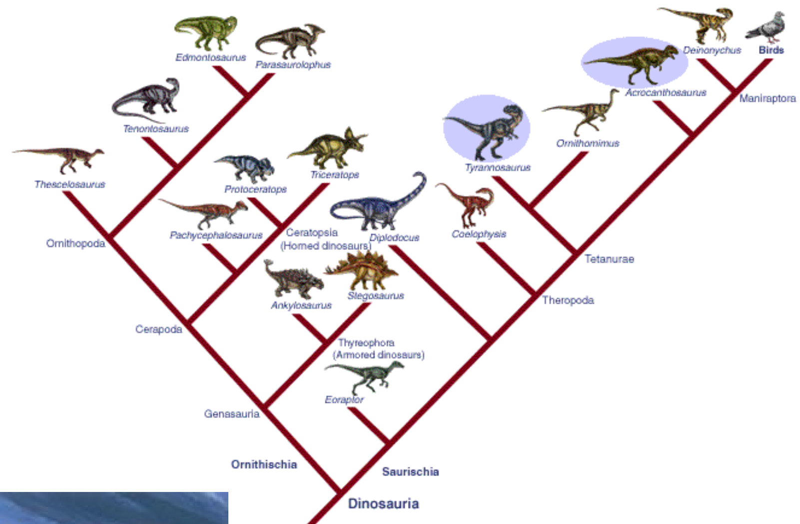
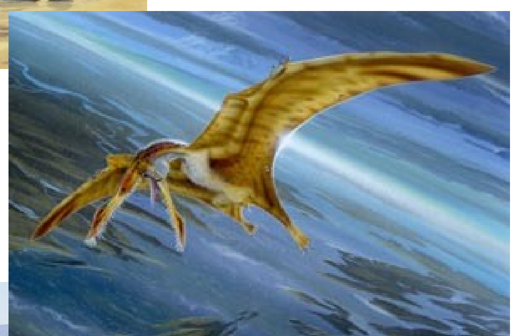
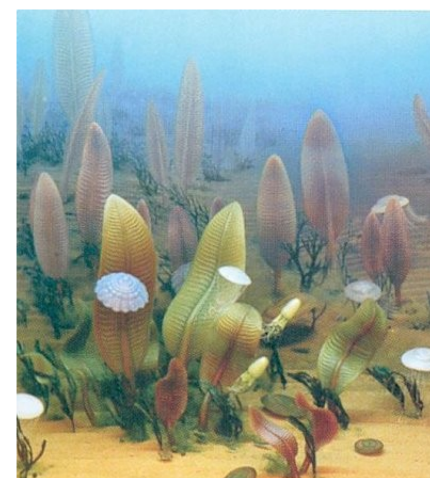
HISTORY OF LIFE ON EARTH



Asteroid Impact David A. Hardy





Systematics and taxonomy

systematics, paleontology $\rightarrow$ history of evolutionary changes

systematics = study of relationships between organisms

taxonomy = theory and practice of classification

category: class, order, family, species, …

taxon: Mammalia, Primates, Hominidae, *Homo sapiens*, …

1. Before Linnaeus

honeybee = *Apis pubescens, thorace subgriseo, abdomine fusco, pedibus posticis glabris utrinque margine ciliatis*

[Bee with soft short hairs, gray chest, dark brown abdomen, legs with no hair, and small sacs with hair-like outgrowths along the edge]

Acaciae quodammodo accedens, Myrobalano chebulo Veslingii similis arbor Americana spinosa, foliis ceratoniae in pediculo geminatis, siliqua bivalvi compressa corniculata seu cochlearum vel arietinorum cornuum in modum incurvata, sive Unguis cati

[A spiny American tree, in some way resembling Acacia, similar to Vesling´s *Myrobalanus chebulae*, with *Ceratonia* leaves in pairs on the pedicle, a silique with two valves, which is compressed, and horn-shaped or curved like the horns of snailshells or ram´s horns, or like a cat´s claws]

European bison = buffle, urus, bubalus, catoblepas, theur, the bubalus of Belon, Scottish bison

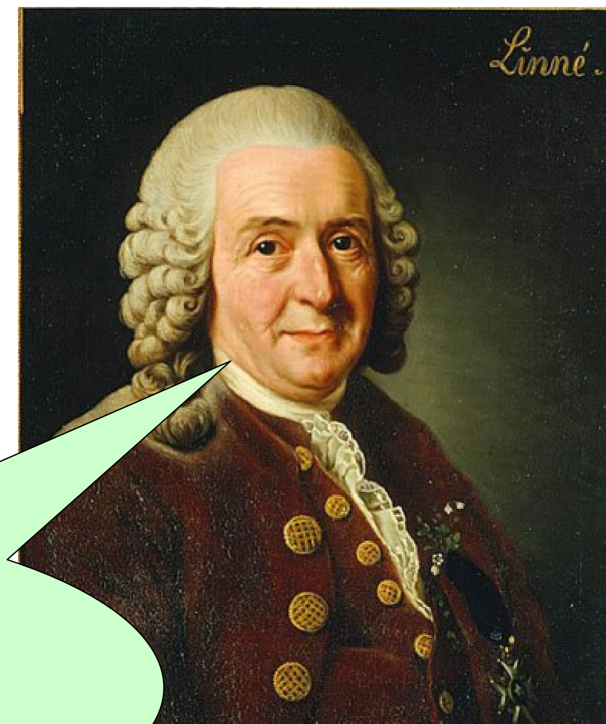
… Aristotle: bonasus → the same?

2. Carolus Linnaeus:

1735 *Systema Naturae*

binomial nomenclature: genus + species

hierarchical classification:
kingdom, class, order, genus, species, (variety/subspecies)



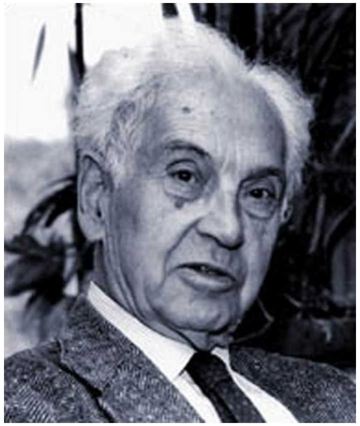
Carolus Linnaeus

Species tot sunt diversae quot diversas formas ab initio creavit infinitum Ens

3. Darwin:

cladogenesis (branching) and anagenesis (change without branching)

a system should reflect a real phylogeny → but HOW?



E. Mayr

Evolutionary systematics

before 1950: common ancestor + adaptive divergence

discussions if adaptive or neutral traits better

subjective and unclear criteria of choosing and weighing of traits ⇒ taxonomy in crisis (⇒ the word „taxonomy" itself replaced by „systematics")

controversy between splitters and lumpers

Numerical taxonomy (phenetics)

Hoplitis

1957: Charles Michener, Robert Sokal, P.H.A. Sneath

taxonomy should be based on a total similarity rather than on a small number of „important“ traits

⇒ as many traits as possible

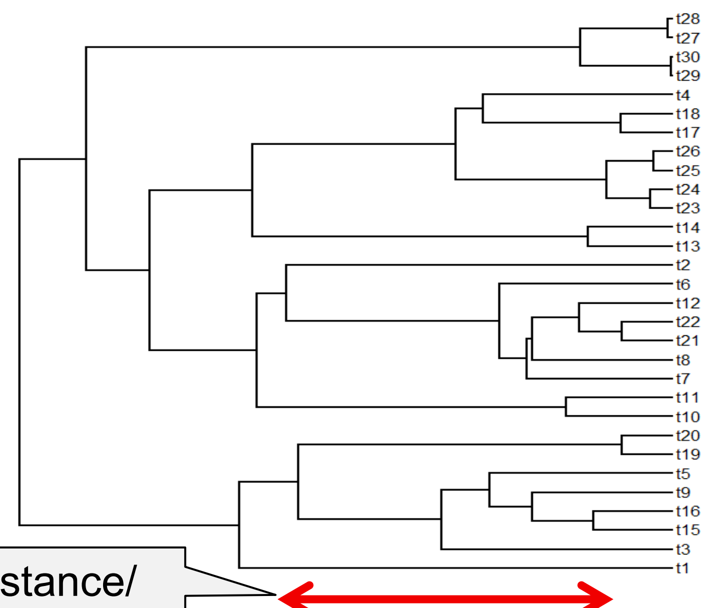
numerical methods: morphological and genetic distances, ordination (PCA, DFA, CVA, MDS, ...), cluster analysis (UPGMA)

phenograms

problems:

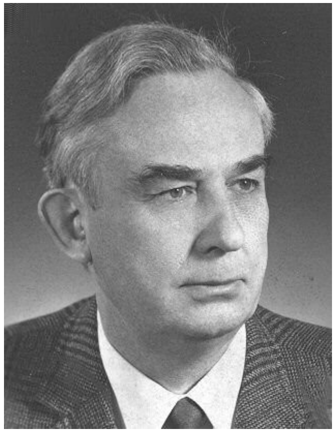
- homoplasy (= convergence, parallelism, reversion)
- shared primitive (ancestral) traits
- unequal rate of evolution

phenogram



distance/
similarity

Phylogenetic systematics (cladistics)

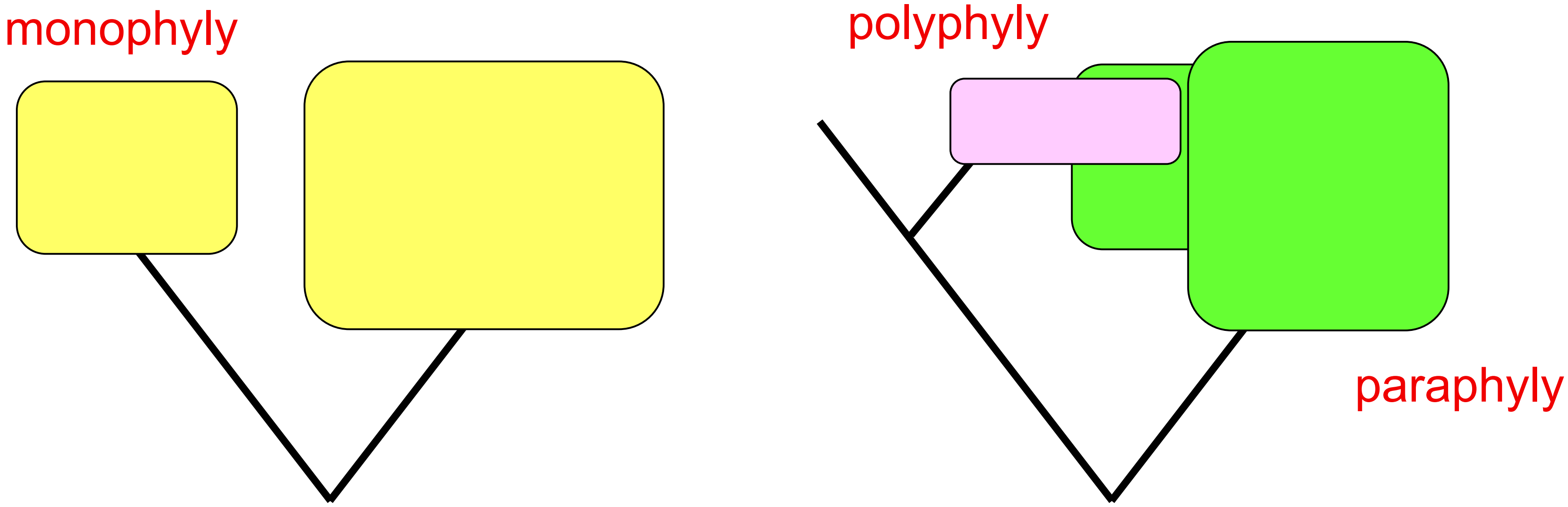

W. Hennig

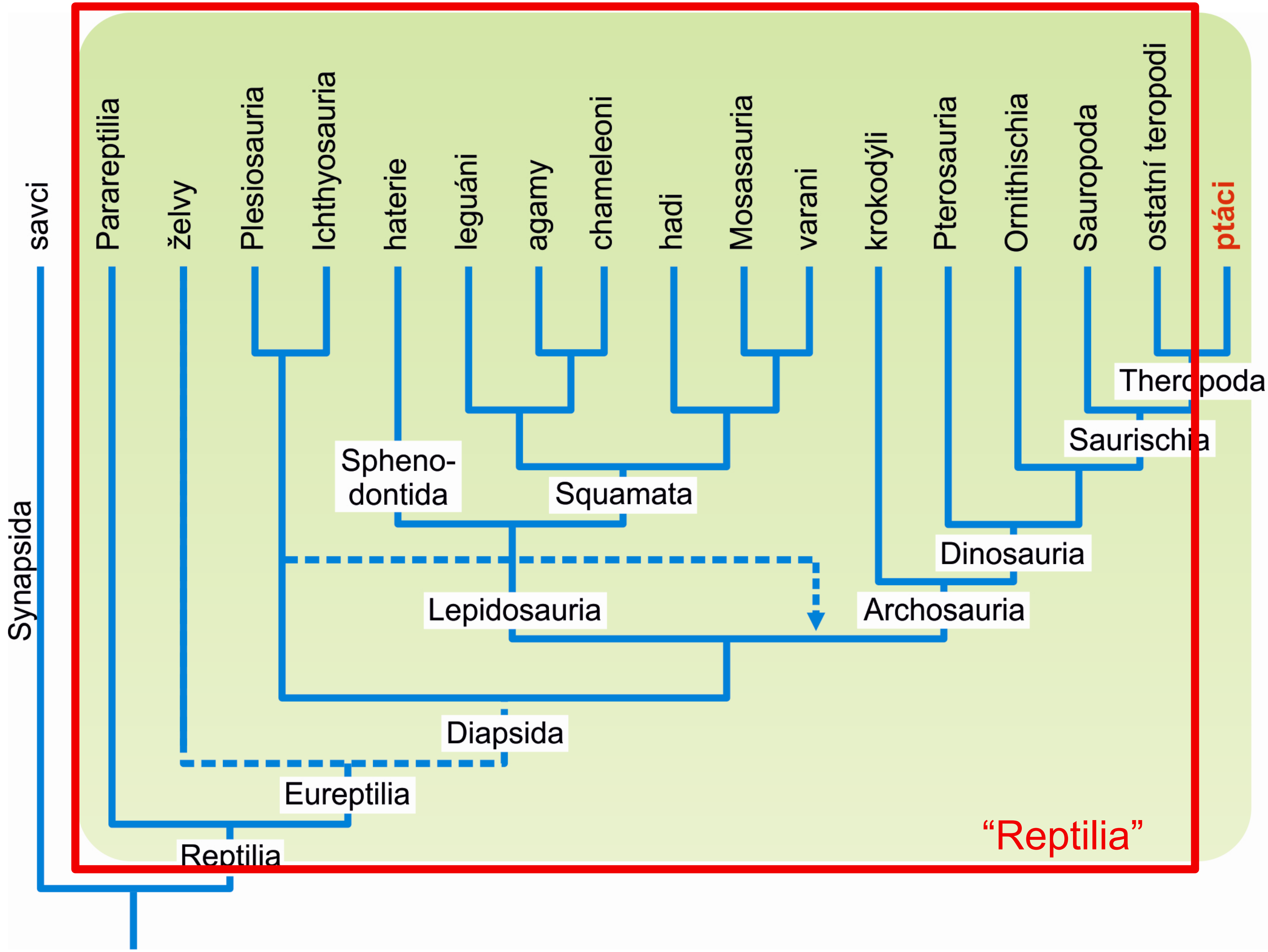
1950, 1966: Willi Hennig: *Phylogenetic Systematics*

only genealogies, not adaptive divergence

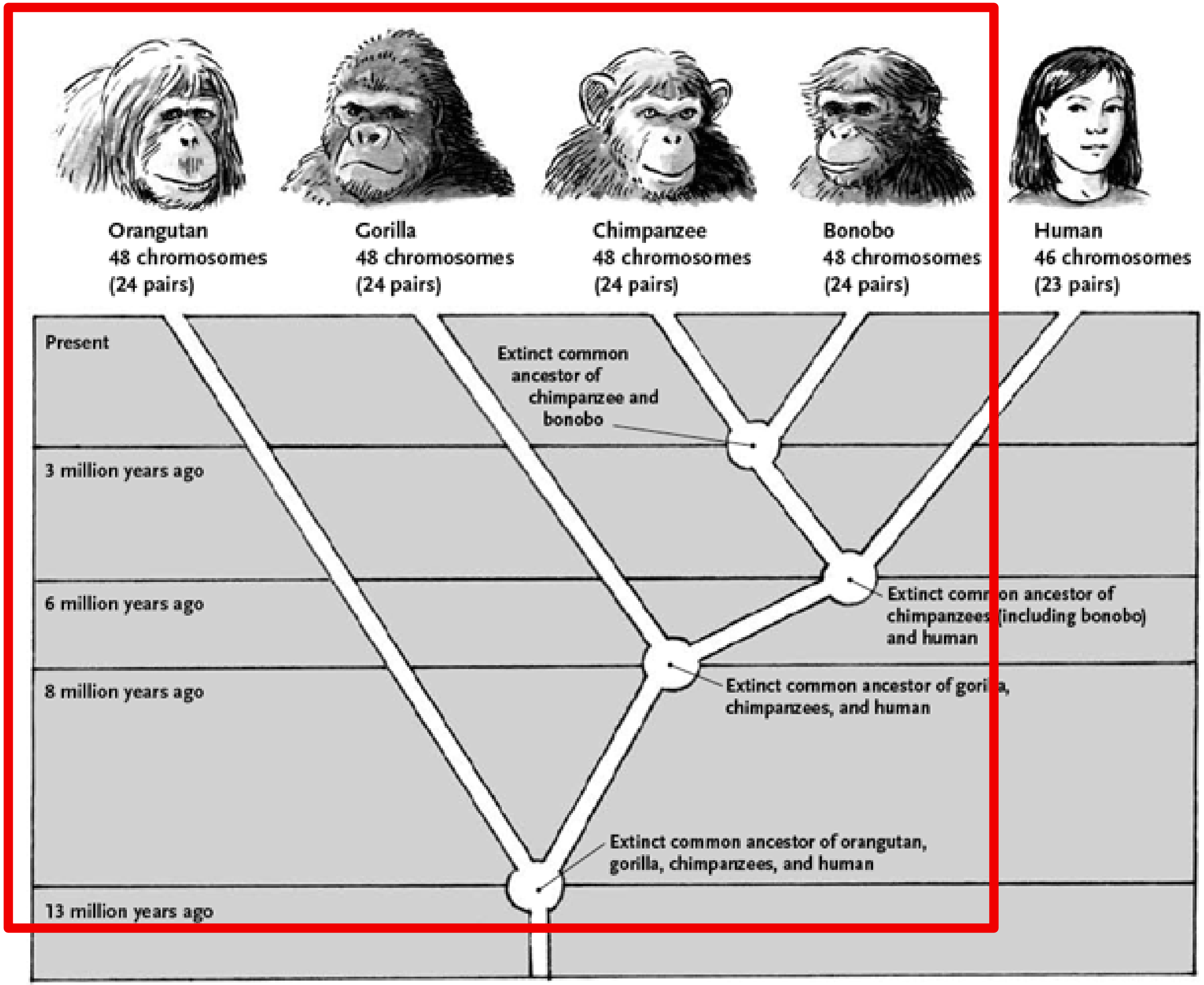
strict monophyly

monophyletic group = clade




savci
Parareptilia
želvy
Plesiosauria
Ichthyosauria
haterie
leguáni
agamy
chameleoni
hadi
Mosasauria
varani
krokodýli
Pterosauria
Ornithischia
Sauropoda
ostatní teropodi
ptáci
Theropoda
Saurischia
Spheno-
dontida
Squamata
Dinosauria
Lepidosauria
Archosauria
Diapsida
Eureptilia
Reptilia
Synapsida
“Reptilia”

“Pongidae”

