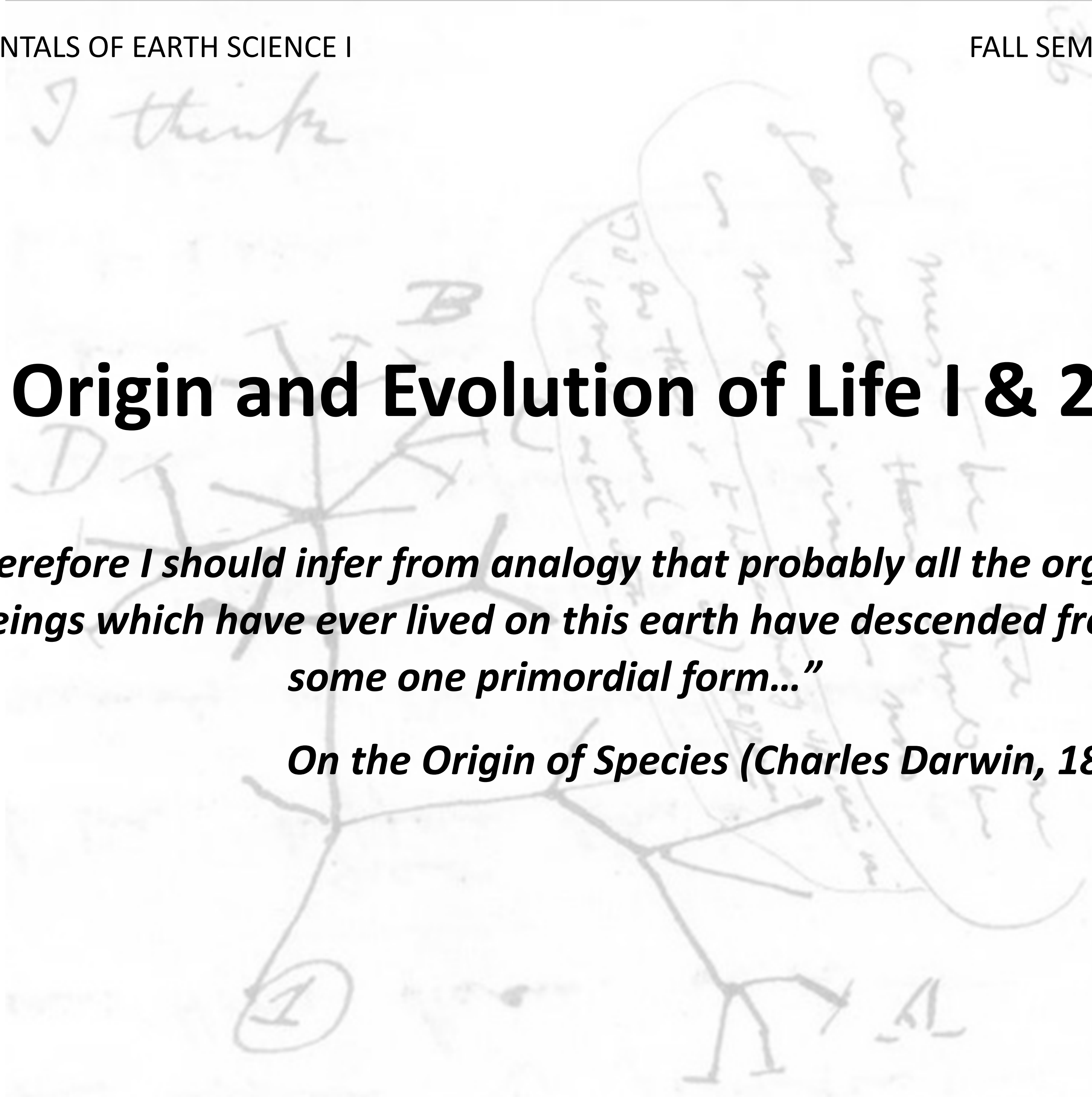


Origin and Evolution of Life I & 2

"Therefore I should infer from analogy that probably all the organic beings which have ever lived on this earth have descended from some one primordial form…"

On the Origin of Species (Charles Darwin, 1859)

✶ What is Life?

- Characteristics of cellular life
  - Growth
  - Reproduction
  - Capacity to evolve
  - Nutrients (C, H, O, N, P, S)
  - Information-carrying, replicating molecule (RNA, DNA)
  - Membrane-bound vesicle
- Basic requirements of life (Earth's like)
  - Liquid water
  - Organic molecules
  - Energy (chemical reactions, light)
- Chemical signature
  - System out of equilibrium (e.g. O_2, left-handed amino acids)

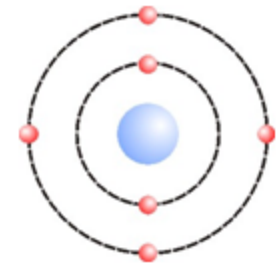
✶ What is life?

- ***Life basic constituents***

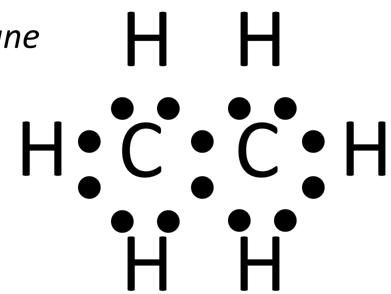
- **C, H, O, N**, P, S

  Carbon has 4 electrons on its outer shell and can form 4 bonds with other elements (including itself), as well as double or even triple bonds.
  Carbon atoms form the backbone of organic molecules.

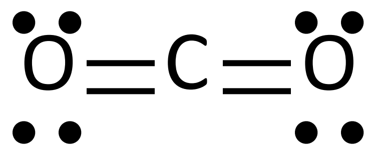
C



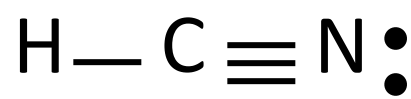
Ethane

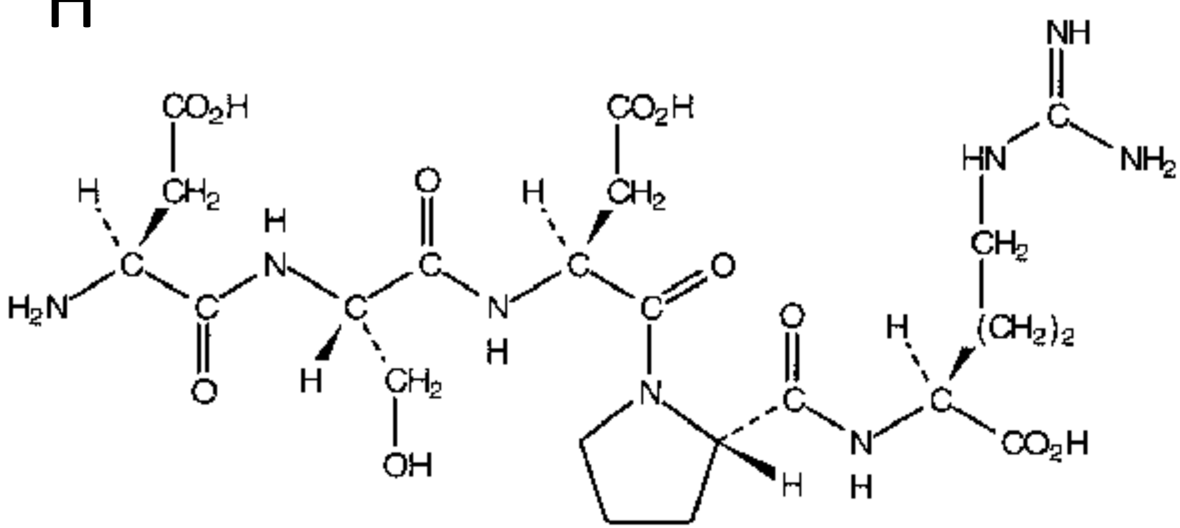


Carbon dioxide



Hydrogen cyanide

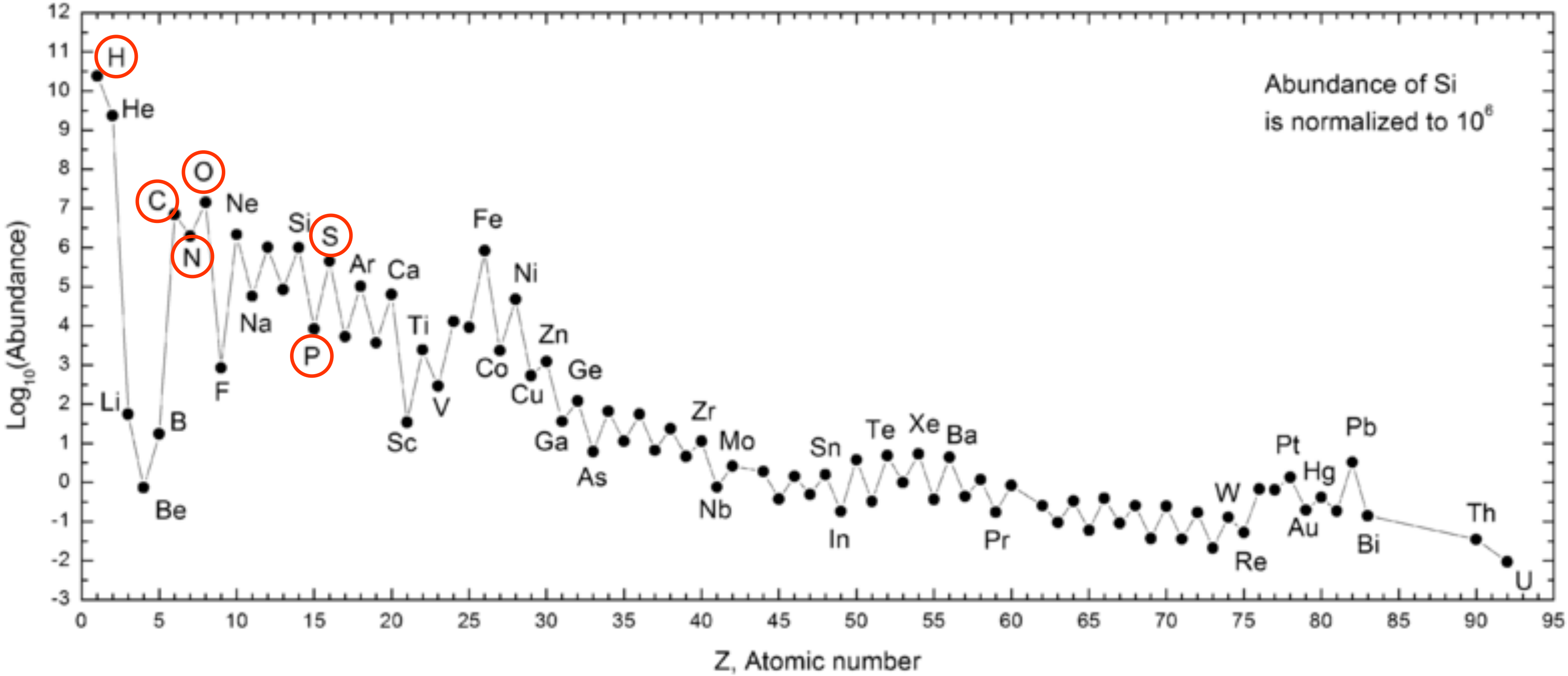




✶ What is life?

• ***Life basic constituents***

Abundances of elements in the Solar System



✶ What is life?

• *Life basic constituents*

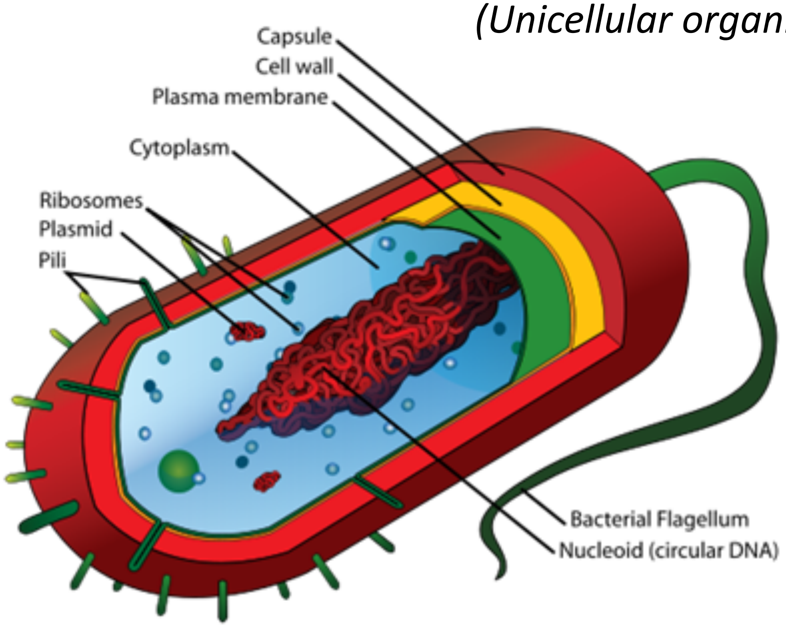
▪ The **cell** is the basic unit of life.

Organisms are either **unicellular** or **multicellular**.

Organisms can be classified into 2 groups based on cell characteristics: **prokaryotes** and **eukaryotes**.

1. The prokaryotic cell

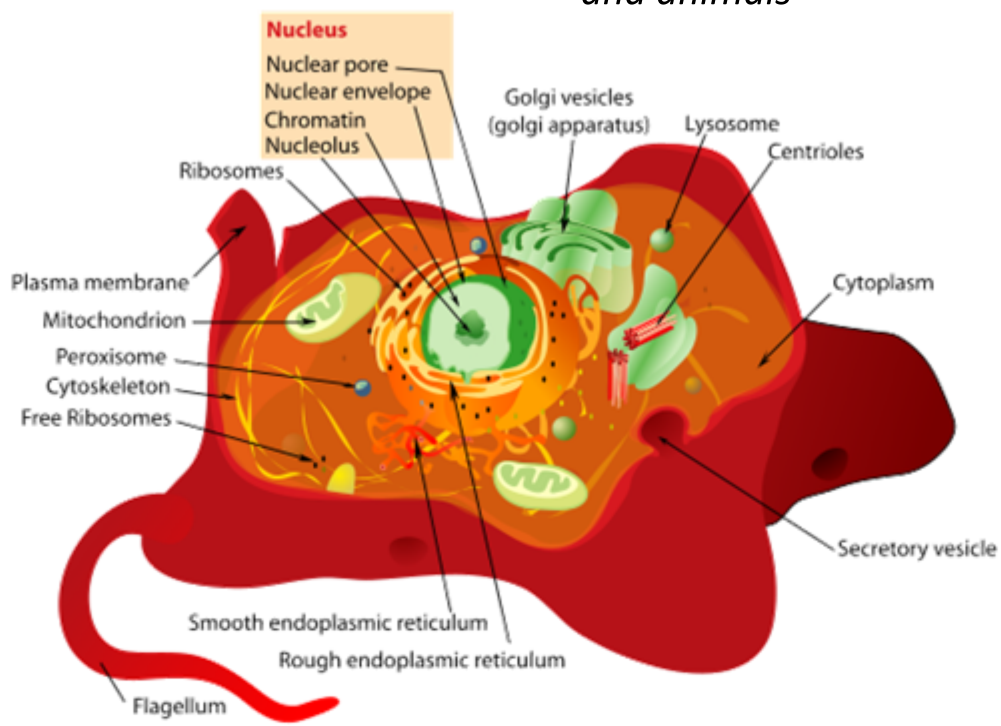
Bacteria and Archaea (Unicellular organisms)



Lack a nucleus and other internal membrane-bound structures

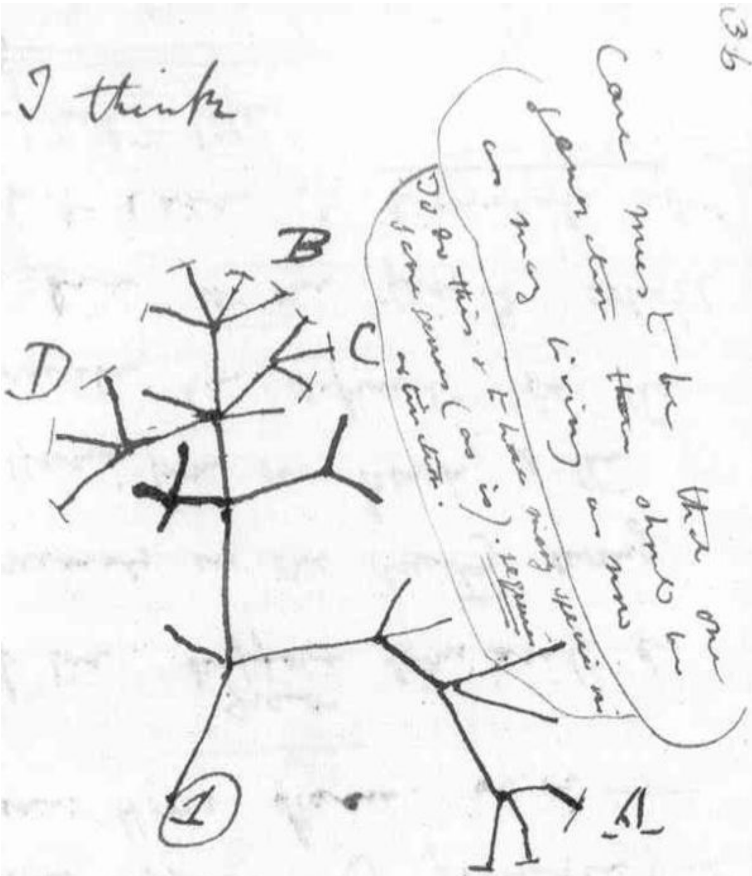
2. The eukaryotic cell

Fungi, algae, plants and animals



Illust.: Mariana Ruiz Villarreal (Wikipedia)

Evolution by natural selection (Charles Darwin, 1809-1882 – Alfred Russel Wallace, 1823-1913)



Darwin's sketch of the evolutionary tree of life

* Physiology refers to the functions of living organisms and their parts (e.g. nutrition, movement, reproduction).

★ Evolution = process by which organisms descend from other -different- preexisting forms (ancestors) through ***modifications***.

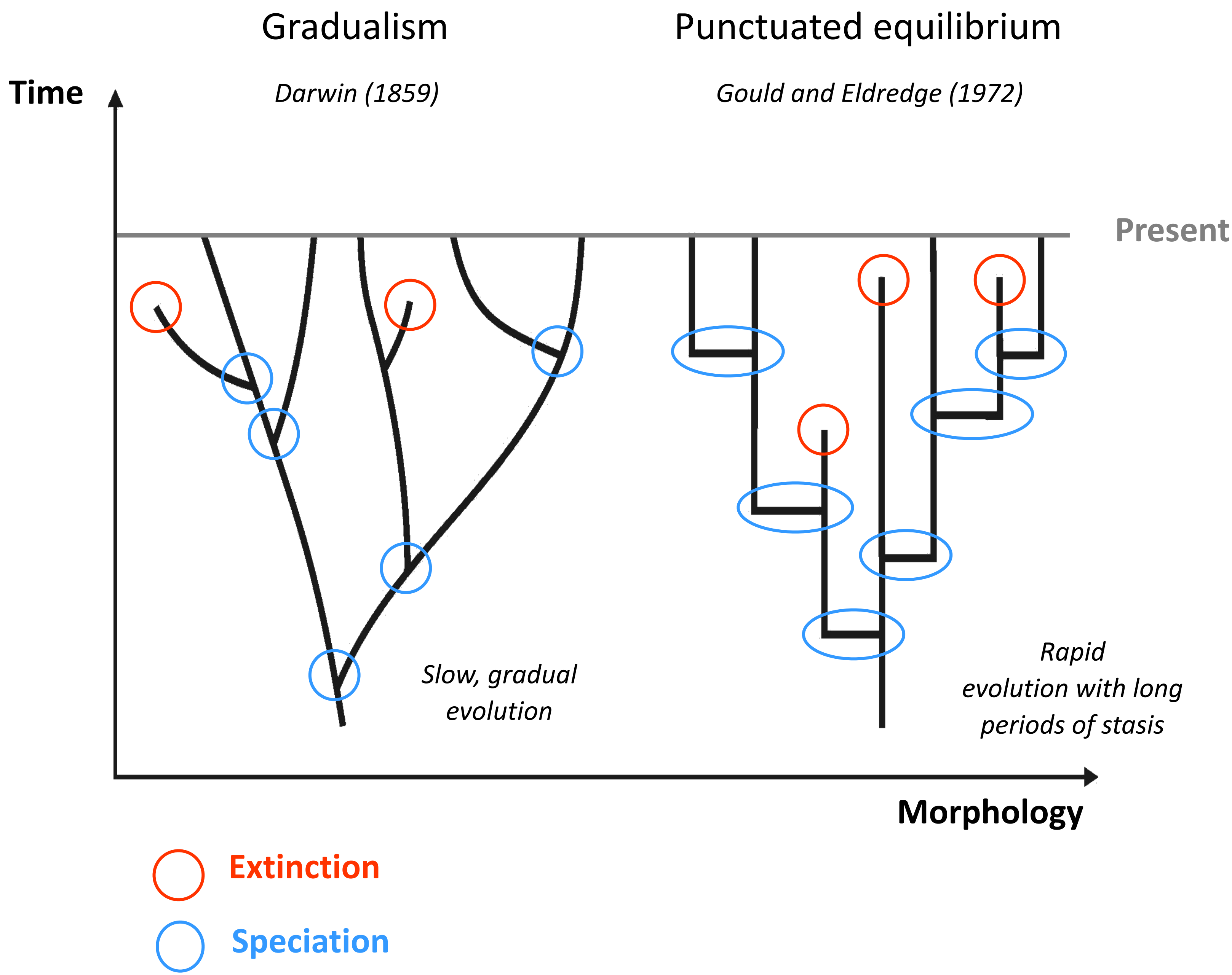
Genetic variations: organisms within the same species show variations in <u>morphology, physiology* and behavior</u> .

Inheritance: some of these traits can be inherited by offspring.

Natural selection: If these traits are beneficial to the organism and increase the chance of survival and reproduction, they will have more chance to be passed on to offspring - they will be "selected".

