# The origin of life and the fossil record

Introduction to Evolution and Scientific Inquiry

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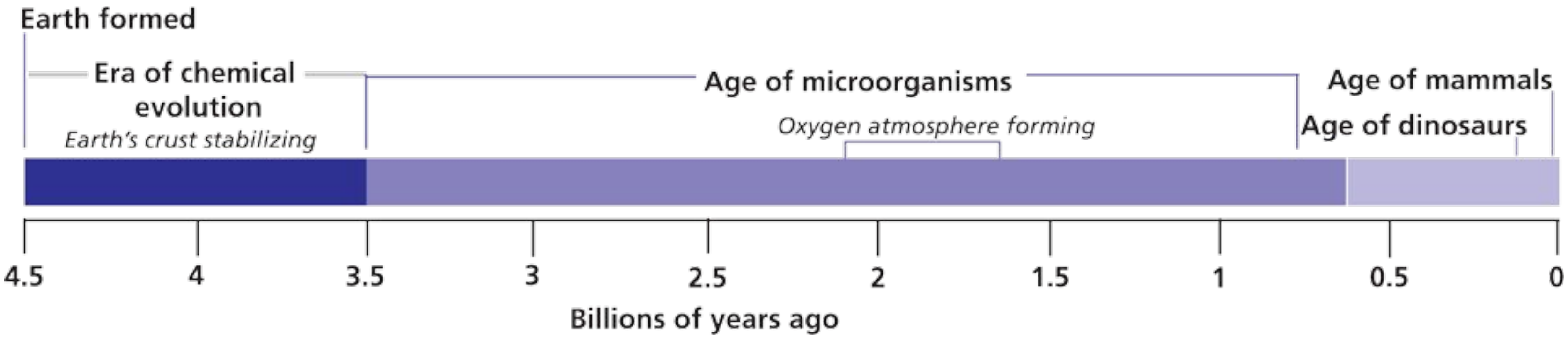
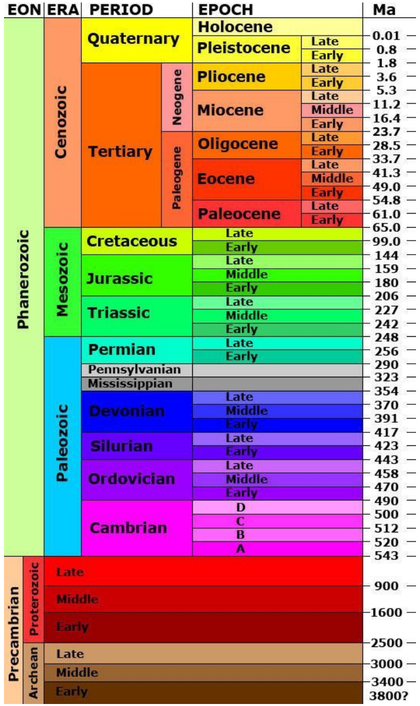
# A brief history of the earth and its life

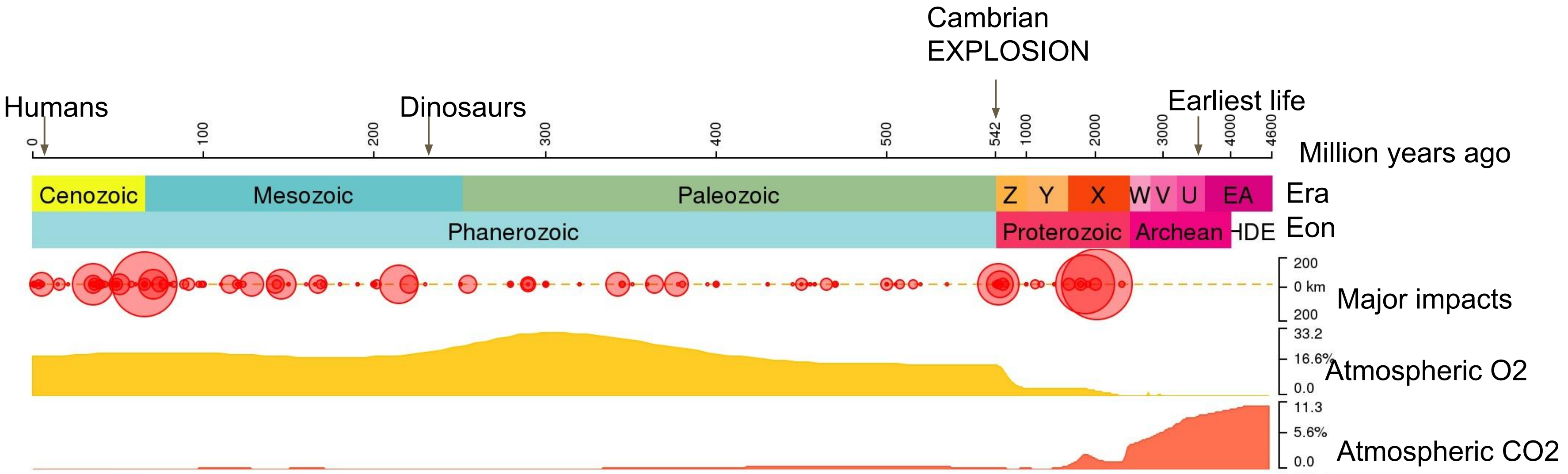


# Geologic ages

- Divisions originally based on fossil ages
- Precambrian Eon = everything before Cambrian
  - Formation of Earth 4000 Mya to ~542 Mya
- Phanerozoic Eon = Cambrian (~542 Mya) through present
  - **Vast majority** of fossil data from this eon
  - Three eras:
    - Paleozoic ("ancient animals")
    - Mesozoic ("middle animals") ← Dinosaurs
    - Cenozoic ("recent animals") ← NOW

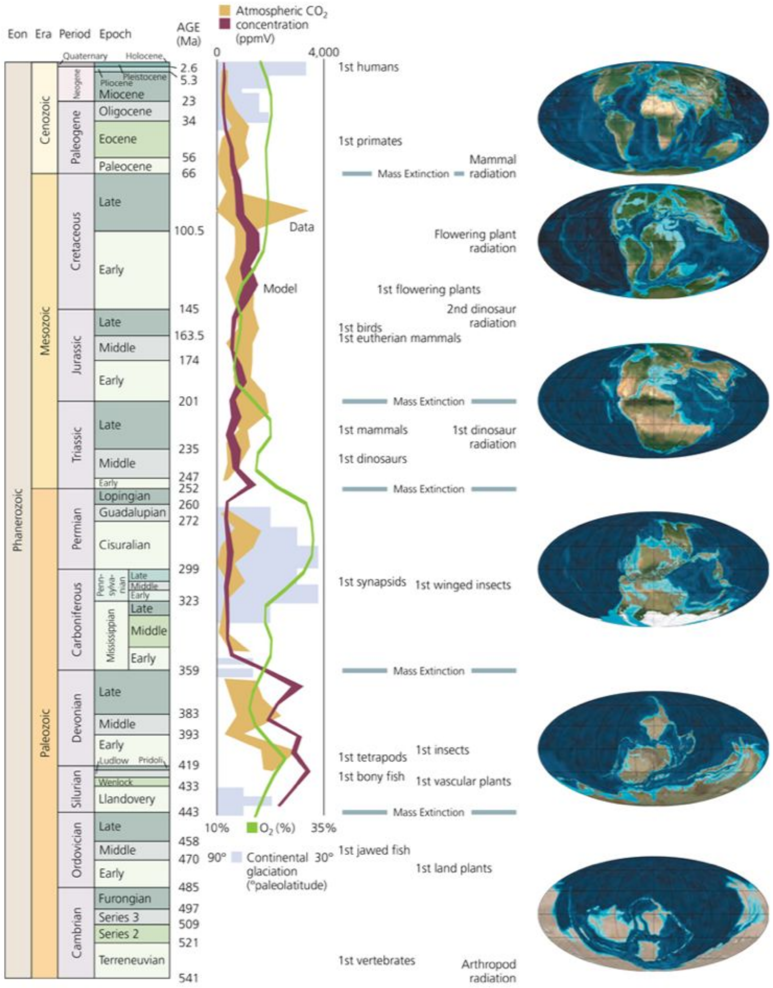


# Properties of different eras

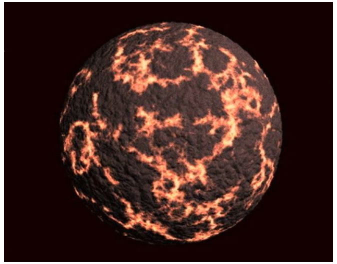


# Key timeline events in the Phanerozoic Era

- The "Big Five" Mass Extinctions
- First vertebrates ~540 Mya
- Land plants ~470 Mya
- First mammals ~200 Mya
    - First *placental* mammals ~164 Mya