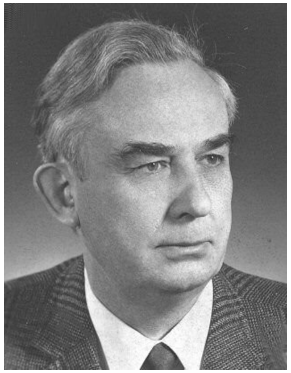


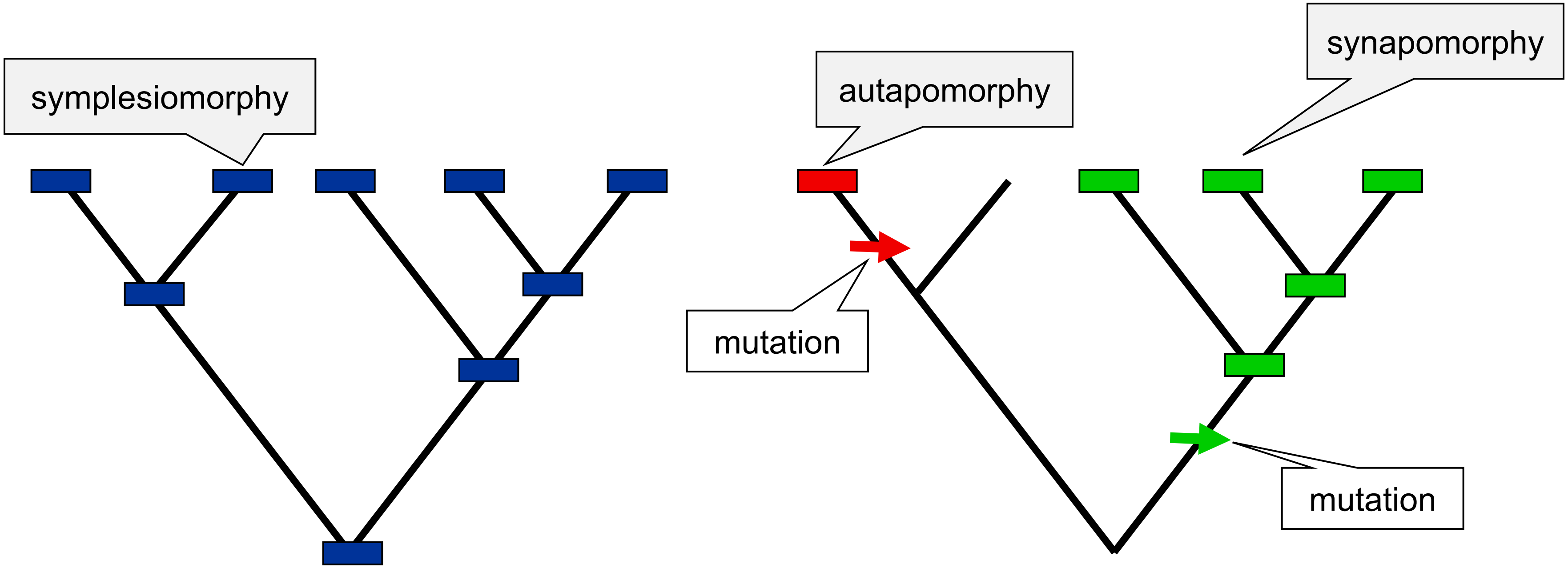
Orangutan
48 chromosomes
(24 pairs)
Gorilla
48 chromosomes
(24 pairs)
Chimpanzee
48 chromosomes
(24 pairs)
Bonobo
48 chromosomes
(24 pairs)
Human
46 chromosomes
(23 pairs)
Present
Extinct common ancestor of chimpanzee and bonobo
3 million years ago
6 million years ago
Extinct common ancestor of chimpanzees (including bonobo) and human
8 million years ago
Extinct common ancestor of gorilla, chimpanzees, and human
Extinct common ancestor of orangutan, gorilla, chimpanzees, and human
13 million years ago

characters:

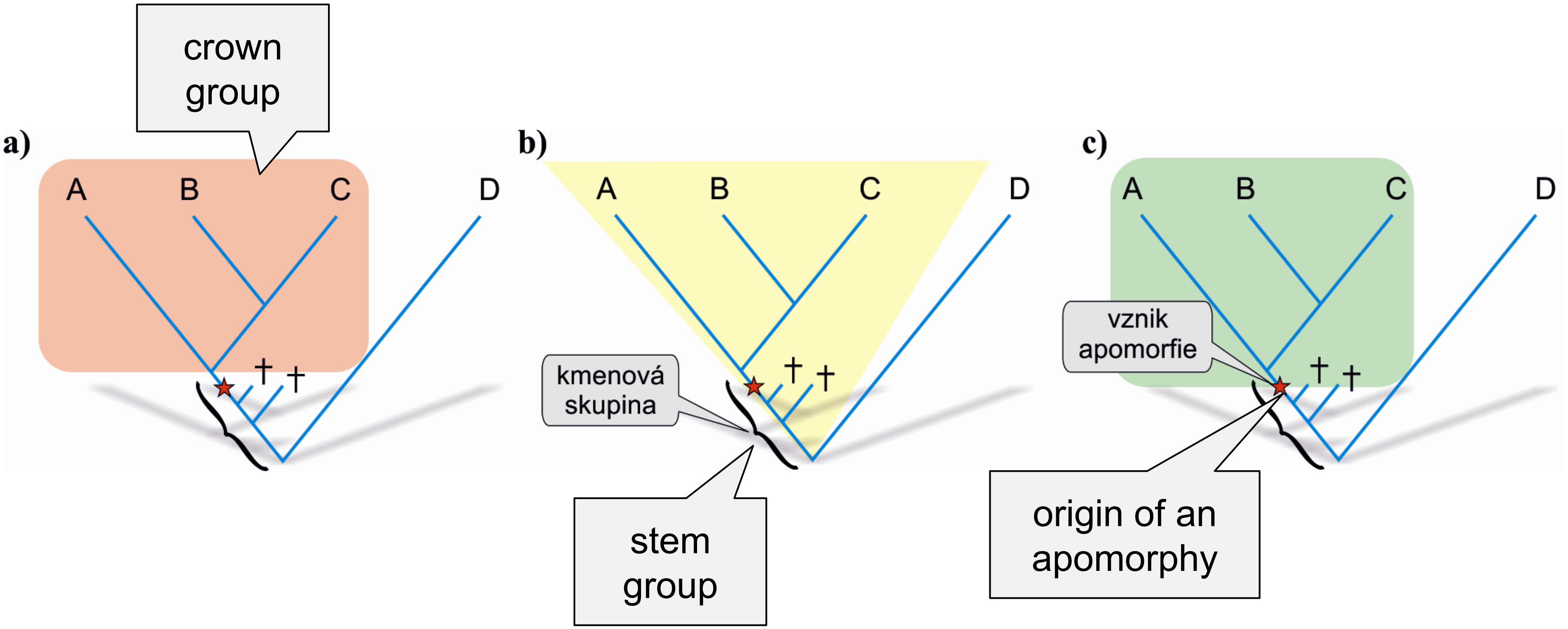
- plesiomorphic (= ancestral, „primitive“)
  - symplesiomorphic (= shared ancestral)
- apomorphic (= derived)
  - synapomorphic (= shared derived)
  - autapomorphic (= unique derived)

clades defined only by synapomorphies

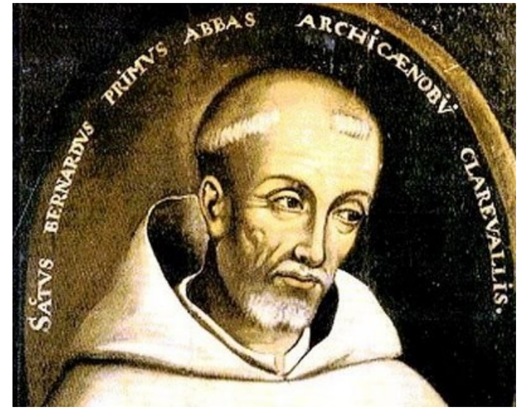




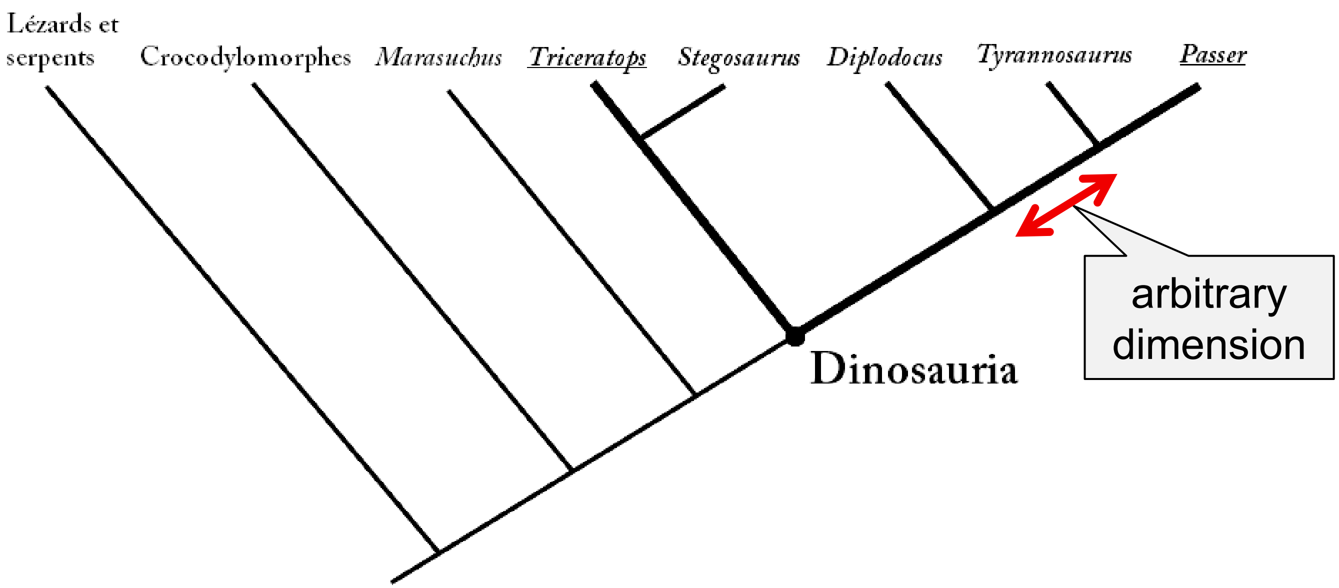
Definition of clades and classification of extinct taxa:



principle of parsimony: Occam´s razor
(William of Ockham, 14th century)



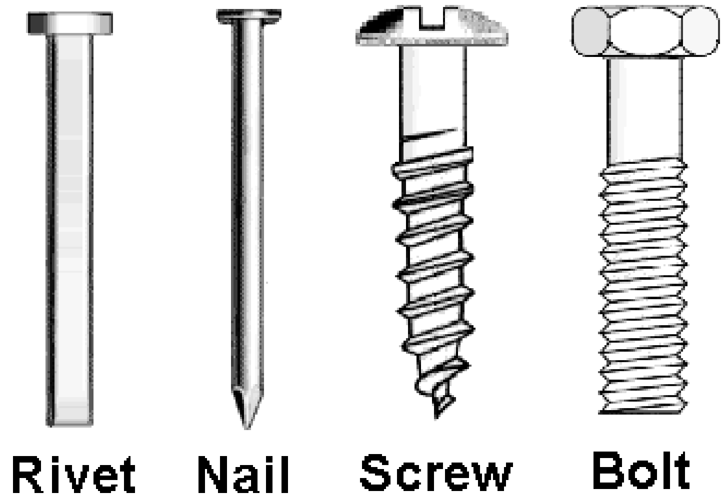
cladograms



PhyloCode (*International Code of Phylogenetic Nomenclature*)
till now somewhat controversial and impractical

problems: homoplasy, rapid evolution

Cladistics and phenetics exemplified by the „evolution“ of fasteners



Rivet: the simplest structure ⇒ we suppose that it is the most similar to the common ancestor of all modern types of fasteners

We can define 7 <u>derived character states</u> (ie. those nonexistent in rivets):

1) notched heads, 2) rounded heads, 3) hex heads, 4) threaded shafts, 5) tapered shafts, 6) pointed tips, and 7) thick diameter.

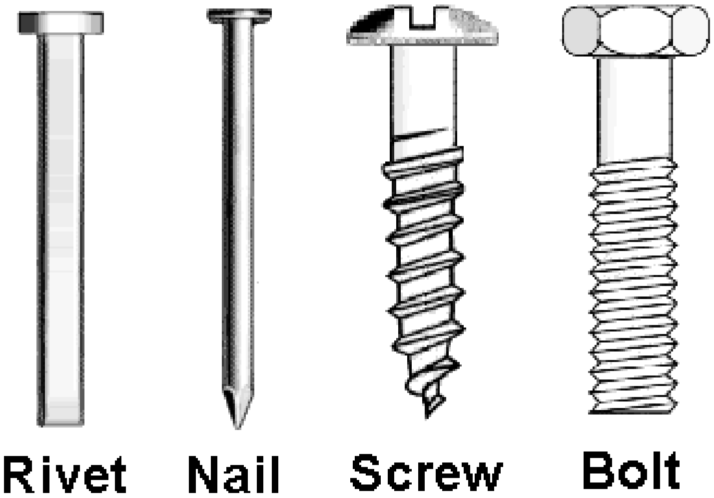
Cladistics and phenetics exemplified by the „evolution" of fasteners

Character states of all 4 types are listen in the following table where

„0" = plesiomorphic („rivet-like") state

„1" = apomorphic (derived) state

Character	Rivet	Nail	Screw	Bolt
Head notch	0	0	1	0
Rounded head	0	0	1	0
Hex head	0	0	0	1
Threaded shaft	0	0	1	1
Tapered shaft	0	0	1	0
Pointed tip	0	1	1	0
Thick diameter	0	0	1	1



Cladistics and phenetics exemplified by the „evolution“ of fasteners

Character	Rivet	Nail	Screw	Bolt
Head notch			1	0
Rounded head			1	0
Hex head			0	1
Threaded shaft			1	1
Tapered shaft			1	0
Pointed tip			1	0
Thick diameter			1	1

Phenetic Comparison (Total of all shared states)				
	Rivet	**Nail**	**Screw**	**Bolt**
Rivet	-	6	1	4
Nail		-	2	3
Screw			-	2
Bolt				-

If we use the phenetic approach we count the total number of shared states (both ancestral and derived).

For example rivet *vs.* nail: 6 similarities, 1 difference

Cladistics and phenetics exemplified by the „evolution“ of fasteners

Character	Rivet	Nail	Screw	Bolt
Head notch	0	0	1	0
Rounded head	0	0	1	0
Hex head	0	0	0	1
Threaded shaft	0	0	[illegible]	[illegible]
Tapered shaft	0	0	1	0
Pointed tip	0	[illegible]	[illegible]	0
Thick diameter	0	0	[illegible]	[illegible]

Cladistic Comparison (Total of derived states only)				
	Rivet	Nail	Screw	Bolt
Rivet	-	0	0	0
Nail		-	1	0
Screw			-	2
Bolt				-

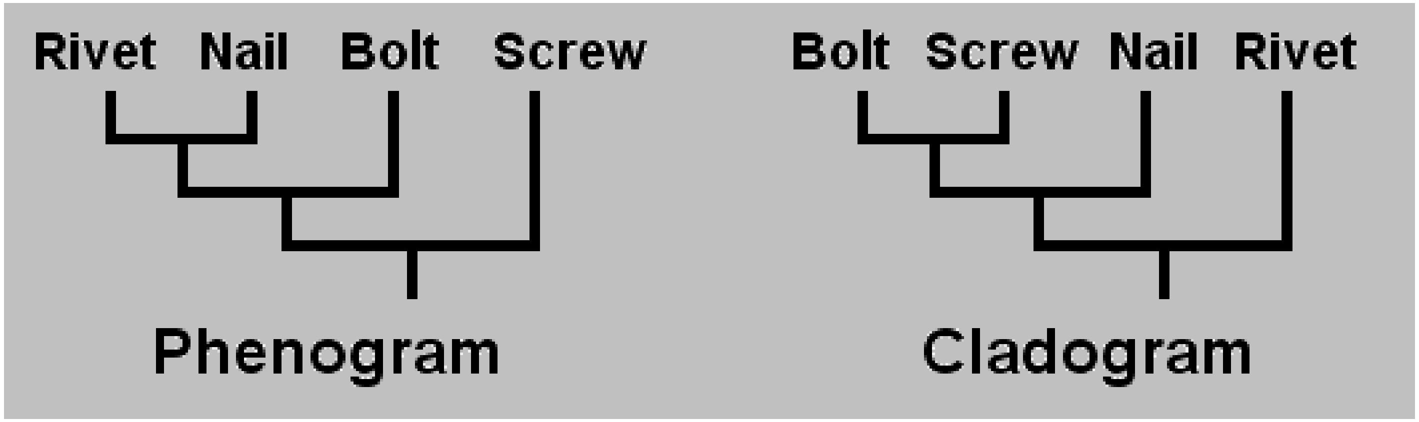
If we use the cladistic approach we take into account only shared derived states.

For example. screw *vs.* bolt: 2 synapomorphies

Cladistics and phenetics exemplified by the „evolution“ of fasteners

Phenetic Comparison (Total of all shared states)				
	Rivet	Nail	Screw	Bolt
Rivet	-	6	1	4
Nail		-	2	3
Screw			-	2
Bolt				-

Cladistic Comparison (Total of derived states only)				
	Rivet	Nail	Screw	Bolt
Rivet	-	0	0	0
Nail		-	1	0
Screw			-	2
Bolt				-



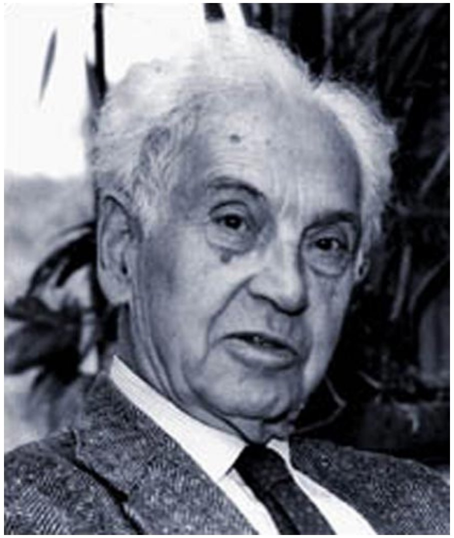
Evolutionary systematics – a response

phylogenetic relationships + degree of divergence ⇒ combination of phenetic and cladistic approach

reflection of both clades and grades

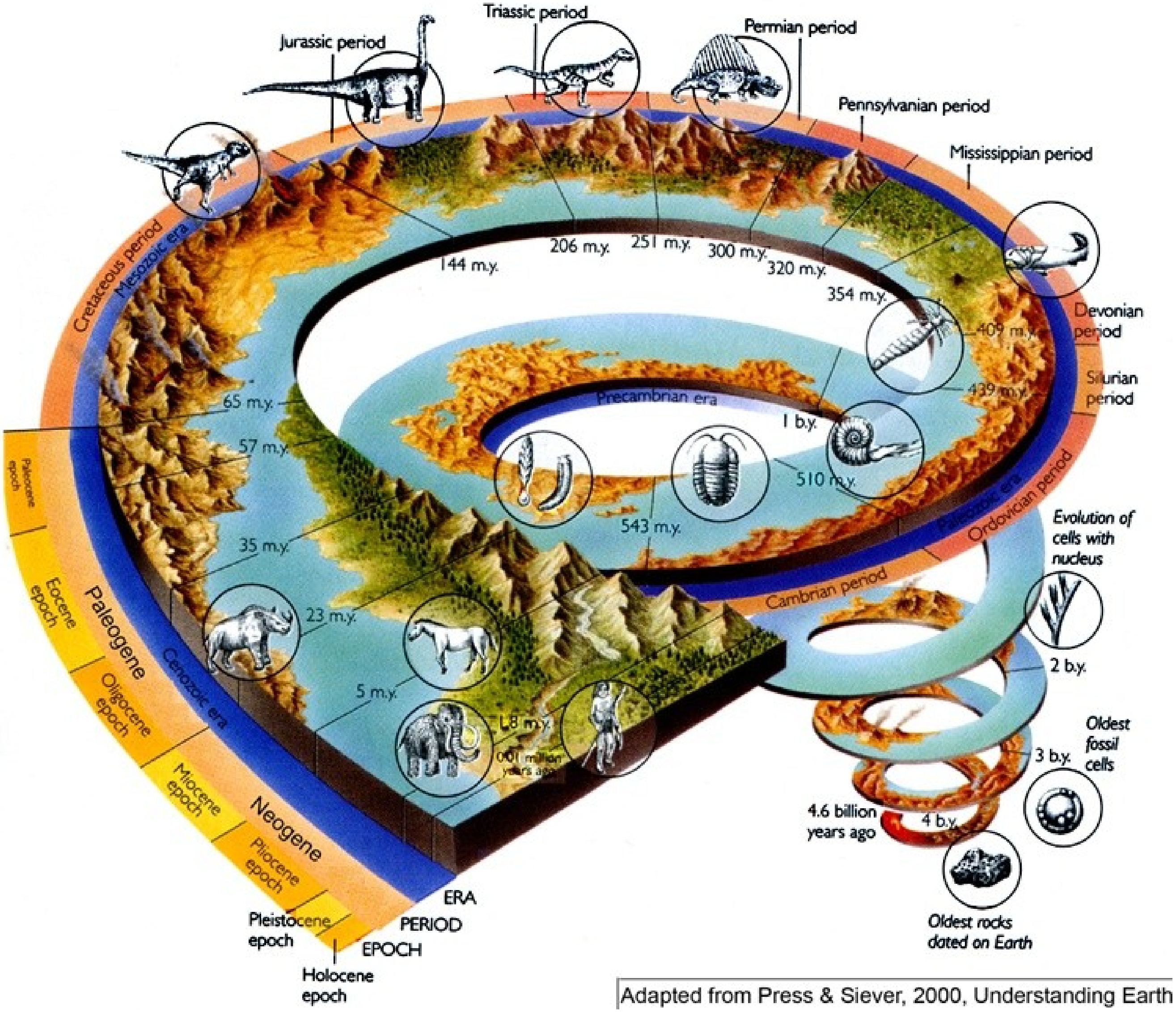
An evolutionary grade is a group of similar species that has given rise to another group that differs markedly from the ancestral condition, and is thus not considered part of the ancestral group.
⇒ the ancestral group is then paraphyletic

