The origin of life, major evolutionary transitions, and the fossil record

Introduction to Evolution and Scientific Inquiry

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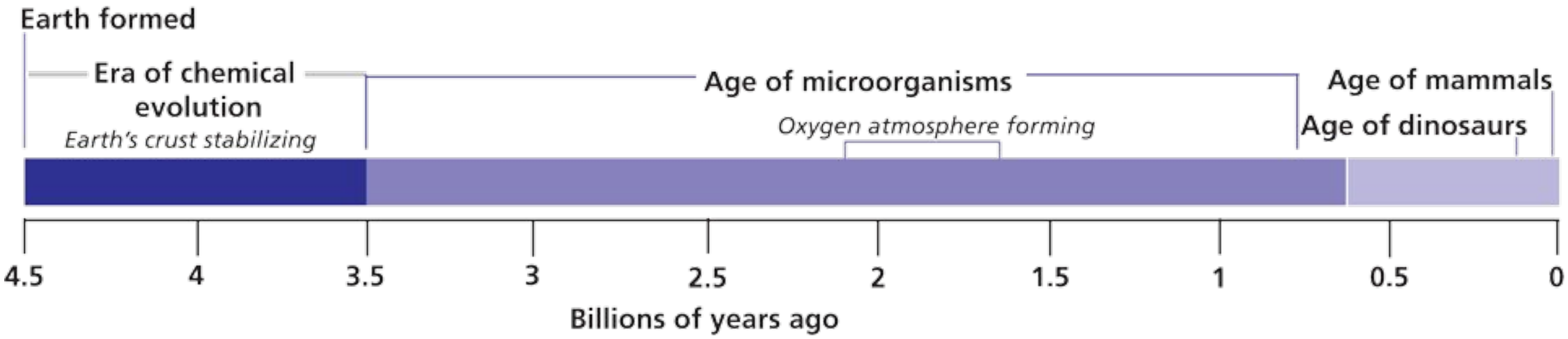
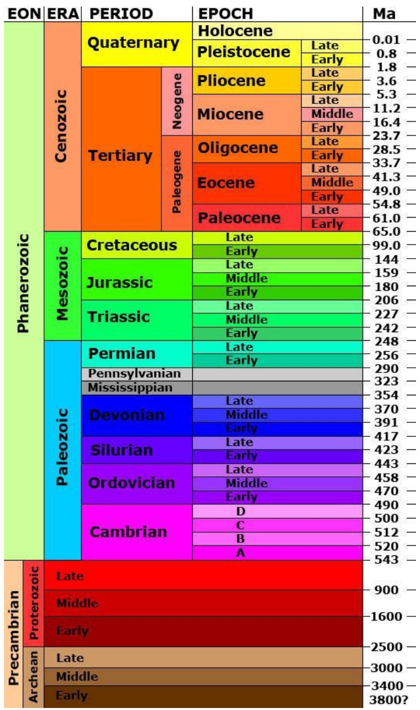
A brief history of the earth and its life

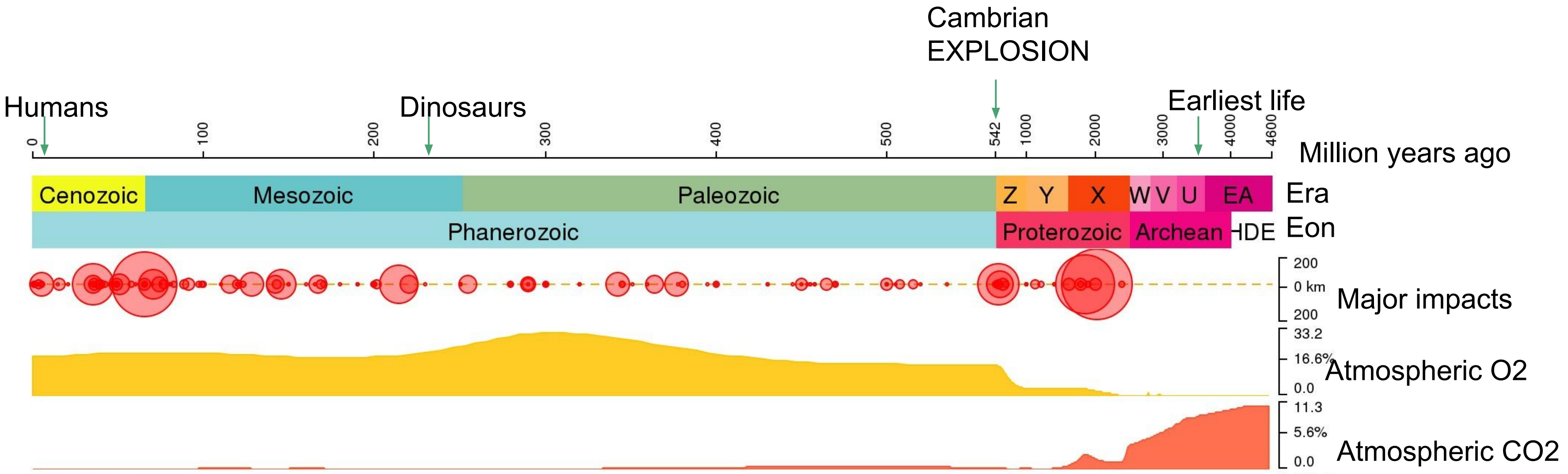


Geologic ages

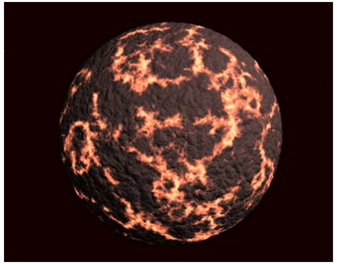
- Divisions originally based on fossil ages
- Precambrian Eon = everything before Cambrian
  - Formation of Earth 4000 Mya to ~542 Mya
- Phanerozoic Eon = Cambrian (~542 Mya) through present
  - **Vast majority** of fossil data from this eon
  - Three eras:
    - Paleozoic ("ancient animals")
    - Mesozoic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



