The North American Plate

- Archean Basement
- Proterozoic Basement
- Orogenic Belts
Rodinia
“Motherland”
Forms 1.2-1.0 Grs

Compiled by Peter R. Johnson
1419 A.H 1998 A.D.

Montana
New York

Rift zone 750-725 Ma resulting in separation of Laurantia and a continental block that became East Gondwana

Rift zone separating Laurentia from a continental block that became West Gondwana

Archaean-Paleoproterozoic cratonic nuclei (cratons)
Grenvillian orogenic belts (>1100 Ma)

After Hoffman (1991), Torsvik and others (1996), and Unrug (1997)
Technical Report USGS-TR-98-3 (IR 948)
Figure 10. The geology of Segment B is extremely complex, particularly in Wyoming and western Montana. The units mapped here are based chiefly on geologic age and origin. Unconsolidated deposits that overlie the mapped rocks coincide with the unconsolidated-deposit aquifers shown in Figure 6.

Sedimentary rocks
- Quaternary and Tertiary valley fill deposits
- Unconsolidated upper Tertiary rocks
- Oligocene White River Group
- Eocene Bridger and Washakie Formations
- Eocene and Palocene Rancholabrean Formation
- Paleocene Fort Union Formation and equivalents
- Upper Cretaceous Hell Creek Formation
- Upper Cretaceous Fox Hills Sandstone
- Upper Cretaceous Bearpaw Shale
- Upper Cretaceous Judith River Formation
- Upper Cretaceous Cretaceous Clay Stone
- Upper Cretaceous Eagle Sandstone
- Upper Cretaceous Cardinale Shale

Upper Cretaceous Willamette Formation
- Upper Cretaceous Greenhorn Limestone and Baca Formation Shale
- Cretaceous Dakota Sandstone and Inyan Keres Group
- Cretaceous Colorado Group and equivalents
- Cretaceous rocks, undivided
- Cretaceous rocks, undivided and Jurassic rocks, undivided
- Lower Cretaceous and Jurassic Cretaceous and Mesozoic Formations through Triassic Limestone
- Jurassic and Triassic rocks, undivided
- Permian and Pennsylvanian rocks, undivided
- Mississippian through Carboniferous rocks, undivided
- Paleozoic rocks, undivided

Sedimentary and metamorphic rocks
- Precambrian Belt Super Group
- Metamorphic rocks
- Precambrian Sioux Quartzite

Igneous rocks
- Quaternary volcanic rocks
- Tertiary intrusive and volcanic rocks
- Tertiary and Cretaceous pyroclastic rocks
- Cretaceous intrusive and volcanic rocks
- Precambrian igneous and metamorphic rocks

Modified from:
**Sedimentary rocks**

- Quaternary and Tertiary valley-fill deposits
- Undifferentiated upper Tertiary rocks
- Oligocene White River Group
- Eocene Bridger and Washakie Formations
- Eocene and Paleocene Wesatch Formation
- Paleocene Toadstool Formation and equivalents
- Upper Cretaceous Hell Creek Formation
- Upper Cretaceous Fox Hills Sandstone
- Upper Cretaceous Bearpaw Shale
- Upper Cretaceous Judith River Formation
- Upper Cretaceous Clagett Formation
- Upper Cretaceous Eagle Sandstone
- Upper Cretaceous Carlisle Shale

**Upper Cretaceous Niobrara Formation**

**Upper Cretaceous Greenhorn Limestone and Belle Fourche Shale**

**Upper Cretaceous Dakota Sandstone and Iryun Kera Group**

**Cretaceous Colorado Group and equivalents**

**Cretaceous rocks, undivided**

**Cretaceous and Jurassic Frontier and Kootenai Formations**

**Lower Cretaceous and Jurassic Cenozoic Group through Twin Creek Limestone**

**Jurassic and Triassic rocks, undivided**

**Permian and Pennsylvanian rocks, undivided**

**Mississippian through Cambrian rocks, undivided**

**Paleozoic rocks, undivided**

**Pre cambrian Belt Supergroup**

**Pre cambrian Sioux Quartzite**

**Igneous rocks**

- Quaternary volcanic rocks
- Tertiary intrusive and volcanic rocks
- Cretaceous intrusive and volcanic rocks
- Precambrian igneous and metamorphic rocks