eg. reptiles (without birds),
fishes in a traditional sense

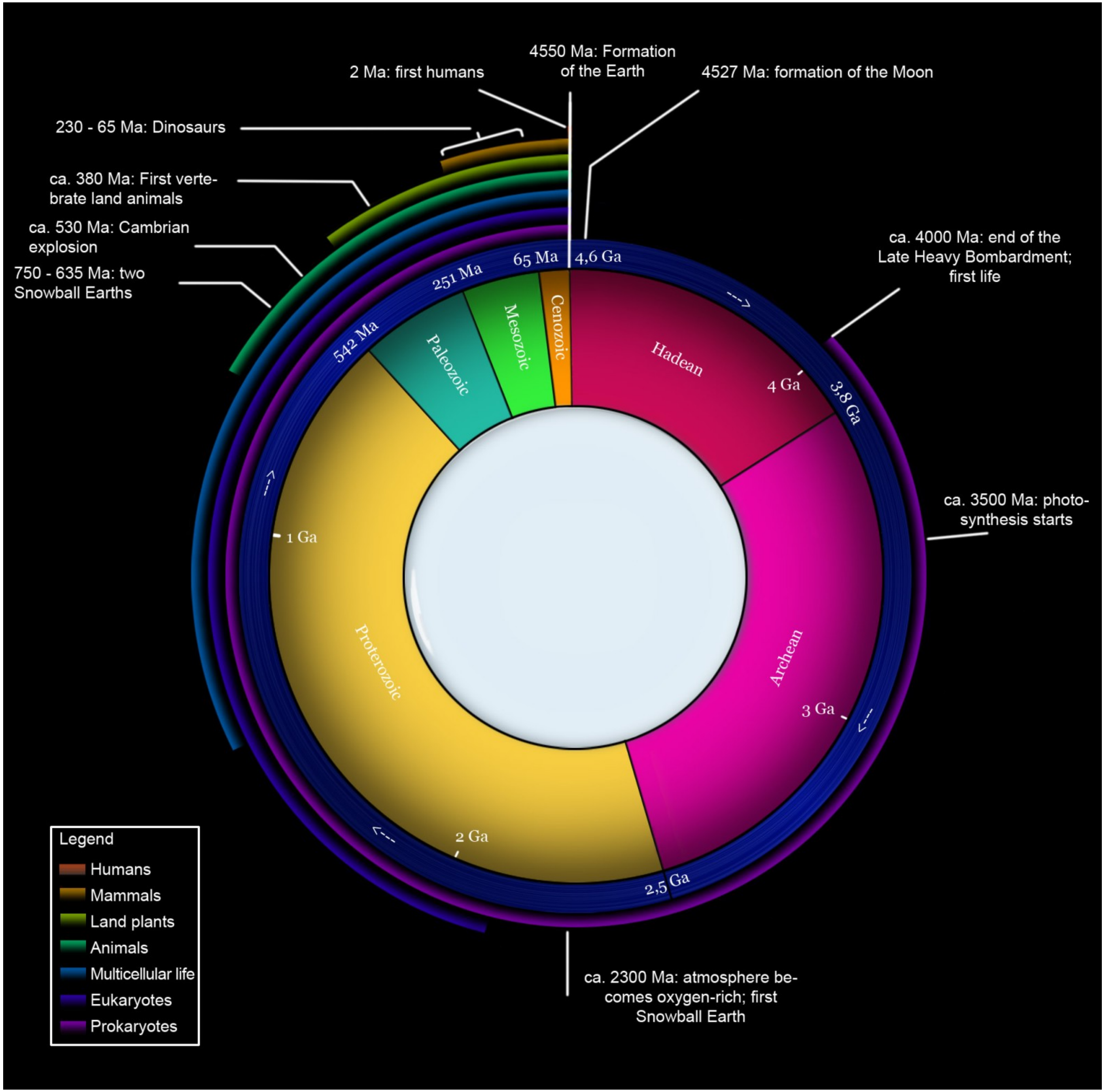


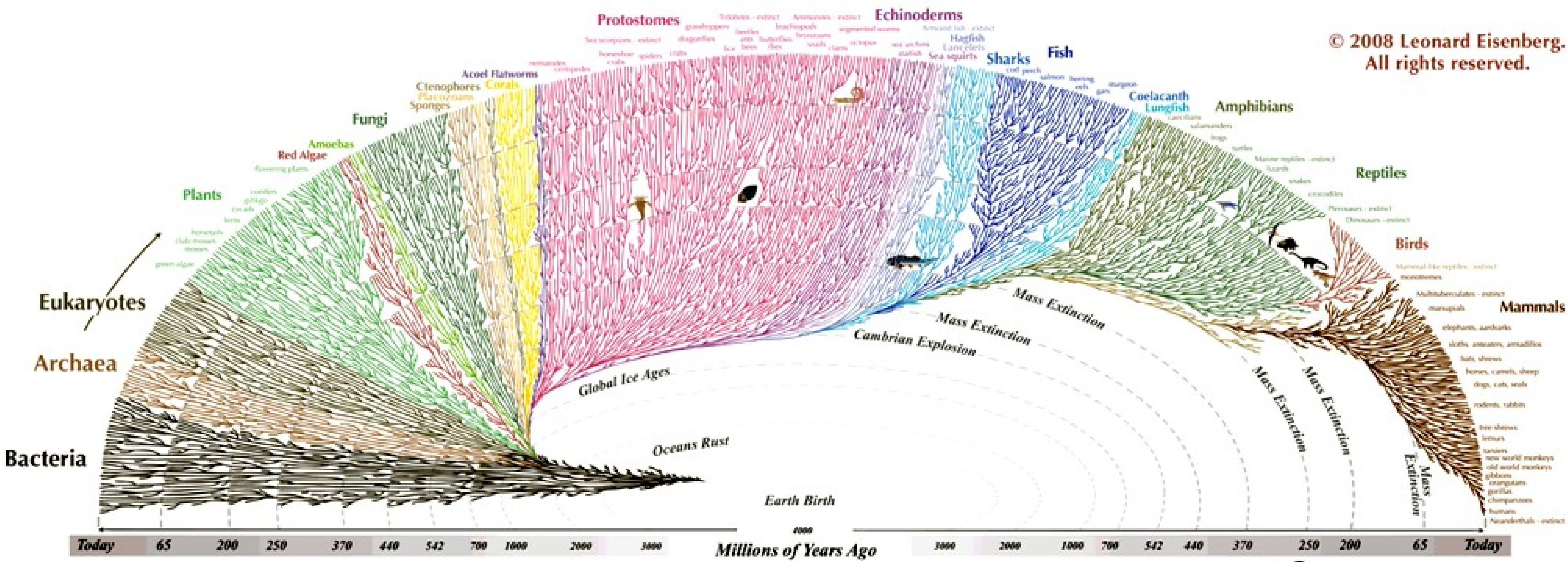
E. Mayr

HISTORY OF LIFE ON EARTH



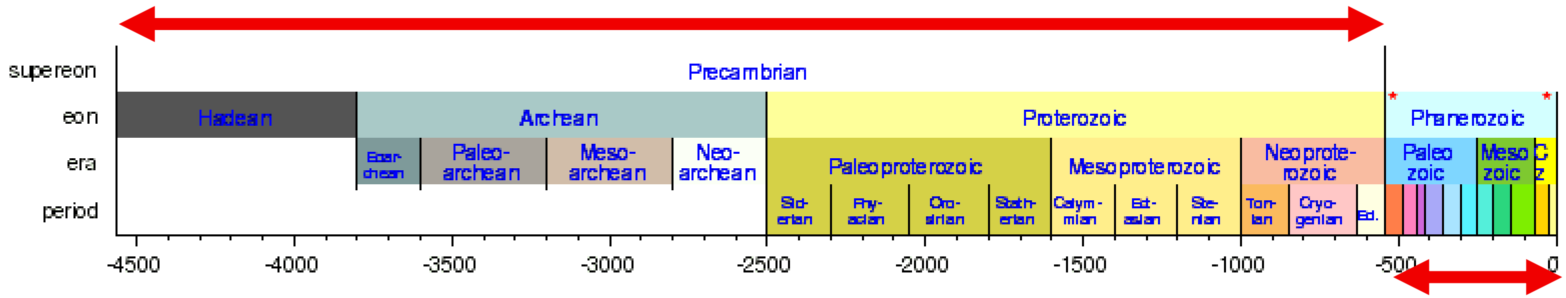
Adapted from Press & Siever, 2000, Understanding Earth


4550 Ma: Formation of the Earth
2 Ma: first humans
4527 Ma: formation of the Moon
230 - 65 Ma: Dinosaurs
ca. 380 Ma: First vertebrate land animals
ca. 530 Ma: Cambrian explosion
750 - 635 Ma: two Snowball Earths
ca. 4000 Ma: end of the Late Heavy Bombardment; first life
ca. 3500 Ma: photosynthesis starts
ca. 2300 Ma: atmosphere becomes oxygen-rich; first Snowball Earth
65 Ma
4,6 Ga
251 Ma
542 Ma
Cenozoic
Mesozoic
Paleozoic
Hadean
4 Ga
3,8 Ga
Archean
3 Ga
2,5 Ga
2 Ga
1 Ga
Proterozoic
Legend
Humans
Mammals
Land plants
Animals
Multicellular life
Eukaryotes
Prokaryotes



All the major and many of the minor living branches of life are shown on this diagram, but only a few of those that have gone extinct are shown. Example: Dinosaurs - extinct

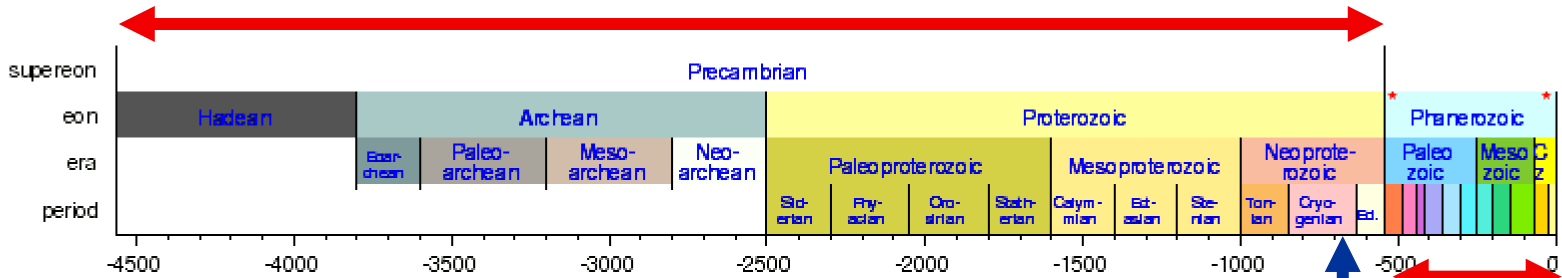
Precambrian



eon Hadean Archean Proterozoic **Phanerozoic**

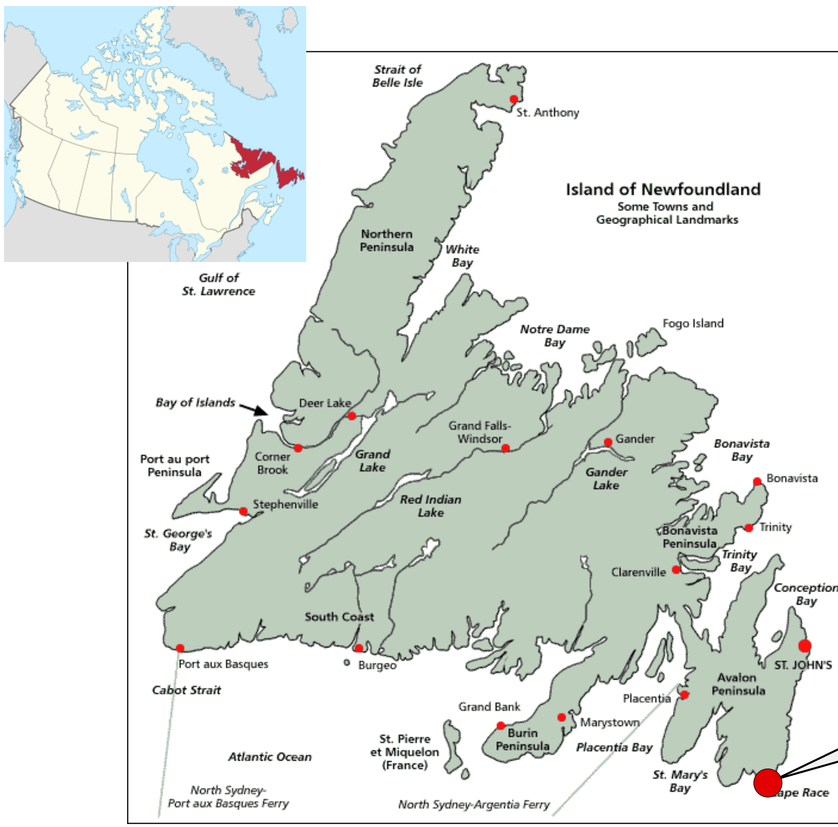
EON	ERA	PERIOD	MILLIONS OF YEARS AGO	KEY EVENTS
Phanerozoic	Caenozoic	Quaternary		Humans evolve
		Tertiary	1.6	
	Mesozoic	Cretaceous		
		Jurassic	138	Extinction of Dinosaurs
		Triassic		
	Paleaozoic	Permian	240	
		Carboniferous	330	Permian mass extinction
		Devonian		
		Silurian	410	
		Ordovician		Invertebrates become common
		Cambrian	500	
Proterozoic		Also known as Precambrian		
Archean			3500	
Hadean				Earliest life

Precambrian



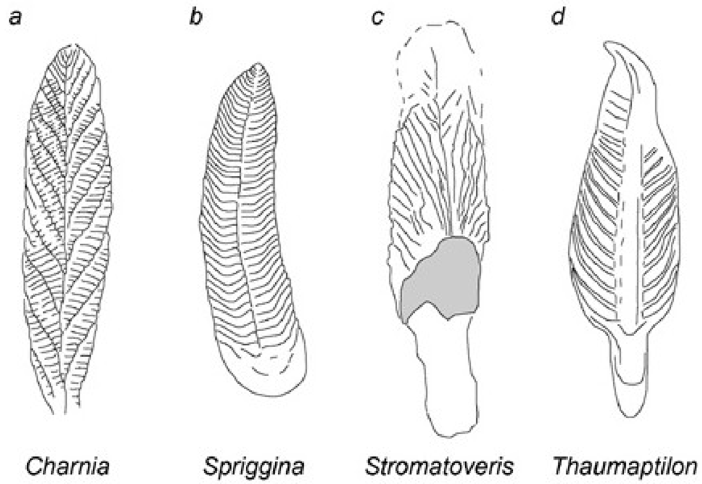
eon Hadean Archean Proterozoic **Phanerozoic**

