Big Bang 15Ga – elementary particles, light elements as H and He – stars and galaxies of the first generation – white dwarfs. Neutron stars, black holes, further light elements – supernovas – heavy elements, stars of the second generation with planets – chemical evolution – geological and biologic evolutiom

EARTH DIFFERENTIATION

- **How did the layering occur?**
  - Two hypotheses
    - Homogenous accretion (cold)
      - uniform density at beginning
      - warming melts iron and nickel etc.
      - warming from?
        - bombardment by particles
        - radioactive decay
        - compression

Homogeneous Accretion Model

uniform density at beginning

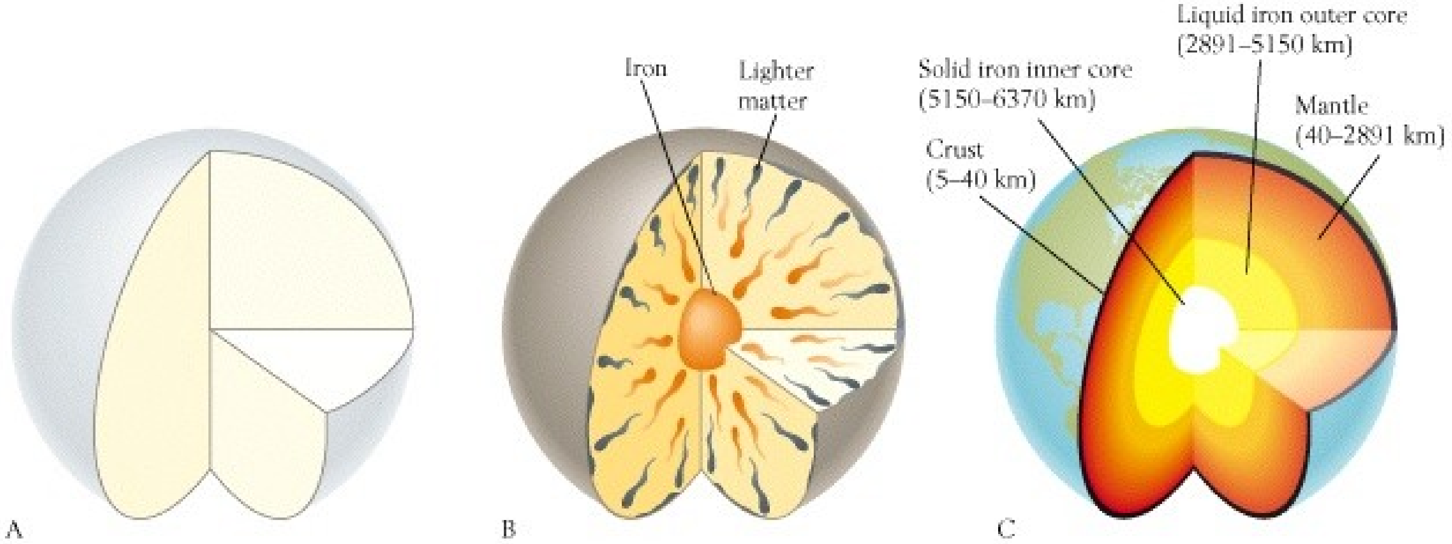
- Material with carbonaceous chondrite composition is heated, melted, and fractionated.

Chondrite - rich in the silicite minerals olivine and pyroxene.

- Fe-Ni settles to core of body (gravity)
- Volatiles are degassed
- Si is concentrated in a "crust"

Origin of Earth (cont.)

Homogeneous molten Earth → Segregation of materials by density → Final differentiation of core/mantle/crust



Heterogeneous Accretion Model

- FeNi and other refractory elements condense first.
- If accretion times are rapid compared to condensation times, an FeNi core accretes first, followed by silicate mantle

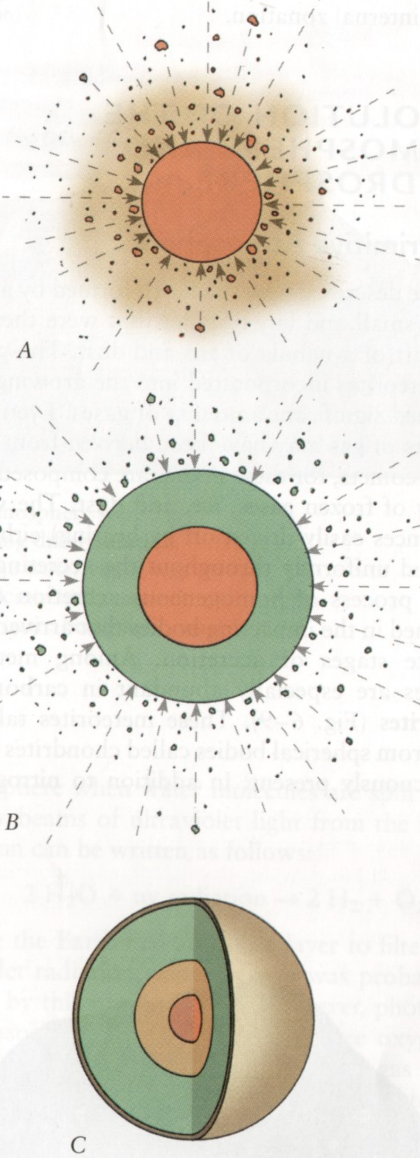
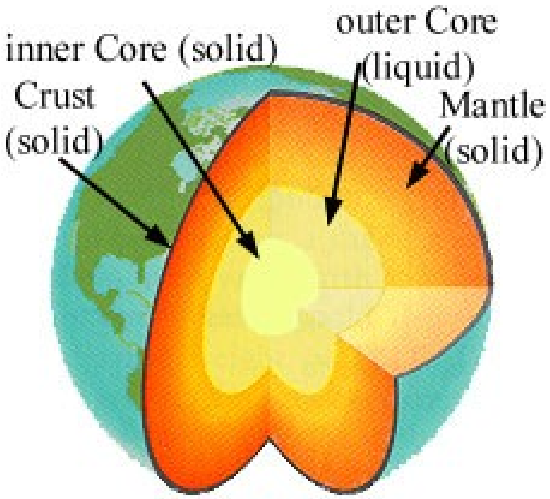
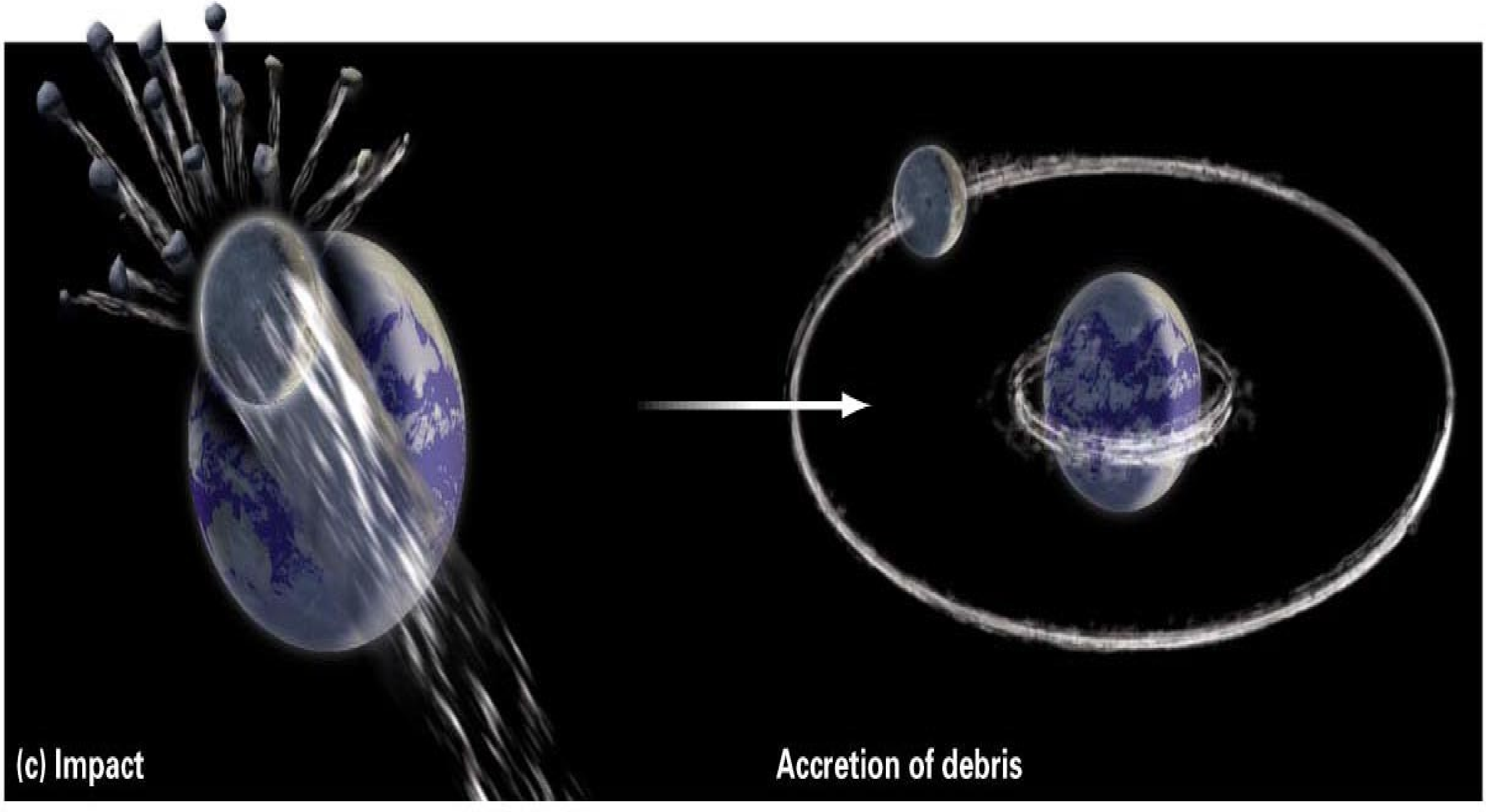


FIGURE 6–8 Origin of the Earth's core according to the hot heterogeneous model of accretion. (A) Primarily iron and nickel condense, collect, and form a core. (B) Silicates envelop the earlier formed core and form a mantle. (C) The mantle differentiates and provides the materials for the crust.



After the initial segregation into a central iron (+nickel) core and an outer silicate shell, further differentiation occurred into an inner (solid) and outer (liquid) **core** (a pressure effect: solid iron is more densely packed than liquid iron), the **mantel** (Fe+Mg silicates) and the **crust** (K+Na silicates). The magma ocean would have cooled to form **a layer of basaltic crust** (such as is present beneath the oceans today). **Continental crust** would have formed form later. It is probable that the Earth’s initial crust was **remelted several times** due to impacts with large asteroids.

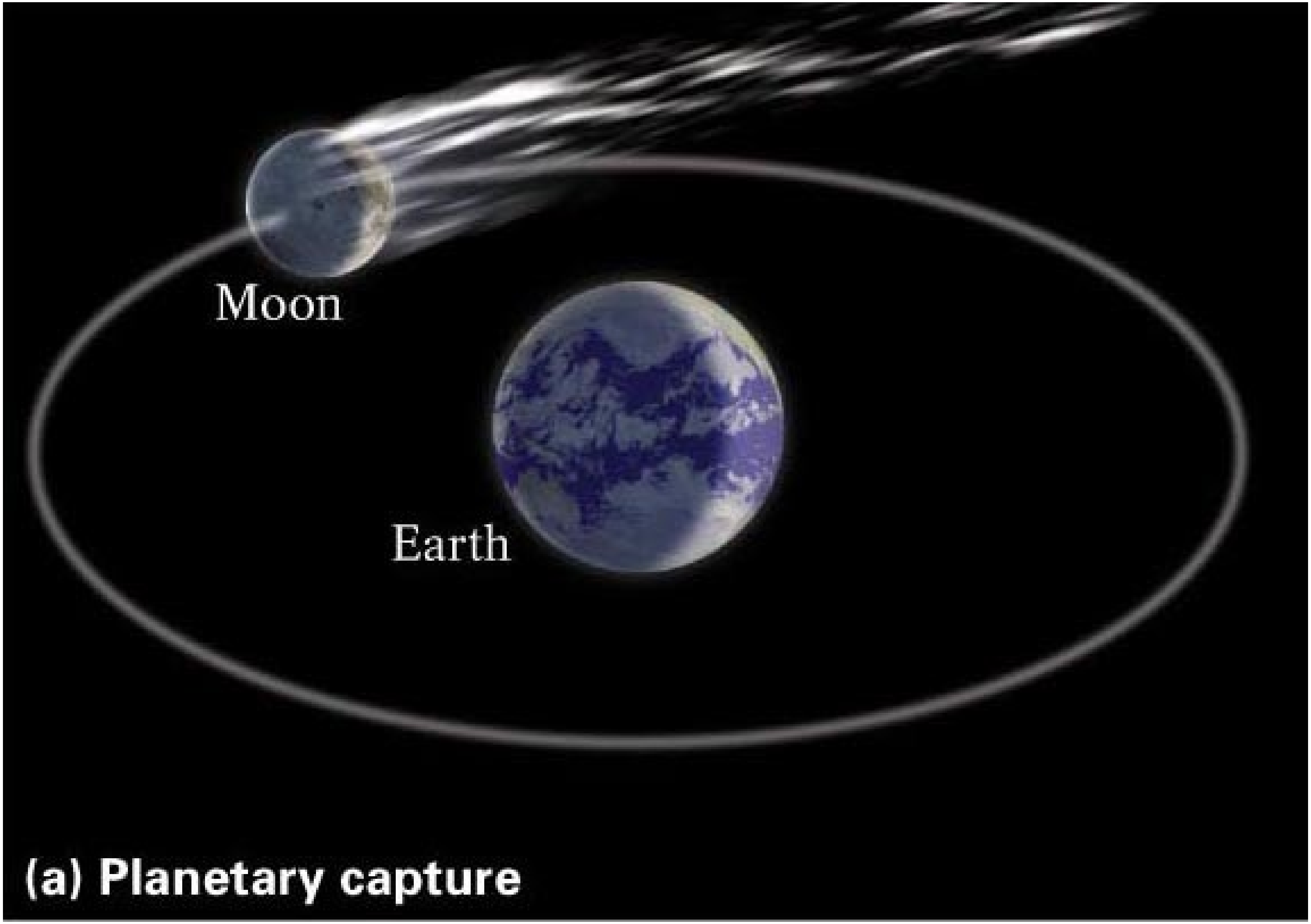
Impact hypothesis



Origin of the Moon

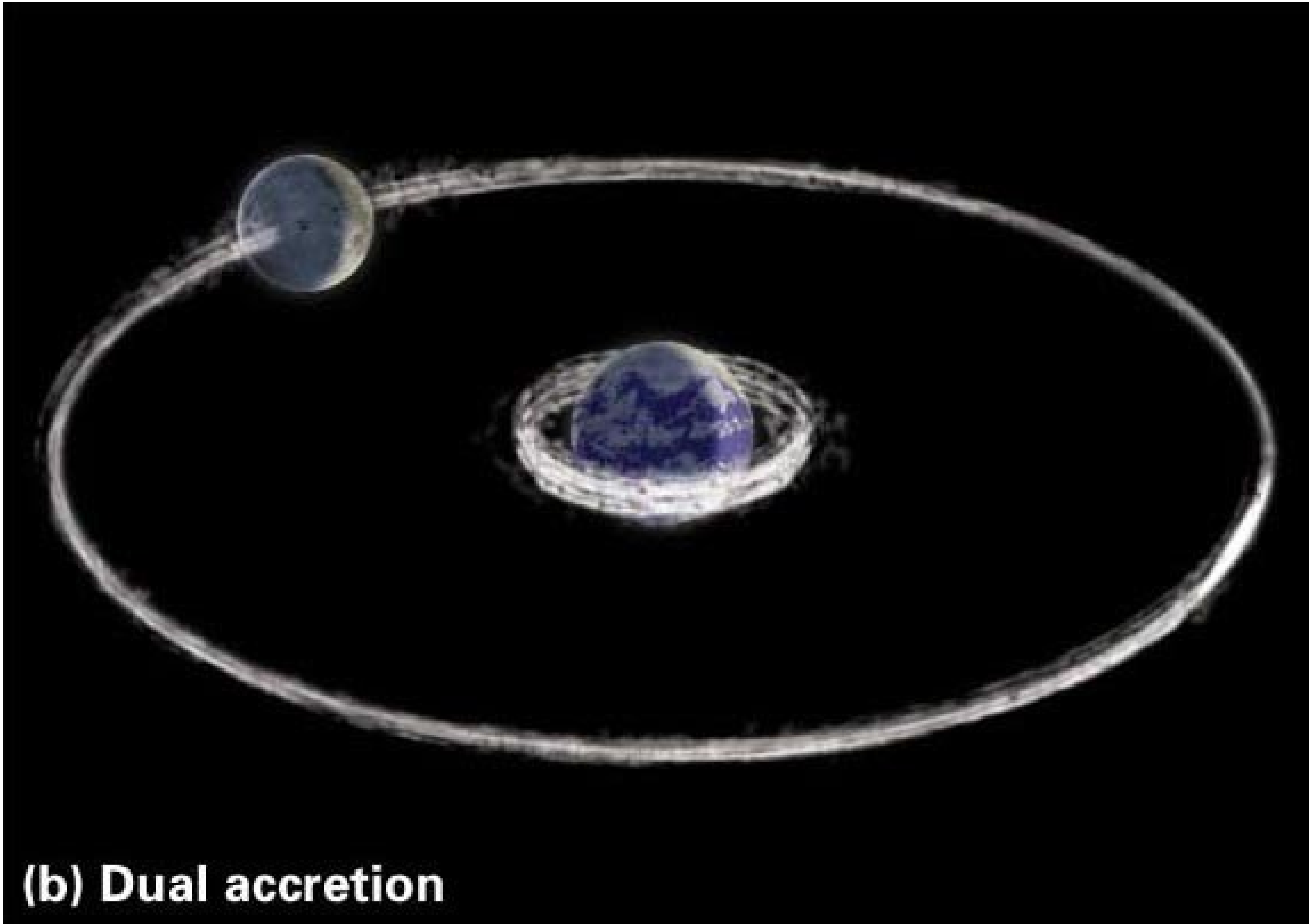
- **Moon** originated when a large (Mars-size) body collided with Earth (“*glancing blow*”)
  - Core of impacting body was absorbed into Earth’s core
  - Remaining mantle of impacting body and was then captured in Earth’s gravitational field
- Collision caused Earth’s *rotation to increase*
- Moon has *no water*, a *metallic core* and *feldspar-rich outer layer*; relative abundance of iron and magnesium differ from that in Earth’s mantle

Planetary capture hypothesis



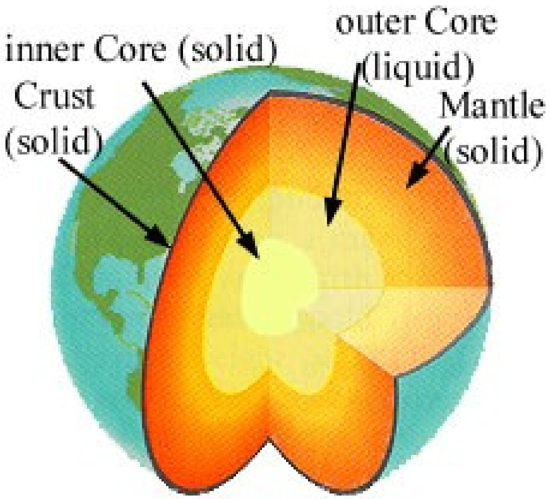
(a) Planetary capture

Dual accretion hypothesis



EARTH DIFFERENTIATION

- **Crust**
  - Oldest rocks on Earth
- **How old is Earth??**
  - Indirect evidence
    - moon rocks - oldest 4.6 by
    - meteorites - oldest 4.6 by



After the initial segregation into a central iron (+nickel) core and an outer silicate shell, further differentiation occurred into an inner (solid) and outer (liquid) **core** (a pressure effect: solid iron is more densely packed than liquid iron), the **mantel** (Fe+Mg silicates) and the **crust** (K+Na silicates). The magma ocean would have cooled to form **a layer of basaltic crust** (such as is present beneath the oceans today). **Continental crust** would have formed form later. It is probable that the Earth's initial crust was **remelted several times** due to impacts with large asteroids.

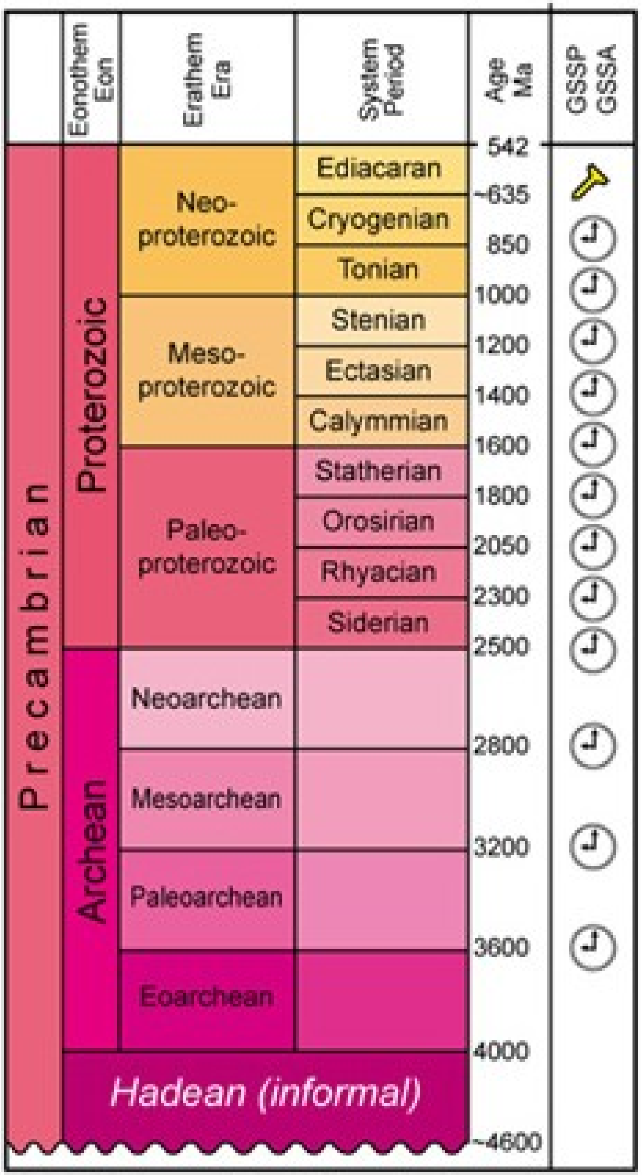
The Precambrian

The Precambrian is an informal name given to the age of the first three eons of Earth history.