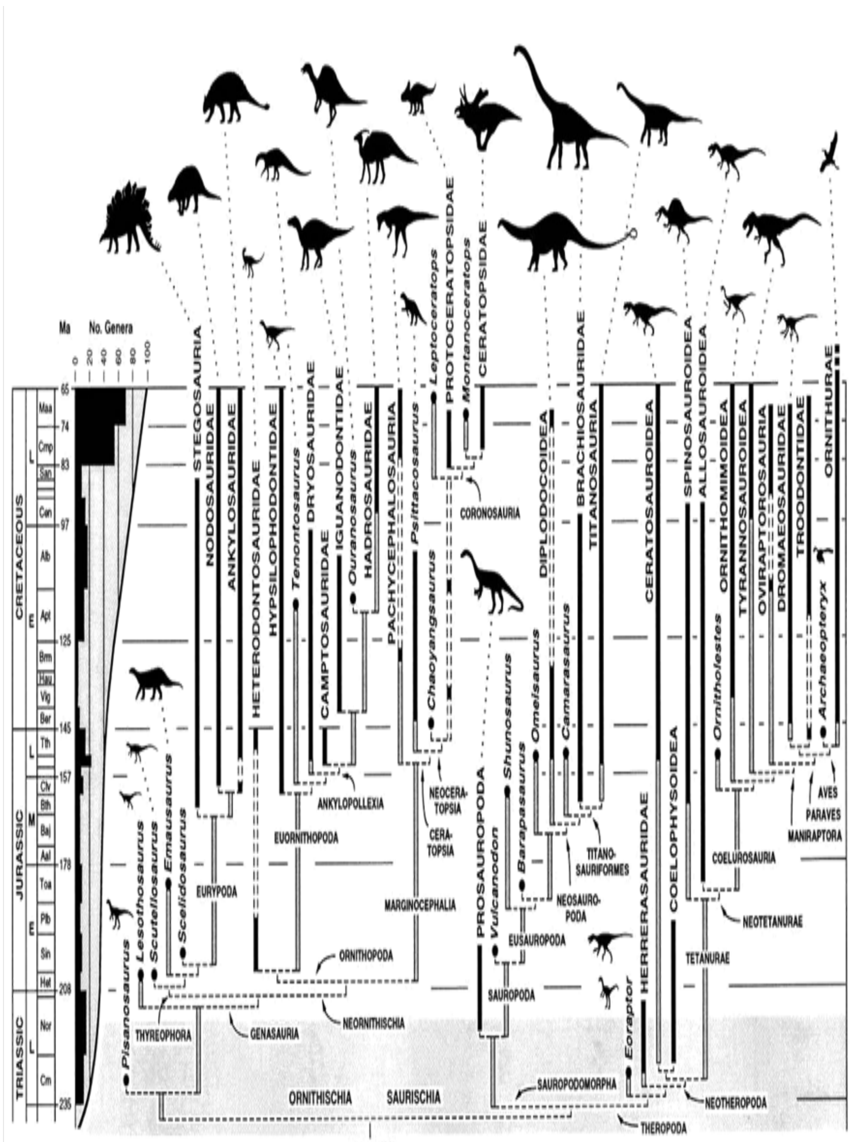
Selective pressure: any phenomenon that can reduce the ability of an individual to produce viable offspring, for example, climate change, introduction of new predator, new disease…

Time: over time, selective pressure can change the genetic make-up of a population and lead to the emergence of a new species


Gradualism
Punctuated equilibrium
Time
Darwin (1859)
Gould and Eldredge (1972)
Present
Slow, gradual
evolution
Rapid
evolution with long
periods of stasis
Morphology
Extinction
Speciation

How to reconstruct the evolutionary tree of life?

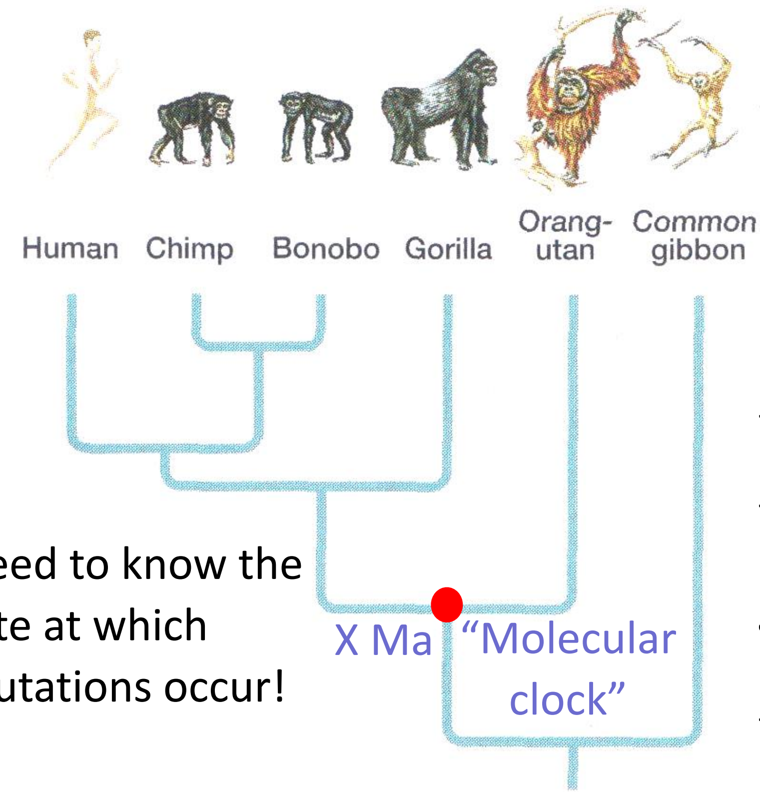
The fossil record



Sereno (1999)

Phylogenetics

The amount of differences in DNA or proteins between extant groups is a function of the time elapsed since they diverged from a common ancestor.



Need to know the rate at which mutations occur!

Biology, Life on Earth 9th ed.

▲ **FIGURE E18-1 Relatedness can be determined by comparing DNA sequences** This evolutionary tree was derived from the nucleotide sequences of several different genes that are common to humans and apes.

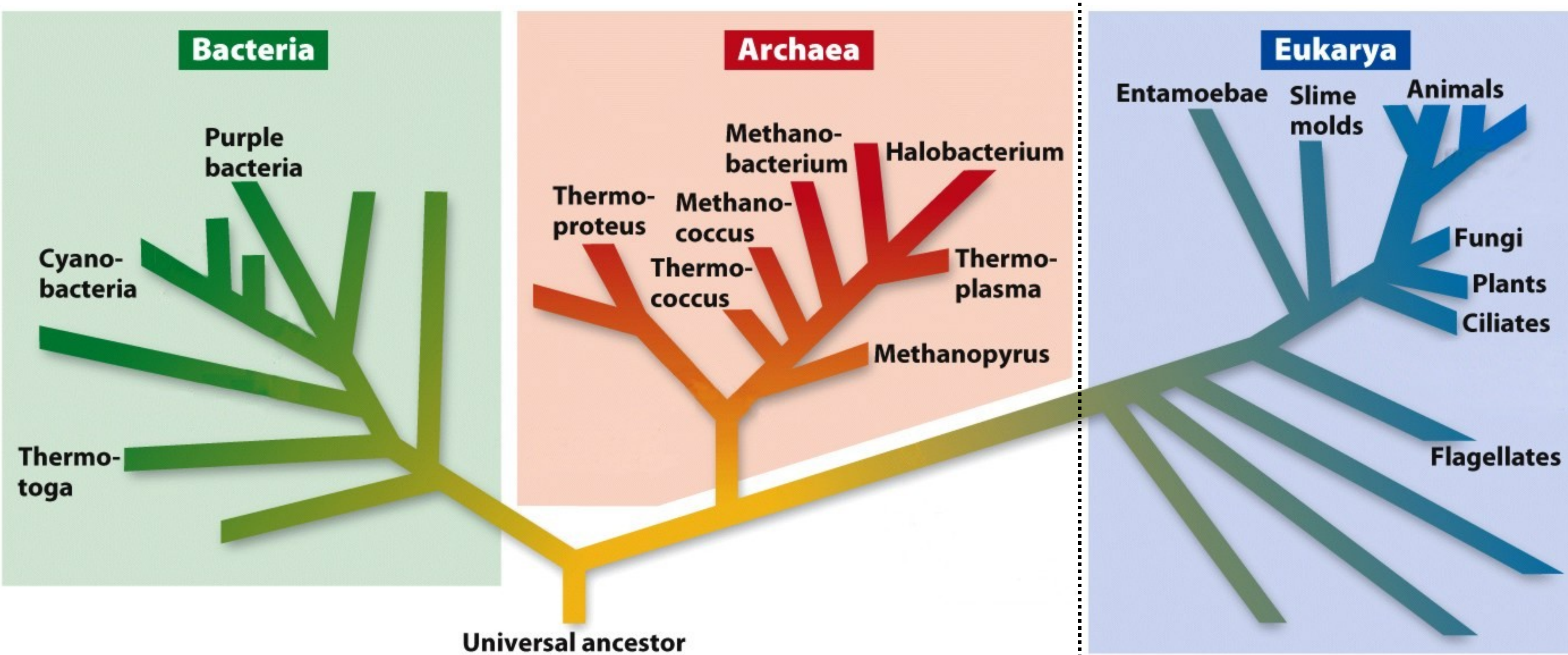
✶ What is life?

- ***The 3 domains of life***

Prokaryotes | **Eukaryotes**

Biochemical differences (cell wall structure, genetic material)

Archaea share some similarities with Eukarya



= EVOLUTIONARY TREE OF LIFE

Modified from Understanding Earth

✶ What is life?

- ***Life strategies: sources of energy and C***

	SOURCE OF CARBON	SOURCE OF ENERGY
HETEROTROPHS	Organic carbon	**1. PHOTOHETEROTROPHS (rare)***
		Sunlight e.g.: anaerobic purple non-sulfure bacteria, heliobacteria, carnivorous plants
		2. CHEMOHETEROTROPHS
		Redox reactions e.g.: animals, fungi (e.g. yeast), bacteria (methanogenic, sulfate-reducing)
AUTOTROPHS	Inorganic carbon (CO_2)	**3. PHOTOAUTOTROPHS** PHOTOSYNTHESIS
		Sunlight e.g.: plants, cyanobacteria (**oxygenic**), green and purple sulfur bacteria (**non-oxygenic**)
		4. CHEMOAUTOTROPHS CHEMOSYNTHESIS
		Redox reactions e.g.: bacteria (sulfide-oxidizing bacteria, methanogenic bacteria)

1 and 3 = PHOTOTROPHS **2 and 4 = CHEMOTROPHS**

* Organisms performing photosynthesis but needing another source of C than CO_2 (ex: carnivorous plants)

Redox reactions are involved in many important biological processes:

- **Photosynthesis**: **synthesis of large organic molecules** from CO_2 using sunlight as the source of energy.
- **Chemosynthesis**: **synthesis of large organic molecules** using the energy released by inorganic chemical reactions.
- **Cellular respiration**: redox reactions with **production of energy**
- **Fermentation (anaerobic cellular respiration)**: redox reactions in which organic molecules serve both as e^- donor and e^- acceptor, resulting in the **production of energy**.

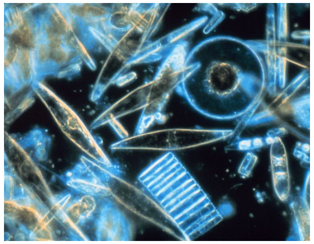
✶ What is life?

- ***Examples of metabolic pathways***

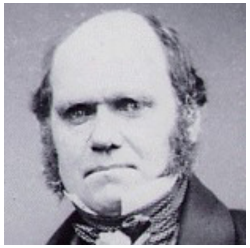
Photoautotrophs (plants, cyanobacteria, phytoplankton)

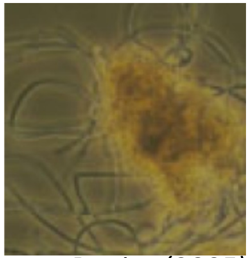
Cox et al. (2005)

Wikipedia



Chemoheterotrophs (animals, some bacteria, yeast)





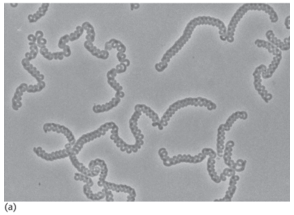
Davies (2005)

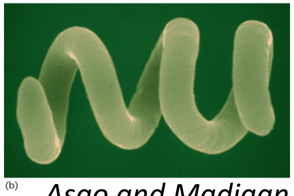
Yeast (alcoholic fermentation)

microbiologyonline.org.uk

→ *Bacteria used for waste-water treatment*

Photoheterotrophs (carnivorous plants, some bacteria)

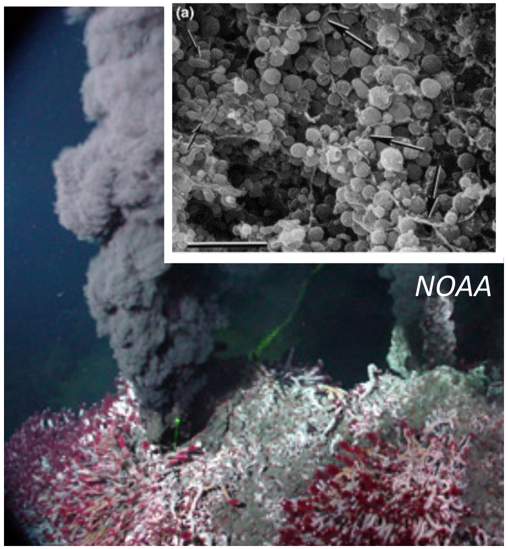




Asao and Madigan (2005)

Noah Elhardt (wiki)

Chemoautotrophs (sulfide-oxidizing bacteria)



$CO_2 + 4H_2S + O_2 \rightarrow CH_2O + 4S + 3H_2O$

Chemosynthesis performed by bacteria generates food for tubeworms

✶ The first cell

Environmental conditions of the early Earth:

- The Earth formed **4.56 Gyr** ago along with the other planets of the Solar System.
- **Meteorite impacts** very intense at the beginning of Earth's history and decreased until 3.9 Gyr (**Hadean Eon**). Meteorite impacts released a lot of heat.
- As the Earth cooled down, **water vapor condensed** into oceans (**oldest sedimentary rocks** dated >3.95 Gyr from Canada and ~3.8 Gyr from Greenland).
- **Sun fainter** than today (less solar heat) but evidence of liquid water and life… **young faint Sun paradox**
- The **primitive atmosphere** was possibly composed of hydrogen, nitrogen, carbon dioxide, and water vapor. **NO OR VERY LITTLE FREE OXYGEN (O_2)!**

→ **Environmental conditions** at the beginning of Earth's history **very different from today**!

3.8 Gyr sedimentary rocks from Greenland
Mojzsis et al. (1996)

✶ The first cell

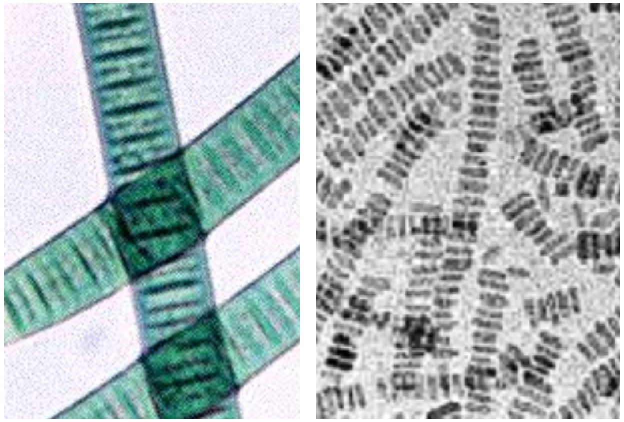
• ***Evidence from the geological record***

PALEONTOLOGICAL

- **Morphological evidence** (microfossils and macroscopic texture, such as microbial mats)

  ⚠ *abiotic origin*

Biotic origin *Abiotic origin*



Berkeley.ac.edu *Livage (2009)*

MINERALOGICAL

- **Biomineralization**

  ⚠ *abiotic origin*

GEOCHEMICAL

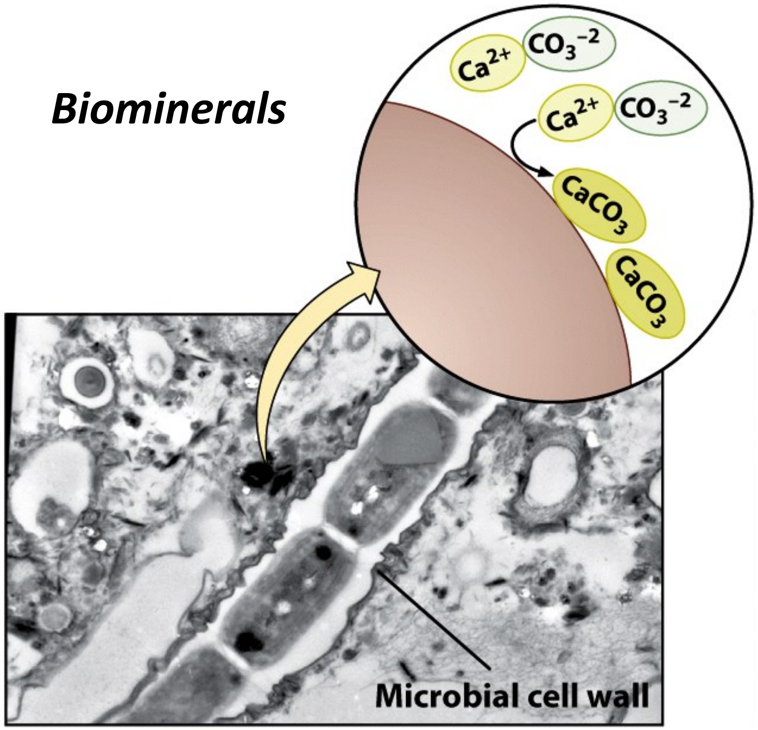
- Biological **fractionation of stable isotopes** ⚠ *contamination*

- **Biomarkers** = large molecules resulting from biological activity, such as polypeptids, triterpenes, steranes ⚠ *contamination* *preservation*

✶ The first cell

• *Evidence from the geological record*

Biominerals



(a) Indirect precipitation of calcium carbonate

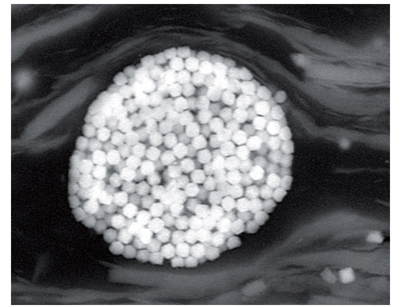
Calcification:

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + \mathbf{CO_2} + H_2O$$

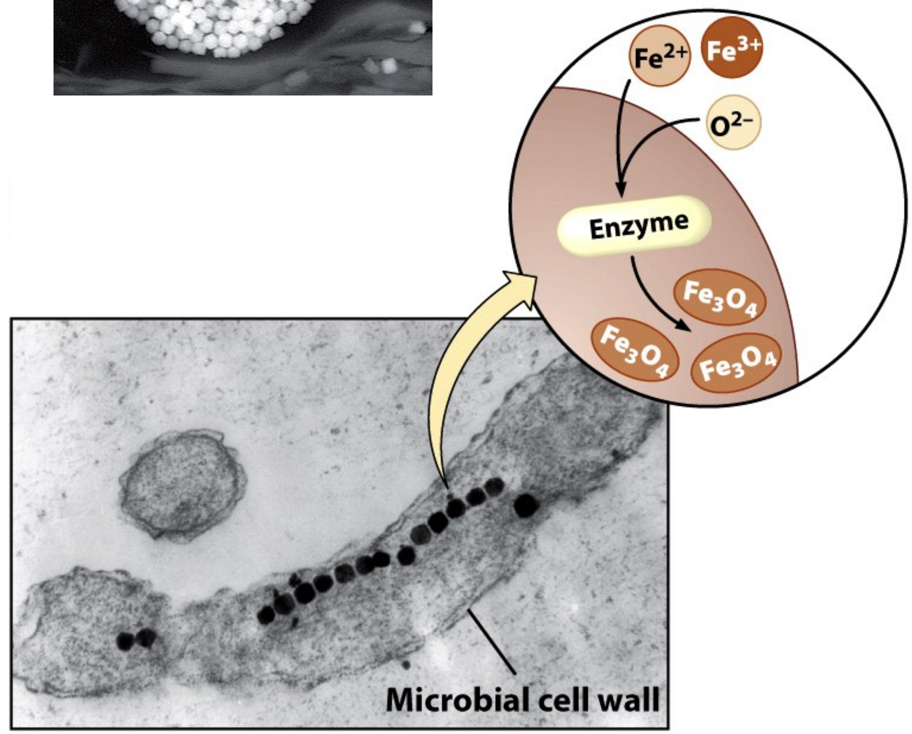
Photosynthesis:

$$6H_2O + \mathbf{6CO_2} + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

e.g.: Cyanobacteria



Indirect precipitation of pyrite (FeS_2) by sulfate-reducing bacteria

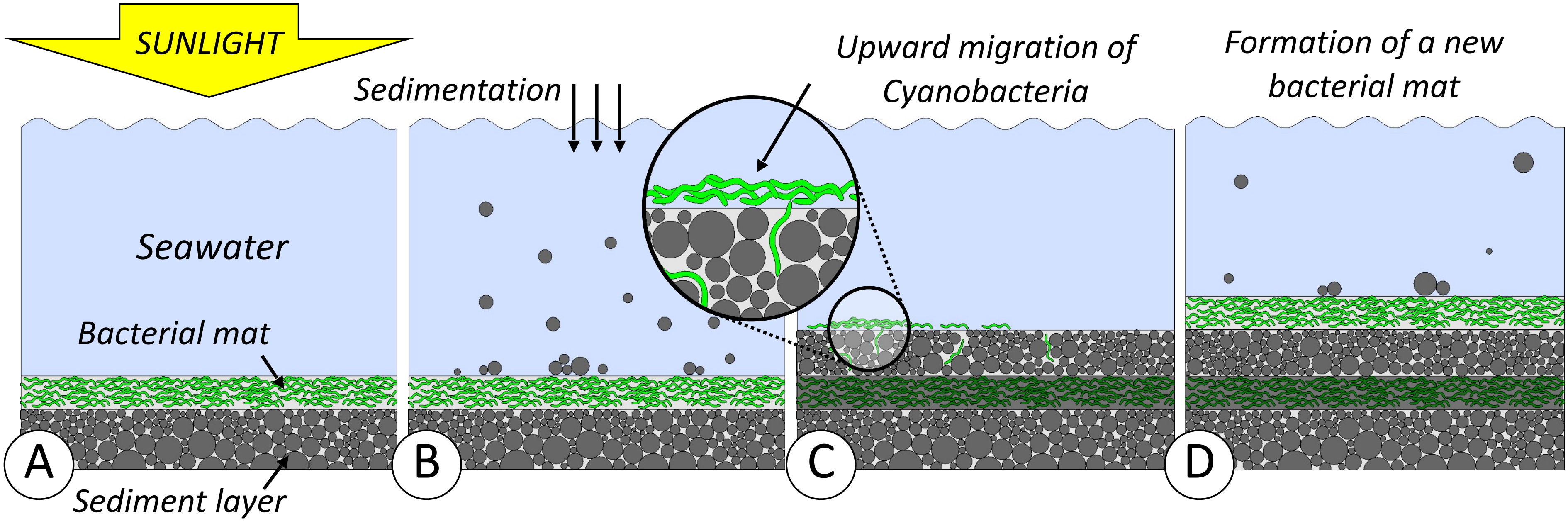


(b) Direct precipitation of magnetite

e.g.: Magnetotactic bacteria

Understanding Earth

Mechanisms of stromatolite formation



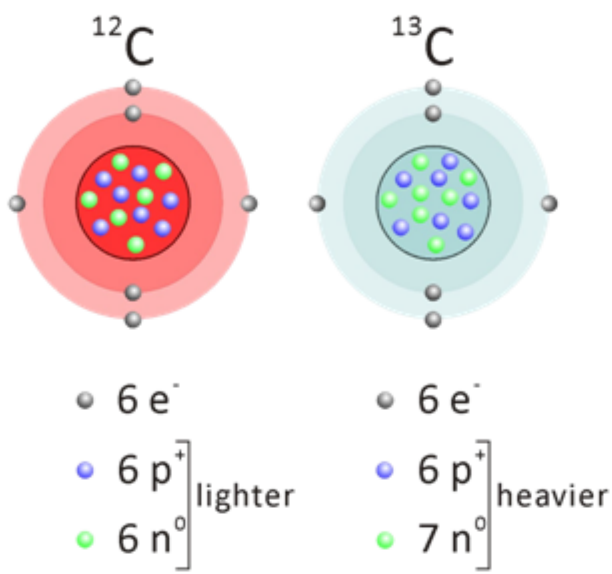
Calcification:

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + CO_2 + H_2O$$

Photosynthesis:

$$6H_2O + 6CO_2 + sunlight \rightarrow C_6H_{12}O_6 + 6O_2$$

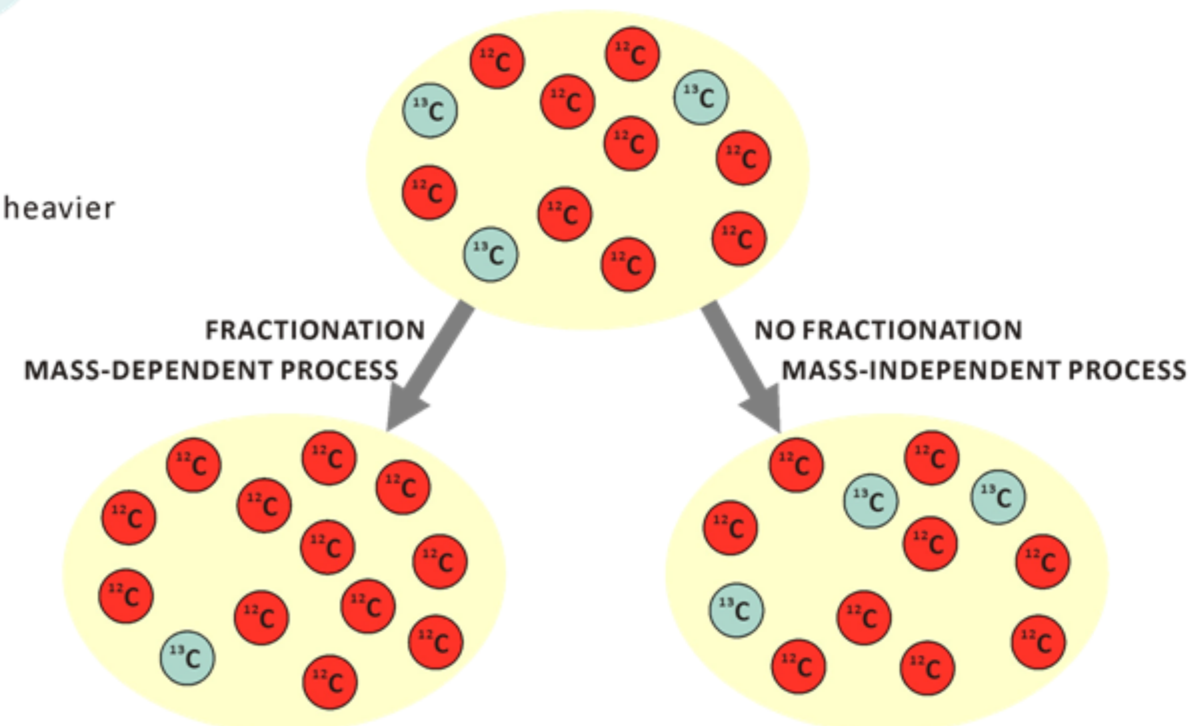
Biological fractionation of stable isotopes



Biological processes result in stable isotope fractionation (e.g. C, S, N, and Fe):

e.g. Photosynthesis

→ *organic carbon enriched in light ^{12}C*
→ *inorganic carbon depleted in light ^{12}C*



By analyzing the isotopic composition of carbon and other elements in a rock sample, we can know whether biological activity was involved or not.