Properties of different eras



The early earth



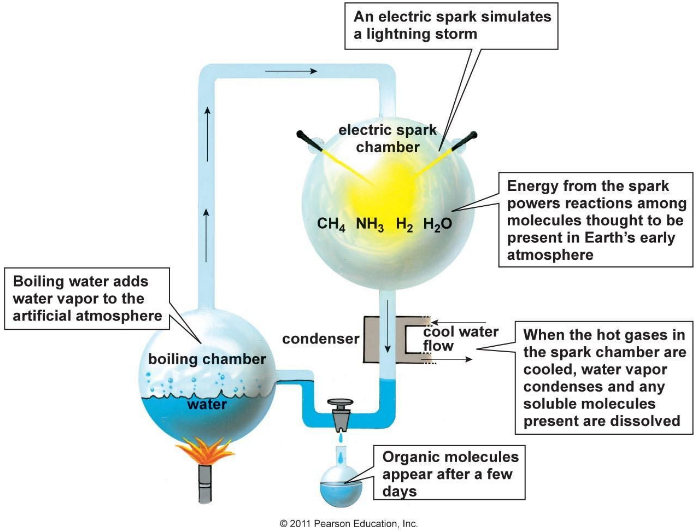
- Earth formed 4.6 billion years ago and is VERY TURBULENT
- Anoxic conditions with surface temperatures of 100 C
- Lots of methane, ammonia, nitrogen, carbon dioxide, hydrogen
- No liquid water, but some in atmosphere
- Constant meteorite bombardment and volcanic activity
  - Moon!
- Plate tectonic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

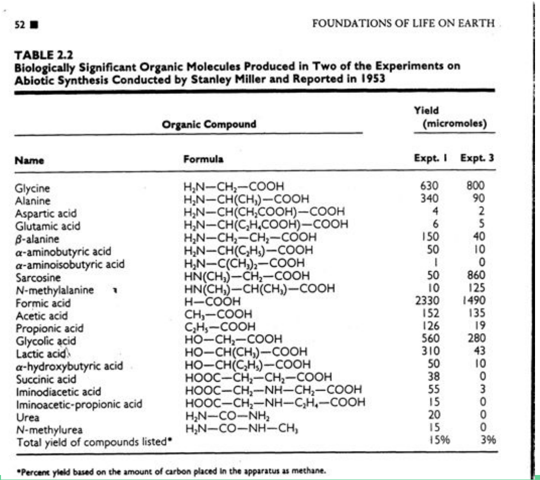
How could life have emerged under these conditions?!

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





52 ■ FOUNDATIONS OF LIFE ON EARTH

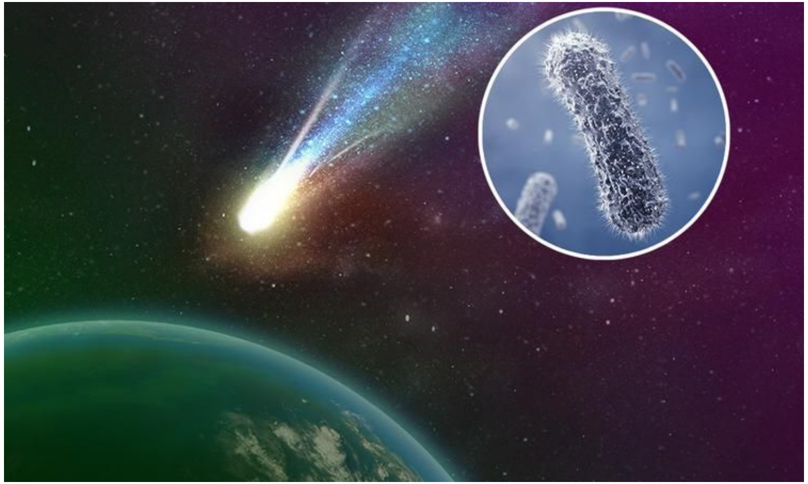
TABLE 2.2
Biologically Significant Organic Molecules Produced in Two of the Experiments on Abiotic Synthesis Conducted by Stanley Miller and Reported in 1953

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.

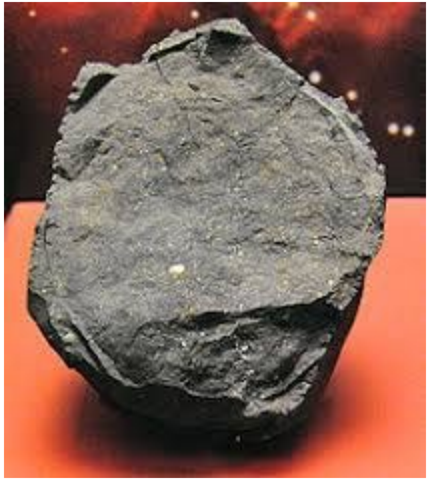
The Panspermia Hypothesis

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

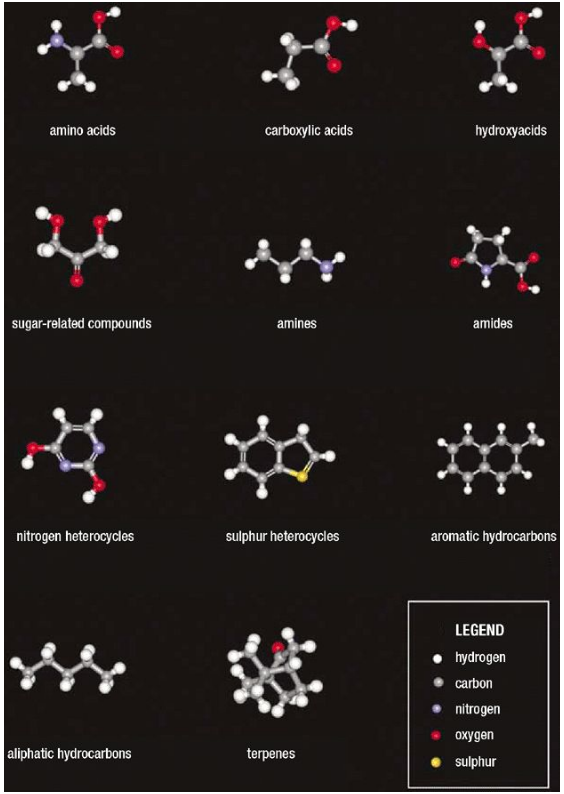


The Murchison Meteorite contains organic compounds

Suggests panspermia is technically possible!