# The early earth



- Earth formed 4.6 billion years ago and is VERY TURBULENT
- Anoxic conditions with surface temperatures of 100 C
- Lots of methane, ammonia, nitrogen, carbon dioxide, hydrogen
- No liquid water, but some in atmosphere
- Constant meteorite bombardment and volcanic activity
    - Moon!
- Plate tectonic activity present by 3.5 billion years ago

**How could life have emerged under these conditions?!**

# The Miller-Urey experiment (1952)

- Simulate early earth conditions in the lab and SPARK with electricity ("lightning")

- Amino acids and other organic compounds "spontaneously" formed from inorganic matter

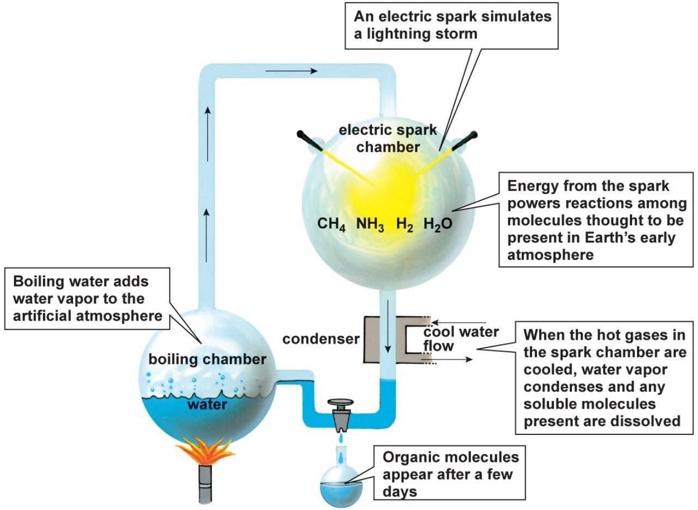






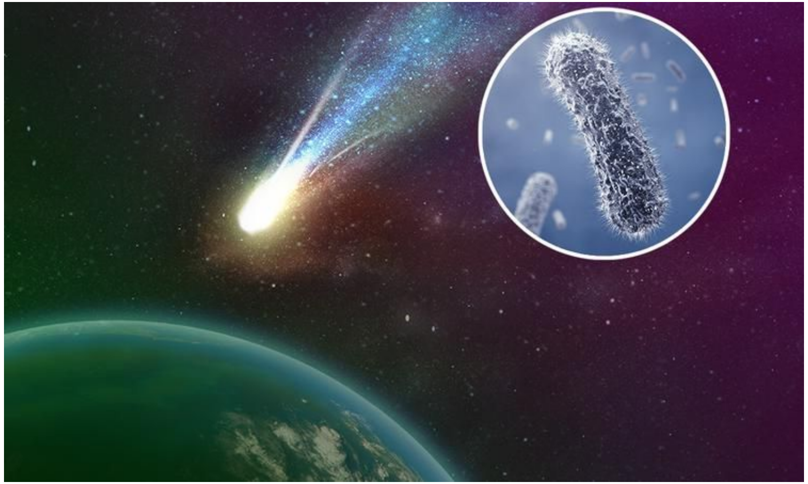
**TABLE 2.2**
**Biologically Significant Organic Molecules Produced in Two of the Experiments on Abiotic Synthesis Conducted by Stanley Miller and Reported in 1953**

| Organic Compound | | Yield (micromoles) | |
|---|---|---|---|
| **Name** | **Formula** | **Expt. 1** | **Expt. 3** |
| Glycine | $H_2N-CH_2-COOH$ | 630 | 800 |
| Alanine | $H_2N-CH(CH_3)-COOH$ | 340 | 90 |
| Aspartic acid | $H_2N-CH(CH_2COOH)-COOH$ | 4 | 2 |
| Glutamic acid | $H_2N-CH(C_2H_4COOH)-COOH$ | 6 | 5 |
| *β*-alanine | $H_2N-CH_2-CH_2-COOH$ | 150 | 40 |
| *α*-aminobutyric acid | $H_2N-CH(C_2H_5)-COOH$ | 50 | 10 |
| *α*-aminoisobutyric acid | $H_2N-C(CH_3)_2-COOH$ | 1 | 0 |
| Sarcosine | $HN(CH_3)-CH_2-COOH$ | 50 | 860 |
| *N*-methylalanine | $HN(CH_3)-CH(CH_3)-COOH$ | 10 | 125 |
| Formic acid | $H-COOH$ | 2330 | 1490 |
| Acetic acid | $CH_3-COOH$ | 152 | 135 |
| Propionic acid | $C_2H_5-COOH$ | 126 | 19 |
| Glycolic acid | $HO-CH_2-COOH$ | 560 | 280 |
| Lactic acid | $HO-CH(CH_3)-COOH$ | 310 | 43 |
| *α*-hydroxybutyric acid | $HO-CH(C_2H_5)-COOH$ | 50 | 10 |
| Succinic acid | $HOOC-CH_2-CH_2-COOH$ | 38 | 0 |
| Iminodiacetic acid | $HOOC-CH_2-NH-CH_2-COOH$ | 55 | 3 |
| Iminoacetic-propionic acid | $HOOC-CH_2-NH-C_2H_4-COOH$ | 15 | 0 |
| Urea | $H_2N-CO-NH_2$ | 20 | 0 |
| N-methylurea | $H_2N-CO-NH-CH_3$ | 15 | 0 |
| Total yield of compounds listed* | | 15% | 3% |

*Percent yield based on the amount of carbon placed in the apparatus as methane.

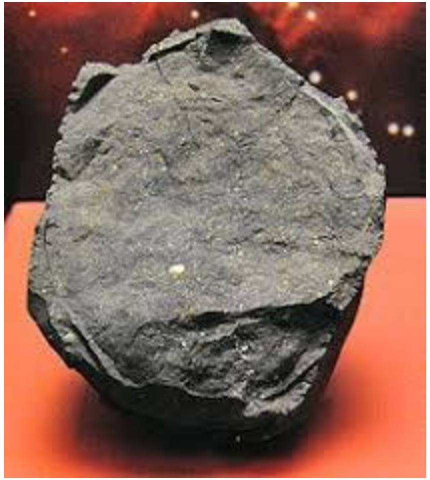
# The Panspermia Hypothesis

- Life on earth COULD HAVE originated from an extraterrestrial impact event carrying life and/or chemical precursors of life from *outer space*

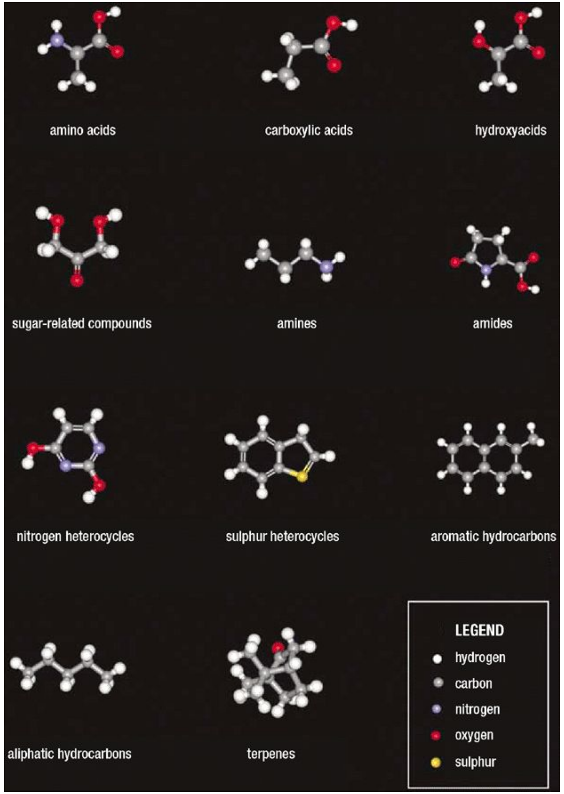


# The Murchison Meteorite contains organic compounds

Suggests panspermia is technically possible!



