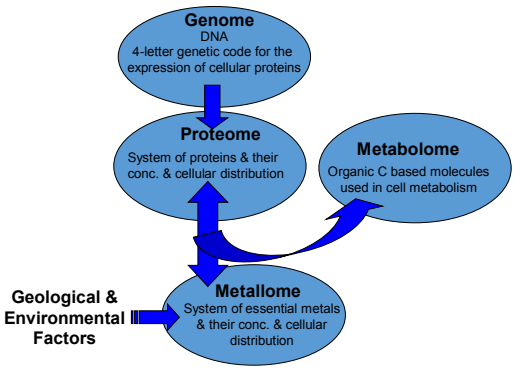
Environmental Microbes / Siderophores

Montemarcello, Italy

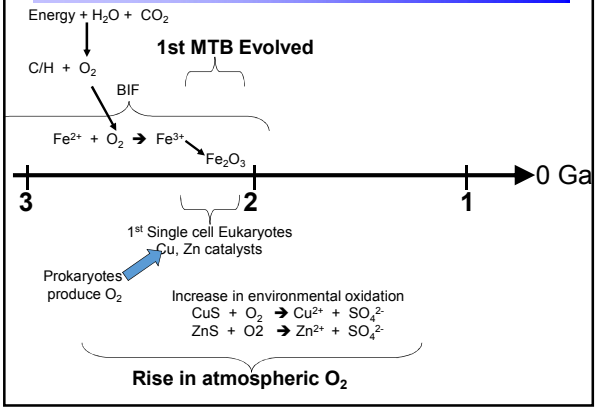
Fe Regulation/Siderophore Synthesis



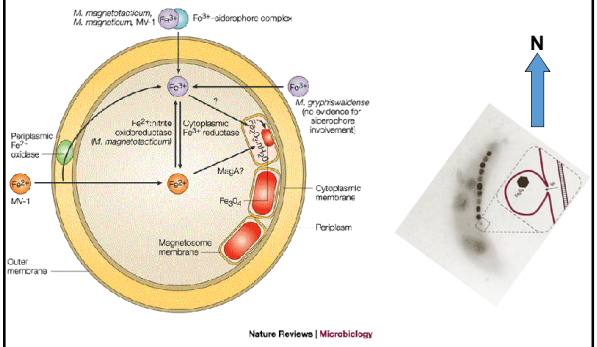
Complex system of feedback & control



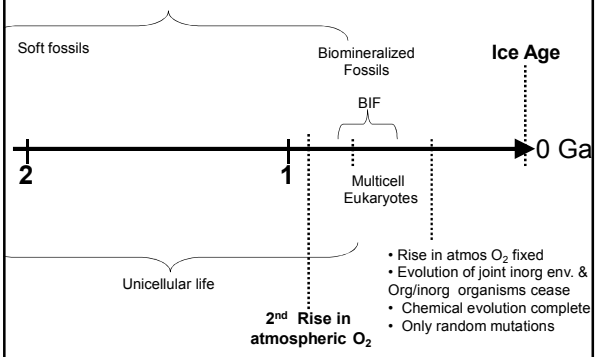
Magnetotactic Bacteria Appear

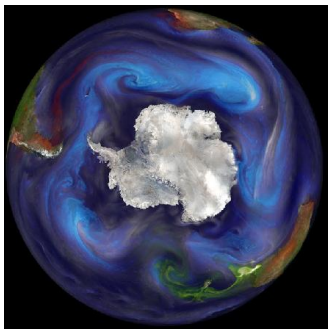


Magnetotactic Bacteria



Iron and Last Ice Age

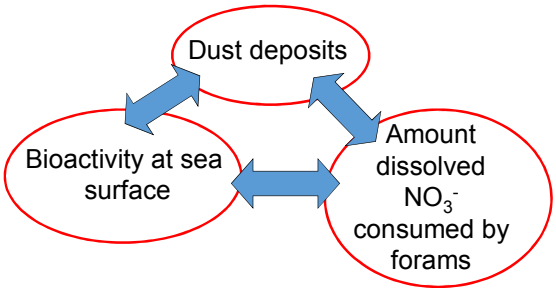


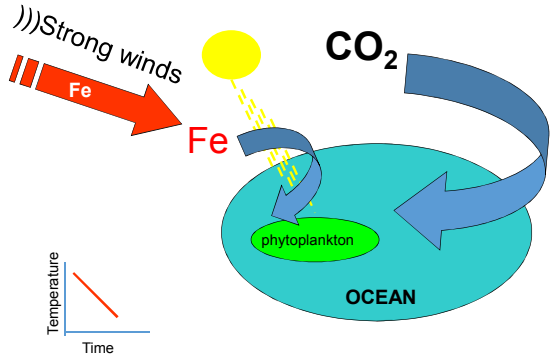


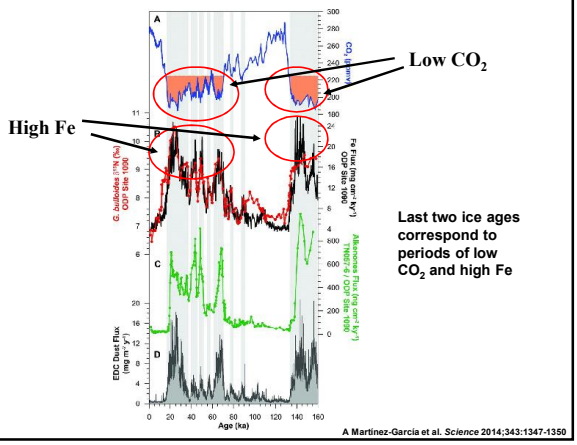
