The Ancient Earth
Geology, Biology, & Evolution
Part I

BY CHARLES J. VELLA, PHD, 2024

Evolution during the Ancient Earth

- Lecture based on 25 documentaries: Netflix Life on Our Planet Earth, PBS Nova's Ancient Earth, and many Eons documentaries, and some Wikipedia data.
- After seeing these films, I realized I had little prior knowledge about how geology and climate on the ancient earth has influenced biological evolution.
- Highly recommend you see the documentaries for the visuals (& Morgan Freeman's voice narration).
- This lecture will summarize the scientific information they contain.
- Life's (via evolution) extraordinary journey to conquer, adapt and survive on Earth across billions of years

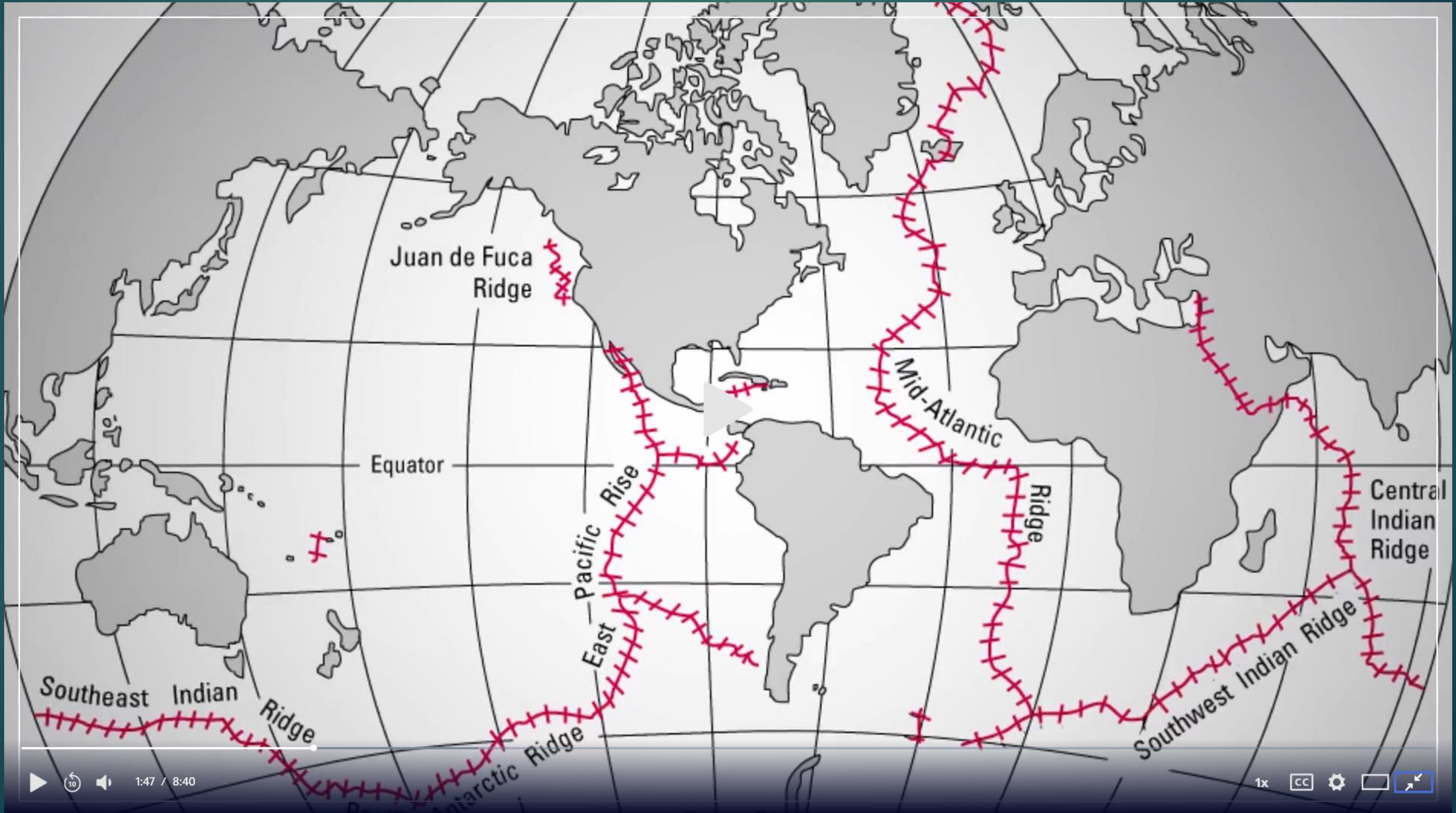
Life on earth in 1 hour

- Imagine all history of life on earth rolling out in 1 hour
- Total time = 4.5 Billion years
- First 50 minutes: microbes, single celled organisms
- Last 10 minutes = 500 Ma: animals
  - Mammals = 200 Ma
- Last 100th of second (last 7 Ma): All of human evolution

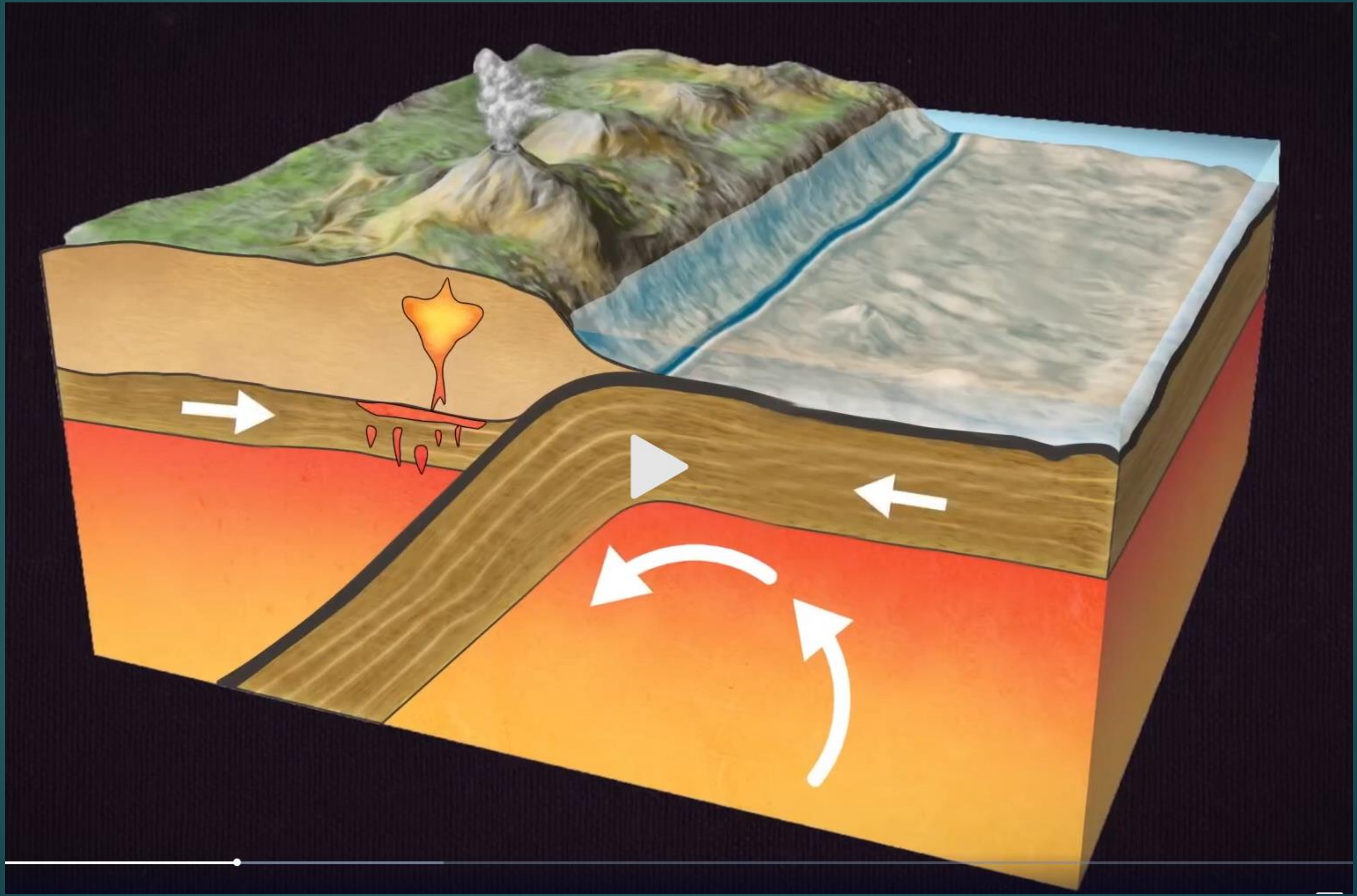
Geological/climactic recycling themes

- 2 major Extinction scenarios:
- Less CO_2 in atmosphere: More plants pull in more CO_2 which makes climate cold; planetary ice ages begin; less nutrients from rocks; less oxygen in ocean; extinction
- More CO_2 in atmosphere: planet warms up; plants dye; this adds more nutrients to ocean; algae blooms; eventually less oxygen; extinction
- We are now at beginning of 2nd cycle type

Continental Drift: active Atlantic Ridge discovered – volcanically active seafloor spreading; divergent plate boundary; creating more land; continents pushed away

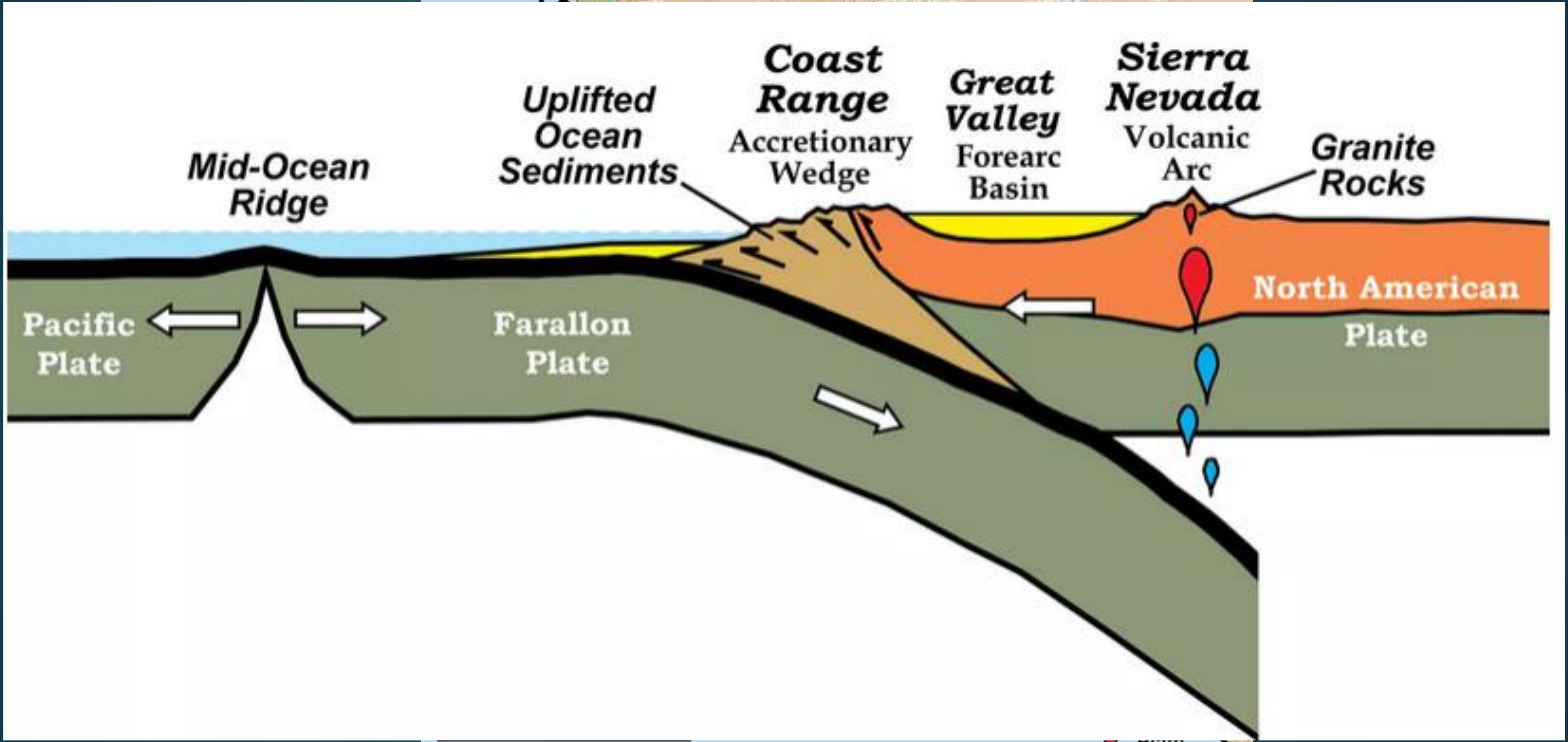


Convergent plate boundaries: Subduction zones & sea floor spreading = plate tectonics



Our 2 Plates

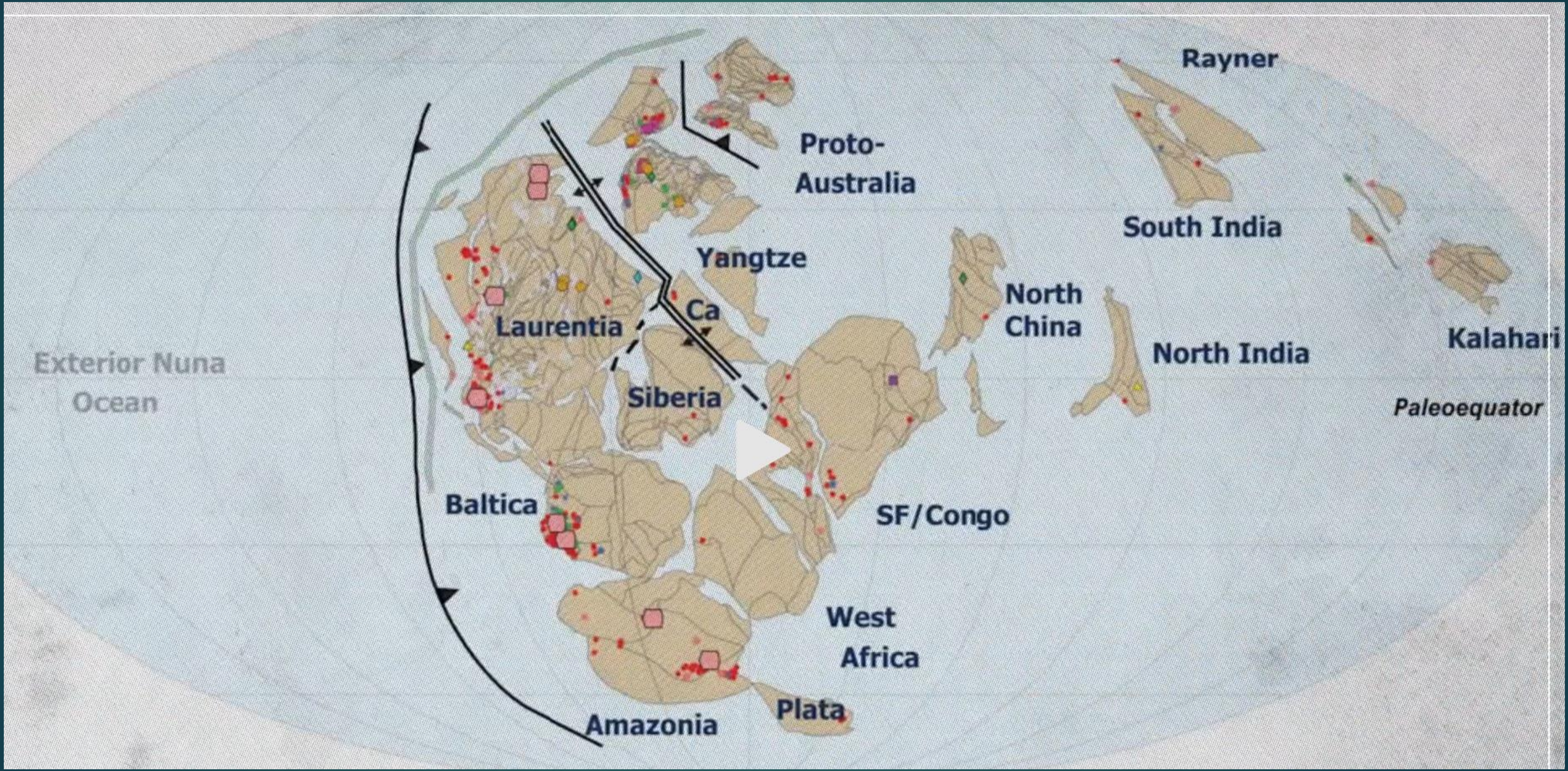
Juan de Fuca Plate
Cascadia Subduction Zone
North
Plate



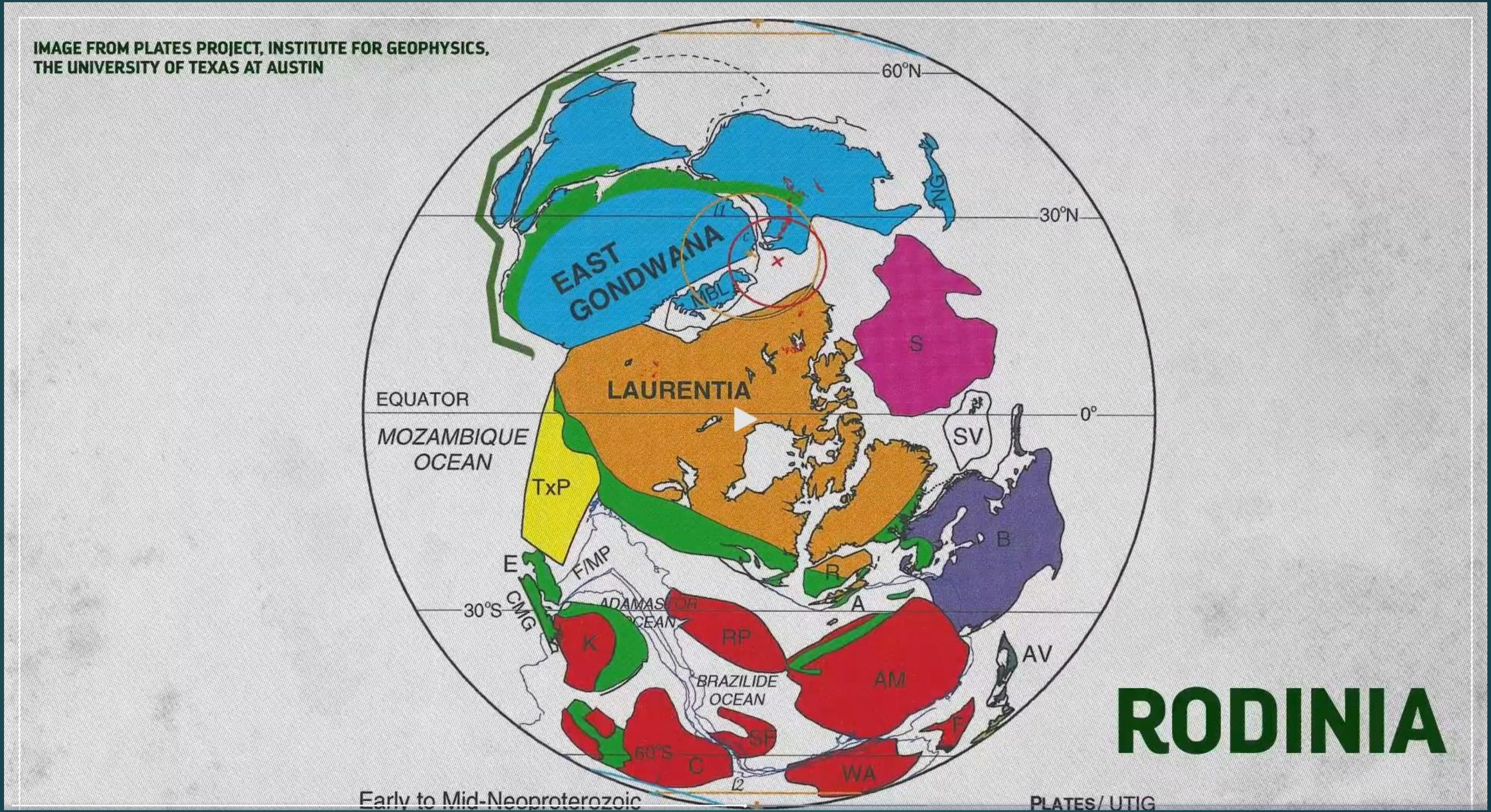
Mid-Ocean Ridge
Uplifted Ocean Sediments
Coast Range
Accretionary Wedge
Great Valley
Forearc Basin
Sierra Nevada
Volcanic Arc
Granite Rocks
Pacific Plate
Farallon Plate
North American Plate

Plate separation = Red Sea & African Rift Valley (Ethiopia)