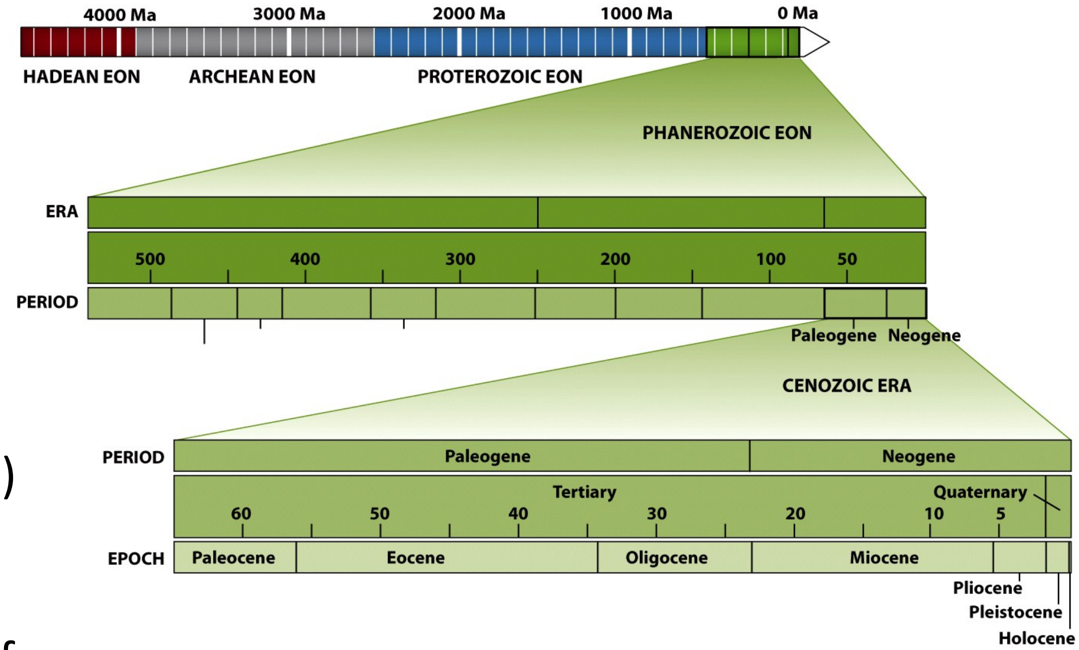
✶ The first cell

• ***When did life begin?***

- **Iron and carbon isotope ratios** suggest the existence of biological activity as early as **3.8 Gyr**, and perhaps even earlier!

- **~3.5-Gyr** old mineralized **microbial mats** (stromatolites) and **microfossils** were discovered in Australia.

- Multiple evidence (morphological and isotopic) supporting the existence of **various kinds of microbes** around **3.4-3.2 Gyr** (first half of the Archean).



Understanding Earth

The geological record enables us to set a minimum age for the existence of life.

LIFE EMERGED POSSIBLY BEFORE 3.8 Gyr AND WAS VERY LIKELY PRESENT BY 3.4 Gyr

✶ The first cell

• ***When did life begin?***

~3.5-Gyr old mineralized microbial mats (stromatolites) and microfossils were discovered in Australia

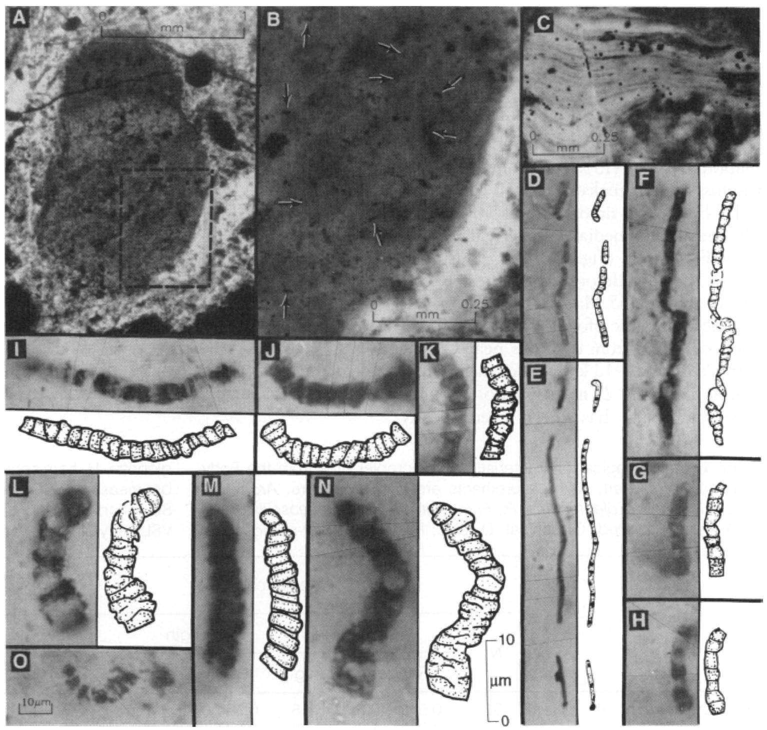


Fig. 3. Microfossiliferous (A and B) and laminated stromatolite-like clasts (C), and carbonaceous and iron-stained (L) microfossils (with interpretive drawings) shown in thin sections of the Early Archean Apex chert of Western Australia. Except as otherwise indicated, magnification of all parts denoted by scale in (N). (D to K) and (N and O) show photomontages of the sinuous three-dimensional microfossils. (**A**) Microfossiliferous clast; area denoted by dashed lines shown in (B). (**B**) Arrows point to minute filamentous microfossils, randomly oriented in the clast. (**C**) Portion of a clast showing stromatolite-like laminae. (**D** and **E**) *Archaeotrichion septatum*, n. sp. (D, holotype). (**F**) *Eoleptonema apex*, n. sp. (holotype). (**G** and **H**) *Primaevifilum minutum*, n. sp. (G, holotype). (**I**, **J**, and **K**) *Primaevifilum delicatulum* Schopf, 1992 (I, holotype) (*3*). (**L**, **M**, **N**, and **O**) *Archaeoscillatoriopsis disciformis*, n. gen., n. sp. (M, holotype).

Schopf (1993)

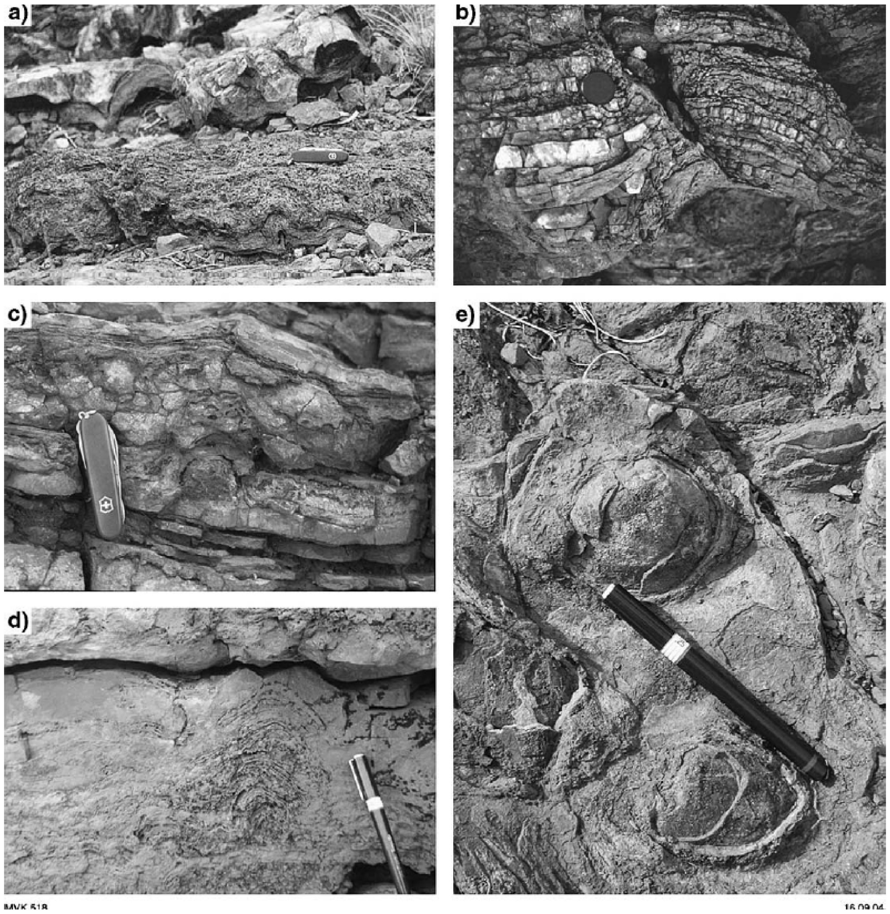


Fig. 10. Probable stromatolites from the 3490 Ma Dresser Formation: a) wrinkly stratiform stromatolite and broad, smooth domical stromatolites; b) broad domical stromatolite, with sediment wedges draped on flank: lenscap is ~5 cm in diameter; c) columnar stromatolite (to right of penknife); d) cross-sectional view of conical stromatolite with wrinkly laminations; e) bedding plane view of conical stromatolites. Knife in a) and c) is 15 cm long; pencap in d) and e) is 3 cm long.

Van Krakendonk (2006)

Early trace of life from 3.95 Ga sedimentary rocks in Labrador, Canada

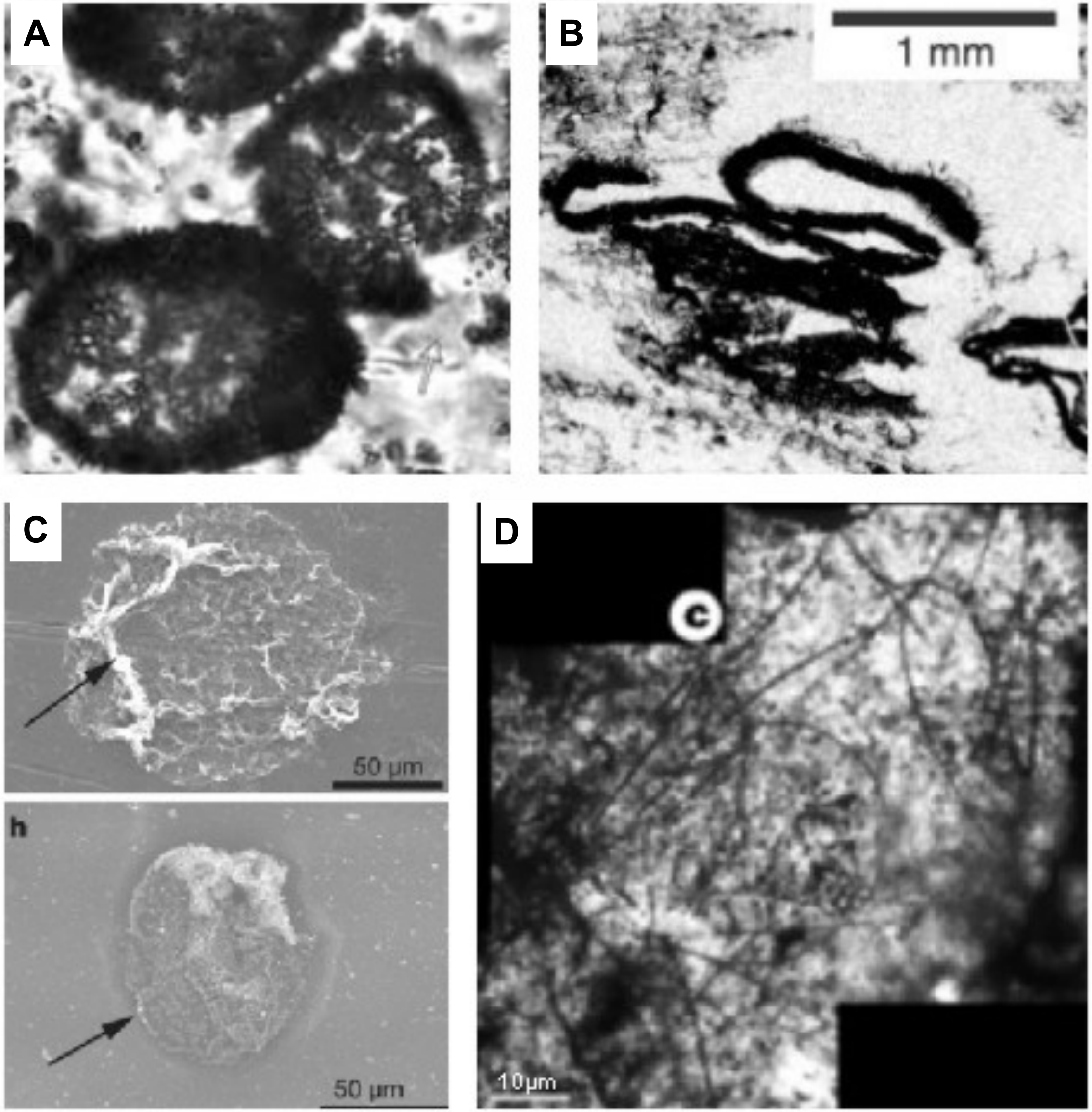
Takayuki Tashiro[1], Akizumi Ishida[2,3], Masako Hori[2,4], Motoko Igisu[5], Mizuho Koike[2], Pauline Méjean[2], Naoto Takahata[2], Yuji Sano[2]§ & Tsuyoshi Komiya[1]§

The vestiges of life in Eoarchean rocks have the potential to elucidate the origin of life. However, gathering evidence from many terrains is not always possible[1–3], and biogenic graphite has thus far been found only in the 3.7–3.8 Ga (gigayears ago) Isua supracrustal belt[4–7]. Here we present the total organic carbon contents and carbon isotope values of graphite ($\delta^{13}C_{org}$) and carbonate ($\delta^{13}C_{carb}$) in the oldest metasedimentary rocks from northern Labrador[8,9]. Some pelitic rocks have low $\delta^{13}C_{org}$ values of −28.2, comparable to the lowest value in younger rocks. The consistency between crystallization temperatures of the graphite and metamorphic temperature of the host rocks establishes that the graphite does not originate from later contamination. A clear correlation between the $\delta^{13}C_{org}$ values and metamorphic grade indicates that variations in the $\delta^{13}C_{org}$ values are due to metamorphism, and that the pre-metamorphic value was lower than the minimum value. We concluded that the large fractionation between the $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ values, up to 25‰, indicates the oldest evidence of organisms greater than 3.95 Ga. The discovery of the biogenic graphite enables geochemical study of the biogenic materials themselves, and will provide insight into early life not only on Earth but also on other planets.

Picture of the metamorphosed sedimentary (or metasedimentary) rocks analyzed in this study

✶ The first cell

- ***When did life begin?***



A) ***3.4 Gyr** bacteria from Australia (probalby characterized by a **sulfur-based metabolism**, Wacey et al., 2011)*

B) ***3.4 Gyr** rolled-up microbial mat from South Africa (probably formed by **anoxigenic photosynthetic bacteria**, Tice and Lowe, 2004)*

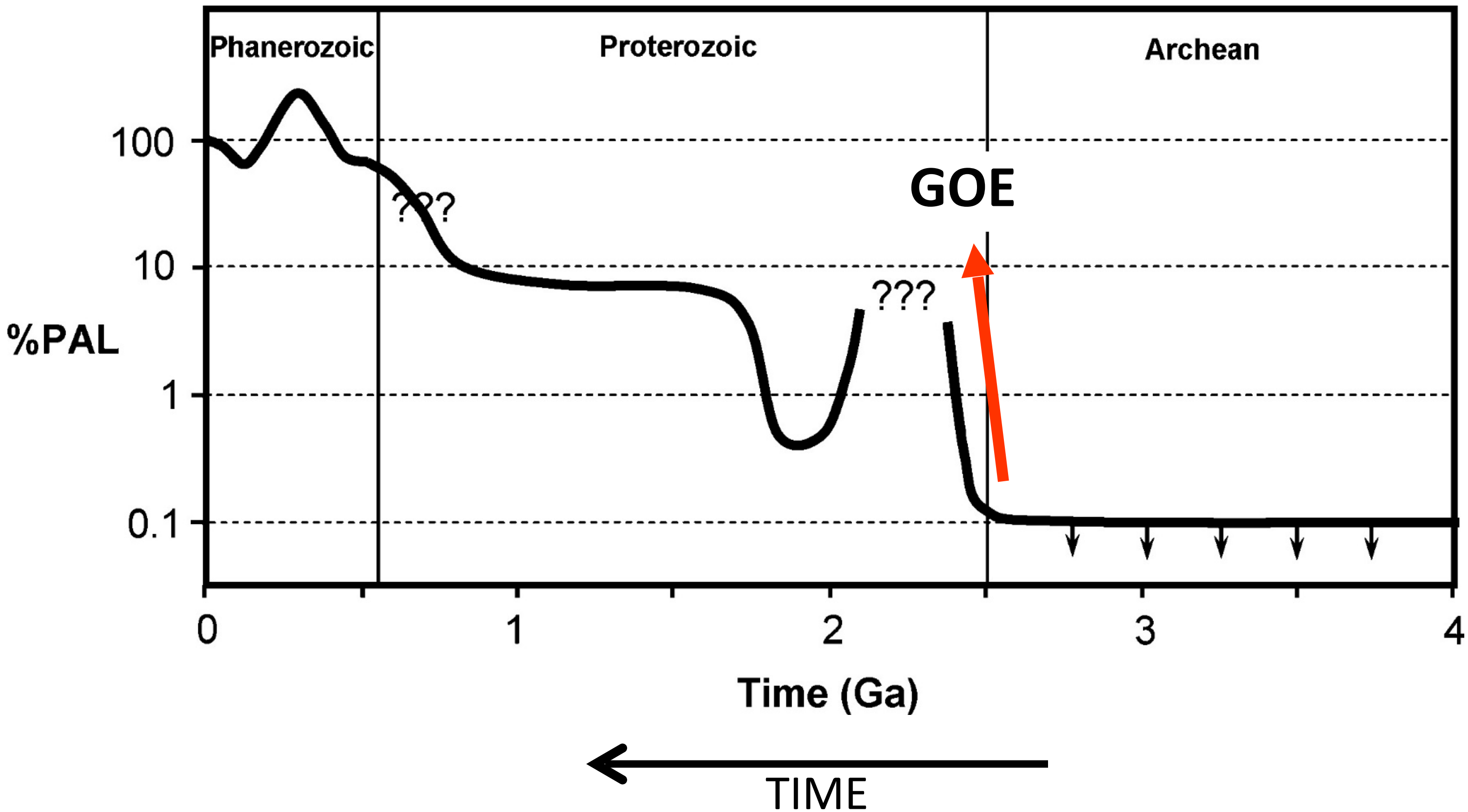
C) ***3.2 Gyr unidentified prokaryotes** from South Africa (Javaux et al., 2010)*

D) ***3.2 Gyr thermophylic filamentous bacteria** from Australia (Rasmussen, 2000).*

✶ The Great Oxygenation Event* (GOE)

*or Great Oxidation Event

Atmospheric oxygen shows a **sharp rise between 2.45-2.32 Gyr**



From Canfield (2005)

✶ The Great Oxygenation Event. *Evidence from the geologic record*

Examples of evidence suggesting an abrupt rise of atmospheric O_2:

1. **Redox sensitive elements**:
   Occurrence of fluvial deposits containing minerals that would not be stable under oxidizing conditions (e.g.: uraninite, pyrite, and siderite) are rare after 2.3 Gyr.

   Uraninite = UO_2

   Pyrite = FeS_2

   Siderite = $FeCO_3$

2.7 Gyr Witwatersrand conglomerate

Natural Museum of Humbolt State Univ.