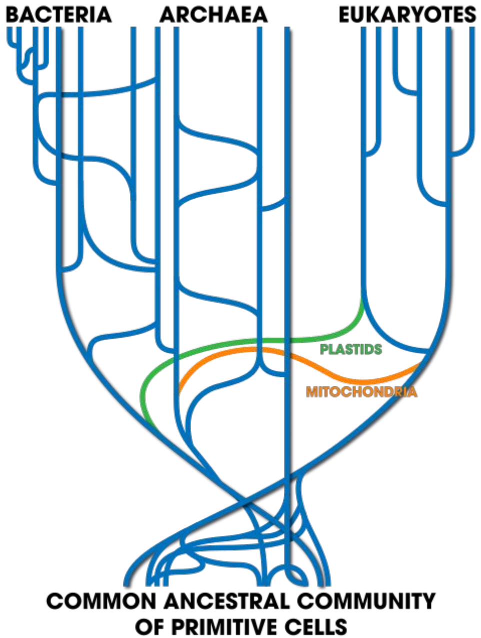
100 kg
Fell to Australia in 1969

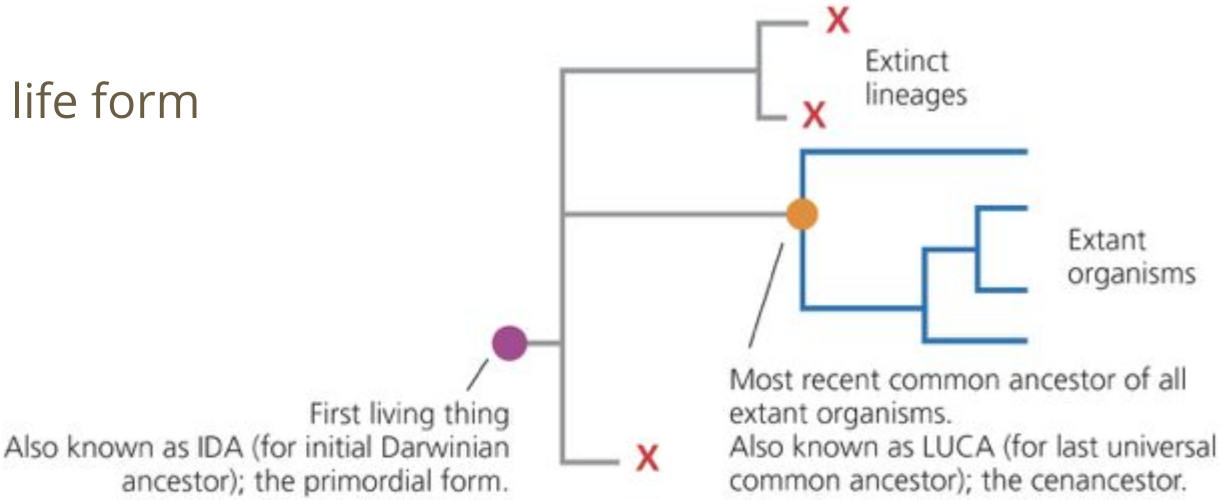



https://doi.org/10.1046/j.1468-4004.2003.45208.x

# LUCA: Last Universal Common Ancestor

- LUCA is NOT the first life form

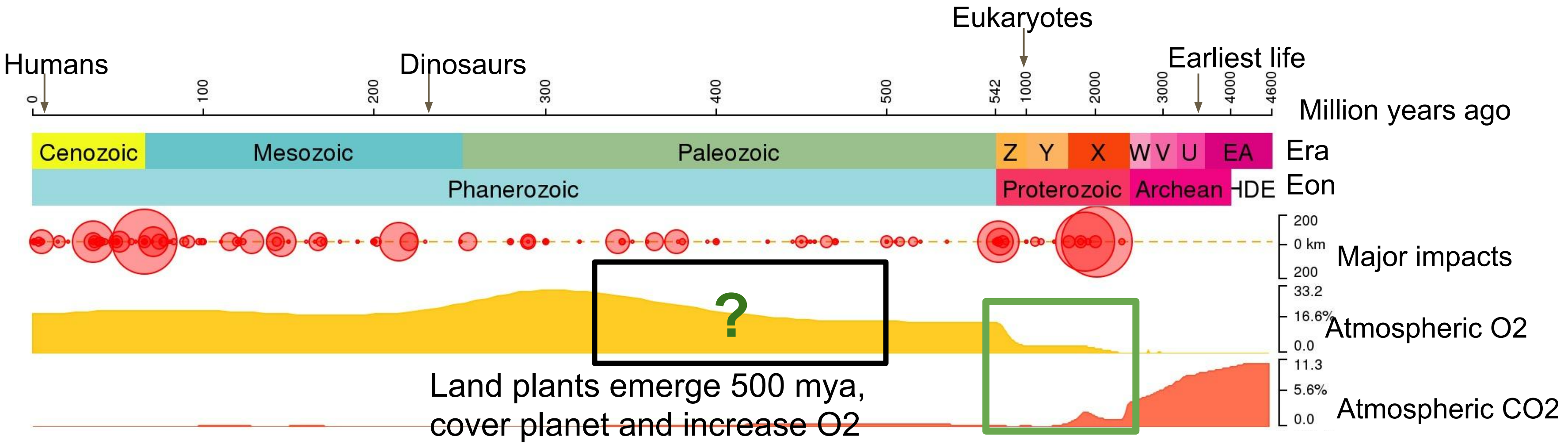


# Cyanobacteria were among the earliest life forms on earth


Early photosynthetic bacteria starts to dump major amounts of Oxygen into ocean, then atmosphere

# Cyanobacteria contribute to swap atmospheric CO2 for O2



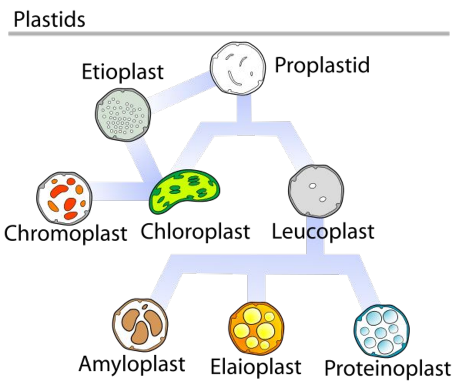

Land plants emerge 500 mya, cover planet and increase O2 even more

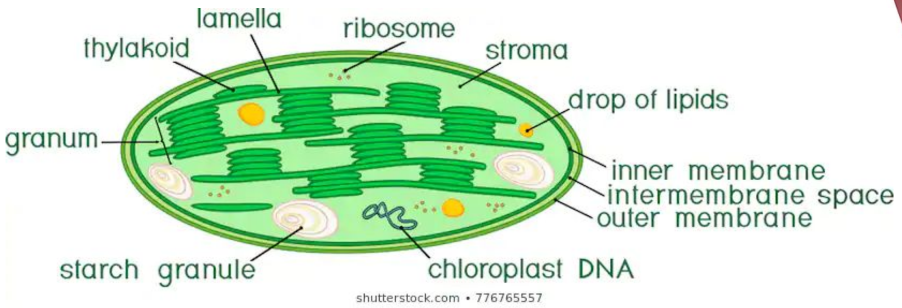
# A few Major Transitions in Evolution

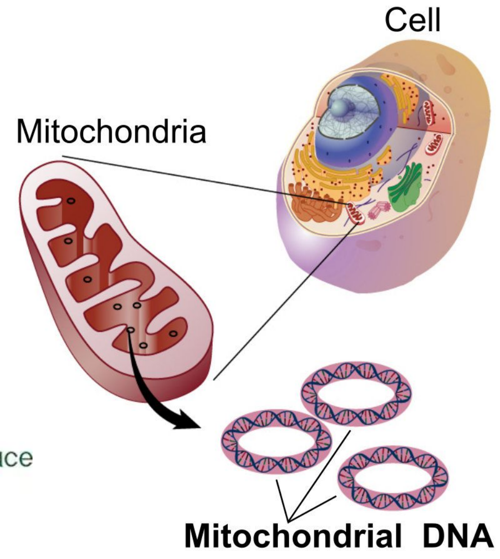
- Emergence of self-replicating molecules (RNA World)
- Replacement of RNA with DNA-protein
  - Happened *before* LUCA emerged
- Emergence of colony-living instead of solitary living
- **Emergence of eukaryotic life (~1.8-2 billion years ago)**
  - Involves acquisition of mitochondria, plastids
- **Emergence of multicellularity**
- Emergence of sexual reproduction