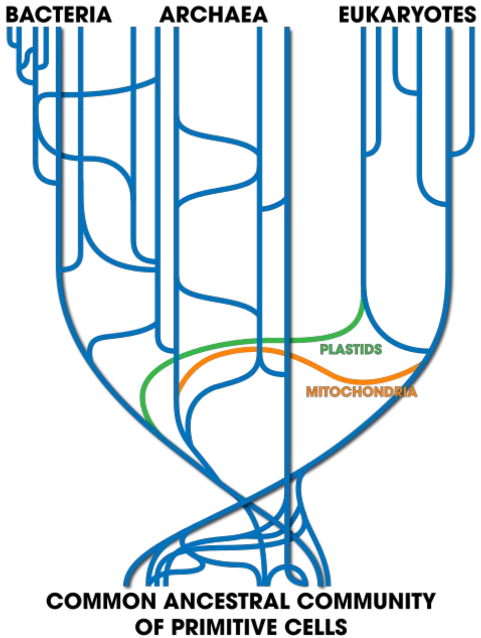
100 kg
Fell to Australia in 1969

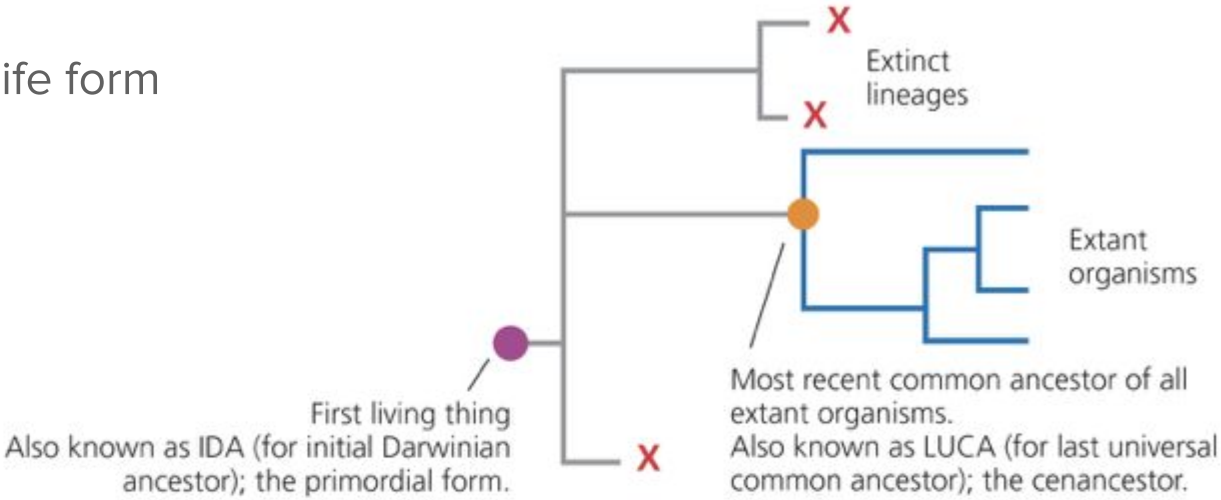


https://doi.org/10.1046/j.1468-4004.2003.45208.x

LUCA: Last Universal Common Ancestor

- LUCA is NOT the first life form

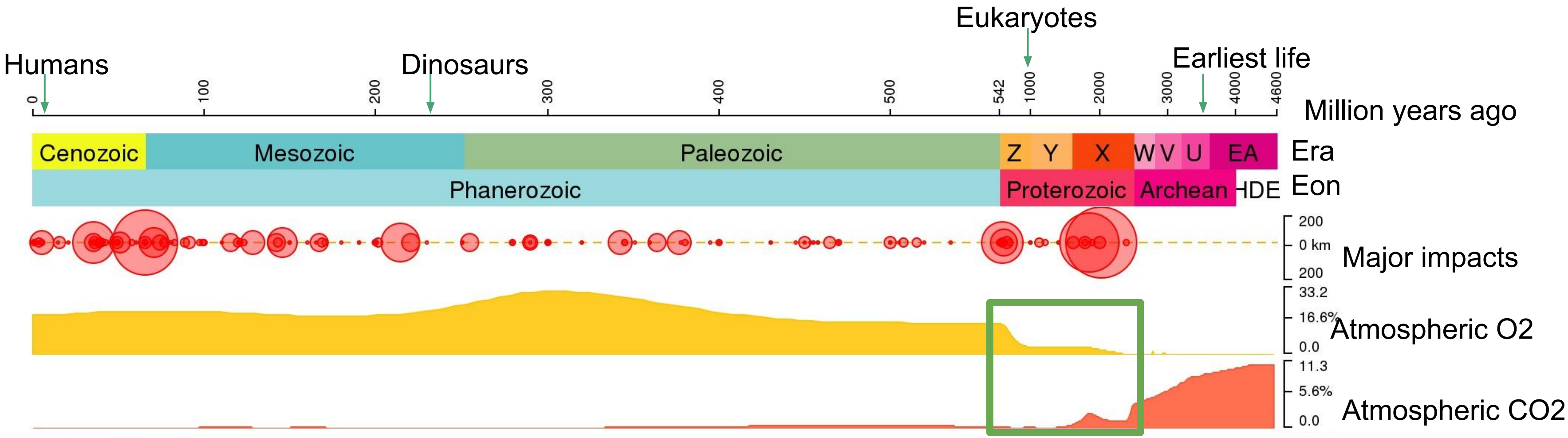




Ancient cyanobacteria were among the earliest life forms on earth

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

Cyanobacteria contribute to swap atmospheric CO2 for O2

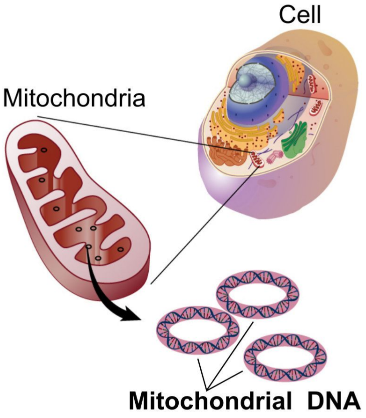


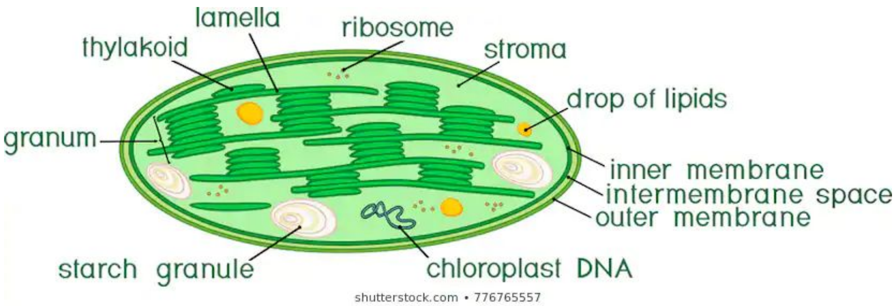
A few Major Transitions in Evolution

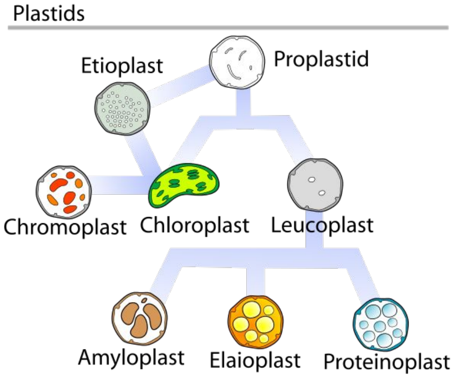
- Emergence of self-replicating molecules (RNA World)
- Replacement of RNA with DNA-protein
    - Happened *before* LUCA emerged
- Emergence of colony-living instead of solitary living
- **Emergence of eukaryotic life (~1.8-2 billion years ago)**
    - Involves acquisition of mitochondria, plastids
-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