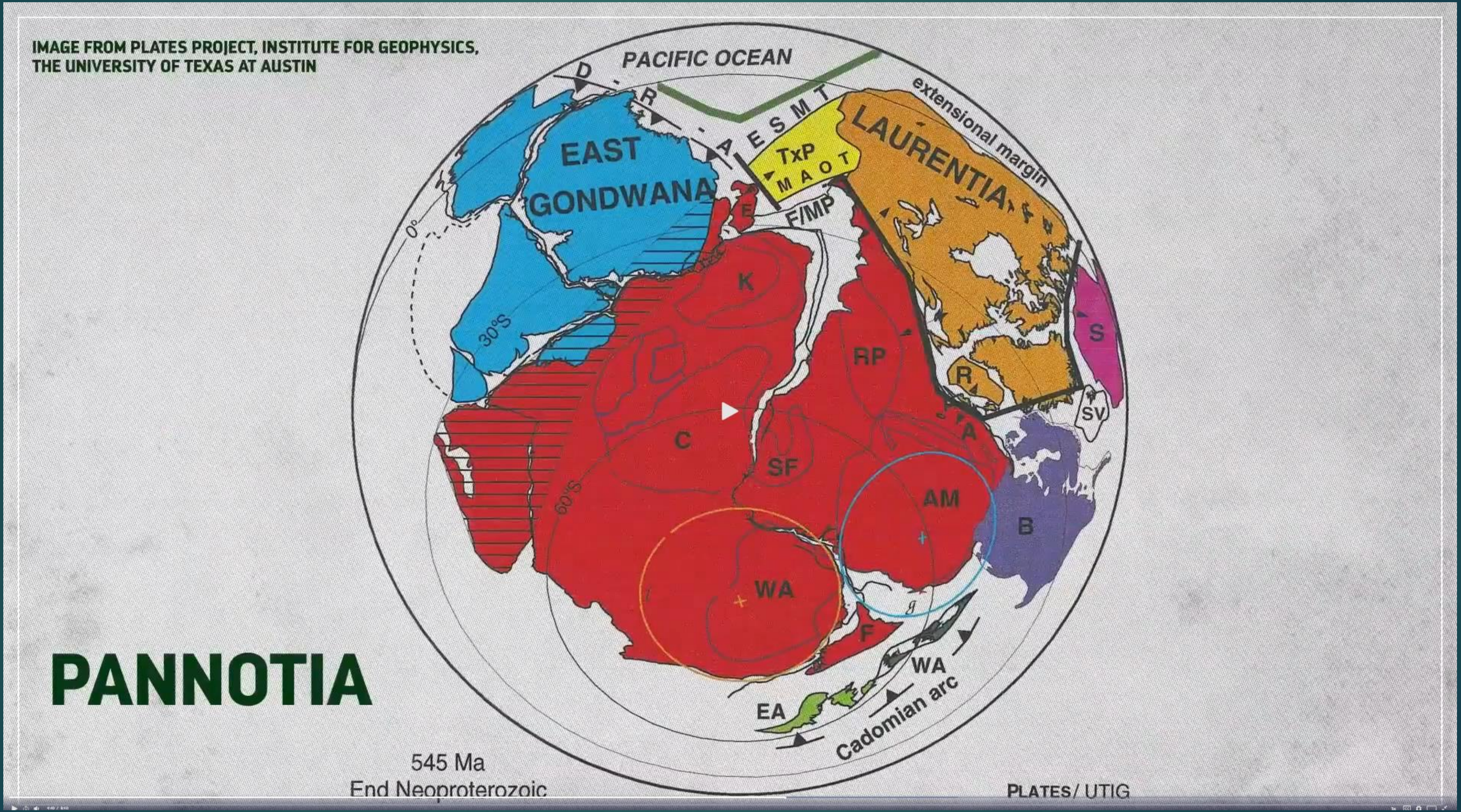
Supercontinents: Nuna, 1.8-1.4 Ga



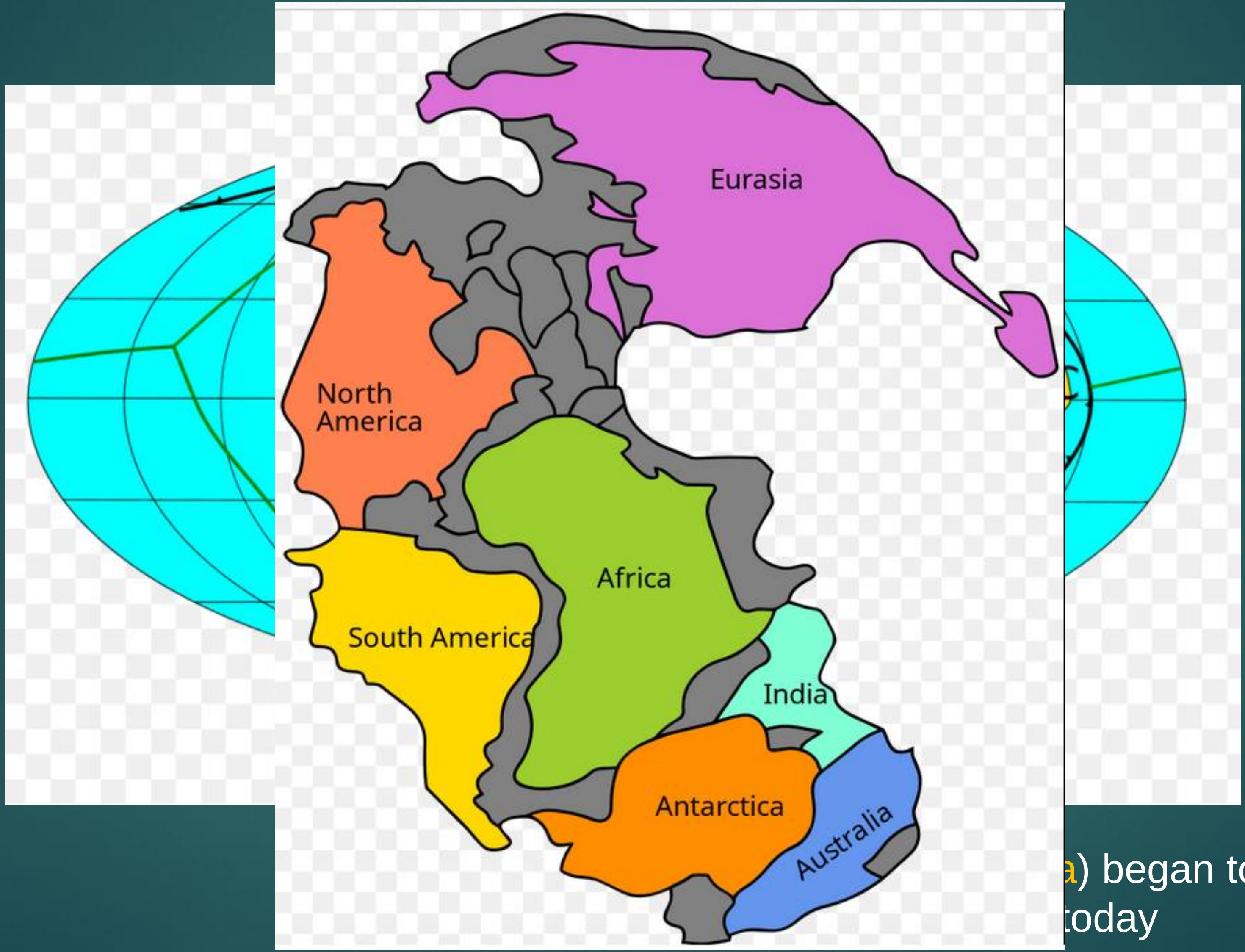
Rodinia, 1.3 Ga - 900 Ma



Pannotia, 546 Ma: 1st animals, Ediacaran & Cambrian



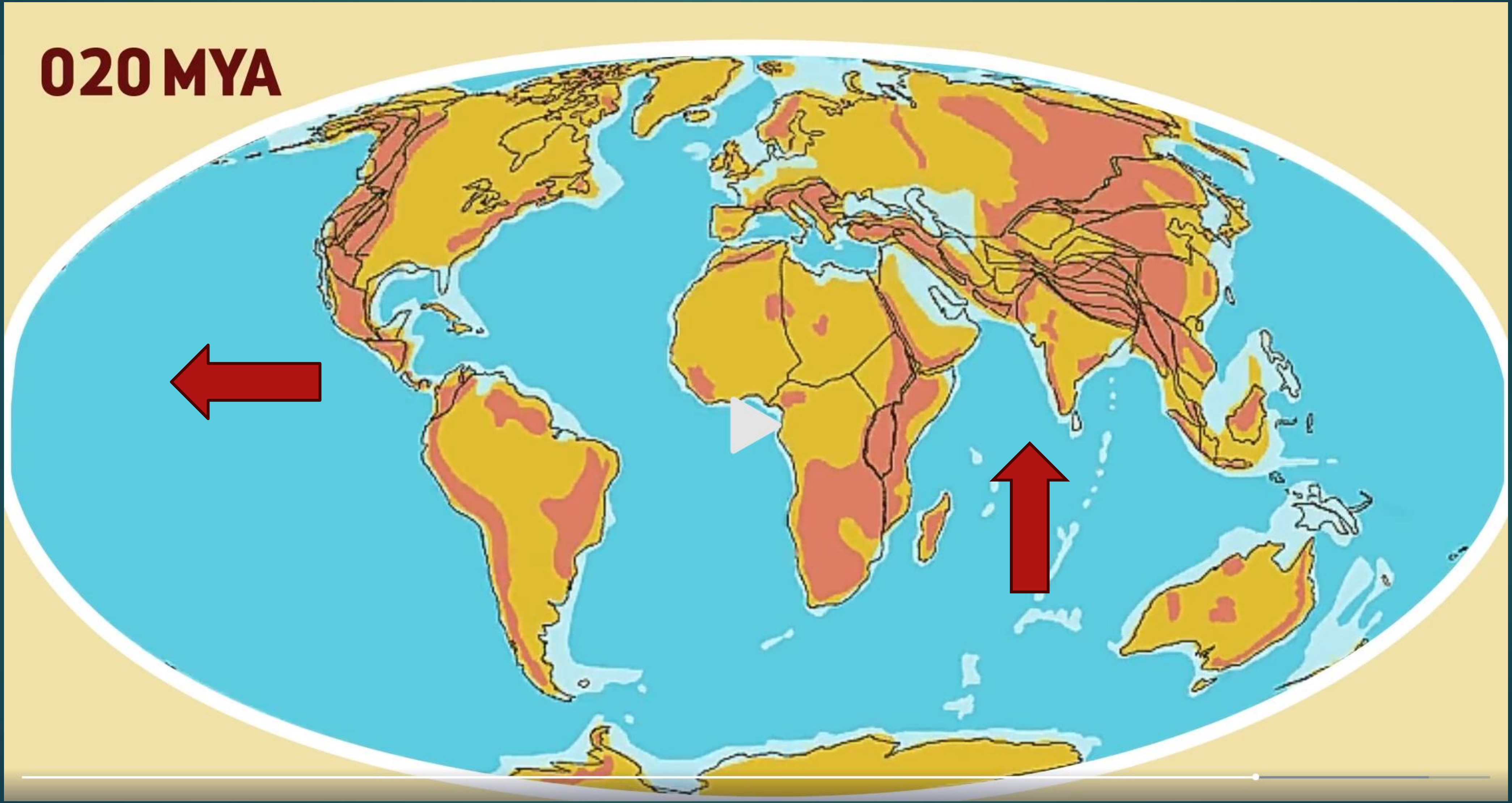
Supercontinent: Pangea



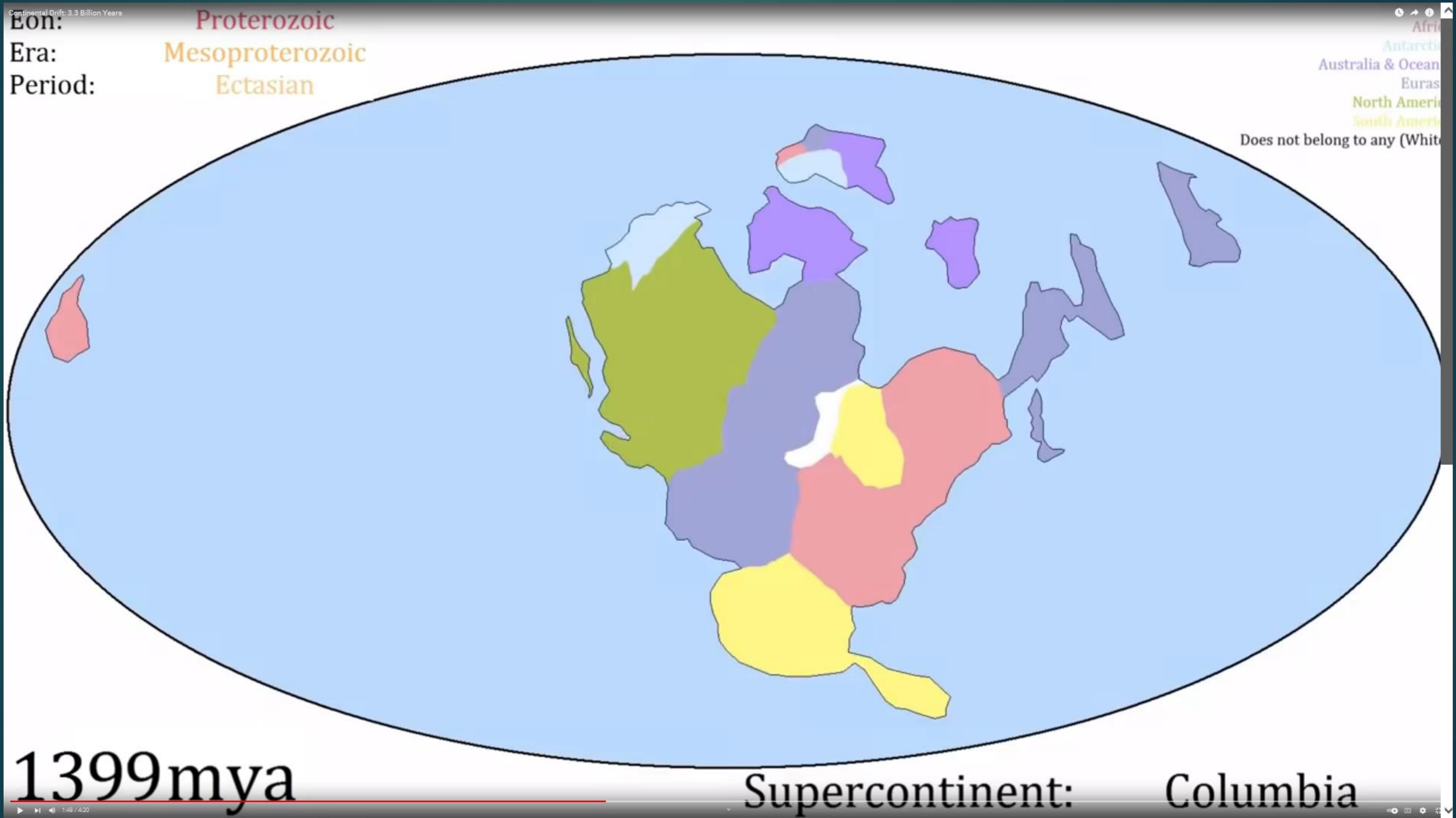
a) began to
today

Supercontinent name	Age (Ma)	Period/Era Range	Comment
Vaalbara	3,636–2,803	Eoarchean-Mesoarchean	Also described as a supercraton or just a continent[9]
Ur	2,803–2,408	Mesoarchean-Siderian	Described as both a continent[2] and a supercontinent[10]
Kenorland	2,720–2,114	Neoarchean-Rhyacian	Alternatively the continents may have formed into two groupings Superia and Sclavia[11][4]
Arctica	2,114–1,995	Rhyacian-Orosirian	Not generally regarded as a supercontinent, depending on definition[2]
Atlantica	1,991–1,124	Orosirian-Stenian	Not generally regarded as a supercontinent, depending on definition[2]
Columbia (Nuna)	1,820–1,350	Orosirian-Ectasian	[11]
Rodinia	1,130–750	Stenian-Tonian	[11]
Pannotia	633–573	Ediacaran	[11]
Gondwana	550–175	Ediacaran-Jurassic	From the Carboniferous, formed part of Pangaea,[4] not always regarded as a supercontinent[12]
Pangaea	336–175	Carboniferous-Jurassic	

Future: N and S America moving West; Africa and Australia moving North; Africa will crash into Europe: Super mountains



Continental Drift from 1.4 Ga – Alfred Wegener, 1912



Age of the Earth = 4.5 Ga

- Our earth is 4.543 ± 0.05 billion years old
- In northwestern Canada, they discovered rocks about 4.03 billion years old. Then, in Australia, they discovered minerals about 4.3 billion years old
- Both moon rocks and meteorite materials date, via radiometric uranium–lead isotope dating methods, to 4.4 and 4.5 billion years.
- Early studies of geological stratigraphy led to realization of how ancient the earth was. Continuous layering of rock from oldest at bottom to youngest at top.

Earliest life on earth

- The starting of life began as inorganic molecules that underwent a natural transformation (through electricity or heat) to become organic molecules. These building blocks joined to form macromolecule chains that eventually made up organisms.

- The earliest known life forms on Earth may be as old as 4.1 billion years old (or Ga) according to carbon graphite inside a single zircon grain in the Jack Hills range of Australia.

- The earliest undisputed evidence of life on Earth dates at least from 3.5 billion years ago, during the Eoarchean Era, after a geological crust started to solidify following the earlier molten Hadean Eon.

Earliest life

- The earliest evidence of life found in a stratigraphic layer unit, not just a single mineral grain, a biogenic substance, is the 3.7 Ga metasedimentary rocks containing graphite from the Isua Supracrustal Belt in Greenland.
- The earliest direct known life on land are microbial mat fossils, stromatolites which have been found in 3.5-billion-year-old geyserite uncovered in the Dresser Formation (sandstone) of the Pilbara Craton of Western Australia.
- According to one of the researchers, "If life arose relatively quickly on Earth … then it could be common in the universe."

Lithified stromatolites: Lake Thetis, Western Australia. Archean stromatolites are the first direct fossil traces of life on Earth. 3.5 Ga

Fossilized cyanobacteria

Evolution began ~3.5 to 3.8 billion years ago

- According to modern biology, the total evolutionary history from the beginning of life to today has taken place since 3.5 to 3.8 billion years ago, the amount of time which passed since the last universal common ancestor (LUCA) of all living organisms as shown by geological dating

- What were the right conditions for life to begin evolve?
  - Liquid water, energy from sun or deep ocean vents, right chemistry
  - And/or extraterrestrial input of amino acids.

Earliest life

- The oceans formed ~4.4 billion years ago
- A molecular clock model suggests that the LUCA may have lived 4.477—4.519 billion years ago, within the Hadean eon.
- In 2018, a study found that 4.5 billion-year-old meteorites found on Earth contained liquid water along with prebiotic complex organic substances that may be ingredients for life. All major amino acids have been found in meteorites.

Origin of life first, then evolution

- Evolution tells us nothing about the origin of life on Earth.
- Life must first originate and begin producing variation -- before natural selection can begin.
- So life must begin before evolution can begin.

Origin of Life

- One of the reasons for interest in the early atmosphere and ocean is that they form the conditions under which life first arose.

- There are many models, but little consensus, on how life emerged from non-living chemicals; chemical systems created in the laboratory fall well short of the minimum complexity for a living organism.

- The first step in the emergence of life may have been inorganic chemical reactions that produced many of the simpler organic compounds, including nucleobases and amino acids, that are the building blocks of life.

Miller & Urey experiment, 1953

- An experiment in 1953 by Stanley Miller and Harold Urey showed that such molecules could form in an atmosphere of water, methane, ammonia and hydrogen with the aid of electrical sparks to mimic the effect of lightning.
- Although atmospheric composition was probably different from that used by Miller and Urey, later experiments with more realistic compositions also managed to synthesize organic molecules.

Origin of Life

- Three possible starting points:
  - self-replication, an organism's ability to produce offspring that are similar to itself
  - metabolism, its ability to feed and repair itself; and
  - external cell membranes, which allow food to enter and waste products to leave, but exclude unwanted substances.

Replication first: RNA World

- All of life now uses DNA to replicate itself and a complex array of RNA and protein molecules to "read" these instructions and use them for growth, maintenance, and self-replication

- The discovery that a kind of RNA molecule called a ribozyme can catalyze both its own replication and the construction of proteins led to the hypothesis that earlier life-forms were based entirely on RNA.

RNA World

- They could have formed an RNA world in which there were individuals but no species, as mutations and horizontal gene transfers would have meant that the offspring in each generation were quite likely to have different genomes from those that their parents started with.

- RNA would later have been replaced by DNA, which is more stable and therefore can build longer genomes, expanding the range of capabilities a single organism can have.

Membrane first: iron-sulfur world

- Another long-standing hypothesis is that the first life was composed of protein molecules.

- Amino acids, the building blocks of proteins, are easily synthesized in plausible prebiotic conditions, as are small peptides (polymers of amino acids) that make good catalysts.

- Self-sustaining synthesis of proteins could have occurred near hydrothermal vents.

Clay theory

- Some clays, notably montmorillonite, have properties that make them plausible accelerators for the emergence of an RNA world: they grow by self-replication of their crystalline pattern, are subject to an analog of natural selection (as the clay "species" that grows fastest in a particular environment rapidly becomes dominant), and can catalyze the formation of RNA molecules.

- Although this idea has not become the scientific consensus, it still has active supporters

- Research in 2003 reported that montmorillonite could also accelerate the conversion of fatty acids into "bubbles", and that the bubbles could encapsulate RNA attached to the clay.

Geothermal springs

- Wet-dry cycles at geothermal springs: The temperatures of geothermal springs are suitable for biomolecules. Silica minerals and metal sulfides in these environments have photocatalytic properties to catalyze biomolecules.

- Solar UV exposure also promotes the synthesis of biomolecules like RNA nucleotides.

- An analysis of modern hydrothermal veins at a 3.5 Ga geothermal spring were found to have elements required for the origin of life, which are potassium, boron, hydrogen, sulfur, phosphorus, zinc, nitrogen, and oxygen.

Deep sea hydrothermal vents

- Catalytic mineral particles and transition metal sulfides at these environments are capable of catalyzing organic compounds.
- Exergonic reactions at hydrothermal vents are suggested to have been a source of free energy that promoted chemical reactions, synthesis of organic molecules, and are inducive to chemical gradients. Nucleobase synthesis could occur by following universally conserved biochemical pathways by using metal ions as catalysts.
- Small mineral cavities or mineral gels could have been a compartment for abiogenic processes.
- A genomic analysis supports this hypothesis as they found 355 genes that likely traced to LUCA upon 6.1 million sequenced prokaryotic genes.

Life "seeded" from space

- The Panspermia hypothesis does not explain how life arose originally, but simply examines the possibility of its coming from somewhere other than Earth. The idea that life on Earth was "seeded" from elsewhere in the Universe dates back at least to the Greek philosopher Anaximander in the sixth century BCE.
- There are three main versions of the "seeded from elsewhere" hypothesis: from elsewhere in our Solar System via fragments knocked into space by a large meteor impact, in which case the most credible sources are Mars and Venus; by alien visitors, possibly as a result of accidental contamination by microorganisms that they brought with them; and from outside the Solar System but by natural means.

LUCA

- LUCA: last universal common ancestor, from which all life descended = evolutionary mother of all planetary life on earth.
- It is believed that of this multiplicity of protocells, only one line survived. LUCA is not the first life. It is the cell that is the ancestor of all life on Earth today.
- It's process & product are still debated; took billion of years for real complexity, like first invertebrates, to develop. A perpetual evolutionary war with multiple dynasties.

- For 3 billion years life consisted of bacterial mats on the ocean floors

LUCA

- LUCA branched out: Archea – a prokaryote; Bacteria; and Eukaryotes (fungi): Eucaryotes are more related to Archea; we are Archea
- Genetic info surrounded by a membrane
- Can now examine genomes for old commonalities; search for minimal genome, least required for survival = 500-1600 genes (DNA, ribosome, metabolism)
- Comparison of Archea and Bacteria show some common genes (metabolize Hydrogen and CO^2) indicate deep sea vent connection
- Not all agree. Research goes on for LUCA.

Last universal common ancestor

- Current phylogenetic evidence suggests that the last universal ancestor (LUCA) lived during the early Archean eon, perhaps 3.5 Ga or earlier.
- It was probably a prokaryote, possessing a cell membrane and probably ribosomes, but lacking a nucleus or membrane-bound organelles such as mitochondria or chloroplasts. Like modern cells, it used DNA as its genetic code, RNA for information transfer and protein synthesis, and enzymes to catalyze reactions.
- Some scientists believe that instead of a single organism being the last universal common ancestor, there were populations of organisms exchanging genes by lateral gene transfer.

Extinction is the norm

- After the extinction of 99% of all lifeforms, today 10 million species of plants and animals – 1% of all that have existed
- It is estimated that over five billion species have gone extinct.
- Estimates on the number of Earth's current species range from 10 million to 14 million, of which about 1.2 million are documented, but over 86 percent have not been described.
- However, it was recently claimed that 1 trillion species currently live on Earth, with only one-thousandth of one percent described.