--- Contact -- Dashed line where approximately located

--- Line of geologic section

--- Fault or probable fault

--- Thrust fault -- Sawtooth on upper plate

--- Axis of anticline

--- Axis of syncline
Figure 10. The geology of Segment 8 is extremely complex, particularly in Wyoming and western Montana. The units mapped here are based chiefly on geologic age and origin. Unconsolidated deposits that overlie the mapped rocks coincide with the unconsolidated-deposit aquifers shown in figure 6.
Belt Supergroup, Montana
West Coast of Laurasia
Mid Continental Rift
(~1.2 to 1.0 Ga)
Rocks of the Grenville Orogeny

1.2-1.0 Gyrs
Continental Rift

- Rift valley
- Volcanic rocks and nonmarine sediments
- Heating of lithosphere
- Continental crust
- Continental lithosphere
- Asthenosphere
Keweenawan Supergroup, MI
Mesoproterozoic Rift Rocks
Rodinia Rifts (750 Myrs)

Rifts to form the (pre-Pacific) Panthalassa Ocean

Rifts to form the (pre-Atlantic) Iapetus Ocean

Compiled by Peter R. Johnson
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Rifting of Rodinia
Gondwana & Laurentia

About 500 Myr
Atmospheric Changes
Oxygen Increases: Carbon Dioxide Decreases

Thanks to...

Time (Billions of Years Ago)

OXYGEN

Proterozoic
BIF’s
(3.5-1.8 Gyrs)
Banded Iron Formation

92% Between 2.5-2.0 Gyrs

The rest in the Neoproterozoic ~ 600-700 Mya
Carol Lake Iron Mine, Canada
Red Beds
< 1.8 Gyrs

After iron in the ocean was used up, oxygen started to accumulate in the atmosphere.
Oxygen Buildup occurs at (the Same Time?) as First Eukaryotes Appear
Atmospheric Changes: UV Protection

$O_2 + UV \rightarrow O_3$ (ozone).

Photosynthetic life in oceans creates $O_2$.

Photosynthetic life on land adds $O_2$.

$O_3$ layer makes surface safe for life.
Where Did All the Atmospheric Carbon Dioxide Go?
Carbon Storage

Rainfall erodes silicate minerals on land.

Silicate minerals react with dissolved CO₂ to form carbonate rocks.

CO₂ in the atmosphere

CO₂ dissolves in ocean.

Subduction of carbonate rocks

Release of CO₂ by volcanism
The Carbon Thermostat, i.e. the greenhouse effect

Carbon burial as carbonates (limestones, dolomites and organic matter) resulted in decreases in atmospheric carbon dioxide, which made it possible for...
Paleoproterozoic (2.2 Gyr)
Gowganda Fm, Canada

Varves

The First Ice Age

Tillite
Major “Ice Ages” in Earth History
Pleistocene ice ages

Present

LGM ~20,000 years ago

sea level -130 m

benthic foram $\delta^{18}O$

ICE

SEA

LGM

more ice

Older Cryogenian ('Sturtian') glacials
730 - 700 Ma
Younger Cryogenian ('Marinoan') glacials
(665 - 635 Ma)
Ice-rafted debris, Ghaub Fm, Namibia
Neoproterozoic (Varangian) Ice Age (800-600 Myr)
Present distribution of Ediacaran glacials
(635 - 542 Ma)
Neoproterozoic Snowball Earth
Papers relating to Precambrian glacials and glaciations

- Harland (1965)
- Knoll et al. (1986)
- Kirschvink (1992)
An extended cold spell causes oceans to start freezing.

- growing polar caps
- volcanic outgassing

Lowered reflectivity causes further cooling, ending in “snowball Earth.”

Frozen oceans stop CO₂ cycle so CO₂ outgassed by ongoing volcanism builds up in atmosphere.

Strong greenhouse effect melts “snowball Earth,” results in “hothouse Earth.”

CO₂ cycle restarts, pulling CO₂ into oceans, reducing greenhouse effect to normal.
Why Banded Iron Formations?