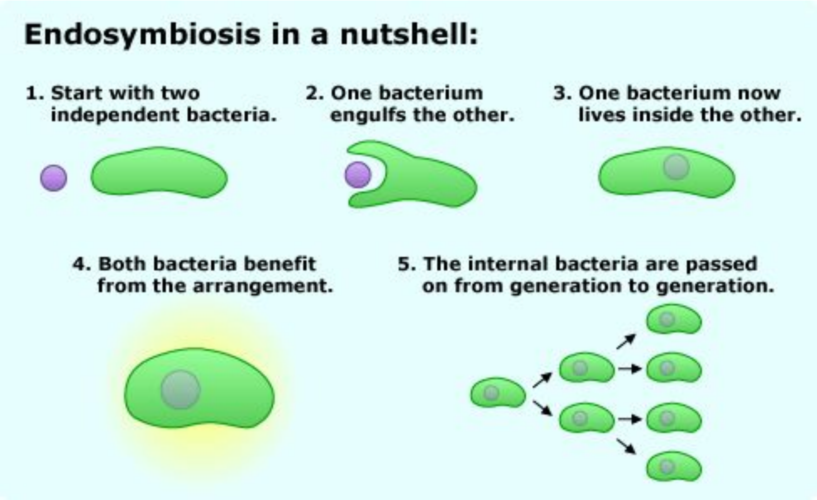




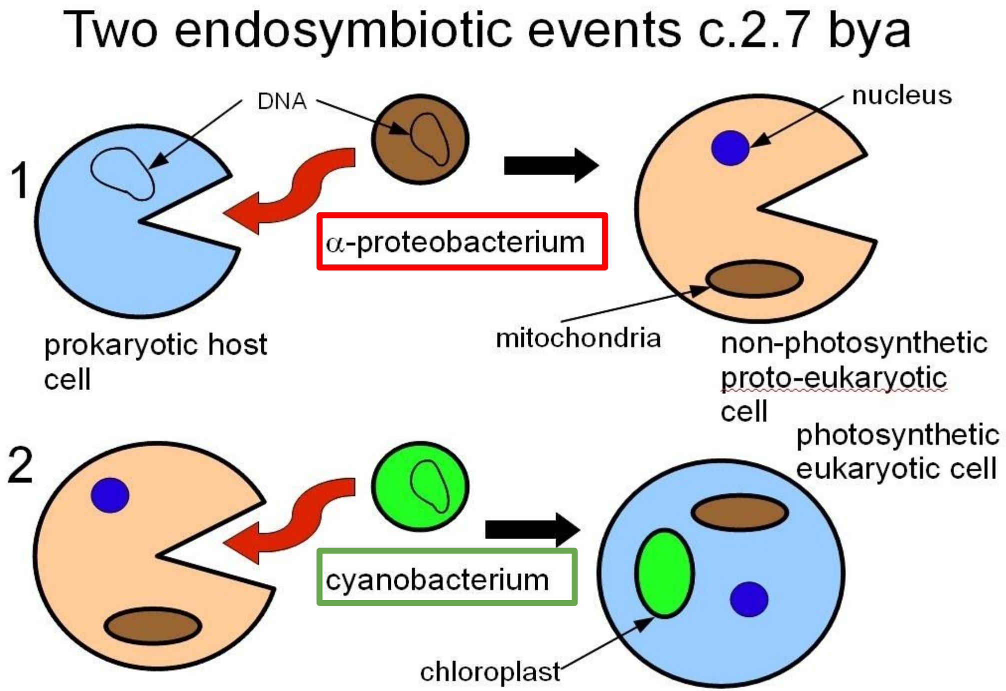


The Endosymbiosis Theory***

- 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

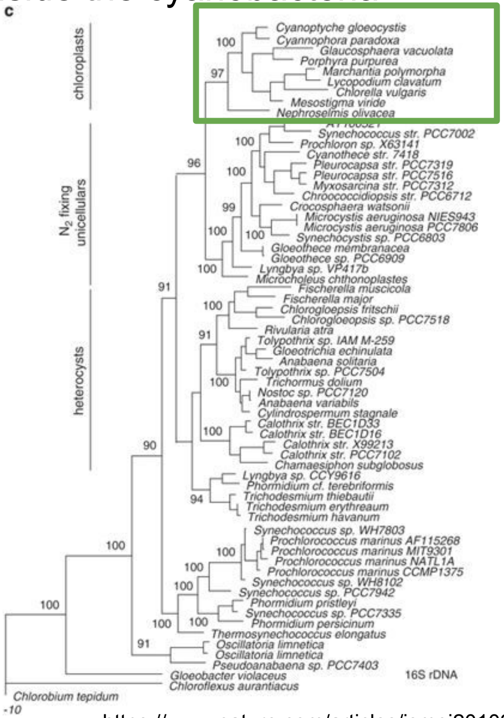


There is phylogenetic evidence for the endosymbiosis theory

Mitochondria are inside the alpha-proteobacteria phylogeny

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

Choloplasts are inside the cyanobacteria phylogeny