NASA/Goddard Space Flight Center, William M. Putman and Arlindo M. da Silva

Life from dust. Iron-rich dust streaming from Patagonian deserts (red plume at left side of image) fertilizes nutrient-poor southern oceans, thereby pulling planet-warming carbon dioxide from the atmosphere.

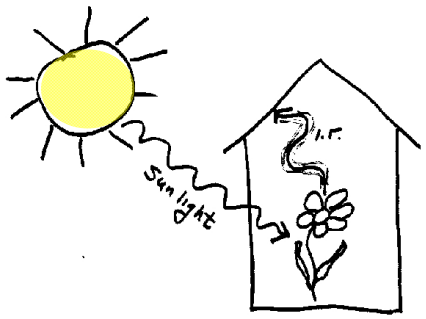
Strong links shown during the last two ice ages



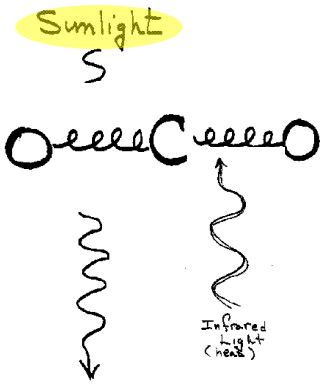




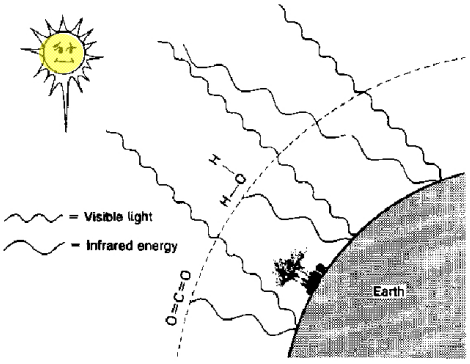
Greenhouse Effect

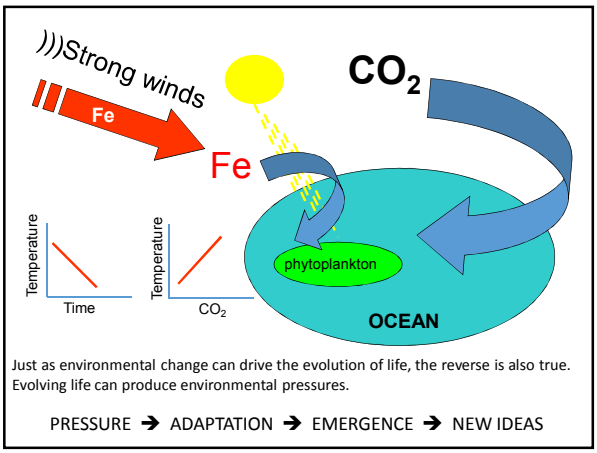


Greenhouse Effect (CO_2)