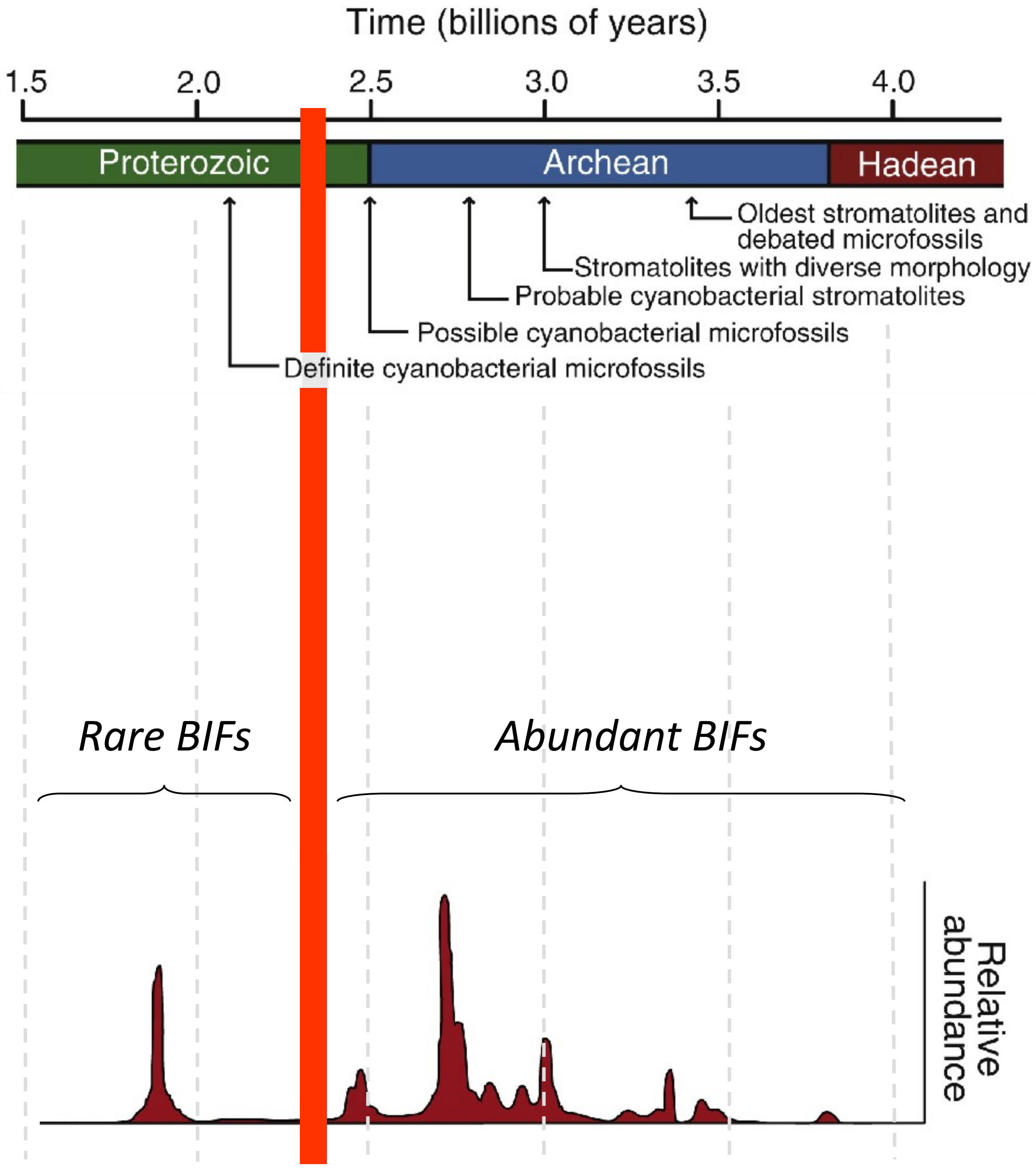
The rounded pebbles in this 2.7 Gyr conglomerate indicate that they were deposited in a stream. The presence of the pyrite flakes and uraninite suggests reducing (anaerobic) conditions.

2. **Banded Iron Formations (BIFs)**:
Banded iron formations are laminated rocks characterized by an alternation of Si-rich and Fe-rich laminations. Fe-rich laminations are rich in iron oxide (Fe_2O_3). They are widespread in the Archean and early Proterozoic.

The Iron oxide was deposited when the anoxic ocean waters (rich in dissolved Fe^{2+}) mixed with O_2-rich waters ("mass rusting").

Once the oxidation process was completed, O_2 started to increase and resulted in the GOE.

Encyclopedia Britannica



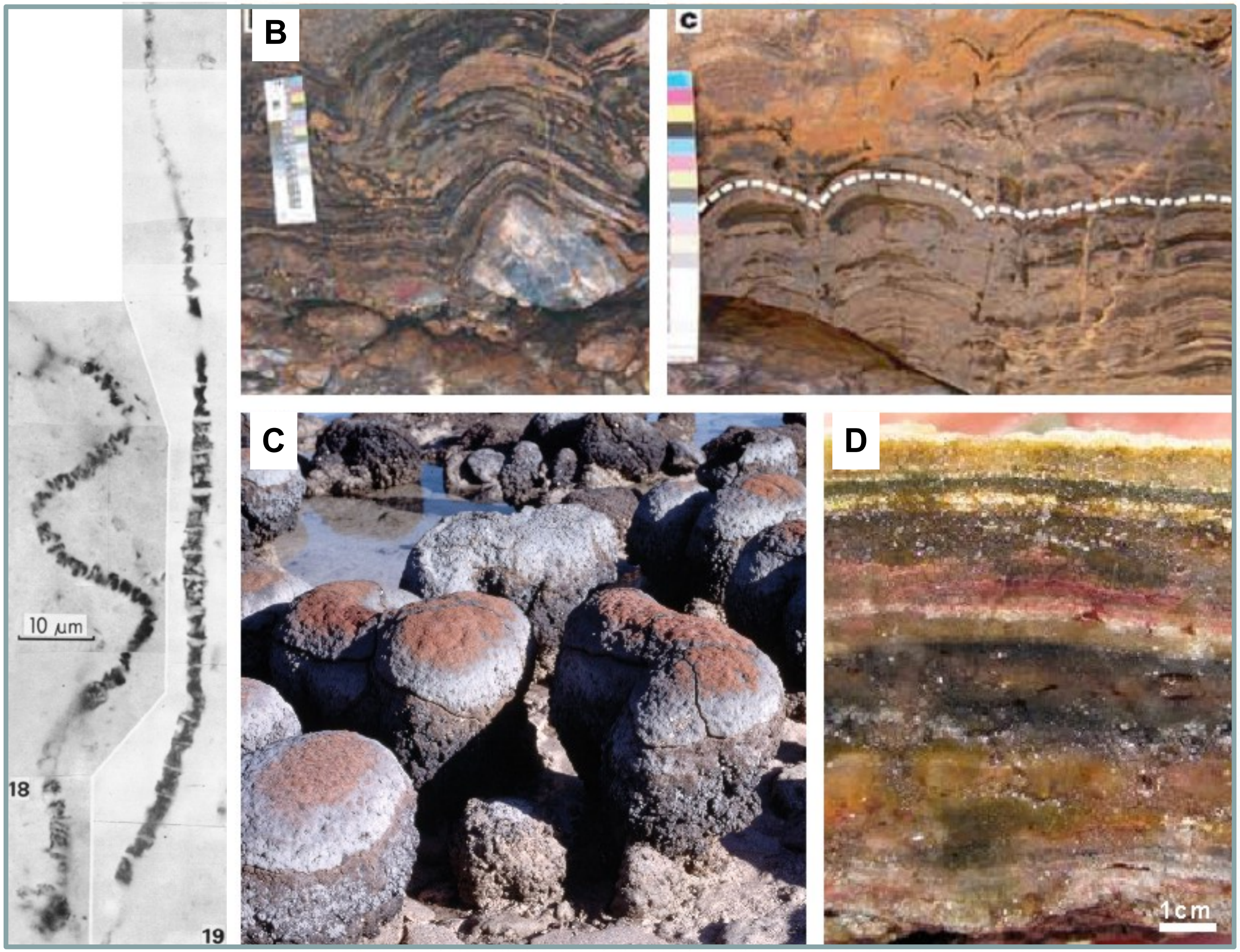
Modified from Sessions et al. (2009)

✶ The Great Oxygenation Event • *Origin of O_2*

Rise in O_2 probably linked to the emergence of photosynthetic **cyanobacteria**

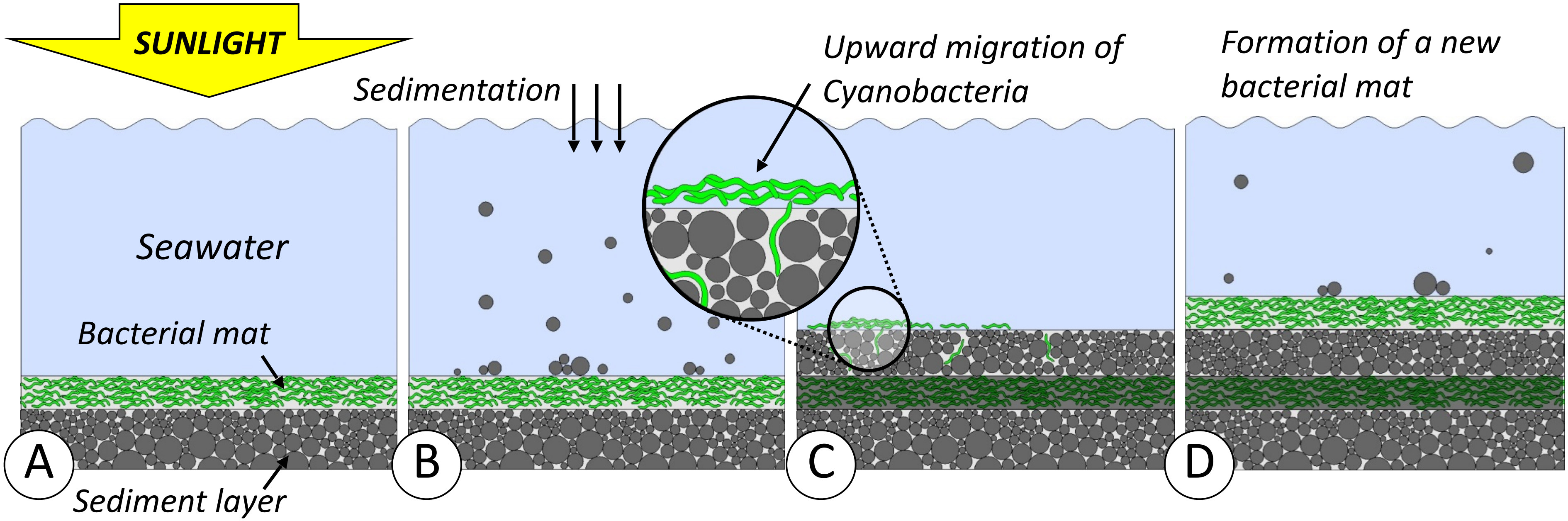
$$6H_2O + 6CO_2 + \text{sunlight} \rightarrow C_6H_{12}O_6 + \boxed{6\mathbf{O_2}}$$

- *The timing of the first appearance of cyanobacteria in the fossil record is controversial. The earliest, unambiguous occurrence of cyanobacteria is in* ***~2.15 Gyr*** *old rocks from Canada.*
- *The existence of older stromatolites (very similar to present-day Shark Bay stromatolites) suggest that the origin of cyanobacteria may be much older than 2.15 Gyr (see 3.5 Gyr stromatolites from Australia)*
- *The geological record and genetic studies suggest that cyanobacteria originated after anoxygenic photosynthetic bacteria and after various other bacteria using different metabolic pathways.*



(A) ***1.9 Gyr cyanobacteria*** *from Canada (Hoffman, 1976), (B)* ***3.4 Gyr stromatolite*** *from Western Australia (Allwood et al., 2006), (C)* ***modern stromatolites*** *from Shark Bay, Australia (from britannica.com), and (D) cross section of a* ***modern stromatolite*** *from Shark Bay (from physorg.com).*

Mechanisms of stromatolite formation



Calcification:

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + \mathbf{CO_2} + H_2O$$

Photosynthesis:

$$6H_2O + 6\mathbf{CO_2} + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

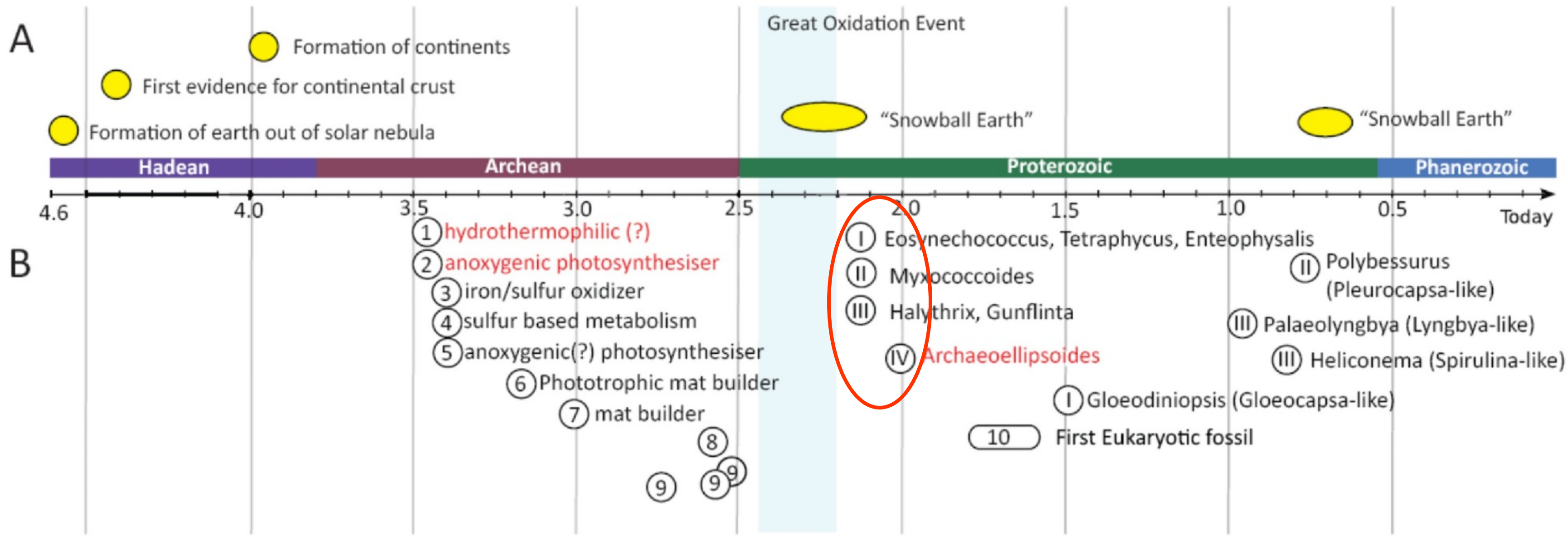


Figure 7 Timeline with prokaryotic fossil record. Timeline with geological events (A) and prokaryotic fossil record (B). (A) Formation of Earth [118], first evidence of continental crust [119], formation of continents [118], and glaciation events described in the Snowball Earth hypothesis [120]. (B) The oldest conclusive cyanobacterial fossils are found in around 2.15 billion year old rocks. 1-7: Fossils from the Archean Eon [23,25,26,84-87]. 8: chroococcacean fossils [24]; 9: oscillatorian fossils [24]. I-V: cyanobacterial fossils [18-20]. 10: eukaryotic fossils [65].

Schirmeister et al. (2011)

✶ The Great Oxygenation Event • *Consequences*

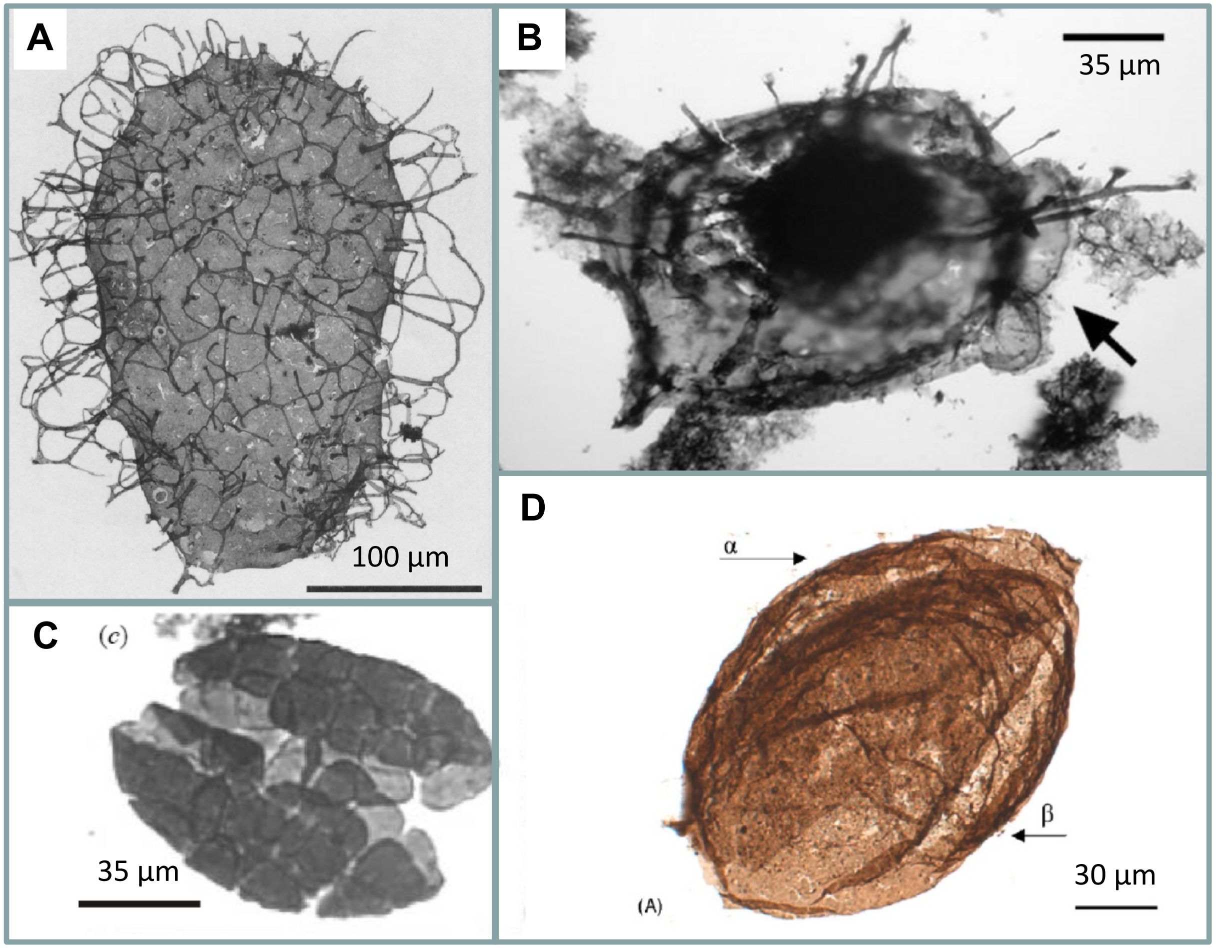
- GOE also called Great Oxygenation Crisis because O_2 was toxic for anaerobic bacteria → likely resulted in **First mass extinction**!

- Emergence of **aerobic respiration** → the energetic advantage of using O_2 as an oxidizing agent in aerobic respiration enabled the evolution of more complex forms of life.

- The selective pressure resulting from the GOE related to the toxicity of O_2 for anaerobic bacteria may have led to the emergence of **the eukaryotic cell** (see Endosymbiont Hypothesis)

✶ The Eukaryotic Cell

- Oldest occurrence of fossils of eukaryotes in **1.8 Gyr**-old rocks from China



A) ***1.4 Gyr** eukaryote from Canada (Butterfield, 2005),*

B) ***1.5 Gyr** eukaryote from Australia (Javaux et al., 2001),*

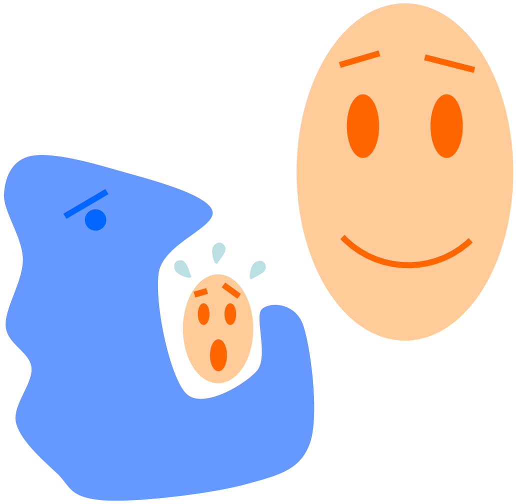
C) ***1.5 Gyr** eukaryote from Australia (Knoll et al., 2006), and*

D) ***1.8 Gyr** eukaryote from China (Lamb et al., 2009)*

✶ Multicellularity • *Advantages*

- In a predator-prey relationship, being larger means a **greater ability to engulf preys** that are comparatively smaller. Also, larger cells have **less chance to be ingested**.

- Growing larger means more exchange of matter between cell and exterior → area/volume ratio decreases rapidly → **limit to growth!** → **solution = multicellularity**

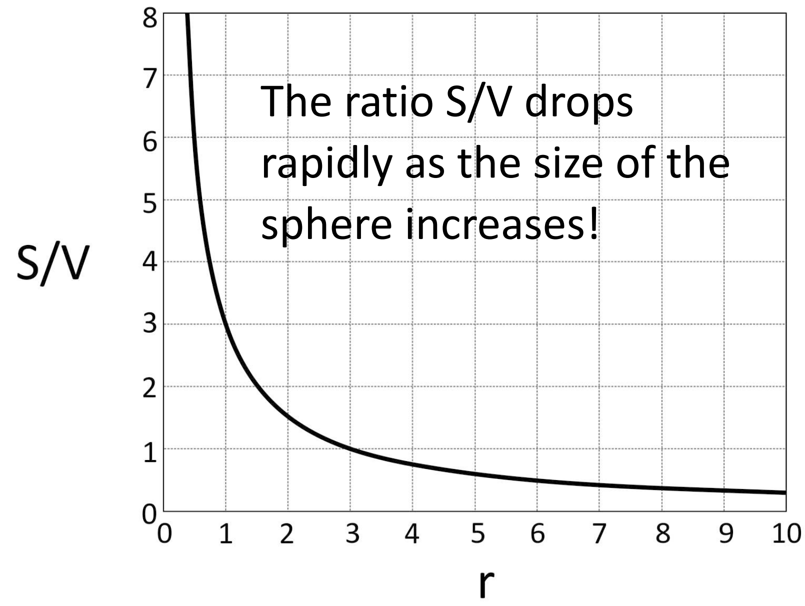


- Advantages of being multicellular is the **specialization of body parts**, additional level of **protection** (replacement of damaged cells), **growth** does not affect metabolism of individual cells (just add new cells).