1. **Hadean (Eon) (Early Archean)** 4.6 - 3.8 bya (or 4.6 - 3.96 bya)
   No rock record. This is the time of the origin of the Earth. Earth was mostly hot molten rock at that time.
2. **Archean Eon**3.8-2.5 bya

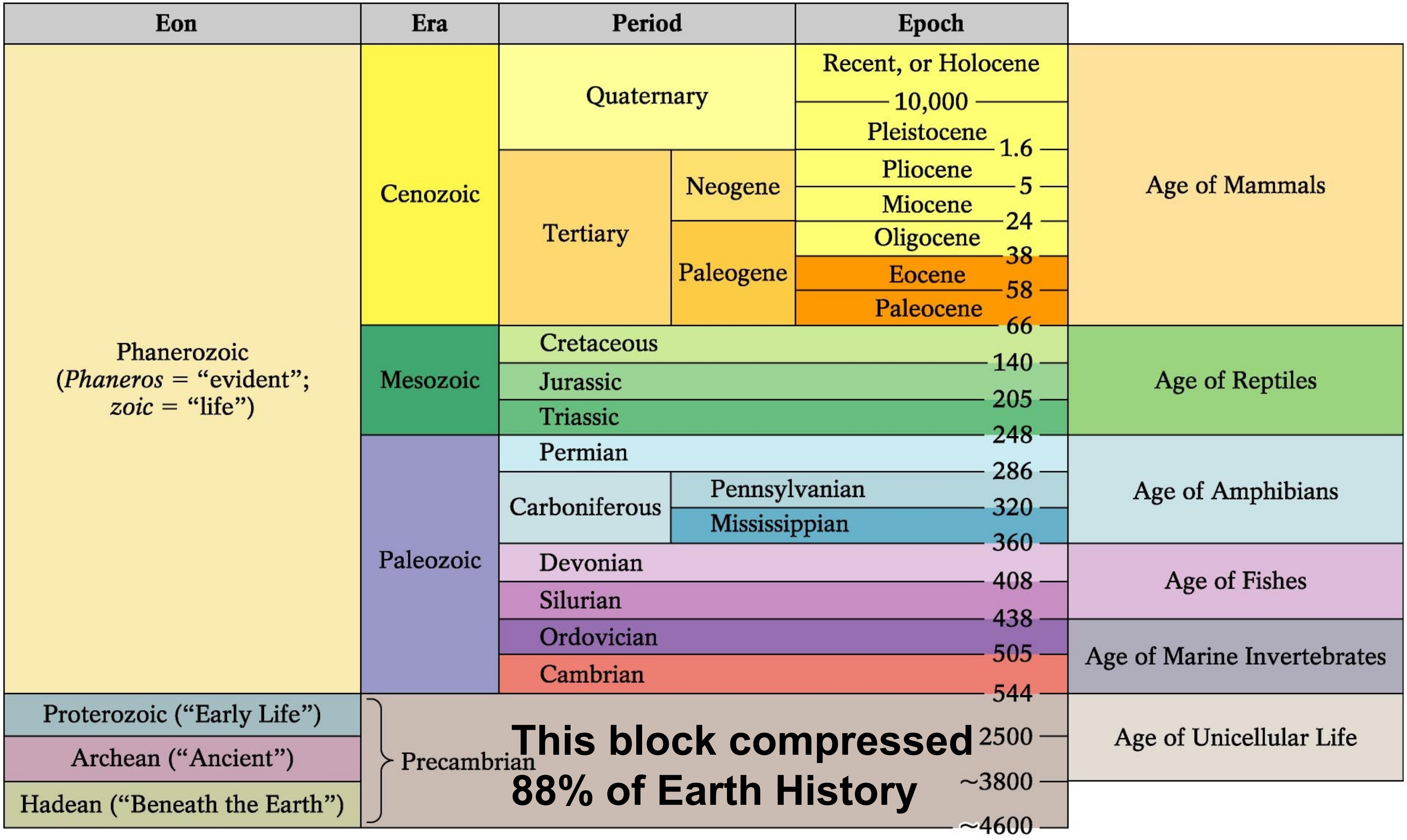
3. **Proterozoic Eon** 2.5-0.544 bya

International Stratigraphical Chart



	Eonothem Eon	Erathem Era	System Period	Age Ma	GSSP GSSA
				542	
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	~635	📍
			Cryogenian	850	🕒
			Tonian	1000	🕒
		Meso-proterozoic	Stenian	1200	🕒
			Ectasian	1400	🕒
			Calymmian	1600	🕒
		Paleo-proterozoic	Statherian	1800	🕒
			Orosirian	2050	🕒
			Rhyacian	2300	🕒
			Siderian	2500	🕒
	Archean	Neoarchean		2800	🕒
		Mesoarchean		3200	🕒
		Paleoarchean		3600	🕒
		Eoarchean		4000	
	Hadean (informal)			~4600	

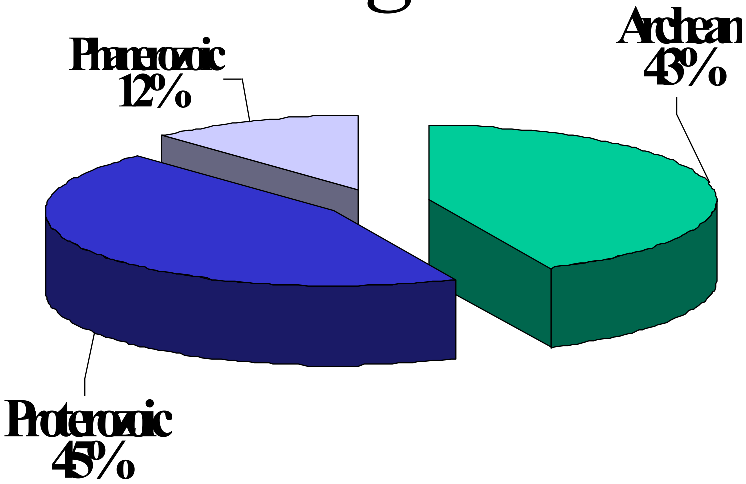
Geologic time scale



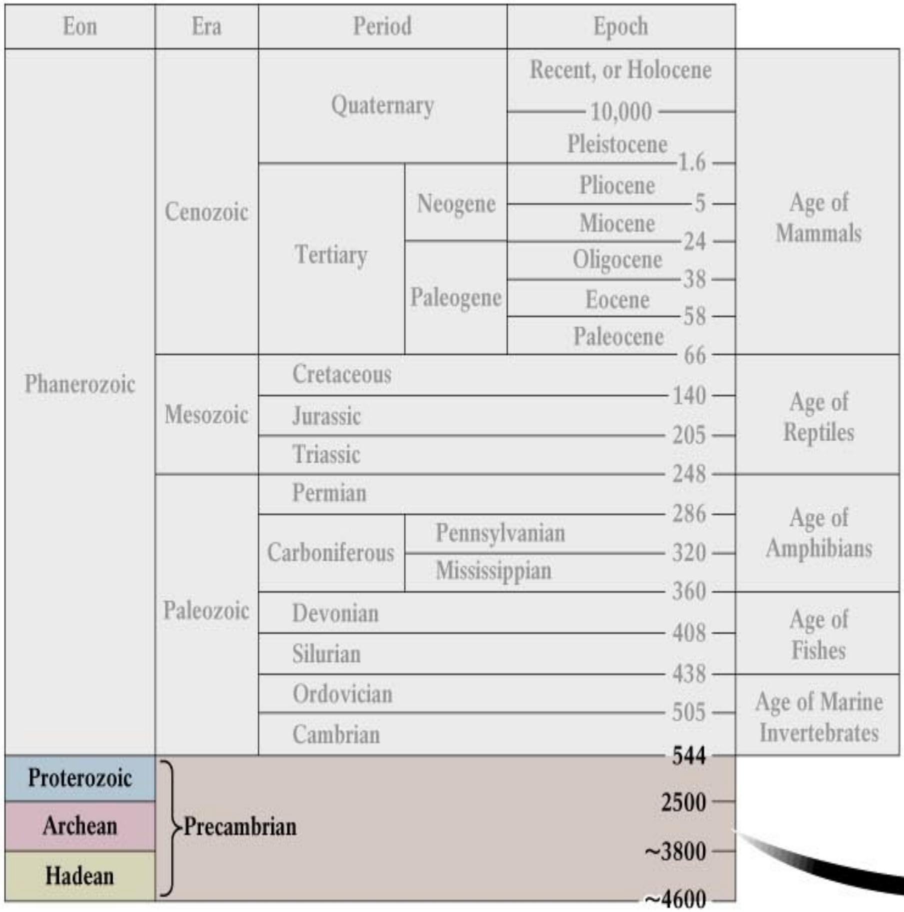
Eon	Era	Period		Epoch		
Phanerozoic (*Phaneros* = "evident"; *zoic* = "life")	Cenozoic	Quaternary		Recent, or Holocene	10,000	Age of Mammals
				Pleistocene	1.6	
		Tertiary	Neogene	Pliocene	5	
				Miocene	24	
			Paleogene	Oligocene	38	
				Eocene	58	
				Paleocene	66	
	Mesozoic	Cretaceous			140	Age of Reptiles
		Jurassic			205	
		Triassic			248	
	Paleozoic	Permian			286	Age of Amphibians
		Carboniferous	Pennsylvanian		320	
			Mississippian		360	
		Devonian			408	Age of Fishes
		Silurian			438	
		Ordovician			505	Age of Marine Invertebrates
		Cambrian			544	
Proterozoic ("Early Life")	Precambrian				2500	Age of Unicellular Life
Archean ("Ancient")					~3800	
Hadean ("Beneath the Earth")					~4600	

This block compressed 88% of Earth History

Geologic time



Key Events of Precambrian time



Eon	Era	Period		Epoch		
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		Devonian			408	Age of Fishes
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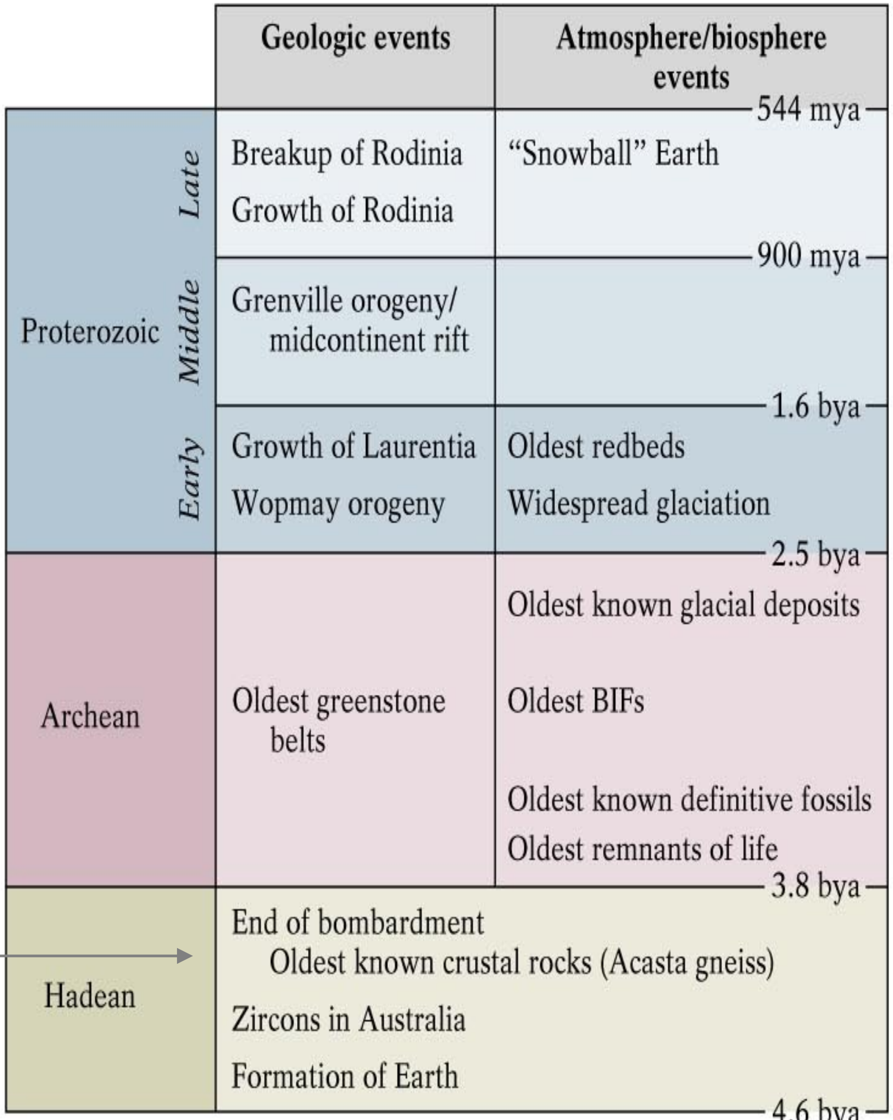
		Ordovician			505	Age of Marine Invertebrates
		Cambrian			**544**	
Proterozoic	**Precambrian**				**2500**	
Archean					**~3800**	
Hadean					**~4600**	



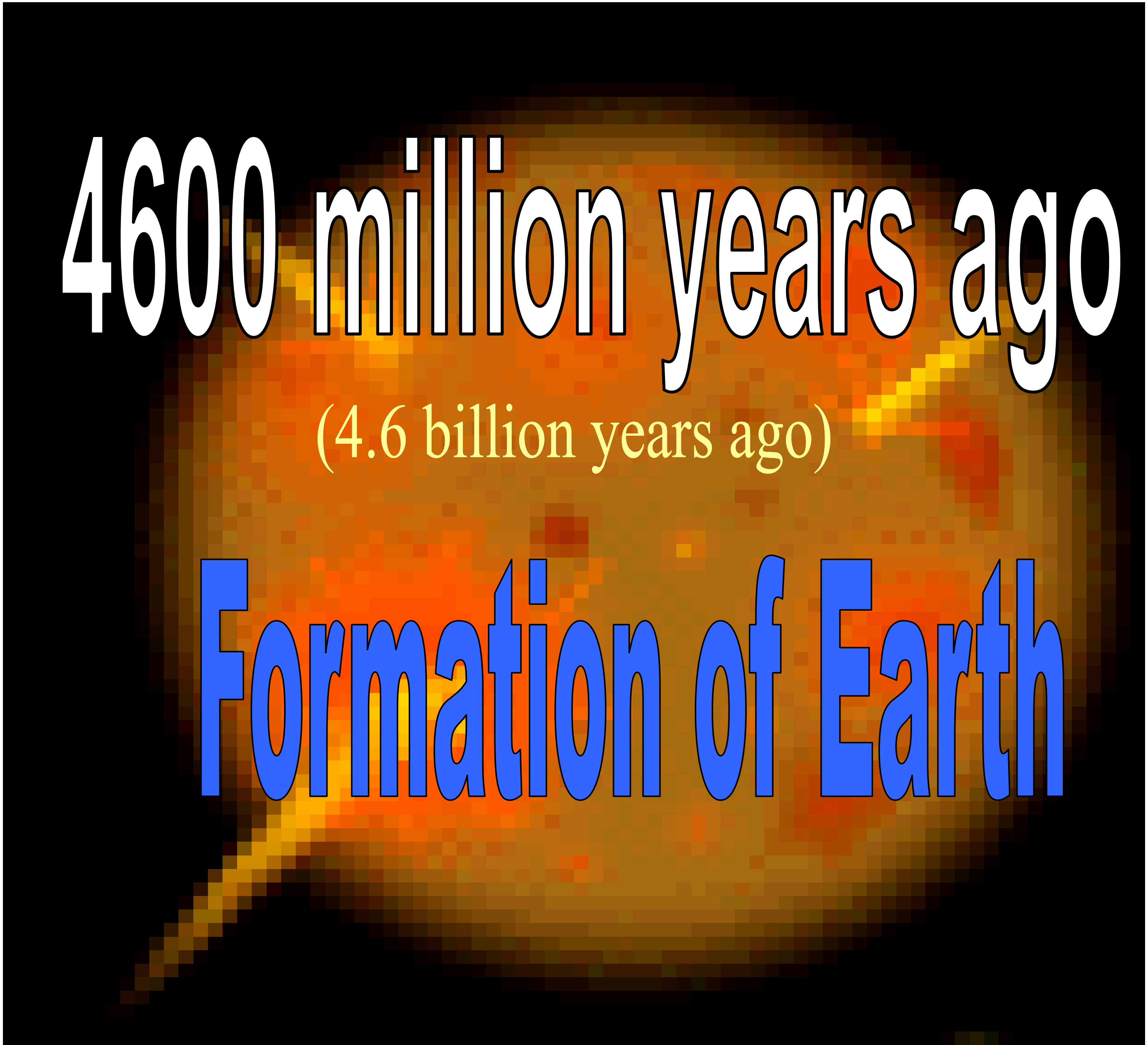
		Geologic events	**Atmosphere/biosphere events**	544 mya
Proterozoic	*Late*	Breakup of Rodinia Growth of Rodinia	"Snowball" Earth	900 mya
	Middle	Grenville orogeny/ midcontinent rift		1.6 bya
	Early	Growth of Laurentia Wopmay orogeny	Oldest redbeds Widespread glaciation	2.5 bya
Archean		Oldest greenstone belts	Oldest known glacial deposits Oldest BIFs Oldest known definitive fossils Oldest remnants of life	3.8 bya
Hadean		End of bombardment Oldest known crustal rocks (Acasta gneiss) Zircons in Australia Formation of Earth		4.6 bya

Acasta Gneiss is dated at
3.96 bya. It is near Yellowknife Lake , NWT Canada
Zircons possibly a bit older in Australia

Hadean

4600 million years ago

(4.6 billion years ago)



Formation of Earth

4500 million years ago

(4.5 billion years ago)

Accretion of Earth

Formation of the Moon

Hot, Barren, Waterless Early Earth

- Shortly after accretion, Earth was
  - a rapidly rotating, hot, barren, waterless planet
  - **bombarded by comets and meteorites**
  - with no continents, intense cosmic radiation
  - widespread volcanism

4200 million years ago

(4.2 billion years ago)

Early Atmosphere

No Life

Earth's early atmosphere

- Earth **did not** inherit its atmosphere from the initial asteroids that coalesced to form it
- Earliest atmosphere was generated by **emission of internal gases** (*similar to those emitted today from volcanoes*):
  - **Origin of the atmosphere**
    Volcanic outgassing (or degassing)
    H_2O, H_2, HCl, CO, CO_2, N_2, Sulfur gases
- Note **absence of oxygen**, which was rare prior to the advent of *photosynthetic organisms*!

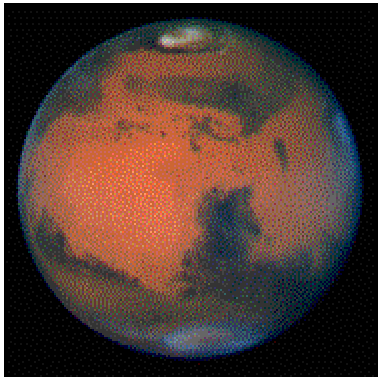
Precambrian

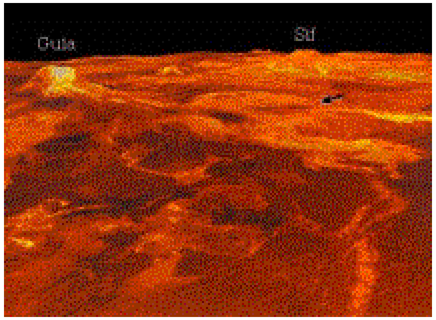
Early Atmosphere

- Early permanent earth atmosphere mostly Nitrogen (inert) and CO_2

  Post-differentiation start of liquid core dynamo

- Liquid water is required to remove CO_2 from atmosphere.
  - Mars is too cold to have liquid water.
  - Venus is too hot.
  - Both have CO_2 atmospheres.
- On Earth, most of the world's CO_2 is locked up in limestones, dolomites, and life!





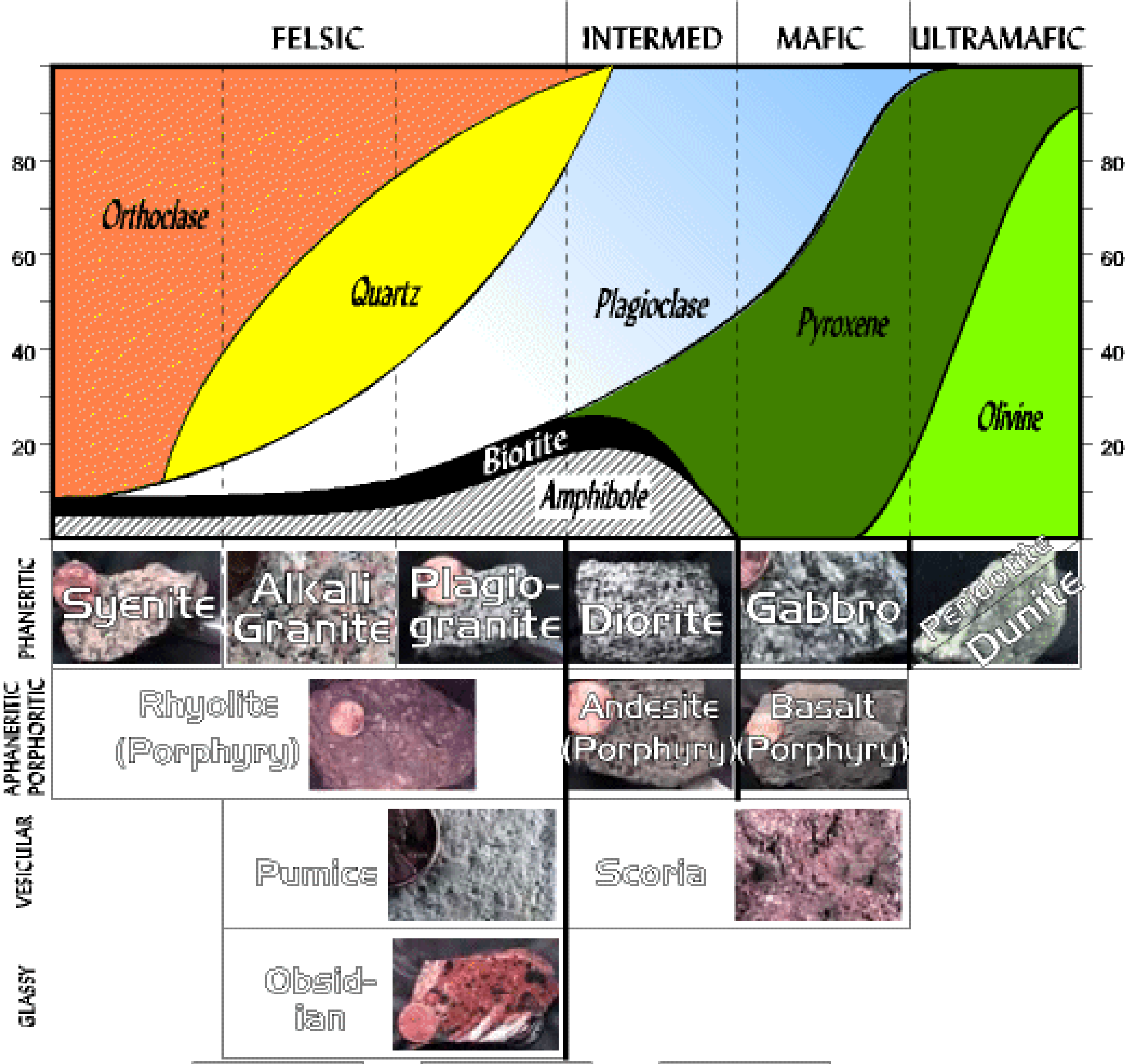
rth

Hadean Crust

- Early Hadean crust was probably thin, unstable and made up of *ultramafic* rock
    - rock with comparatively little silica

- This ultramafic crust was disrupted
    - by upwelling basaltic magma at ridges
    - and consumed at subduction zones

- Later Hadean continental crust may have formed by evolution of *felsic* material
    - only felsic crust, because of its lower density, is immune to destruction by subduction



The rocks to the left do not fit easily into the the chart above.