Ediacaran (Vendian) fauna
~635-542 M



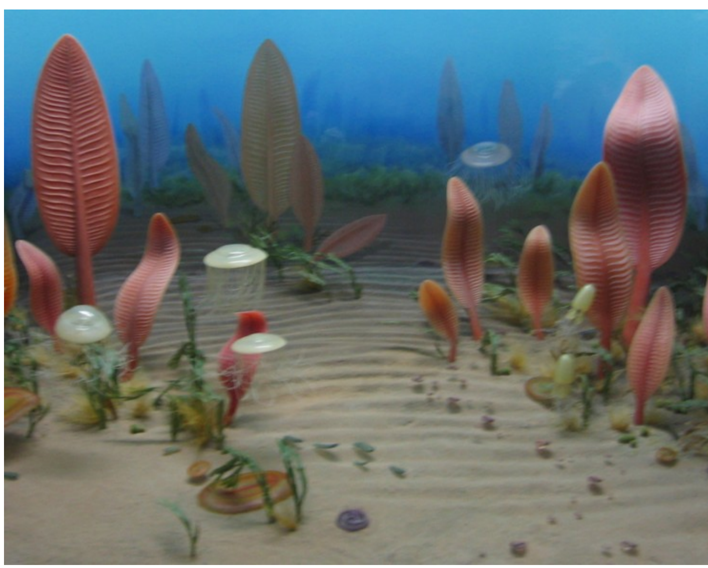
Mistaken Point, Newfounland
~ 565 M

Charnwood, Leicestershire
~ 560 M



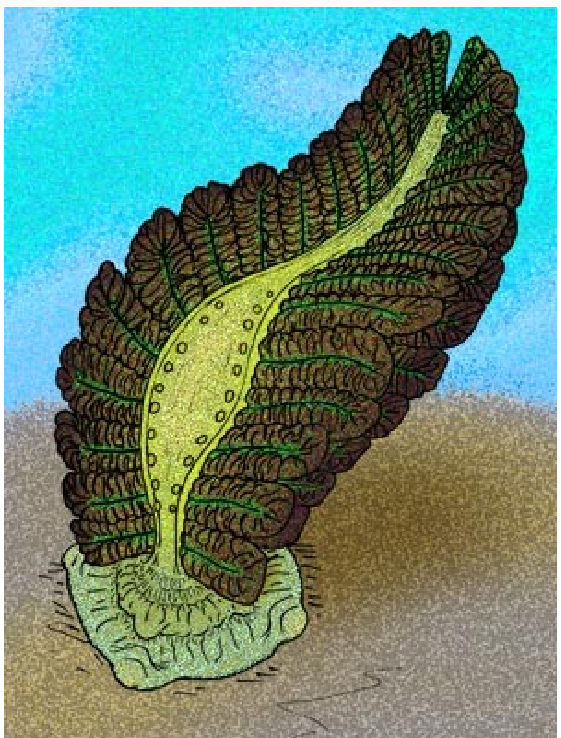
Charnia

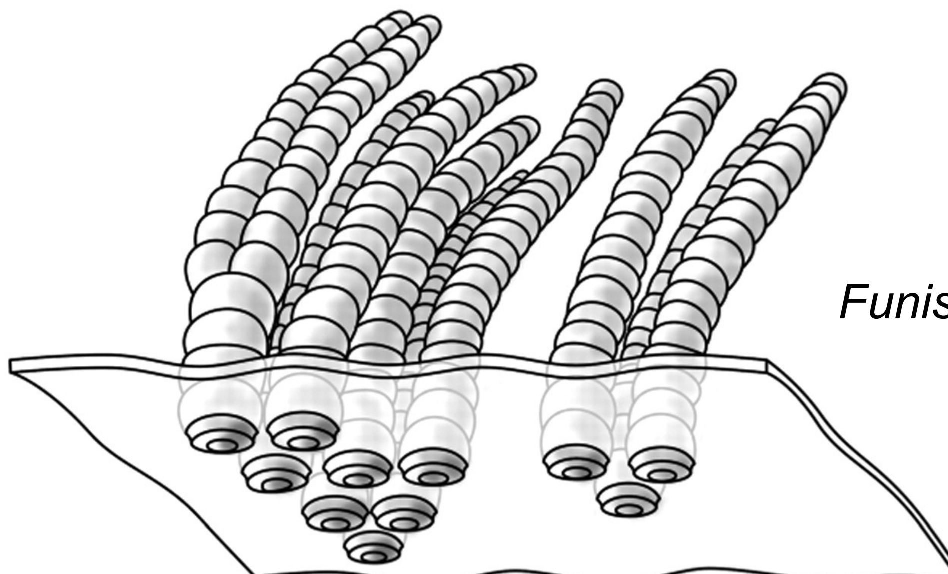
Spriggina



Dickinsonia
~ 580 M

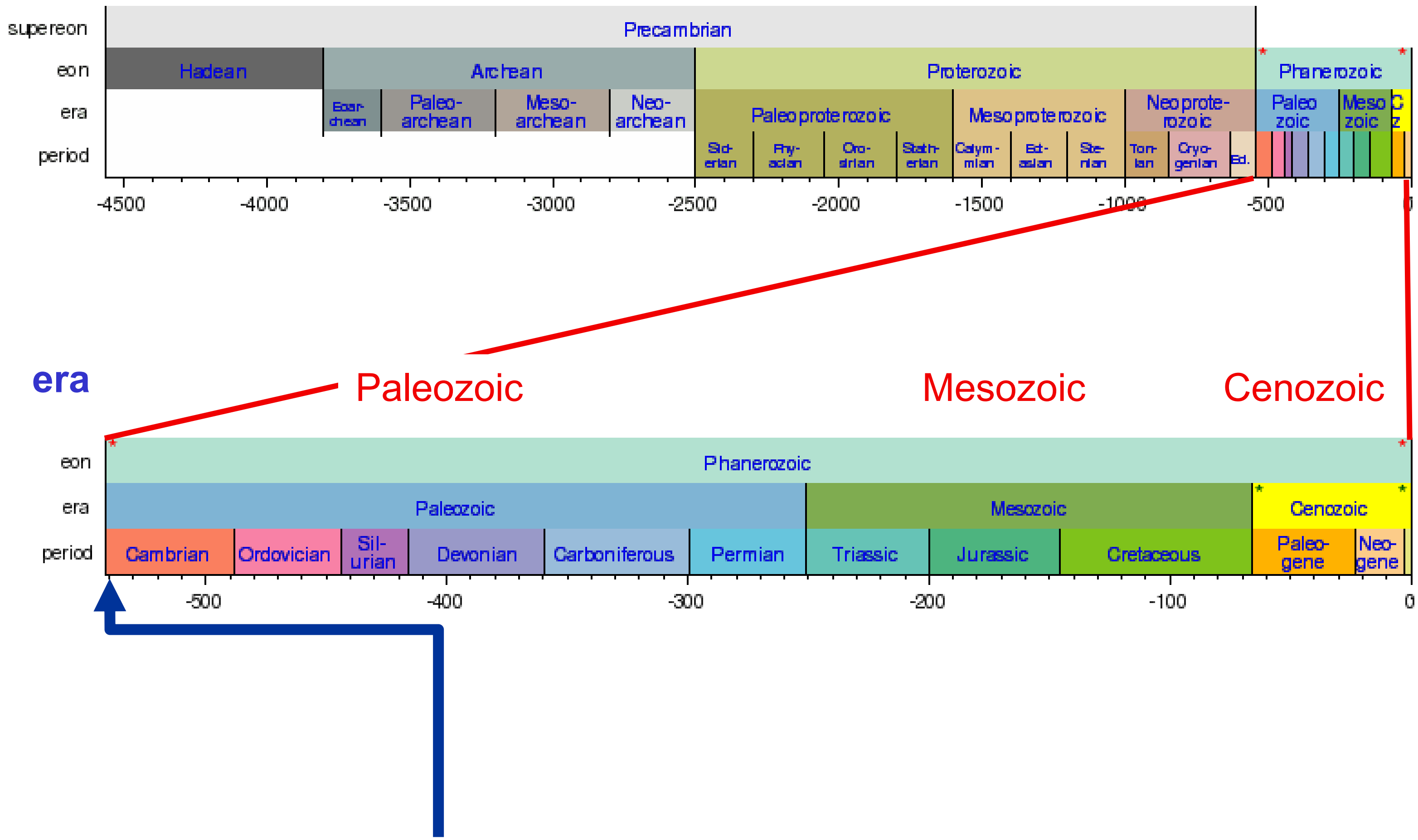
Spriggina





Funisia: sex?

Phanerozoic



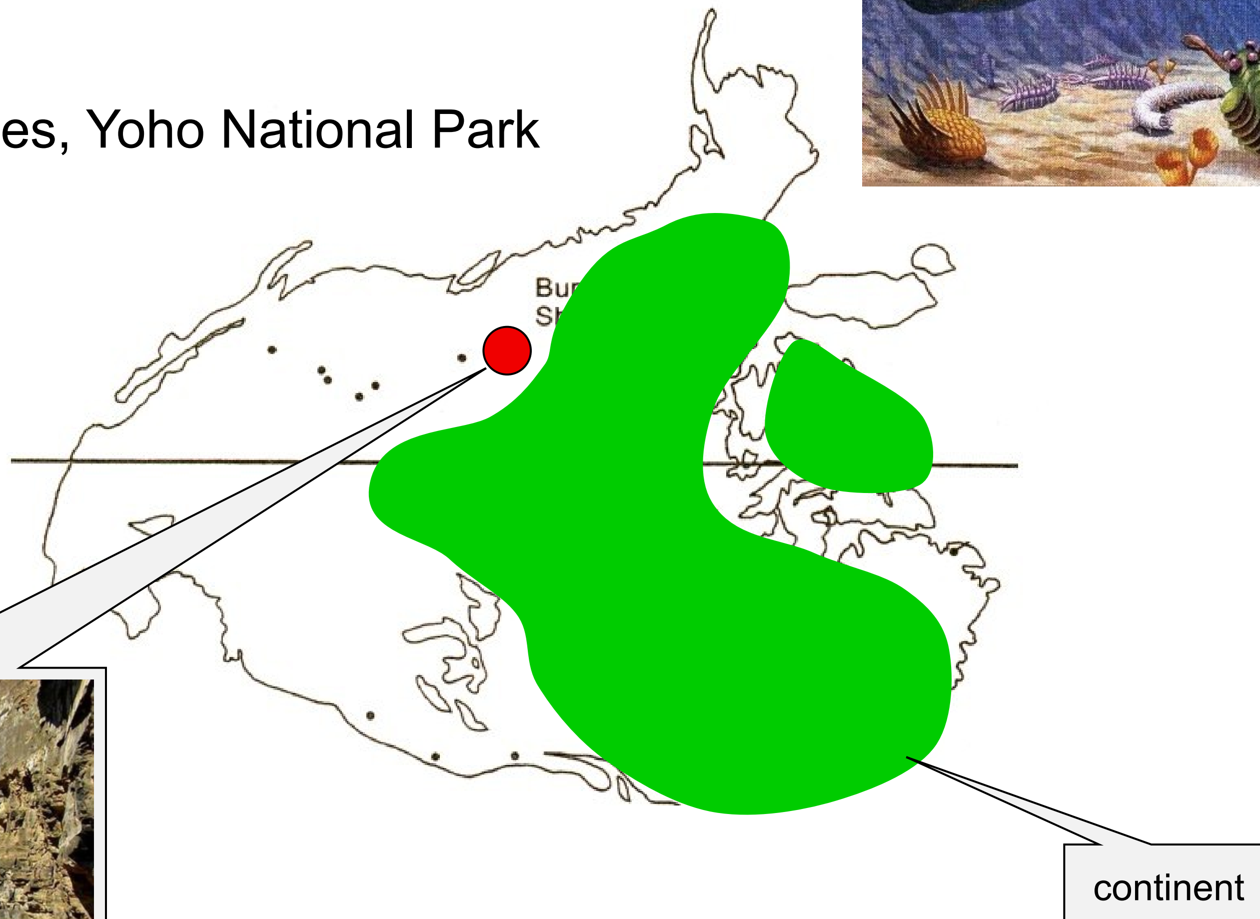
Cambrian explosion
~ 542-520 M

Cambrian explosion

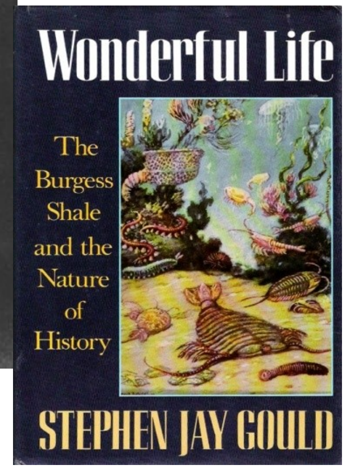
Burgess Shale

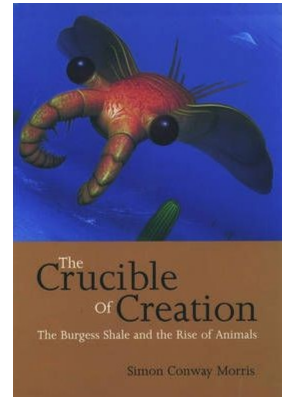
~ 542-520 M

Canadian Rockies, Yoho National Park

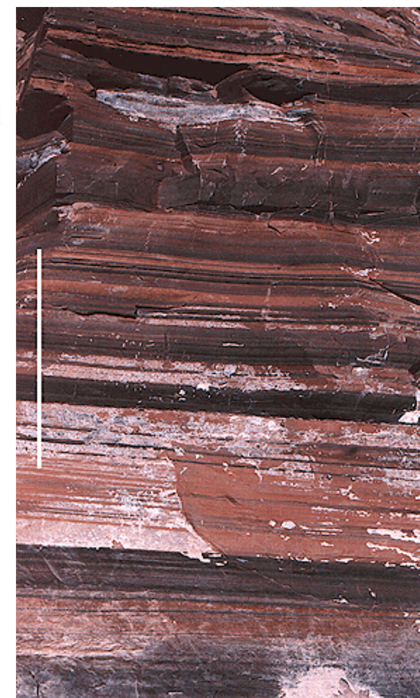


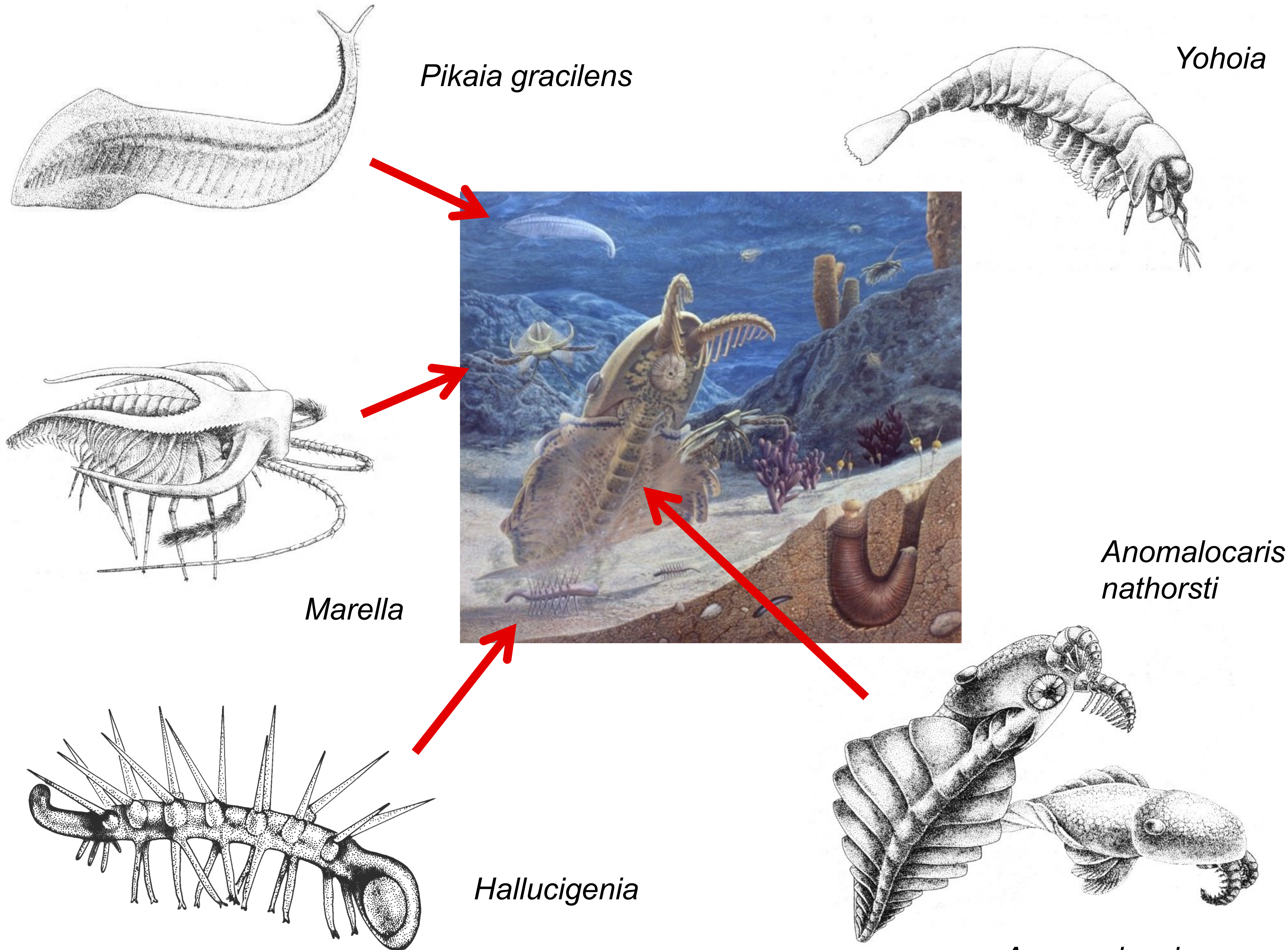
Charles Doolittle Walcott (1909)

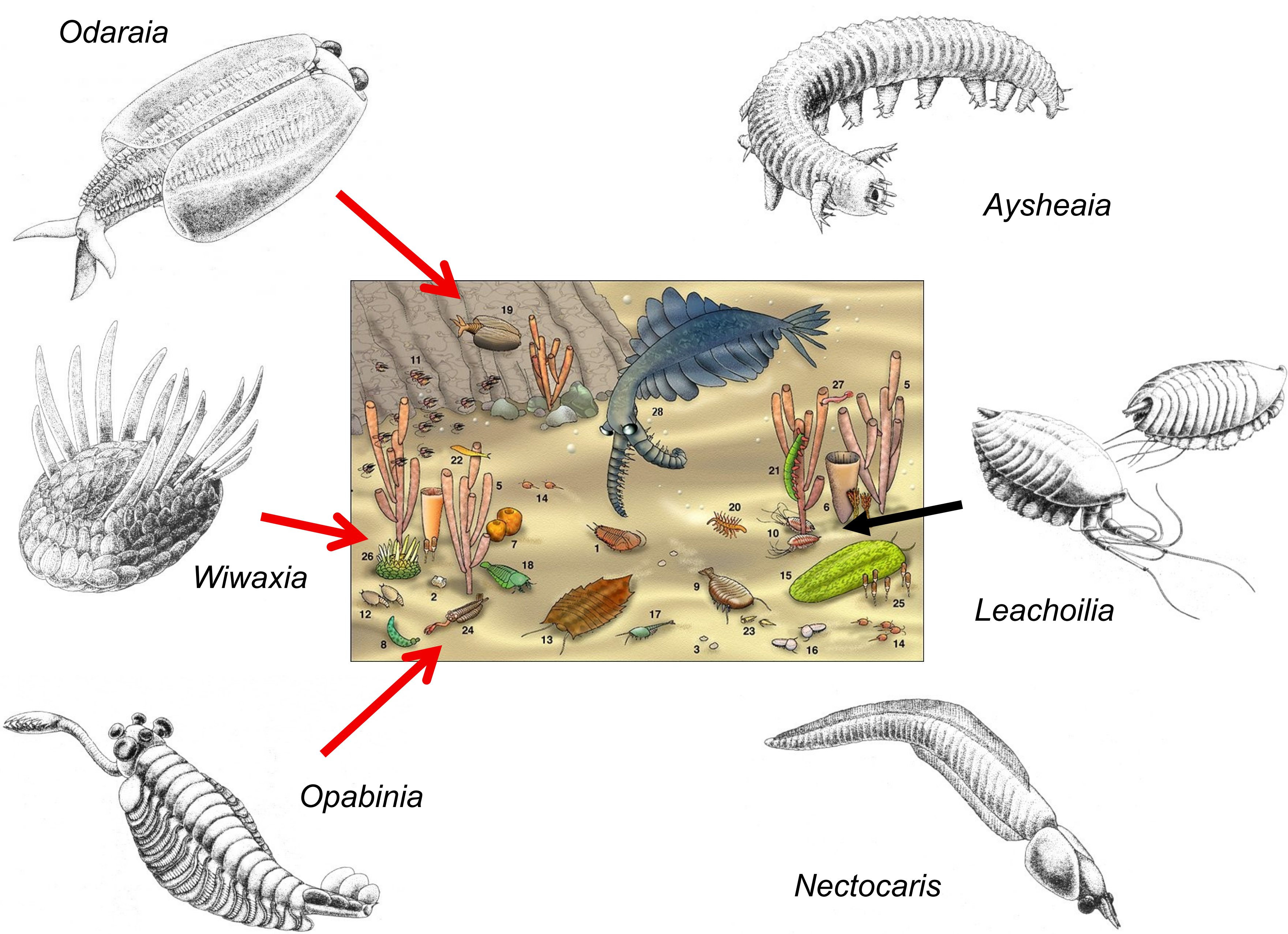


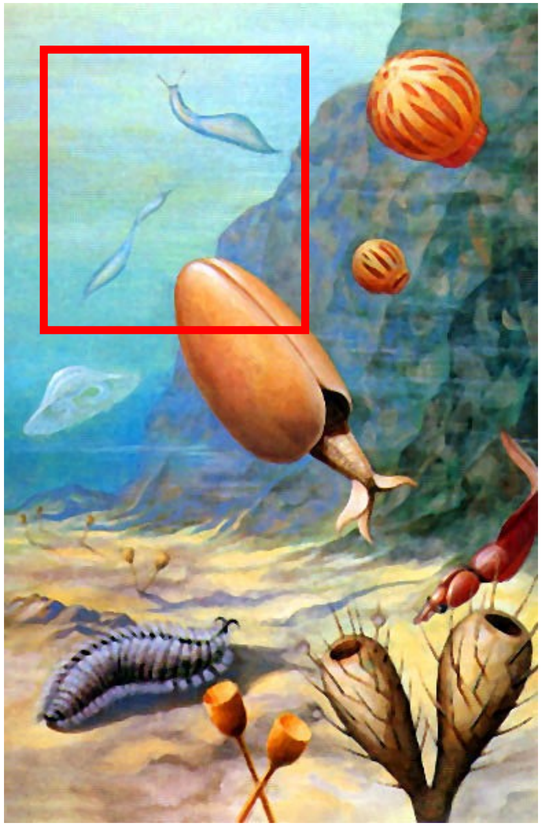


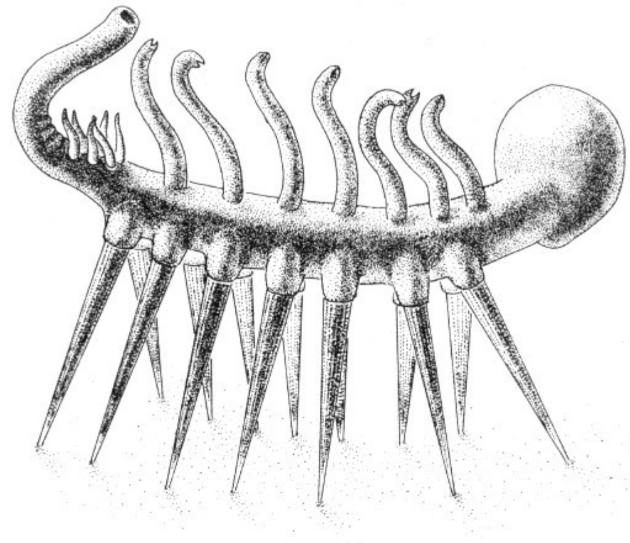
Simon Conway Morris



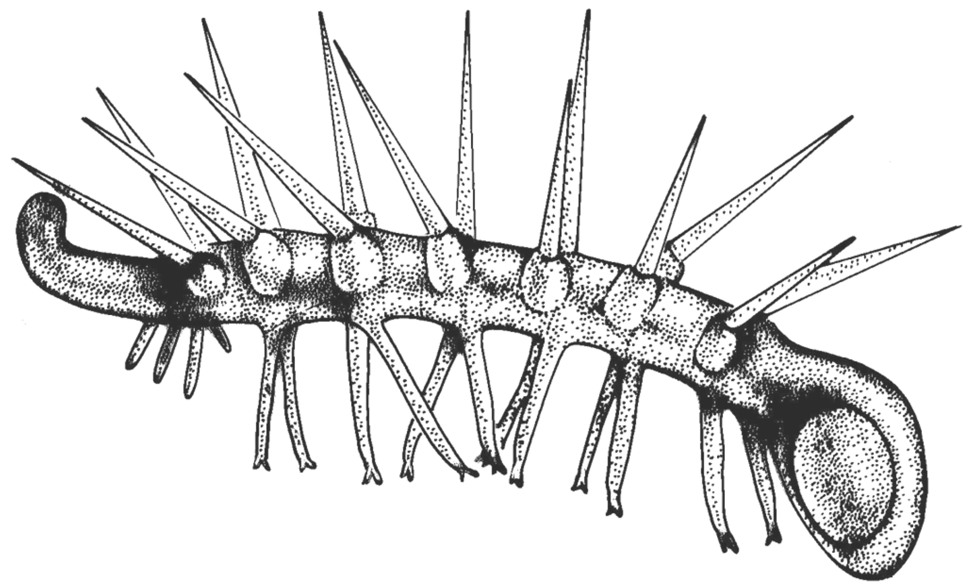

Pikaia gracilens
Yohoia
Marella
Anomalocaris nathorsti
Hallucigenia
A. canadensis