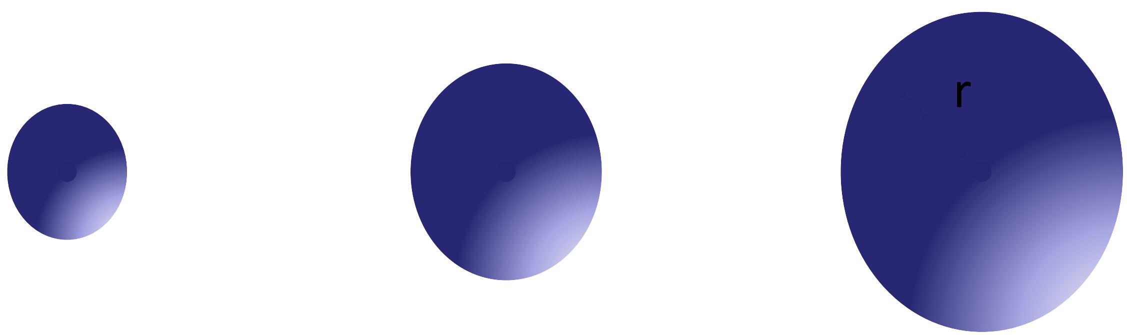
Surface of a sphere $S = 4\pi r^2$

Volume of a sphere $V = \dfrac{4\pi r^3}{3}$

$S/V = 3/r$



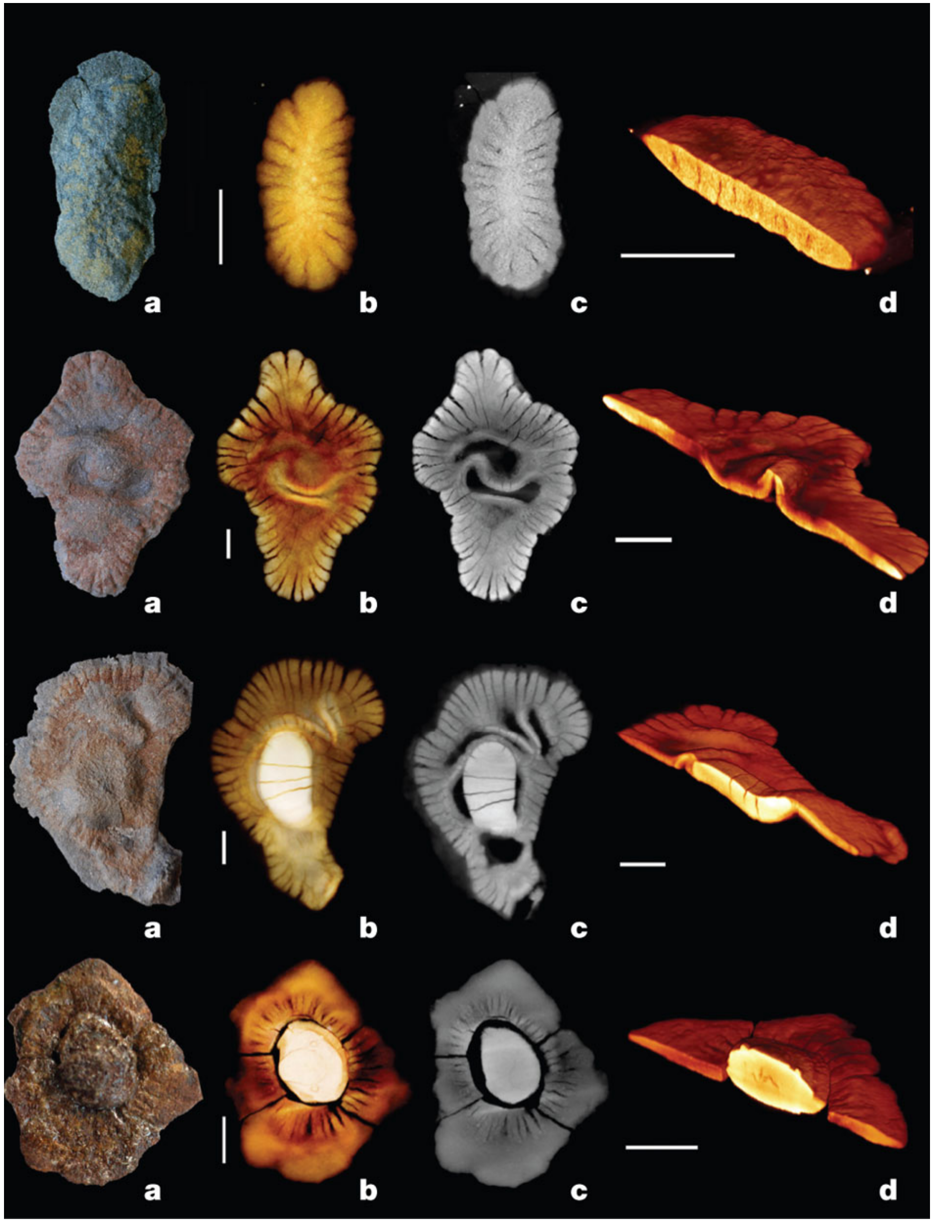
The ratio S/V is inversely proportional to the size of the sphere



Distance to center (r)	1.0	2.0	4.0
Surf. area (S)	12.6	50.3	201.1
Volume (V)	4.2	33.5	268.1
S/V	3.0	1.5	0.75

✶ Multicellularity

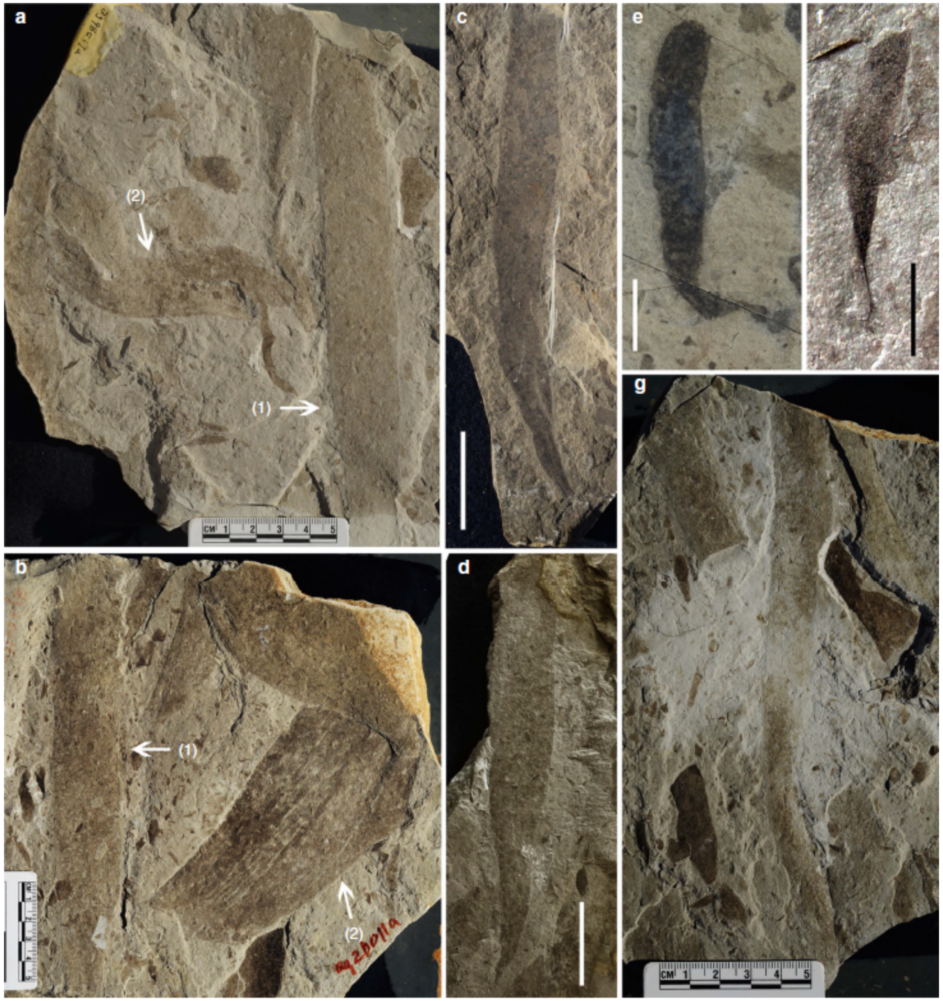
• *Evidence from the geological record*

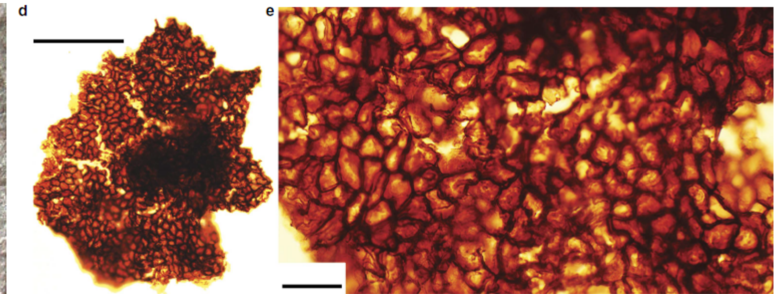


***2.1 Gyr** fossil of a macroscopic organism from Gabon whose affinity is uncertain. It may be a **multicellular eukaryote** or a **bacterial colony**.*

Scale bars = 5 mm

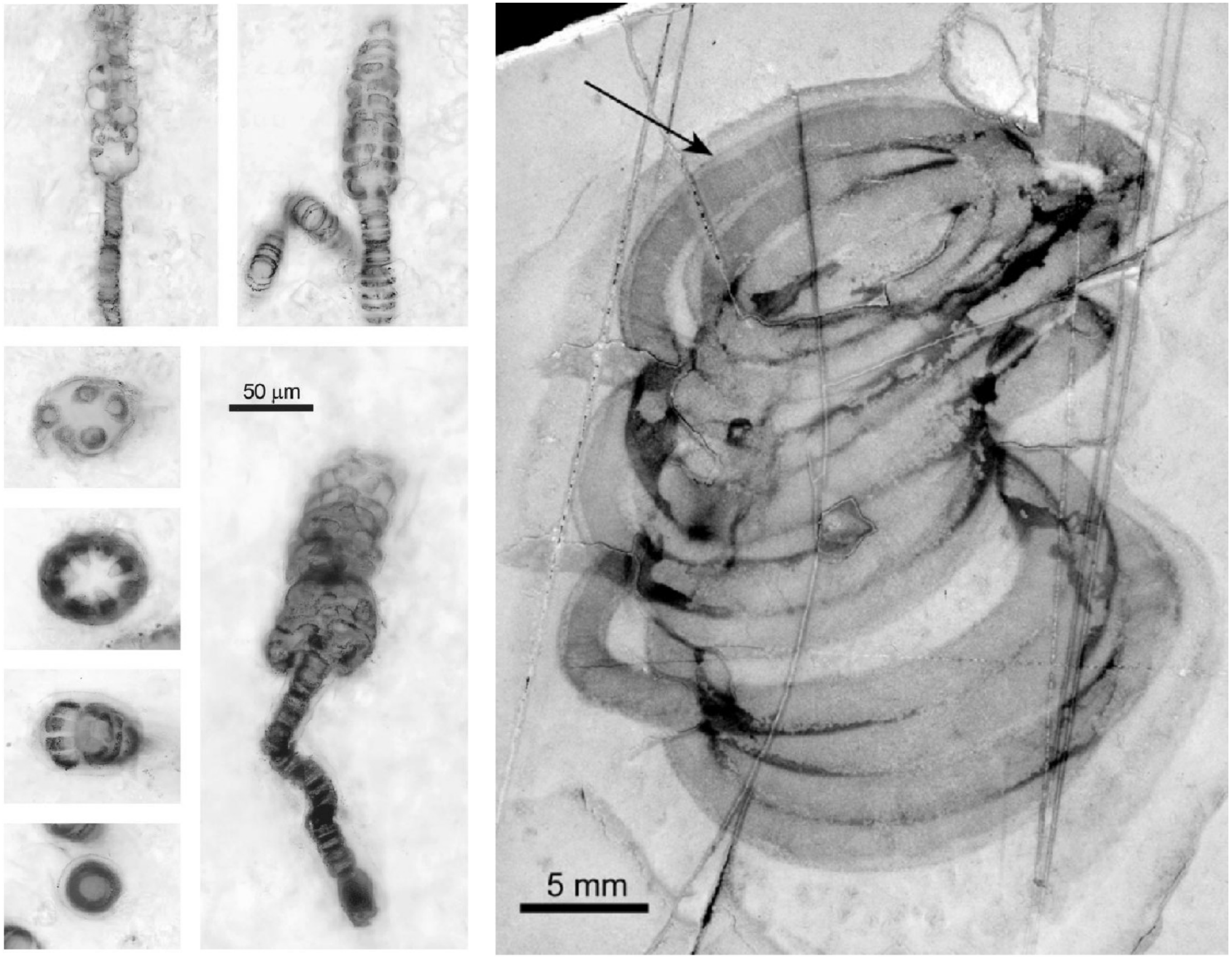
(from El Albani et al., 2010)





***1.56 Gyr** fossils of a **macroscopic multicellular eukaryotes** from the Gaoyuzhuang Formation in China. Scale bars on left panel: 5 cm (in a,b,g), 20mm (in c), 40mm (in d) and 5mm(in e,f). Scale bars on right panel: 100 mm (in d), 20 mm (in e).*

(from Zhu et al., 2016)

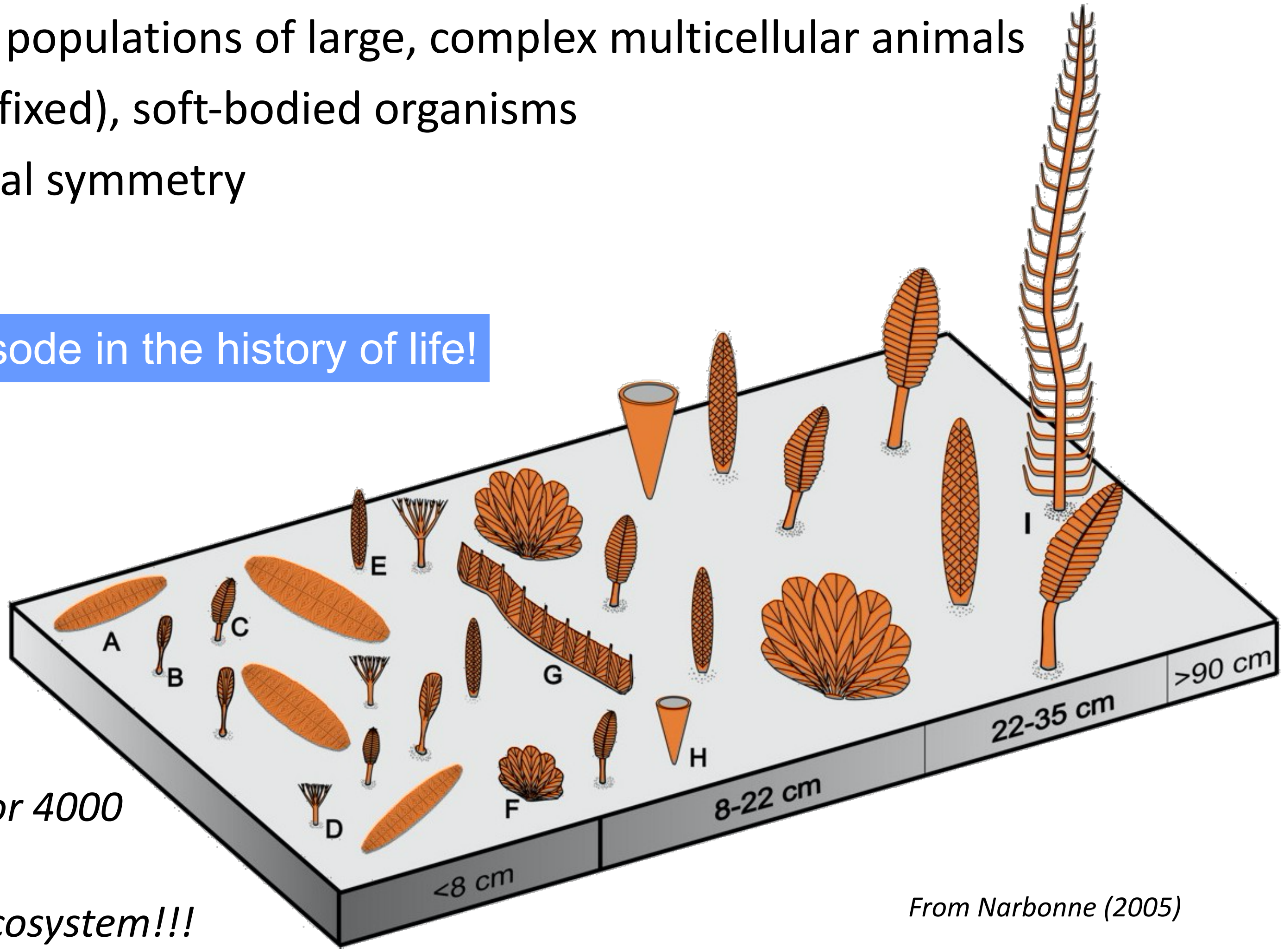


(A) ***1.2 Gyr*** *multicellular* ***red algae Bangiomorpha pubescens*** *from arctic Canada (Butterfield, 2000), (B)* ***1.6 Gyr*** *problematic* ***Grypania spiralis*** *from India (Butterfield, 2009)*

✶ Ediacara biota (575-542 million years ago)

- Earliest diverse populations of large, complex multicellular animals
- Mostly sessile (fixed), soft-bodied organisms
- Bilateral or radial symmetry
- High diversity

Short-lived episode in the history of life!



From Narbonne (2005)

Locally, up to 3000 or 4000 individuals per m²!
Highly productive ecosystem!!!

Ediacara biota "reported from nearly 30 localities on 5 continents" (Narbonne, 2005)

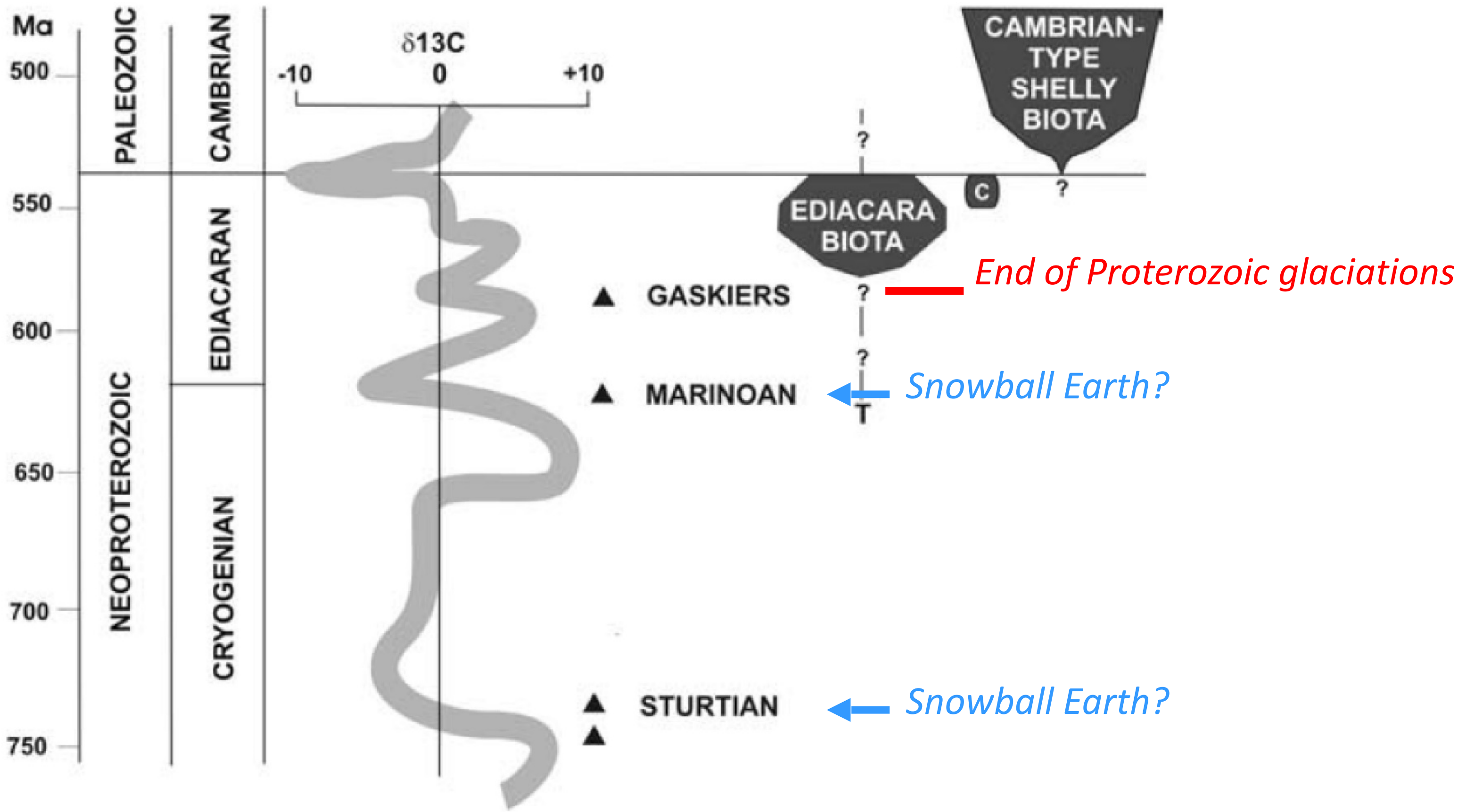


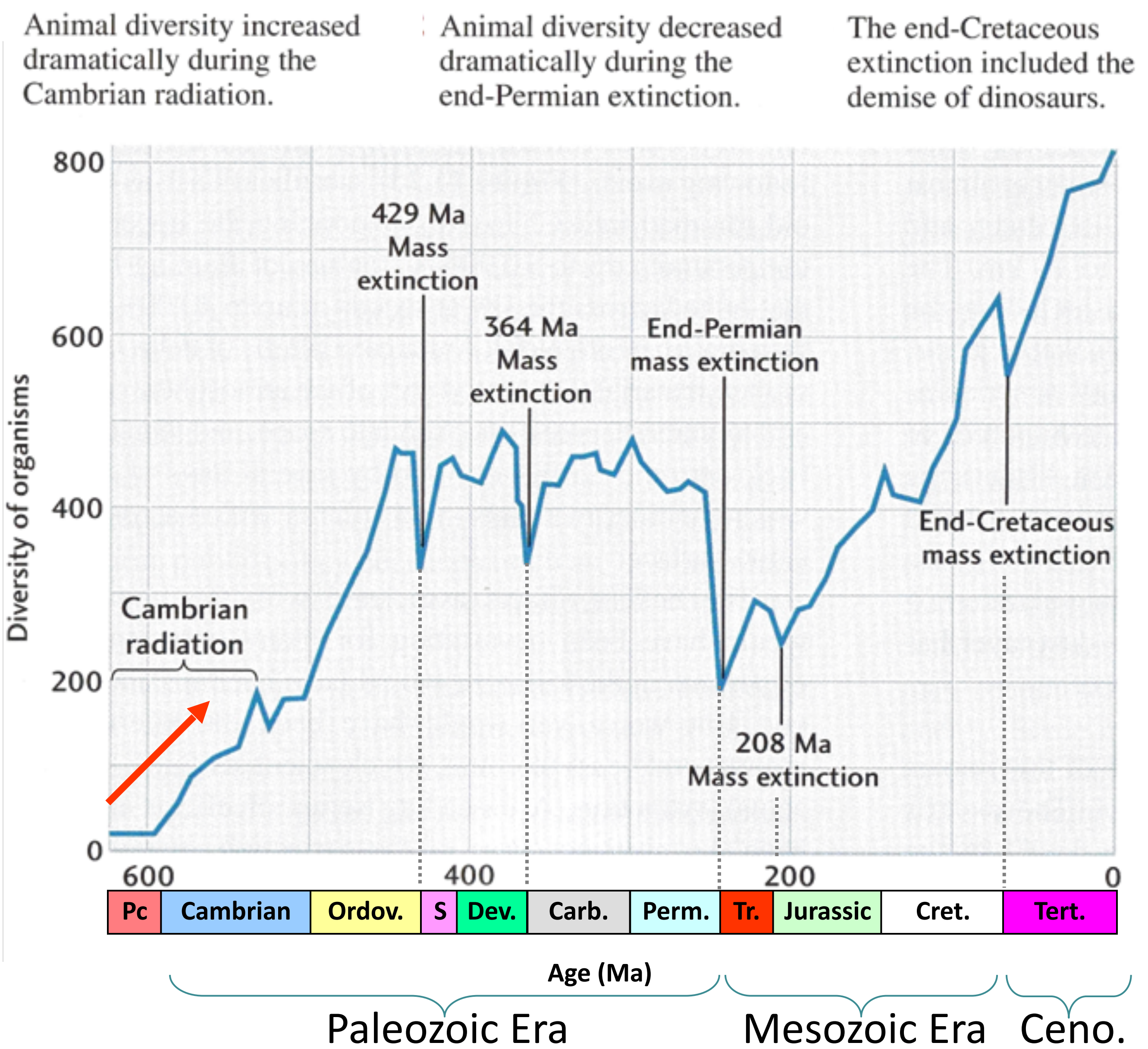
Figure 1 Stratigraphic setting of the Ediacara biota in relation to Neoproterozoic global change [carbon isotopes and global glaciations (▲)] and major evolutionary events. "T" marks the position of the Twitya discs; "C" marks the position of Ediacaran calcified metazoans.