If O₂ is absent, iron is soluble as ferrous (Fe²⁺) ion. If O₂ is present, iron is insoluble as ferric (Fe³⁺) ion.

Snowball earth: anoxic ocean

Deglaciation: ocean ventilation
There is an evolutionary radiation of multicellular organisms at the near of the Ice Age.

Coincidence or not?
Early Life on the Earth

Figures from Brock; Biology of Microorganisms, 11th ed., Madigan and Martinko
What is Life? (Reminder)

• Composed of organic compounds
• Resistance to entropy (disorder)
  – Requires energy (must be able to gather and process (metabolize) energy)
• Ability to maintain a controlled environment
  – Requires ability to be isolated from environment
• Information storage
• Self replication
  – Including ability to pass on information
• Ability to adapt to its environment
  – Undergoes biological evolution
DNA is responsible for reproduction

RNA makes proteins

1. Energy (ATP)
2. Precursors of Macromolecules (sugars, amino acids, fatty acids, etc.)

Replication

Transcription

Translation

Protein

Reproduction (growth)
Typical eukaryotic cell

- Virus
- Prokaryotic cell
- Nucleus

1000 nm (1 μm)
Surface area \((4\pi r^2)\) = 12.6 \(\mu m^2\)
Volume \(\left(\frac{4}{3} \pi r^3\right)\) = 4.2 \(\mu m^3\)

\[
\frac{\text{Surface}}{\text{Volume}} = 3
\]

Surface area = 50.3 \(\mu m^2\)
Volume = 33.5 \(\mu m^3\)

\[
\frac{\text{Surface}}{\text{Volume}} = 1.5
\]
Prokaryote

- Cytoplasm
- Nucleoid
- Ribosomes
- Cell wall
- Cytoplasmic membrane

Eukaryote

- Cytoplasmic membrane
- Endoplasmic reticulum
- Ribosomes
- Nucleus
- Nucleolus
- Nuclear membrane
- Cytoplasm
- Mitochondrion
- Chloroplast

`0.5 \mu m`

`10 \mu m`
Endosymbiosis in a nutshell:

1. Start with two independent bacteria.
2. One bacterium engulfs the other.
3. One bacterium now lives inside the other.
4. Both bacteria benefit from the arrangement.
5. The internal bacteria are passed on from generation to generation.
1. Attachment (adsorption)

2. Penetration (injection)

3. Synthesis of nucleic acid and protein

4. Assembly and packaging

5. Release (lysis)

Virus particle

DNA

Cell (host)

Protein coat remains outside

Viral DNA enters

Mature virus particles
Mitochondria strips H from NADPH and FADH to create ATP. A small electron gradient is set up here to pump $H^+$ across a membrane.
Chloroplast

A small electron gradient is set up here in order to reduce carbon.

Chloroplast

(b)

Outer membrane

Inner membrane

Stroma

Thylakoid membrane

Stacked thylakoids forming grana

Uses sunlight to excite electrons
Both plants and animals have mitochondria but only plants have chloroplasts so we separated from ‘plants’ after mitochondria evolved.
Two branches of Chemistry: Thermodynamics and Kinetics

How life manipulates this to its advantage

Thermodynamics: Equilibrium States and Changes in Energy;

In what direction will a chemical reaction *spontaneously* occur? Some reactions require input of energy. They are **endergonic**. Some reactions give off energy. They are **exergonic**. Living cells use reactions that give off energy to power reactions that require energy.

  e.g. Iron oxidation (rust) and methane or octane oxidation are both spontaneous. They release energy (exergonic)

Kinetics: Rates of reactions;

How fast will a chemical reaction occur? **Enzymes** are **catalysts** that *speed up reactions*. They do this by lowering the activation energy of chemical reactions.

  e.g. decarboxylase makes CO2 exchange rates millions of times faster; important for ridding fish gills and human blood of CO2. Putting iron in salt water will speed up the reaction because it gives faster pathways for the oxidation to occur.
Organisms use enzymes to encourage certain reactions.

The diagram illustrates the free energy changes for a reaction. Without an enzyme, the activation energy is higher, and the reaction is less efficient. With an enzyme, the activation energy is lower, and the reaction proceeds more efficiently.