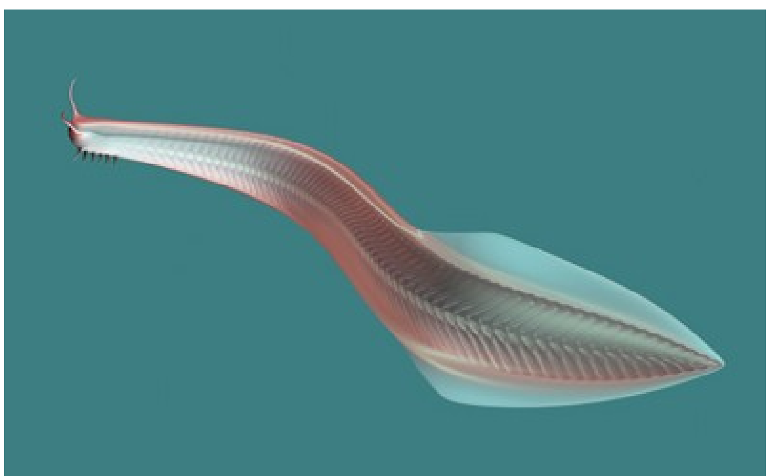

Odaraia
Aysheaia
Wiwaxia
Leachoilia
Opabinia
Nectocaris





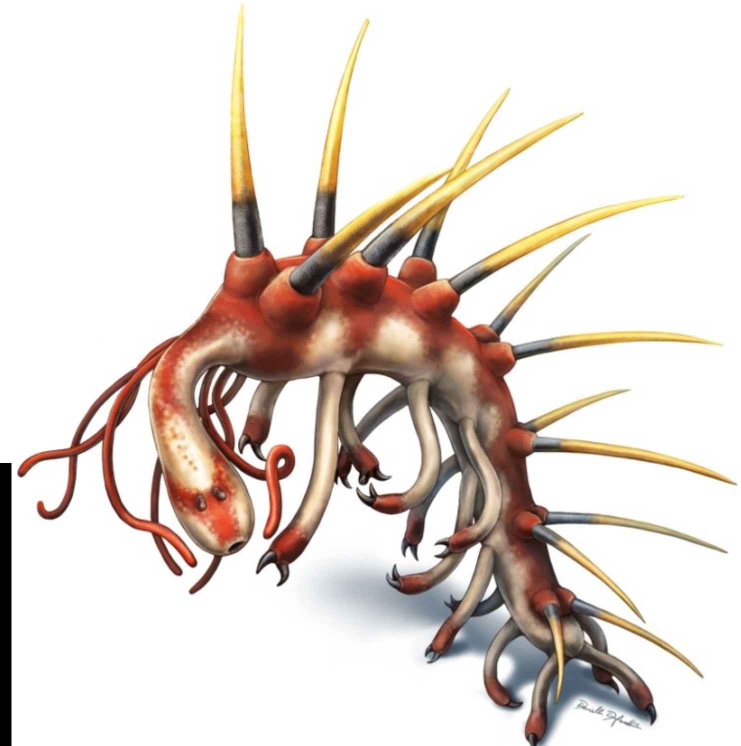
Hallucigenia



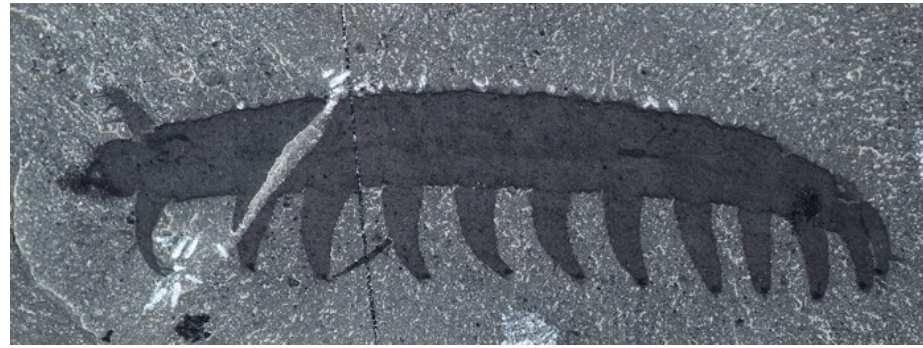


Pikaia gracilens (Chordata)

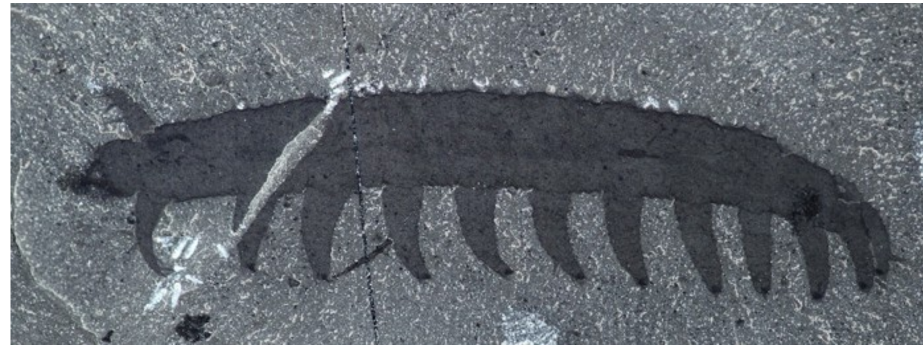

© Lars Fields



Aysheaia



Transition from sea to land?




Onychophora

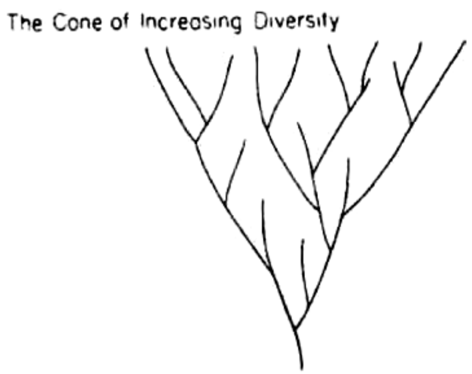
diversity and disparity:

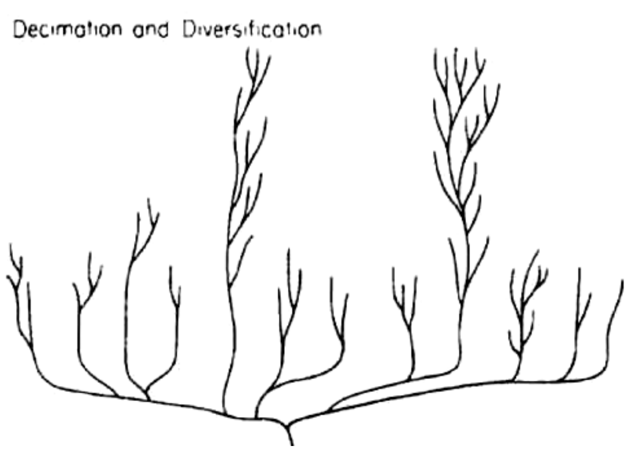
interpretation of Burgess fossils

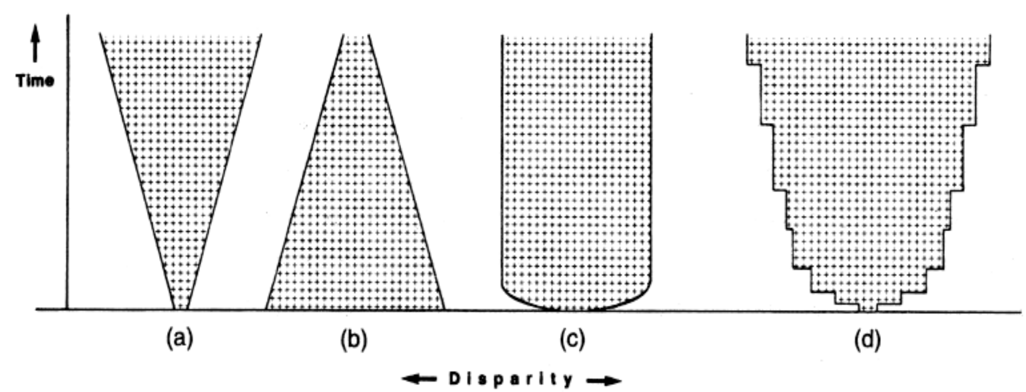
Stephen Jay Gould vs. Simon Conway Morris

diversity = number of species

disparity = number of „Bauplans“



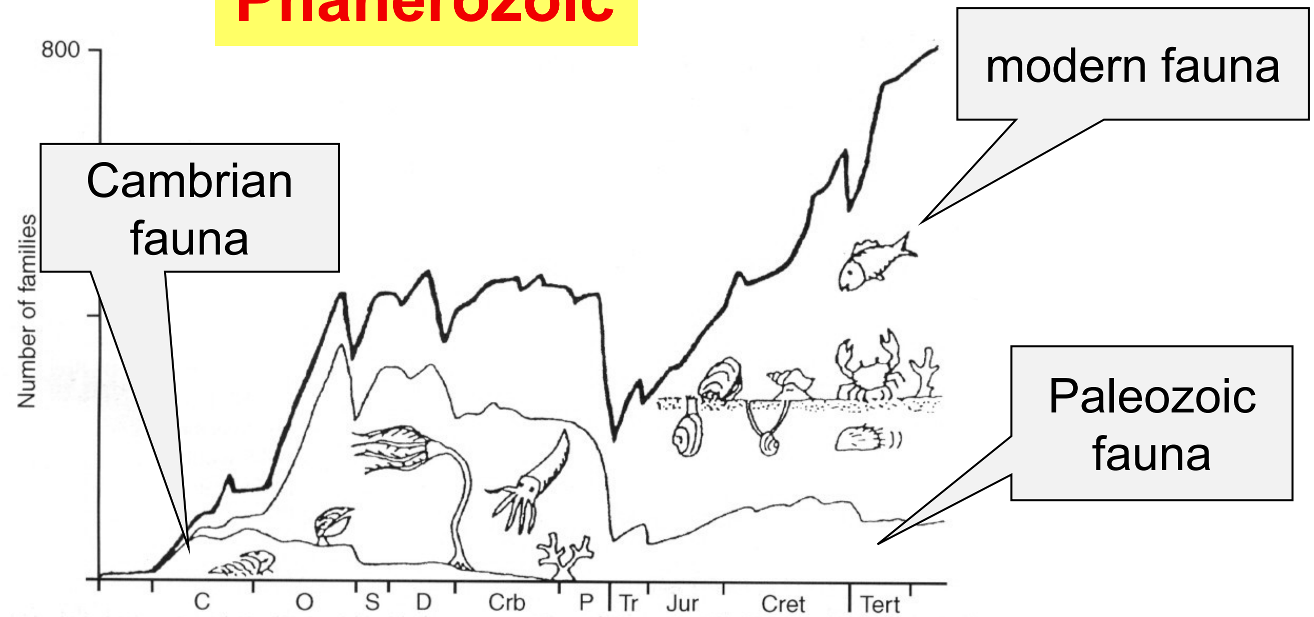




traditional Gould Conway Morris

Phanerozoic

increasing diversity

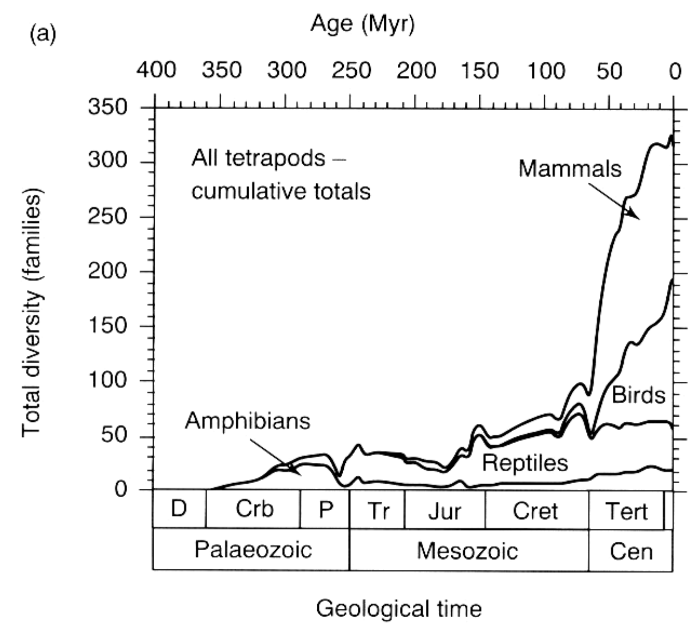


Jack J. Sepkoski (1981): logistic model

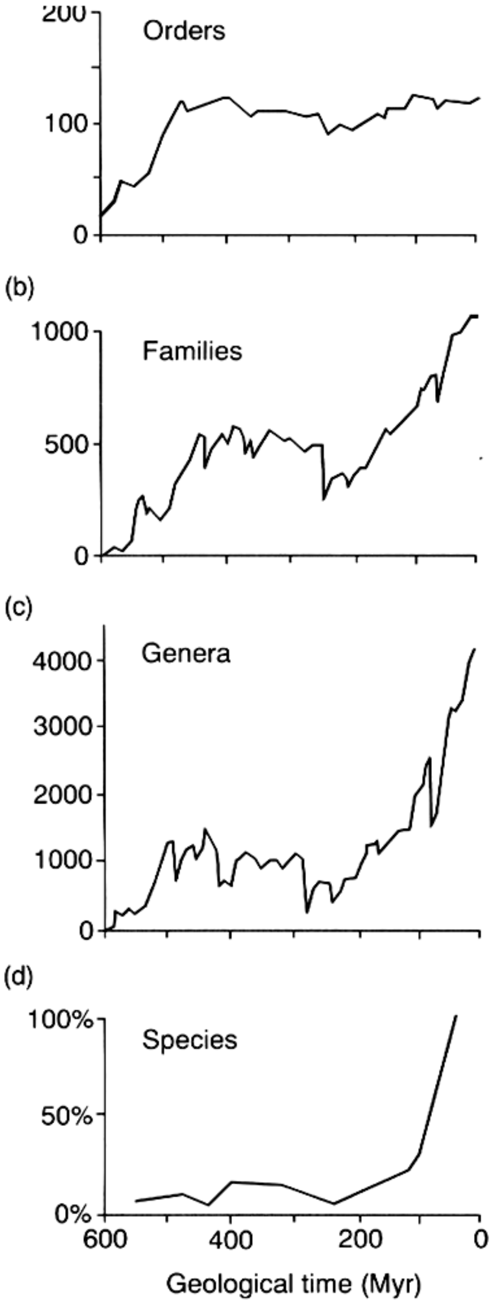
Michael J. Benton (1997):

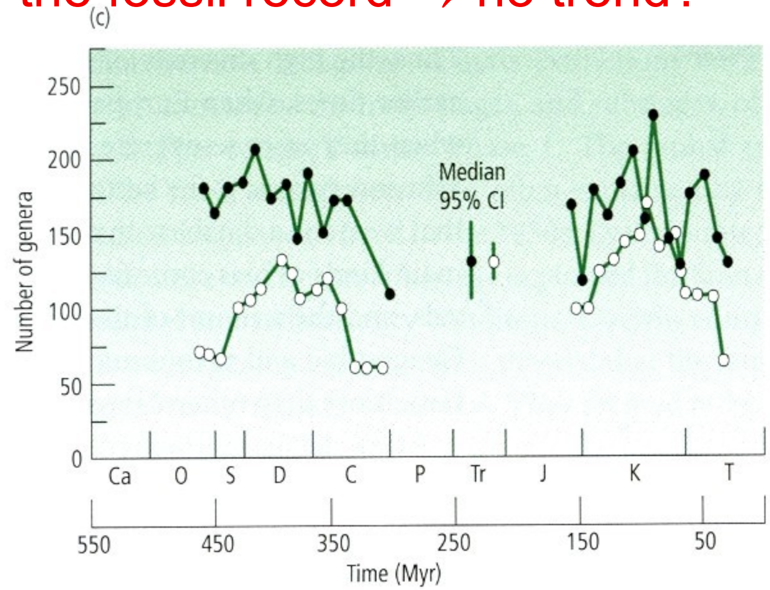
curve for terrestrial organisms differs

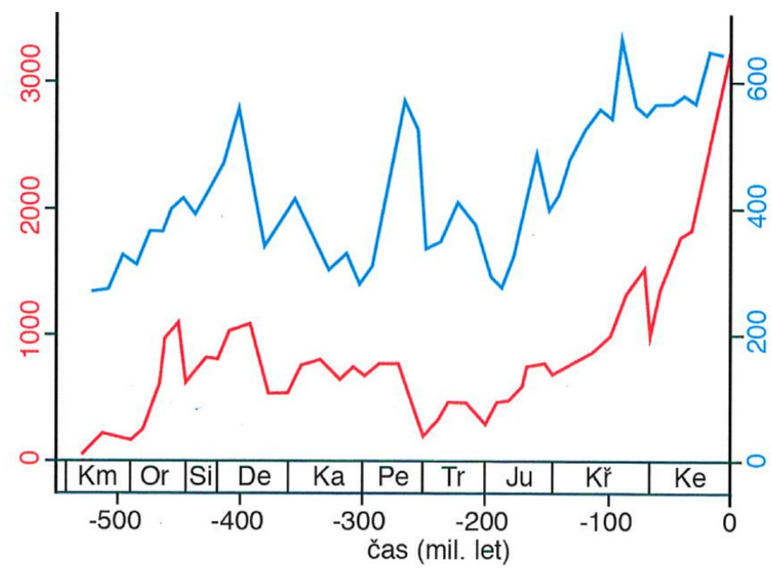
exponential model



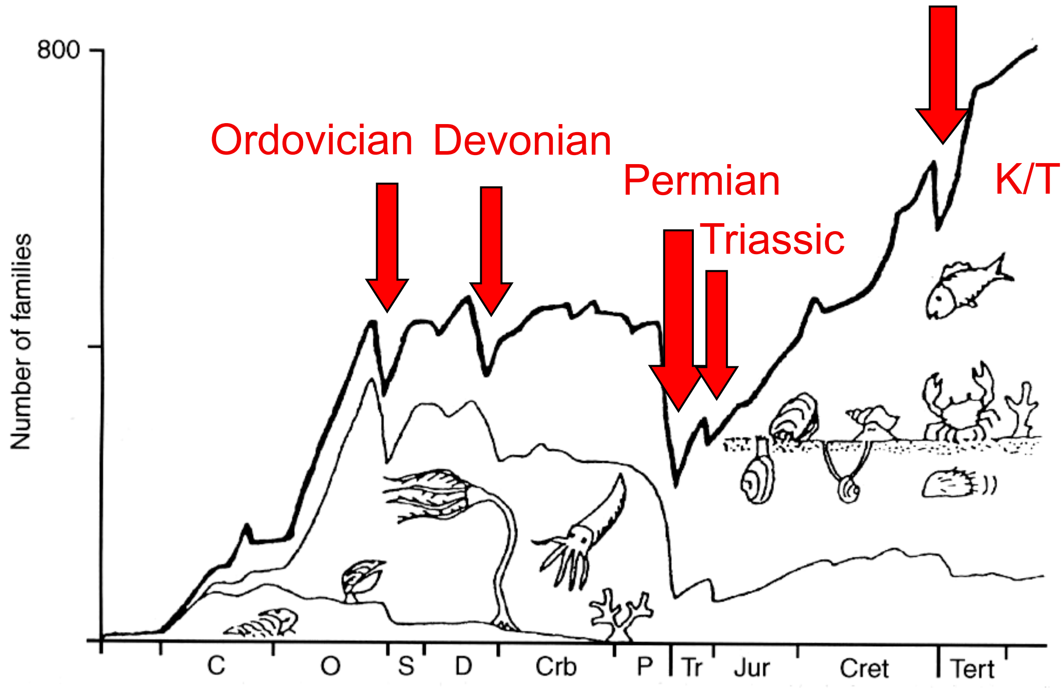
If we take into account incompleteness of the fossil record → no trend?