Oldest rock – Hudson Bay, **Nuvvuagittuq greenstone belt,** amphibolites

Nuvvuagittuq greenstone belt

The **Nuvvuagittuq greenstone belt**, originally named the **Porpoise Cove greenstone belt**, is a greenstone belt on the eastern shore of Hudson Bay in northern Quebec, Canada.

They measured tiny variations in the isotopes (or species of an element that have different numbers of neutrons) of the rare earth elements neodymium and samarium in the rocks and determined that the samples were **from 3.8 to 4.28** billion years old. The Nuvvuagittuq greenstone belt is mainly composed of cummingtonite-plagioclase-biotite-garnet mafic amphibolites called the Ujaraaluk unit (formerly called the "Faux-amphibolite" due to its unusual color).

Rocks from the Ujaraaluk unit have a neodymium-142 isotopic signature that can only be acquired in the Hadean, prior to 4 billion years ago. This isotopic tool has been used to date these rocks at up to 4.3 billion years old.

The mafic rocks from the Nuvvuagittuq belt are interpreted to be volcanic rocks that were hydrothermally altered and includes a **banded iron formation** between a lower **basalt** and an upper unit which includes **basalt and andesite**.

In 2014, a detailed geochemical analysis, revealing layered gradients of ytterbium and niobium, suggested that this formation consists of **pillow lavas from a tectonic subduction zone**, similar to the modern Mariana trench.

4000 million years ago

(4.0 billion years ago)

Oldest continental crust

Originally only oceanic crust - subducted

The Earth’s Oldest Crustal Rocks

The Acasta gneiss in Canada’s NWT was formed 4.0 Byr ago. Along with similar metamorphic rocks in southern Greenland, these are the most ancient pieces of crust remaining on Earth.

Oldest Rock on Earth

- Acasta Gneiss

Origin of Continental Crust

- 3.9 to 4.2 Bya
- Acasta Gneiss
  - 3.96 Ga +/- 3 Ma

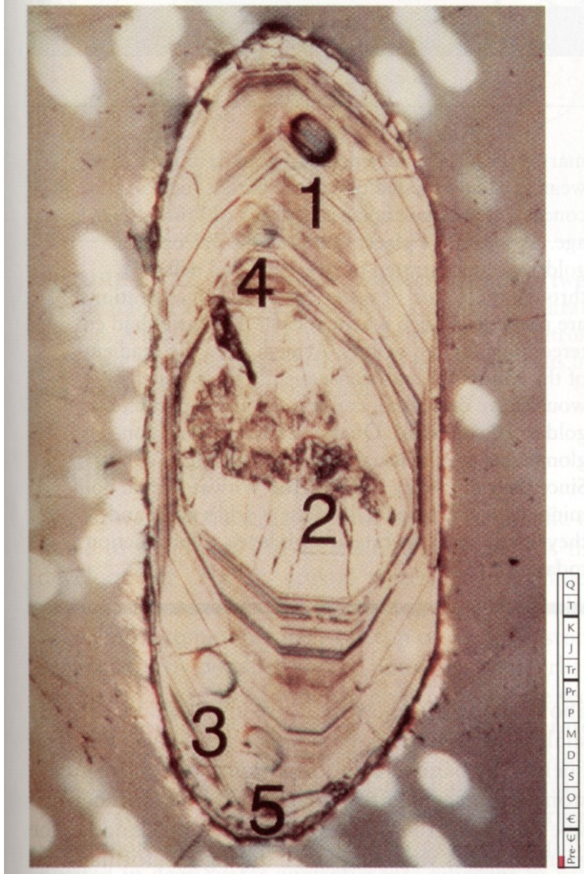
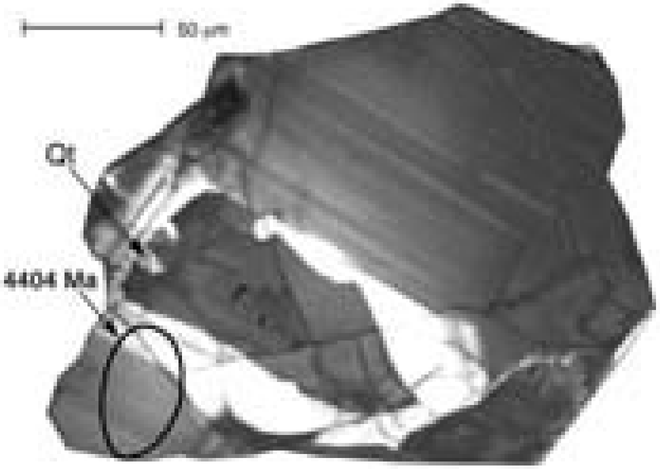


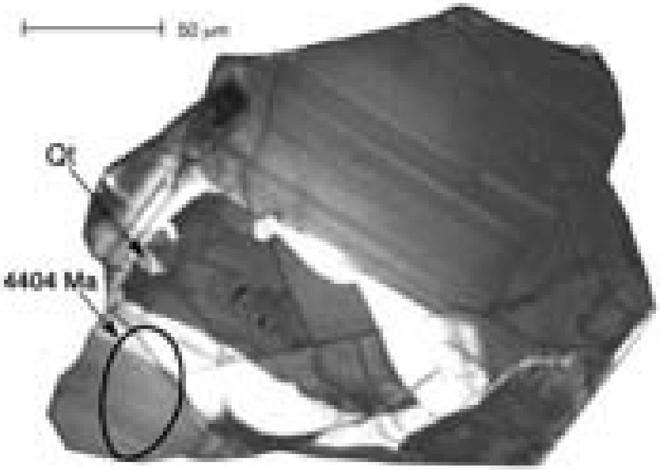
FIGURE 6–18 **Photomicrograph of one of the 3.96-billion-year-old zircon grains extracted from the Acasta Gneiss, Slave province, Northwest Territories of Canada.** The grain is 0.5 mm long. Its polished surface has been etched with acid to highlight crystal growth zones. Numbers refer to points selected for analysis. *(Courtesy of S. A. Bowring.)* Why are zircon crystals particularly valuable in determining isotopic ages?

Oldest Rock on Earth

- Zircon from an Australian sedimentary rock indicates an age of 4.4 Gyr years old.



In addition, the oxygen isotopic compositions of some of these zircons have been interpreted to indicate that more than 4.4 billion years ago there was already water on the surface of the Earth

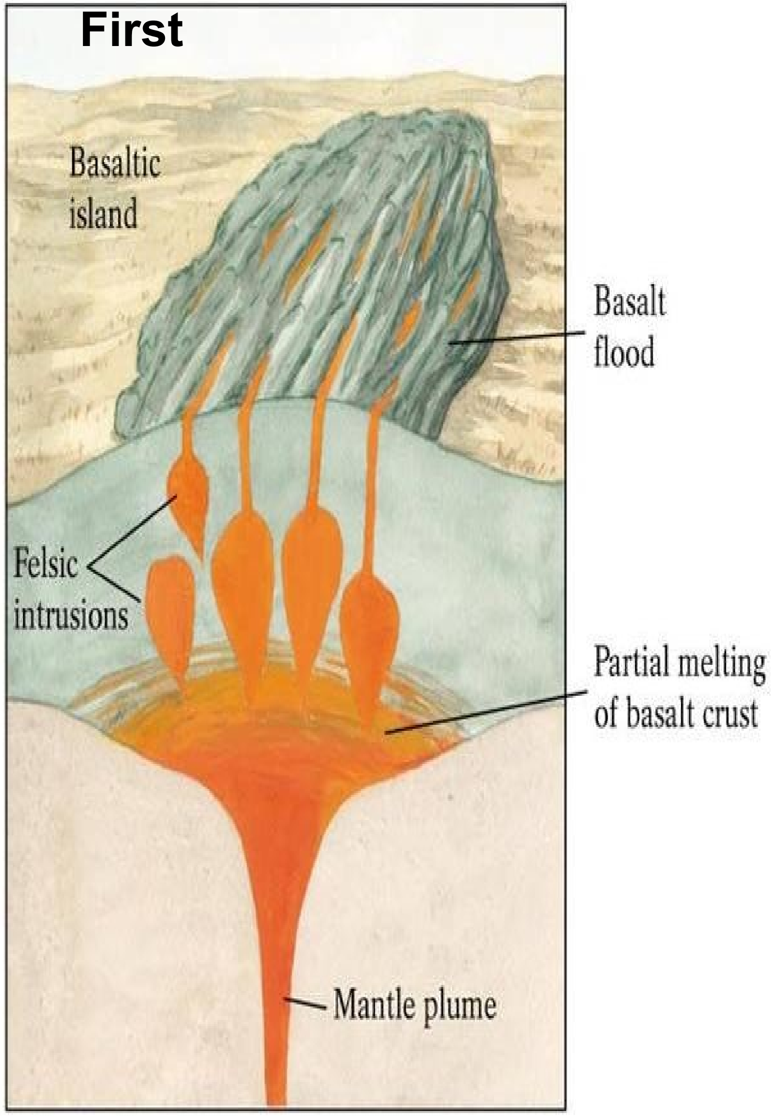


Oldest ContinentalRocks

- Judging from the oldest known rocks on Earth
    - the 4.03-billion-year-old Acasta Gneiss in Canada, some continental crust had evolved prior to 4 billion years ago
- Sedimentary rocks in Australia contain detrital zircons dated at 4.4 billion years old
- These rocks indicted that some kind of Hadean crust was certainly present
    - – distribution is unknown

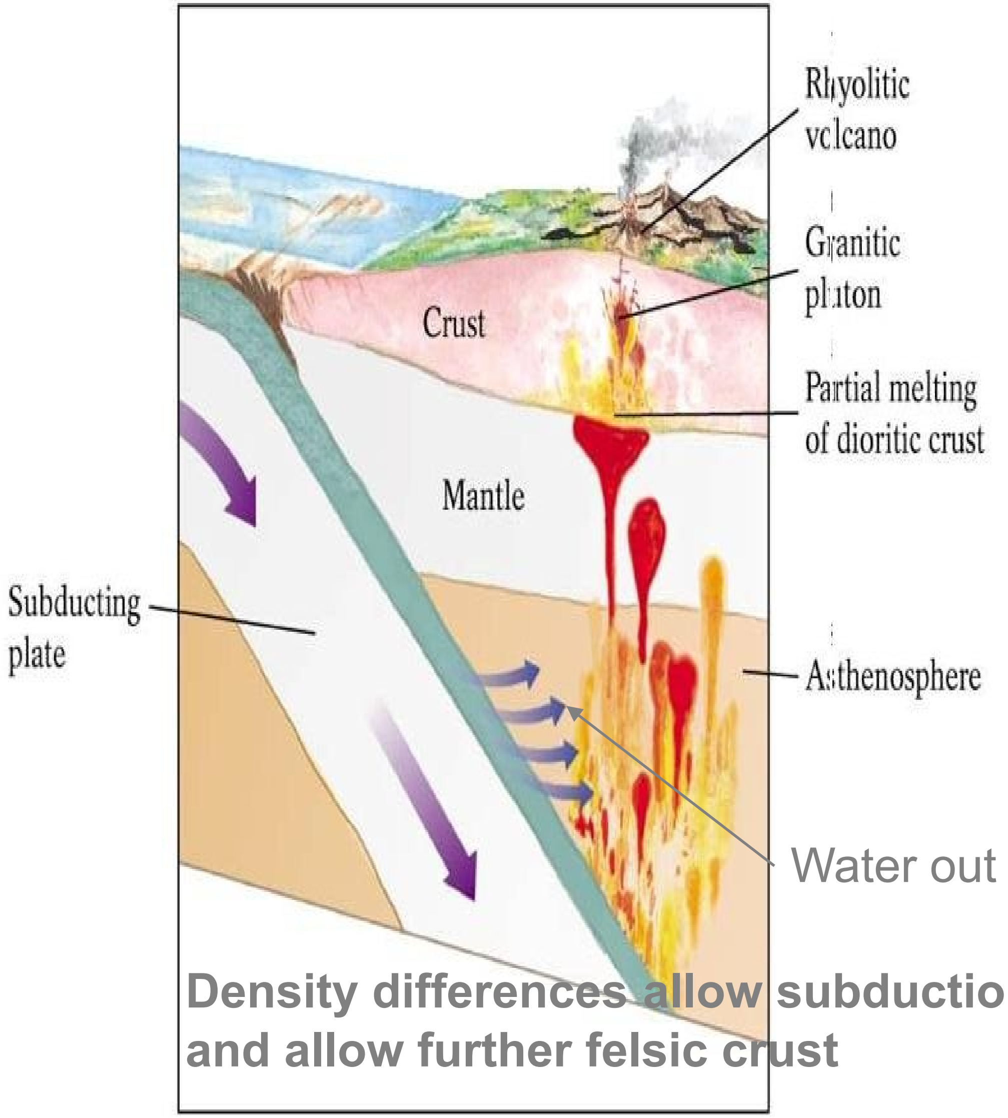
First continental crust

First



(b)

Then:



Water out

Density differences allow subduction and allow further felsic crust

3900 million years ago

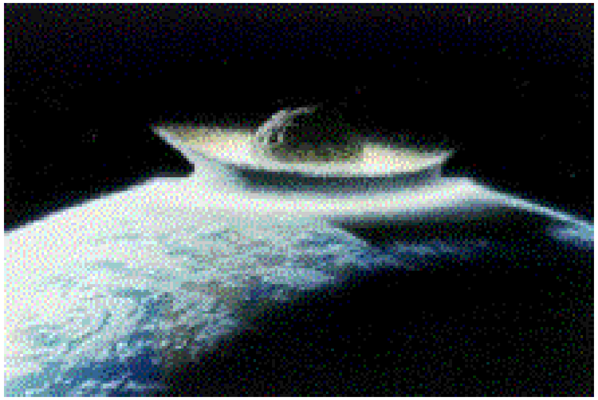
(3.9 billion years ago)

Liquid Water Present
Early Oceans Form

Precambrian

Early Oceans from 4 bya

- Much water vapor from volcanic degassing.
- Salt in oceans is derived from weathering and carried to the oceans by rivers.
- Part of the earth’s water probably came from comets.
  - Comets are literally large dirty snowballs.
  - Provide fresh water.



Hadean

- A time of major changes and Earth formation.
  No rock record.
- **Differentiation of the Earth to form crust, mantle and core**

- **Origin of the atmosphere**
  Volcanic outgassing (or degassing)
  H_2O, H_2, HCl, CO, CO_2, N_2, Sulfur gases
  Little or no free oxygen (O_2); would lead to rapid oxidation of iron minerals
- **Condensation of water vapor formed the hydrosphere**
  ((3,9, ?4,4 Ga) rain; runoff leads to lakes, rivers, oceans
  originally freshwater (rain); may have been acidic from sulfurous gases
  slow accumulation of salts due to weathering
- Beginnning of formation of **oceanic and continental crust** of Earth.

Archean

3800 million years ago

(3.8 billion years ago)

First Bacteria
(Prokaryotic)

3800 million years ago

Oldest oceanic crust

Ophiolite fragment embedded in the Isua supracrustal belt in south-west Greenland.

An ophiolite is a section of the Earth's oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often emplaced onto continental crustal rocks.

Life appeared on Earth during the Archean (3.5 - 3.8 bya).

Geochemical **evidence of photosynthesis** in rocks **3.8 billion years old on Greenland**.
Anomalously high C^{12}/C^{13} ratio, consistent with photosynthesis

Earliest cells were **prokaryotic** (did not have a nucleus or organelles) like bacteria
The earliest cells had to form and exist in **anoxic** conditions.

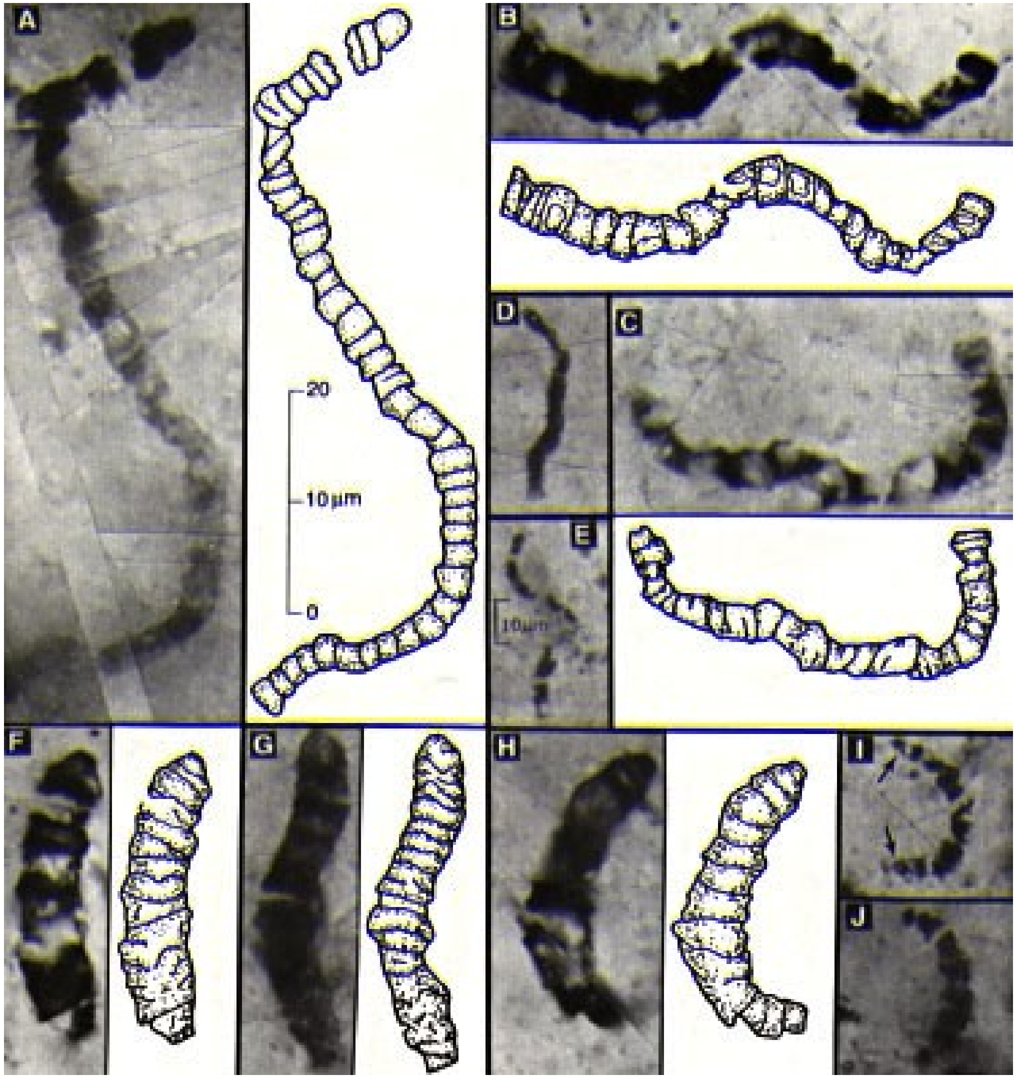
Probably **chemosynthetic**, producing H_2S or CO_2 **Some of the early organisms became photosynthetic** possibly due to a shortage of raw materials for energy.

- Fossils and organo-sedimentary structures remaining from this early life include:
- **Algal filament fossils**
  3.5 b.y. at North Pole, western Australia
- **Spheroidal bacterial structures (Kingdom Monera)**
  Fig Tree Group, South Africa
  3.0 - 3.1 by
  prokaryotic cells; appear to show various stages of cell division
- **Stromatolites** (cyanobacteria or blue-green algae)
  in carbonate sediment
  oldest are 3.4 - 3.5 by old
  also in rocks 2.8 - 3 by old more abundant in Proterozoic rocks

7. Oxygen began to build up in the atmosphere as a waste product of photosynthesis

Chemosynthesis is the process by which certain microbes create energy by mediating chemical reactions.

3.5 bya – first evidence of life on earth!



Microfossils from Western Australia

3700 million years ago

(3.7 billion years ago)

Bacteria

Blue-green algae

3600 million years ago

(3.6 billion years ago)

Bacteria

Blue-green algae

3500 million years ago

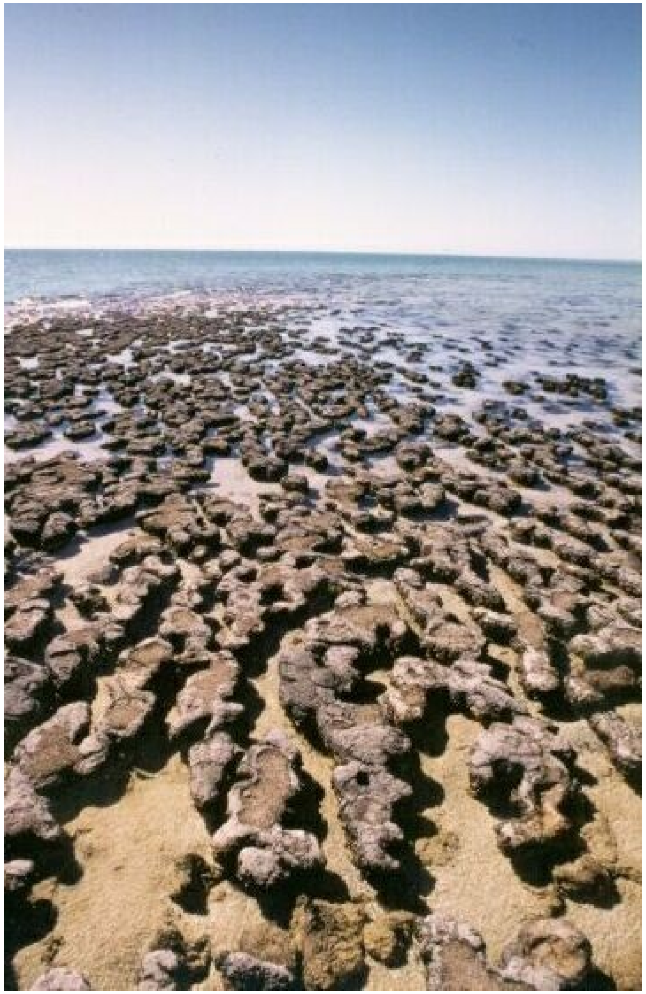
(3.5 billion years ago)

Stromatolites

Cyanobacteria
(aka blue green algae)

Photosynthesis Produces Oxygen!