Sequence of Life

- Sequence of life in history of Earth:
  - Anaerobic organisms first
  - Production of oxygen
  - Plants and animals in the oceans and then on land;
  - then amphibians on land; with 4 limbs and backbone who still needed water;
  - then reptiles with dry land capability;
  - then dinosaurs (245 to 65.5 Ma) – 150 million years of stability
  - then birds and mammals

3 Rules of life on Earth

- 1 – Best adapted will survive: adaptation = natural selection
  - i.e. butterfly egg survival = eggs look identical but each are genetically unique; 1 may have a new variant mutation that enables better adaptation to the environment (for both survival & reproduction) and becomes new species = evolution by natural selection
  - But plants that butterflies feed on also evolve in defending themselves from caterpillars; chemical warfare of plants vs butterflies; poison in the leaves that kill caterpillars or growths that mimic bf eggs with nectar that attracts ants which feed on caterpillars
  - First rule produces tremendous variation on which natural selection works

- 2 – Competition drives adaptation – most competition from one's own kind; between and within species competition drives evolution

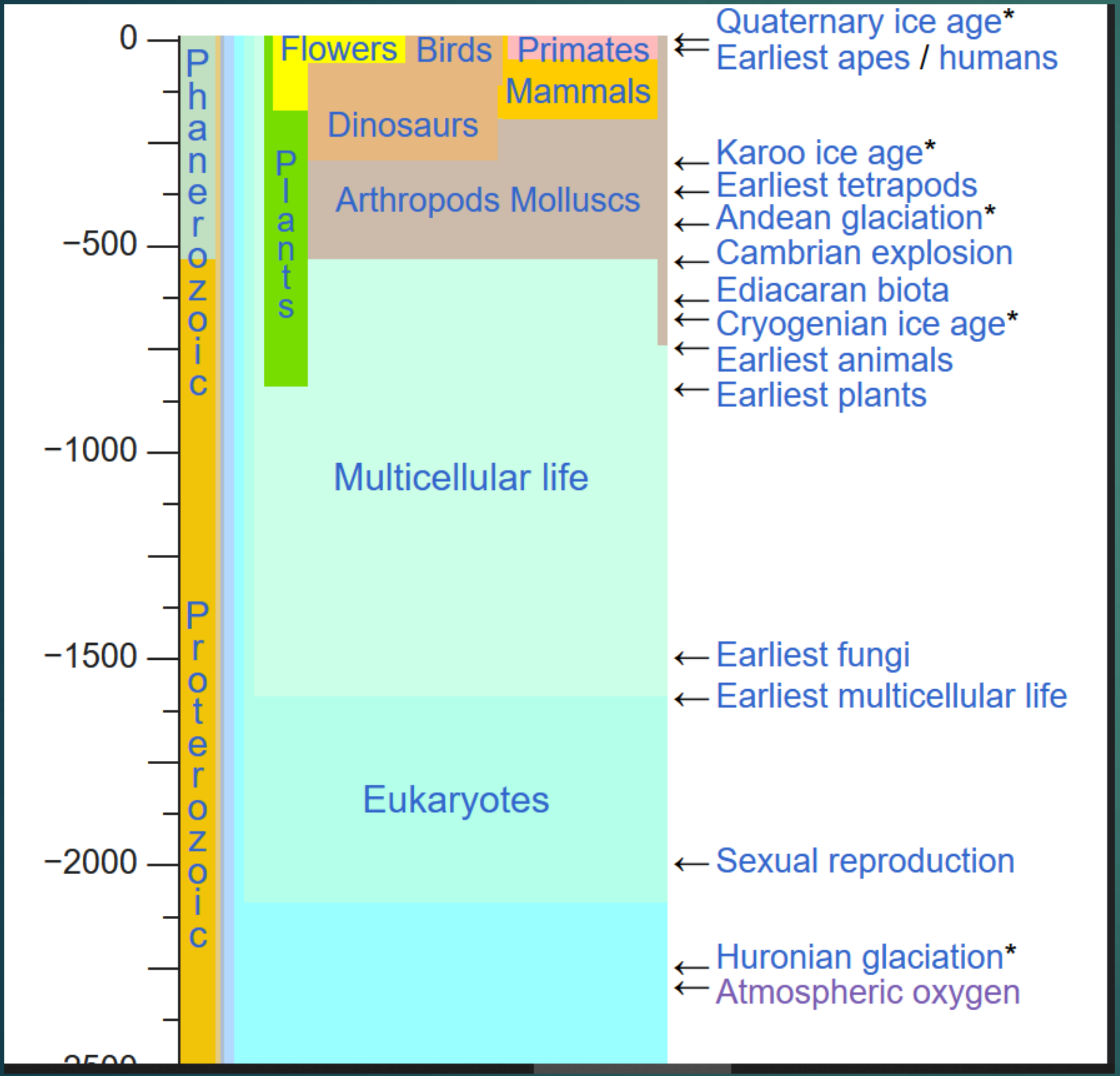
3 Rules of life on Earth

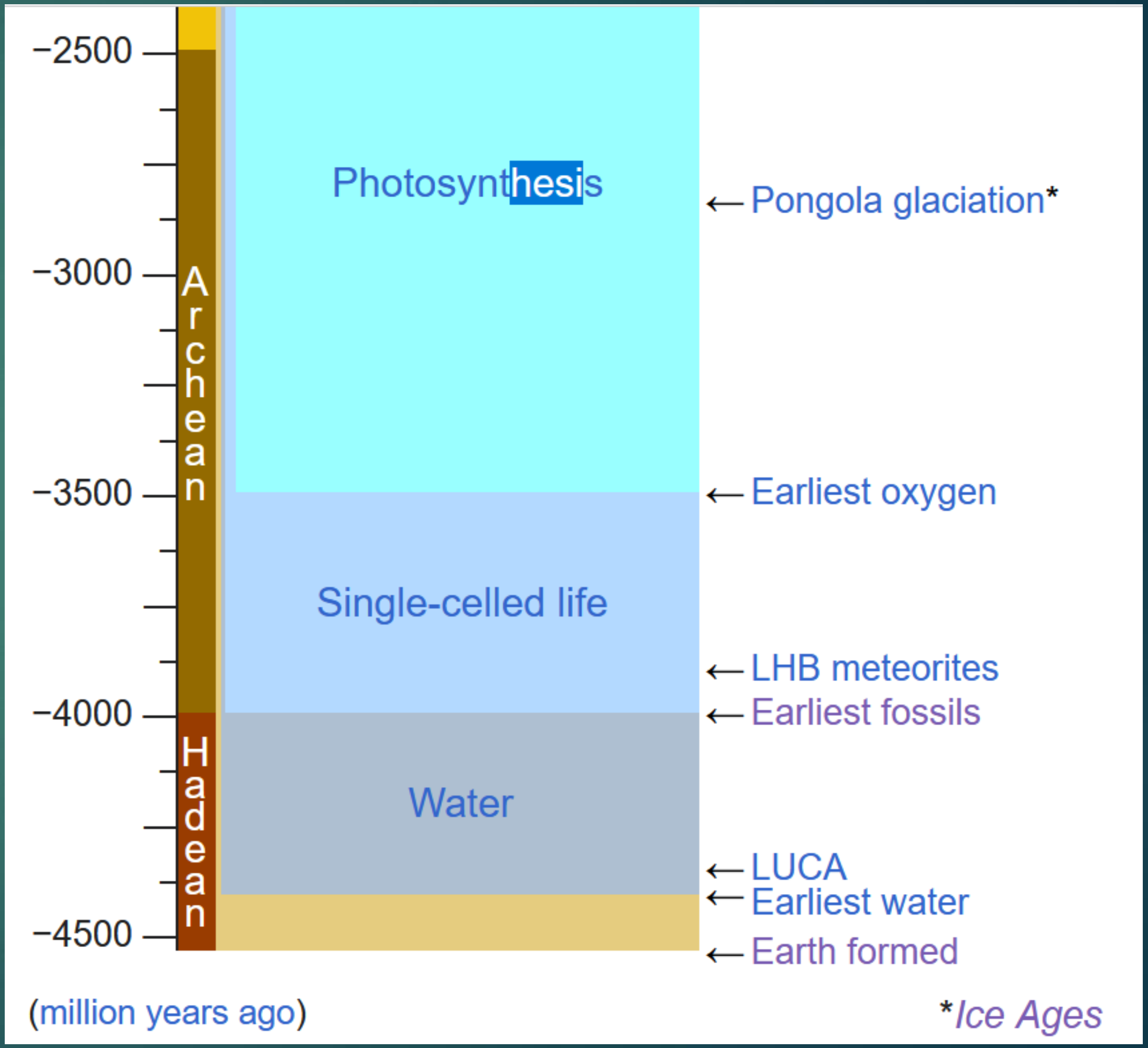
- 3 – Geology of the earth never stays stable; geological change is constant and both helps and hinders life on the plant
  - Supercontinents and tectonic plate movements
  - Volcanoes have been one of greatest agents for biological change; eruptions that last 1000s to millions of years; toxic gas releases, causing climate change; producing mass extinctions
  - Climate challenges include fire, ice, toxic seas and atmosphere, endless rain periods; ice sheets; global waste lands
  - Geological changes have triggered significant biological evolution. The two are fundamentally interlaced.
  - Global mass extinction events = 75%+ of life have been extinguished at least five major times and multiple minor times

Eons

- The Hadean eon represents the time before a reliable (fossil) record of life; it began with the formation of the planet and ended 4.0 billion years ago.
- The following Archean and Proterozoic eons produced the beginnings of life on Earth and its earliest evolution.
- The succeeding eon is the Phanerozoic, divided into three eras:
  - Paleozoic, an era of arthropods, fishes, and the first life on land
  - Mesozoic, which spanned the rise, reign, and climactic extinction of the non-avian dinosaurs;
  - Cenozoic, which saw the rise of mammals.
- Recognizable hominins emerged at most 2 million years ago, a vanishingly small period on the geological scale.

Life Timeline





4 Major Geological Eras – A quick tour
Hadean: 4.54-4.0 Ga

- Hadean Eon: 4.54-4.0 Ga
- The Earth is formed out of debris around the solar protoplanetary disk.
- There are no fossils; only organic carbon
- Temperatures are extremely hot, with frequent volcanic activity and hellish-looking environments, with a mostly molten surface (hence the eon's name, which comes from Hades) and mass impacts.
- The original atmosphere is nebular.
- Early ocean or bodies of liquid water.
- The Moon is formed around this time; probably due to a protoplanet's collision into Earth.

Archean: 4.0 to 2.5 Ga

- Archean: 4.0 to 2.5 Ga:
- The atmosphere is composed of volcanic and greenhouse gases (CO2).
- Bacterial mats in oceans; stromatolites
- Prokaryote life, the first form of life, emerges at the very beginning of this eon, in a process known as abiogenesis (life from inorganics). Prokaryotes are microscopic organisms belonging to the domains Bacteria and Archaea. (Eukarya, the third, contains all eukaryotes, including animals, plants, and fungi.) Bacteria and archaea are single-celled, while most eukaryotes are multicellular.
- The first continents of Ur, Vaalbara and Kenorland may have existed around this time.

Tectonic plates at 3 Ga

- Mantle convection, the process that drives plate tectonics, is a result of heat flow from the Earth's interior to the Earth's surface. It involves the creation of rigid tectonic plates at mid-oceanic ridges. These plates are destroyed by subduction into the mantle at subduction zones.

- During the early Archean (about 4.0 Ga) the mantle was much hotter than today, so convection in the mantle was faster.

- Plate tectonics would have gone faster too. It is likely that during the Hadean and Archean, subduction zones were more common, and therefore tectonic plates were smaller.

Continents, 4 Ga

- The initial crust, formed when the Earth's surface first solidified, totally disappeared from a combination of this fast Hadean plate tectonics and the intense impacts of the Late Heavy Bombardment. However, it is thought that it was basaltic in composition, like today's oceanic crust,

- The first larger pieces of continental crust, which is a product of differentiation of lighter elements during partial melting in the lower crust, appeared at the end of the Hadean, about 4.0 Ga.

- What is left of these first small continents are called cratons. These pieces of late Hadean and early Archean crust form the cores around which today's continents grew.

Proterozoic: 2.5 Ga to 539 Ma

- The name of this eon means "early life".
- Eukaryotes, a more complex form of life, emerge, including some forms of multicellular organisms.
- Bacteria begin producing oxygen (cyanobacteria with photosynthesis; extinguishes all prior anaerobic life), shaping the third and current of Earth's atmospheres.
- Plants, later animals and possibly earlier forms of fungi form around this time.
- The early and late phases of this eon may have undergone "Snowball Earth" periods, in which all of the planet suffered below-zero temperatures.
- The early continents of Columbia, Rodinia and Pannotia, in that order, may have existed in this eon.

Avalon Explosion: 575 Ma in the Ediacaran period

- Multicellular life 33 M years before Cambrian – 270 species
- Post Cryogenian Period (720-635 Ma) – rock nutrients, mass blooms of cyanobacteria in oceans; more oxygen; then at 575 Ma, the Avalon Explosion
- 560-575 Ma on Avalon peninsula, 1000s of Precambrian fossils; rangeomorphs with fractal branching growth; some organisms with trilateral and bilateral symmetry; muscles; sensory organs
- 542 Ma: end of Ediacaran period

Phanerozoic Eon, 541-present;
Paleozoic: 541 to 252 Ma: From Cambrian to Great Dying

- Cambrian: 541 to 485 Ma: evolutionary innovation – oxygen levels up; all major animals today developed in 1st 40 Ma years of Cambrian, incl. 1st eye, calcified hard parts, flexible limbs; 1st predatory organisms; exoskeletons in arthropods

- Mass extinction at 488 Ma: Cambrian-Ordovician Extinction; oxygen crash; loss of trilobites

Paleozoic: 541 to 252 Ma

- Ordovician, 485-443: Great Ordovician Biodiversification Event for 40 M years; continental movement at 470 Ma: 1st fish; 6-meter Cameroceras cephalopod and Nautiloids; 1st land plants – took in so much CO^2 that it led to ice age at 444 Ma

- Carboniferous, 359-298 Ma: atmospheric Oxygen up; swamps and dense forests

Paleozoic – 541-252 Ma

- Ordovician-Silurian Extinction Event – 86% of marine species die = Great Dying;

- Silurian: 443-420 Ma: warming occurs, plants increase; 1st vascular plants like Cooksonia, 1st terrestrial fungi; 1st jawed fish; then drop in sea levels

- Devonian: 419-358 Ma: vertebrate fish take over seas; Placoderms (armored fish); 1st sharks; Dunkleosteus; arthropods on land -1st insects; Trees – 1st terrestrial ecosystems; lobe-fin fish in shallows; at 397 Ma, hauled themselves onto land; by 365, Ma tetrapods across entire globe

Paleozoic

- 2 Phase Late Devonian Extinctions, 375-358 Ma: drop in oxygen levels in sea; trilobites disappear
- Carboniferous, 358-298 Ma: oxygen up; humid warm climate; arthropods get huge; Tetrapods start laying eggs with shells on land at 340 Ma; formation of Pangaea – moisture could not reach inland – drop in humidity wipes out forests at 305 Ma (Carboniferous Rain Forest Collapse), replaced by giant desert mid continent; Tetrapods split into synapsids (stem mammals) and reptiles
- Permian, 299-251 Ma: Tetrapods spread across Pangaea; 1st large herbivores; then got hotter and drier; Gorgonopsids
- Permian-Triassic Extinction, 252 Ma: via volcanic activity and climate change; 96% of marine life and 70% of land animals extinguished

Phanerozoic: 538 Ma to present

- Complex life, including vertebrates, begin to dominate the Earth's ocean in a process known as the Cambrian explosion.
- Pangaea forms at 299 Ma (with desert at center) and later breaks up into Laurasia and Gondwana, which in turn dissolve into the current continents.
- Gradually, life expands to land and familiar forms of plants, animals and fungi begin appearing, including worms, insects and reptiles, hence the eon's name, which means "visible life".
- Several mass extinctions occur, among which birds, the descendants of non-avian dinosaurs, and more recently mammals emerge.
- Modern animals—including humans—evolve at the most recent phases of this eon.

Insects, 400 Ma

- The earliest fossils of insects have been found in Early Devonian rocks from about 400 Ma, which preserve only a few varieties of flightless insect.

- The Mazon Creek lagerstätten from the Late Carboniferous, about 300 Ma, include about 200 species, some gigantic by modern standards, and indicate that insects had occupied their main modern ecological niches as herbivores, detritivores and insectivores.

- Social termites and ants first appeared in the Early Cretaceous, and advanced social bees have been found in Late Cretaceous rocks but did not become abundant until the Middle Cenozoic.

Insects

- 10 Quintillion (18 zeros) insects today
- 350 Ma: some giant insects; 28-inch dragonfly-like insect
- Arthropuera – 100 lb millipede
- Size related to oxygen at 35%; large size until about 305 Ma when oxygen reduced

385 Ma: When fish first breathed air

- Devonian, 419-358 Ma:
- 385 Ma:
  - Lobe-finned fish; Icthyostega at 364 Ma– like salamander; moved with front legs;
  - Tiktaalick at 375 MA with stiff leg-like fins – classic transitional fossil;
  - All these had gill arches; big hole on face; primitive lungs developed; from swim bladders with blood vessels that supplied oxygen; eventually nostrils
- Drop of Oxygen in ocean; plants dying on land; added nutrients to ocean; algae blooms; eventually less atmospheric oxygen

When insects learned to fly

- Rhyniognatha Hirsti, 400 Ma – sflying insect or centipede?
- Delitzschala bitterfeldensis: debate = 25 Ma – a mayfly
- Hexapoda gap, 380-325 Ma: few fossils
- Carboniferous: Flying insects take off
- 2014 study: molecular clock – 406 Ma for Butterflies; 1st insect at 440 Ma
- 1st fossil wings: 325 Ma
- Wings: Origin as gill structures or as totally new structure
- No universally accepted theory

Hadean Eon: Hellish, 4.5 Ga

- The first eon in Earth's history, the *Hadean*, 4.5 Ga, begins with the Earth's formation and is followed by the *Archean* eon at 3.8 Ga.
- The giant impact hypothesis for the Moon's formation states that shortly after formation of an initial crust, the proto-Earth was impacted by a smaller protoplanet the size of Mars (named Theia), which ejected part of the mantle and crust into space and created the Moon.

Creation of the Earth

- In a process known as runaway accretion, successively larger fragments of dust and debris clumped together to form planets.
- Earth formed in this manner about 4.54 billion years ago and was largely completed within 10–20 million years.
- In June 2023, scientists reported evidence that the planet Earth may have formed in just three million years, much faster than the 10−100 million years thought earlier

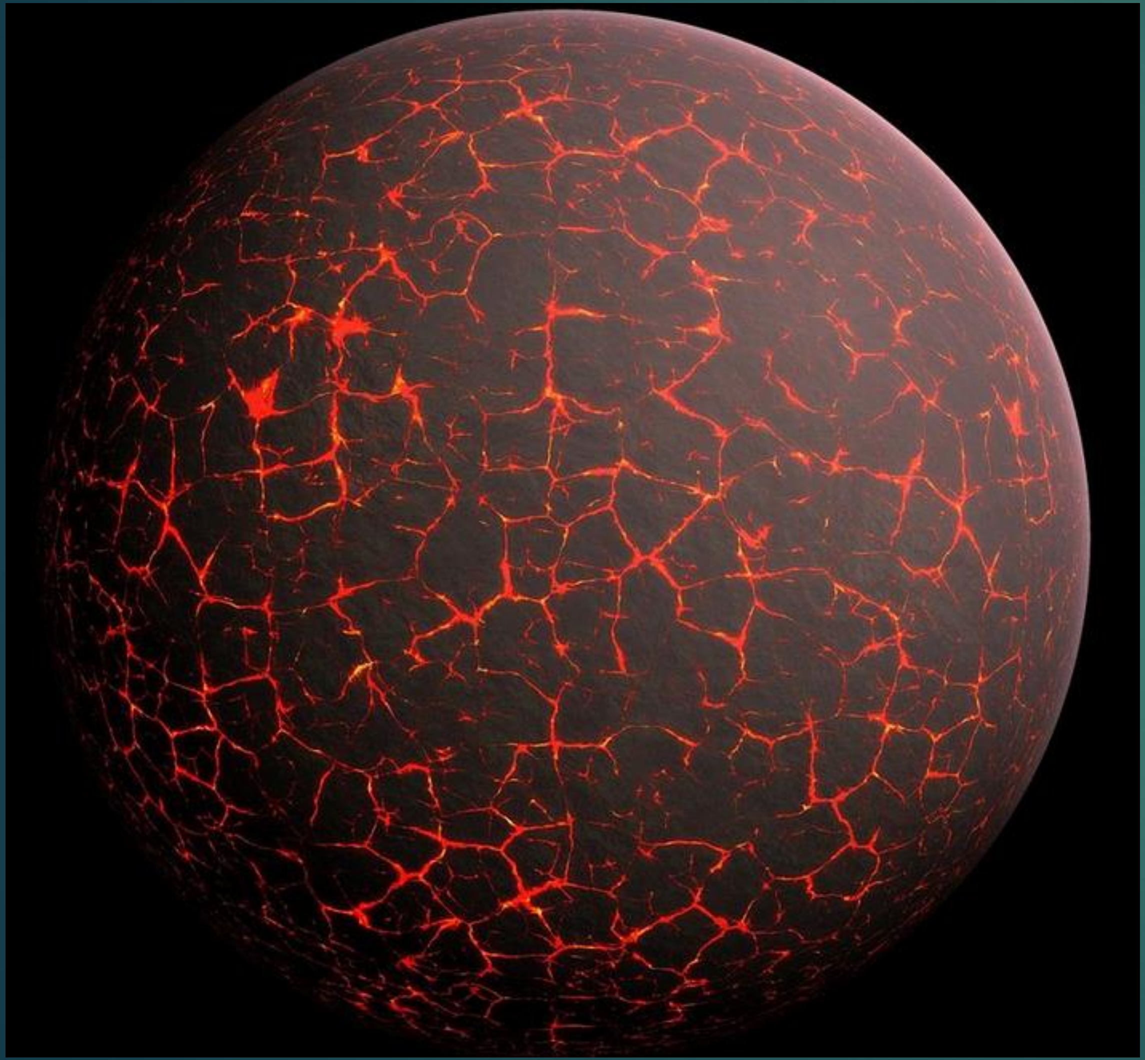
Creation of Earth

- The proto-Earth grew by accretion until its interior was hot enough to melt the heavy, iron metals.

- Having higher densities than the silicates, these metals sank. This so-called *iron catastrophe* resulted in the separation of a primitive mantle and a (metallic) core only 10 million years after the Earth began to form, producing the layered structure of Earth and setting up the formation of Earth's magnetic field.

- This magnetic field protects our planet from cosmic radiation and from the charged particles emitted by our Sun

Hadean Epoch & Creation of Moon (4.5 Ga)



Hadean

- From crater counts on other celestial bodies, it is inferred that a period of intense meteorite impacts, called the *Late Heavy Bombardment*, began about 4.1 Ga, and concluded around 4.0 Ga, at the end of the Hadean.

- In addition, volcanism was severe due to the large heat flow and geothermal gradient (lower is hotter).

- Nevertheless, zircon crystals dated to 4.4 Ga show evidence of having undergone contact with liquid water, suggesting that the Earth already had oceans or seas at that time.

- Recent measurements of the chemical composition of Moon rocks suggest that Earth was born with its water already present.

Hadean landscape with Moon in background

Birth of the Sky

- Hadean Epoch: 4.5 Ga – utterly desolate rock and volcanic activity; lava; meteors and asteroids bombarding from above; extremely hot; initially no atmosphere; UV radiation and solar radiation; inhospitable to life

- Much of the Earth was molten because of frequent collisions with other bodies which led to extreme volcanism.

- Over time, the Earth cooled, causing the formation of a solid crust, and allowing liquid water on the surface.

- Volcanic outgassing probably created the primordial atmosphere and then the ocean, but the early atmosphere contained almost no oxygen. Atmosphere = 2000 degrees F

Nova - Ancient Earth: Birth of the Sky

- How did our familiar blue sky – the thin, life-giving band of gasses protecting our planet – come to be?

- Earth's current atmosphere: like skin thickness on an apple; 8000-mile diameter & 60 miles of atmosphere; composed of oxygen, carbon dioxide, nitrogen, ozone (which protects us from UV); insulates us from cold of space

Our blue 60-mile thick atmosphere

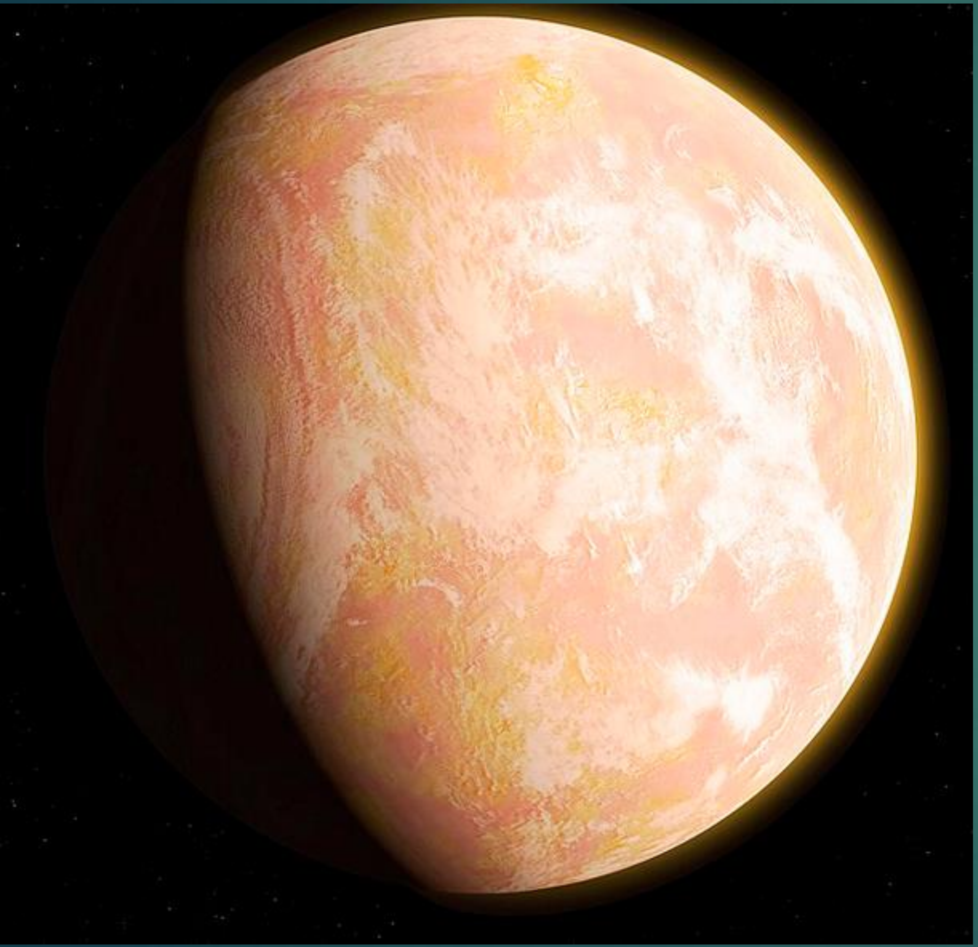
Atmosphere, 4.4 Ga

- Hadean earth: volcanic eruptions with multiple gases: carbon dioxide, nitrogen, methane, water vapor = 1st atmosphere (their chemical fingerprints trapped in rocks)

- Dating via study of rocks: meteorites/chondrites at 4.5 Ga

- First atmosphere was likely orange haze via methane (and carbon monoxide, water vapor, nitrogen, cyanide). No oxygen. No liquid water yet.