Obr. 7.27: Růst globální diverzity: červená křivka popisuje růst počtu „rodů" na základě prvního a posledního výskytu ve fosilním záznamu, modrá křivka počet „rodů" po odstranění „tahu přítomnosti" (viz text).

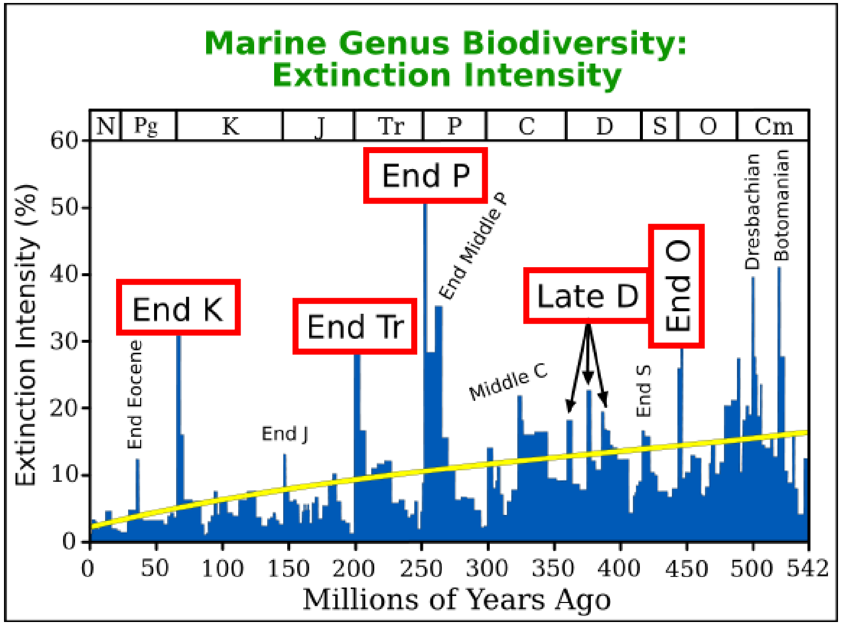


Extinction:

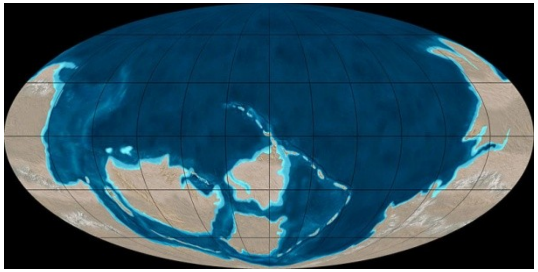
background extinctions

mass extinctions → „Big Five“

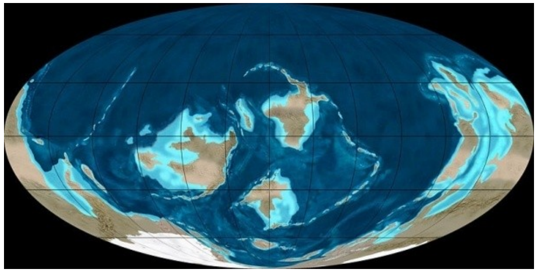
greatest: end of the Permian



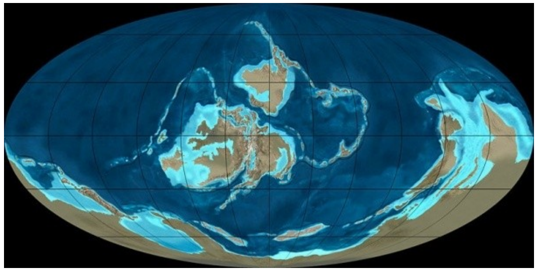
Paleozoic



Cambrian:
single supercontinent Rodinia (Proterozoic) →
Gondwana, Laurentia, Baltica, Angara (Siberia),
Avalonia …

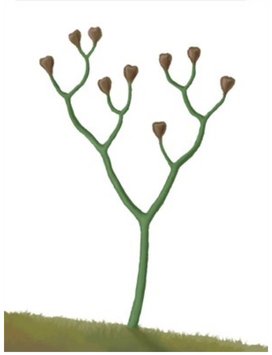


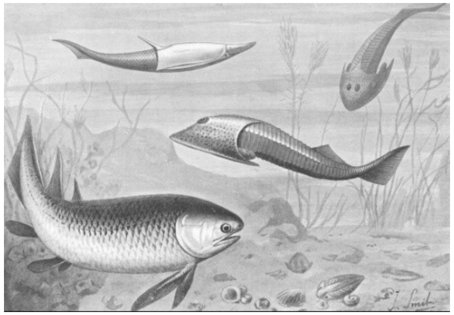
Ordovician:
increase of diversity
(marine organisms)
the end: 1st mass extinction

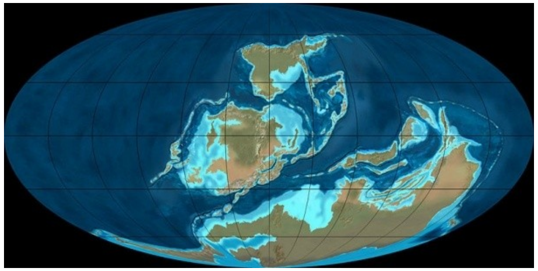


Laurentia+Baltica = Laurasia

Silurian:
gnathostomes
first terrestrial o.
(plants, scorpions)

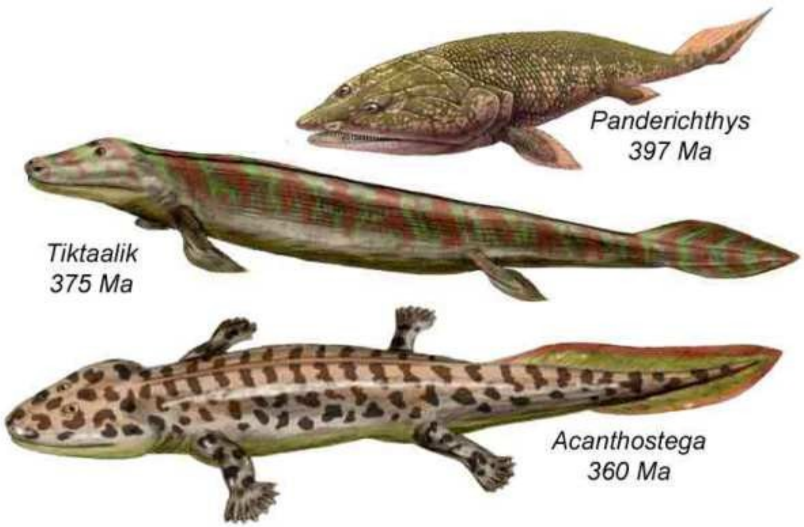


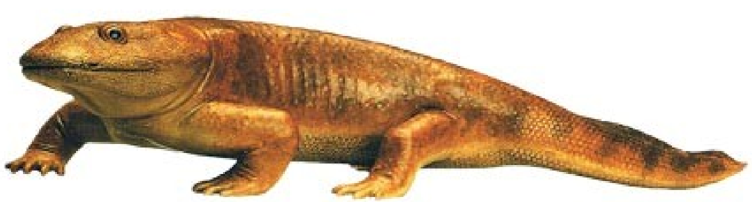




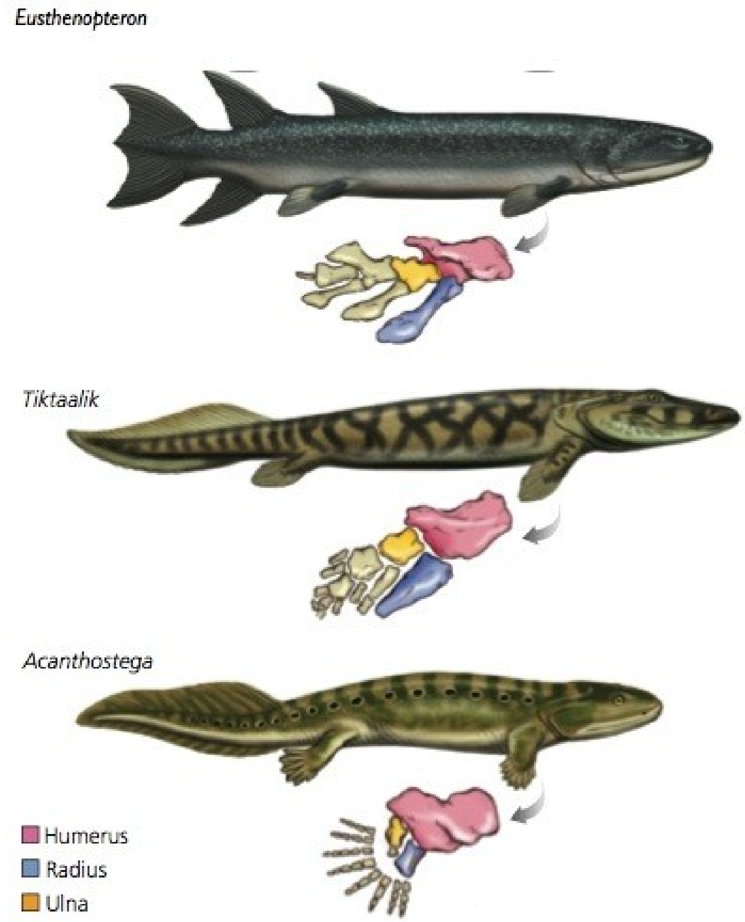
Devon:

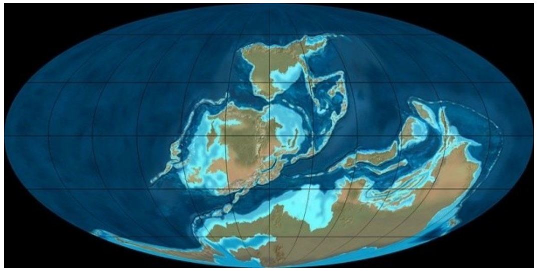
radiace ryb, první žraloci, lalokoploutví, obojživelníci
na konci 2. masová extinkce





Ichthyostega
365 Ma

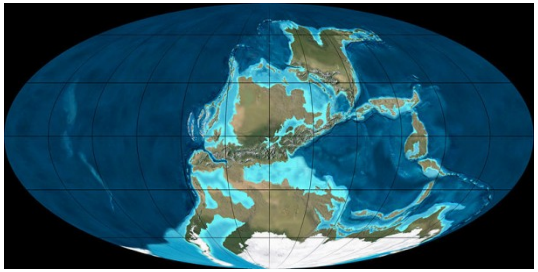




Devon:

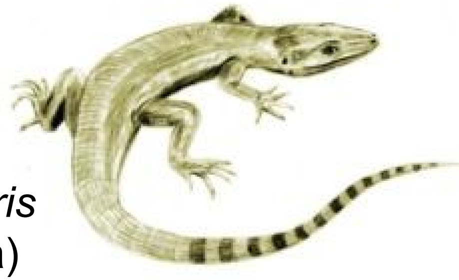
radiace ryb, první žraloci, lalokoploutví, obojživelníci

na konci 2. masová extinkce

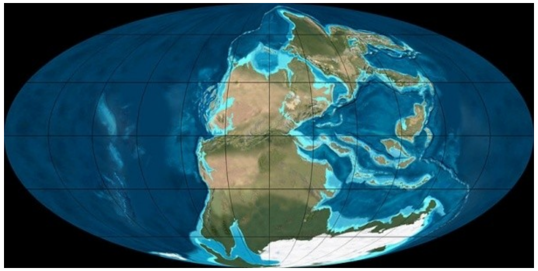


Karbon:

přesličky, hmyz, první plazi



Archaeothyris
(Synapsida)



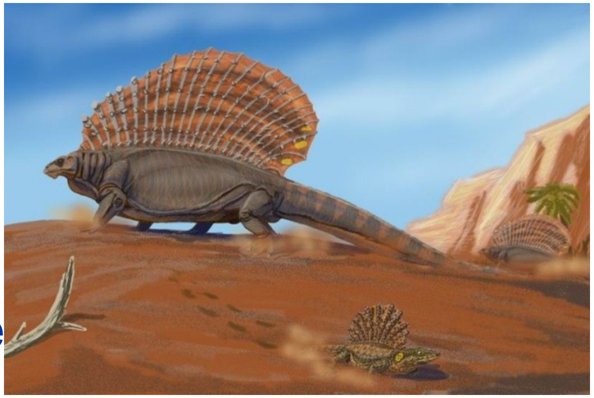
Perm:

Pangea

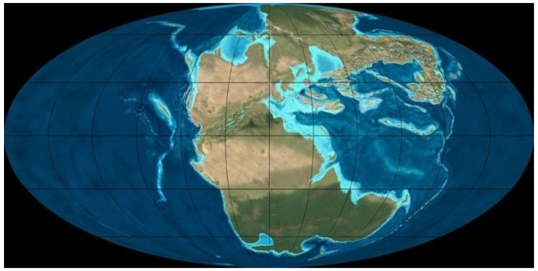
Therapsida (→ savci)

na konci 3. masová extinkce

Edaphosaurus
(Pelycosauria)



Mesozoic



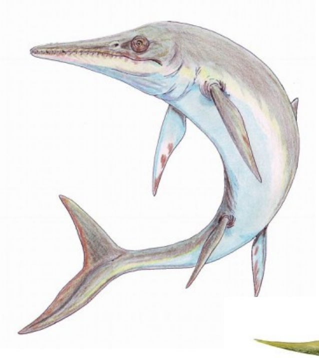
Triassic:

butterflies, dipterans

radiation of reptiles (tortoises, ichthyosars, plesiosaurs, pterosaurs)

the end: dinosars, mammals, 4th extinction

synapsid
Pelycosauria
(*Palaeohatteria*)



ichthyosaurs

plesiosaurs

Therapsida

cynodont
(*Cynognathus*)

pterosaurs

primitive mammal (*Castorocauda*)

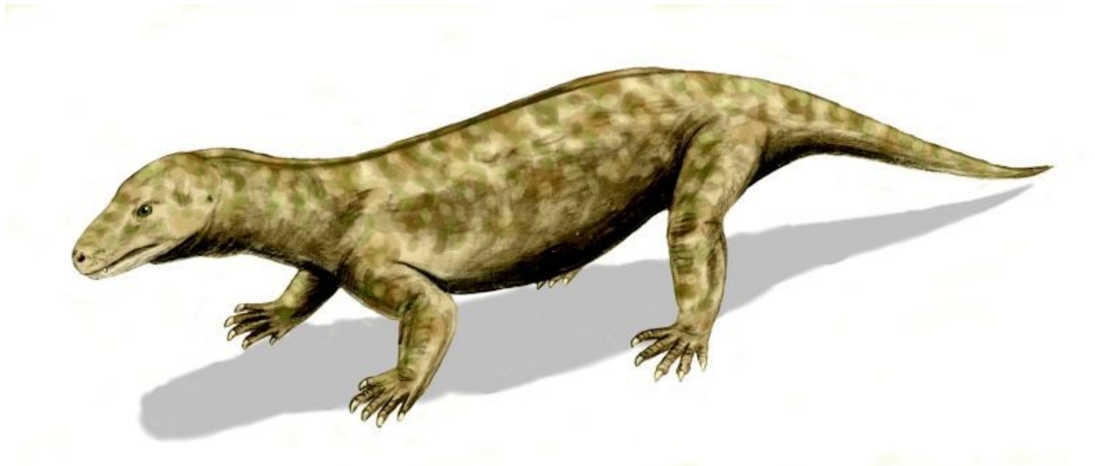
Evolution of mammals

Sphenacodon: Lower Permian (270 M) – mandible from several bones, reptile-like articulation, no eardrum

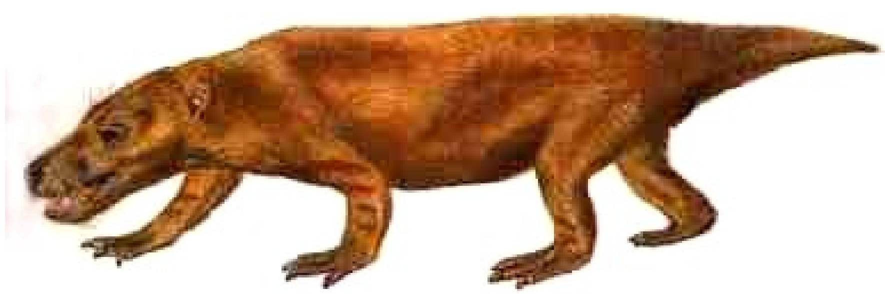
Biarmosuchia: Upper Permian – one of the first therapsids, articulation already more mammal-like, knit upper jaw, hind legs more upright

Biarmosuchus

Procynosuchus: end of Permian – primitive cynodont



Thrinaxodon: Lower Triassic – more derived cynodont, eardrum in the lower jaw

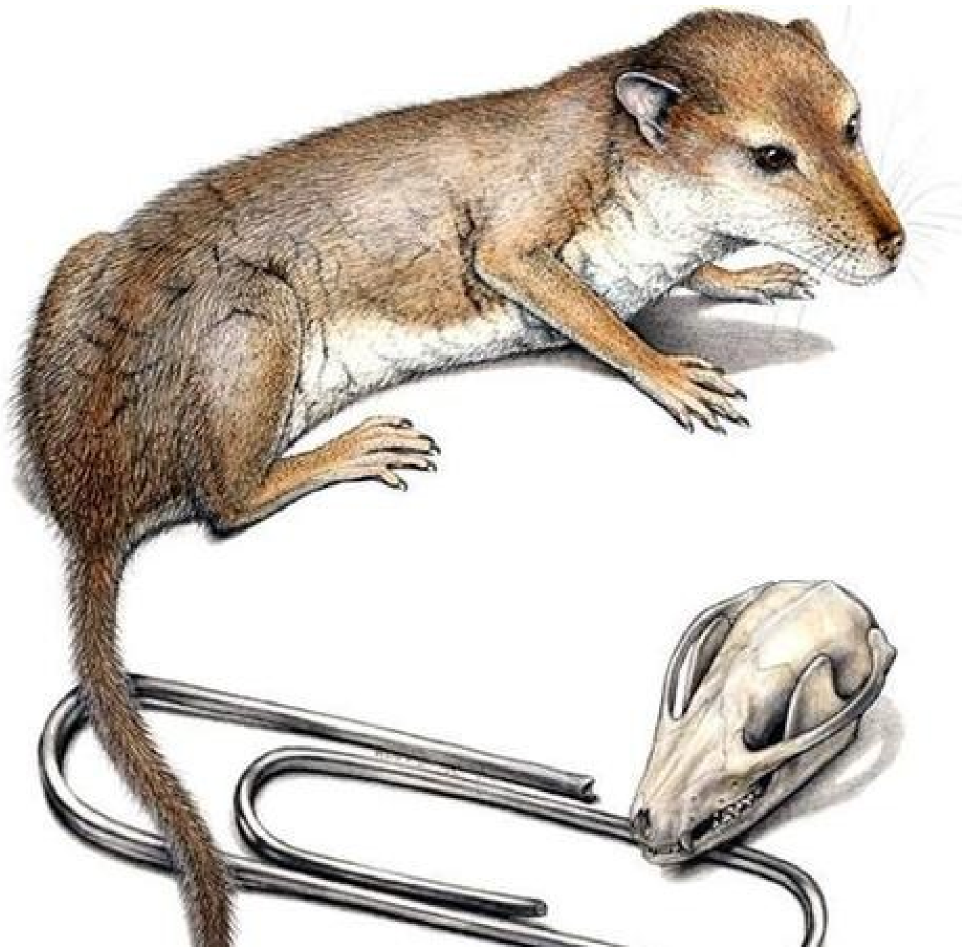


Probainognathus: Middle Triassic (~ 235 M) – 2 joints: mammalian+reptilian

Diarbrognathus: Lower Jurassic (~ 209 M) – advanced cynodont, although still 2 joints, but the reptilian one used almost entirely for hearing