# Eukaryotes have *membrane-bound* organelles

- Like certain free-living cells, mitochondria and plastids..
  - Have their own membrane
  - Can self-replicate
  - Have haploid genomes

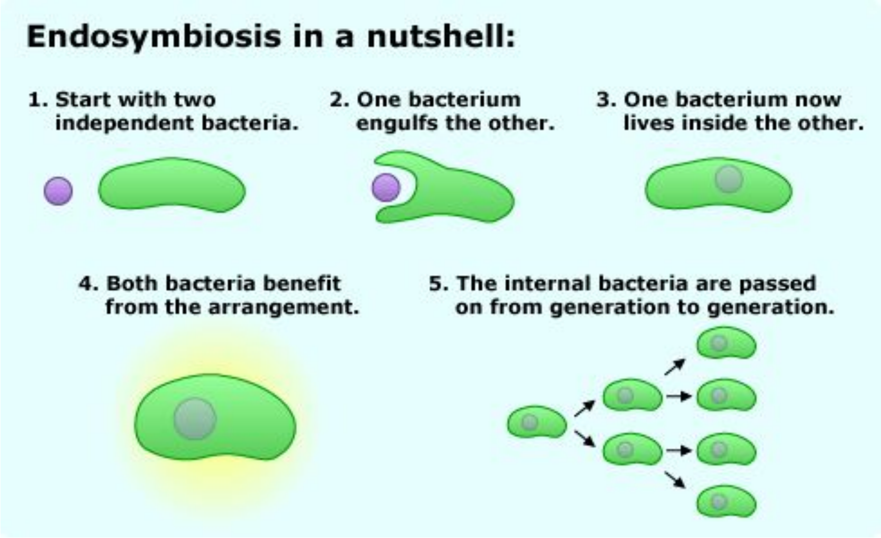


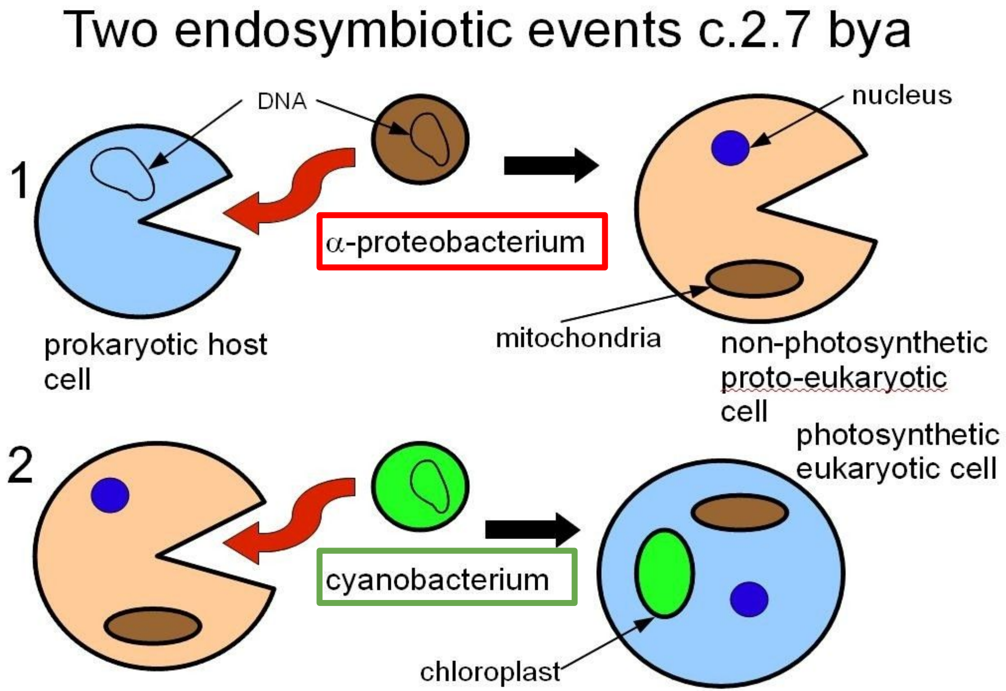



# The Endosymbiosis Theory

- Endosymbiont: A symbiont that lives *inside* the host and is vertically transmitted to progeny
    - Many endosymbiont genes are *lost* or *transferred* to host nucleus
    - Neither the host nor the endosymbiont can live independently anymore

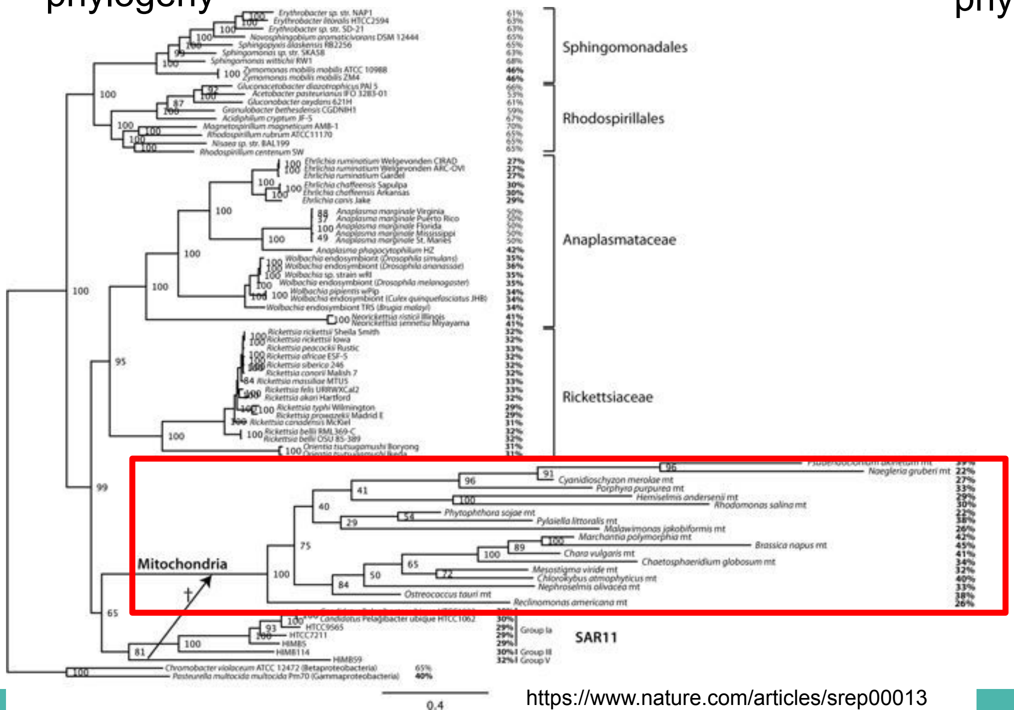


# "Acquisition" of mitochondria marks origin of eukaryotes



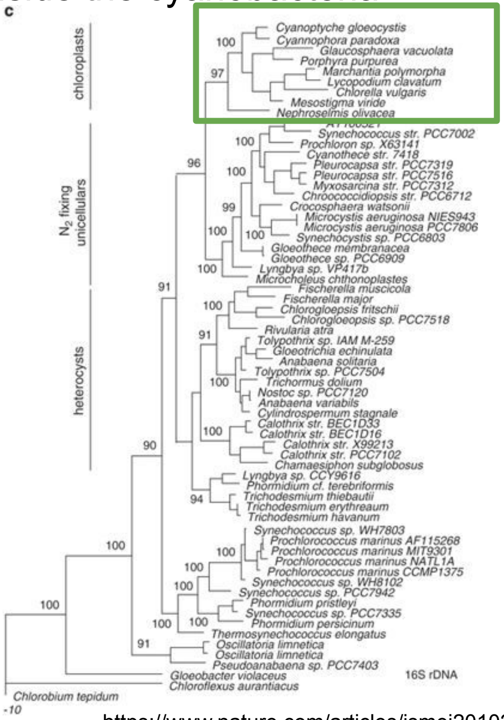
# There is phylogenetic evidence for the endosymbiosis theory