Earth with hazy orange methane-rich prebiotic atmosphere



First water

- Today 71% of planet is water; 366 trillion galleons of water
- Most water is in rocks: Minerals have 18 x amount of water in oceans
- Moon Europa: is quarter of our size, but has 2 x as much water
- Original earth material: iron, silica, oxygen (most common element on planet due to reactivity) but not hydrogen

Water

- Origination of liquid water: Hydrogen and water vaper via minerals in asteroids and meteorites (chondrites); in Hadean, they melted when hit molten earth and accumulated in the mantle; and Hydrogen finally met Oxygen, forming water vapor gas which entered the high atmosphere

- 4.4 Ga: earliest rocks had been in contact with ocean.

- Earth's heat radiates out into space and a cooling begins. A deluge of rain begins to pour to surface. Oceans of superheated water. Key life ingredient.

- Original water is still constantly recycled.

Archean, 4 Ga

- By the beginning of the Archean, the Earth had cooled significantly.
- Present life forms could not have survived at Earth's surface, because the Archean atmosphere lacked oxygen hence had no ozone layer to block ultraviolet light.
- Nevertheless, it is believed that primordial life began to evolve by the early Archean, with candidate fossils dated to around 3.5 Ga.
- Some scientists even speculate that life could have begun during the early Hadean, as far back as 4.4 Ga, surviving the possible Late Heavy Bombardment period in hydrothermal vents below the Earth's surface.

Archean, 4 Ga

- 4.0 Ga – Archean eon: Earth is now a water world.

- Origin of life– we do not know how, when or where life started yet.
- Theories: water + q way to harness energy
  - shallow rock pools with repeated wetting and drying – formation of molecule – precursor of RNA or DNA
  - Deep sea hyperthermal vent –hydrogen sulfide & CO^2 reaction
  - Amino acids on meteorites
  - A genetic material enclosed in fatty bubble

Earth's 2nd Atmosphere, 4 Ga

- In early models for the formation of the atmosphere and ocean, the second atmosphere was formed by outgassing of volatiles from the Earth's interior.

- Now it is considered likely that many of the volatiles were delivered during accretion by a process known as *impact degassing* in which incoming bodies vaporize on impact.

4.0 Ga

- The ocean and atmosphere would, therefore, have started to form even as the Earth formed. The new atmosphere probably contained water vapor, carbon dioxide, nitrogen, and smaller amounts of other gases.

- The water must have been supplied by meteorites from the outer asteroid belt and some large planetary embryos from beyond 2.5 AU. Comets may also have contributed.

Ocean by 4.4 Ga

- As the Earth cooled, clouds formed. Rain created the oceans. Recent evidence suggests the oceans may have begun forming as early as 4.4 Ga. By the start of the Archean eon, they already covered much of the Earth.

- There was enough carbon dioxide and methane to produce a greenhouse effect. The carbon dioxide would have been produced by volcanoes and the methane by early microbes. It is hypothesized that there also existed an organic haze created from the products of methane creation that caused an anti-greenhouse effect as well.

3.8 Ga: First came anoxygenic photosynthesis

- Some organisms, including purple bacteria and green sulfur bacteria, use an anoxygenic form of photosynthesis that uses alternatives to hydrogen stripped from water as electron donors; examples are hydrogen sulfide, sulfur and iron.

- Such extremophile organisms are restricted to otherwise inhospitable environments such as hot springs and hydrothermal vents.

- The simpler anoxygenic form arose about 3.8 Ga, not long after the appearance of life.

Oxygen Revolution: photosynthesis

- The earliest cells absorbed energy and food from the surrounding environment. They used fermentation. Fermentation can only occur in an *anaerobic* (oxygen-free) environment..
- Most of the life that covers the surface of the Earth today depends directly or indirectly on oxygen from photosynthesis. The evolution of photosynthesis made it possible for cells to derive energy from the Sun
- The most common form, oxygenic photosynthesis, turns carbon dioxide, water, and sunlight into food. It captures the energy of sunlight in energy-rich molecules such as ATP, which then provide the energy to make sugars. To supply the electrons in the circuit, hydrogen is stripped from water, leaving oxygen as a waste product.

Oxygenic photosynthesis, 3.2-2.4 Ga, Earth's 3rd Atmosphere

- Earth's 3rd Atmosphere: The timing of oxygenic photosynthesis is more controversial; it had certainly appeared by about 2.4 Ga, but some put it back as far as 3.2 Ga. Among the oldest remnants of oxygen-producing lifeforms are fossil stromatolites.
- At first, the released oxygen in the ocean was bound up with limestone, iron, and other minerals. The oxidized iron appears as red layers in geological strata called banded iron formations that formed in abundance during the Siderian period (between 2.5 -2.3 Ga).
- When most of the exposed readily reacting minerals were oxidized, oxygen finally began to accumulate in the atmosphere. Though each cell only produced a minute amount of oxygen, the combined metabolism of many cells over a vast time transformed Earth's atmosphere to its current state. This was Earth's third atmosphere.

Ozone and the Oxygen Catastrophe

- Some oxygen was stimulated by solar ultraviolet radiation to form ozone, which collected in a layer near the upper part of the atmosphere. The ozone layer absorbed, and still absorbs, a significant amount of the ultraviolet radiation that once had passed through the atmosphere. It allowed cells to colonize the surface of the ocean and eventually the land: without the ozone layer, ultraviolet radiation bombarding land and sea would have caused unsustainable levels of mutation in exposed cells
- Photosynthesis had another major impact. Oxygen was toxic; much life on Earth probably died out as its levels rose in what is known as the *Oxygen Catastrophe*. Resistant forms survived and thrived, and some developed the ability to use oxygen to increase their metabolism and obtain more energy from the same food

Life helped produce our atmosphere

- Early life existed in high temperatures and acidic conditions, tolerant of high UV radiation (no ozone layer yet), and no oxygen

- First life forms produced methane; Took in hydrogen, carbon dioxide; produced water and methane; methane entered atmosphere

- Evolution of life on earth is story of life producing our atmosphere; life can change a planet fundamentally; environment changing life and life changing the environment; produced blue, oxygen rich atmosphere of today

- 3.8 Ga: earliest oceans are blue-green, full of dissolved iron, and carbon dioxide, making them acidic

Cyanobacteria: 3.5 Ga

- There is suggestive evidence that photosynthetic organisms were present approximately 3.2 to 3.5 billion years ago, in the form of stromatolites, layered structures similar to forms that are produced by some modern cyanobacteria,
- Earth's oxygen supply originated with **cyanobacteria**, tiny water-dwelling organisms that survive by photosynthesis. In that process, the bacteria convert carbon dioxide and water into organic carbon and free oxygen = basis of animal life; for next several billion years
- Byproduct of photosynthesis: oxygen – At first, the oxygen produced by cyanobacteria was sequestered in minerals and seawater.
- But **between 2.4 and 2.5 billion years ago**, cyanobacteria were producing enough oxygen to be stored in Earth's atmosphere

A new revolution: photosynthesis

- Geysers high in Andes are boiling water, acidic, lots of UV, but have thriving bacterial colonies = modern extremophiles (live in 122º C & well below freezing); hint at early life possibilities

- Source of energy limits your growth

- Today, every drop of water contains 10s of 1000s of cells, incl. cyanobacteria -2000 types today

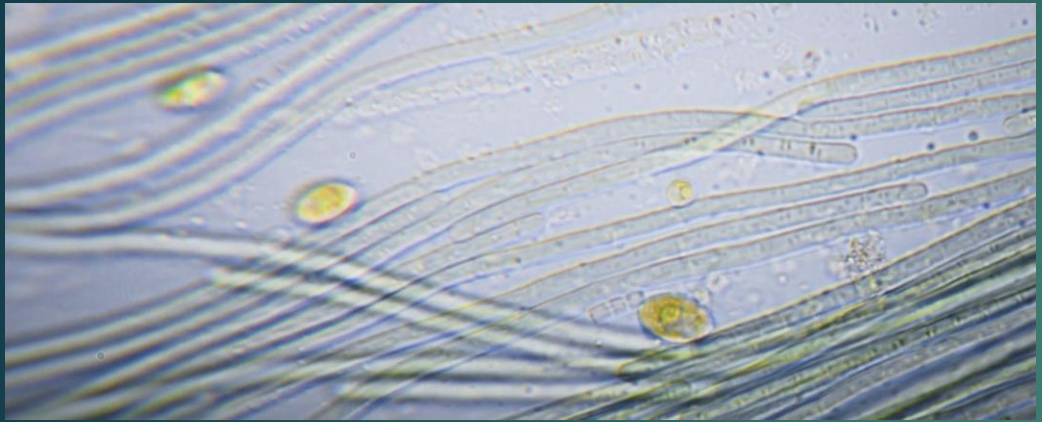
Photosynthesis

- Cyanobacteria originated ~3 Ga; stromatolites are colonies of cyanobacteria
- Changed fundamental basis of our atmosphere with unique way to produce energy: capture sunlight and use it to combine hydrogen from water with carbon dioxide in ocean which produces carbohydrates with very reactive waste byproduct, oxygen = photosynthesis

Cyanobacteria

- Cyanobacteria were the first, and only, organism to evolve oxygen-producing photosynthesis
- Water as the fuel; the oceans as giant reservoir of oxygen production via cyanobacteria
- Oxygen producing photosynthesis- organisms shallowed cyanobacteria = algae; algae became plants
- Emergence of large continental masses had massive effect on climate, triggering a near modern weather pattern

Cyanobacteria: completely transformed the world



Earth is a Fire planet

- Earth is only planet with fire; sun, lava, lightning are not fire
- Fire requires life
- Fire originates at 2.4 Ga: post photosynthesis of O_2 (dioxygen); Great Oxygenation Event; 1st O combined with iron oxide, rust; sank to bottom of ocean; created banded iron formation
- Fire is due to combustion: fuel + 02; releases water vapor and CO_2; light and heat; best fuel = lots of C and Hydrogen = cellulose
- Evidence of life on land during Cambrian; Protaxities (giant fungal towers) – fossil charcoal of these – lightening hits = wildfires; no decomposition

Fire

- Carboniferous = golden age of wildfires = coal layers
- Increase in O_2 (30% then): produces large arthropods – meter long scorpion; 100 lb millipede – dragon fly 50 cm wingspan;
- Fires huge due to high oxygen; 100-meter high fires
- 150 Ma = pines; adaptations to fire; 89 Ma = extra thick bark and consumption by fire for seed process; in response to amount of fire
- 66 Ma post asteroid– layer of worldwide charcoal layer implies fire spread over planet; then grasslands; fire clears

Proterozoic eon: 2.5 Ga

- The Proterozoic eon lasted from 2.5 Ga to 538.8 Ma ago.
- In this time span, cratons grew into continents with modern sizes.
- The change to an oxygen-rich atmosphere was a crucial development. Life developed from prokaryotes into eukaryotes and multicellular forms.
- The Proterozoic saw a couple of severe ice ages called Snowball Earths. After the last Snowball Earth about 600 Ma, the evolution of life on Earth accelerated.
- About 580 Ma, the Ediacaran biota formed the prelude for the Cambrian Explosion.

Ancient Life – Life Rising

- 4 Ga: Early Archean Eon: at first only a few volcanic basaltic islands in vast ocean; no continents (until 3.3 Ga); islands smashed to pieces by high tides from closer moon
- Origins of plate tectonics is highly controversial. Density differences in rocks with gravity pulling down heavier. Or asteroid hits may have triggered tectonics
- 3.26 Ga: subducting plates brings water & O^2 to interior, creating granite; 10% less dense than basalt and will rise higher; helps produce first landmasses
- The arrival of plants on Earth – from ocean to the land
- Plants have transformed geology of planet, turning rock into soil

Oxygen

- 3 Ga: oxygen being produced in ocean, but at first does not reach atmosphere due to its reactivity.
- A lot of dissolved iron and other metals in oceans with which oxygen reacted and bonded with: for half a billion years
- 2.5 Ga: Rust forms from combo and sinks to ocean bottom
- Bands of banded iron sedimentary rock created – layers of iron precipitation on ocean bottom; iron in ocean begins to dimmish
- Great Oxidation Event: For few million years, oxygen escapes into atmosphere – completely changed environment and possibilities for life; new chemical possibilities
- Organisms that use oxygen are 19 x more efficient

Banded iron in rock layers

Fossils from Australia provide the first direct evidence that photosynthesis was happening at least 2.5 billion years ago.

- 2.45 Ga: The Great Oxidation Event saw oxygen levels on Earth rise dramatically

- Scientists collected fossils from Australia, Canada and the Democratic Republic of Congo and found the samples from Australia and Canada contained evidence of cyanobacteria, the oldest known lifeform on Earth. Scientists believe that cyanobacteria first emerged 2 to 3 billion years ago,

- The earliest direct evidence of photosynthesis has been discovered in fossils dating back to 1.75 billion years ago.

Great Oxidation Event

- The rise in atmospheric oxygen transformed life on Earth. It unlocked aerobic respiration for many lifeforms and increased the rate at which minerals weathered and provided nutrients to different environments.

- The exact biological and physical drivers of the Great Oxidation Event are deeply debated amongst scientists.

- Though cyanobacterial photosynthesis is generally accepted as the key reason why oxygen concentrations increased, drivers like volcanic eruptions or a decreased level of iron in the oceans may have also played a part.

2.4 Ga: Effect of oxygen

- 2.4 Ga: new atmospheric oxygen begins to react with iron in rocks and massive dust storms emerge; new minerals are created by addition of O^2; interacted with copper, molybdenum, uranium, cobalt, etc.
- More acids created – nitric, sulfuric; dissolving rocks, weathering; metals became more abundant
- Nutrients flowed into ocean

Coevolution of life and geology

- 2.3 Ga: Ox in air reacts with methane producing carbon dioxide and water and begins to create blue sky
- And creates a new molecule, ozone (3 bonded Ox) which protects life from UV radiation
- Level of O^2 will fluctuate for 2 billion years, reaching 21% today
- Pattern is now reverting by our pumping carbon dioxide into atmosphere

Correlates of Earth’s oxygen level:

- It is thought that the Earth's oxygen content has risen in stages: six or seven steps that are timed very closely to the development of Earth's supercontinents.

1. Continents collide
2. Supermountains form
3. Erosion of super mountains
4. Large quantities of minerals and nutrients (nitrogen, phosphorus, and silicon nutrients are used by the tiny single-celled plants to grow); wash out to open ocean
5. Explosion of marine algae life (partly sourced from noted nutrients)
6. Mass amounts of oxygen produced during photosynthesis

Colonization of the land – Prokaryotes, 3 Ga

- Oxygen accumulation from photosynthesis resulted in the formation of an ozone layer that absorbed much of the Sun's ultraviolet radiation, meaning unicellular organisms that reached land were less likely to die, and prokaryotes began to multiply and become better adapted to survival out of the water.
- Prokaryote lineages had probably colonized the land as early as 3 Ga even before the origin of the eukaryotes. For a long time, the land remained barren of multicellular organisms. The supercontinent Pannotia formed around 600 Ma and then broke apart a short 50 million years later.
- Fish, the earliest vertebrates, evolved in the oceans around 530 Ma.

2 Ga: “Boring Billion” (1.8 Ga to .8 Ga), Proterozoic

- Inhospitable ocean – little O^2, high Sulphur; only cyanobacteria and lichens
- Stable temperature, no tectonics yet (mantle too hot, bound plates together in supercontinent)
- In reality, important period for beginnings of plate tectonics (= subduction (creates mountains), seafloor spreading, volcano creation) – eventually produced Himalayas (50 Ma), East African Rift Zone, Pacific Ring of fire)
- 2.78 Ga, late Archean: supercontinents breaking apart, mountain building, metamorphism; but subduction was shallow, plates stayed shallower and softer; plates created from crust, creation of supercontinent Numa

Boring Billion

- Start of eukaryotic (have nucleus) life (1.7 Ga) following some 1 to 1.5 billion years of prokaryotic evolution: Only microbes in ocean (low oxygen, high hydrogen sulfide) = most of the life was prokaryotic (no nucleus) = archea and cyanobacteria, purple and green sulfur bacteria

- At 750 Ma, beginning of real modern plate tectonics during breakup of Rodinia: plates began to really separate forming rift valleys and deep subduction zones, seafloor spreading with hyperthermal vents; more biodiversity with continental fragmentation

Emergence of Eukaryotes, 1.7 Ga

- Modern taxonomy classifies life into three domains. The time of their origin is uncertain.
  - The Bacteria domain probably first split off from the other forms of life (sometimes called Neomura), but this supposition is controversial.
  - Soon after this, by1.7 Ga, the Neomura split into the Archaea and the Eukaryota.

- Eukaryotic cells (Eukaryota) are larger and more complex than prokaryotic cells (Bacteria and Archaea).

- The earliest fossils possessing features typical of fungi date to the Paleoproterozoic era, some 2.4 Ga ago; these multicellular benthic (ocean bottom) organisms had filamentous structures capable of anastomosis (cross channeling).

Evolution of soil, 2 Ga

- Before the colonization of land there was no soil, a combination of mineral particles and decomposed organic matter.
- Land surfaces were either barren rock or shifting sand produced by weathering (rock dissolution, then erosion). Water and dissolved nutrients would have drained away very quickly.
- Films of cyanobacteria (which are not plants but use the same photosynthesis mechanisms) have been found in modern deserts in areas unsuitable for vascular plants.
- This suggests that microbial mats may have been the first organisms to colonize dry land, possibly in the Precambrian. Mat-forming cyanobacteria could have gradually evolved resistance to desiccation as they spread from the seas to intertidal zones and then to land.

Plants reach land via symbiosis, 1 Ga-500 Ma

- 1 Ga: landmasses with minerals with nutrients like potassium and phosphorus
- Marine algae in shallow coastal waters; use of photosynthesis – sunlight energy combined with water & carbon dioxide and produce oxygen and glucose; algae use chloroplasts which have chlorophyl (green color)
- Algae take up residence in fresh water; at 500 Ma, begin move to land; develop waxy coating (prevents drying out, but makes it more difficult to absorb nutrients)

Plants reach land

- Rhynie chert at 200 Ma – reveals algae stems combined with fungi

- <u>Fungi arrived on land 100s of millions of years before plants</u>; used organic acids on their filaments to penetrate rock; fungi got sugars from plants, plants got nutrients broken down from rocks by fungi

Proto-mitochondrion, 1.5 Ga

- Around this time, the first proto-mitochondrion was formed.

- A bacterial cell which had evolved to metabolize oxygen, entered a larger prokaryotic cell, which lacked that capability. Perhaps the large cell attempted to digest the smaller one but failed (possibly due to the evolution of prey defenses). The smaller cell may have tried to parasitize the larger one. In any case, the smaller cell survived inside the larger cell. Using oxygen, it metabolized the larger cell's waste products and derived more energy
- The larger cell could not survive without the energy produced by the smaller ones, and these, in turn, could not survive without the raw materials provided by the larger cell.
- Smaller cells are classified as organelles called mitochondria.

Photosynthetic cells

- A similar event occurred with photosynthetic cyanobacteria entering large heterotrophic cells and becoming chloroplasts.

- Probably as a result of these changes, a line of cells capable of photosynthesis split off from the other eukaryotes more than 1 billion years ago. There were probably several such inclusion events.

- Archaeans, bacteria, and eukaryotes continued to diversify and to become more complex and better adapted to their environments. Each domain repeatedly split into multiple lineages.

1.1 Ga: single cells, then multicellular

- Around 1.1 Ga, the plant, animal, and fungi lines had split, though they still existed as solitary cells. Some of these lived in colonies, and gradually a division of labor began to take place; for instance, cells on the periphery might have started to assume different roles from those in the interior.

- Around 1 billion years ago, the first multicellular plants emerged, probably green algae. Possibly by around 900 Ma true multicellularity had also evolved in animals.

- At first, it probably resembled today's sponges.

Supercontinents, 1.3 Ga

- A Precambrian supercontinent, named 'Pangaea I'. It was renamed 'Rodinia' (meaning "motherland") in 1990.
- Supercontinent that assembled 1.26–0.90 billion years ago and broke up 750–633 million years ago.
- Rodinia formed at c. 1.23 Ga by accretion and collision of fragments produced by breakup of an older supercontinent, Columbia, assembled by global-scale 2.0–1.8 Ga collisional events.
- Rodinia broke up with its continental fragments reassembled to form Pannotia 633–573 million years ago

Breakup of Rodinia, circa 800 Ma

- The extreme cooling of the global climate around 850–635 million years ago (the so-called Snowball Earth of the Cryogenian period).
- One theory is that the glaciation was triggered by the evolution of large cells, and possibly also multicellular organisms, that sank to the seabed after dying. This would have sucked CO_2 out of the atmosphere, weakening the greenhouse effect and thus lowering global temperatures.
- The rapid evolution of primitive life during the subsequent Ediacaran and Cambrian periods are thought to have been triggered by the breaking up of Rodinia or to a slowing down of tectonic processes
- The causes of supercontinent assembly and dispersal are thought to be driven by convection processes in Earth's mantle

On the land – 1 Ga – 700 Ma

- Several hundred million years ago, plants (probably resembling algae) and fungi started growing at the edges of the water, and then out of it.

- The oldest fossils of land fungi and plants date to 480–460 Ma, though molecular evidence suggests the fungi may have colonized the land as early as 1000 Ma and the plants 700 Ma.

- Initially remaining close to the water's edge, mutations and variations resulted in further colonization of this new environment.
- The timing of the first animals to leave the oceans is not precisely known: the oldest clear evidence is of arthropods on land around 450 Ma, perhaps thriving and becoming better adapted due to the vast food source provided by the terrestrial plants.
- There is also unconfirmed evidence that arthropods may have appeared on land as early as 530 Ma.

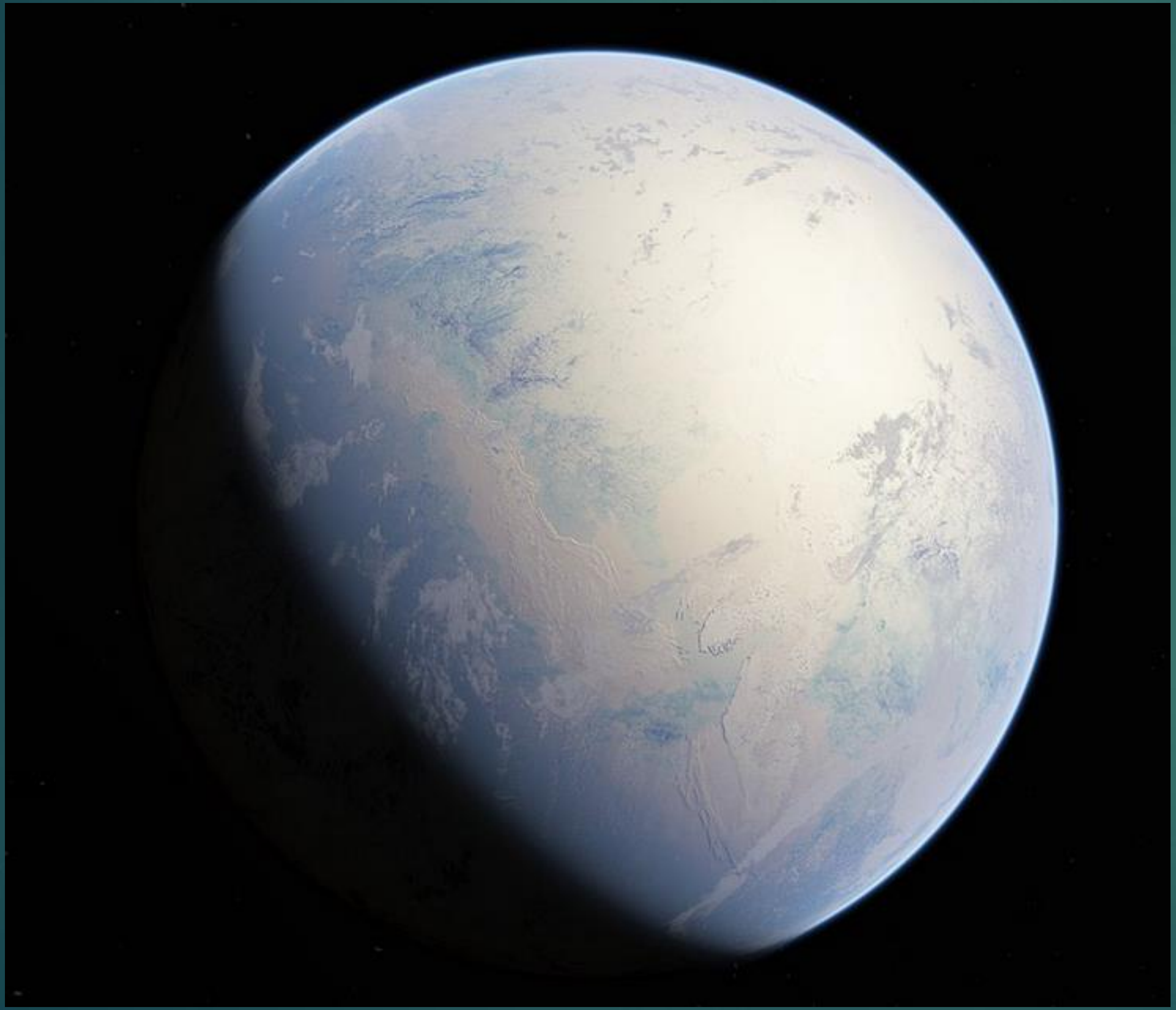
History of Ice on Earth

- In 1864, James Croll, a Scottish jack-of-all-trades who had taught himself physics, proposed that periodic changes in Earth's orbit change the amount of sunshine reaching the planet at various times of the year. Less sunshine in winter, he argued, would lead to snow accumulating. As ice sheets began to grow, the Earth would reflect more heat, amplifying the effect of the orbital changes and leading to ice ages.
- Unlike Croll, Milankovitch focused on how orbital changes affect the amount of summer sunshine in the far north. Colder winters make no difference to ice sheet growth, he reasoned, but colder summers do. If the snow that falls during winter does not melt completely in the summer, ice sheets will grow; when summer melting gains the upper hand, ice sheets will shrink.
- The tilt of Earth's axis increases and decreases every 41,000 years, making summers hotter and winters colder. Sometimes changes to 100,000 years

History of Ice

- The planet seems to have three main settings:
  - "greenhouse", when tropical temperatures extend to the poles and there are no ice sheets at all
  - "icehouse", when there is some permanent ice, although its extent varies greatly;
  - "snowball", in which the planet's entire surface is frozen over
  - overall reason behind ice ages: the gradually falling levels of CO_2 in our atmosphere.
- A coherent story. Ice sheets build up until they near the brink of stability, at which point a modest rise in summer sunshine is enough to tip them over the edge. As the ice sheets melt, fresh water is released into the Atlantic, shutting down ocean circulation and pumping CO_2 into the atmosphere. As long as the combined effect of extra summer sunshine and rising CO_2 outweighs the regional cooling produced by the shutdown of ocean circulation, the ice keeps melting, pouring more fresh water into the Atlantic. And the melting of a really large ice sheet keeps ocean circulation shut down for a long time, eventually pumping so much CO_2 into the atmosphere that the ice sheets melt away in just a few thousand years.