3.5-2.0 bya only prokaryotes lived

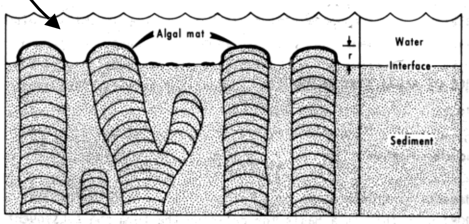


At right is a layered **stromatolite**, produced by the activity of ancient cyanobacteria. The layers were produced as **calcium carbonate** precipitated over the growing mat of bacterial filaments; photosynthesis in the bacteria depleted carbon dioxide in the surrounding water, initiating the precipitation. The minerals, along with grains of sediment precipitating from the water, were then trapped within the sticky layer of mucilage that surrounds the bacterial colonies, which then continued to grow upwards through the sediment to form a new layer. As this process occured over and over again, the layers of sediment were created. This process still occurs today; Shark Bay in western Australia is well known for the stromatolite "turfs" rising along its beaches.

The Archean fossil record (cont.)

3.2 billion year old stromatolite from South Africa

Growth of cyanobacterial mats



3400 million years ago

(3.4 billion years ago)

Stromatolites

Cyanobacteria
(aka blue green algae)

Photosynthesis Produces Oxygen!

3300 million years ago

(3.3 billion years ago)

Stromatolites

Cyanobacteria
(aka blue green algae)

Photosynthesis Produces Oxygen!

3100 million years ago

(3.1 billion years ago)

Stromatolites

Cyanobacteria

Photosynthesis Produces Oxygen!

2500 million years ago

(2.5 billion years ago)

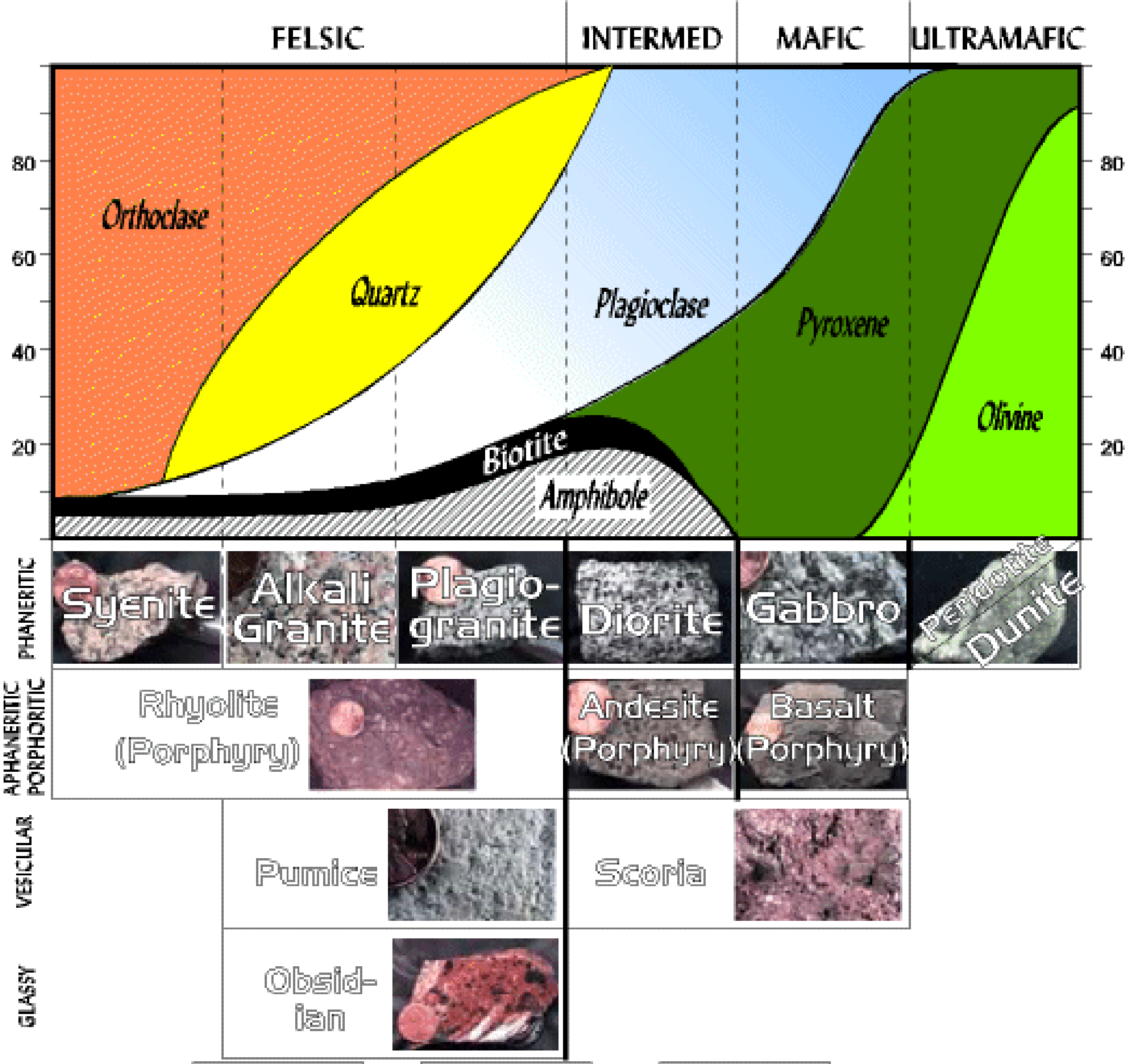
Stromatolites

Photosynthesis Produces Oxygen!

Archaean Crustal Evolution and the Formation of Continents

The earth began in a state similar to the moon with a crustal (lithospheric) surface composed dominantly of **mafic/ultramafic igneous rocks and anorthosites**. With the formation of the oceans the early earth would have been a relatively simple world compared with today - oceans from pole to pole, with occasional scattered hot spot volcanos. Quickly, however, **convection cells** established divergent and convergent plate boundaries which began the **fractionation processes** that would build the continents.

The sequence of cross sections below illustrate the kinds of processes by which initial volcanic arcs could increase in size to form **protocontinents**, then through cordilleran orogenies and collisions form protocontinets, which would grow to form **microcontinents**, which would eventually grow to form **supercontinents.** All of these processes constitute variations on the Wilson cycle. The combinations and permutations of relationships is virtually endless. Anything that could reasonably happen, probably happened.



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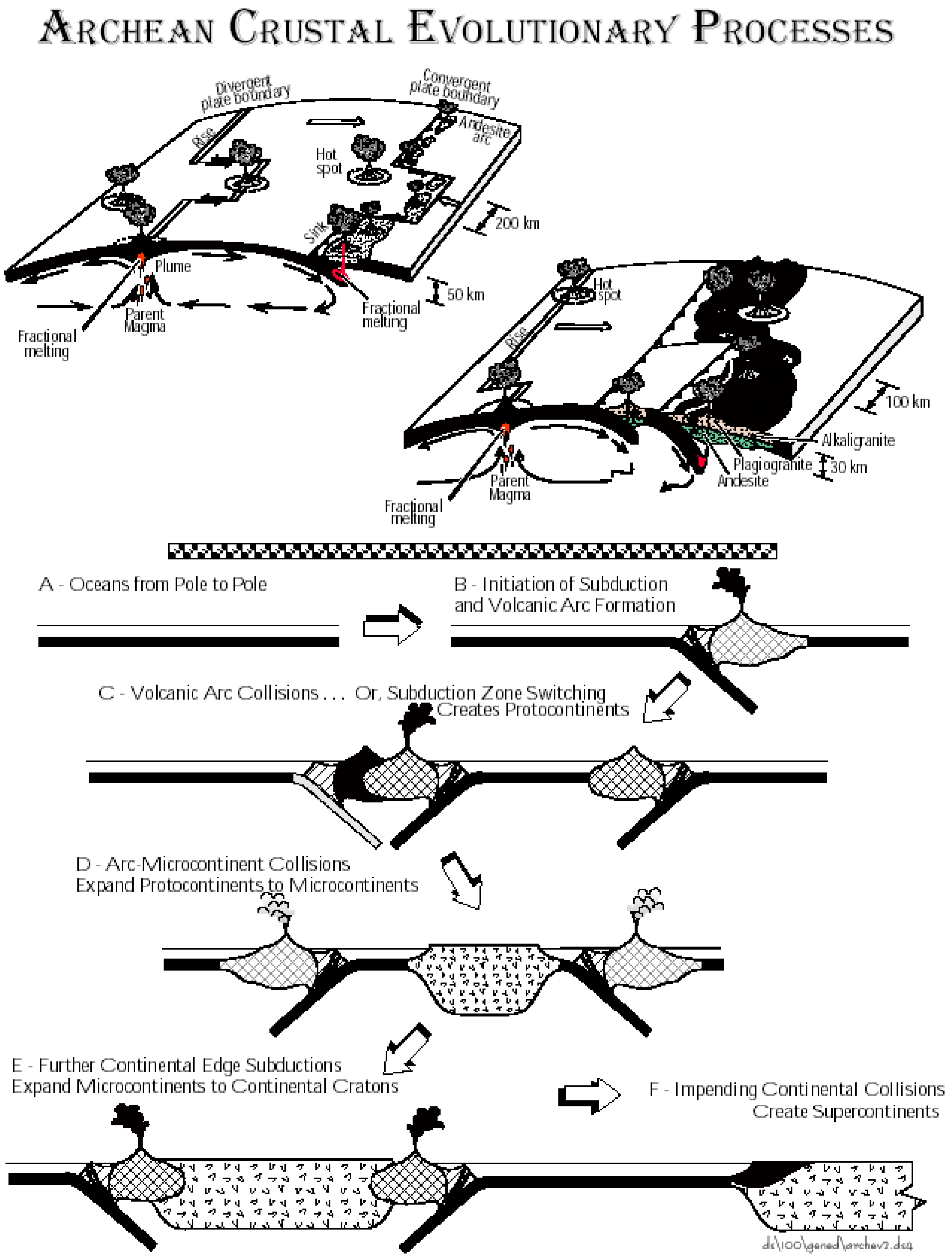
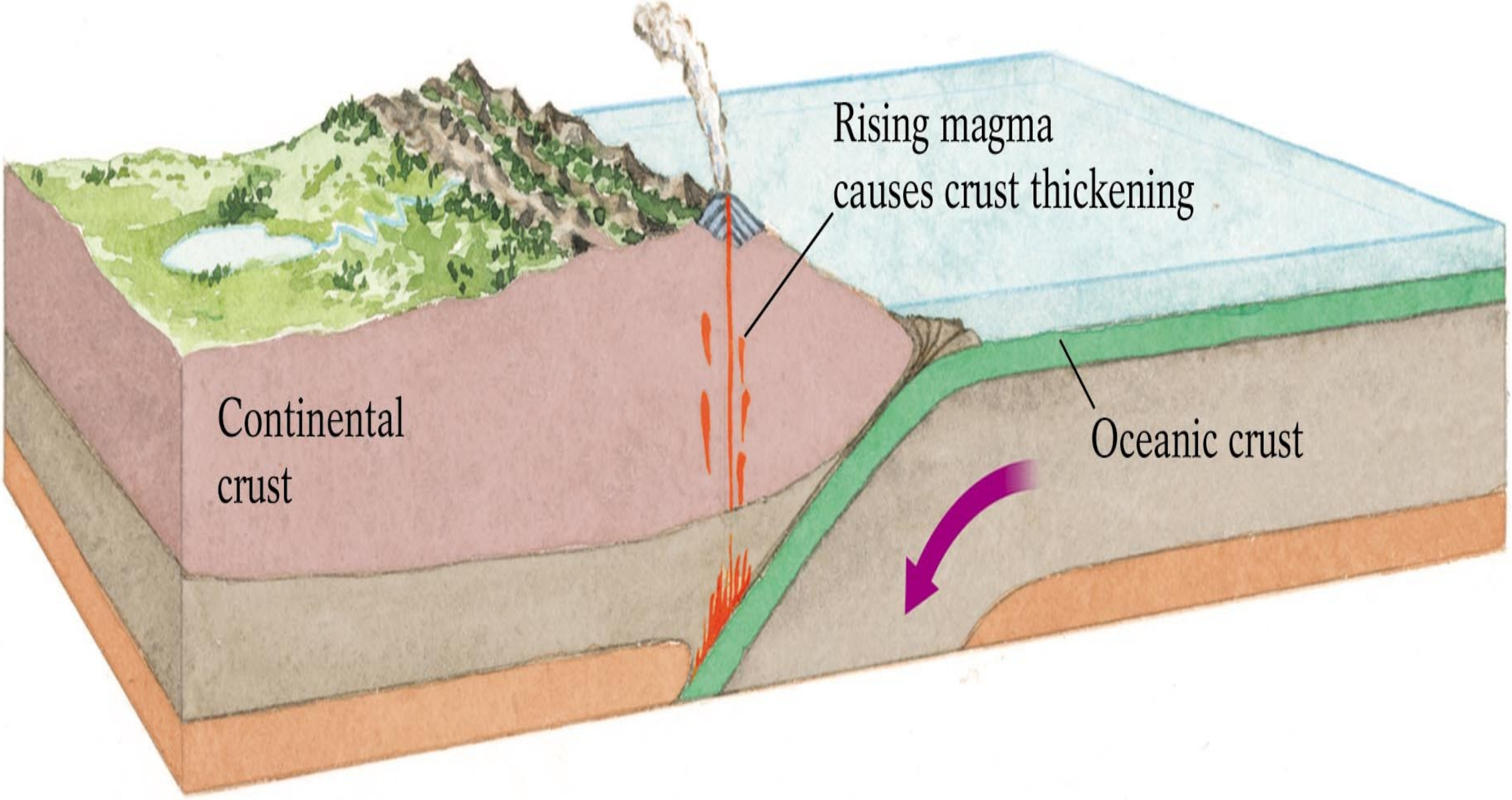


Growth of the early continents

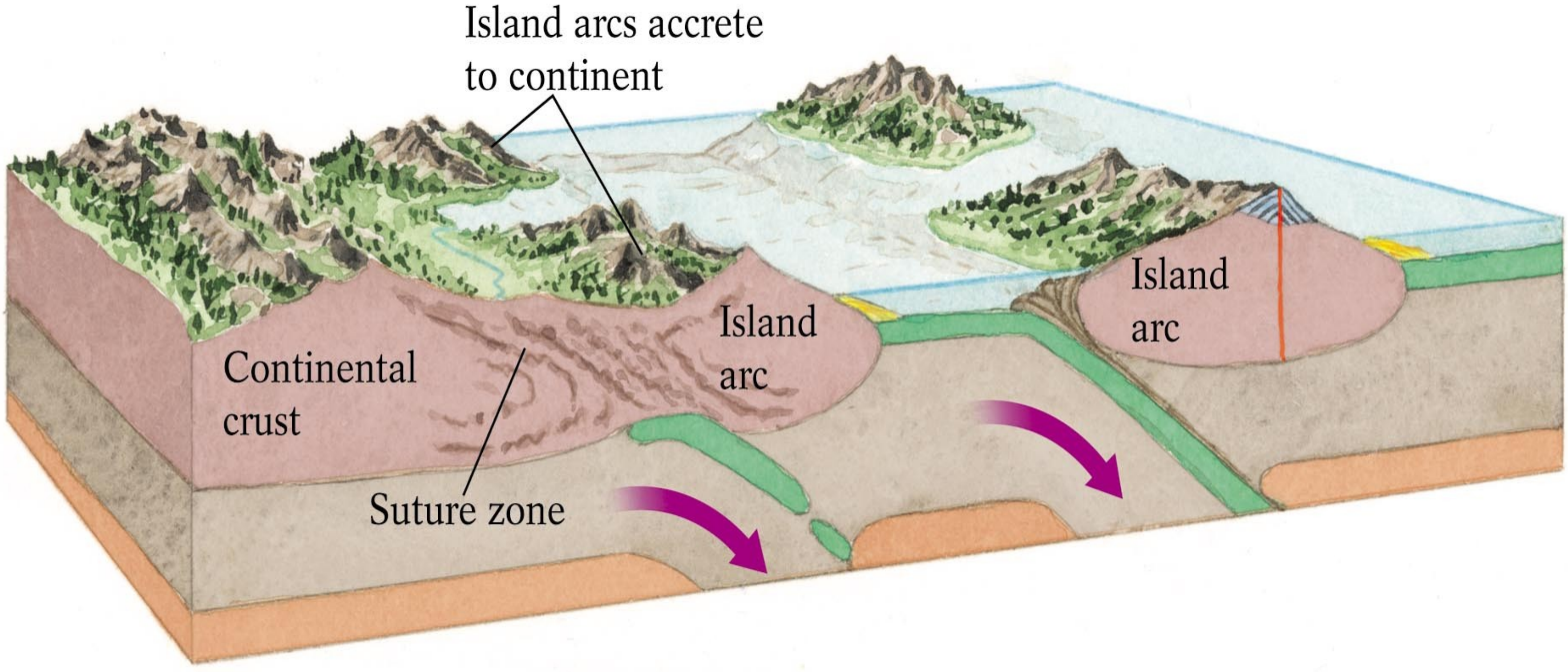
Magmatism from Subduction Zones causes thickening



Growth of the early continents

Island Arcs and other terranes accrete as intervening ocean crust is subducted

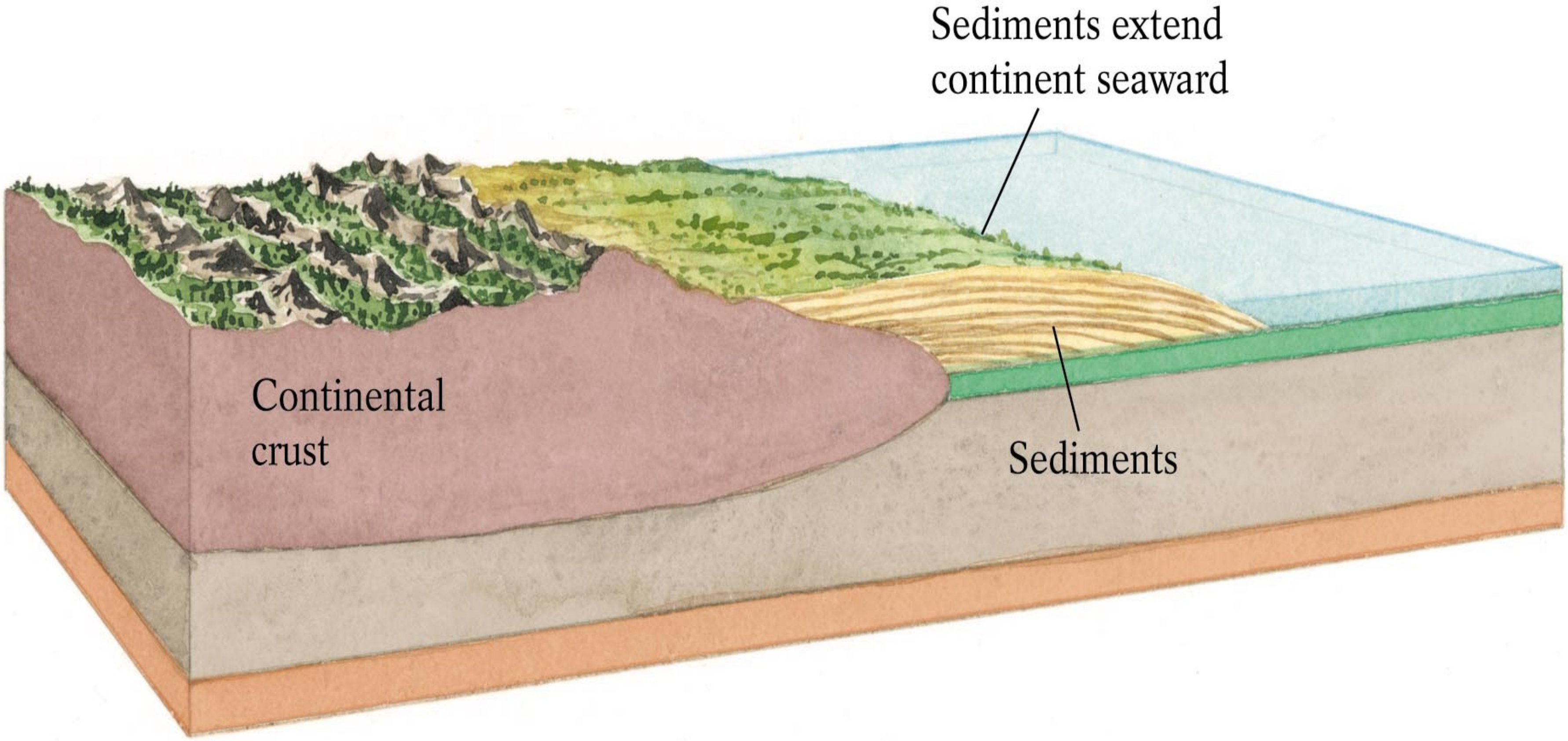
Little Archean ocean crust survives, nearly all subducted



(b)

Growth of the early continents

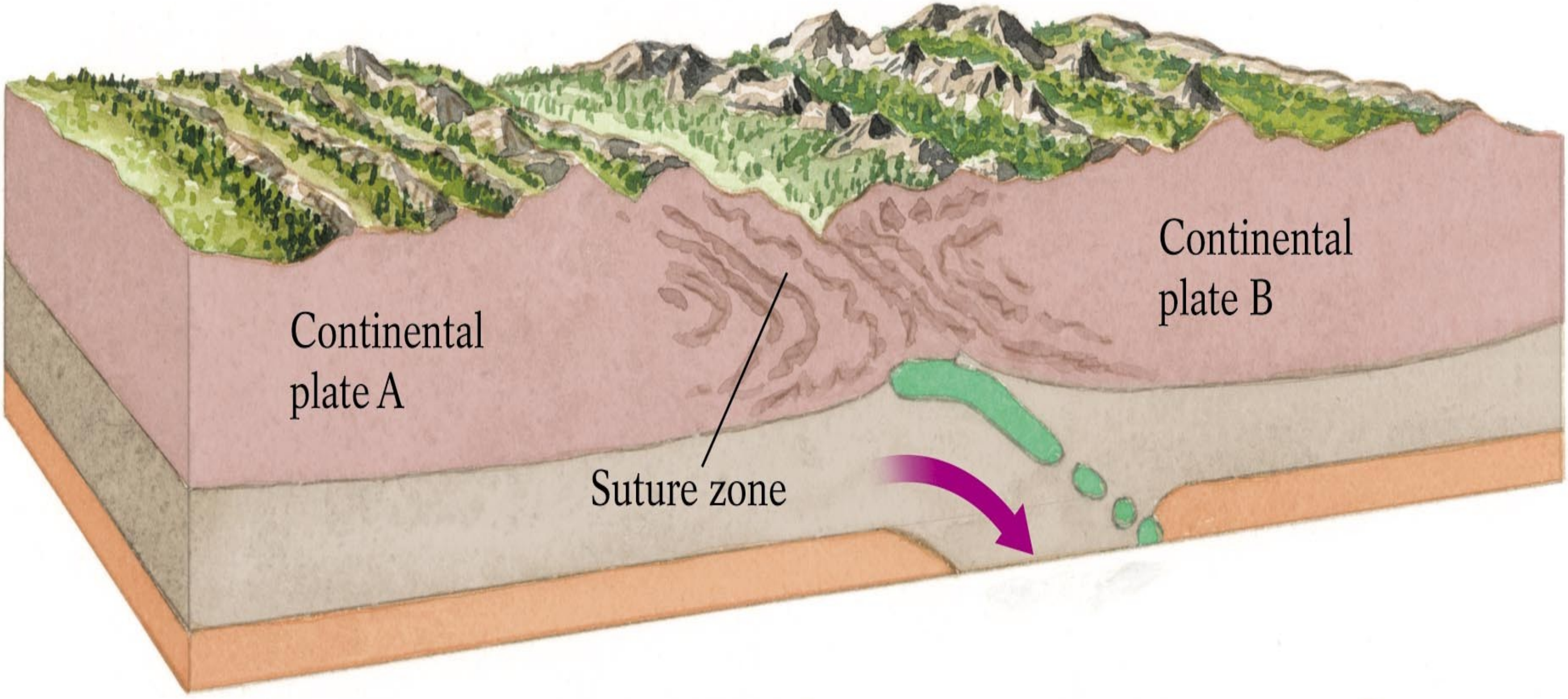
Sediments extend continental materials seaward



(c)

Growth of the early continents

- •Continent-Content collisions result in larger continents
- •Again, not very big in Archean, Plate Tectonics too fast



(d)

The period, from about 3.0 to 2.5 billion years ago, was the period of maximum **continent formation**. **70%** of continental landmasses date from this period (Thus, most of the continents are extremely ancient). Modern Earth sciences recognize that the present continents are built around cores of extremely ancient rock, called **"shields".** A large part of Australia is a "shield", as is much of Canada, India, Siberia, and Scandinavia.