Mitochondria are inside the alpha-proteobacteria phylogeny




https://www.nature.com/articles/srep00013

Choloplasts are inside the cyanobacteria phylogeny

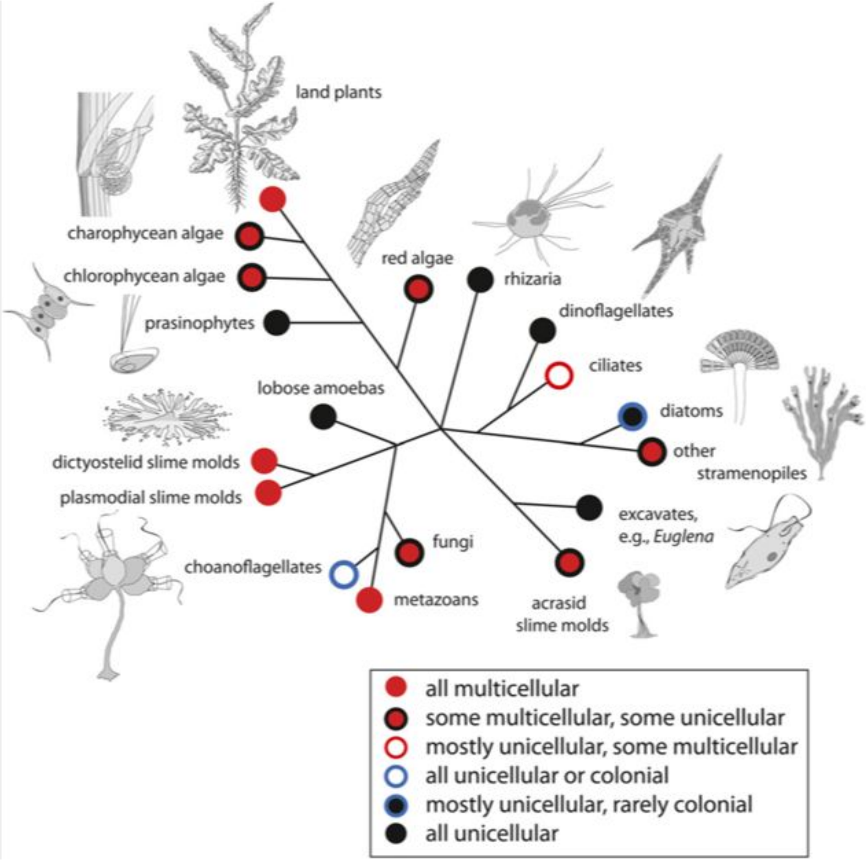



https://www.nature.com/articles/ismej20102#f1

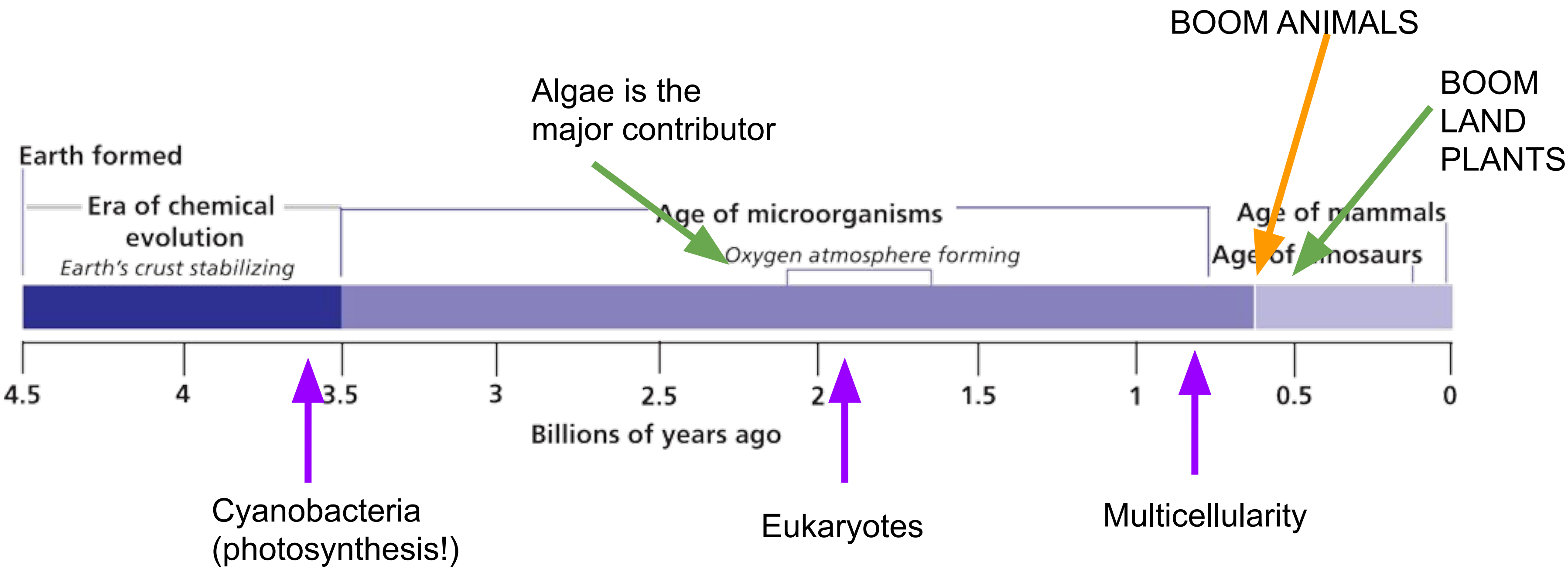
# Emergence of multicellularity began 600 million years ago

- Features of multicellularity
  - Cells must *adhere*
  - Cells must *cooperate*
  - Cells must *share resources and energy*
  - Cells should show *division of labor*
  - A division between somatic cells and germline cells = cooperation extraordinaire!

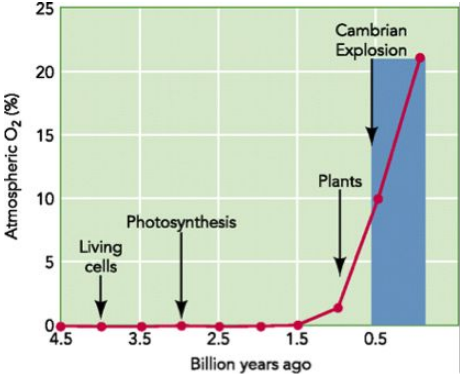
- It has evolved *convergently* many times (over TWENTY, just once in animals)

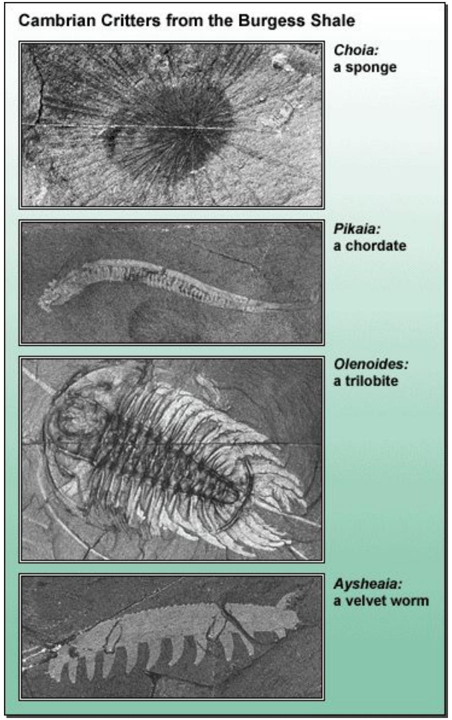


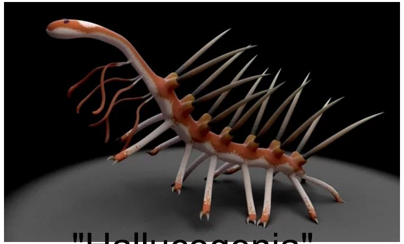
# Where are we so far?