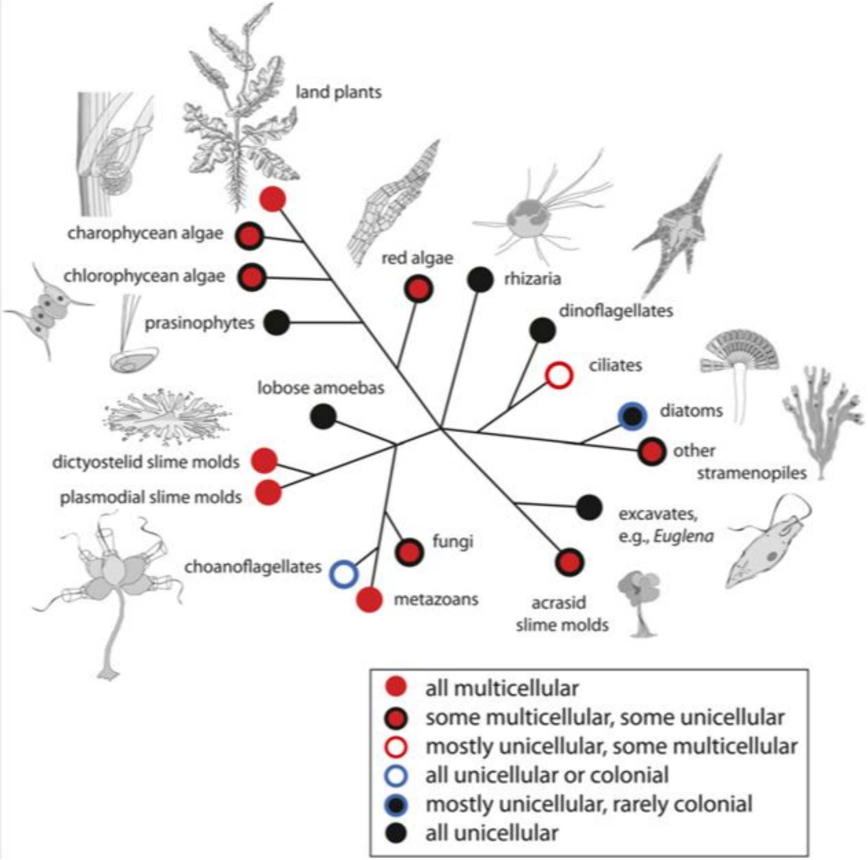


https://www.nature.com/articles/ismej20102#f1

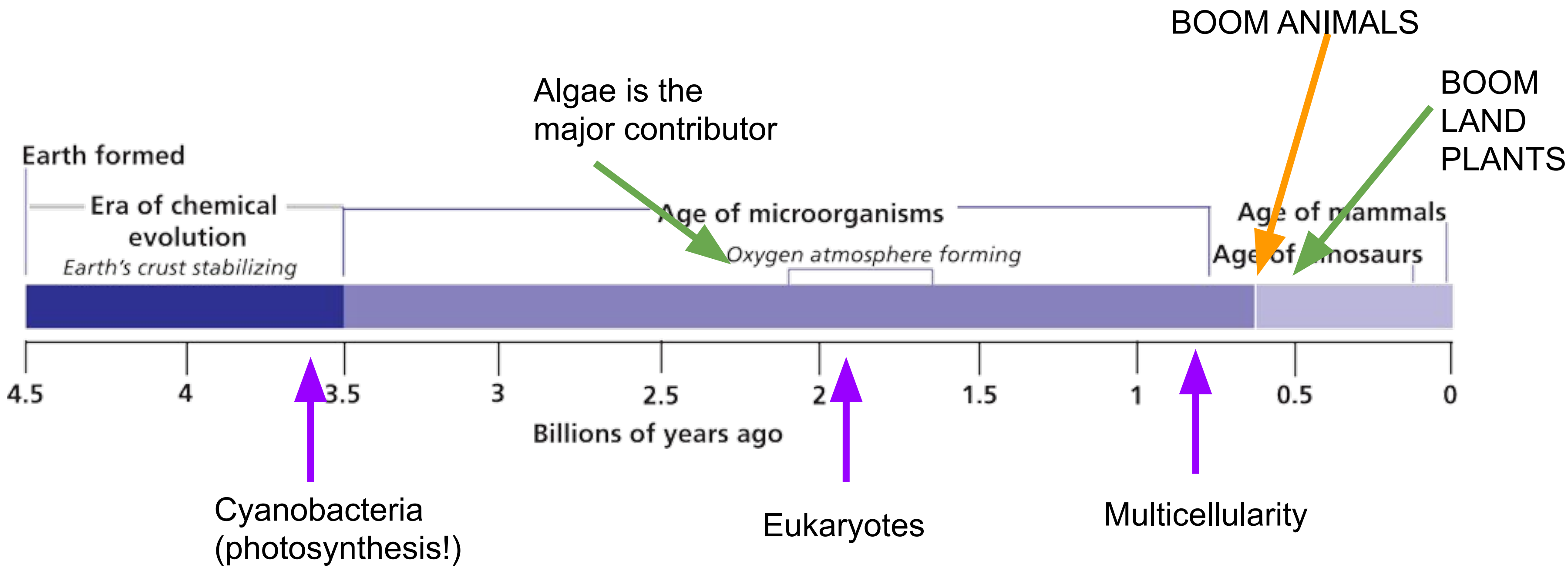
Emergence of multicellularity began 600 million years ago

- 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!

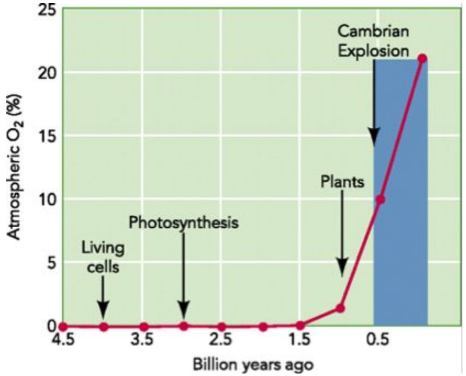
- It has evolved *convergently* many times (over TWENTY, just once in animals)

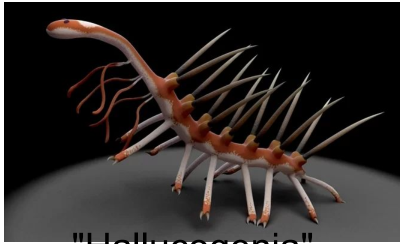


Where are we so far?