Archean Rocks

1. **Granulites, gneisses** high grade metamorphic rocks – continental crust, originally granodiorites,

tonalites and anorthosites.

Anorthosite is a intrusive igneous rock characterized by a predominance of plagioclase feldspar (90–100%), and a minimal mafic component (0–10%

2. **Greenstone belts** - volcanic and sedimentary rocks commonly metamorphosed chlorite produces green color

Areas of granitic rock (now gneisses) separated by greenstone belts: bands of sequences of weakly metamorphosed komatiites -> basalts -> felsic volcanics -> marine sediments (turbidites, cherts, banded iron formations, etc.).

3. **Sedimentary rocks** clastic, altered to metasedimentary rocks
metagraywackes, slates, schists, metaconglomerates, diamictites
some relict sedimentary structure

Banded Iron Formations red chert (jasper) and unoxidized iron-rich sedimentary rocks. First appear 3.8 Ga; much more common in Proterozoic. Rare after 1.9 Ga, last appear c. 720 Ma. Major iron ore.

TABLE 6–3 Summary of the Characteristics of the Earth's Early Oceanic and Continental Crust

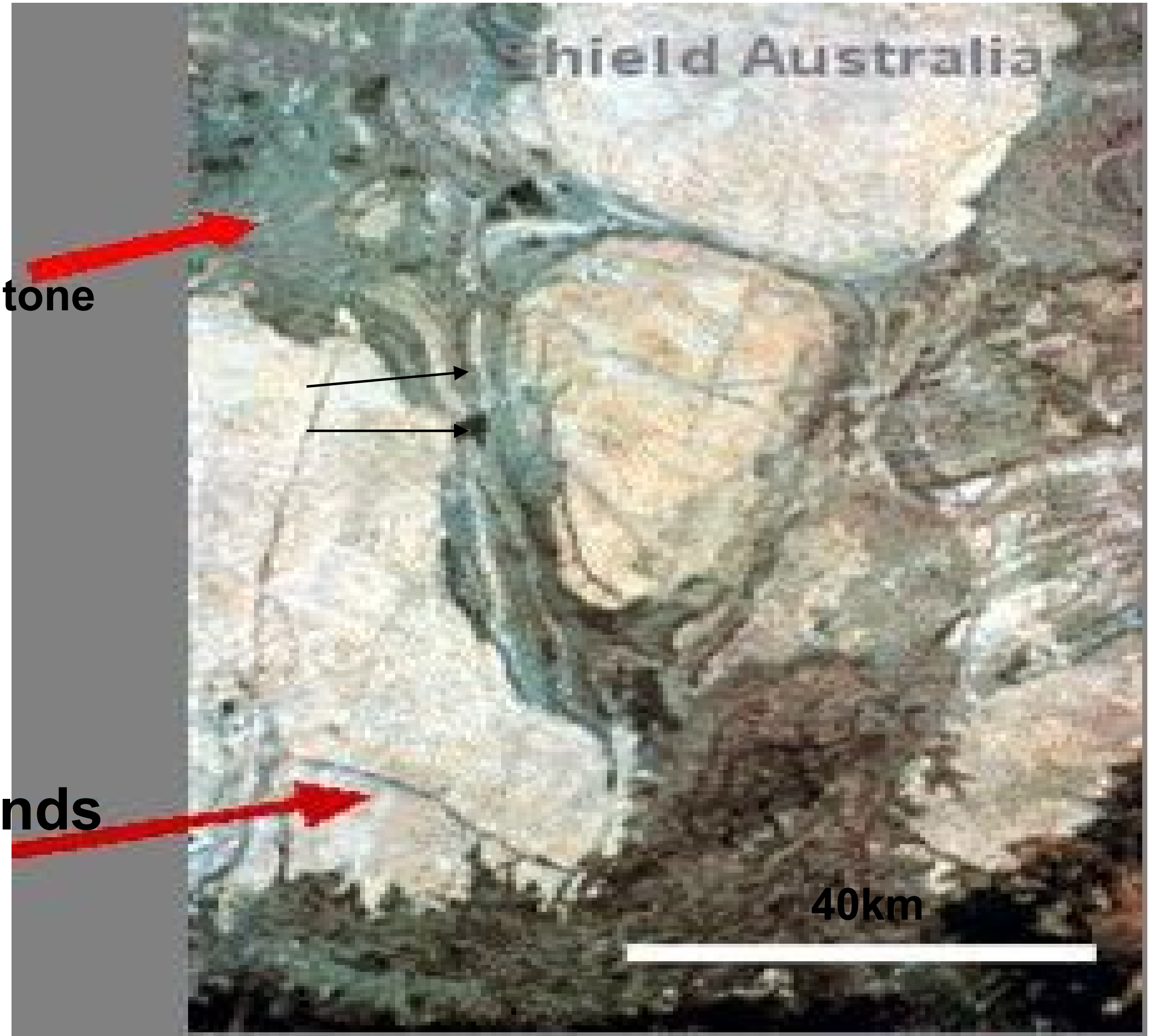
	Oceanic Crust	Continental Crust
First appearance	About 4.5 billion years ago	About 4.0 billion years ago
Where formed	Ocean ridges (spreading centers)	Subduction zones
Composition	Komatiite–basalt	Tonalite–granodiorite
Lateral extent	Widespread	Local
How generated	Partial melting of ultramafic rocks in upper mantle	Partial melting of wet mafic rocks in descending slabs

Source: Condie, K. C. 1989. Origin of the Earth's crust. *Paleogeography, Paleoclimatology, Paleoecology* 75:57–81, with permission.

Precambrian

Early Continents (Cratons)

- Archean cratons consist of regions of light-colored felsic rock (gneisses)
- surrounded by pods of dark-colored greenstone (chlorite rich metamorphic rocks).
  - Pilbara Shield, Australia
  - Canadian Shield
  - South African Shield.



Komatiite?

- Ultramafic lava flow
- Rich in high Mg olivine
- Olivine alters to serpentine
- Only occurs in Archaean terrains, rare in Proterozoic
- High temperatures - associated with mantle plumes
- Archaean greenstone belts – occurs as altered komatiite flows

Oldest 4.03 Ga, disappear around 2.5 Ga.

Greenstone belts consist primarily of volcanic rocks, typically basalts that have been altered by low grade metamorphism which produces chlorite - a greenish mineral. Some belts include ultramafic lava flows which require near surface temperatures of 1600°C (komatiites). This means that the early mantle was nearly 300°C hotter than today. This suggests that the earth has cooled, probably as a result of a loss of radiogenic heat.
Two models have been proposed for the evolution of greenstone belts. 1) **Back-arc** spreading in marginal basins and 2) **Plate tectonic model** 2) **mantle plumes**

Back-arc model

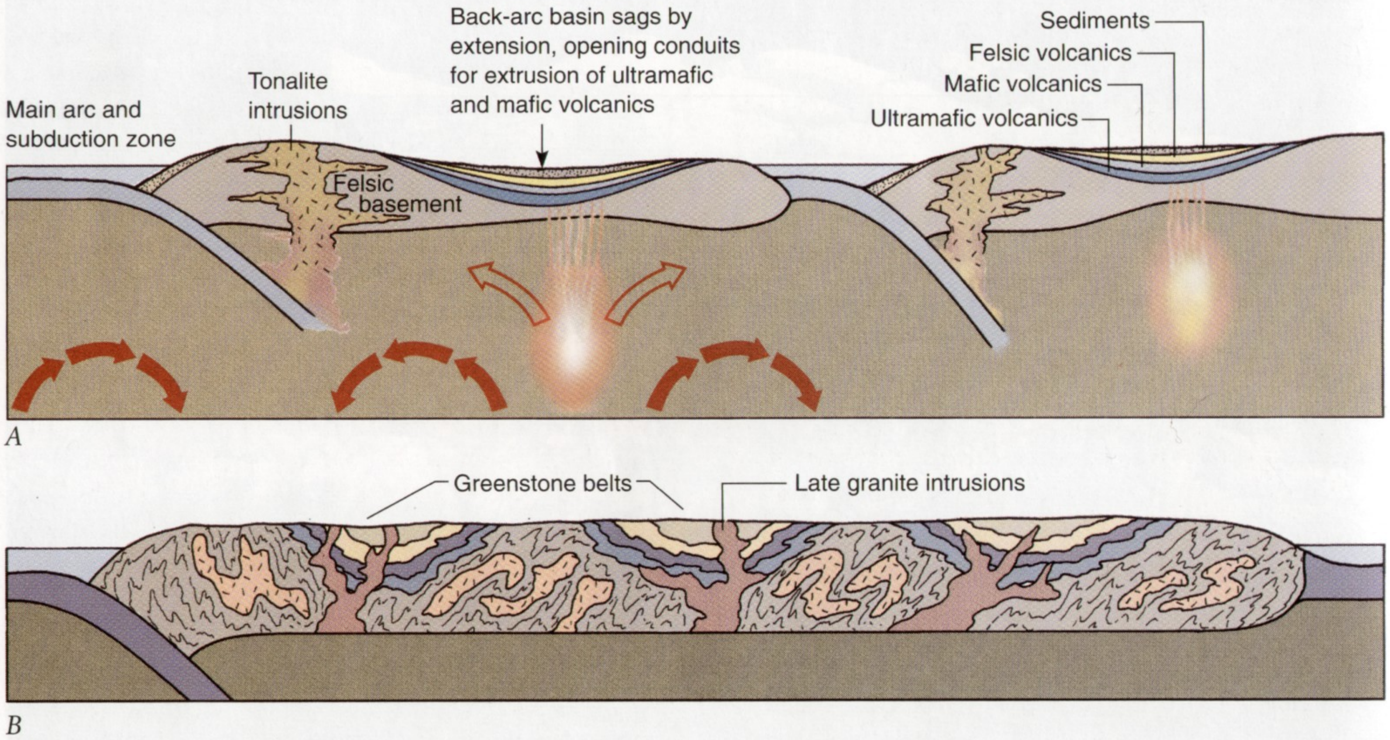


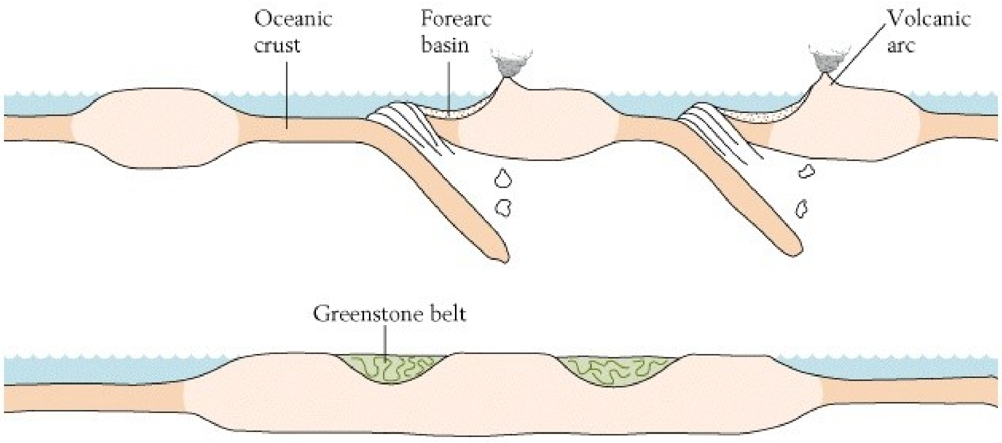
FIGURE 6–24 Plate tectonics model for the development of greenstone belts and growth of continental crust. (A) Plates are in motion, driven by convection cells in the upper mantle. Subduction provides for the emplacement of wedges of oceanic crust and for mixing and melting to provide tonalite intrusions. Behind the main arc, the back arc sags by extension, and the greenstone volcanic sequence is extruded. (B) Compression has occurred to create the greenstone belts with their synclinal form and to aggregate small continental patches into a larger continental mass. Later, granites are intruded in and around greenstone belts. *(Simplified from a model proposed by B. F. Windley, 1984.* The Evolving Continents, *2nd ed. New York: John Wiley & Sons.)*

Plate tectonic model

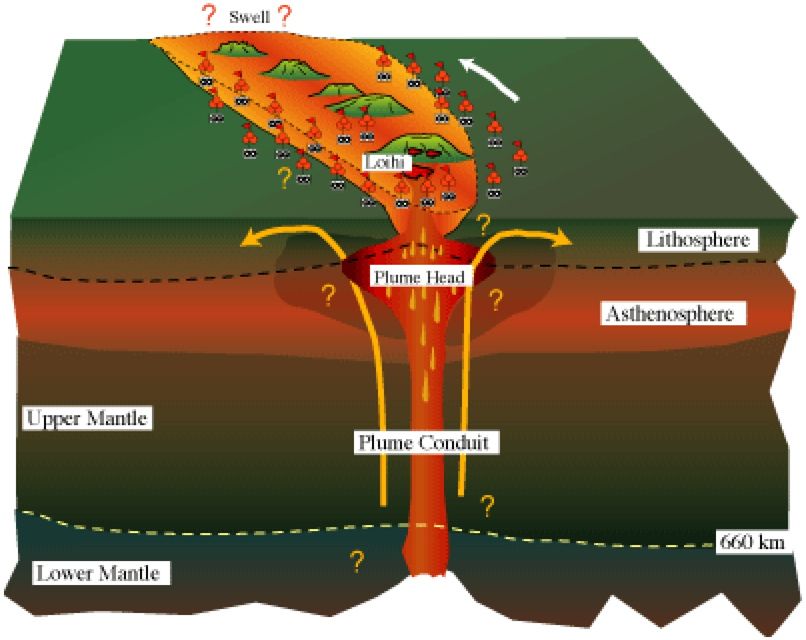
Formation of greenstone belts

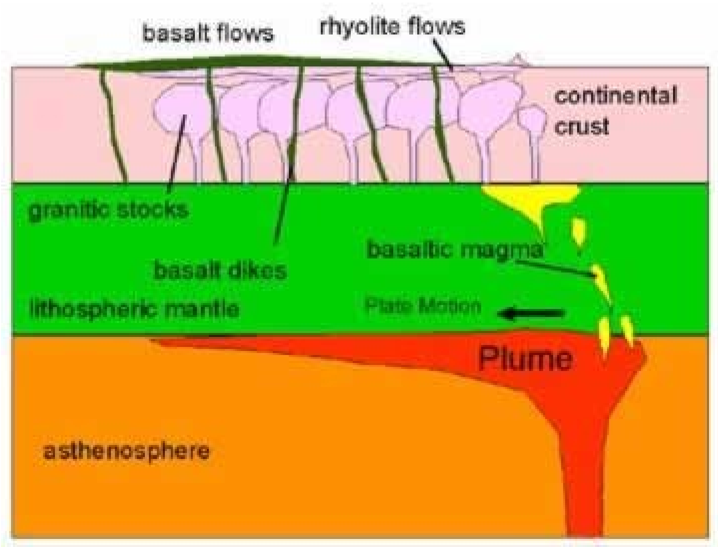
Time 1

Time 2



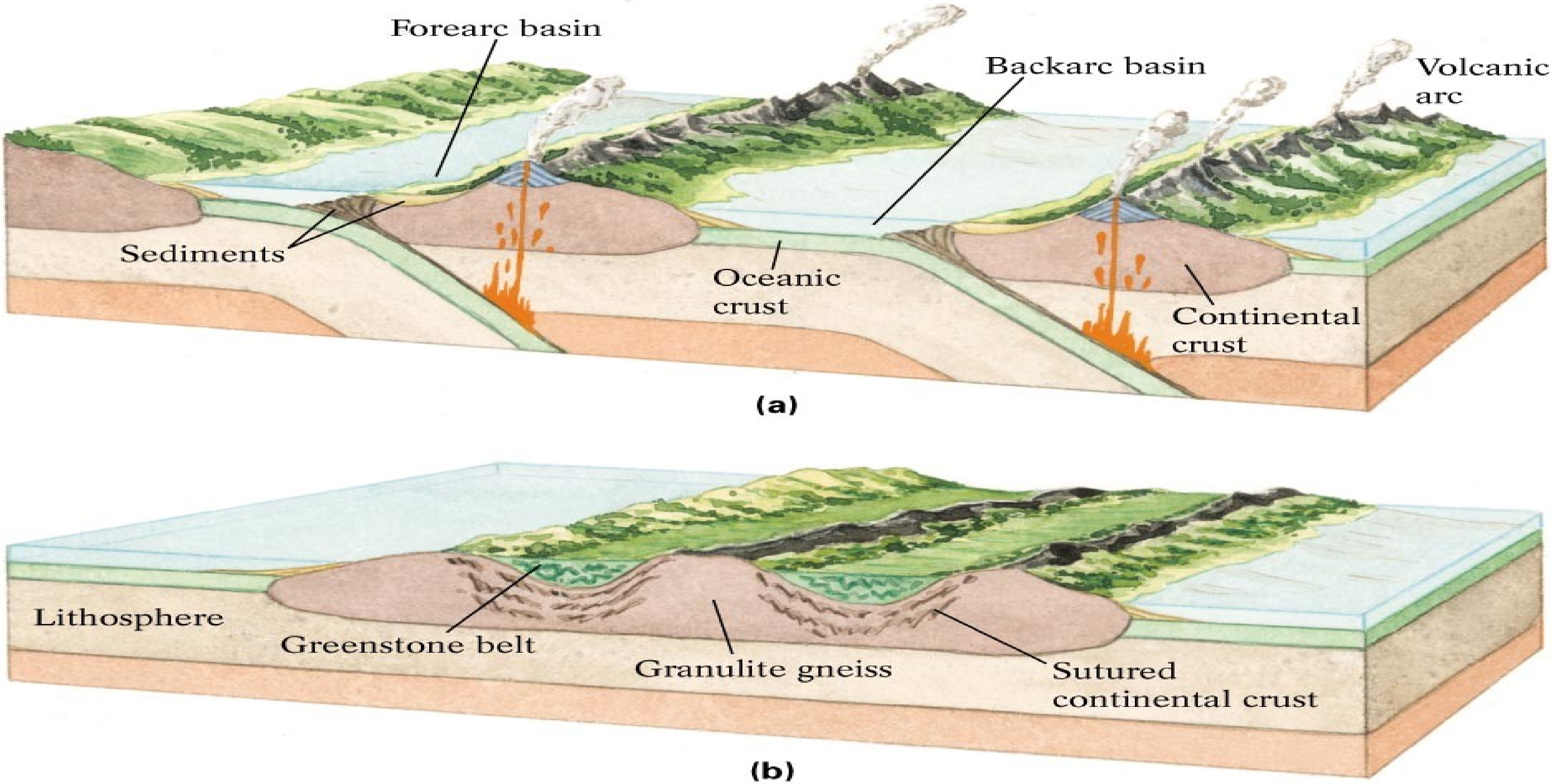
Mantle plume model



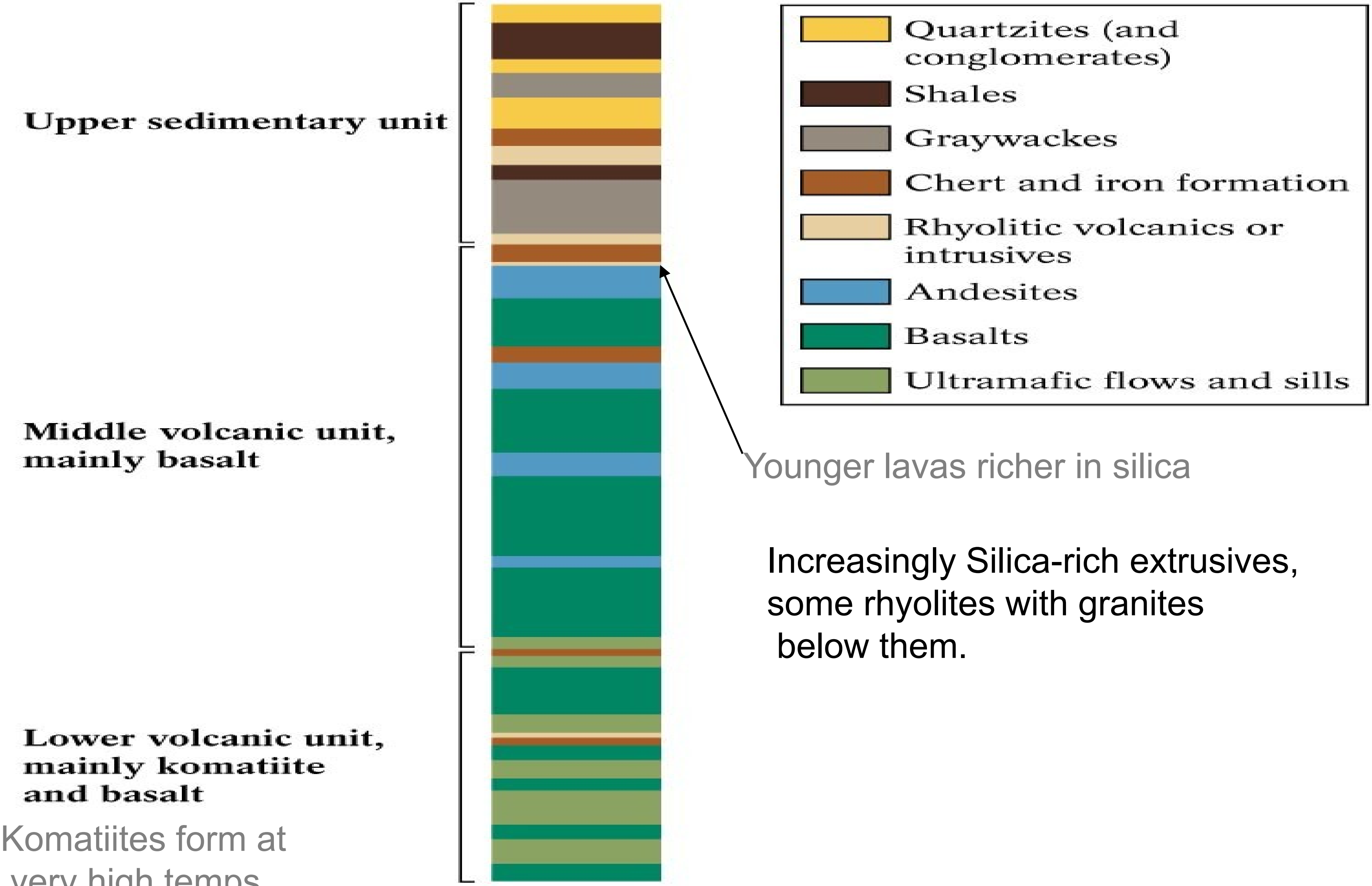


Formation of greenstone belts

- **Early continents formed by collision of felsic proto-continents.**
- **Greenstone belts represent volcanic rocks and sediments that accumulated along subduction zones and then were sutured to the protocontinents during collisions.**
- Protocontinents small, rapid convection breaks them up



Stratigraphic Sequence of a Greenstone belt



Younger lavas richer in silica

Increasingly Silica-rich extrusives, some rhyolites with granites below them.