Oxygenated fully-frozen Snowball Earth with no remaining liquid surface water.



There are **three** periods of the past that are generally suspected to have been Snowball Earth events:
the Huronian glaciation (~2.4-2.1 billion years ago),
the Sturtian glaciation (~720-660 million years ago), and
the Marinoan glaciation (~645-635 million years ago).

First Snowball Earth, 2.2 Ga

- The natural evolution of the Sun made it progressively more luminous during the Archean and Proterozoic eons; the Sun's luminosity increases 6% every billion years. As a result, the Earth began to receive more heat from the Sun in the Proterozoic eon. However, the Earth did not get warmer.
- Instead, the geological record suggests it cooled dramatically during the early Proterozoic. Glacial deposits found in South Africa date back to 2.2 Ga, at which time, based on paleomagnetic evidence, they must have been located near the equator. Thus, this glaciation, known as the Huronian glaciation, may have been global. Some scientists suggest this was so severe that the Earth was frozen over from the poles to the equator, a hypothesis called Snowball Earth.
- Triggered by a 250-million-year lull in volcanic activity, which would have meant less carbon dioxide being pumped into the atmosphere, and a reduced greenhouse effects

Snowball Earth

- The Huronian ice age might have been caused by the increased oxygen concentration in the atmosphere, which caused the decrease of methane (CH_4) in the atmosphere.

- Methane is a strong greenhouse gas, but with oxygen it reacts to form CO_2, a less effective greenhouse gas.

- When free oxygen became available in the atmosphere, the concentration of methane could have decreased dramatically, enough to counter the effect of the increasing heat flow from the Sun.

Late Proterozoic climate and life, 716 Ma

- The end of the Proterozoic saw at least two Snowball Earths, so severe that the surface of the oceans may have been completely frozen.

- This happened about 716.5 and 635 Ma, in the Cryogenian period. Most paleoclimatologists think the cold episodes were linked to the formation of the supercontinent Rodinia.

- Because Rodinia was centered on the equator, rates of chemical weathering increased and carbon dioxide (CO_2) was taken from the atmosphere. Because CO_2 is an important greenhouse gas, climates cooled globally.

Ancient Earth: Frozen, 850 Ma

- 850 Ma: single supercontinent of Rodinia – no plants or animals; living bacterial mats (prokaryotic Cyanobacteria, also known as blue-green algae) in coastal waters = extent of life on earth for 3 B years)
- Eventually giant cells above the mats = Eukaryotes (evolved over a billion years); ancestors of all plants and animals
- Prokaryotes = simple bacteria
- Eukaryotes carry DNA in a nucleus; also have organelles

Geology & Biology

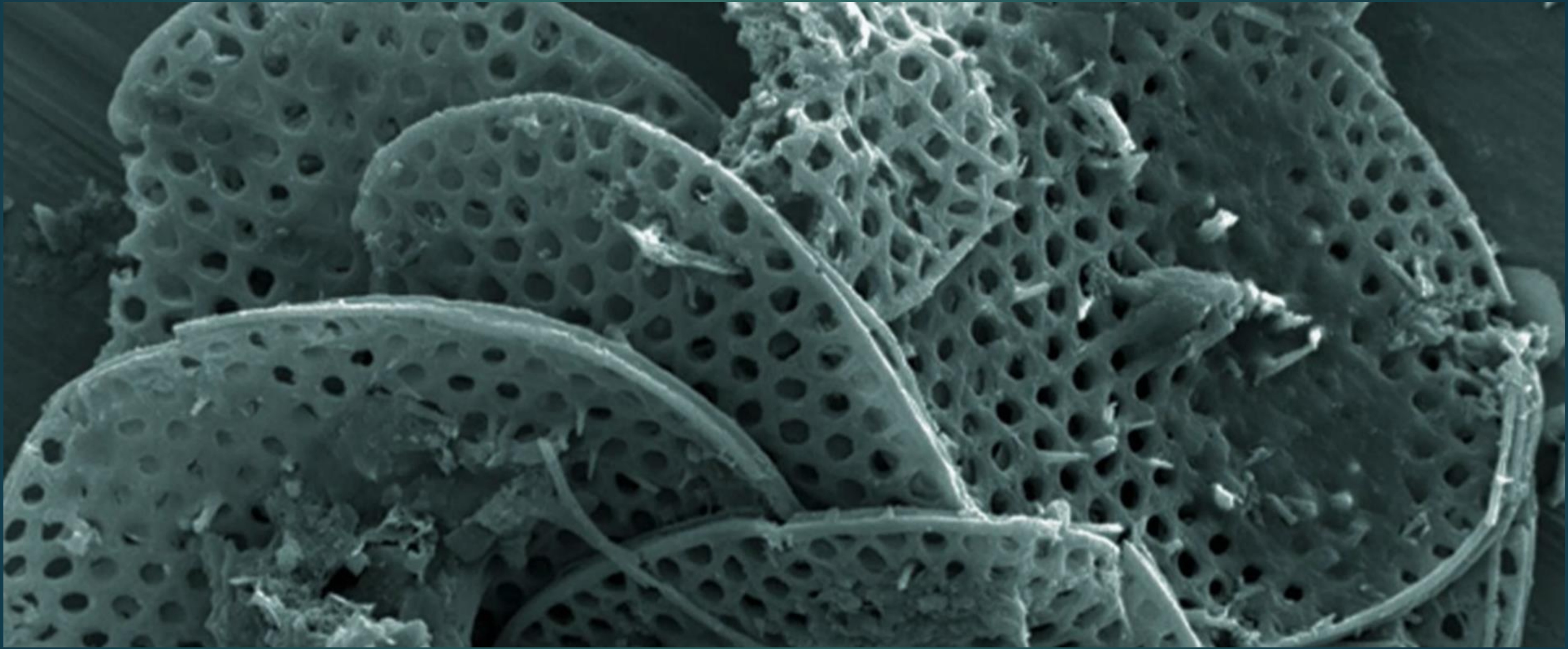
- Story of life is story of our planet's changing geology; life and rocks have co-evolved; totally interconnected and interdependent; geology & biology

- Epic geological event on Rodinia changes life forever: tectonic movement (1-2 inches per year); 800 Ma Rodinia began to divide

Bacterial mats

Eukaryotes

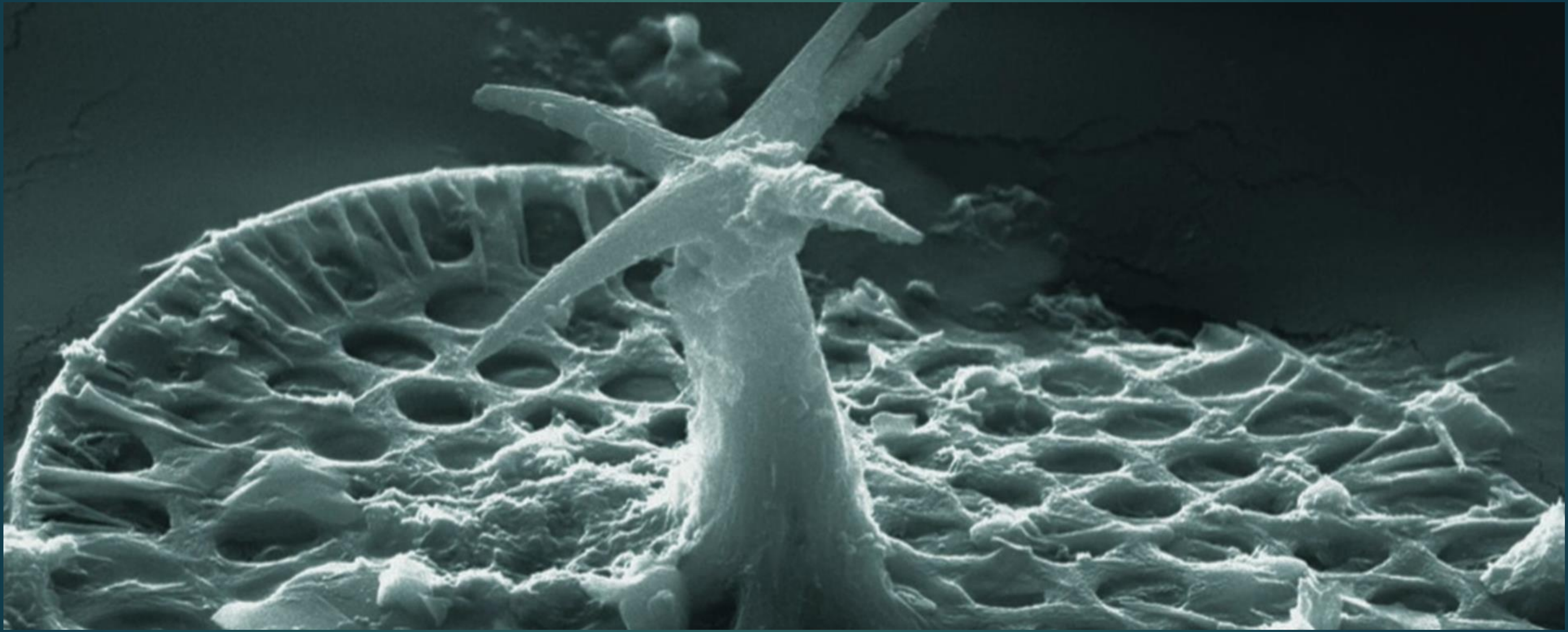
Fossilized eukaryotes



Snowball Earth, 717 Ma

- Division of Rodinia caused increased rocky nutrients (minerals), to flow into oceans, enriching eukaryotes; more complex life
- Eukaryotes developed new spiny structures = first evidence of predation in fossil record
- What was eating them? Similar to testate amoebe of today that drill holes in bacteria
- 700 Ma: in central Rodinia – molten rock covers 800 K sq miles around the tropics; cools into basalt; basalt breaks down much quicker than granite; forms carbonates, producing more carbon dioxide; location of basalt was in tropics with lots of rainfall pumping more carbon dioxide into atmosphere, cooling the earth over millions of years

New more defensive forms of eukaryotes



Snowball Earth

- 717 Ma: Snowball Earth begins: Ice forms first at poles
- Why did cooling turn into runaway deep freeze? Various theories: new lifeforms captured more CO^2; volcanic gases created more sulphury acid which reflects sunlight
- Ice albedo effect – more ice, more sun reflection, more cooling down
- Ice covers entire planet
- Evidence: Drop stones: When ice sheets melt, rocks at bottom of glaciers, drop to ocean bottom and get incorporated into rock layers; they are found all over the world
- Continuing life: Cryoconite is powdery windblown dust made of a combination of small rock particles, soot and microbes. Melts snow below it forming pockets of life – fungi, micro-animals. Eukaryotic life survived. In croconite holes, hot springs, caves, deep oceans

Drop rocks: evidence of Snowball Earth

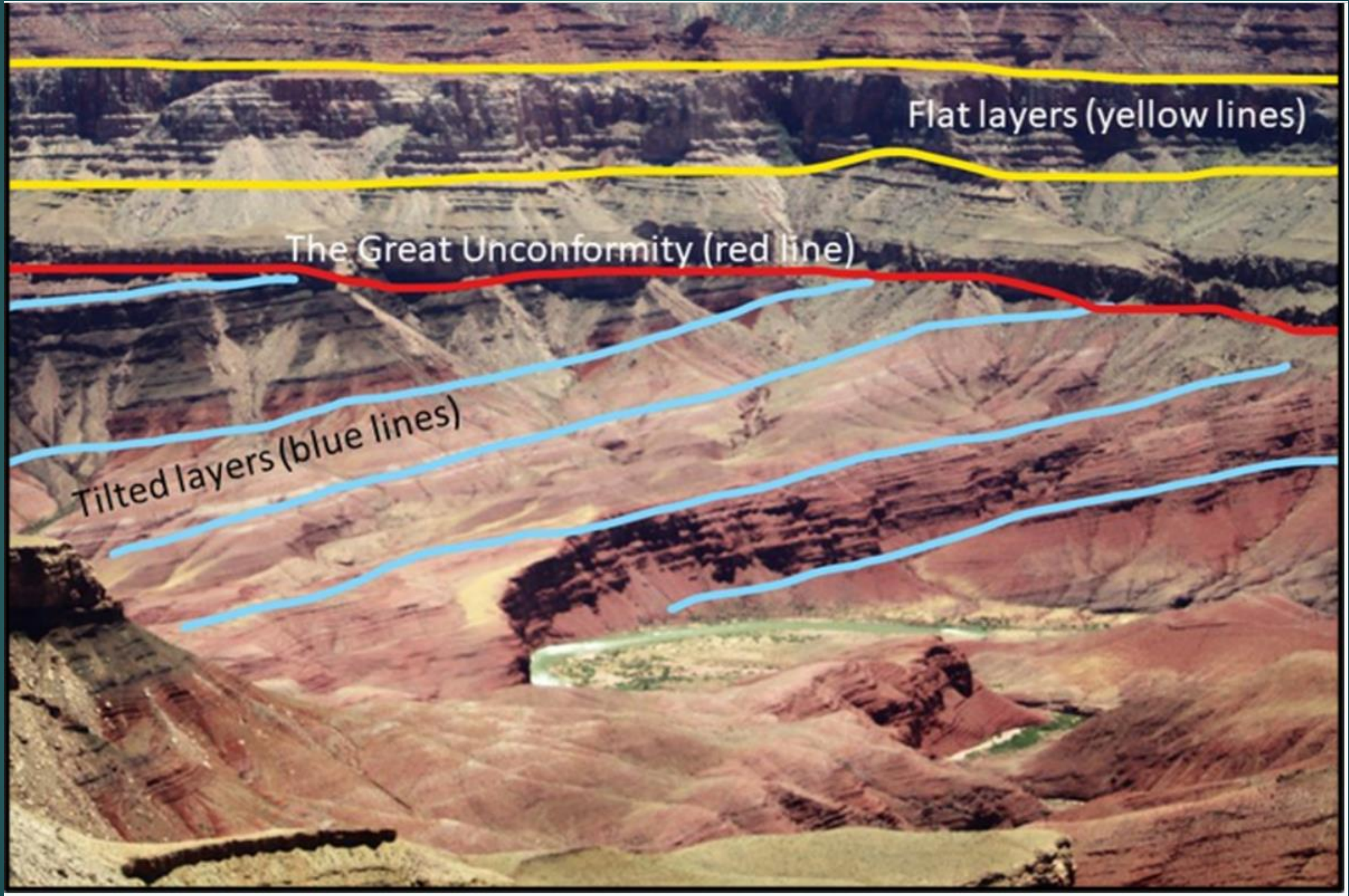
Snowball Earth thawing

- 640 Ma: After 50 M years of ice, Earth thaws: Plate tectonics and volcanism continue over millions of years. Increases carbon dioxide in atmosphere, trapping heat, warming the earth. Intense chemical weathering. Thawing begins. Water vapor release acted as greenhouse gas.
- How long is debated (1000 years to 1 M years).
- Normal process of rock weathering pulls CO^2 from the atmosphere, cooling temperature. But ice cover shuts off this process.
- Turbulent time: massive amount of water released – 600 feet sea level rise every decade; acid rain; 120º F at equator – freeze to fry period; glaciers removed 2 miles of material below them (removing evidence of what occurred)

Effects of great thaw, 634 Ma

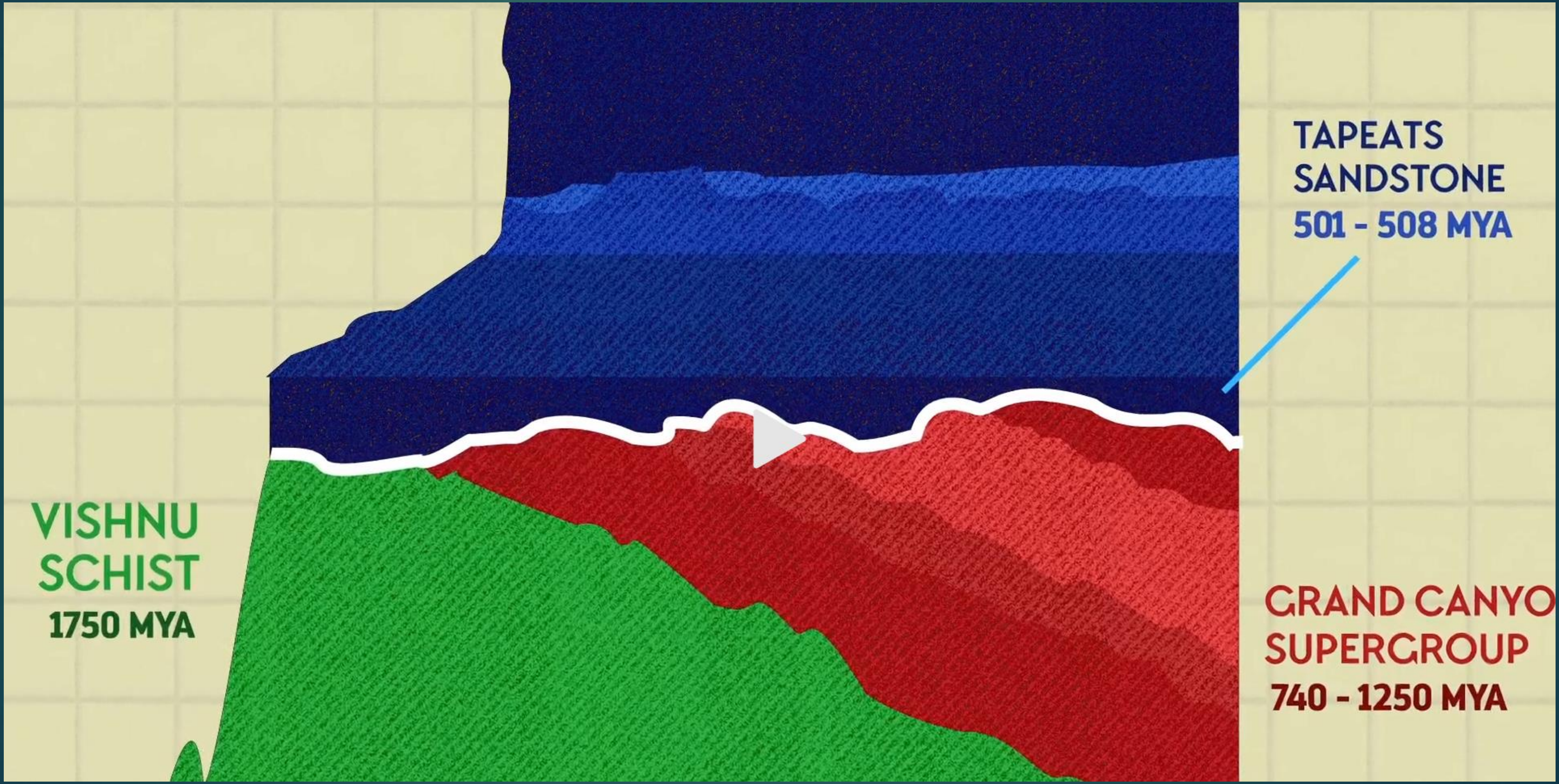
- Geological mystery of Great Unconformity: in Grand Canyon = 500 M year old rock sits on top of 3 G year old rock; 2.5 B years missing in stratigraphy; via glacier erosion during Snowball earth?
- More than a vertical mile of earth (billion billion tons) eroded
- 634 Ma: This amount of ground up rock enters the oceans increasing nutrients for ocean life, esp. algae which have massive blooms and increased photosynthesis and oxygen; more shallow marine habitats; increase in oxygen and phosphorus and more time create setting for major eukaryotic evolution
- 550 Ma: First truly complex, non-microscopic, lifeforms, the Ediacaran revolution; fossil record of movement; sponges are only survivors of this period

Grand Canyon Unconformity – Biblical Flood or Snowball Earth

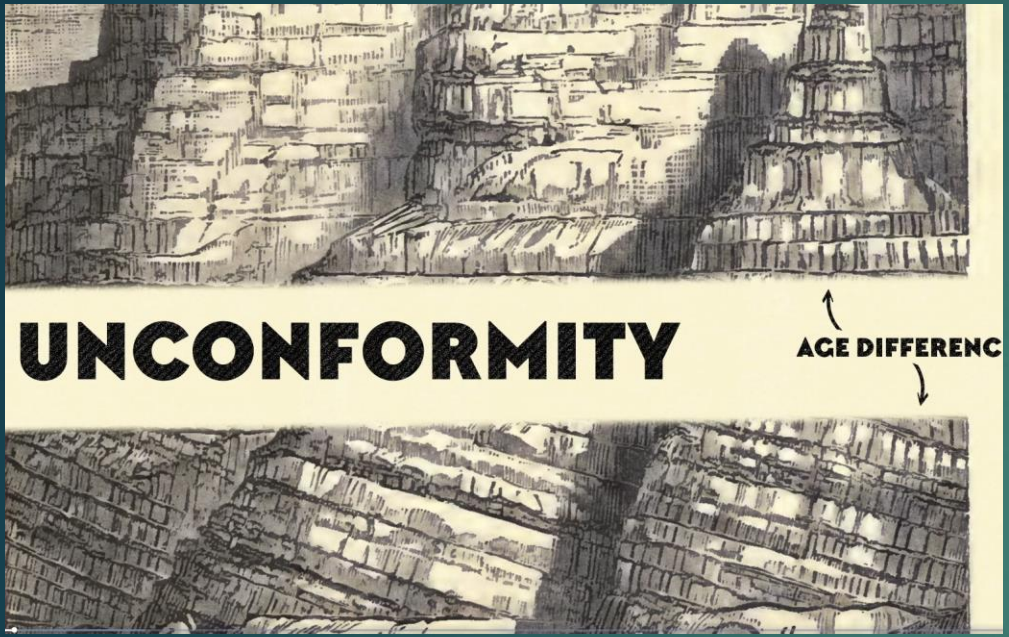


Grand Canyon Great Unconformity (red line) from Walhalla Plateau

Great Unconformity



Great Unconformity: age difference between strata



- Great Unconformity: age difference between strata; usually by erosion
- Grand Canyon: toward bottom, sandstone rock layer on top of Great unconformity (Cambrian, 500 Ma), then Great Unconformity, and then below shist (1.75 Ga)
- Rodinia from 1.3 Ga to 900 Ma; started breakup ~750 Ma; Snowball Earth 760-635 Ma;

Erosion

- Breakup of Rodinia: tectonic uplift from 850 to 680 Ma due to fragmenting supercontinents; several kms of rock lifted up and then eroded; a global erosion that created Great Unconformity
- Erosion captured large amounts of CO_2 resulting in global cooling and Snowball Earth
- 2018 study: great unconformity helped start Snowball Earth
- 2019 study argues opposite; Snowball Earth glaciers caused Great Unconformity by grinding away continental crust stripping a billion years of strata
- This strata ended up in ocean as increased nutrients which formed basis of explosion of Ediacaran biota

Snowball Earth

Snowball Earth

- The term Snowball Earth is more commonly used to describe later extreme ice ages during the Cryogenian period (720–635 Ma).