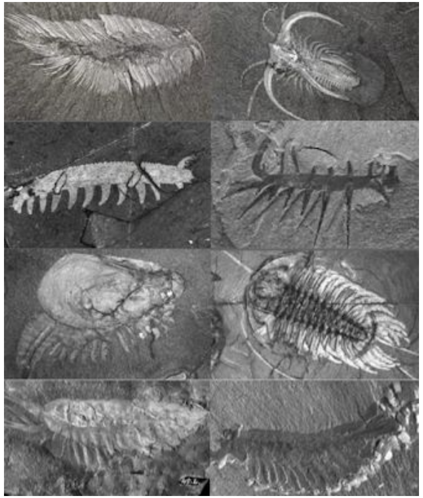
# The Cambrian EXPLOSION! (542 Mya)



"Hallucogenia"



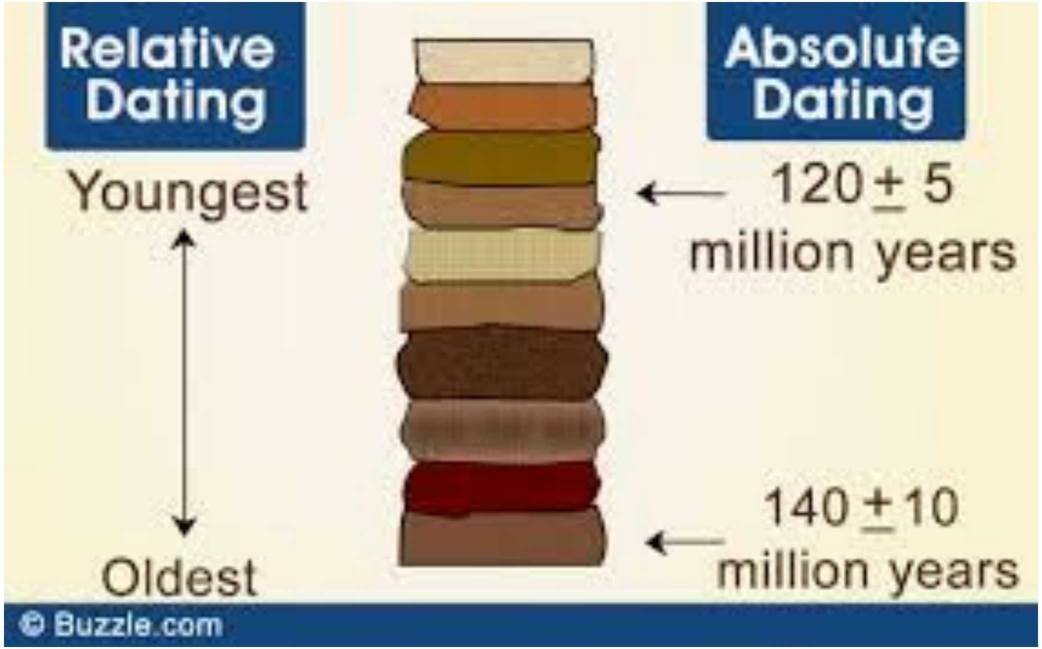
Burgess Shale in British Columbia, Canada

# Fossils!

- Fossil = any trace of past life preserved in the geologic record
  - Body parts e.g. teeth, bones, shells
  - "Trace" fossils like footprints, body imprints, burrows
  - "Chemical" fossils: biological molecules preserved in rock

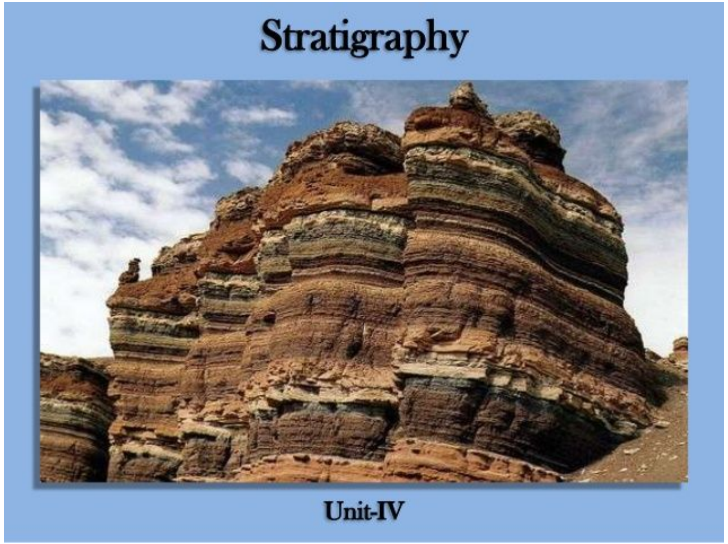
- Soft-bodied animals and soft tissue (muscle, fascia, tendons..) don't fossilize well
- You will become a fossil if you die in the right place, right time in **sedimentary rock**
  - Rock formed by *deposition* of material as it layers over time