Komatiites form at very high temps

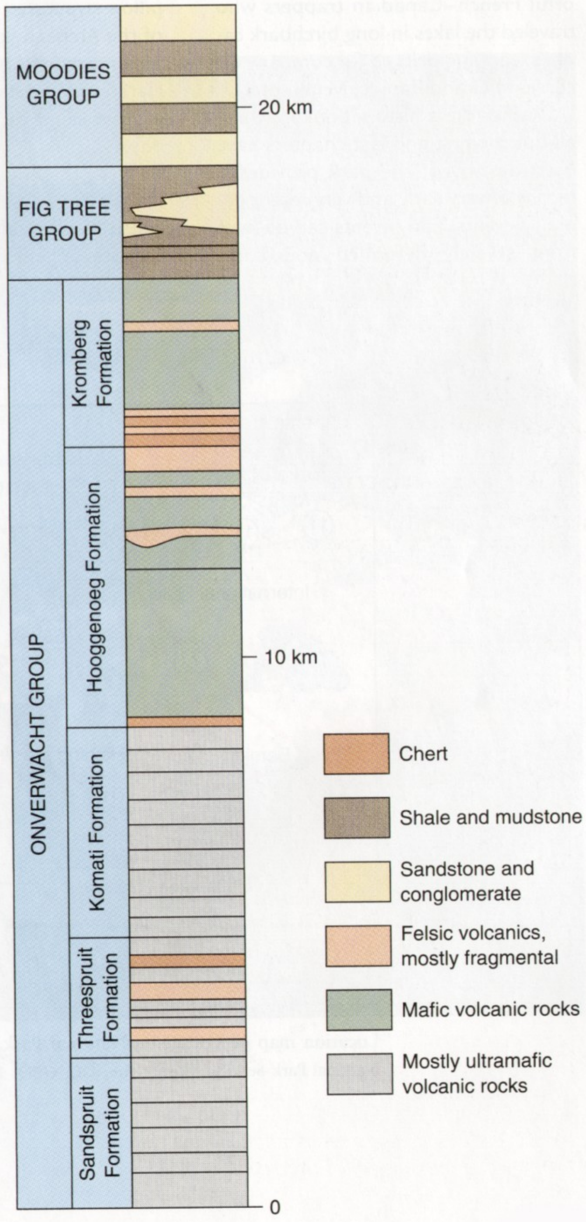
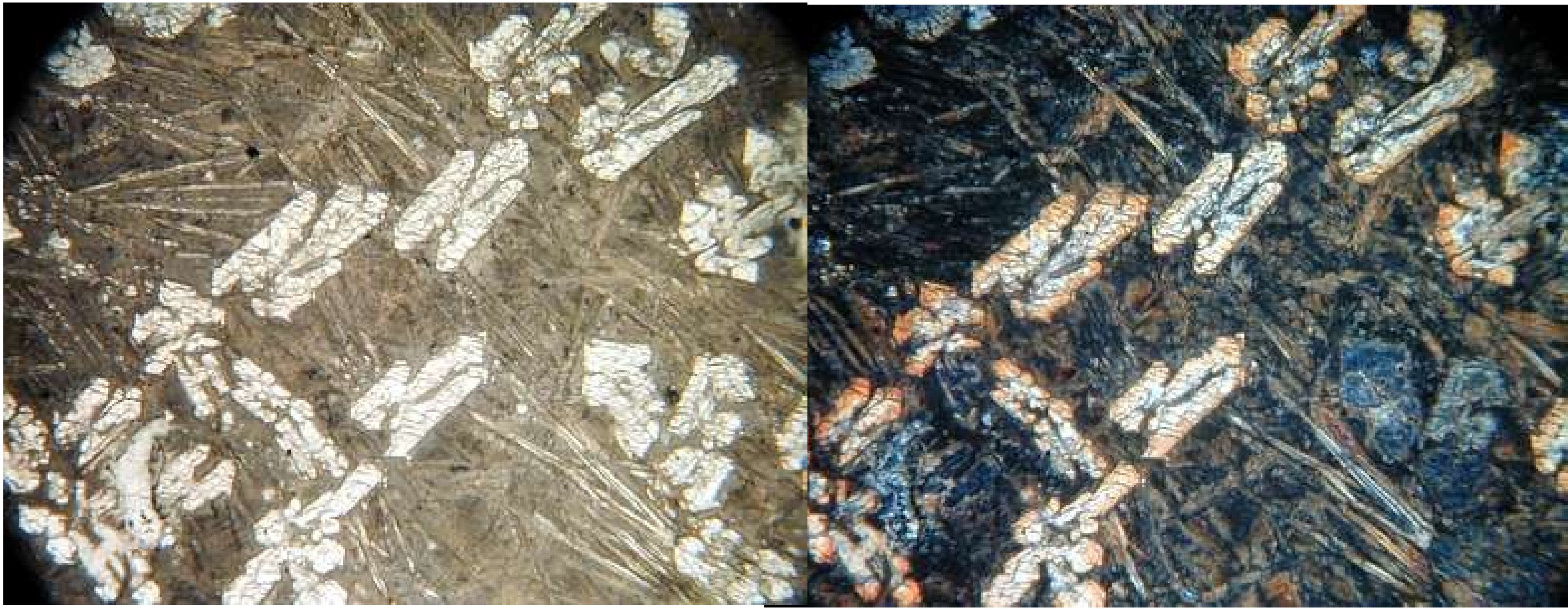


FIGURE 6–23 Stratigraphic sequence in a greenstone belt in Barberton Mountain Land, South Africa. *(After D. R. Lowe. 1980.* Ann. Rev. Earth Planet. Sci. *8:145–167.)*

- **Komatiite**: Ultramafic volcanics, very common in Archean, very rare afterwards. Require temperatures of greater than 1600 şC (modern lavas max out at 1350 şC). Hint at the extreme activity of Archean mantle.

Clinopyroxen crystals and spinifex texture in komatiite



Komatiites are **ultramafic** volcanic rocks, having very low *silica* contents (~40-45%) and very high MgO contents (~18%. These ancient lava flows erupted at a time when the *Earth's internal heat* was much greater than today, thus generating exceptionally hot, fluid lavas with calculated eruption temperatures in excess of 1,600 degrees C (2,900 degrees F). In comparison, typical basaltic lavas erupting today have eruption temperatures of about 1,100 degrees C.

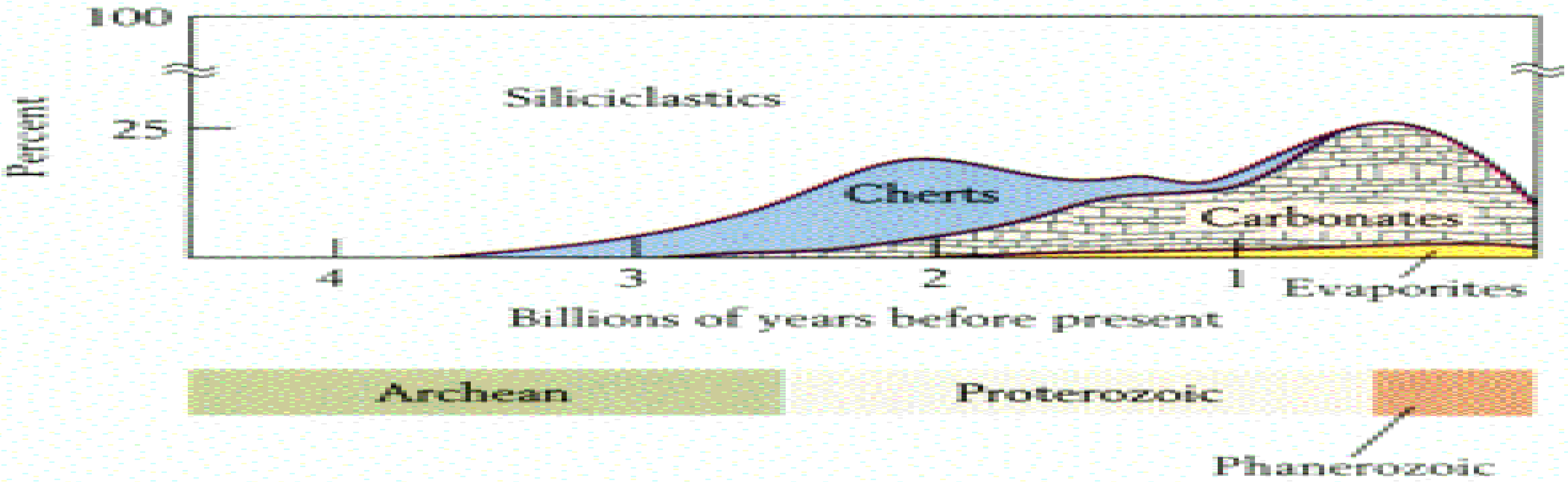
FIGURE 6–19 Archean tonalite gneiss, about 3.8 billion years old, exposed near Lile Narssuaq, Greenland.

Would tonalite be considered a felsic or mafic rock?

Archean To Proterozoic Sedimentary Rocks

- Archean Mostly deep water clastic deposits such as mudstones and muddy sandstones.
  - high concentration of eroded volcanic minerals.
- Absence of shallow water shelf carbonates.
  - Mostly chert.
- low oxygen levels, free iron was much more common in the Archean.
  - Free iron formed “chemical sinks” that consumed much of the early planetary oxygen.
  - Formed banded ironstones, commonly with interbedded chert.

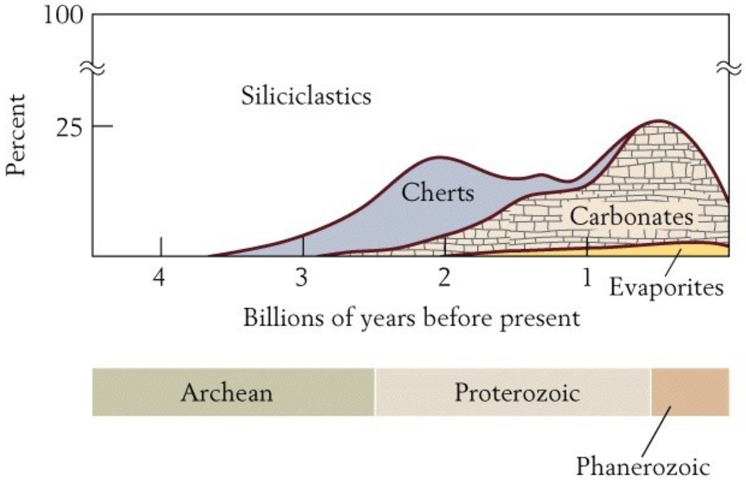
– Proterozoic – Carbonates become important



Archean rocks

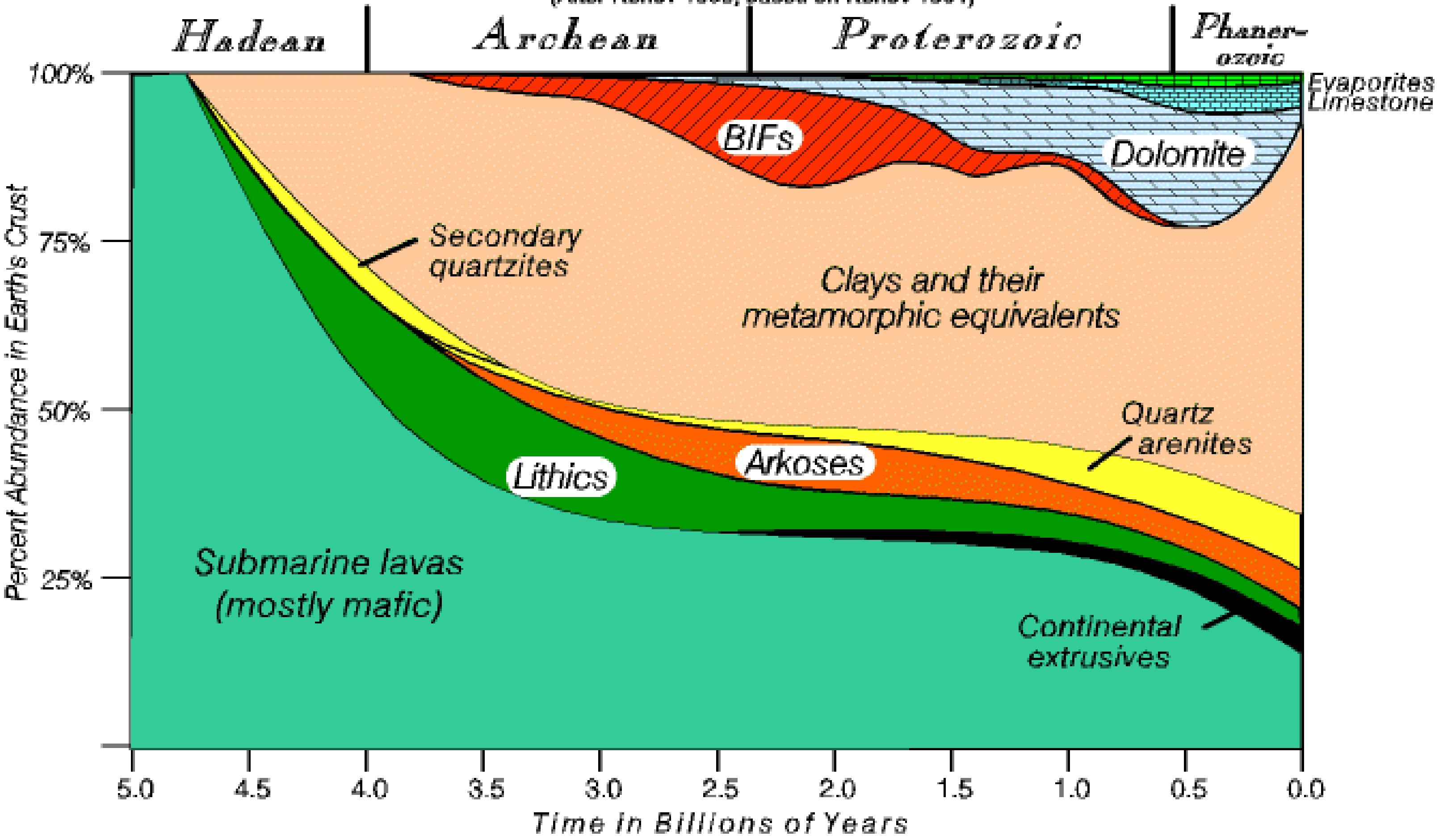
- **Archean sedimentary rocks** are mostly of *deep-water origin*
  - Sandstones, cherts, shales, banded-iron formations
  - Very few, if any, limestones or evaporites
  - No well developed continental shelves for accumulation of shallow-water deposits

Archean rocks



Compositional Evolution of Earth Rocks

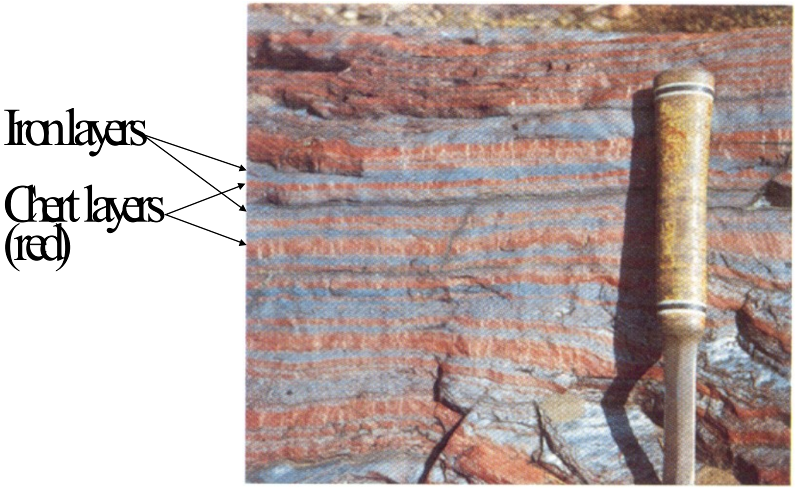
(After Renov 1968, based on Renov 1964)



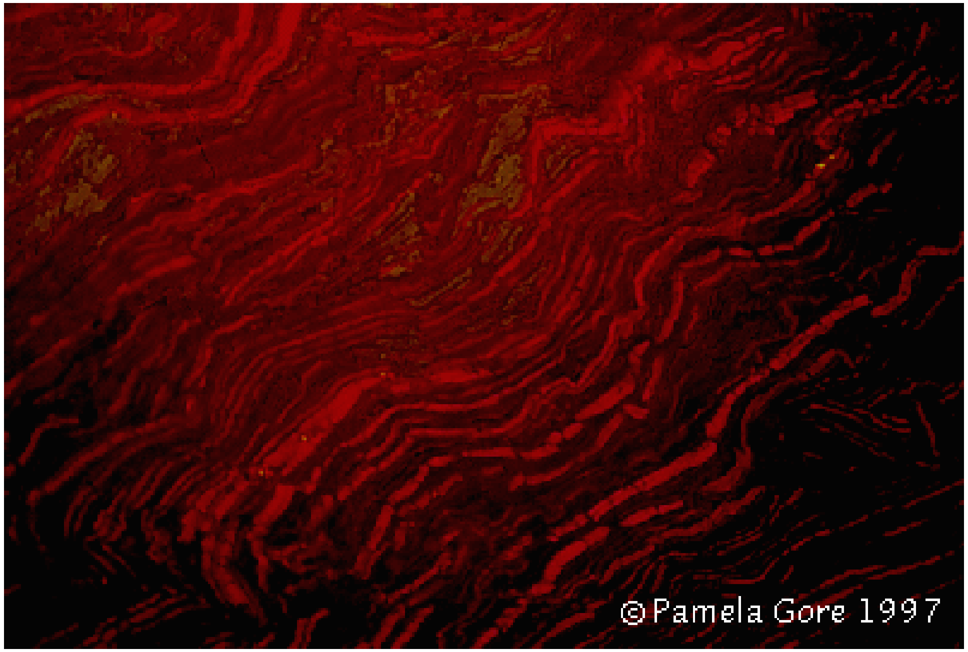
Archean rocks (cont.)

- **Banded iron formations**
  - Alternating bands of **iron-rich** layers and **chert** layers
  - Thought to have **precipitated from hot marine water** associated with igneous activity
  - Iron is **weakly oxidized** (looks like iron), suggesting little or no exposure to oxygen
    - Very few banded iron formations younger than 1.9 billion years old (when atmospheric O_2 increased)
    - Most iron deposits younger than 1.9 billion are highly oxidized (red beds)
  - Principal source of world's **iron ore**

Banded iron formations



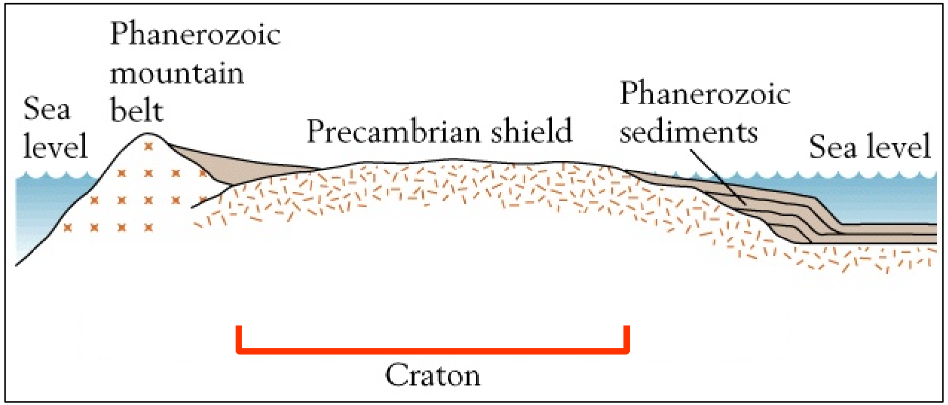
Banded Iron Formation,
Alternating bands of red jasper and black hematite, about 2250 million years old (2.55 billion years old) Jasper Knob, Ishpeming, Michigan



Banding of BIF: record of episodic growth of microbes
- precipitation of Fe oxides followed by depletion of O2
- cycle repeats many times

Precambrian rocks

- **<u>Cratons</u>** are the large, stable, interior regions of continents that *have not undergone major deformation since Precambrian or early Phanerozoic time*
- Most Precambrian rocks are confined to cratons, where they may be exposed in a '**<u>Precambrian shield</u>**'



