Major Proterozoic Events
Formation of large continents

- Archean microcontinents (granite plutons and greenstone belts) accrete to form the nuclei of large continents such as Laurentia (North America and Greenland) - *Cratonization*.

- Essentially modern plate tectonics:
  - Passive margin continental shelves.
  - Orogenic belts (plate collisions forming mountain chains).
**Major Proterozoic Events**

**Increase in atmospheric $O_2$**

- 3.0 - 2.0 Ga - Abundant BIFs - oxygen reacting with iron in the oceans, not entering the atmosphere - $O_2$ produced by evolution of cyanobacteria?
- 1.9 Ga - First extensive red beds - oxygen building up in the atmosphere.
Banded iron formation, 2.1 Ga (Early Proterozoic - Canada) - oxidation of iron in the oceans and deposition of oxide on the seafloor.

Blouberg Formation red beds, South Africa about 1.9 Ga (Early Proterozoic Eon) - evidence for rising levels of atmospheric oxygen.

Major Proterozoic Events

Glaciation

- 2.0 Ga - First evidence for glaciation (Ice Age)
- Gowganda Formation, Canada
  - Tillite - mix of boulders, cobbles, sand and mud deposited by glacial ice.
  - Dropstones - cobbles and pebbles in laminated shales - released by melting icebergs over deep water.
- Triggered by removal of CH$_4$ greenhouse by buildup of oxygen in the atmosphere?
Gowganda tillite and dropstone 1.8 Ga, Canada

The Great Oxygenation Event 2.0 - 2.3 Billion Years Ago

Methane is oxidized by $O_2$ to $CO_2$ and blue skies appear!

Major Proterozoic Events

Diversification of stromatolites

- Bacterial mats evolve to thrive in a wide variety of environments.
- Stromatolite structures become abundant and diverse.
- Reef-like masses develop along shorelines.
- Stromatolites promote formation of limestone (carbonate sedimentary rock).
  - Limestone removes $CO_2$ from the atmosphere.
Modern Stromatolites

Proterozoic Stromatolites - when bacterial mats ruled!

Rimmed shelf

Ramp

Proterozoic Stromatolites
Major Proterozoic Events

Snowball Earth?

- 750 - 600 Ma (Late Proterozoic) - Evidence for repeated global glaciations.
- Paleogeographic reconstructions show most continents near the equator.
- Late Proterozoic rocks include interlayered tillites and thick carbonates (limestones).
- Alternating glacial and tropical periods near the equator. Earth’s climate shifts between extreme icehouse and extreme greenhouse!
Rodinia
Supercontinent

Location of glacial deposits

Major Proterozoic Events

Snowball Earth?

- Large continental glaciers near the equator imply a very cold Earth.
- Carbon isotopes in limestones below the glacial deposits are depleted in $^{12}$C - high bio-productivity
- The capping limestones above the glacial deposits are enriched in $^{12}$C - low bio-productivity.
- Global ice age wiped out bio-productivity in the oceans?
Global ice age

Less $^{12}$C because plankton are thriving and removing $^{12}$C from the water.

More $^{12}$C because most plankton were killed off by the ice age.

$^{12}$C decreases as plankton recover and begin thriving again.

$^{12}$C $<$ $^{13}$C

$^{12}$C $=$ $^{13}$C

$^{12}$C $>$ $^{13}$C

$^{12}$C $<$ $^{13}$C

Earth’s Thermostat

- Carbon dioxide (CO$_2$) is a greenhouse gas.
- Volcanoes pump CO$_2$ into the atmosphere - turns up the heat.
- Carbonate burial removes CO$_2$ from the atmosphere - cools the Earth.

Snowball Earth

Stage One

- Continents near equator develop large carbonate deposits along their continental shelves.
- This may have increased when Rodinia began to split up.
- CO$_2$ levels drop, greenhouse reduced, Earth cools.
• Cooling Earth develops sea ice cover and continental glaciers.
• Increased albedo reflects sunlight, enhances cooling.
• Formation of carbonate stops.
• CO₂ no longer removed from the atmosphere.

Snowball Earth
Stage Two

• Earth is completely covered in ice - icehouse condition.
• Surface temperature from 0°C to -40°C.
• Volcanoes continue to erupt.
• CO₂ levels rise in the atmosphere, but biological activity takes time to recover.

Snowball Earth
Stage Three

• Lag in biological production of limestone and removal of CO₂.
• CO₂ reaches 100 times normal level to form greenhouse.
• Glaciers and sea ice melt rapidly, greenhouse accelerates.
• Hothouse Earth develops massive carbonate deposits.
• Carbonate formation reduces CO₂, starts cycle again.
Unanswered Questions about Snowball Earth

- How extensive was the ice cover across the planet?
- What brought the snowball Earth period to an end?
- How does the snowball Earth interval relate to the first appearance of marine animal fossils shortly after the end of the last glaciation?
- Could mixing and oxygenation of the ocean due to cold water currents have triggered the evolution of animal life (the Ediacaran fauna and later the Cambrian explosion)?