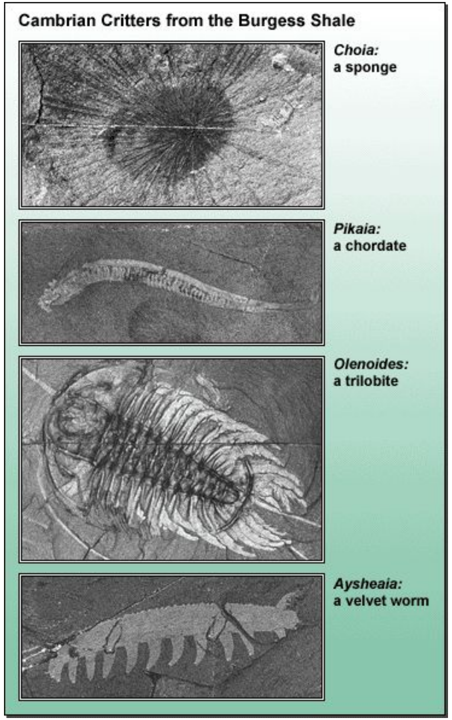


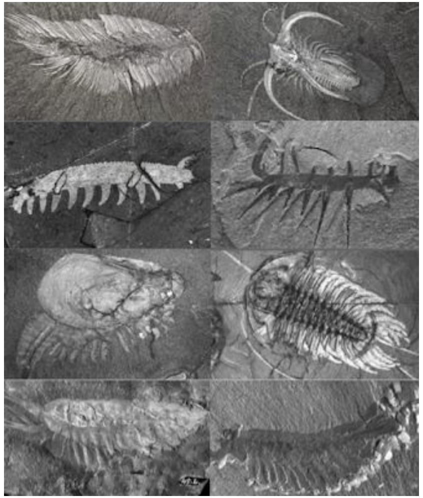
The Cambrian EXPLOSION! (542 Mya)





"Hallucogenia"





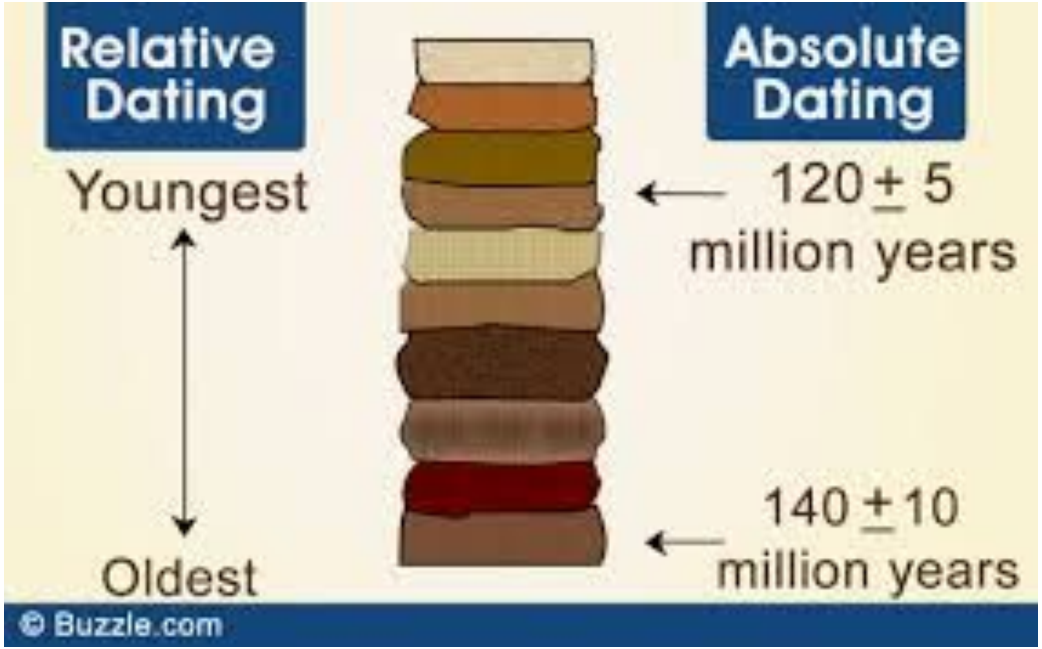
Burgess Shale in British Columbia, Canada

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

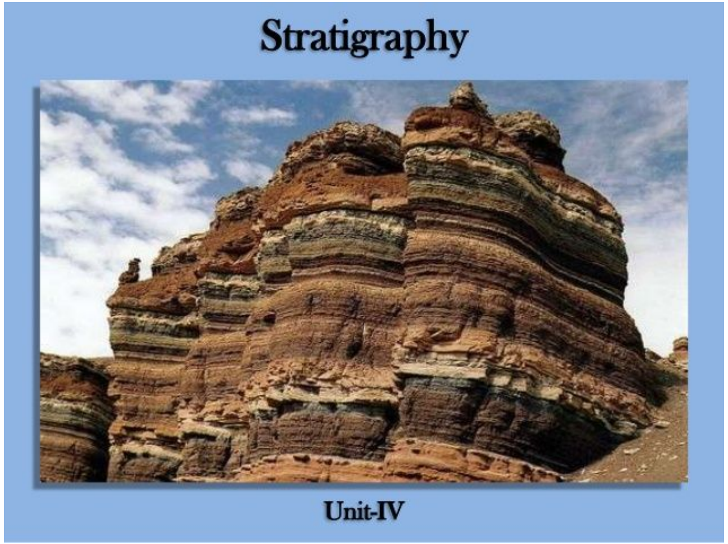
- Soft-bodied animals and soft tissue (muscle, fascia, tendons..) don't fossilize well
- You will become a fossil if you die in the right place, right time in **sedimentary rock**
  - Rock formed by *deposition* of material as it layers over time