Morganucodon: Lower Jurassic (~ 220 M) – still a residue of the reptilian joint

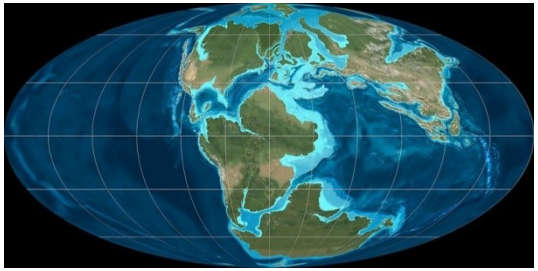
Hadrocodium: Lower Jurassic – transition of the middle ear ossicles from the jaw to the cranium



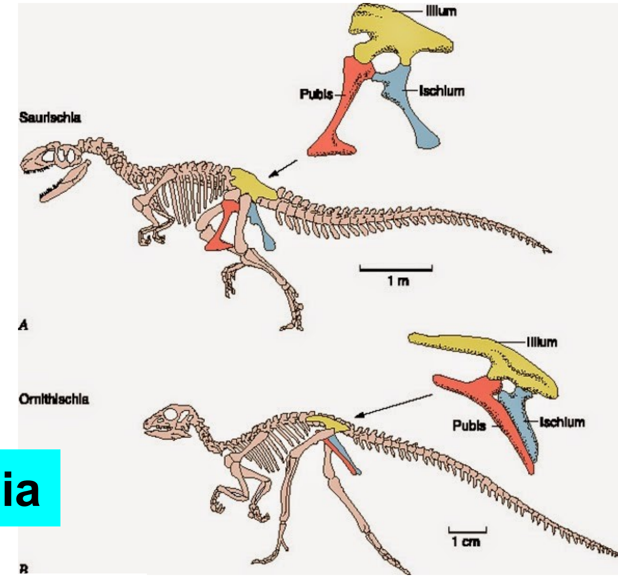
Juramaia sinensis (jurasic mother from China): first known placental mammal

160 M

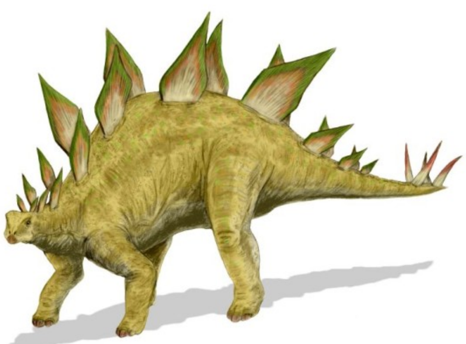
Mesozoic



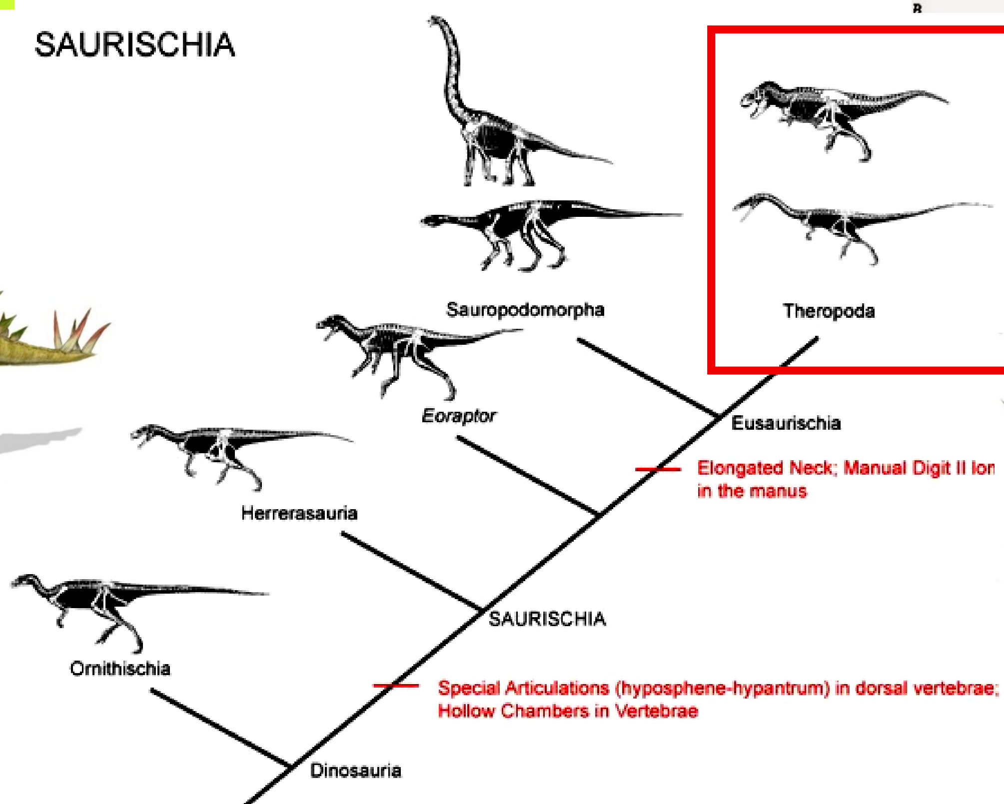
Jurassic:
bone fishes
bird evolution

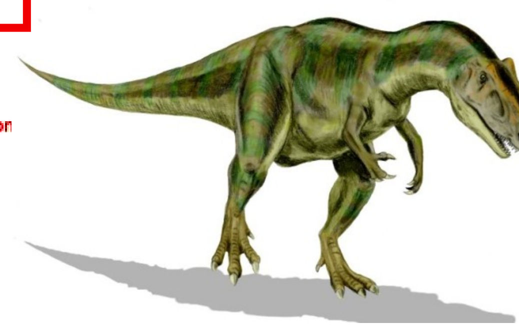


Ornithischia ← **dinosaurs** → **Saurischia**



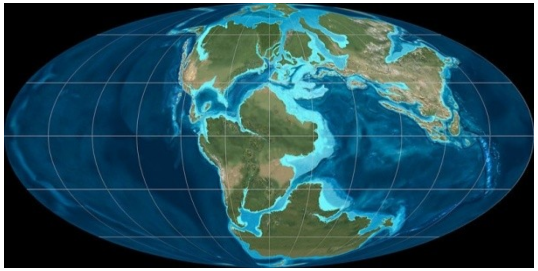
Stegosaurus



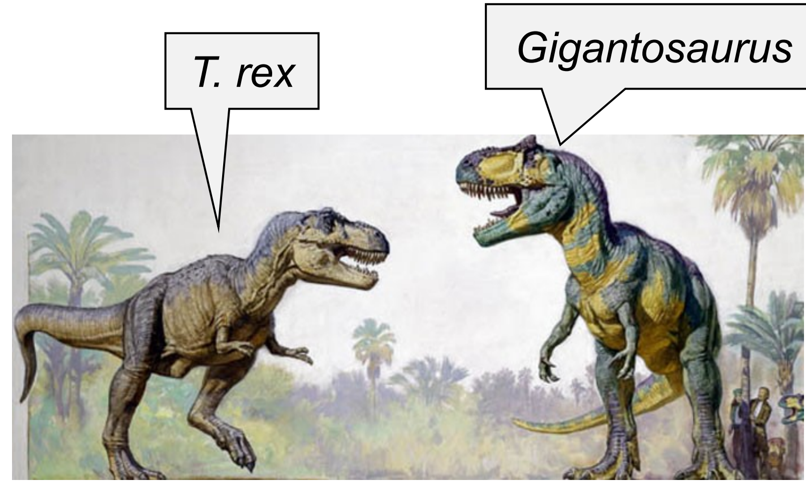


Allosaurus

Mesozoic



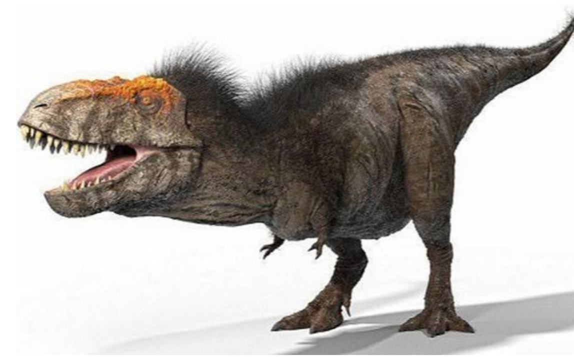
Jurassic:
bone fishes
bird evolution



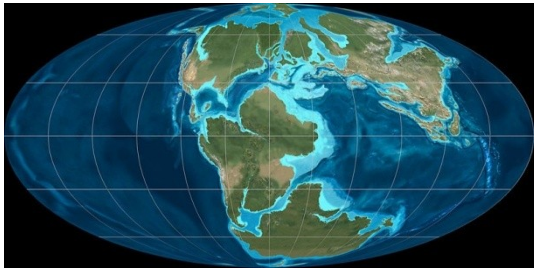
theropod dinosaurs

↓ **Maniraptora**

→ **tyrannosaurs (Cretaceous)**



Mesozoic



Jurassic:
bone fishes
bird evolution

T. rex

Gigantosaurus

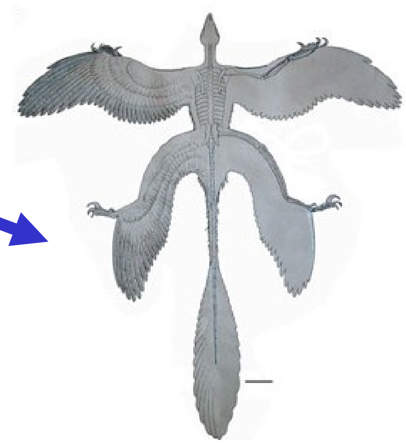
theropod dinosaurs

Maniraptora

tyrannosaurs (Cretaceous)

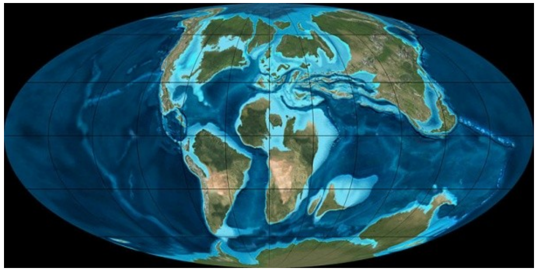
Archaeopteryx lithographica

birds

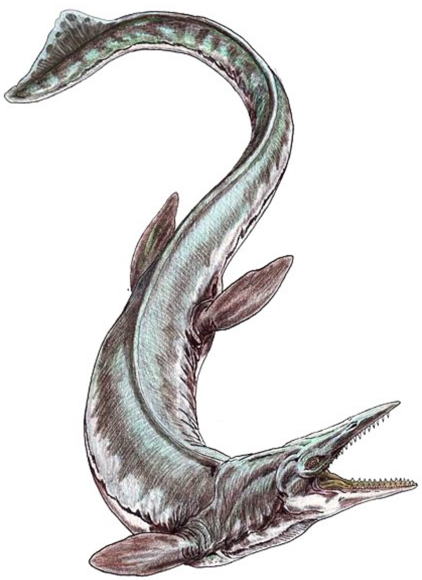


Microraptor gui

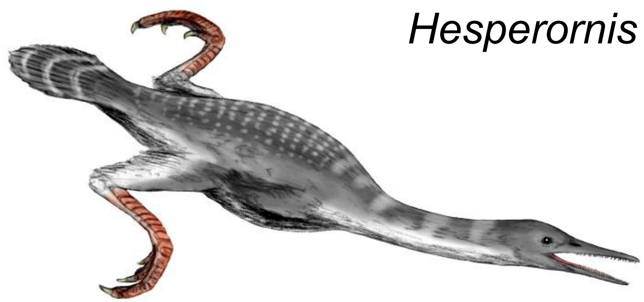
Mesozoic



Cretaceous:
angiosperms
modern sharks and rays, mosasaurs, first snakes, birds
mammals: divergenc of marsupials and placentals

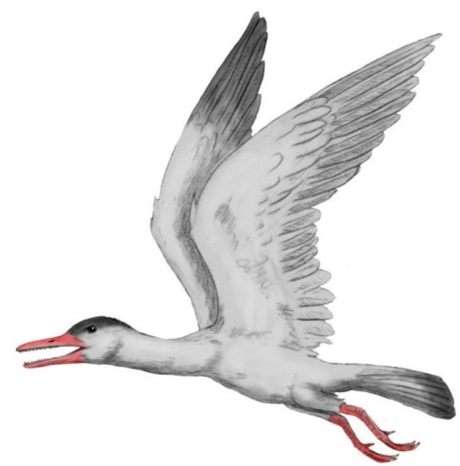


mosasaurs



Hesperornis

Ichthyornis



the end: 5th extinction, 66 M

→ the cause??

Extinction on the K/T* (K/Pg**) boundary:

*) Cretaceous/Tertiary
**) Cretaceous /Paleogene

1980 Louis Alvarez et al.:

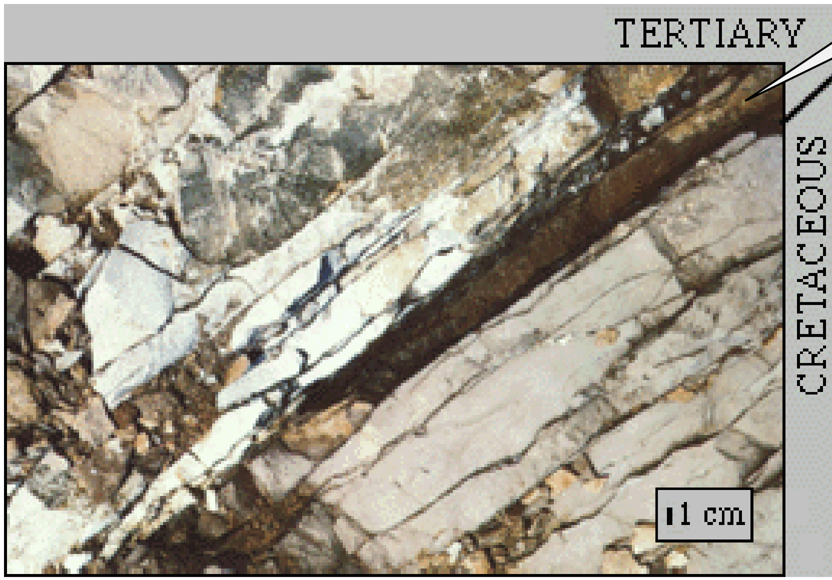
catastrophic hypothesis – asteroid 10 km in diameter
$10^9 \times$ more than Hiroshima

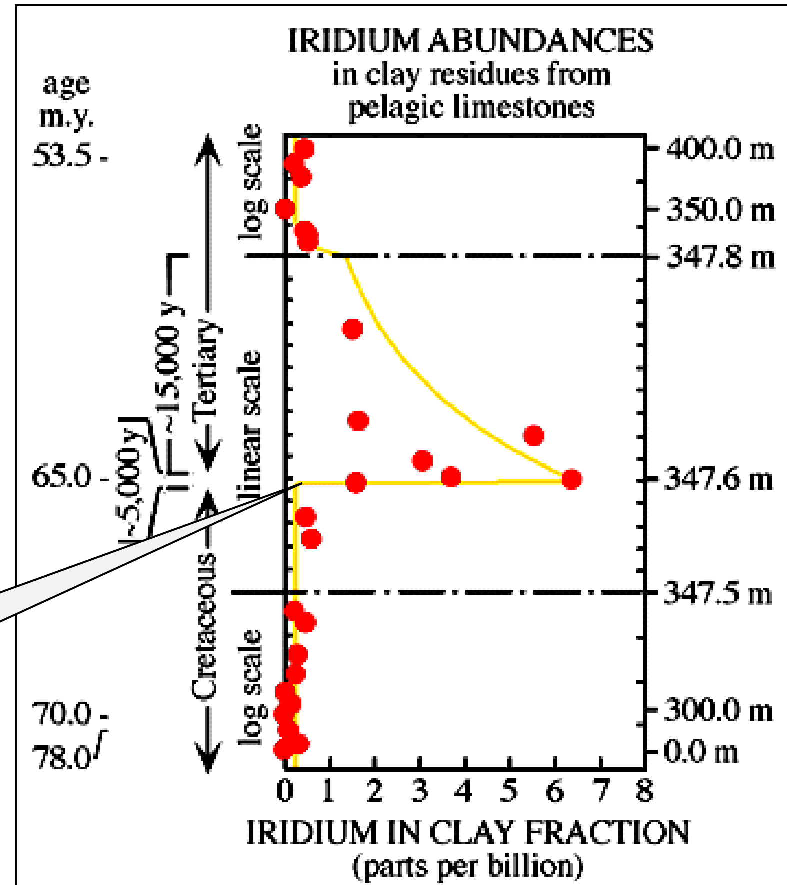
L. Alvarez

Extinction on the K/T (K/Pg) boundary:

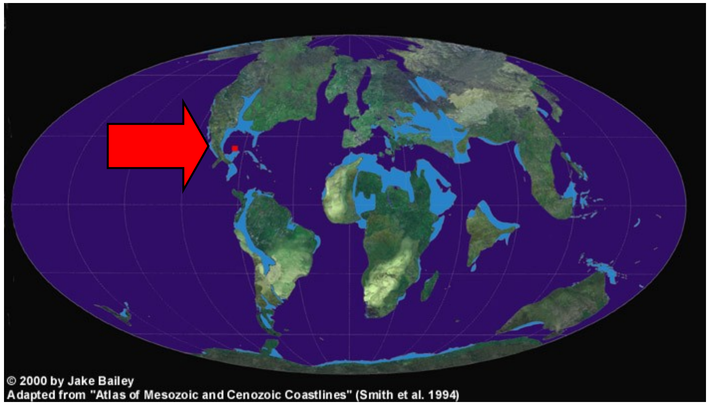
iridium on the boundary

K/T boundary

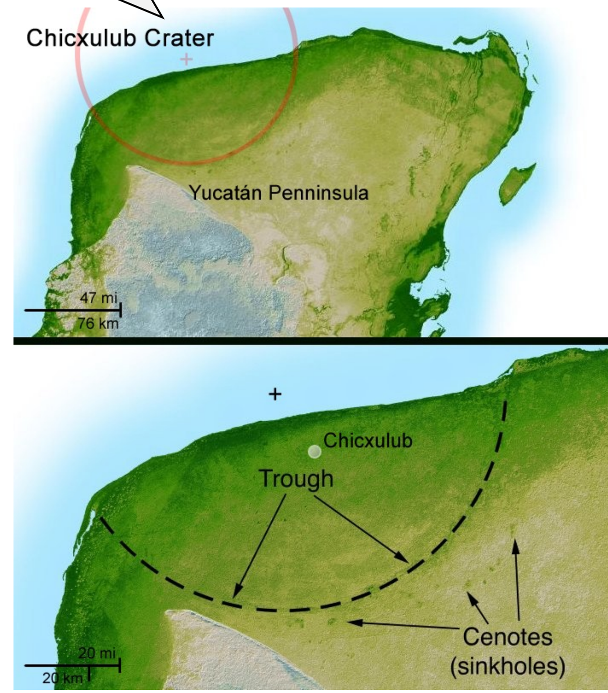




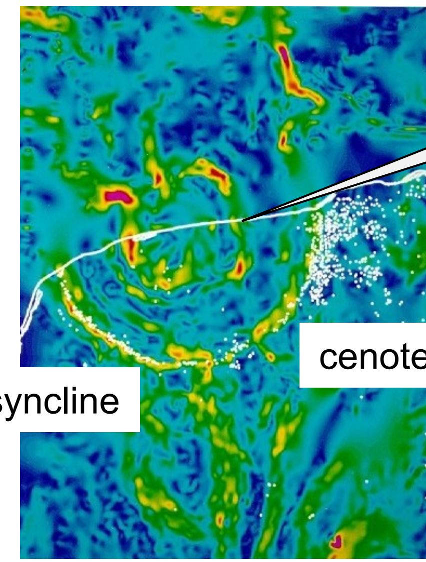
cca. 100-fold increase of the amount of iridium