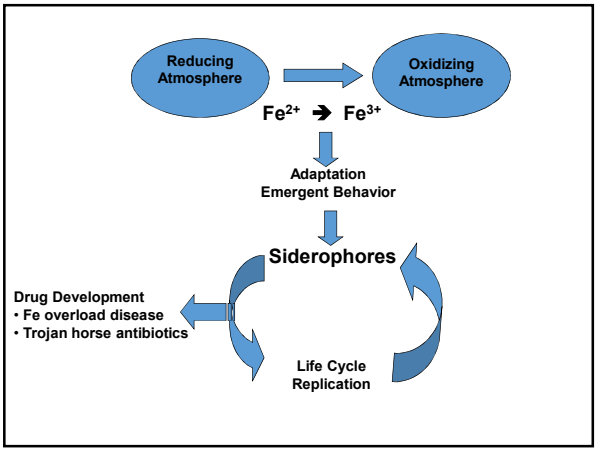
Greenhouse Effect





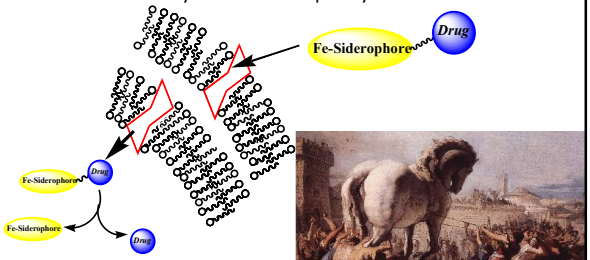
Just as environmental change can drive the evolution of life, the reverse is also true. Evolving life can produce environmental pressures.

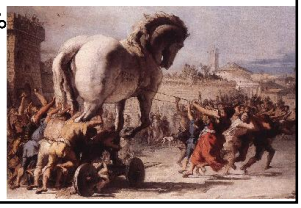
PRESSURE ➔ ADAPTATION ➔ EMERGENCE ➔ NEW IDEAS



Trojan Horse Antibiotics

- Direct attachment of antimicrobial agents to siderophores or siderophore analogues may allow the drug to be actively carried into microbial cells by their iron transport systems

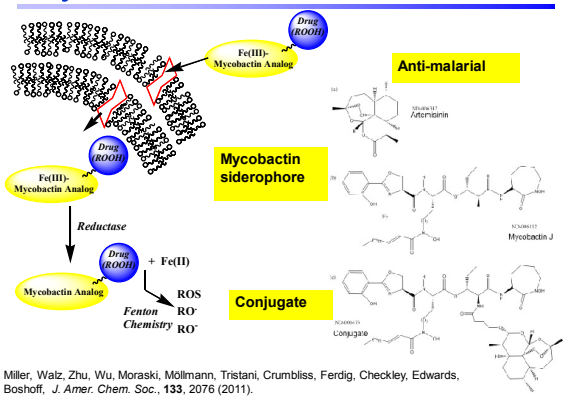




- **Advantage:**

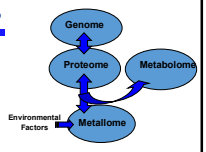
Effective and species selective

Trojan Horse Antibiotics



Miller, Walz, Zhu, Wu, Moraski, Möllmann, Tristani, Crumbliss, Ferdig, Checkley, Edwards, Boshoff, *J. Amer. Chem. Soc.*, **133**, 2076 (2011).

Summary / Pivotal Events



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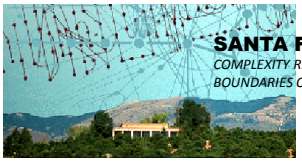

SANTA FE INSTITUTE

COMPLEXITY RESEARCH EXPANDING THE BOUNDARIES OF SCIENCE