From Narbonne (2005)

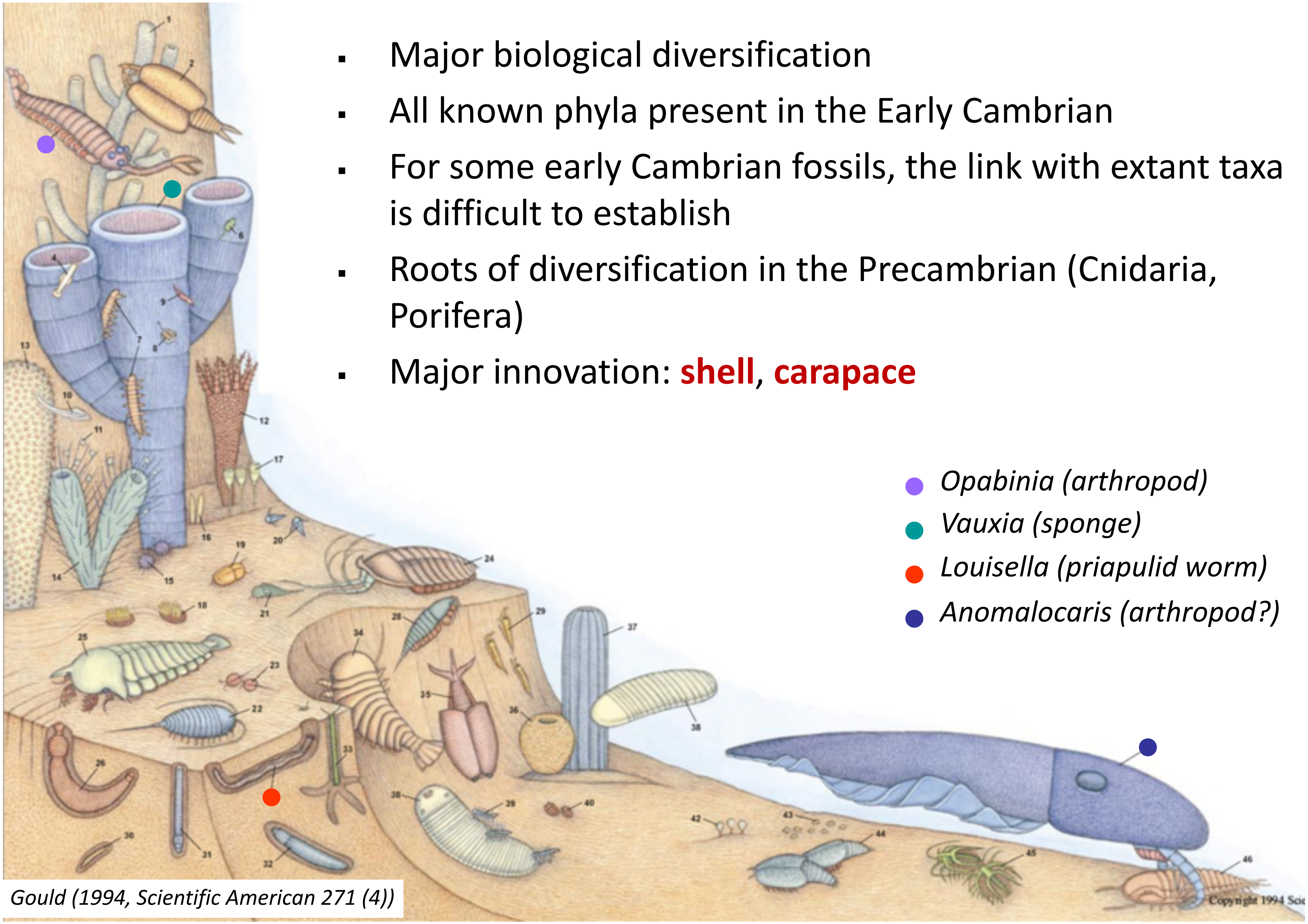
Probable tracks left by an organism (indicates that motile forms possibly existed at that time)

From Narbonne (2005)

✶ The Cambrian Radiation of Life (540 million years ago)

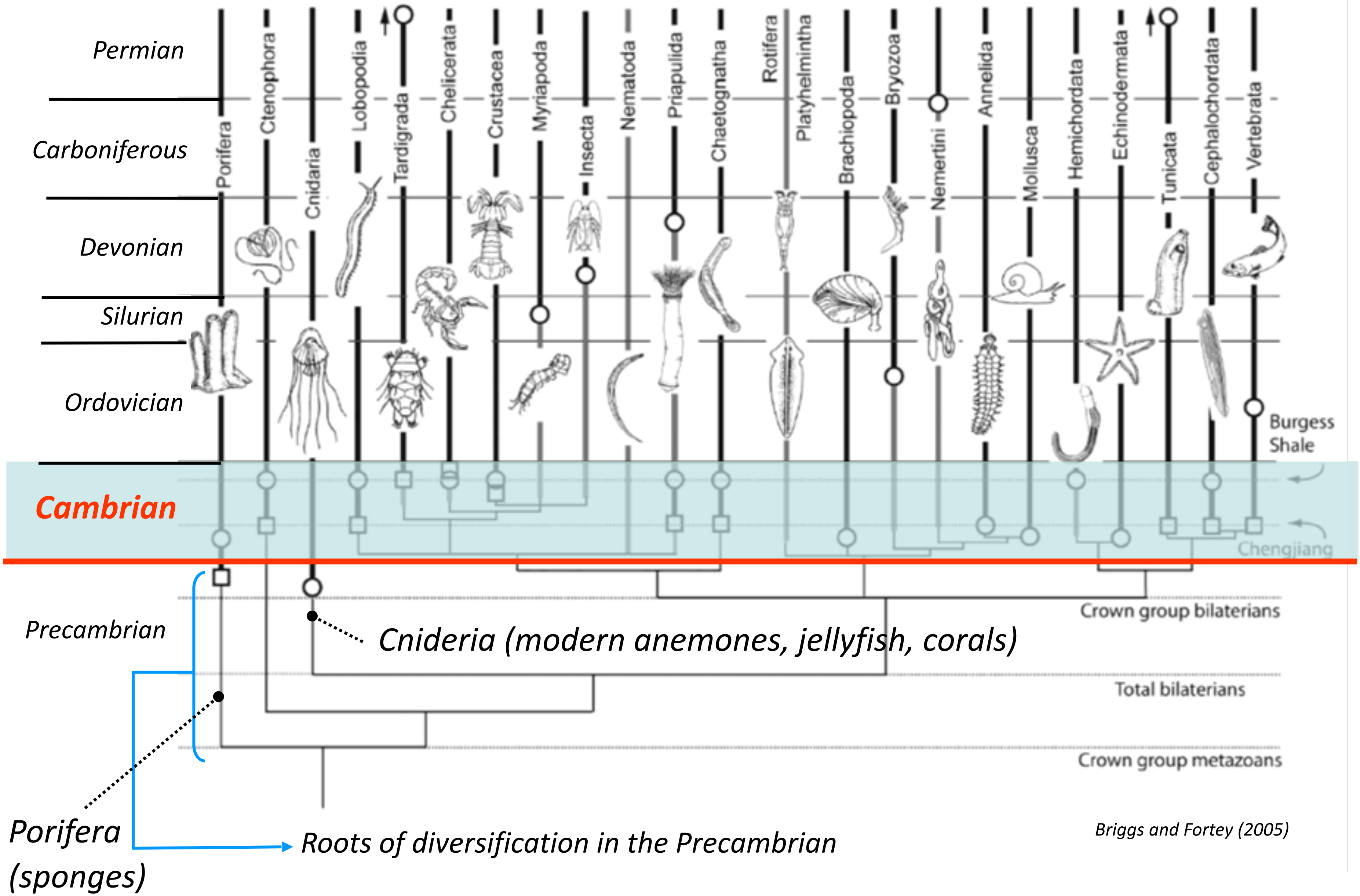


- Major biological diversification
- All known phyla present in the Early Cambrian
- For some early Cambrian fossils, the link with extant taxa is difficult to establish
- Roots of diversification in the Precambrian (Cnidaria, Porifera)
- Major innovation: **shell**, **carapace**

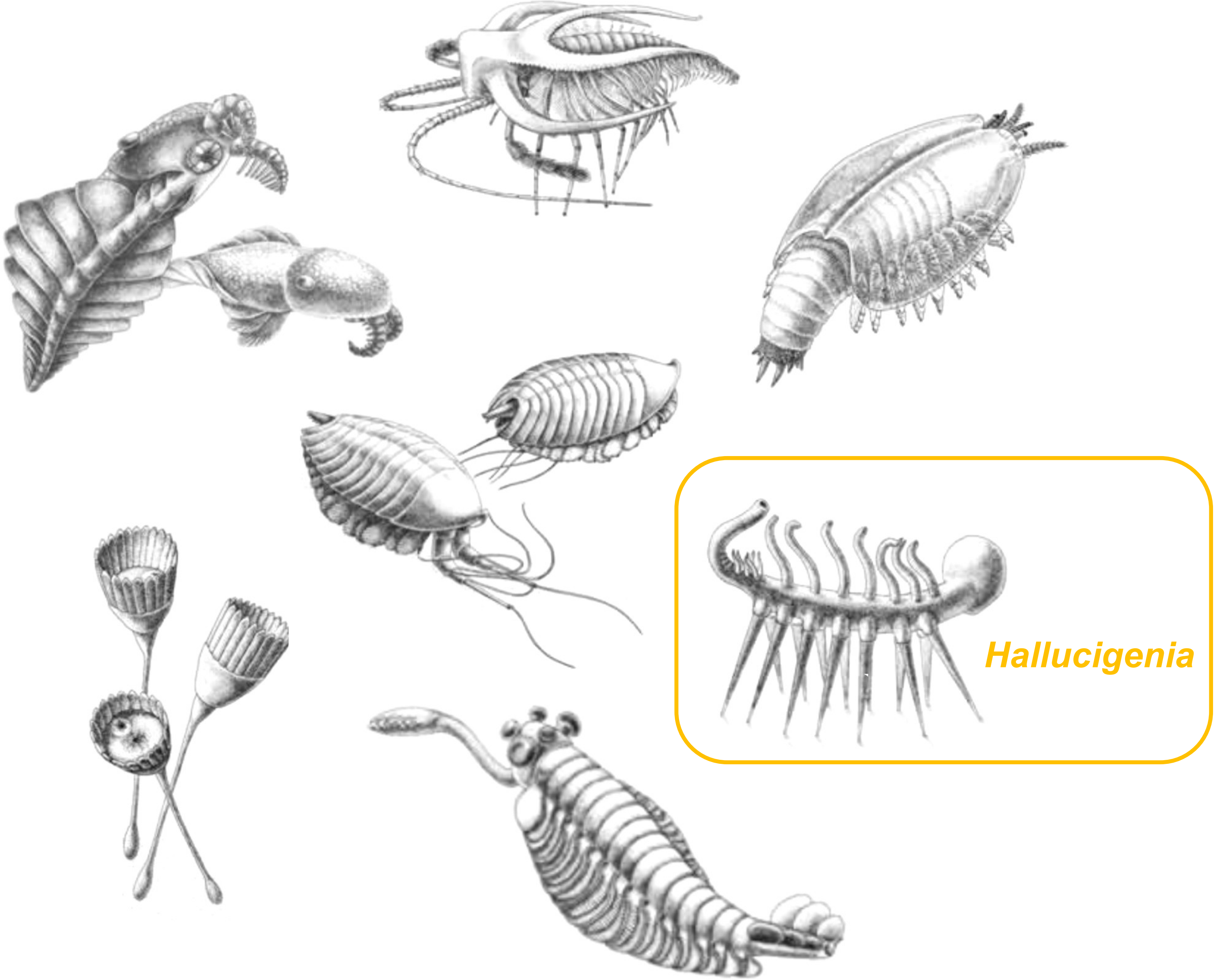


- *Opabinia (arthropod)*
- *Vauxia (sponge)*
- *Louisella (priapulid worm)*
- *Anomalocaris (arthropod?)*

Gould (1994, Scientific American 271 (4))



Briggs and Fortey (2005)


Hallucigenia

Possible triggering factors

1. Environmental factors

- End of Proterozoic glaciations
- Rise of O_2
- Change in ocean chemistry promoting biomineralization

2. Genetic factors

- Emergence of key developmental genes (without which certain adaptations would not be possible)

3. Ecological factors

- Adaptations related to predation-prey relationship (shell, carapace, pelagism, body parts improving mobility, sensory organs…)

→ Coevolution – groups of organisms can affect each other's evolution

- As a prey, you tend to evolve traits to escape predators
- As a predator, you tend to evolve traits to catch preys

e.g. Think about a mollusk, like a slug. It may evolve a shell to protect itself. Predators may in turn evolve specialized tools to break or drill that shell (e.g. crab's claws, carnivorous snail's radula).

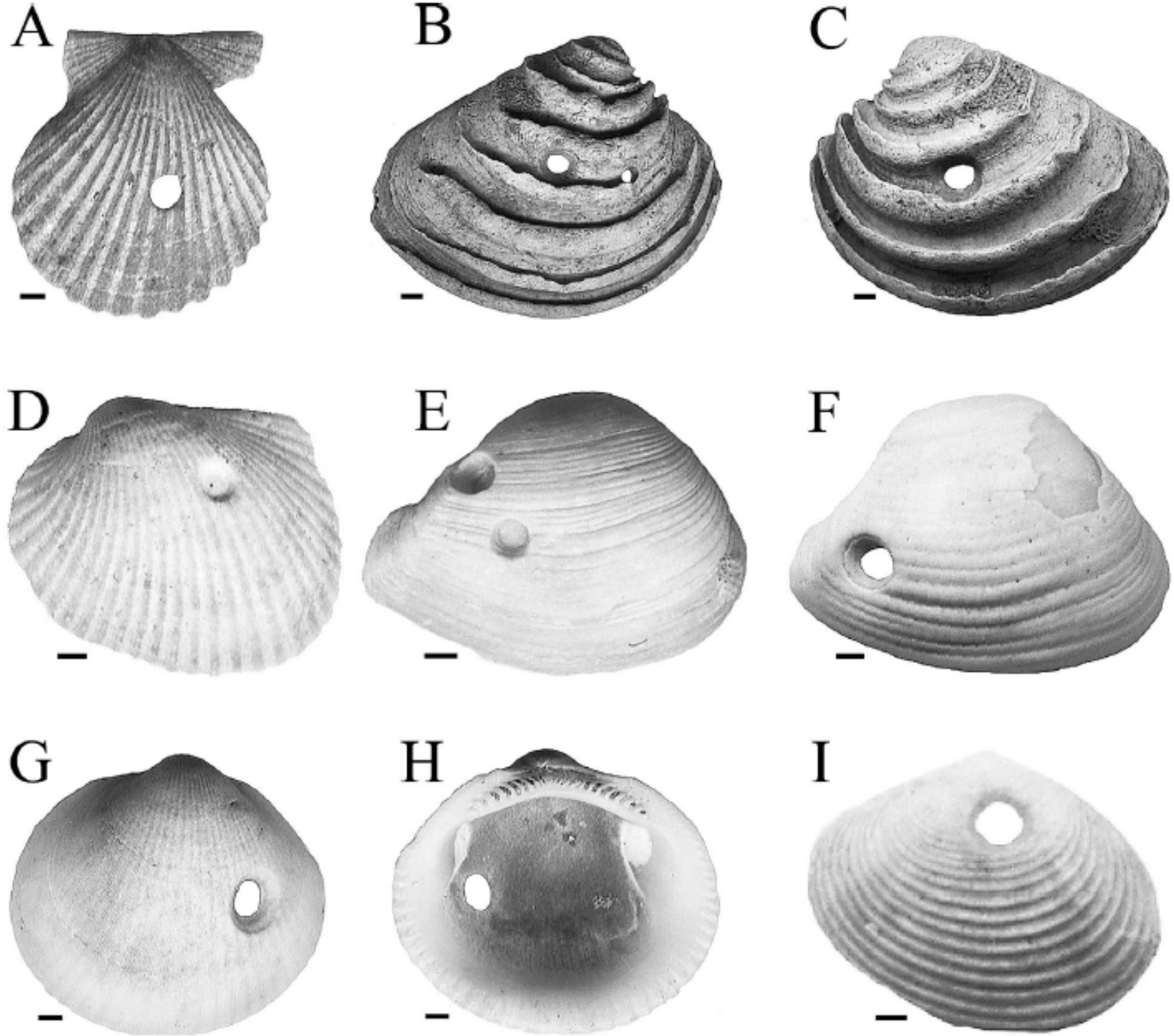
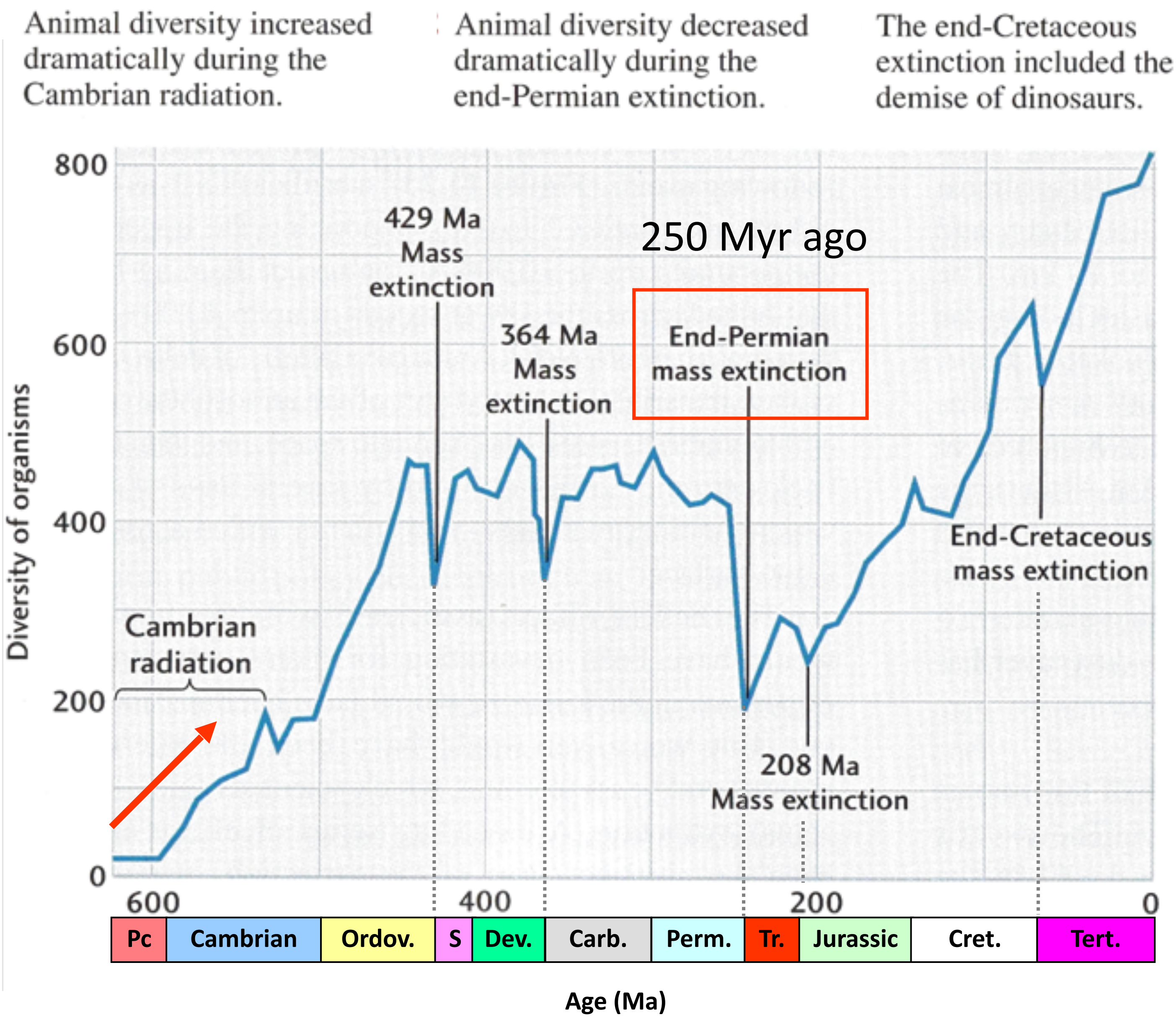


FIGURE 5—Drill holes in shells of bivalve mollusks. A) Complete hole in right valve of *Chlamys* sp., specimen DZP-18551, Picinguaba Bay, 10 m depth. B–C) *Chione* sp., DZP-18552 and DZP-18553, Picinguaba Bay, 15 m depth; B) multiple complete holes in right valve, and C) single complete hole in left valve. D) Incomplete hole in left valve of *Anadara* sp., specimen DZP-18554, Ubatuba Bay, 10 m depth. E–F) Right valves of *Corbula* sp., Picinguaba Bay, 15 m and 10 m depths, respectively; E) specimen DZP-18555 with multiple incomplete holes, and F) single complete hole in specimen DZP-18556. G–H) Left valve of *Glycymeris* sp., DZP-18557, Ubatuba Bay, 10 m depth; G) external view of complete hole, and H) internal view of same specimen. I) Complete hole in right valve of *Amiantes* sp., DZP-18558, Picinguaba Bav. 45 m depth. Scale bars = 1 mm.

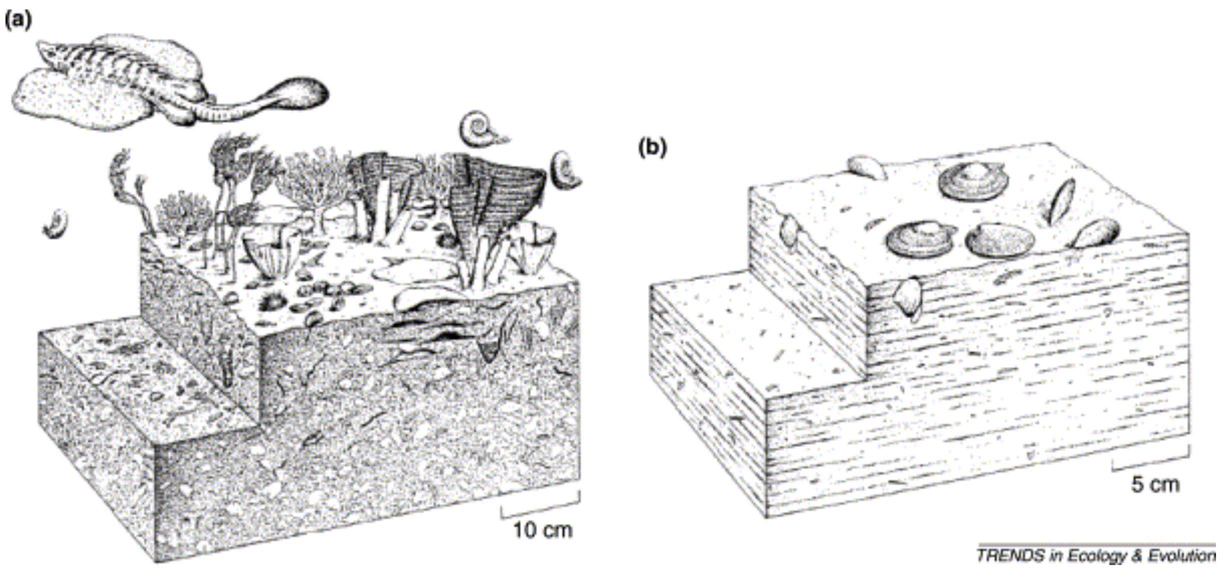
Simoes et al. (2006)

✶ End-Permian mass extinction



% of taxa extinct		End-Ordovician	End-Devonian	End-Permian	End-Triassic	End-Cretaceous
	Families	20-26	21-22	**50-57**	22-23	15-16
	Genera	50-60	47-57	**70-83**	40-53	40-50
	Species	85	70-80	**85-96**	76	76

Lethiers (1998)

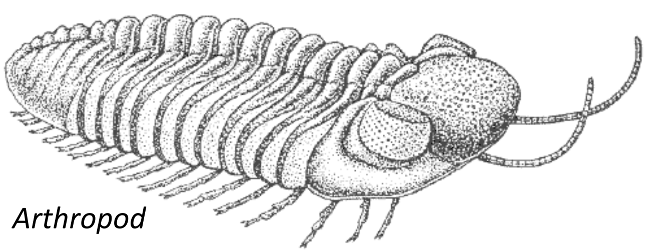


Sketch of the sea bed in southern China before (a) and after (b) the en-Permian mass extinction. A marine fauna of 100 or more species is reduced to 4 or 5. From Benton and Twitchett (2003).