- There were four periods, each lasting about 10 million years, between 750 and 580 million years ago, when the Earth is thought to have been covered with ice apart from the highest mountains, and average temperatures were about −50 °C (−58 °F).

- The snowball may have been partly due to the location of the supercontinent Rodinia straddling the Equator.

Snowball Earth

- Carbon dioxide combines with rain to weather rocks to form carbonic acid, which is then washed out to sea, thus extracting the greenhouse gas from the atmosphere

- When the continents are near the poles, the advance of ice covers the rocks, slowing the reduction in carbon dioxide, but in the Cryogenian the weathering of Rodinia was able to continue unchecked until the ice advanced to the tropics.

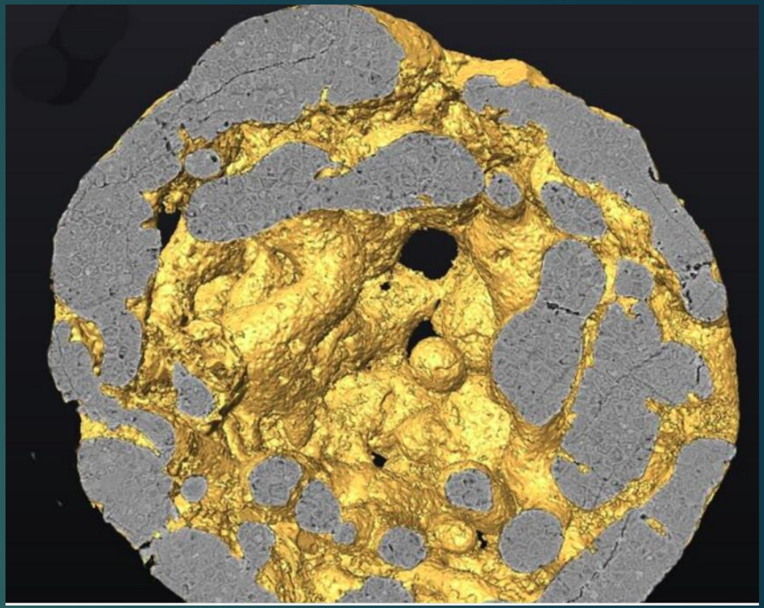
- The process may have finally been reversed by the emission of carbon dioxide from volcanoes or the destabilization of methane gas hydrates.

- According to the alternative Slushball Earth theory, even at the height of the ice ages there was still open water at the Equator.

Emergence of animals, 750 Ma

- Animals are multicellular eukaryotes, and are distinguished from plants, algae, and fungi by lacking cell walls.
- Animal cells are enclosed in a more flexible cell membrane. All animals are motile.
- All animals except sponges have bodies differentiated into separate tissues, including muscles, which move parts of the animal by contracting, and nerve tissue, which transmits and processes signals.

Animals



- In November 2019, researchers reported the discovery of *Caveasphaera*, a multicellular organism found in 609-million-year-old rocks, that is not easily defined as an animal or non-animal, which may be related to one of the earliest instances of animal evolution. Developed distinct tissue layers and organs

- Fossil studies of *Caveasphaera* had animal-like embryonic development; studies suggesting that animal evolution may have begun about 750 million years ago.

580 Ma

- The earliest widely accepted animal fossils are the rather modern-looking cnidarians (the group that includes jellyfish, sea anemones and *Hydra*), possibly from around 580 Ma.

- The Ediacaran biota, which flourished for the last 40 million years before the start of the Cambrian, were the first animals more than a very few centimeters long. Many were flat and had a "quilted" appearance, and seemed so strange that there was a proposal to classify them as a separate kingdom, Vendozoa.

- Others, however, have been interpreted as early molluscs (*Kimberella*), echinoderms (*Arkarua*), and arthropods (*Spriggina*, *Parvancorina*).

Ediacaran: 635-539 Ma

- The Ediacaran marks the first widespread appearance of complex multicellular fauna following the end of Snowball Earth.

- Now-extinct, relatively simple soft-bodied animal phyla such as
  - Proarticulata (bilaterians with simple articulation, e.g. *Dickinsonia* and *Spriggina*),
  - Petalonamae (sea pen-like animals, e.g. *Charnia*), Aspidella (radial-shaped animals, e.g. *Cyclomedusa*) and
  - Trilobozoa (animals with tri-radial symmetry, e.g. *Tribrachidium*).

Ediacaran

- Most of these organisms appeared ~575 million years ago and died out during the End-Ediacaran extinction event 539 million years ago.

- Forerunners of some modern animal phyla also appeared during this period, including cnidarians (jellyfish) and early bilaterians such as Xenacoelomorpha, as well as mollusc-like *Kimberella*.

Ediacaran: 635-539 Ma

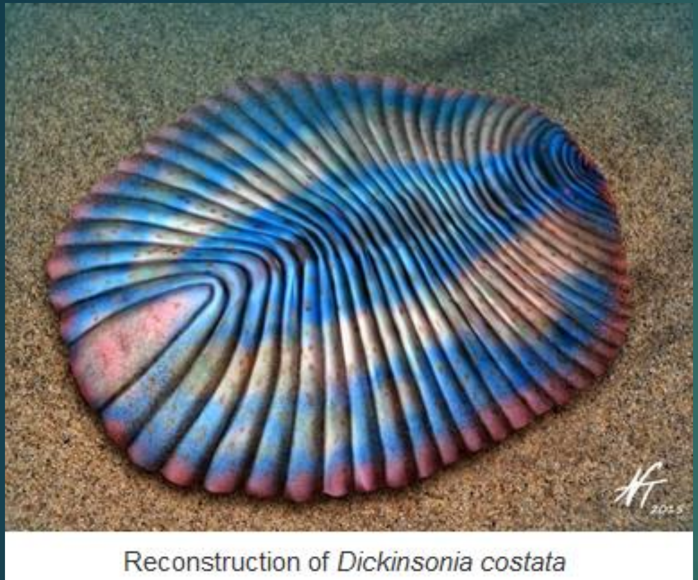
- The fossil record from the Ediacaran Period is sparse, as more easily fossilized hard-shelled animals had yet to evolve. The Ediacaran biota include the oldest definite multicellular organisms (with specialized tissues), the most common types of which resemble segmented worms, fronds, disks, or immobile bags.

- Hard-bodied organisms with mineralized shells or endoskeletons, which can be fossilized and preserved, were yet to evolve and would not appear until the superseding Cambrian Explosion some 35 million years later.

Ediacaran period (635 and 542 MYA): Metazoan animals that were bags. No mouth, no gut and no anus. No enemies.

Arose after end of Snowball earth glaciations & increase in global oxygenation

Ediacaran organisms



Dickinsonia

Spriggina

Aspidella

Charnia

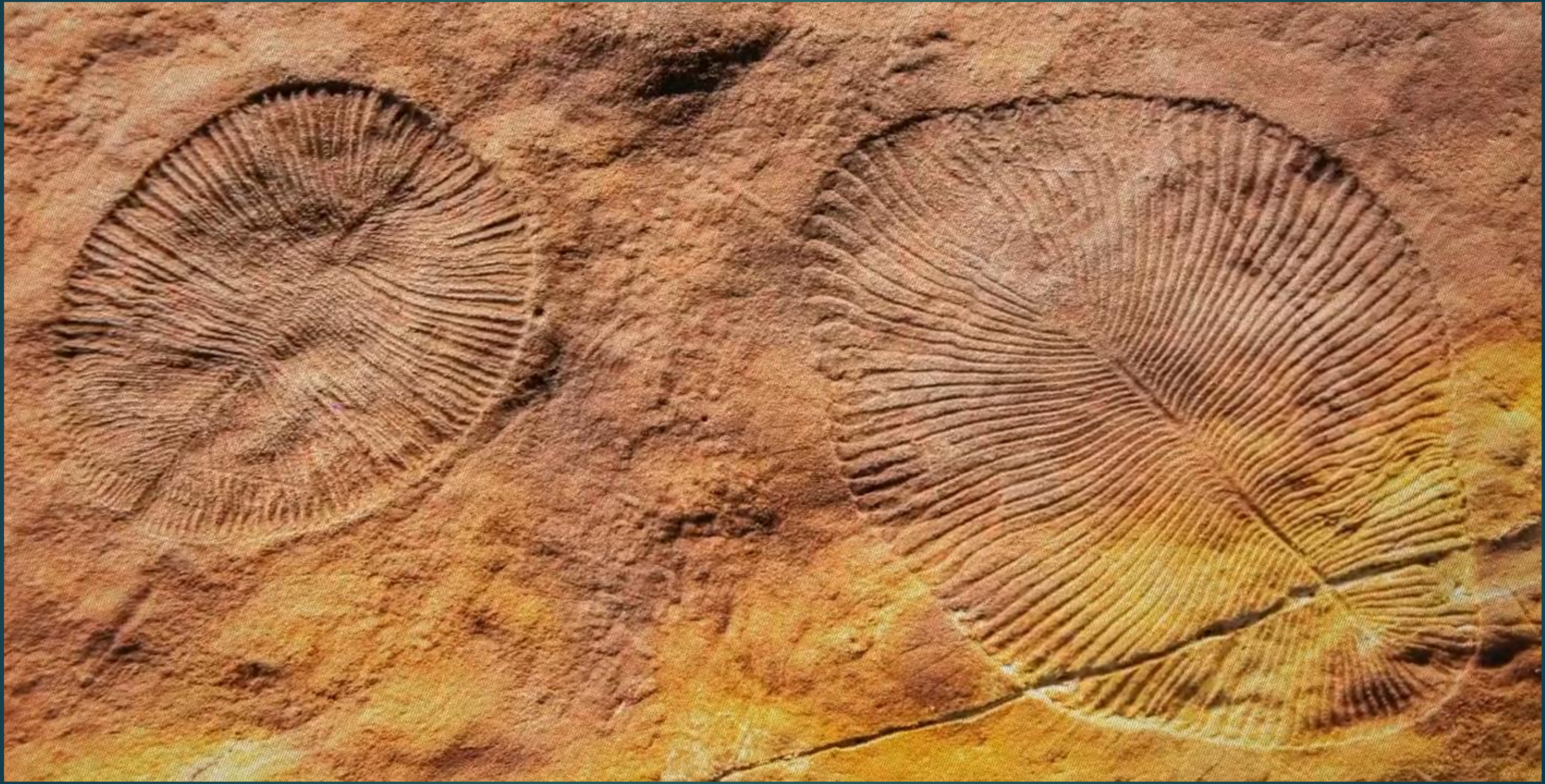
Trilobozoa

Edicarian seascape

Edicarian

Very rare fossil Icarian organisms

Dickinsonia, 500 Ma



Dickinsonia

- Dickinsonia: up to 1.4 meter-long blob
- Study found cholesteroids in fossils meaning it was an animal
- 2020 study: from 650 to 635, environment filled with algae, the food for Dickinsonia
- Cause for disappearance of Ediacaran biota is unknown

Cambrian, 539 – 485 Ma

- The Cambrian marked a profound change in life on Earth: prior to the Cambrian, the majority of living organisms on the whole were small, unicellular and simple (Ediacaran fauna and earlier Tonian Huainan biota being notable exceptions).

- Complex, multicellular organisms gradually became more common in the millions of years immediately preceding the Cambrian, but it was not until this period that mineralized – hence readily fossilized – organisms became common.

- The rapid diversification of lifeforms in the Cambrian, known as the Cambrian explosion, produced the first representatives of most modern animal phyla.

Cambrian, 539 – 485 Ma

- Phylogenetic analysis has supported the view that before the Cambrian radiation, animals evolved monophyletically from a single common ancestor: flagellated colonial protists similar to modern choanoflagellates.

- Although diverse life forms prospered in the oceans, the land is thought to have been comparatively barren – with nothing more complex than a microbial soil crust and a few molluscs and arthropods (albeit not terrestrial) that emerged to browse on the microbial biofilm.

Cambrian

- The Cambrian explosion was a period of rapid multicellular growth.
- Most animal life during the Cambrian was aquatic.
- No land plant (embryophyte) fossils are known from the Cambrian.
- However, biofilms and microbial mats were well developed on Cambrian tidal flats and beaches 500 mya, and microbes forming microbial Earth ecosystems, comparable with modern soil crust of desert regions, contributing to soil formation.
- Trilobites were once assumed to be the dominant life form at that time, but this has proven to be incorrect. Arthropods were by far the most dominant animals in the ocean.

Cambrian

- While the early Cambrian showed such diversification that it has been named the Cambrian Explosion, this changed later in the period, when there occurred a sharp drop in biodiversity.

- About 515 million years ago, the number of species going extinct exceeded the number of new species appearing.

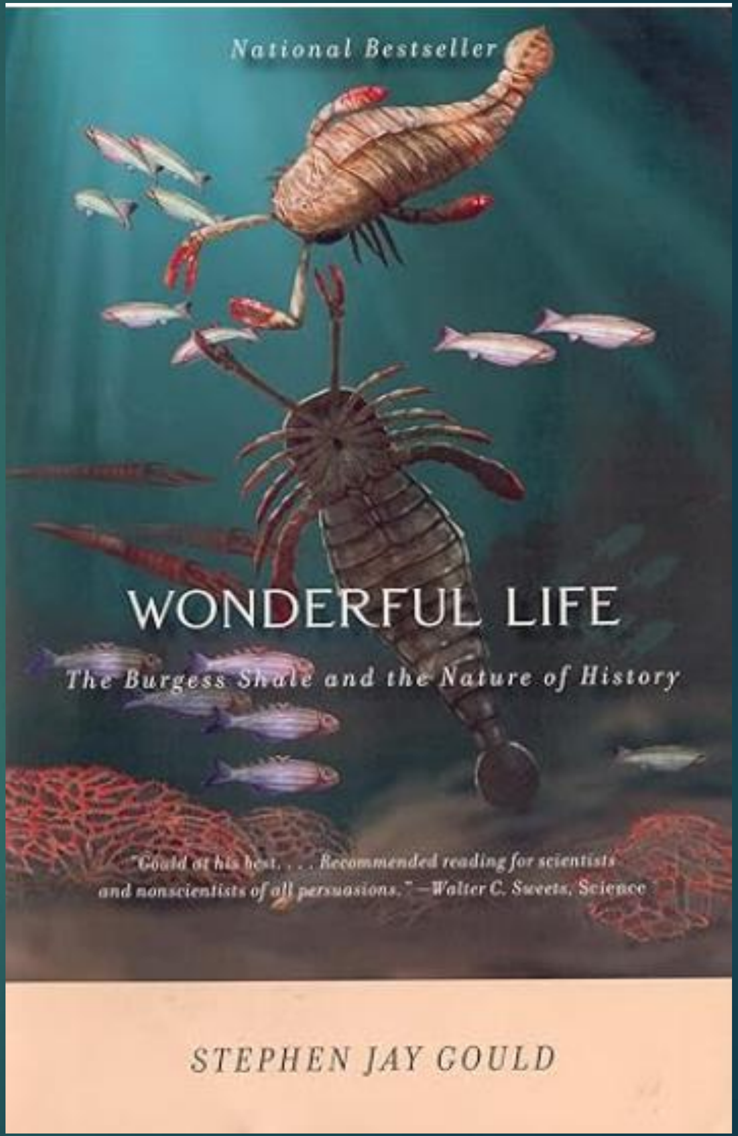
- In contrast to later periods, the Cambrian fauna was somewhat restricted; free-floating organisms were rare, with the majority living on or close to the sea floor;

Cambrian Revolution: 539 – 485 Ma

- In 40 M years:
  - All animal phyla appeared
  - 75% still with us
  - No new phyla since
  - All used olfaction
  - No complex behavior before
  - After, complex sensory systems, especially in predators
  - Movement beyond just reaction to stimuli
  - Then ability to learn, ability to predict, ability to control
  - Cambrian bloodbath of predator eating predator that probably supplied the selective force necessary for the evolution of the first brains.
  - Development of olfactory navigational system, which could map spatial valences, lead to an arms race between predators and prey

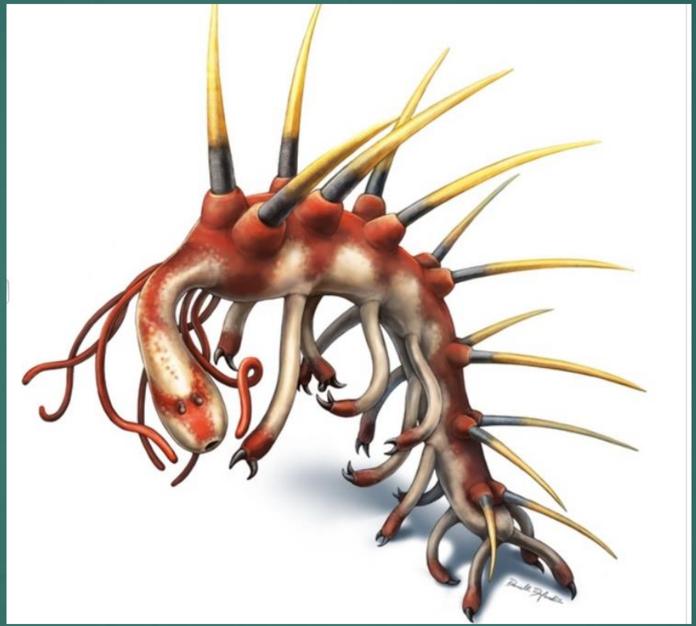
Wonderful Life: Burgess Shale & Nature of History
- Stephen Jay Gould, 1989

The **Burgess Shale** is a fossil-bearing deposit exposed in the Canadian Rockies of British Columbia, Canada; north of Banff, off of Highway 1

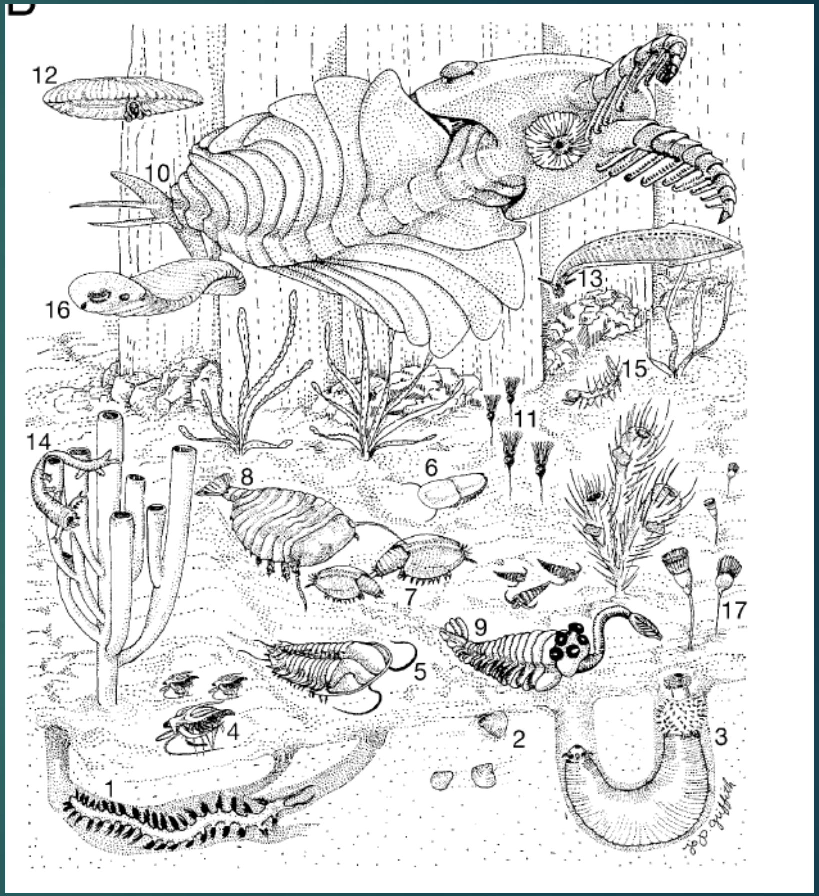


Evolution's Big Bang = Cambrian Explosion: The blood bath – first arms war; Predation requires nervous systems

Anomalocaris: up to 2 meters



Hallucigenia: teethy smiling worm

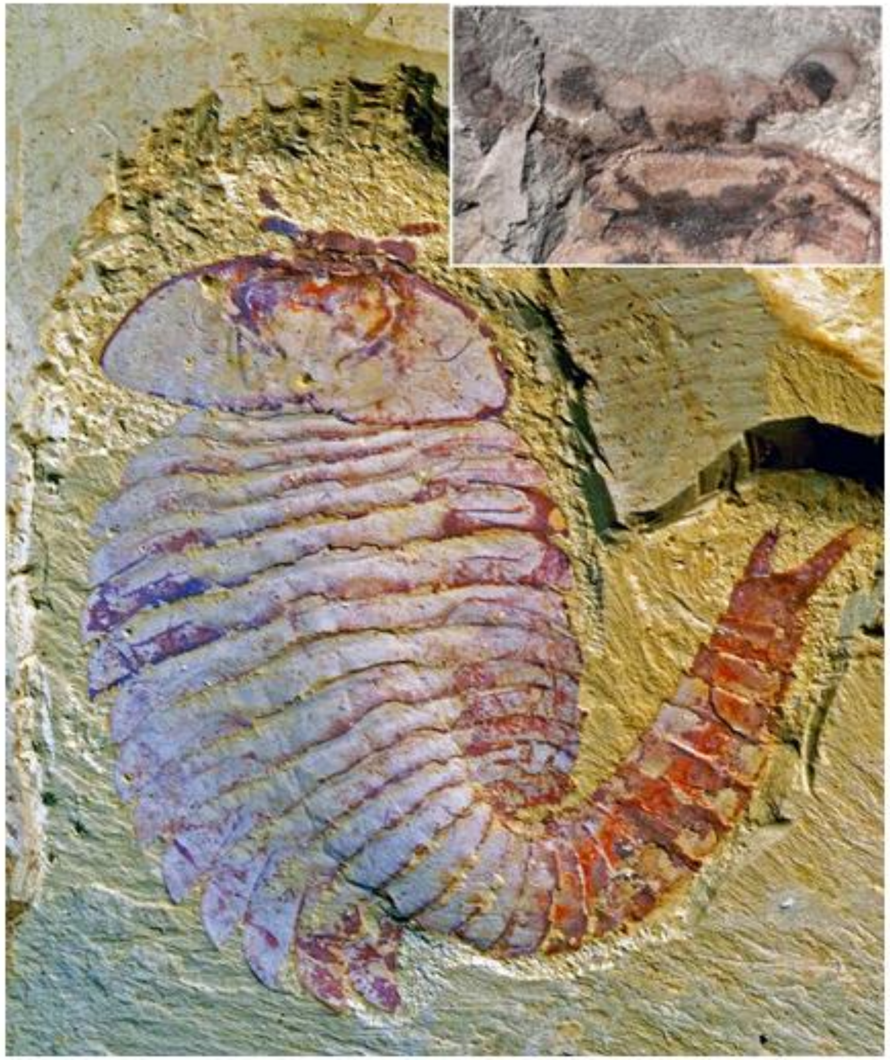


Bilaterians: bilateral animals — body plans that have a left and right side, a top and bottom, and a mouth and anus. Mostly predators.