Relative vs absolute dating

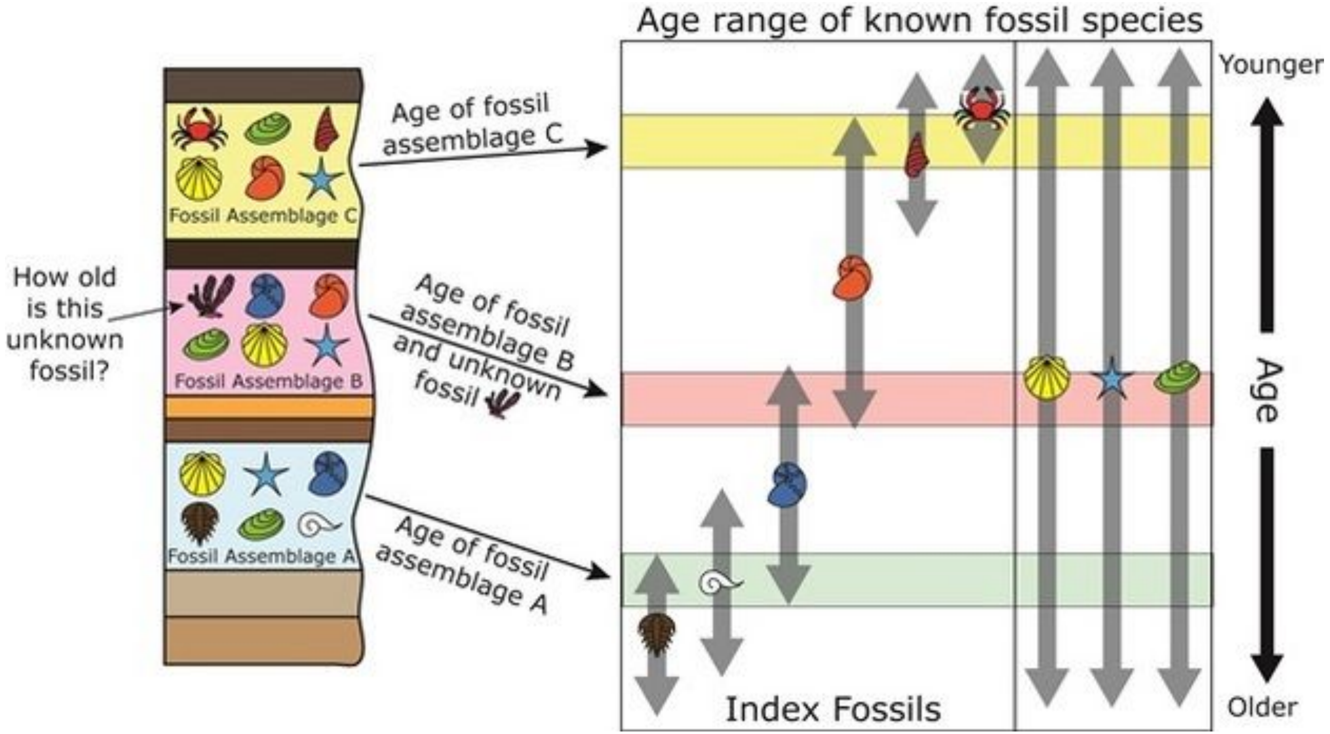


Relative dating with stratigraphy

- 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

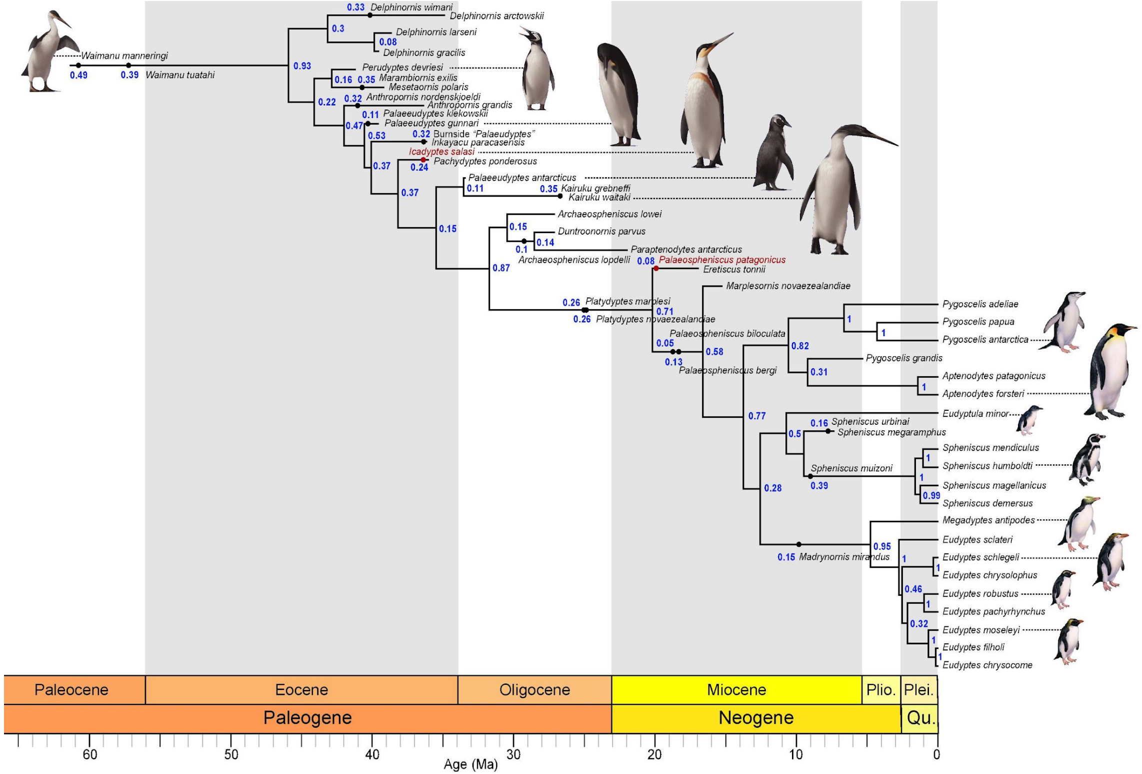


Pop quiz!