- **Most severe** mass extinction
- **~90%** of all species went extinct!
- **Marine** and **continental** life affected

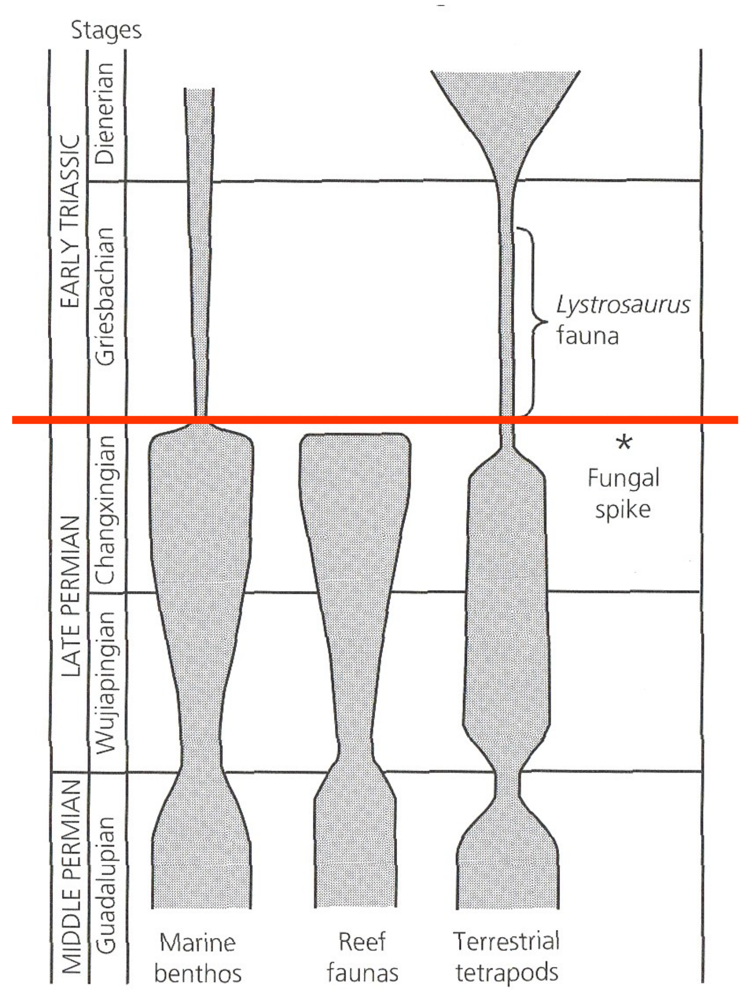
Family Therapsidae (includes ancestors of mammals)

Gorgonopsians



Arthropod

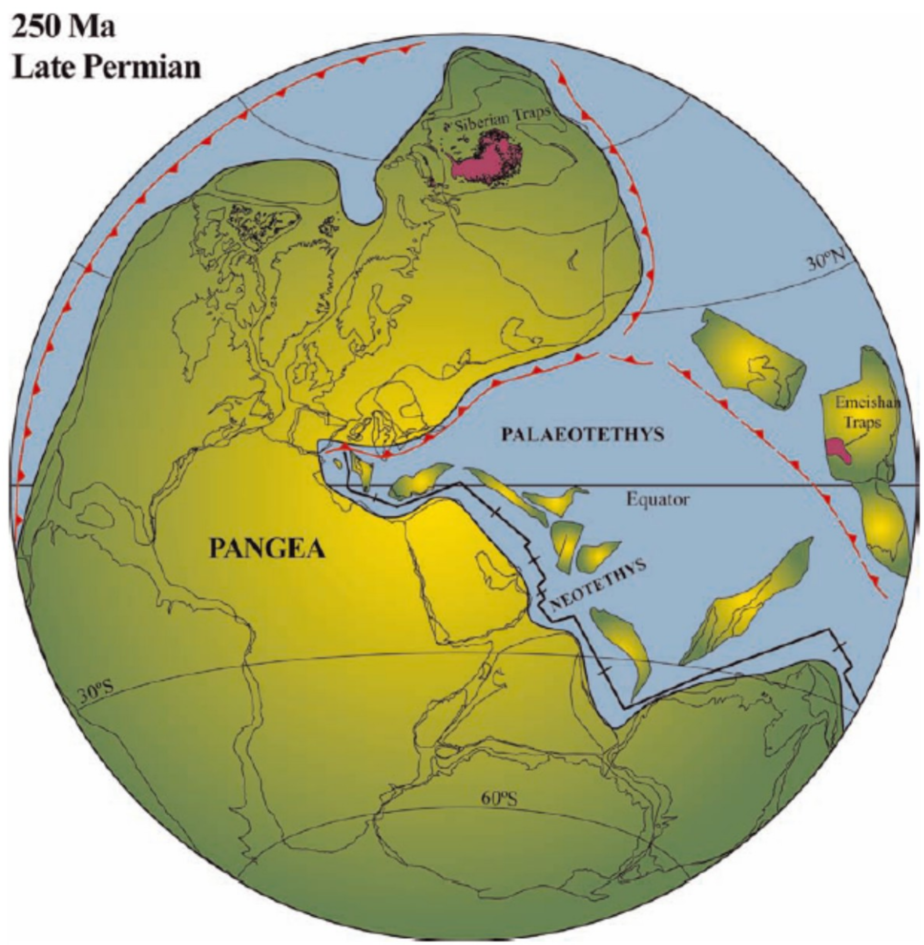
Trilobites



Wignall (2001)

✶ End-Permian mass extinction • *Possible causes*

Supercontinent Pangaea



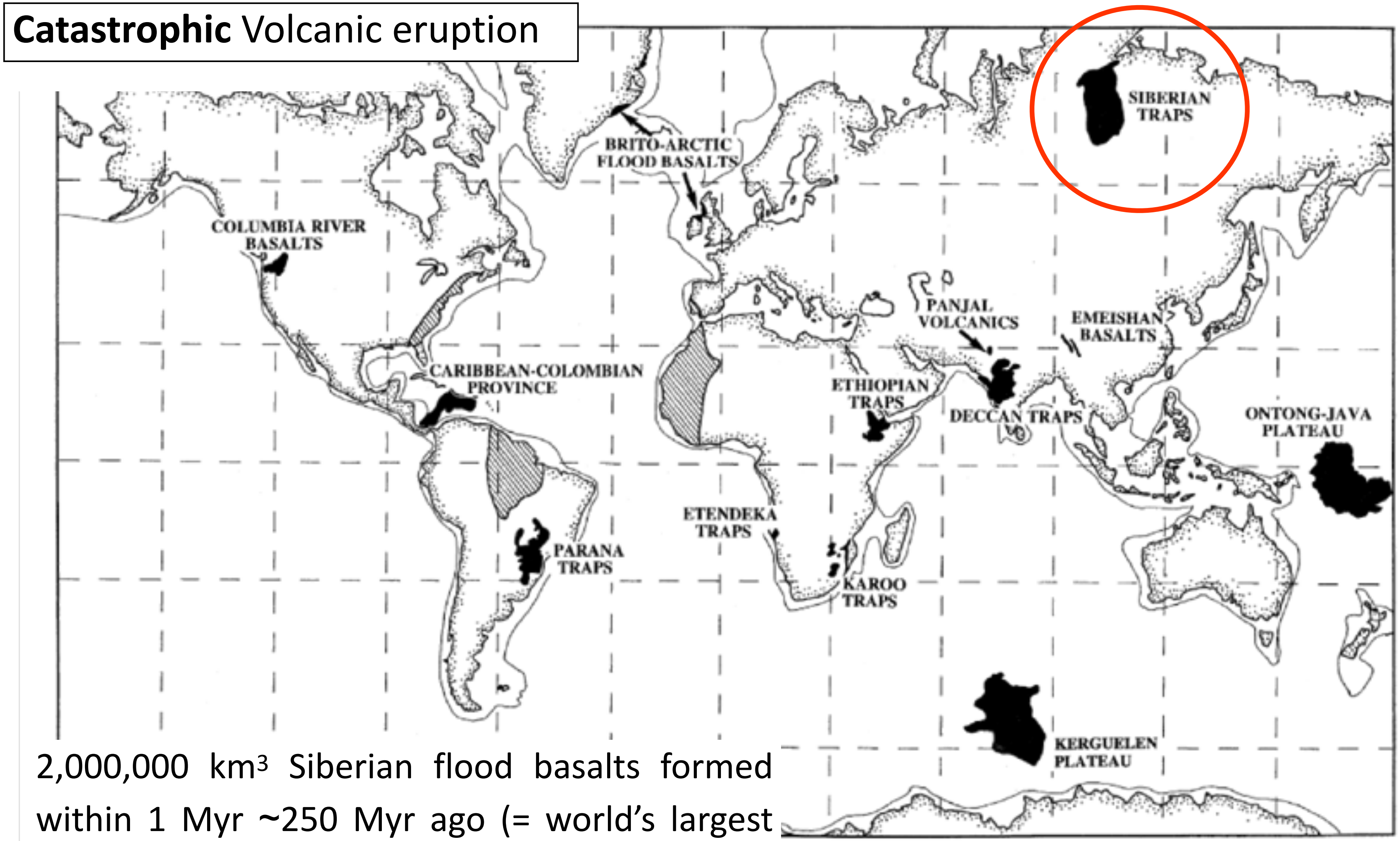
Less shallow marine environment - increased competition for resources

NB: Meteorite impact

Evidence for end-Permian impact has been published by several authors but the effect of the impact on the environment (and the existence of the impact itself) is controversial.

Cocks and Torsvisk(2006)

Catastrophic Volcanic eruption



2,000,000 km3 Siberian flood basalts formed within 1 Myr ~250 Myr ago (= world's largest continental flood basalt province!)

Wignall (2001)

✶ End-Permian mass extinction • *Effects on environment*

Catastrophic volcanic eruptions in Siberia released massive amounts of CO_2 and SO_2 in the atmosphere (+ some Cl and F).

- **Short-lived global cooling** due to the presence of dust and sulfate aerosols in the atmosphere (SO_2 + water → sulfate aerosols)

- **Acid rains** (H_2SO_4, HCl, HF)

- **Long-term global warming** caused by greenhouse gas CO_2

Examples of extreme consequences of global warming:

- **Ocean anoxia**

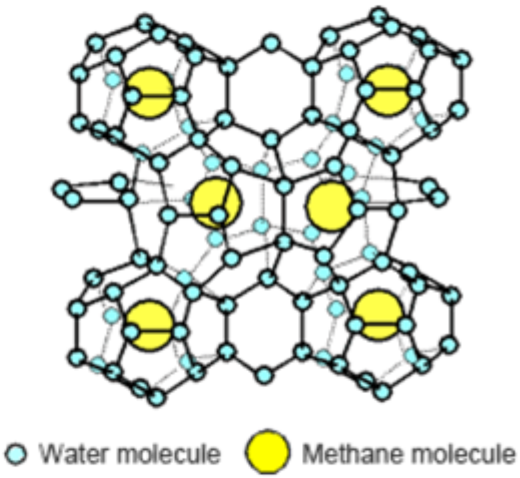
  Global warming lowers O_2 solubility and slows down the thermohaline circulation.

- **Catastrophic release of Methane in the atmosphere**

  Large amounts of CH_4 present in deep-sea sediments and high-latitude permafrost as CH_4 hydrate (stable at high P and low T).

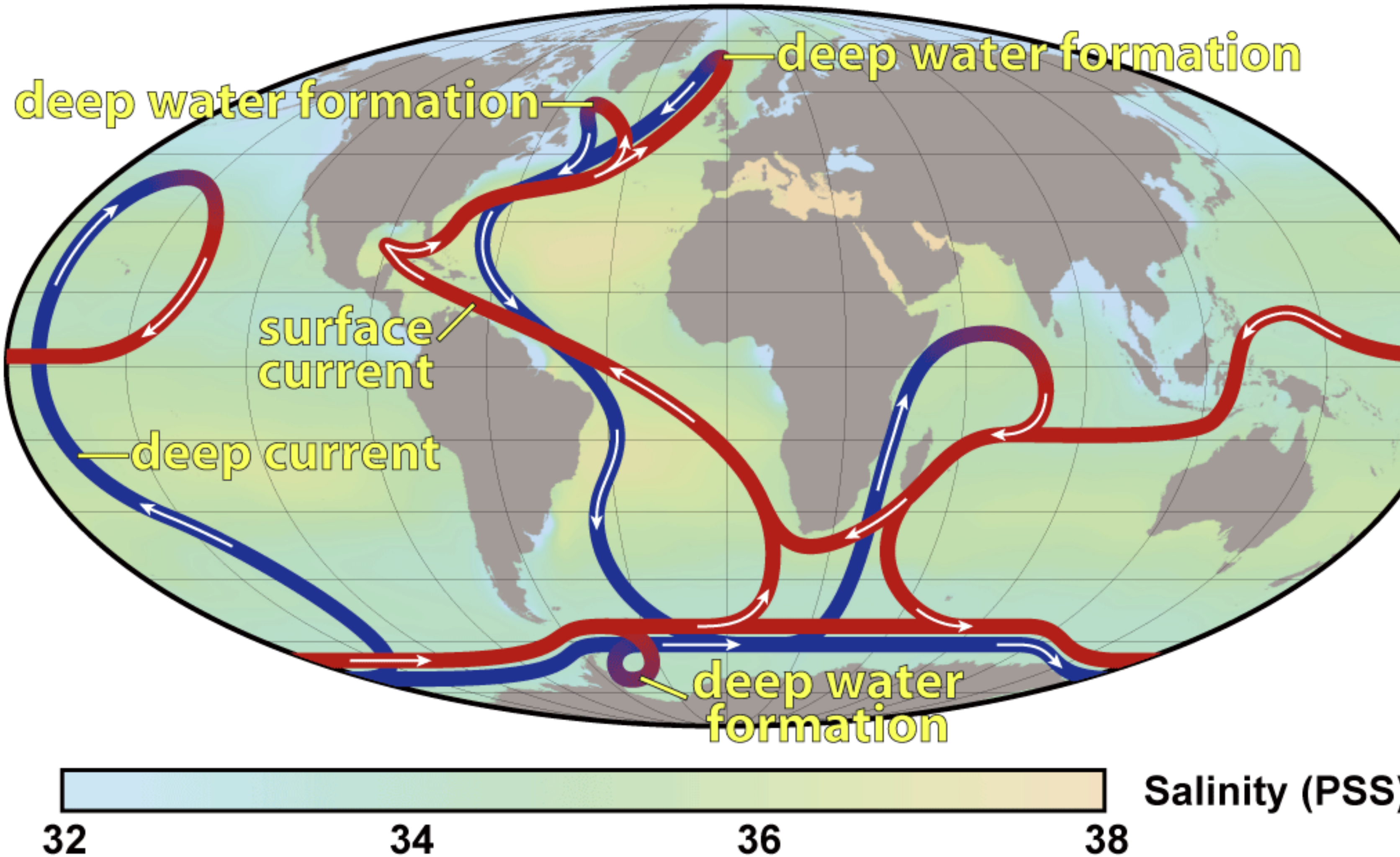
Increased T may induce melting of CH_4 hydrate. The release of CH_4 in the atmosphere may further enhance global warming, creating a **positive feedback loop**!

Methane hydrate

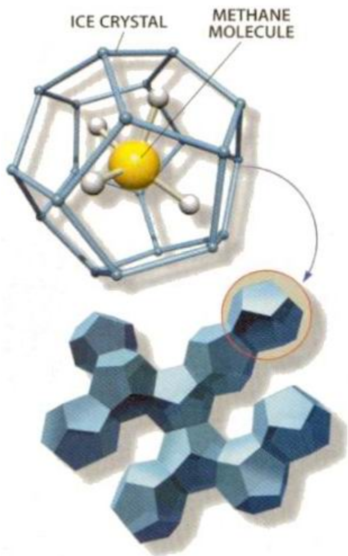


Tokyo Gas

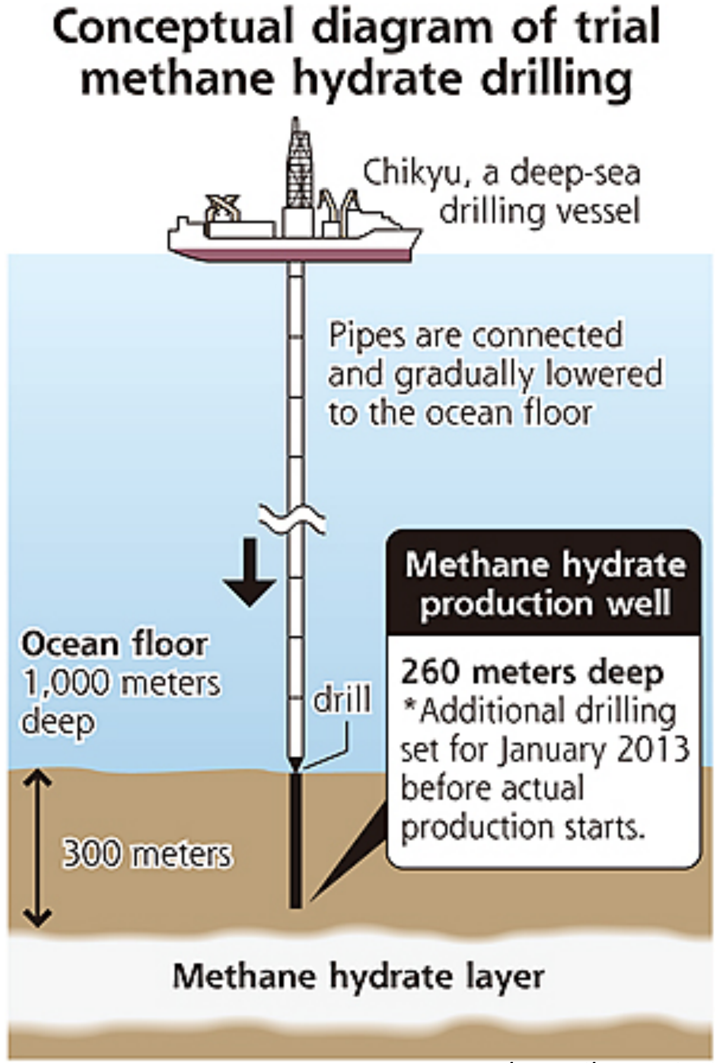
Thermohaline Circulation



Credit: R. Simmon/R. Rohde/NASA



NASA



The Daily Yomiuri

U.S. Department of State

NASA

"Work toward prospective drilling for methane hydrate began at sea about 70 kilometers off Atsumi Peninsula, Aichi Prefecture, on Tuesday morning…
…The operation marks the first-ever attempt to drill into the ocean floor for the energy source."

The Daily Yomiuri (February 15, 2012)

BIOGENIC METHANE

Organic matter settles at the bottom of the ocean and is decomposed by microorganisms through fermentation. **Methanogen Archaea** use the byproducts of fermentation (acetate, H_2, and CO_2) to obtain energy.

Two main pathways:

Acetate fermentation:

$$CH_3OOH \rightarrow CH_4 + CO_2 + NRG$$

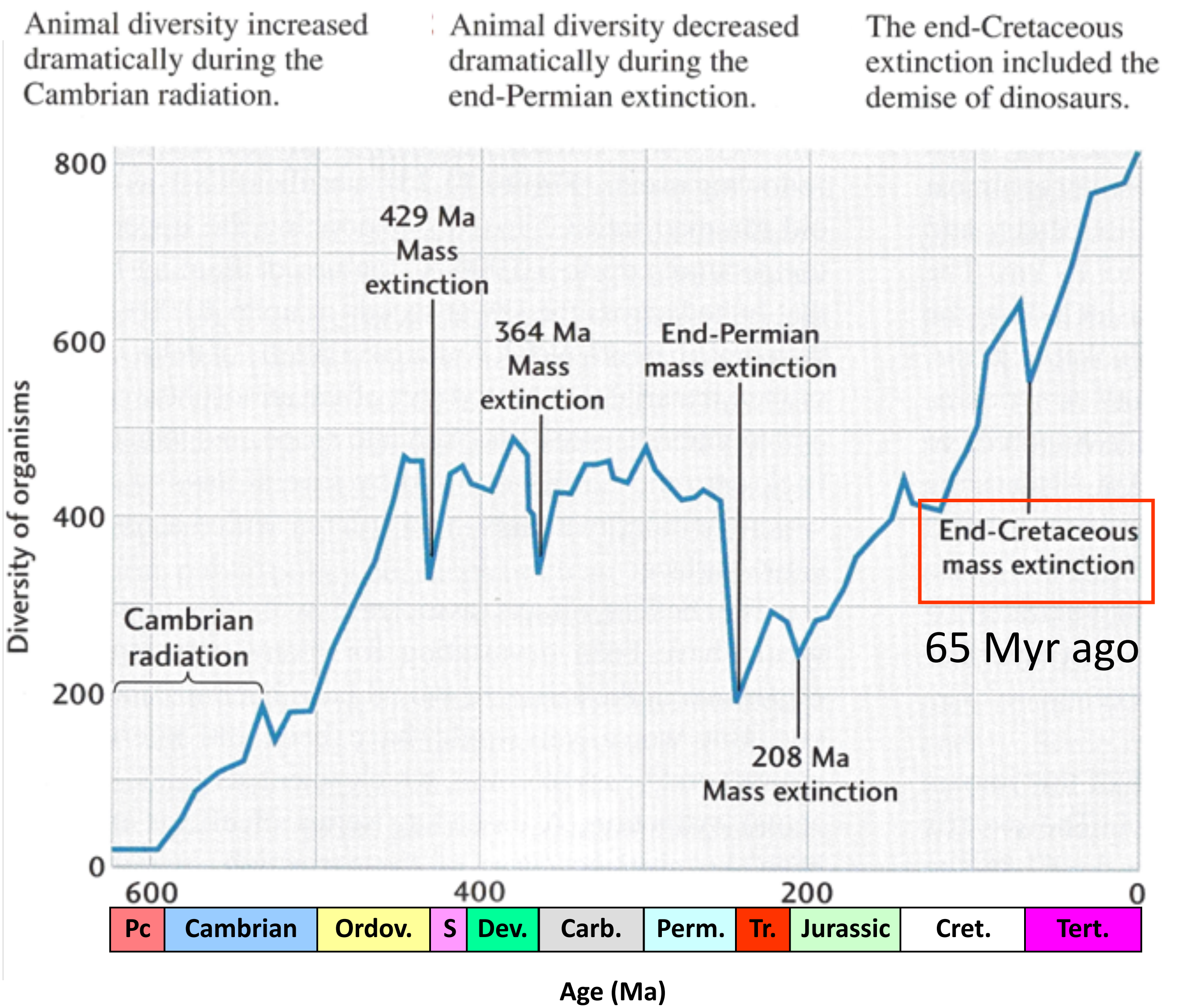
Anaerobic respiration using H_2 as e^- donor and CO_2 as e^- acceptor:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O + NRG$$

THERMOGENIC METHANE

Product of metamorphism of org. C-rich deposits.