Anomalocaris during Cambrian

Anomalocaris

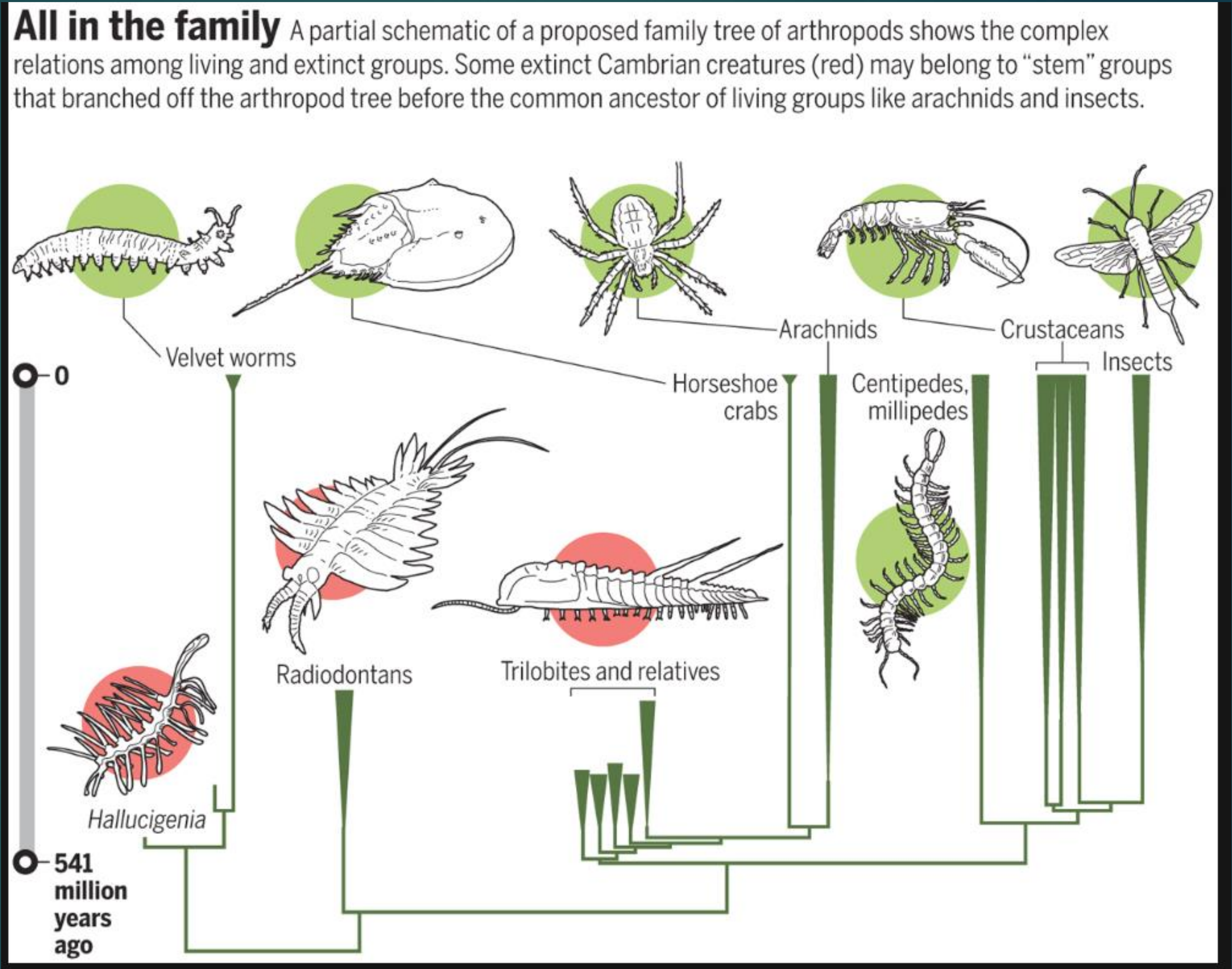
First fossil arthropod discovery with neural network: 520 MYA



3-inch, 520-million-year-old fossil of Fuxianhuia protensa. Insert shows dark features associated with putative 'brain' structure like that in modern organisms (Credit: Xiaoya Ma, insert: Nicholas Strausfeld).

Ma et al., *Current Biology,2015*

Arthropod Tree

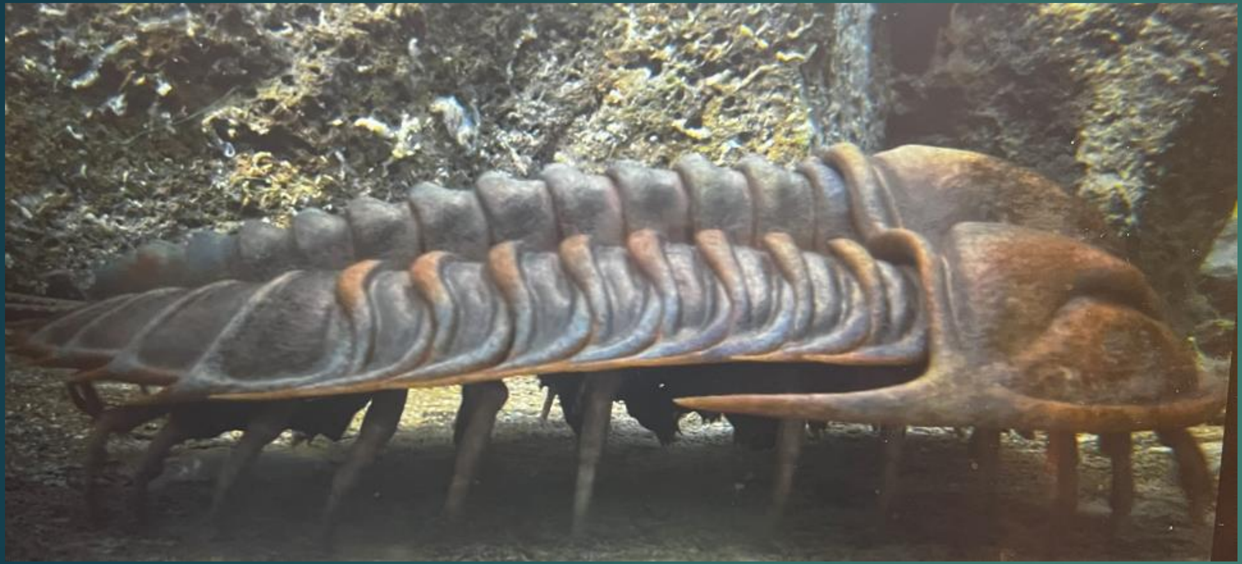


530 Ma – Arrival of predation

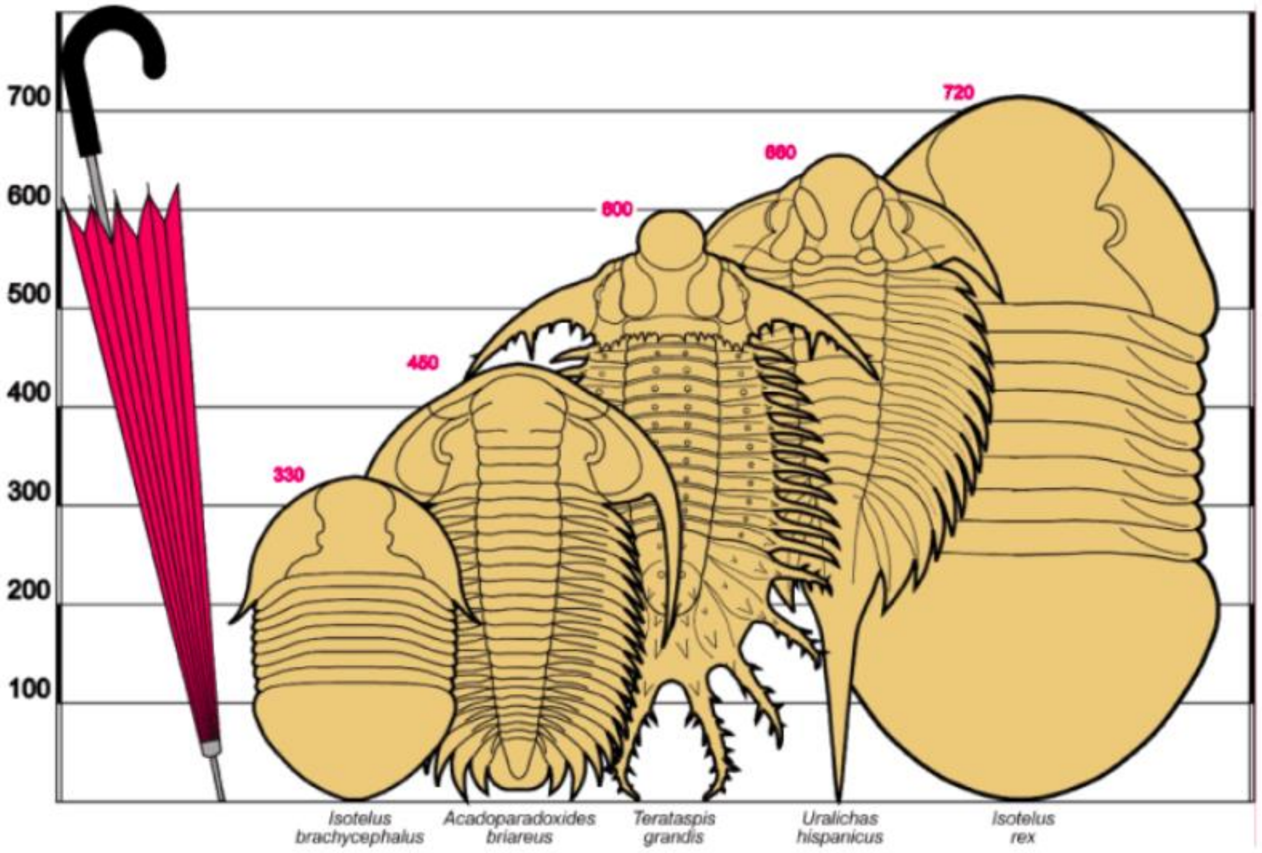
- Most initial aquatic animals were soft bodied, attached to ground; have senses; often filter feeding
- 530 Ma: arrival of jellyfish
- Anemones were equipped to kill jellyfish
- Jellies were first animal to escape seabed and become mobile; and move to big blue ocean which had no existing predators
- 521-252 Ma: Trilobites with armor as external skeleton: 1 of first arthropods; could become impenetrable ball; 80% of all modern animals (insects, spiders, crabs) related to this species
- Their enemies: Anomalocaris ("abnormal shrimp"): first apex predator – very fast; & later Orthoceras – 18-foot nautiloid

Trilobites first appeared during the Cambrian period (521 Ma) and ended at end Permean (252 Ma). Trilobites were among the most successful of all early animals, existing in oceans for almost 270 million years, with over 22,000 species having been described.

Trilobite

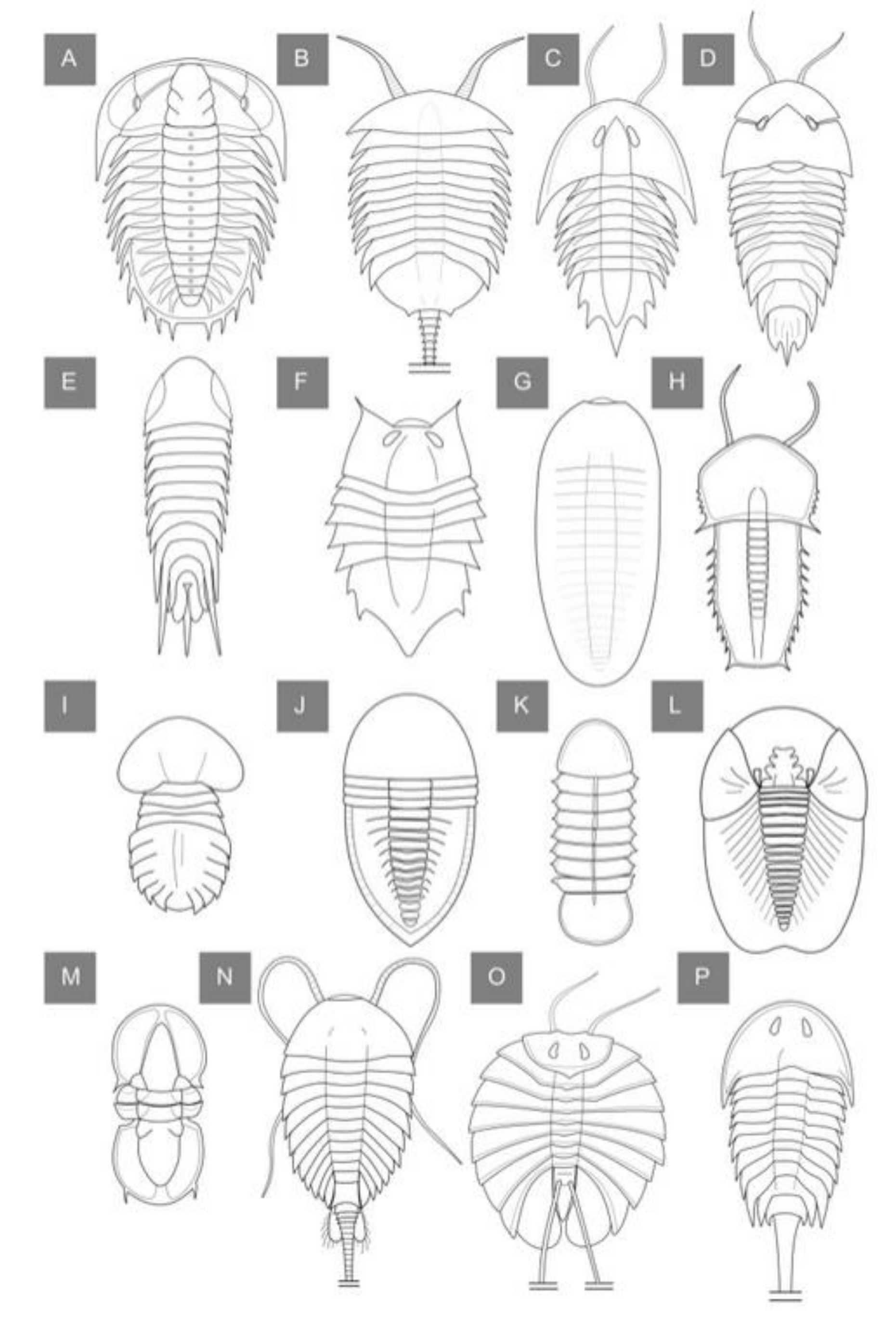


Trilobite size: 2 inch to 2 ft



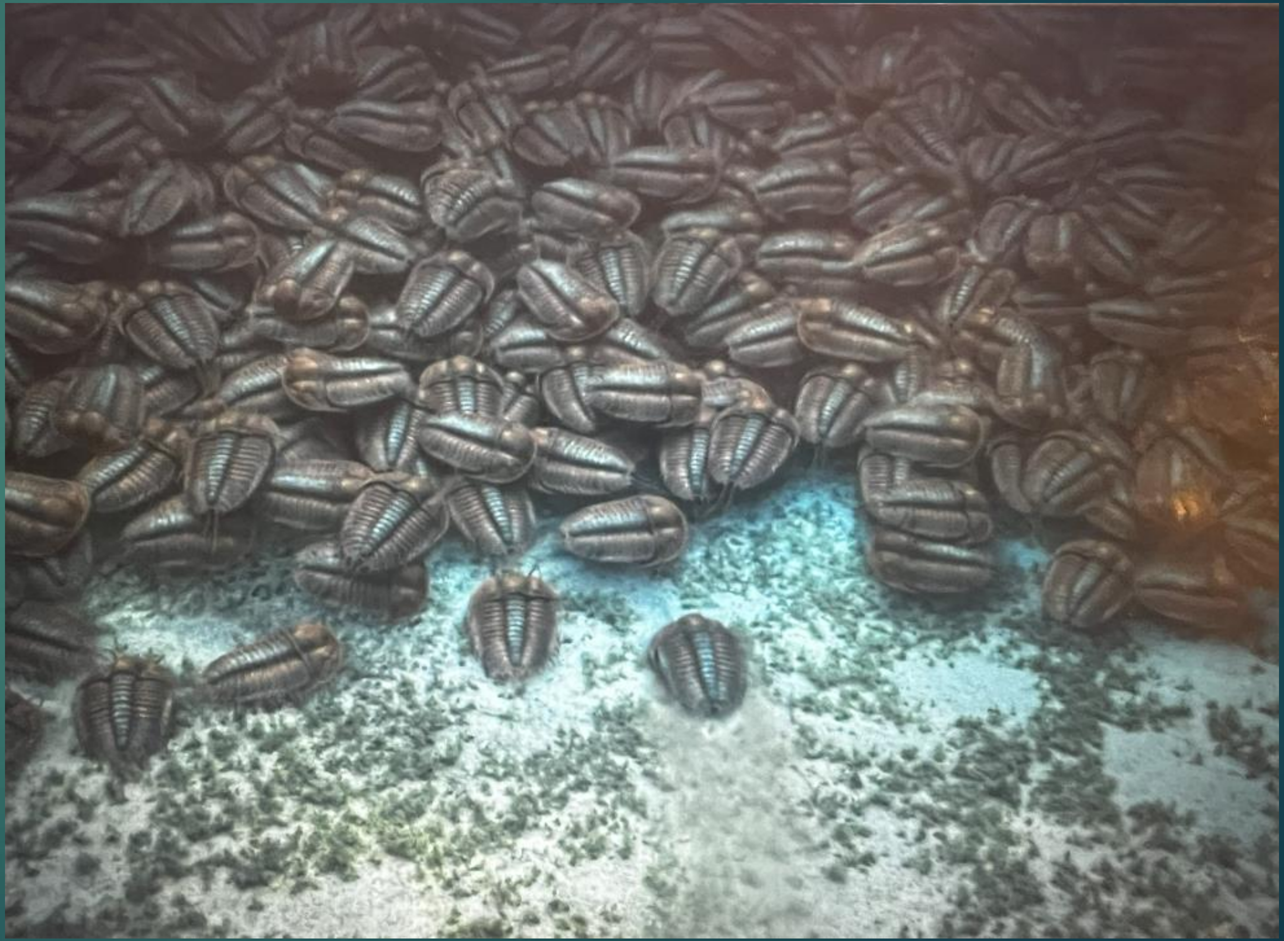
Trilobite Comparison Chart with Isotelus Rex the Largest

Trilobite variations

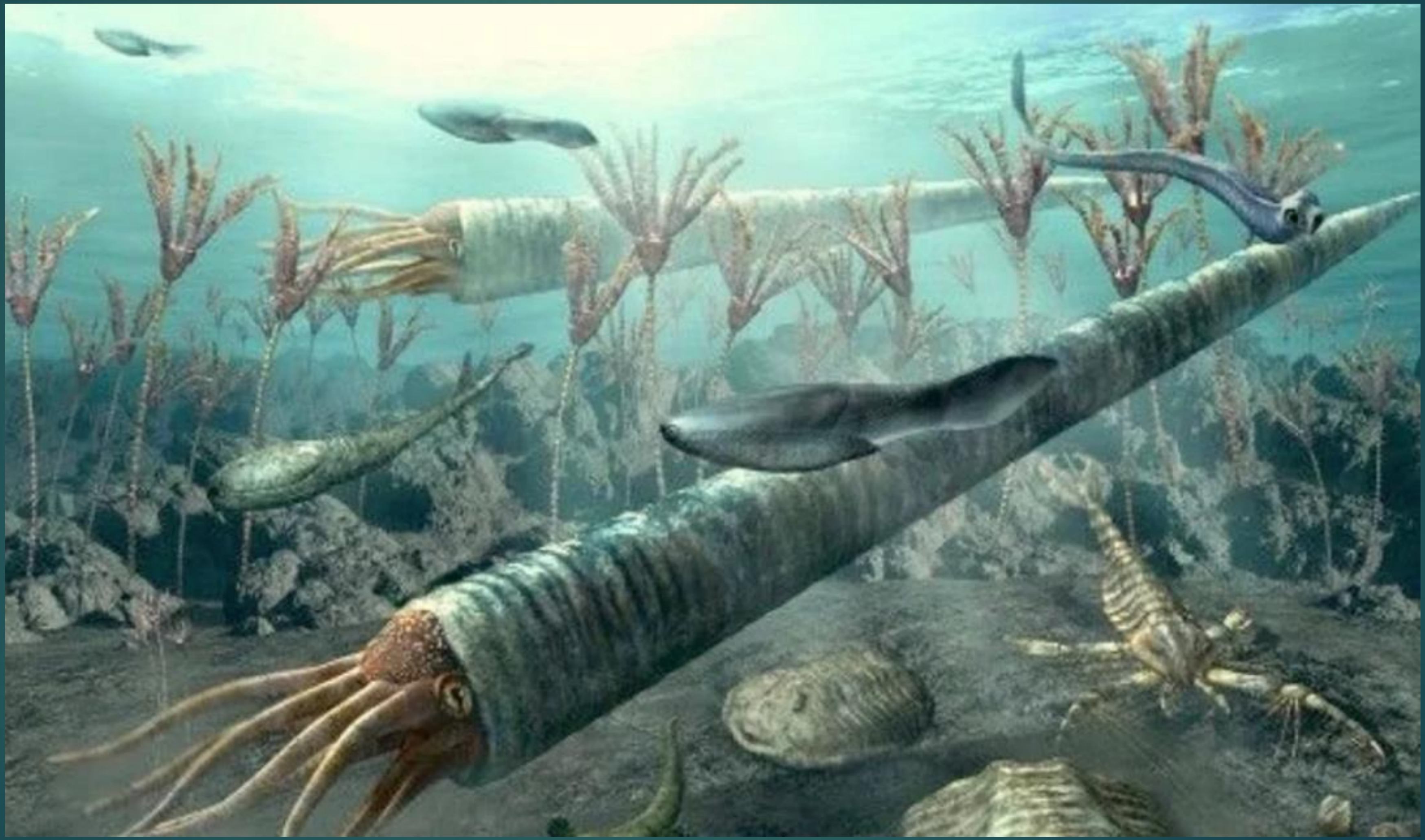


Trilobite

Trilobites



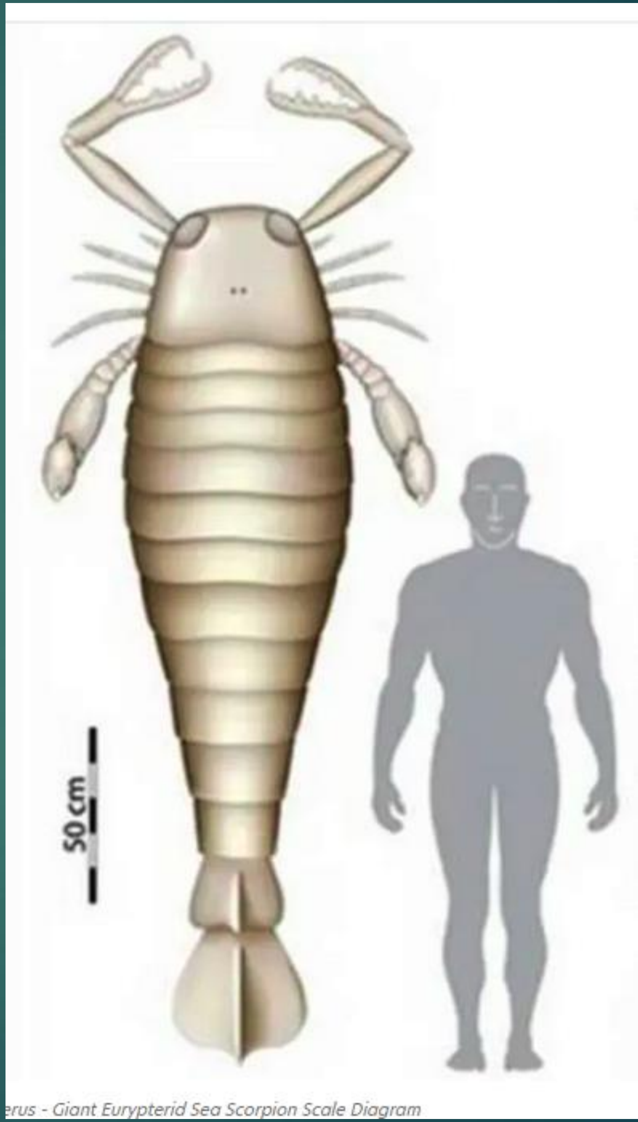
Orthoceras: 18-foot cephalopod: The T-Rex of the Ordovician, 490-443 Ma was a cephalopod nautiloid



Orthoceras

Orthoceras

Eurypterid Sea Scorpions: 460 – 248 Ma

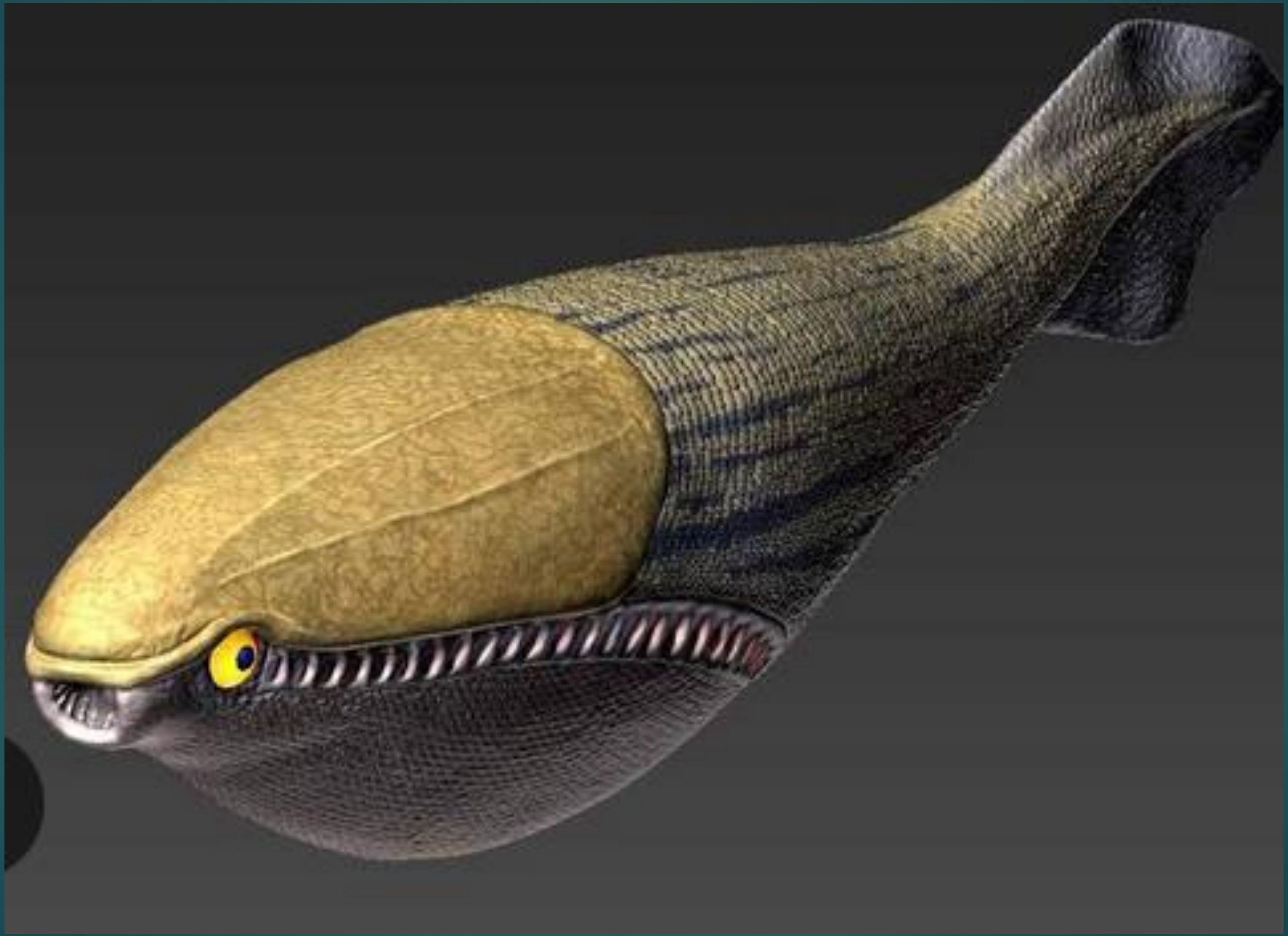


Giant Ammonite, 180 -145 Ma

Cephalopods

- 468 Ma: dominated by cephalopods (ancestors of octopus); largest had a towering shell 8 meters long (Cameroceras); can use sight and touch with tenacles
- Arandaspis, 480 Ma: jawless fish; oldest known vertebrate with a backbone; ancestor of all amphibians, reptiles, mammals, and birds

Arandaspis: vertebrate fish, 480 Ma, first backbone?