The equation for the change in Gibbs free energy is:

$$\Delta G_0' = G_0^f (C + D) - G_0^f (A + B)$$
**Respiration** $\Rightarrow$ \\
$\Leftarrow$ **Photo(chemo)synthesis** \\

**Oxidation** $\Rightarrow$ \\
$\Leftarrow$ **Reduction**

**Oxic photosynthesis and respiration**

*Oxic respiration* $\Rightarrow$

$\text{CH}_2\text{O} + \text{O}_2 \leftrightarrow \text{CO}_2 + \text{H}_2\text{O}$

$\Leftarrow$ **Photosynthesis**

**Sulfur chemosynthesis and respiration**

*Sulfate reduction, i.e., anoxic respiration* $\Rightarrow$

$2 \text{CH}_2\text{O} + \text{SO}_4^{2-} \leftrightarrow 2 \text{HCO}_3^- + \text{H}_2\text{S}$

$\Leftarrow$ **Chemosynthesis**
Chemotrophy

Better living through chemistry

But there is more energy available from the Sun

Chemotrophy

Chemicals

Organic chemicals
(glucose, acetate, etc.)

Inorganic chemicals
(H₂, H₂S, Fe²⁺, NH₄⁺, etc.)

Chemoorganotrophs
(glucose + O₂ → CO₂ + H₂O)

Chemolithotrophs
(H₂ + O₂ → H₂O)

Phototrophs
(light → ATP)

ATP
Chlorophyll

Chlorophyll is a pigment found in plants, algae, and some bacteria. It is responsible for the green color of leaves and is involved in the process of photosynthesis. The diagram shows the molecular structure of Chlorophyll a, which consists of a porphyrin ring with a magnesium atom at the center, bound to phytol and carotenoids. The absorbance spectrum on the right indicates the wavelength at which Chlorophyll a absorbs light, with peaks at 430 and 660 nm, which are used for photosynthesis.
How photosynthesis works

Light (photons), captured by chlorophyll, excite an electron to a high energy state.

It then descends a chemical (enzyme) ladder, releasing energy to other compounds, while returning to its original state.
Bacteria have other photosystems, and respond to slightly different wavelengths.
Higher plants have two photosystems
All life must respire in order to have energy to live.

This is how it is done in all higher organisms.

Energy from glucose is converted to ATP, FADH and NADPH, and CO₂ is released.
FADH and NADPH are later converted to ATP.
This branch is somewhat counterintuitive
Archaea: two groups

- **Hyperthermophiles**
  - **Methanogens**
  - **Halophiles**
  - **Acidophiles**

- **Env-marine**

  - **Halobacterium**
  - **Natronobacterium**
  - **Halophilic methanogens**
  - **Methanobacterium**
  - **Methanococcus**
  - **Pyrococcus**
  - **Pyrolobus**
  - **Thermoproteus**
  - **Desulfurococcus**

- **Sulfolobus**

- **Methanogens, halophiles, acidophiles**
Ester

\[
\text{CH}_2\text{OH} \quad \text{O} \\
\text{H} \quad \text{O} \quad \text{C} \quad \text{CH}_2 - (\text{CH}_2)_ {13} - \text{CH}_3 \\
\text{CH}_2\text{OH}
\]

*Bacteria, Eukarya*

Ether

\[
\text{CH}_2\text{OH} \\
\text{H} \quad \text{O} \quad \text{C} \quad \text{CH}_2 - \text{C} - (\text{CH}_2)_3 - \text{C} - (\text{CH}_2)_3 - \text{C} - (\text{CH}_2)_3 - \text{C} - \text{CH}_3 \\
\text{CH}_2\text{OH} \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 
\]

*Archaea*
Bacteria

- Spirochetes
- Planctomycetes
- Green sulfur bacteria
- Cyanobacteria
- Gram-positive bacteria
- Proteobacteria
- Thermotoga
- Deinococcus
- Green nonsulfur bacteria
- Aquifex
- Env-OP2
Eukarya

- Flagellates
- Slime molds
- Diplomonads
- Trichomonads

Early-branching, lack mitochondria

Ciliates
- Animals
  - Green algae
  - Plants
  - Red algae
  - Fungi
- Diatoms
- Brown algae
Life in the Precambrian
Major Steps in the Precambrian Evolution of Life