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

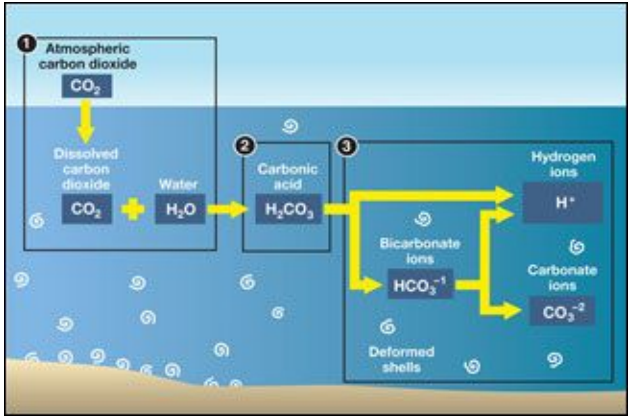
	Extinction	Date	Losses
	Ordovician-Silurian	440-450 Ma	27% of families, 57% of genera
	Late Devonian	360-375 Ma	19% of families, 50% of genera, 70% of species
P-T	Permian-Triassic	251 Ma	57% of families, 80% of genera, 96% marine species, 70% land species
	Triassic-Jurassic	205 Ma	23% of families, 48% 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

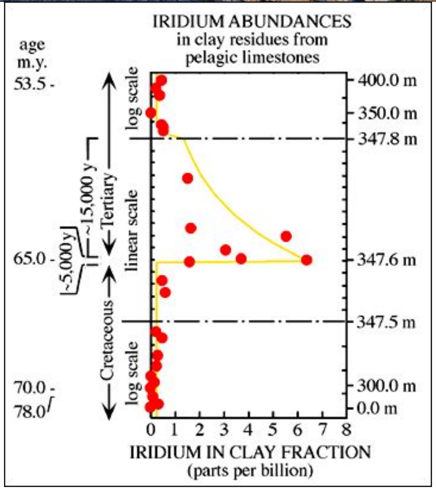
- Oceans become *much* warmer **and** they absorb much of the released CO2 ➜ ocean acidification
- **Ocean acidification kills just about everything**



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)

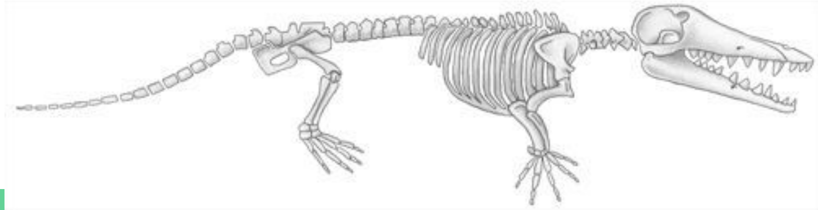
Evolutionary transition from fish ➔ tetrapod

Archaeopteryx (150 Mya)

Transition from dinosaur to bird

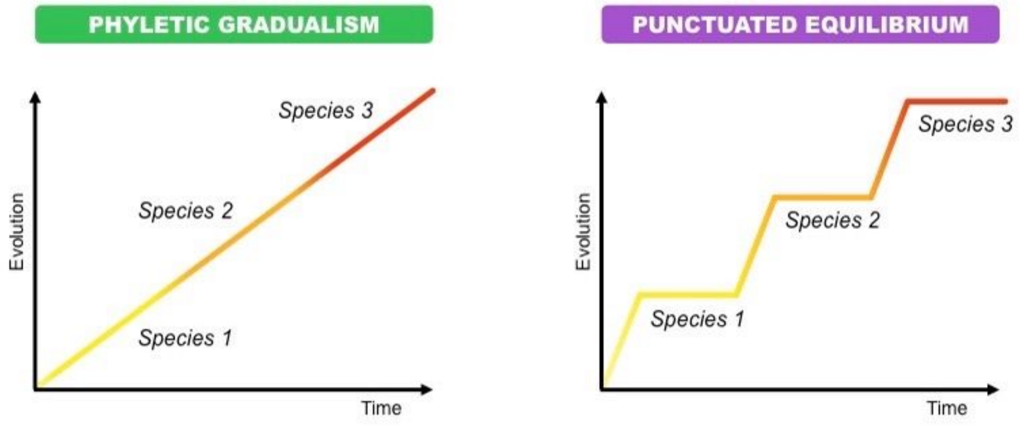
Ambulocetus (45 Mya)

Transition to cetaceans (whales, dolphins)

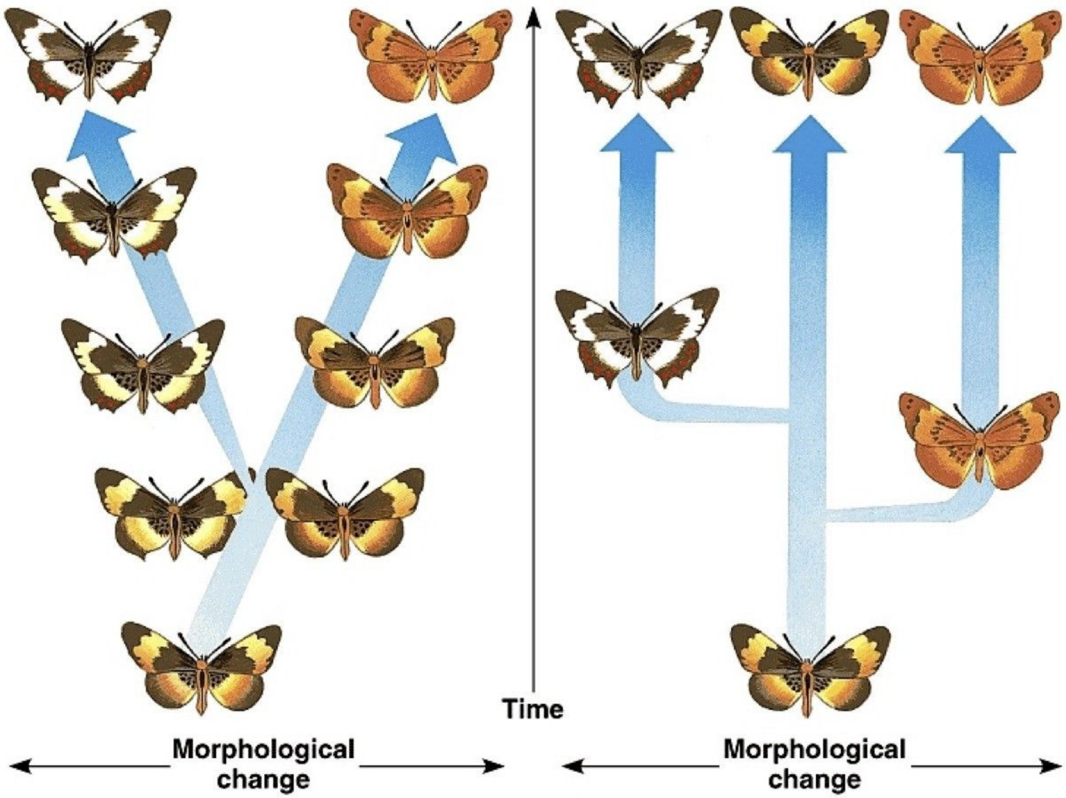


Modes of macroevolution

- **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