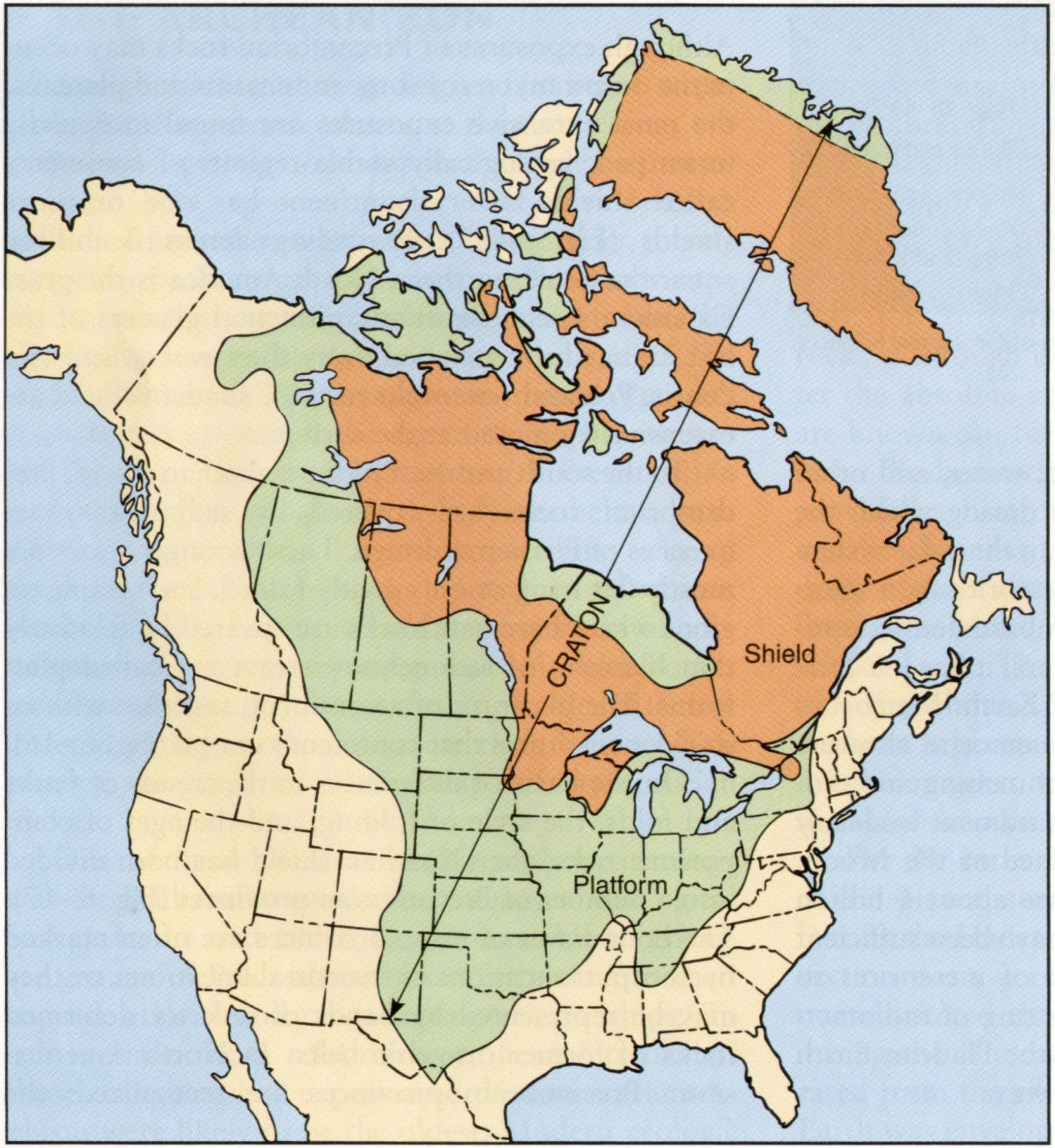
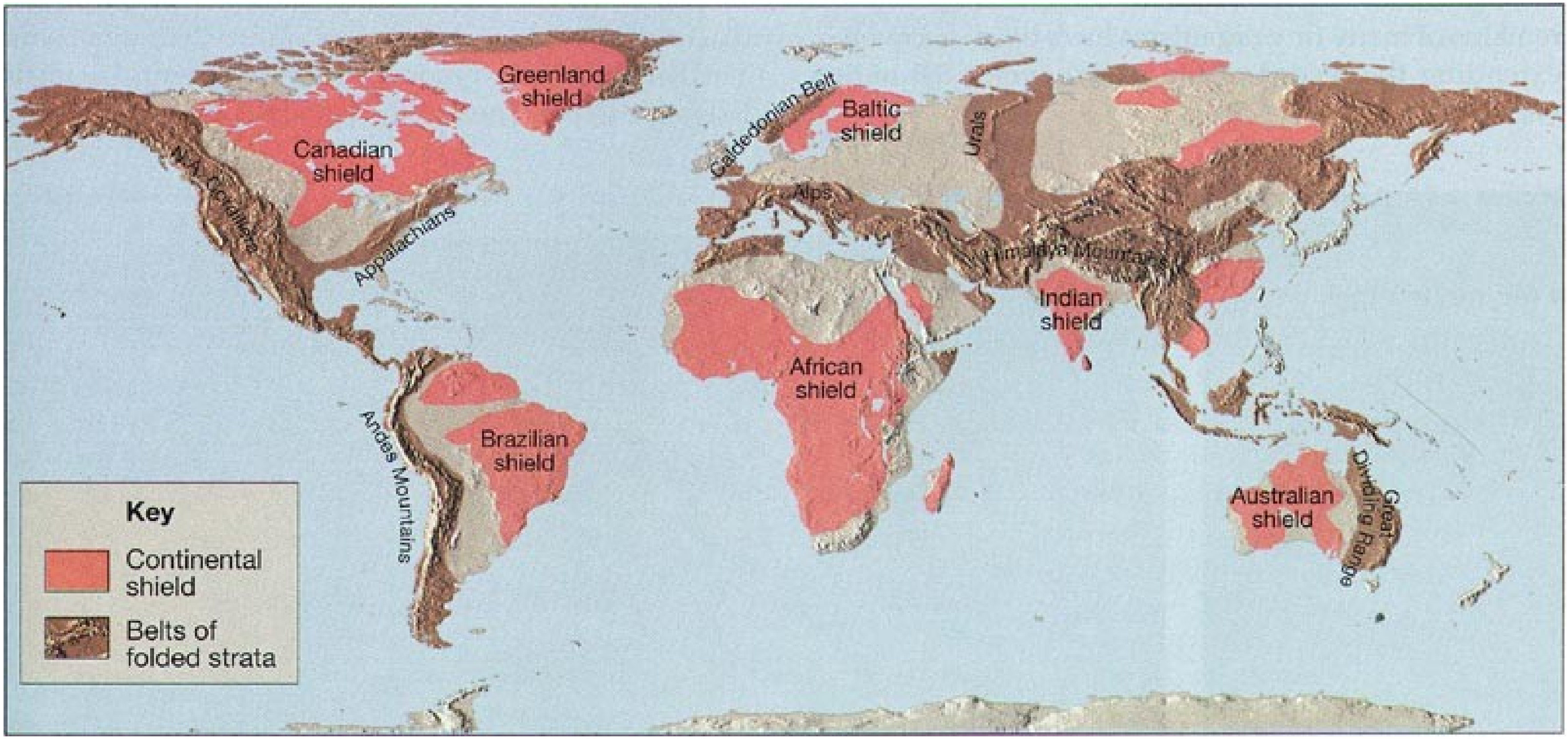
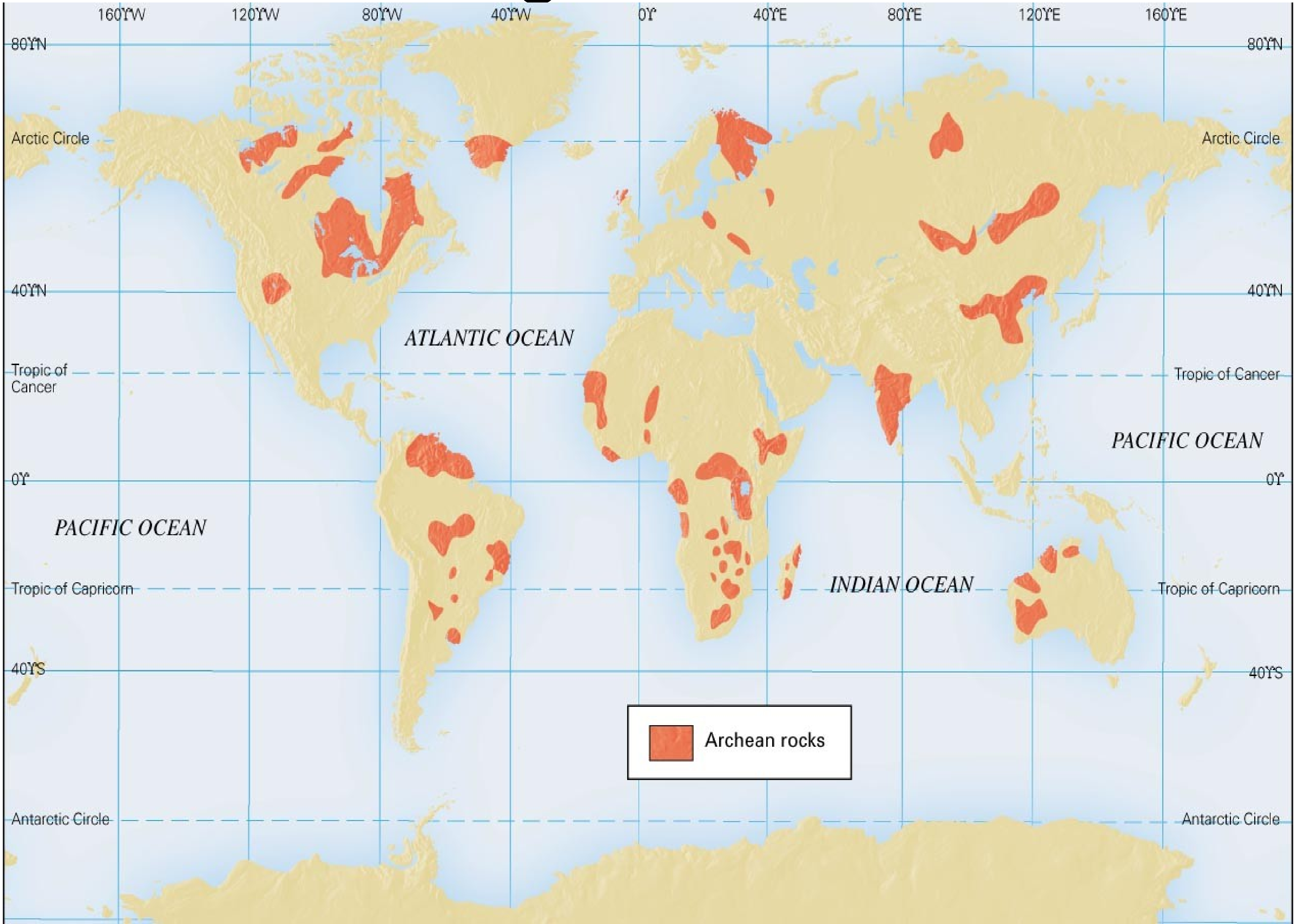


FIGURE 6–16 North American craton, shield, and platform. ❓ What is the difference between shield and platform?



Greenland shield
Canadian shield
N.A. Cordillera
Appalachians
Andes Mountains
Brazilian shield
Caledonian Belt
Baltic shield
Urals
Alps
Himalaya Mountains
Indian shield
African shield
Australian shield
Great Dividing Range
Key
Continental shield
Belts of folded strata

Archean-Age Surface Rocks



Origin of Life

Origin of Archaebacteria 3.5 bya

- Archaebacteria are the most primitive fossil life forms
  - Likely ancestors of all life.
- Primitive Archaebacteria are hyperthermophiles that thrive in boiling point of water.
  - Modern Archaebacteria live in deep-sea volcanic vents.
- Some Archaebacteria feed directly on sulfur (chemoautotrophs).
  - Archean life probably arose in deep oceans hydrothermal, volcanic vents that would have dotted the ocean floor near rifting zones.
  - Vents provide:
    - chemical and heat energy,
    - abundant chemical and mineral compounds, including sulfur
    - protection from oxygen and ultraviolet radiation.

Origin of life

- **Where did life form?**
  - –Probably *not at the Earth's surface* in shallow pools, as once believed
    - Presence of *oxygen would have inhibited* the "cooking" of "Stanley Miller soup"
  - –Most likely in the **deep sea**, away from O_2, and probably near a "vent" of hot water
    - Modern *chemosynthetic bacteria* are abundant near vents on mid-ocean ridges
    - They derive energy by **consuming chemical compounds** and allowing reactions to occur within their cell membranes

Some of the early organisms became photosynthetic possibly due to a shortage of raw materials for energy.
Photosynthesis was an adaptive advantage.

Produced their own raw materials. Autotrophs.

Examples = cyanobacteria (stromatolites)

Oxygen was a **WASTE PRODUCT.**

Autotrophs

- Autotrophs use an abiotic source of energy to convert inorganic material into organic compounds for growth and reproduction.
- Autotrophs produce food, and are known as “primary producers”.
    - Inorganic vs. organic material.
        - Inorganic = CO_2, NH_3, NO_3^{2-}, PO_4^{3-}, etc
        - Organic = living, or derived from living tissue (proteins, lipids, carbohydrates, nucleic acids, or containing C-C bonds (petroleum products).
    - Plants are autotrophs and the primary producers in most ecosystems.
        - Energy source is the Sun.
    - Chemosynthetic bacteria are autotrophs and primary producers in deep vent communities
        - Energy source is inorganic sulfur molecules, NOT SUN!

Chemosynthetic Organisms

- ➢ **Use sulfur or sulfides**
- ➢ **Use methane**
- ➢ **Bacteria and cyanobacteria**

Life appeared on Earth during the Archean (3.5 - 3.8 bya).

Geochemical **evidence of photosynthesis** in rocks **3.8 billion years old on Greenland**.
Anomalously high C^{12}/C^{13} ratio, consistent with photosynthesis

Earliest cells were **prokaryotic** (did not have a nucleus or organelles) like bacteria
The earliest cells had to form and exist in **anoxic** conditions.

Probably **chemosynthetic**, producing H_2S or CO_2 **Some of the early organisms became photosynthetic** possibly due to a shortage of raw materials for energy.

- Fossils and organo-sedimentary structures remaining from this early life include:
- **Stromatolites** (cyanobacteria or blue-green algae)
  in carbonate sediment
  oldest are 3.4 - 3.5 by old
  also in rocks 2.8 - 3 by old more abundant in Proterozoic rocks
- **Algal filament fossils**
  3.5 b.y. at North Pole, western Australia
- **Spheroidal bacterial structures (Kingdom Monera)**
  Fig Tree Group, South Africa
  3.0 - 3.1 by
  prokaryotic cells; appear to show various stages of cell division

7. Oxygen began to build up in the atmosphere as a waste product of photosynthesis

When did life arise on Earth?

- Probably before 3.85 billion years ago.
- Shortly after end of heavy bombardment, 4.2-3.9 billion years ago.
- Evidence from fossils, carbon isotopes.

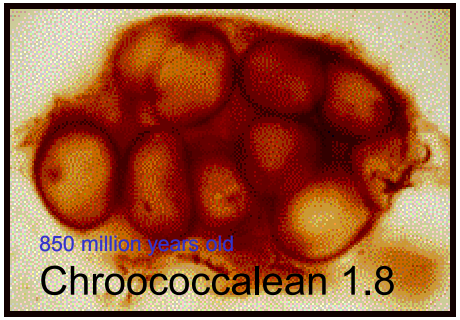
3800 million years ago

(3.8 billion years ago)

First Bacteria
(Prokaryotic)

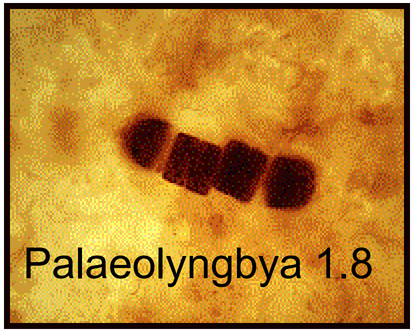
Fossil Bacteria

- Prokaryotic archaebacteria and eubacteria are dominant. 2 bya
  - Eubacteria form stromatolites (photosynthetic).
  - More common in upper Archean as shallow water shelves began to form along margins of early continents.
  - Archean is the age of pond-scum.
- Molds of individual bacterial cells found in Precambrian cherts.



850 million years old

Chroococcalean 1.8



Palaeolyngbya 1.8

3500 million years ago

(3.5 billion years ago)

Stromatolites

Cyanobacteria

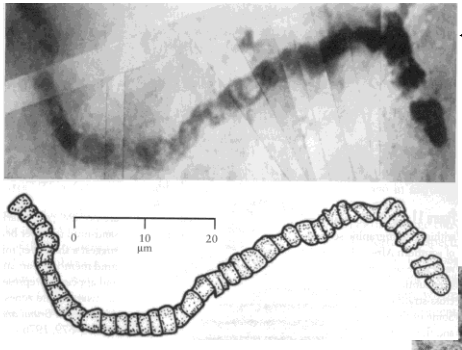
(aka blue green algae)

Photosynthesis Produces Oxygen!

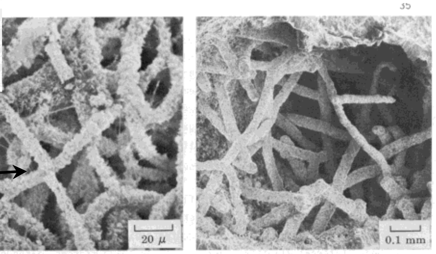
Fossil evidence for microbes 3.5 billion years ago

- Already fairly complex life (photosynthesis), suggesting much earlier origin.

The Archean fossil record (cont.)



3.5 billion year old bacteria preserved in chert from Western Australia

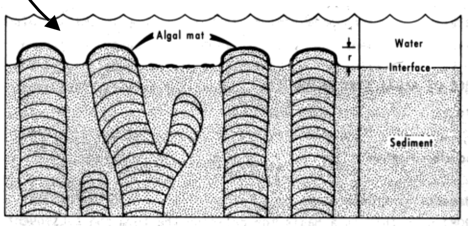


Modern cyanobacterial filaments

The Archean fossil record (cont.)

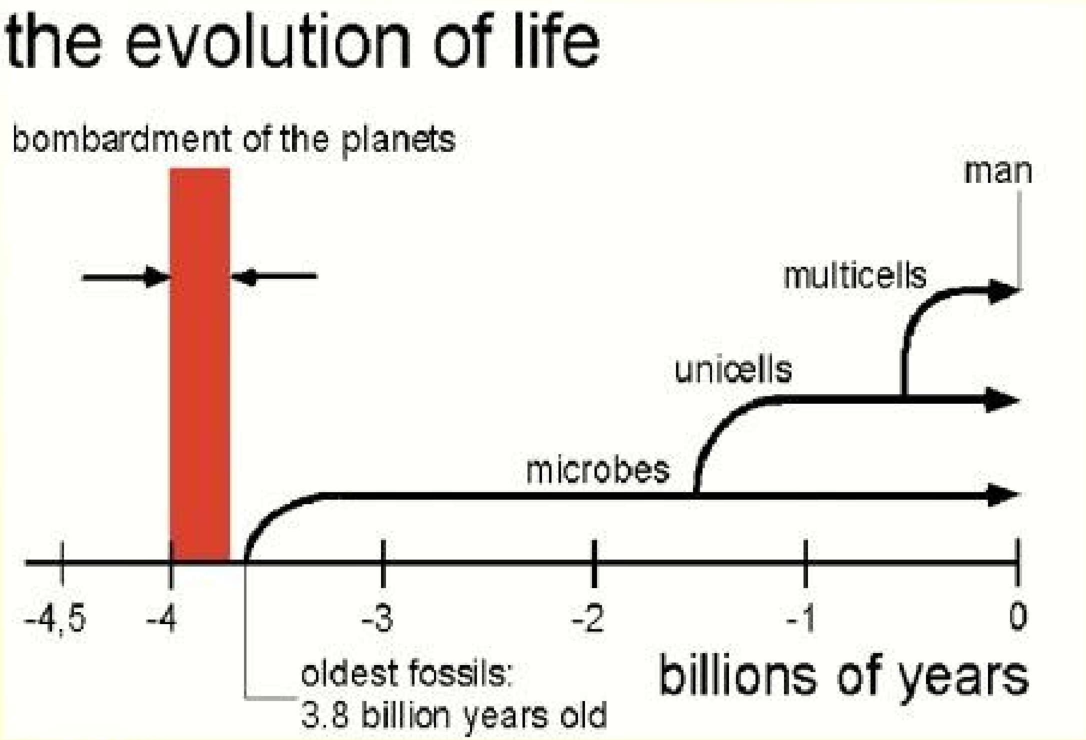
3.2 billion year old stromatolite from South Africa

Growth of cyanobacterial mats

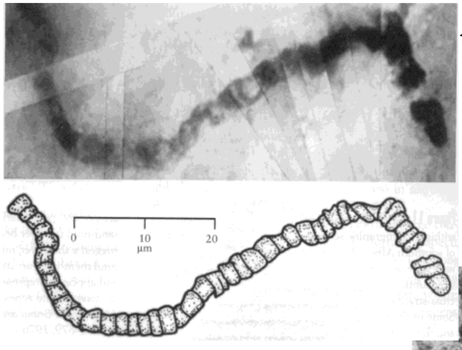


At right is a layered **stromatolite**, produced by the activity of ancient cyanobacteria. The layers were produced as **calcium carbonate** precipitated over the growing mat of bacterial filaments; photosynthesis in the bacteria depleted carbon dioxide in the surrounding water, initiating the precipitation. The minerals, along with grains of sediment precipitating from the water, were then trapped within the sticky layer of mucilage that surrounds the bacterial colonies, which then continued to grow upwards through the sediment to form a new layer. As this process occured over and over again, the layers of sediment were created. This process still occurs today; Shark Bay in western Australia is well known for the stromatolite "turfs" rising along its beaches.

Origin of life on Earth



The Archean fossil record (cont.)



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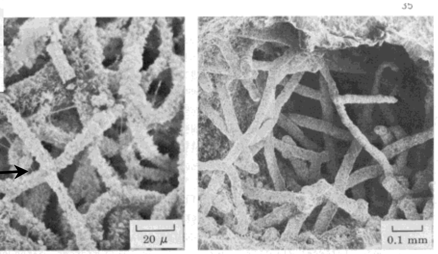
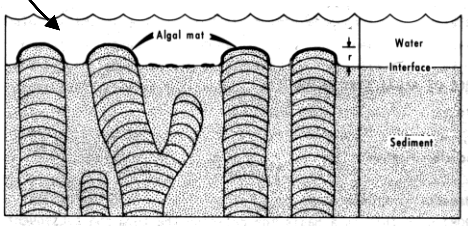


Modern cyanobacterial filaments

The Archean fossil record (cont.)