# Relative vs absolute dating

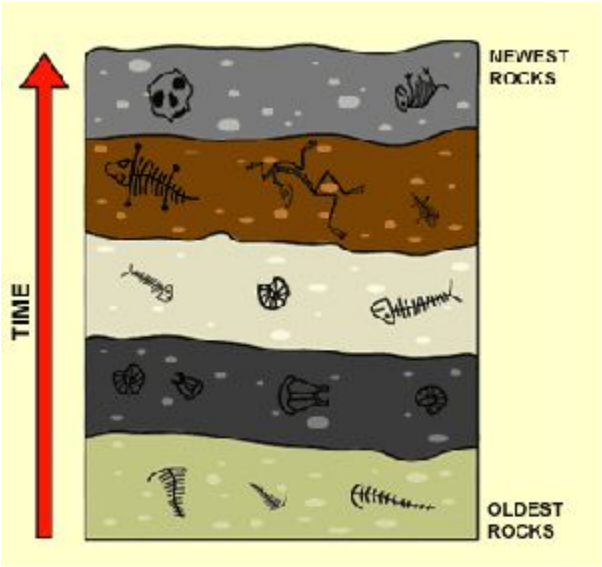


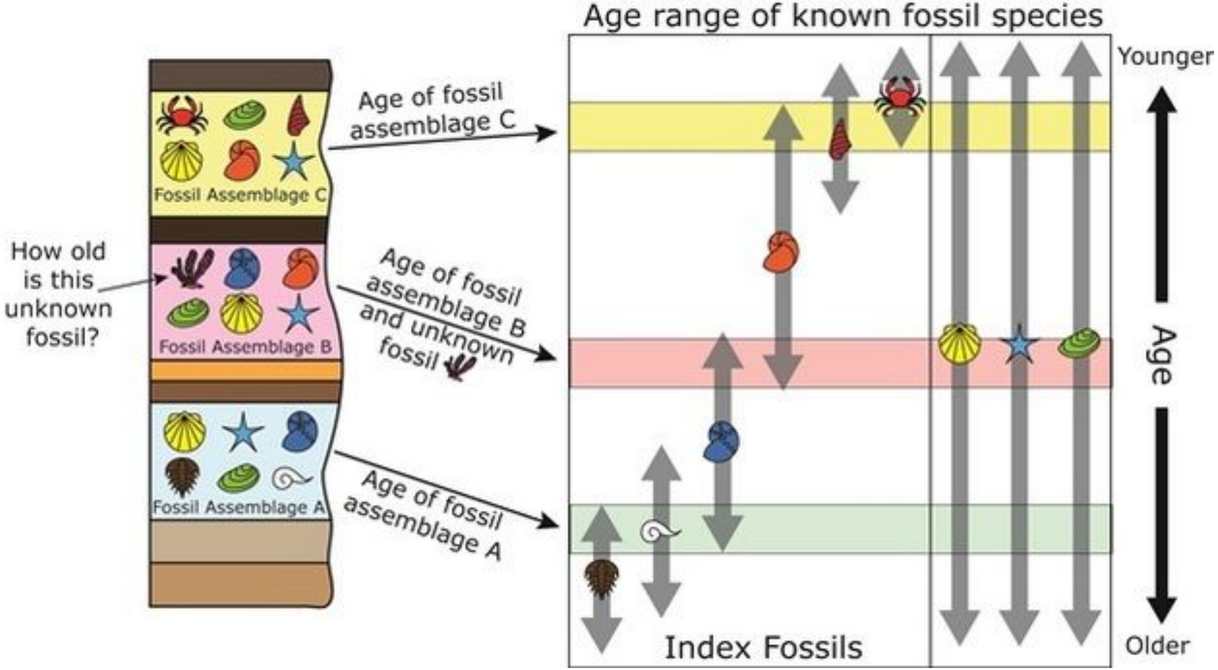
# Relative dating with stratigraphy

- The Law of Superposition
  - Younger rock layers ("strata") are deposited on top of older strata
  - Rock layers on top are younger than layers on the bottom



# Relative dating, for example

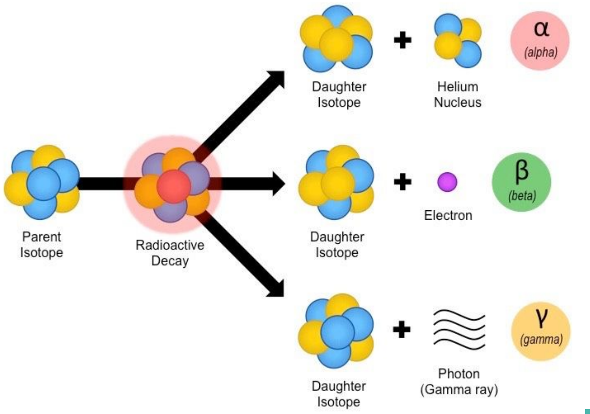


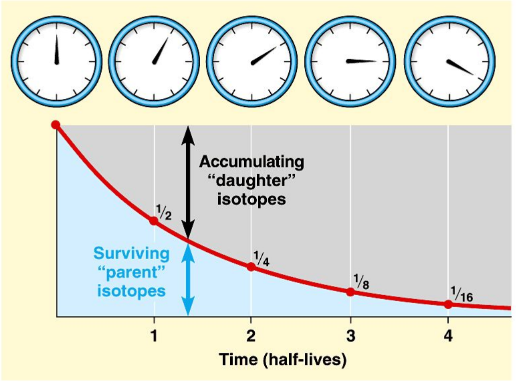



# Absolute dating with radioactive isotopes ("radiometric dating")

Radioactive isotopes decay at a very predictable rate (measured in half-lives).

Comparing the ratios of parent and daughter isotopes allows us to estimate the age of a rock.



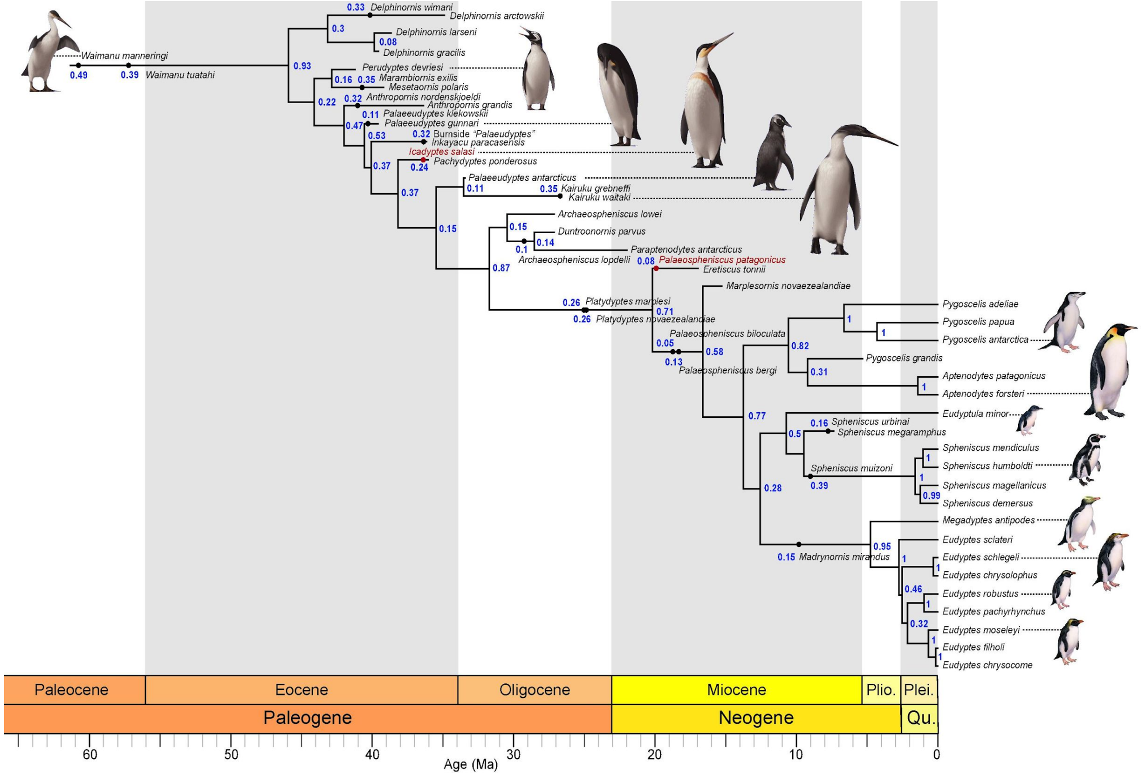



# Pop quiz!

We found a fossil in a stratigraphic layer we dated to be 325 million years old.

What does this age tell us about when this organism who fossilized lived? First evolved?

# Incorporate fossils into phylogeny to find absolute divergence dates: "Molecular Clock"




DOI:10.1093/sysbio/syw060

# Five big mass extinction events

Note, 99.9% of all life that ever existed is now extinct!

Possible causes include..

- Climate change
- Change in sea levels
- Global catastrophes
  - Earthquakes, volcanoes
- Extraterrestrial impact events
  - (meteor)

**Brief summary of major extinction events**

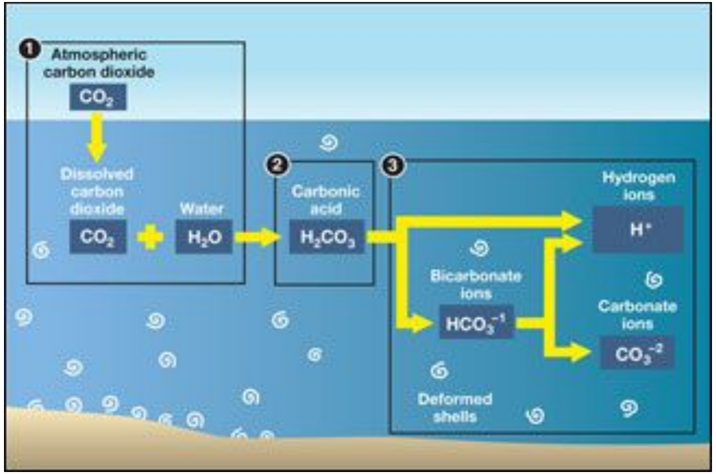
| | Extinction | Date | Losses |
|---|---|---|---|
| | Ordovician-Silurian | 440-450 Ma | 27% of families, 57% of genera |
| | Late Devonian | 360-375 Ma | 19% of families, 50% of genera, 70% of species |
| **P-T** | Permian-Triassic | 251 Ma | 57% of families, 80% of genera, 96% marine species, 70% land species |
| | Triassic-Jurassic | 205 Ma | 23% of families, 48% of genera |
| **K-Pg** | Cretaceous-Tertiary | 65.5 Ma | 17% of families, 50% of genera, 75% of species |
| | Quaternary Extinction | NOW | ongoing and accelerating... |