Cambrian was dominated by arthropods

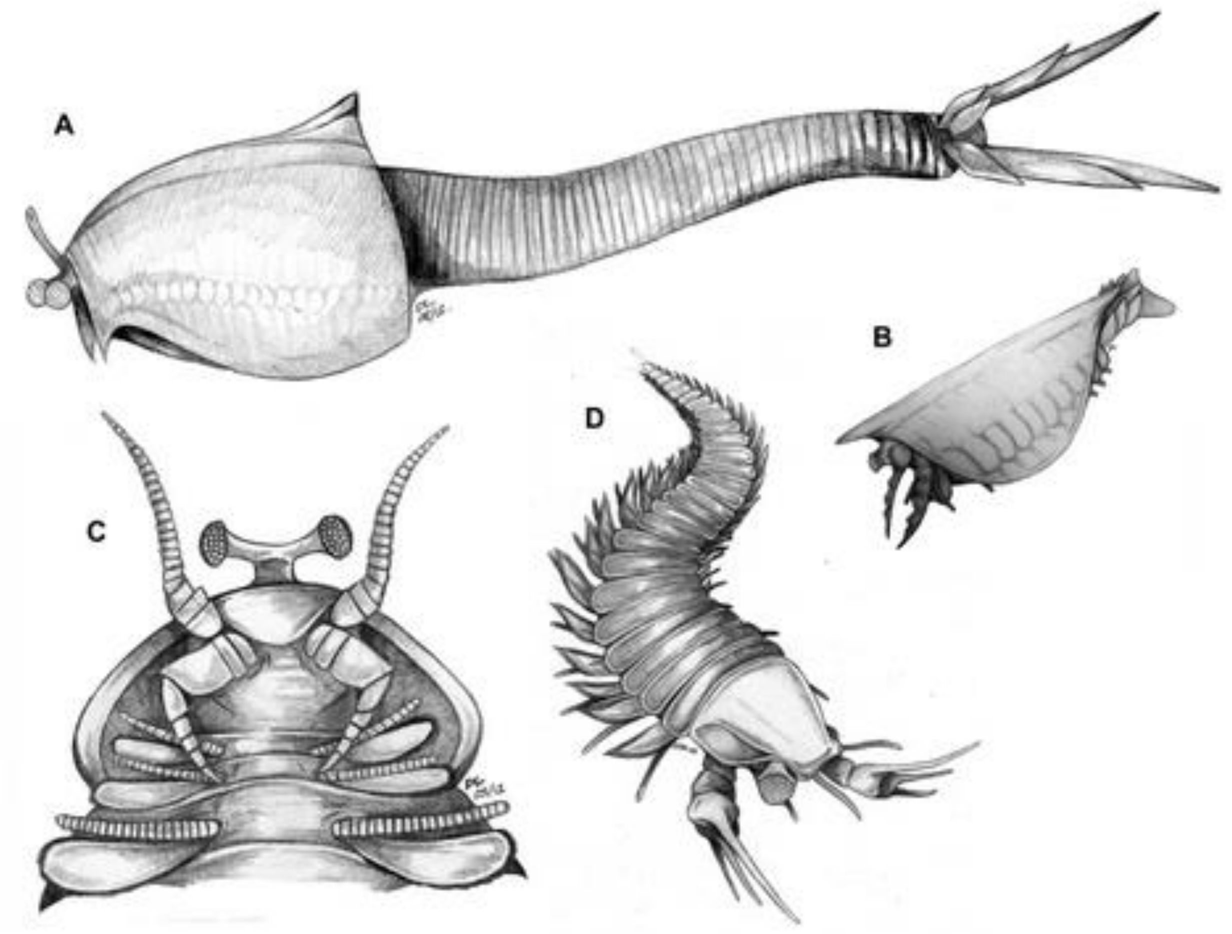


Figure 3 – The diversity of Cambrian arthropods. A, The bivalved arthropod *Nereocaris exilis* (source). B, The bivalved arthropod *Isoxys acutangulus* (source). C, The head region of *Fuxianhuia protensa*. D, The great-appendage arthropod *Kootenichela deppi* (source).

Invasion of the Land

- 500 Ma: For most of Earth's history, land had been inhospitable to life. A desolate realm; more like moon landscape.
- From beneath the waves, 1 curious lifeform emerged = Lichen. A combination of fungi and algae. Ground baking. As they spread, filaments broke down rock and created first soil.
- Then came microplants like moss. Carpeting the land. Ruled land alone for 40 million years
- Next revolution was compound lignon which strengthened plants cell walls, allowing them to grow bigger and stronger; trees: battled for real estate above; fighting for access to light
- Redwoods are tallest living things, at 100 meters, to have ever existed.

470 Ma: 1st plants; 370 Ma: Leaves

- 470 Ma: first plants on land; for 80 M years, no leaves, roots; restricted to being near water
- 430 Ma: first vascular plant; could lift above ground; had photosynthetic green stems with chlorophyl; had spores; compared to plants with leaves which capture 200% more sunlight
- 390 Ma: microphylls with leaves with single vein
- 375 Ma: CO2 took a dive by 90% by 350 MA which resulted in 2 minor ice ages that wiped out 75% of ocean species
- 350 Ma: Rise of real leaves (megaphylls) linked to this CO^2 decline; number of stomatas thru which they take in CO^2 significantly increased; as well as treelike form
- Feedback loop: Climate (CO2 drop) changed how plants evolved and in turn plants changed climate (trapped more carbon leading to mass extinction)

Biggest Extinctions start at 444 Ma

- The first of five great mass extinctions was the Ordovician-Silurian extinction (444 Ma). Its possible cause was the intense glaciation of Gondwana, carbon sequestration, which eventually led to a Snowball Earth. 60% of marine invertebrates became extinct and 25% of all families. = 86%

- The second mass extinction was the Late Devonian extinction (360 Ma), probably caused by the evolution of trees, which could have led to the depletion of greenhouse gases (like CO_2) or the eutrophication of water (accumulation of nutrients with algae blooms and oxygen drops), with severe cooling. 75% of all species became extinct.

Great Dying

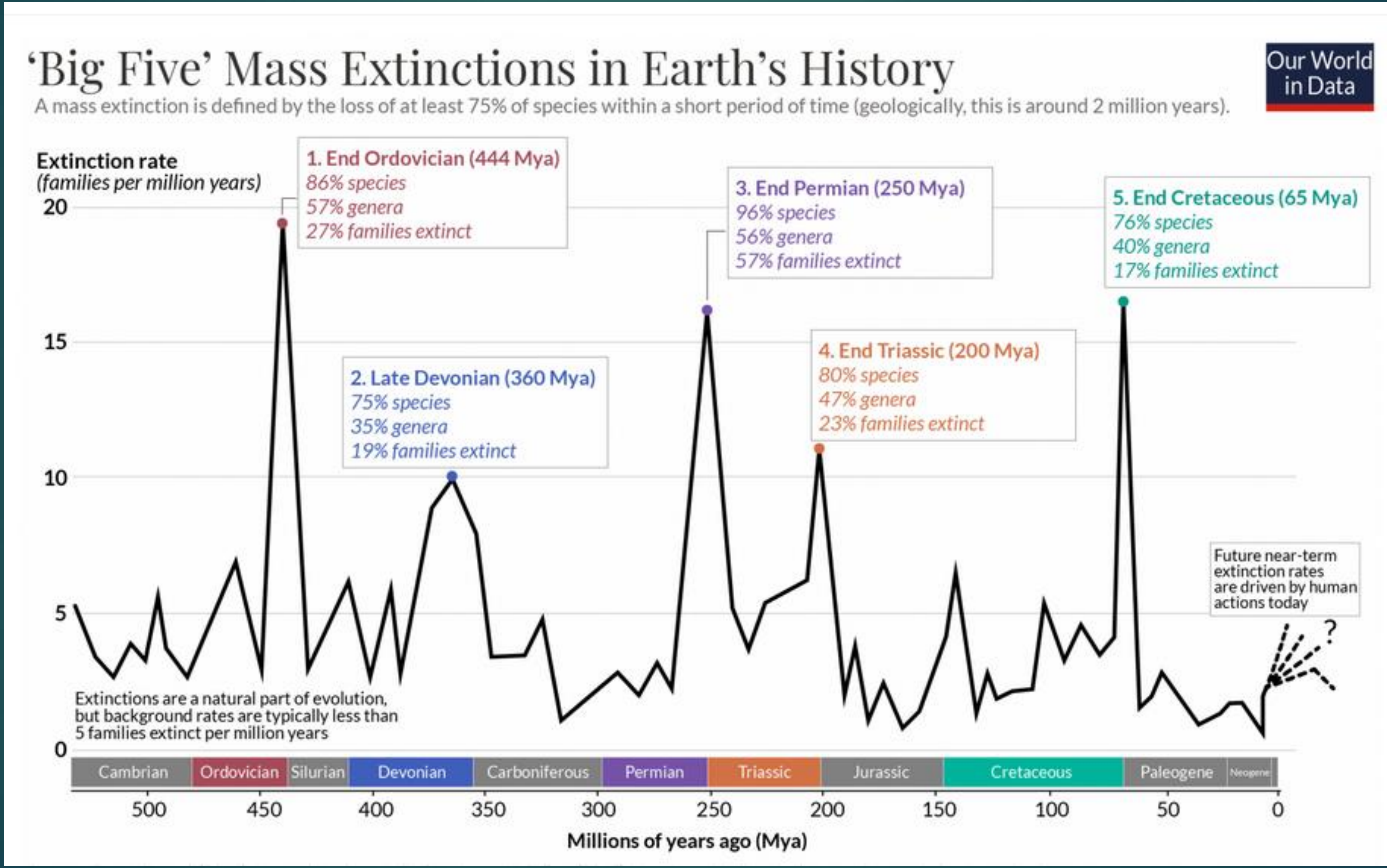
- The third mass extinction was the Permian-Triassic, or the Great Dying, 252 Ma, event was possibly caused by some combination of the Siberian Traps volcanic event, an asteroid impact, methane hydrate gasification, ocean acidification, and a major anoxic event.
- This was by far the deadliest extinction ever, with about 57% of all families and 83% of all genera killed. = 96%

Extinctions

- The fourth mass extinction was the Triassic-Jurassic extinction event (200 Ma) in which almost all synapsids and archosaurs became extinct, probably due to global warming and new competition from dinosaurs. = 80%

- The fifth and most recent mass extinction was the Cretaceous-Paleogene (K-Pg) extinction event. In 65 Ma, a 10-kilometer (6.2 mi) asteroid struck Earth just off the Yucatán Peninsula—somewhere in the southwestern tip of then Laurasia—where the Chicxulub crater is today.. 75% of all life, including the non-avian dinosaurs, became extinct. Predated by significant increase in volcanism.

There have been many more mass extinctions (~160)



How plants caused first mass extinction

- Cambrian, 535 Ma: no plants on land except microbial mats of cyanobacteria and fungi
- Caused increase in coldness and draining of Ox from oceans at 450 Ma, end Ordovician extinction event, 1st of big 5
- First land plants: Plant spore fossils from 452 Ma and 470 Ma; but molecular clock dates them to 515 Ma for 1st land plants; nonvascular, mosslike, algae or liverwort, with waxy coverings

Plants

- These clung to rock (cryptogamic cover) and weathered it producing phosphorus, potassium, & iron run offs

- Phosphorus following into ocean sediment cause massive algae blooms; algae decay produces anoxic conditions which buries carbon (black shale), cooling the atmosphere (dating to late Ordovician, 485 Ma for 44 M years)

- Volcanic activity also increased during this period

Ordovician–Silurian extinction events (End Ordovician): 445–444 Ma,

•Two events occurred that killed off 27% of all families, 57% of all genera and 85% of all species.

•Second-largest of the five major extinctions in Earth's history in terms of percentage of genera that became extinct.

- 460 to 430 million years ago mass extinction - Straddling the late Ordovician period and the early Silurian period –
- 1-2 punch: 1st = CO^2 drop, cooling, the Andean-Saharan ice age'
- 2nd = temp went back up, killing off cold adapted sea life; 80% death in oceans (corals, trilobites)

Ordovician–Silurian extinction events

Controversy: In May 2020, studies suggested that the causes of the mass extinction were global warming, related to volcanism, and anoxia, and not, as considered earlier, cooling and glaciation. However, this is at odds with numerous previous studies, which have indicated global cooling as the primary driver.

Most recently, the deposition of volcanic ash has been suggested to be the trigger for reductions in atmospheric carbon dioxide leading to the glaciation and anoxia observed in the geological record.

445 Ma

- 445 Ma: *World’s First Mass Extinction*: sea began to freeze; shallow seas became frozen graveyard. Fatal freeze caused by 60% drop in carbon dioxide (warming gas). Planet enters massive ice age, Snowball Earth, for 200 K years. At peak 50% of earth covered with ice; 85% of all life went extinct.

- Tropical coastal seas gone; only survivors in deeper ocean, i.e. nautili's – below 600 meters rarely changes temperature; cephalopods thrived – evolved without shells into every size and shape

- Only 10% of fish today live in the dark deep ocean

Dunkleosteus, 382 Ma

- 374 Ma: 70 million years after Great Melt, the Devonian; vertebrates made their move
- Dunkleosteus: 382–358 million years ago. It was a 9 meter pelagic fish with jaws and armor inhabiting open waters, and one of the first apex predators of any ecosystem; reigned for 20 million years
- Demise of Dunkleosteus: 2nd Mass extinction: Sudden surge in ocean nutrients caused massive plankton increase; thick soup rotted massively reducing oxygen; many species suffocated and coastlines filled with the dead; 80 percent of marine life went extinct
- Nutrients came from land plants – the greening of planet earth

Dunkleosteus, 382 Ma

Current Phanerozoic Eon, 539 Ma

- The Phanerozoic is the current eon on Earth, which started approximately 539 Ma. 3 eras: The Paleozoic, Mesozoic, and Cenozoic; the time when multi-cellular life greatly diversified into almost all the organisms known today.

- The Paleozoic ("old life") era was the first and longest era of the Phanerozoic eon, lasting from 538.8 to 251.9 Ma. During the Paleozoic, many modern groups of life came into existence. Life colonized the land, first plants, then animals. Two major extinctions occurred.

- The continents formed at the break-up of Pannotia and Rodinia at the end of the Proterozoic slowly moved together again, forming the supercontinent Pangaea in the late Paleozoic.

Mesozoic & Cenozoic

- The Mesozoic ("middle life") era lasted from 252 Ma to 66 Ma. It is subdivided into the Triassic, Jurassic, and Cretaceous periods.
- The era began with the Permian–Triassic extinction event, the most severe extinction event in the fossil record; 95% of the species on Earth died out. It ended with the end Permian extinction that wiped out the non-avian dinosaurs.
- The Cenozoic ("new life") era began at 66 Ma, Mammals, birds, amphibians, crocodilians, turtles, and lepidosaurs survived the extinction event that killed off the non-avian dinosaurs and many other forms of life, and this is the era during which they diversified into their modern forms.

Cenozoic, 66 Ma

- For first 10 million years, desolate world; open ecological niches
- Modern animals appear in the Cenozoic: Ungulate mammals, carnivorous creodons, earliest primates
- 55-34 Ma, Eocene: warmed up, a thermal maximum; largest snake at 13 meters; giant turtles
- 49 Ma: got colder: Azolia plant in Artic took up 50% of CO_2; 45 groups of mammals disappeared

Cenozoic

- Oligocene, 33-23 Ma:
  - old world monkeys; ice age in Europe;
  - 1st appearance of grasslands; ruminants develop with extra stomach;
  - 1st new world monkeys at 26 Ma in S America

- Miocene, 23-5 Ma: Himalayas, Pyrenes, Alps begin; first apes – Proconsul; grasslands spread

- 13 Ma: orangutans spit, 10 Ma gorillas, 7 Ma chimps and humans

- Pliocene, 5- 2.5 Ma: Australopithecus at 4 Ma; Homo at 2.8 Ma

- Quaternary, 2.5 Ma-present: cooling, megafauna

Colonization of land, 488 Ma

- Adaptation to life on land is a major challenge: all land organisms need to avoid drying-out and all those above microscopic size must create special structures to withstand gravity; respiration and gas exchange systems have to change; reproductive systems cannot depend on water to carry eggs and sperm towards each other.

- Although the earliest good evidence of land plants and animals dates back to the Ordovician period (488 to 444 Ma), and a number of microorganism lineages made it onto land much earlier, modern land ecosystems only appeared in the Late Devonian, about 385 to 359 Ma.

Life on land; bacteria and fungus first

- In May 2017, evidence of the earliest known life on land may have been found in 3.48-billion-year-old geyserite and other related mineral deposits (often found around hot springs and geysers) uncovered in the Pilbara Craton of Western Australia.

- In July 2018, scientists reported that the earliest life on land may have been bacteria living on land 3.2 billion years ago.

- In May 2019, scientists reported the discovery of a fossilized fungus, named *Ourasphaira giraldae*, in the Canadian Arctic, that may have grown on land a billion years ago, well before plants were living on land.

Land invertebrates, 490 Ma

- The oldest animal with evidence of air-breathing, although not being the oldest myriapod fossil record, is *Pneumodesmus*, an archipolypodan millipede from the Early Devonian, about 414 Ma.

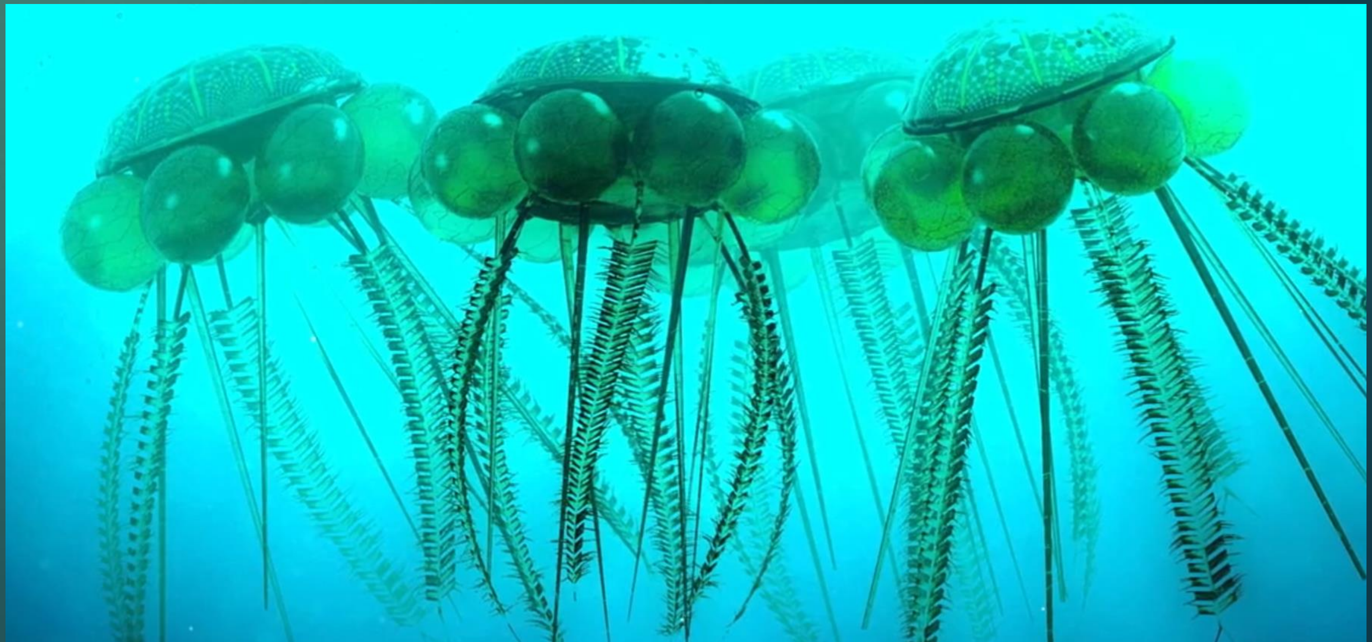
- However, some earlier trace fossils from the Cambrian-Ordovician boundary about 490 Ma are interpreted as the tracks of large amphibious arthropods on coastal sand dunes, and may have been made by euthycarcinoids.

Insects, ~480 Ma

- Insects originated at about the same time terrestrial plants appeared.
- Insects are thought to have evolved from a group of crustaceans. The first insects were flightless, but about 400 Ma ago one lineage of insects evolved flight, the first animals to do so.
- The earliest confirmed fossils of flying insects date from the Late Carboniferous, but it is thought that insects developed the ability to fly earlier in the Early Carboniferous or even Late Devonian. This gave them a wider range of ecological niches for feeding and breeding, and a means of escape from predators and from unfavorable changes in the environment.
- About 99% of modern insect species fly or are descendants of flying species.

485 Ma - Silurian

- Filter feeding Graptolites became motile
- 15 recurrent extinctions; no Ox at bottom of ocean; high hydrogen sulfide; 95% of graptolites disappear in mid Silurian
- No plants on land
- Supercontinent Gondwana near South Pole; massive dust storms



Plants, 476 Ma

- Life on land requires plants to become internally more complex and specialized: photosynthesis is most efficient at the top; roots extract water and nutrients from the ground; and the intermediate parts support and transport.

- Spores of land plants resembling liverworts have been found in Middle Ordovician rocks from 476 Ma. Middle Silurian rocks from 430 Ma contain fossils of true plants, including clubmosses; most were under 3.9 in high, and some appear closely related to vascular plants, the group that includes trees.

420-359 Ma, Devonian: Plants

- Plants at first are moss like (470 Ma); newer small plant at 407 Ma consisting of wood that held water; stomata to absorb CO^2
- Wood developed 5 different times as way to keep plants hydrated in dry areas
- 30-meter fernlike Archaeopteris at 385 Ma, one of first modern trees; had roots, wood, seeds; roots created more soil which allowed for meandering rivers;
- CO2 began to decline, leading to mass extinction in oceans at end of Devonian

Fernlike 30 meter tree: *Archaeopteris*

End Ancient Earth, Part I