3.2 billion year old stromatolite from South Africa

Growth of cyanobacterial mats



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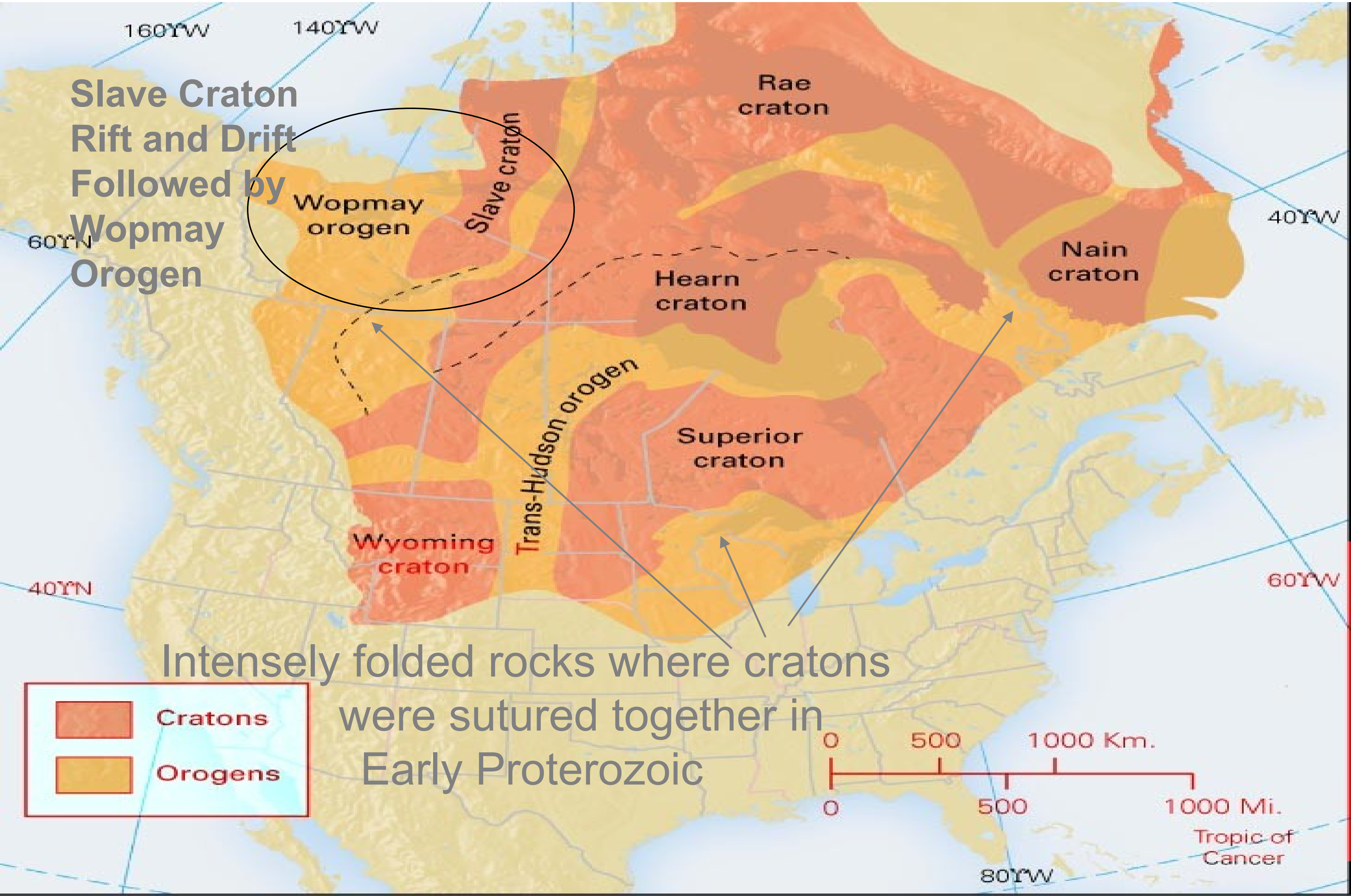
Crustal provinces: Proterozoic Tectonics



Slave Craton Rift and Drift Followed by Wopmay Orogen

Intensely folded rocks where cratons were sutured together in Early Proterozoic

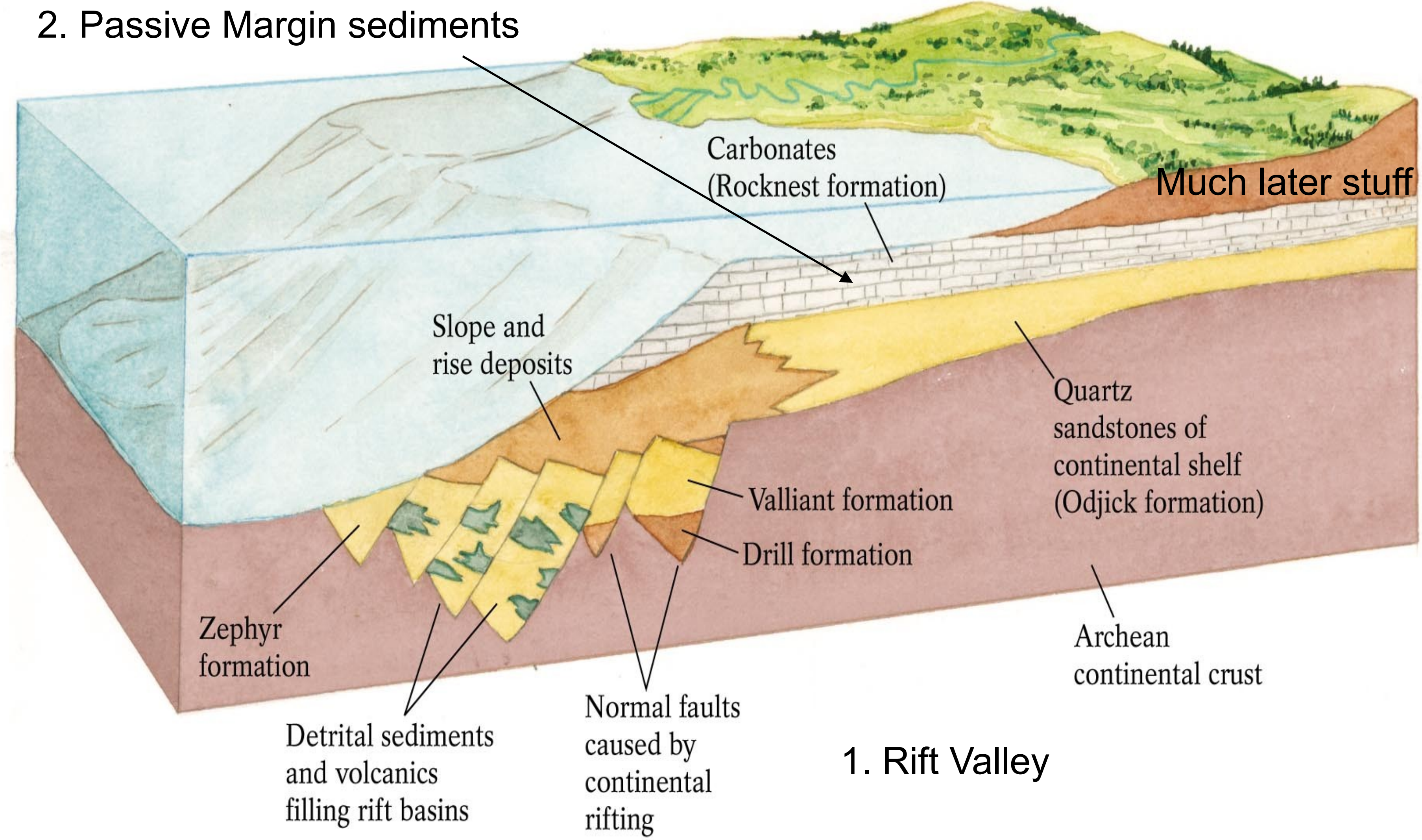
Proterozoic Tectonics: The Wilson Cycle

- Proterozoic – Convection Slows
- Rift Phase
  - Coarse border, valley and lava rocks in normal faulted basins

- Drift Phase
  - Passive margin sediments

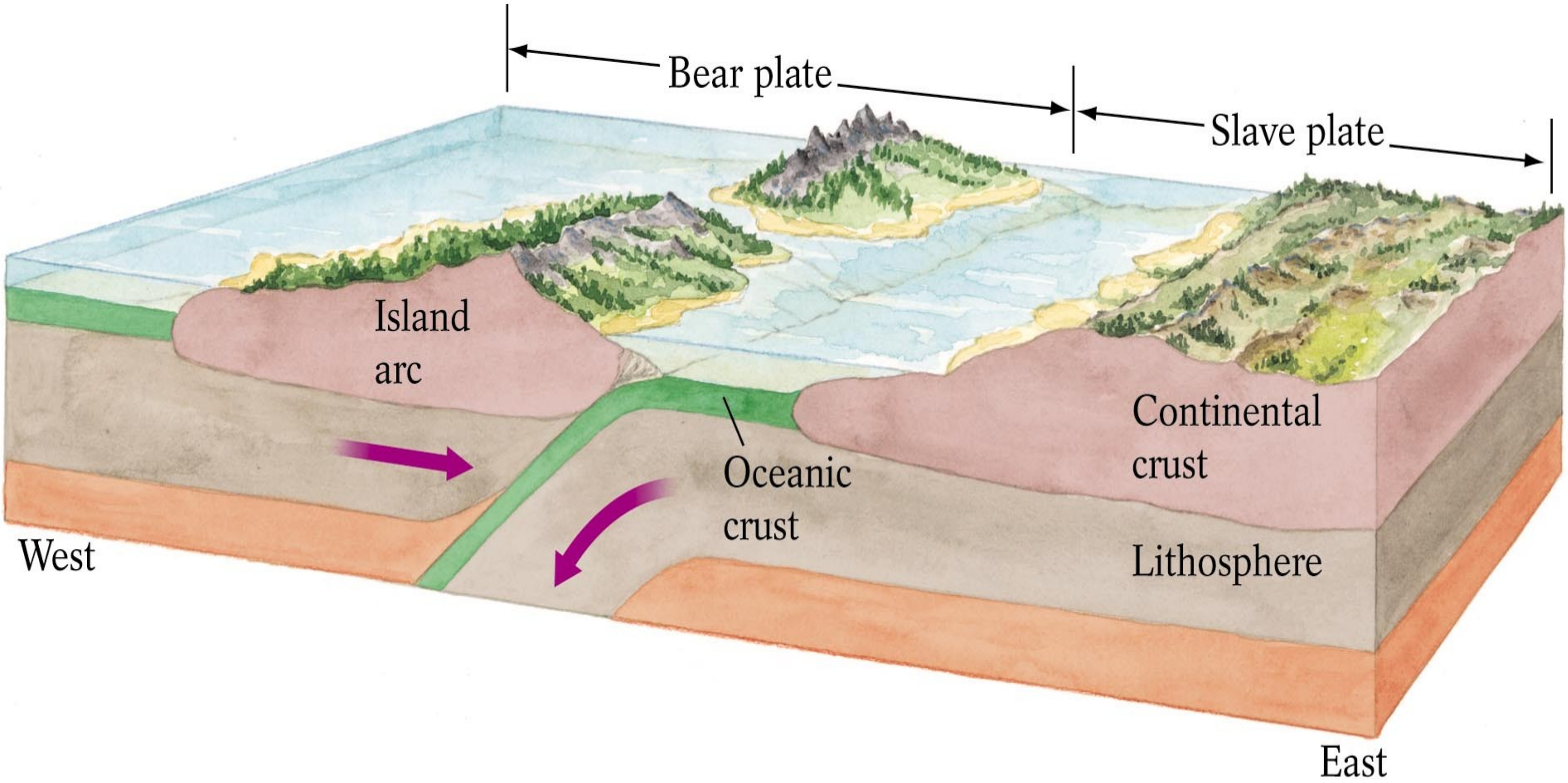
- Collision Phase
  - Subduction of ocean floor, collision with Island Arcs

Wilson Cycle 1&2 Rift & Drift Coronation Supergroup

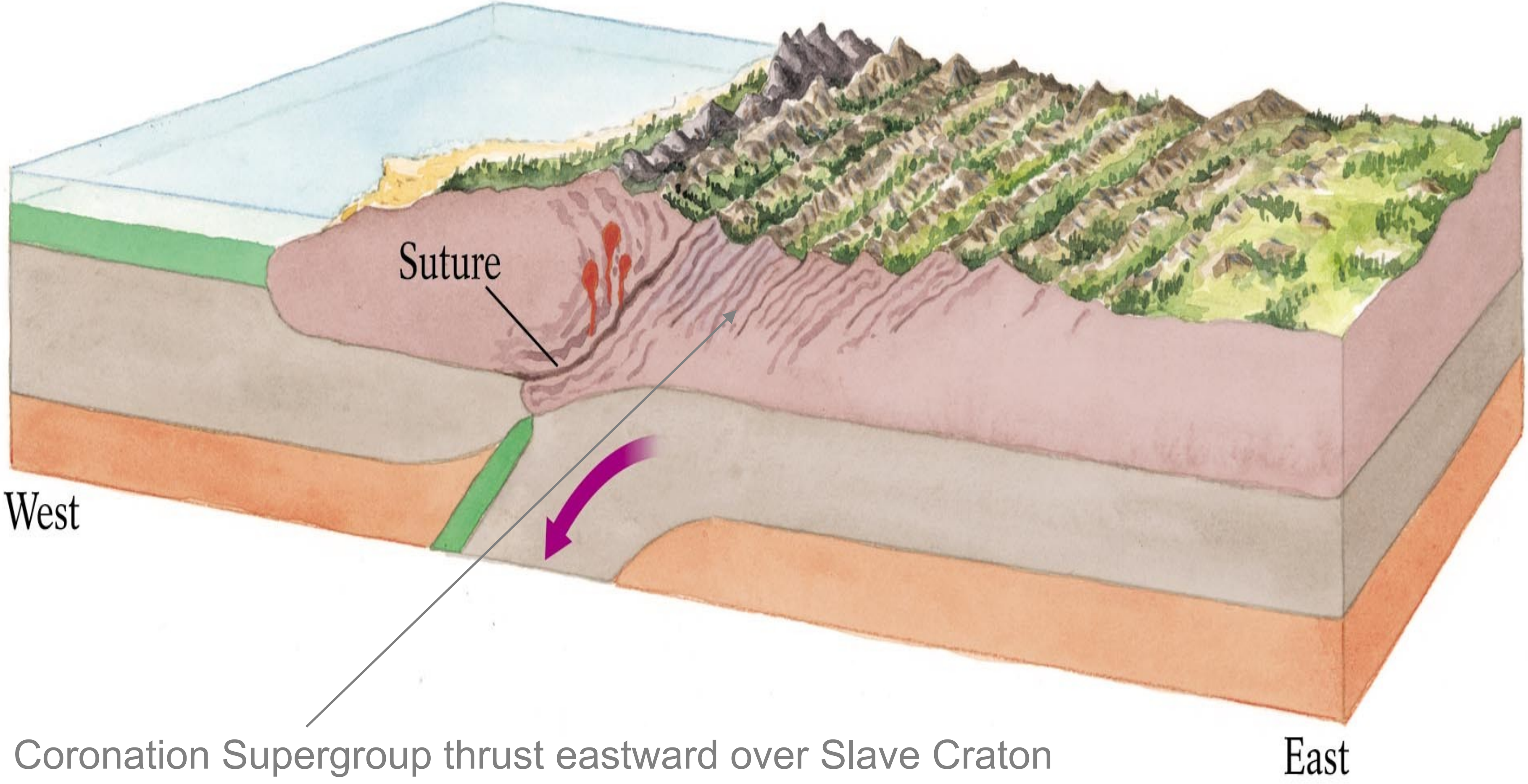


Proterozoic 2 bya as Slave craton pulled apart

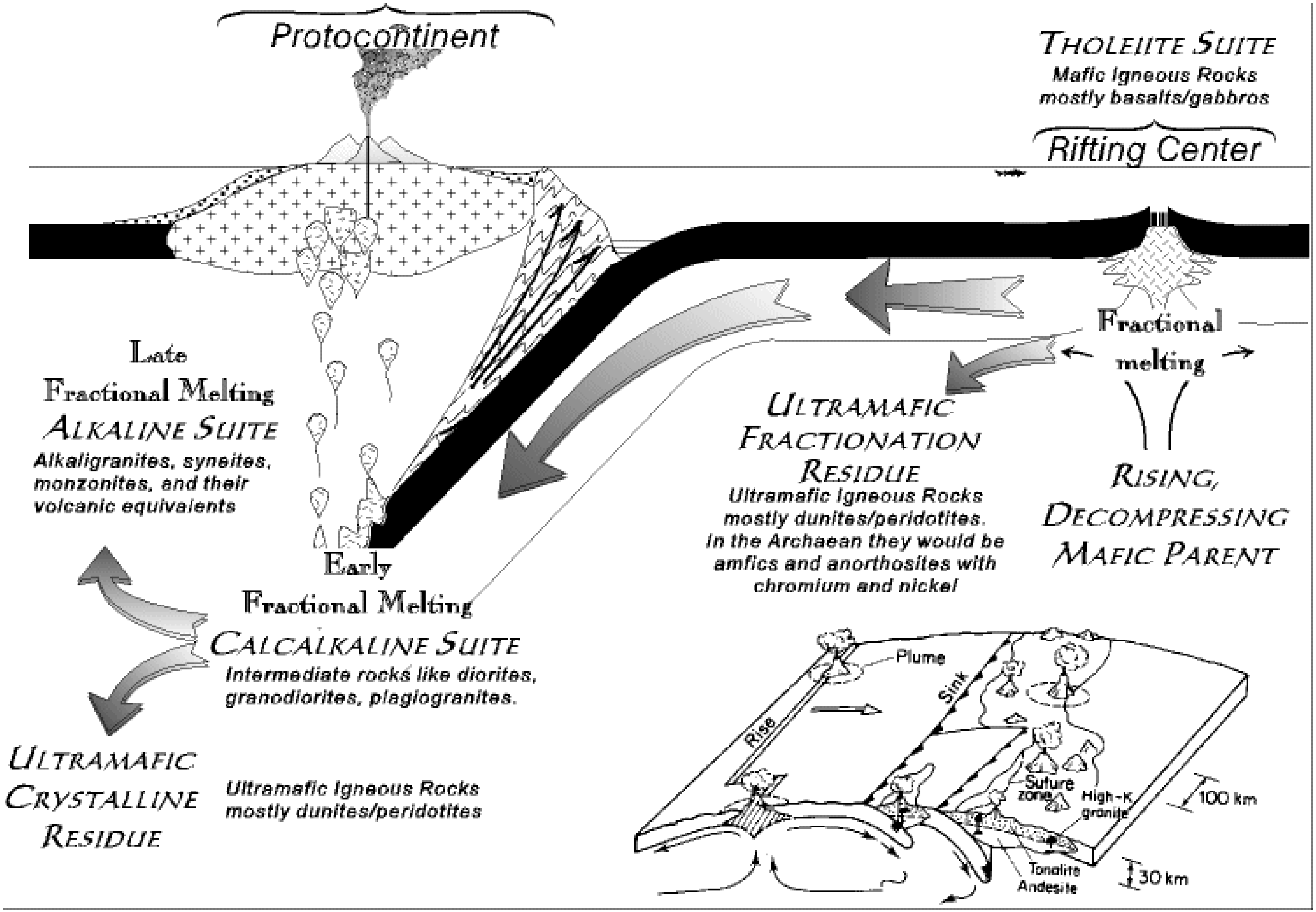
Near-collision phase of the Wilson Cycle in the Wopmay Orogen



3. End of Wilson cycle in the Wopmay orogen



Coronation Supergroup thrust eastward over Slave Craton
Note the vertical exaggeration



Protocontinent

THOLEIITE SUITE

Mafic Igneous Rocks
mostly basalts/gabbros

Rifting Center

Fractional melting

Late
Fractional Melting
ALKALINE SUITE

Alkaligranites, syneites,
monzonites, and their
volcanic equivalents

ULTRAMAFIC
FRACTIONATION
RESIDUE

Ultramafic Igneous Rocks
mostly dunites/peridotites.
In the Archaean they would be
amfics and anorthosites with
chromium and nickel

RISING,
DECOMPRESSING
MAFIC PARENT

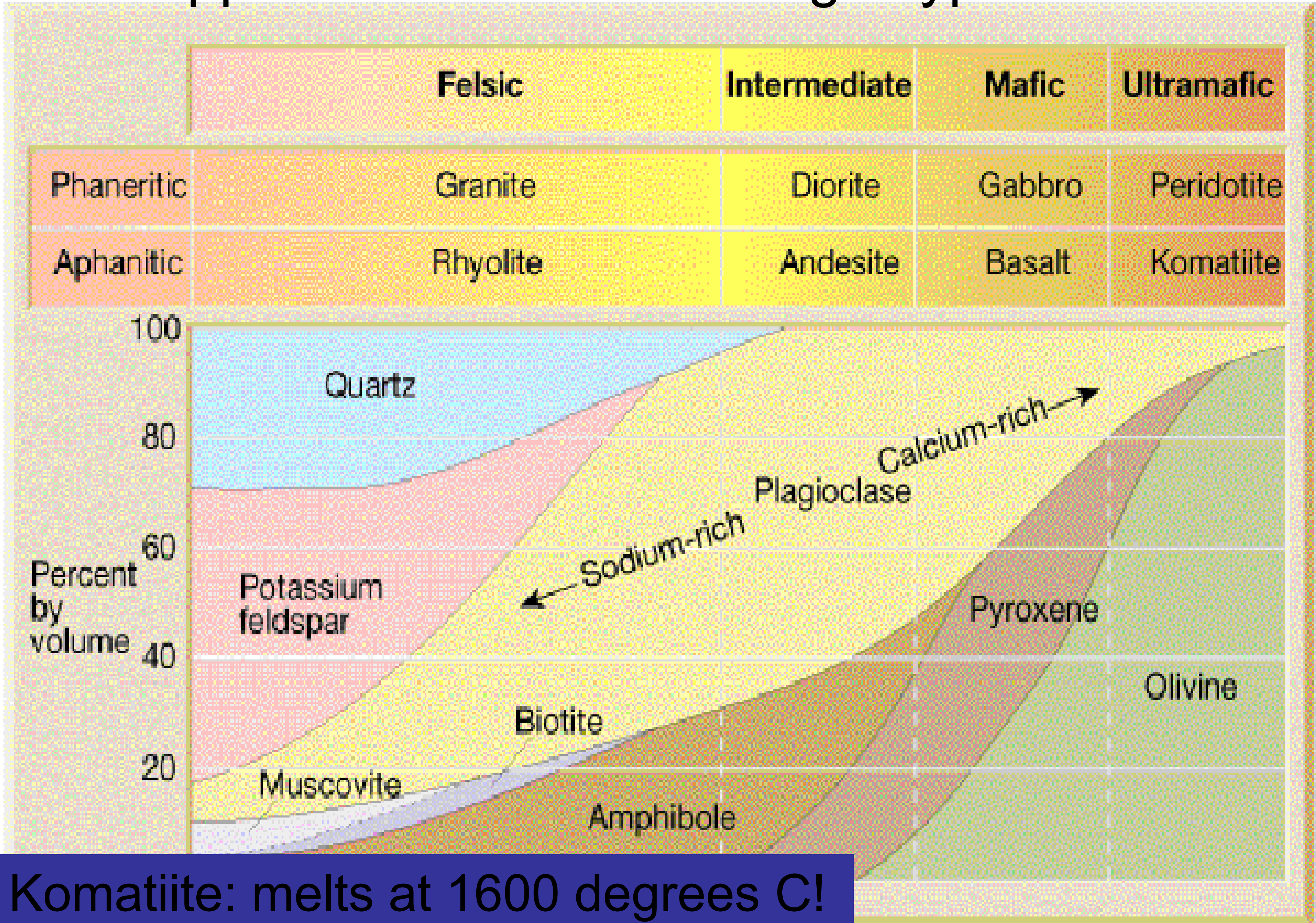
Early
Fractional Melting
CALCALKALINE SUITE

Intermediate rocks like diorites,
granodiorites, plagiogranites.

ULTRAMAFIC
CRYSTALLINE
RESIDUE

Ultramafic Igneous Rocks
mostly dunites/peridotites

Upper mantle hotter during Cryptozoic?



Komatiite: melts at 1600 degrees C!