(Ma = million years ago)

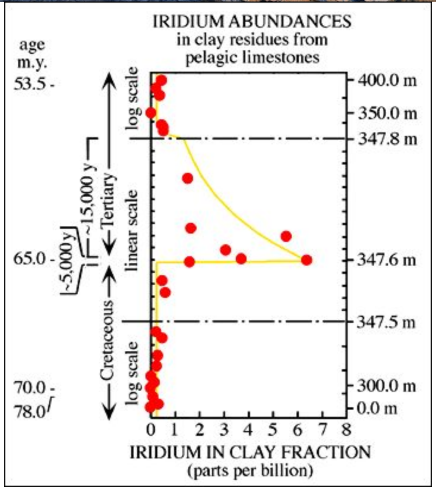
# P-T Extinction: The "Great Dying"


- MASSIVE BEYOND ALL REASON volcanism releases tons of carbon from deep in the earth into the atmosphere

- Oceans become *much* warmer **and** they absorb much of the released CO2 → ocean acidification
- **Ocean acidification kills just about everything**



# K-Pg (or K-T)  Extinction: Goodbye dinosaurs




- K-Pg boundary is rock layer separating K-Pg
- K ~ Cretaceous
- T ~ Tertiary = Paleogene

- Massive Iridium spike at this location in sedimentary rock
  - Iridium is a VERY rare element…how so much?!

# "Transitionary" Fossils

- Likely represent "intermediate" forms of life during an evolutionary transition
  - **But remember - evolution has NO GOAL!**

- If we fossilize when we die, we will *all be* transitionary fossils for human descendents 10 million years from now*
  - *Excepting global nuclear annihilation, etc...

# Tiktaalik (375 Mya)

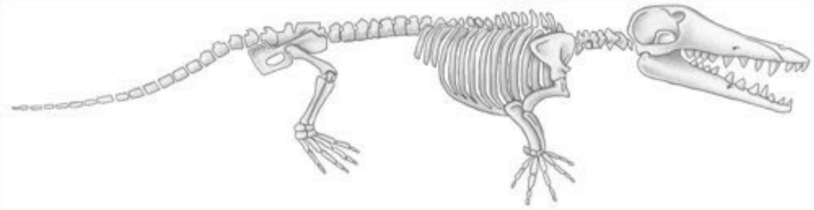
Evolutionary transition from fish → tetrapod

# Archaeopteryx (150 Mya)

Transition from dinosaur to bird

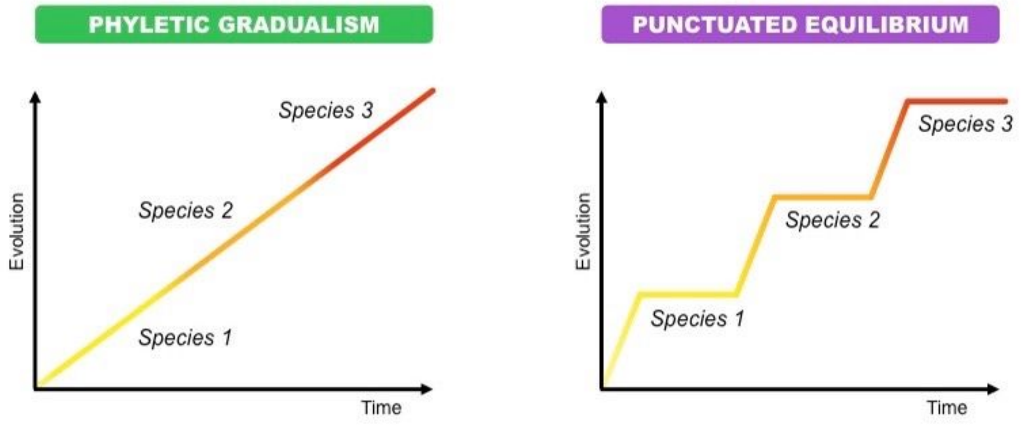
# Ambulocetus (45 Mya)

Transition to cetaceans (whales, dolphins)

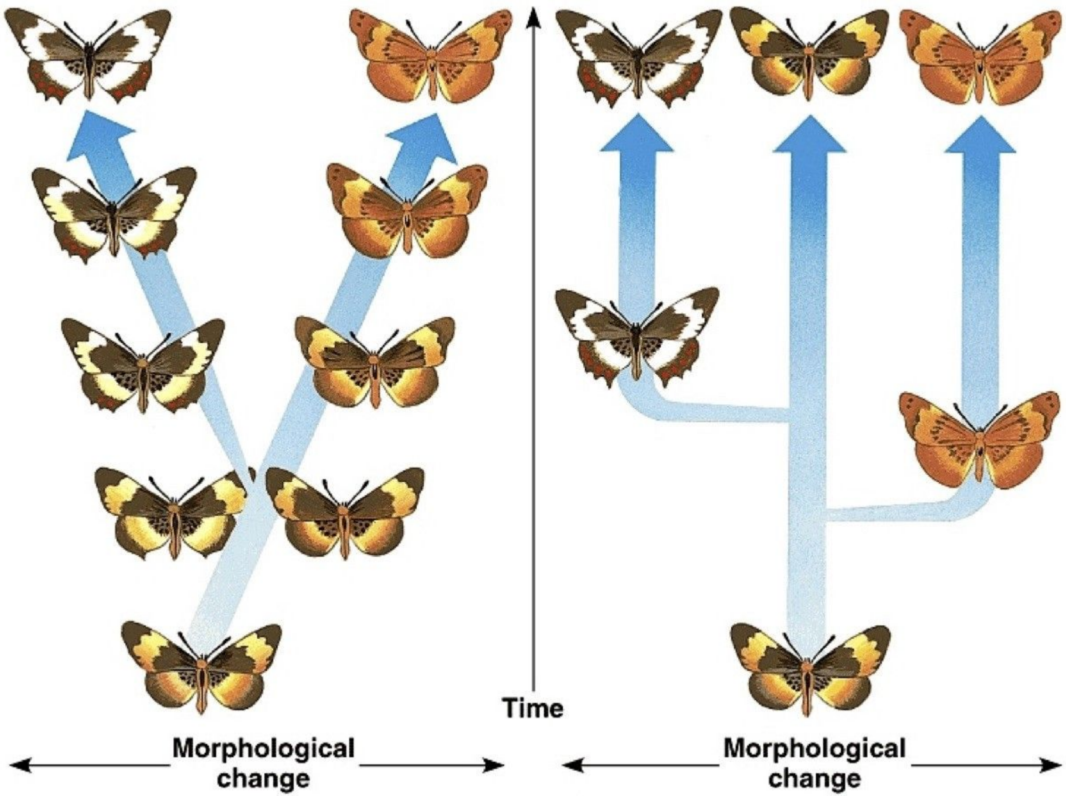


# Modes of macroevolution

- **Punctuated Equilibrium**
  - Periods of relatively little evolutionary change are <u>punctuated</u> by bursts rapid morphological change
- **Gradualism**
  - Slow, gradual change in phenotype with gradual rates of speciation



# Punctuated equilibrium vs gradualism?



# Rates of macroevolution

Rate of morphological change can vary substantially in deep time.

Some species show **morphological stasis:**

Horseshoe crab fossil: 245 Mya

Coelocanth fossil: 300 Mya

# Rate of morphological change does not always match rate of molecular change