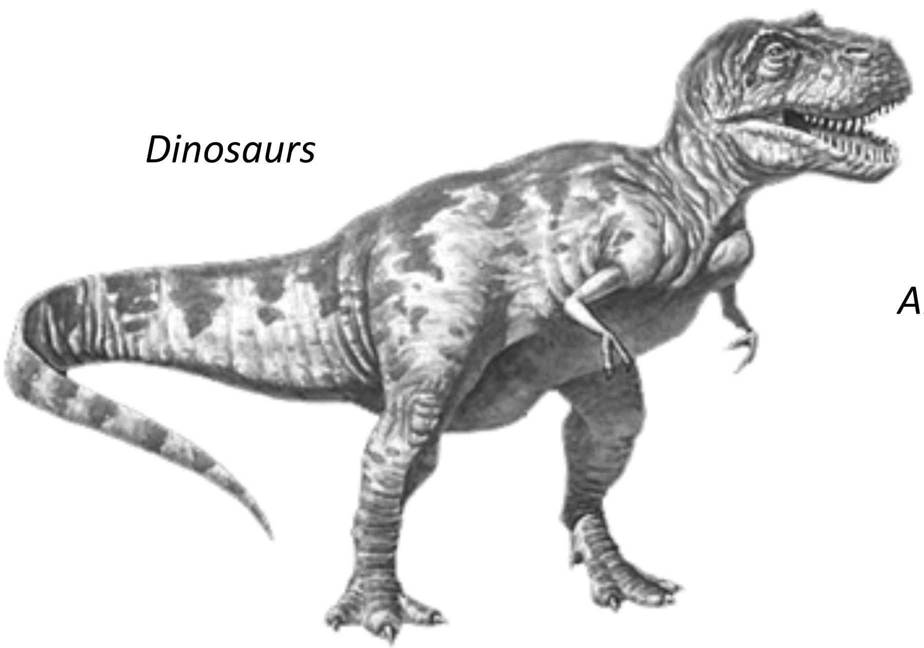
✶ End-Cretaceous mass extinction



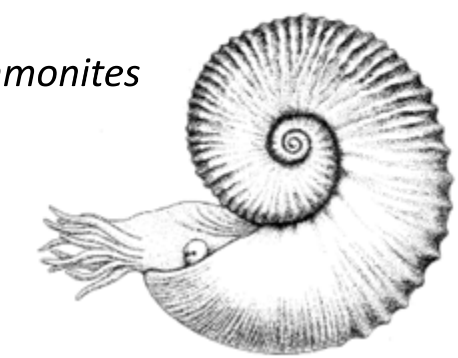
		End-Ordovician	End-Devonian	End-Permian	End-Triassic	End-Cretaceous
% of taxa extinct	Families	20-26	21-22	50-57	22-23	**15-16**
	Genera	50-60	47-57	70-83	40-53	**40-50**
	Species	85	70-80	85-96	76	**76**

Lethiers (1998)

Dinosaurs



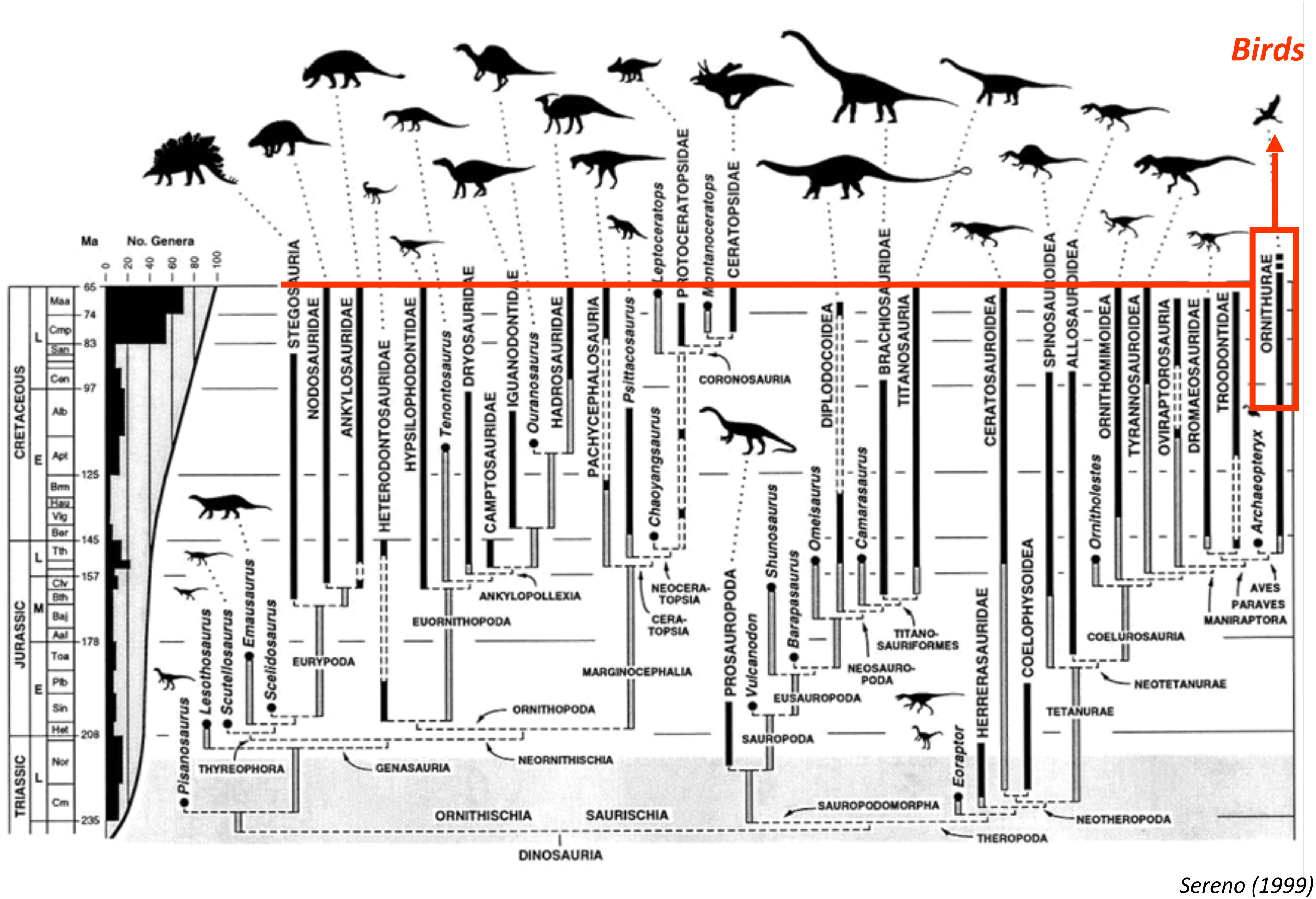
Ammonites



- **~75%** of all species went extinct
- **Marine** and **continental** life affected
- Very abrupt extinction

- The end-Cretaceous (K-T or K-Pg boundary) associated with a thin, **distinctive sedimentary layer** that can be traced worldwide.

By Kirk Johnson (Denver Museum of Nature and Science)

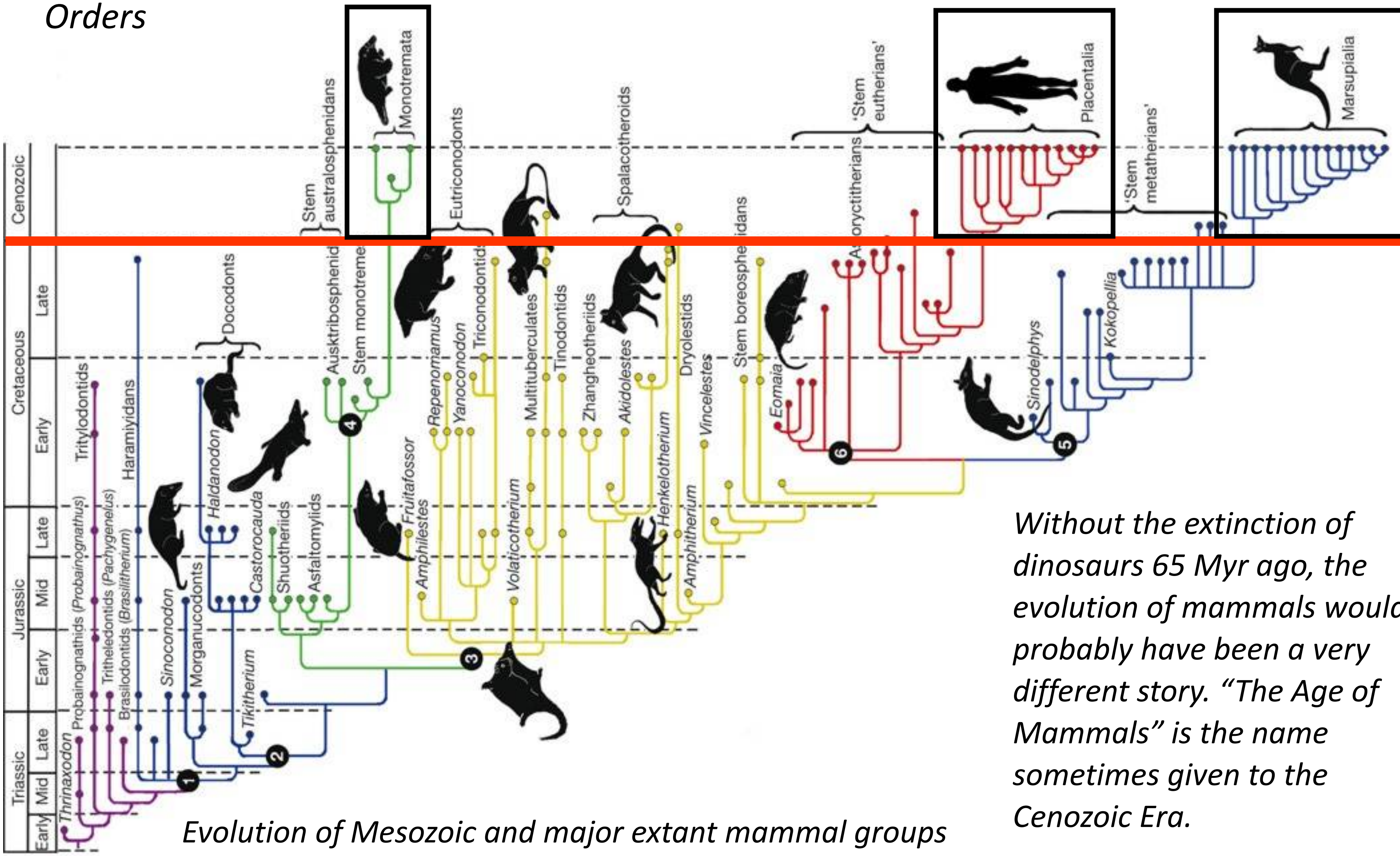

Birds
Ma
No. Genera
CRETACEOUS
JURASSIC
TRIASSIC
STEGOSAURIA
NODOSAURIDAE
ANKYLOSAURIDAE
HETERODONTOSAURIDAE
HYPSILOPHODONTIDAE
DRYOSAURIDAE
CAMPTOSAURIDAE
IGUANODONTIDAE
HADROSAURIDAE
PACHYCEPHALOSAURIA
PROTOCERATOPSIDAE
CERATOPSIDAE
DIPLODOCOIDEA
BRACHIOSAURIDAE
TITANOSAURIA
CERATOSAUROIDEA
SPINOSAUROIDEA
ALLOSAUROIDEA
ORNITHOMIMOIDEA
TYRANNOSAUROIDEA
OVIRAPTOROSAURIA
DROMAEOSAURIDAE
TROODONTIDAE
ORNITHURAE
PROSAUROPODA
HERRERASAURIDAE
COELOPHYSOIDEA
THYREOPHORA
GENASAURIA
EURYPODA
ORNITHOPODA
NEORNITHISCHIA
EUORNITHOPODA
ANKYLOPOLLEXIA
MARGINOCEPHALIA
CERATOPSIA
NEOCERATOPSIA
CORONOSAURIA
SAUROPODA
EUSAUROPODA
NEOSAUROPODA
TITANOSAURIFORMES
SAUROPODOMORPHA
THEROPODA
NEOTHEROPODA
TETANURAE
NEOTETANURAE
COELUROSAURIA
MANIRAPTORA
PARAVES
AVES
ORNITHISCHIA
SAURISCHIA
DINOSAURIA
Sereno (1999)

Mammalian Orders

Monotremata
Mammals laying eggs
(e.g. Platypus)

Placentalia

Marsupialia



Evolution of Mesozoic and major extant mammal groups

Without the extinction of dinosaurs 65 Myr ago, the evolution of mammals would probably have been a very different story. "The Age of Mammals" is the name sometimes given to the Cenozoic Era.

Luo (2007)

✶ End-Cretaceous mass extinction • *Large meteorite impact*

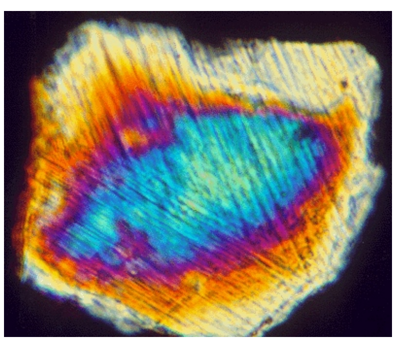
- A 10km-large **meteorite** impacted the Earth 65 Myr ago.

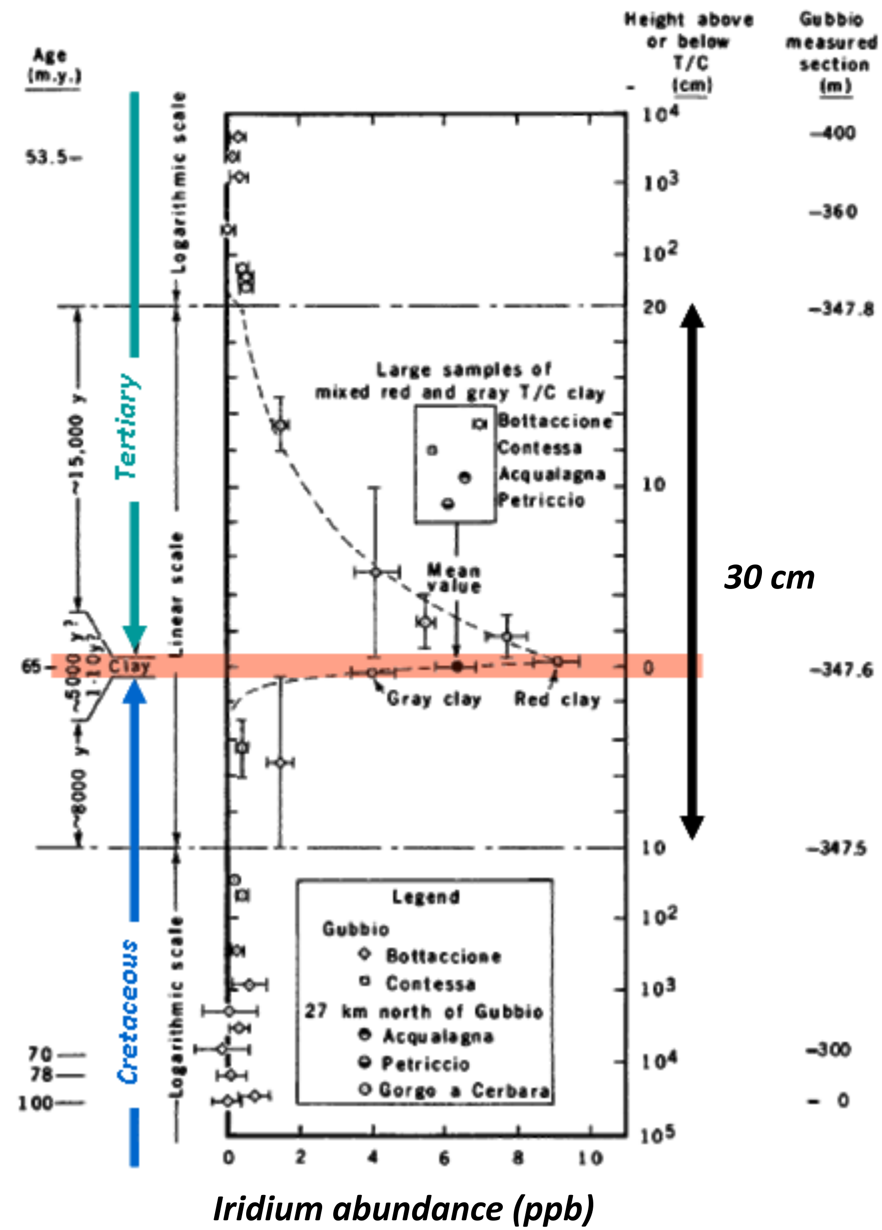
- **Main Evidence**

  An iridium peak at the K-T boundary around the world. Iridium abundance is very low in the Earth's crust and mantle, and comparatively very high in chondritic meteorites.

- **Other lines of evidence**

  shocked quartz, tektites, nanodiamonds…



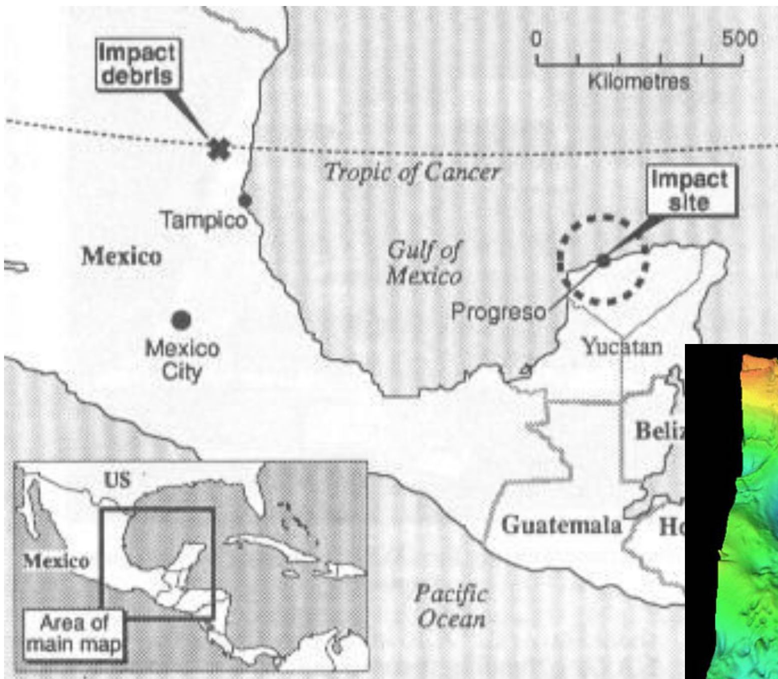


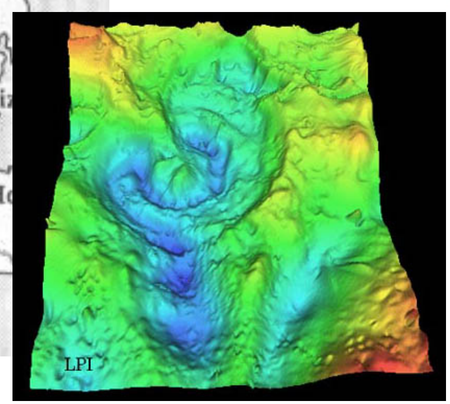
Alvarez et al. (1980)

- **Candidate crater** for the K/T impact:
  Chicxulub crater, Yucatan peninsula, Mexico

End-Cretaceous paleogeography

http://www2.nau.edu/rcb7/globehighres.html





Relief-shaded gravity anomaly data

Sharpton et al. (1993)

✶ End-Cretaceous mass extinction • *Consequences*

- **Nitric and sulfuric acid rains** (months or years; **global**)
  - Atmosphere is shock-heated and nitric oxide is produced
  - The site of the Chicxulub is rich in anhydrite ($CaSO_4$)*. Hence, sulfur-rich vapor was injected in the atmosphere due to the impact.

- **Short-lived global cooling** (months or years; **global**)
  - Sunlight is masked by dust and sulfate aerosols*: impact on photosynthesis (collapse of primary producers) and surface temperatures

- **Long-term global warming** (decades; **global**)
  - CO_2, CH_4, and water released by the impact and CO_2 produced by wildfires might have caused global warming after dust and aerosols had settled.

- **Wildfires** (extent debated)
  - Affecting an area maybe as large as the American continent
- **Ozone destruction** (years, **global**)
  - O_3 destroyed by heat and Cl and Br from the vaporized projectile.
- **Local and regional effects**:
  - Powerful earthquake (>11)
  - Gigantic tsunami (1-km high)
  - Heat pulse (10,000 °C at impact site)

TABLE 1. Suggested Mechanisms for K-T Extinctions

Agent	*Mechanism*	*Time-scale**	*Geographic Scale†*
Dust loading	cooling	Y	G
	cessation of photosynthesis	M	
	loss of vision	M	
Fires	burning	M	G
	soot cooling	M	
	pyrotoxins	M	
	acid rain	M	
NO_x generation	ozone loss	Y	G
	acid rain	M	R
	cooling	Y	G
Shock wave	high wind	I	R
Earthquakes	shaking	I	R
Tsunami	drowning	I	R
Heavy metals, etc.	poisoning	Y	G
Water/CO_2 injections	warming	D	G
SO_2 injections	cooling	Y	G
	acid rain	Y	G

*I, instantaneous; M, months; Y, years; D, decades.
†L, local; R, regional (10^6 km^2); G, global.

?

Toon et al. (1997)

Has the Earth's sixth mass extinction already arrived?

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Palaeontologists characterize mass extinctions as times when the Earth loses more than three-quarters of its species in a geologically short interval, as has happened only five times in the past 540 million years or so. Biologists now suggest that a sixth mass extinction may be under way, given the known species losses over the past few centuries and millennia. Here we review how differences between fossil and modern data and the addition of recently available palaeontological information influence our understanding of the current extinction crisis. Our results confirm that current extinction rates are higher than would be expected from the fossil record, highlighting the need for effective conservation measures.

Of the four billion species estimated to have evolved on the Earth over the last 3.5 billion years, some 99% are gone[1]. That shows how very common extinction is, but normally it is balanced by speciation. The balance wavers such that at several times in life's history extinction rates appear somewhat elevated, but only five times qualify for 'mass extinction' status: near the end of the Ordovician, Devonian, Permian, Triassic and Cretaceous Periods[2,3]. These are the 'Big Five' mass extinctions (two are technically 'mass depletions')[4]. Different causes are thought to have precipitated the extinctions (Table 1), and the extent of each extinction above the background level varies depending on analytical technique[4,5], but they all stand out in having extinction rates spiking higher than in any other geological interval of the last ~540 million years[3] and exhibiting a loss of over 75% of estimated species[2].

Increasingly, scientists are recognizing modern extinctions of species[6,7] and populations[8,9]. Documented numbers are likely to be serious underestimates, because most species have not yet been formally described[10,11]. Such observations suggest that humans are now causing the sixth mass extinction[10,12–17], through co-opting resources, fragmenting habitats, introducing non-native species, spreading pathogens, killing species directly, and changing global climate[10,12–20]. If so, recovery of biodiversity will not occur on any timeframe meaningful to people: evolution of new species typically takes at least hundreds of thousands of years[21,22], and recovery from mass extinction episodes probably occurs on timescales encompassing millions of years[5,23].

Although there are many definitions of mass extinction and gradations of extinction intensity[4,5], here we take a conservative approach to assessing the seriousness of the ongoing extinction crisis, by setting a high bar for recognizing mass extinction, that is, the extreme diversity loss that characterized the very unusual Big Five (Table 1). We find that the Earth could reach that extreme within just a few centuries if current threats to many species are not alleviated.

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