1. Origin of Life (4.0 - 3.8 Gyrs)
2. Photosynthesis (3.8 - 3.5 Gyrs)  *Carbon isotopes*
3. Aerobic (Oxygen-based) Respiration (3-2 Gyrs)
4. Eukaryotes / Endosymbiosis (2.1-1.6 Gyrs)
5. Sex / Death (1.2 - 1 Gyrs)
6. Multicellular Life (1,000 - 800 Myrs)
7. Skeletons & Shells (600 Myrs)

* All dates are approximate
Oldest Fossils: Apex Chert, Australia (3.5 Gyr)
Apex Chert Fossils (3.5 Gyr)
First Fossils of a Photosynthetic organism
Cyanobacteria from Apex Chert

3.5 Ga
Figure 11-23

*Earth System History, Third Edition*

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Formed Colonies called Stromatolites
Stromatolites
Mats of Cyanobacteria
Modern Stromatolites: Shark Bay, Australia
North Pole, Australia Stromatolite
(3.5 Gyrs)

Existed on Earth for over 3.5 Gyrs!
Precambrian conical **stromatolite** from the McArthur Group, Australia. Field photo showing weathered outcrop of small conical stromatolites (*Conophyton*) in the Tooganinnie Formation, McArthur Group, near Tanumbirini, 700 km southeast of Darwin, Northern Territory, Australia. **1.6 billion years old.**
Belt Super Group
(~1.4 Ga)
Laminated siltstones and Stromatolites
Precambrian cyanobacterial colony.

*Eoentophysalis belcerensis*

Kasegalik Formation, Belcher Group *(2 billion years old)*
Gunflint Formation, Canada

1.9 Gyrs
Precambrian filamentous cyanobacteria. Cyanobacteria (*Nostocales*) from the Bitter Springs Chert of Central Australia, 850 million years old
4. Eukaryotes & Endosymbiosis

*Chuaria circularis*  
*Tawuia dalensis*  

800 Myrs

Fossil Acritarch  
First Appear **1.6 Gyrs**
Oldest Eukaryote

*Grypania spiralis*

1.3 Gyrs

2.1 Gyrs
Endosymbiosis in Action

Coral Polyps

Zooxanthellae
5. Sexual Reproduction

Bottom Line: Increase in Genetic Diversity
Evolution can occur faster
The Price of Sex:

With Sex comes “True Genetic Death”
6. Multi-Celled Organism

Colony - Group of cells each functioning as a single organism

Multi-Celled Organism - Group of cells that have differentiated to perform different tasks - together make up a single organism
A Modern Colony

Volvax (algae)

Plant’s are the first to ‘colonize’, then Animals
Multicellular Animal Embryos

Doushantuo Formation, China
~ 590 to 560 Myr

Fossil Embryo from Neoproterozoic
Major Steps in the Precambrian Evolution of Life

1. Origin of Life (3.8-3.5 Gyrs)
2. Photosynthesis (3.5 Gyrs)
3. Aerobic (Oxygen-based) Respiration (3-2 Gyrs)
4. Eukaryotes / Endosymbiosis (2.1-1.5 Gyrs)
5. Sex / Death (1 Gyrs)
6. Multicellular Life (800 Myrs)
7. Skeletons & Shells (600 Myrs)

* All dates are approximate
Ediacara Hills, Australia

Dickinsonia
Ediacara Fauna

**Spriggina floundersi**
*Early arthropod (trilobite)?*
Microdictyon
Segmented worm?

Cyclomedusa
jellyfish?
Cyclomedusa
Charnia Spun

Ediacaran Trace fossil
Charnia (a sea pen: a colonial cnidarian)
Kimberella quadrata
A mollusk?
Yorgia trace
Late Precambrian Trace Fossils
7. Skeletons and Shells

Small Shelly Fossils (SSF’s)

Tommotian Fauna: first skeletons, then vanished
Cambrian Explosion
Life on Earth - Timing

4.6 Byrs

No Life

Single Celled Life Only

First Photosynthesis & Stromatolites

Oxygen Revolution
Aerobic Respiration

First Eukaryotes

First Sex

Multi-Celled

Today