Chicxulub crater (Mexico)



map of gravitational field

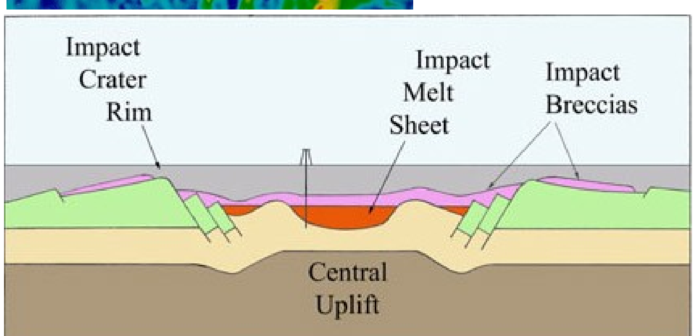


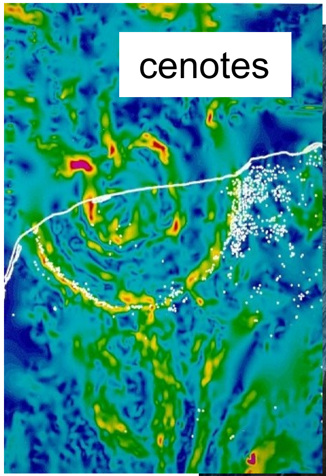
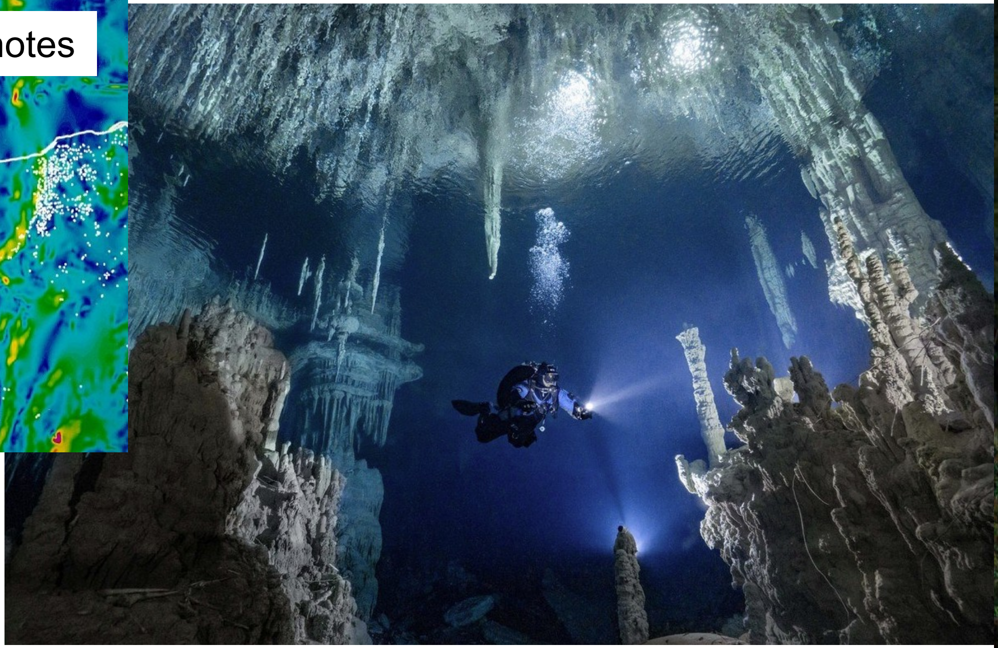
cenotes

syncline

tektites from the K/T

shock crystal




cenotes



Asteroid Chicxulub:

~ 8 trillions tonnes, ~ 2 600 km^3

velocity ~ 20 km/s; explosion ~ 300 mil. Mt of TNT

crater diameter 180–240 km

ca. after 2 min, 400 km from the epicentre extremely strong earthquake

after 20–25 min 2 waves:

1. huge sonic boom
2. few sec later: extreme vortexes similar to tornados ca. 350 m/s (1 260 km/h)

Experiment (Naafs et al. *Nature Geoscience* 2018)

laser ablation of carbonate (from Chicxulub)

Simulated conditions of late Cretaceous atmosphere
(0,16 % CO_2, 30 % O_2, 69,84 % N_2,
pressure 1 bars, temperature 25 °C

→ shock wave = 4,5 km/s (16 200 km/h)
→ expanding cloud = 2,3 km/s (8 280 km/h)

Plasma temp. in 0,2 microseconds ~ 18 000 K , → after 4 μs decrease to ~ 6 900 K

At the beginning: plasma temp. In the impact site more than 3-fold of that of the Sun surface.

Problems of the impact theory:

extinctions not that sudden for most animals, occurring before the impact

species have been disappearing in several phases from more thermophilic to less thermophilic

the impact by ca. 300 ky older than the extinction (but it may have trigger tsunamies and earthquakes ⇒ mixing of layers)

locality El Penon (Mexico): same species above and below the „impact“ layer)

Alternative hypothesis:

gradual cooling caused by giant volcano erruptions on the Deccan Plateau in India

basalt layer 1200-1800 m thick, 100 000 km^2 ⇒ during 1 MY → min. 1,5 mil. km^3 of basalts

the origin of the plateau at the turn of the Cretaceous and Tertiary

Recent findings:

According to new dating the Deccan event appeared before the impact – problém: inaccurate dating of the Indian event

More precise dating: the Chicxulub crater corresponds with the extinction

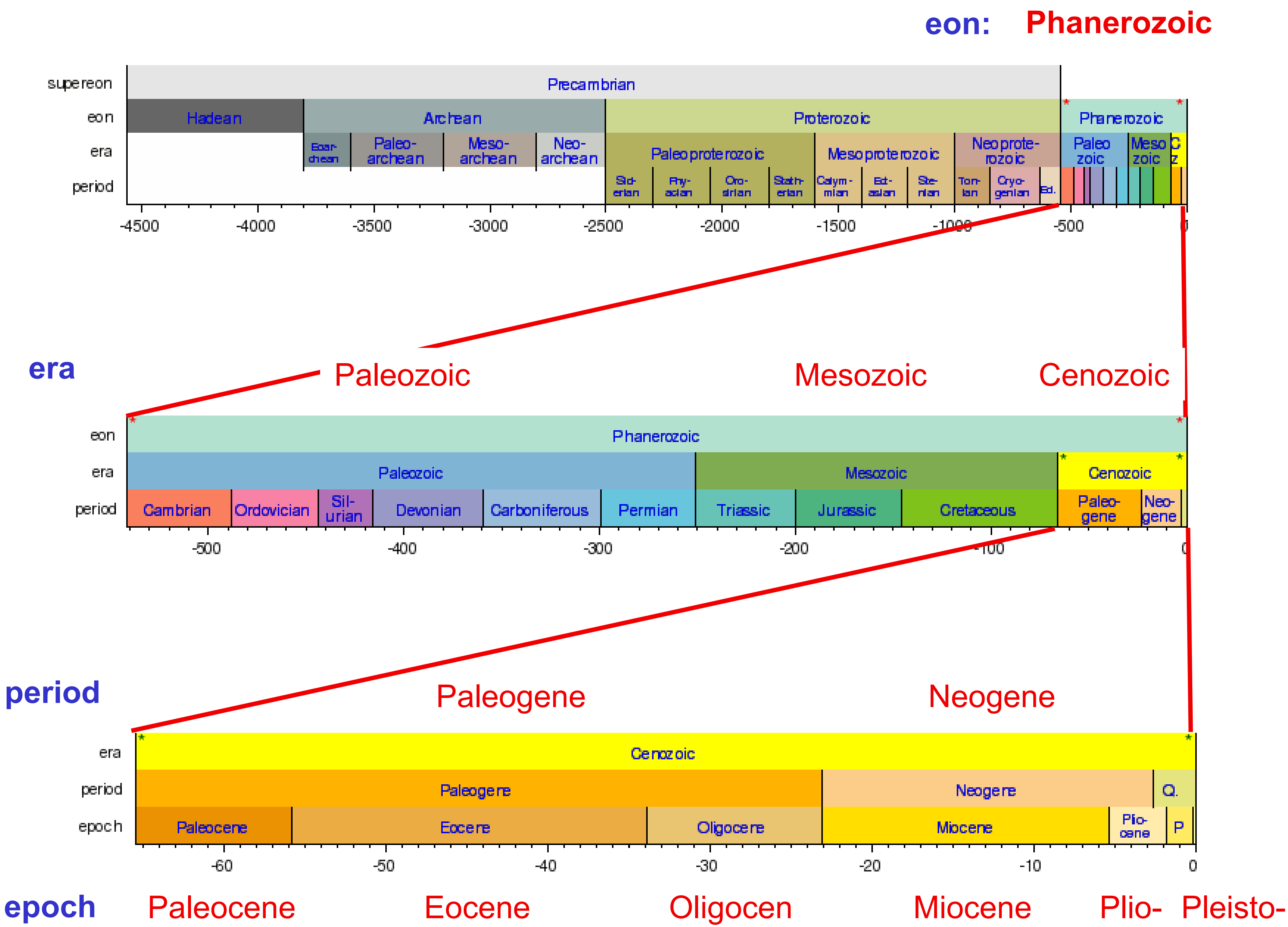
~ 100 ky before the impact cooling by 6–8 °C, probably as a consequence of the Deccan catastrophe – the impact then as the „coup of grace“

Cyanobacteria as a result of the greenhouse effect?

Some theories: two consecutive impacts

Animations:

eg. https://www.youtube.com/watch?v=bU1QPtOZQZU



eon:
Phanerozoic
supereon
eon
era
period
Precambrian
Hadean
Archean
Proterozoic
Phanerozoic
Eoar-
chean
Paleo-
archean
Meso-
archean
Neo-
archean
Paleoproterozoic
Mesoproterozoic
Neoprote-
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Devonian
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Permian
Triassic
Jurassic
Cretaceous
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gene
-500
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-300
-200
-100
0
period
Paleogene
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period
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Oligocene
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-10
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epoch
Paleocene
Eocene
Oligocen
Miocene
Plio-
Pleisto-

Paleontological vs. molecular data

When have animal phyla and mammalian/bird orders emerged?

Cambrian explosion?

molecular data (Wray et al. 1996):

Protostomia-Deuterostomia ~ 1200 M
Chordata-Echinodermata ~ 1000 M

„phylogenetic fuse“?

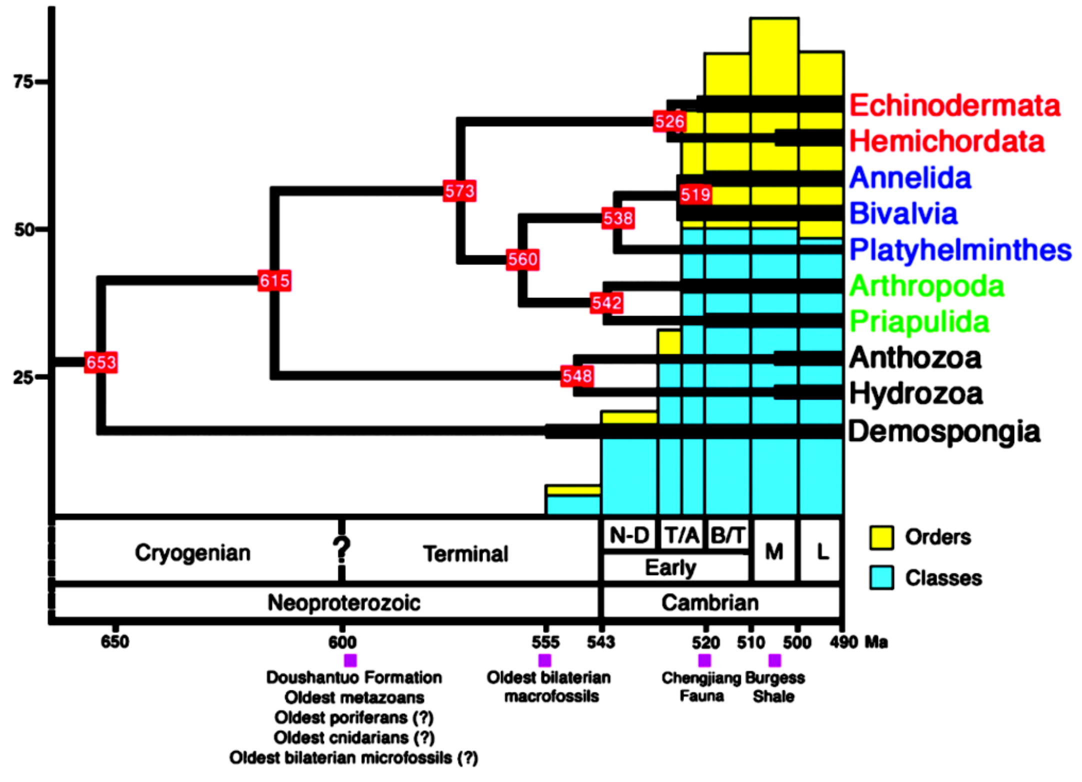
Paleontological vs. molecular data

When have animal phyla and mammalian/bird orders emerged?

Cambrian explosion?

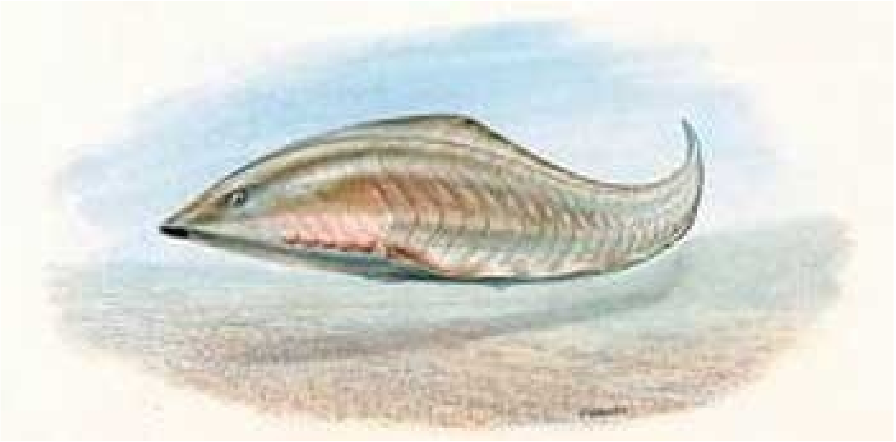
recent molecular estimates closer to the Cambrian explosion:

Metazoa ~ 650 M (Peterson et al. 2004)
Protostomia-Deuterostomia ~ 582 M
(Aris-Brosou and Yang 2003)



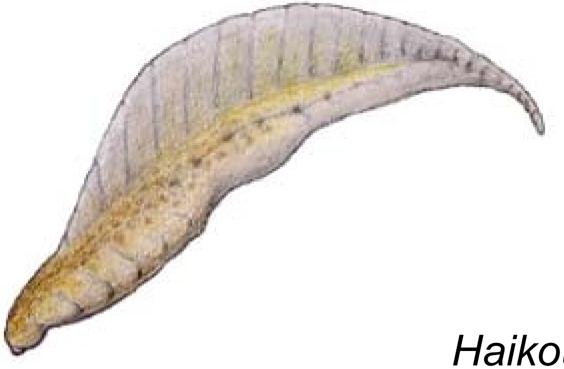
Cambrian explosion?

fauna of Chengjiang (Chína) ~ 525 M

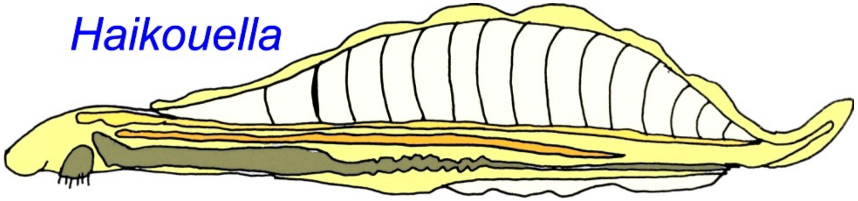


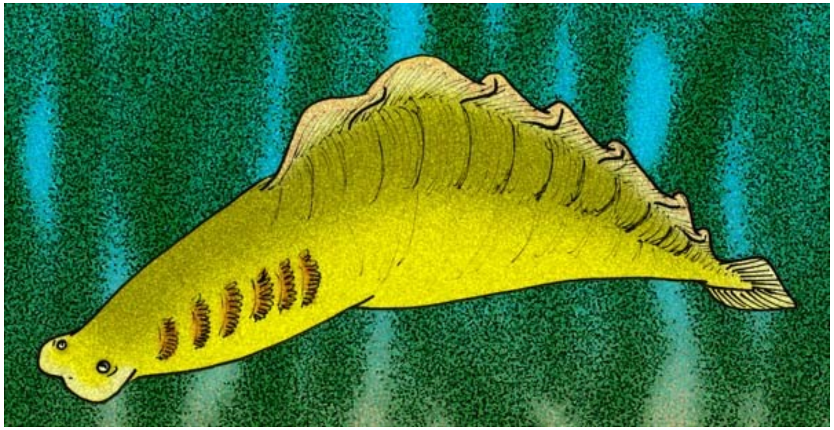
Myllokunmingia

Yunnanozoon lividum



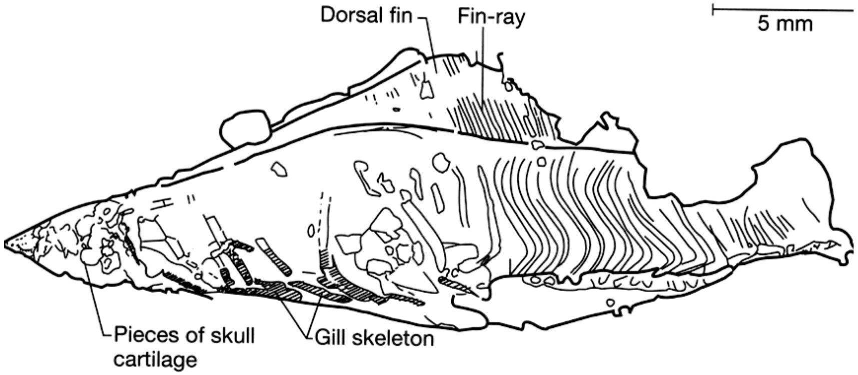
Haikouella lanceolata





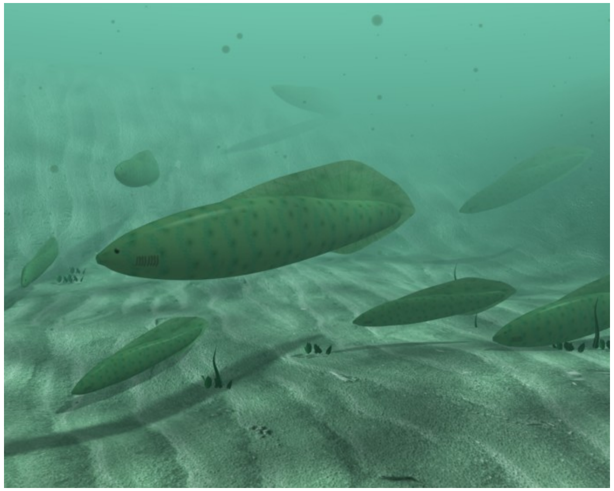
Cambrian explosion?

fauna of Chengjiang (China) ~ 525 M



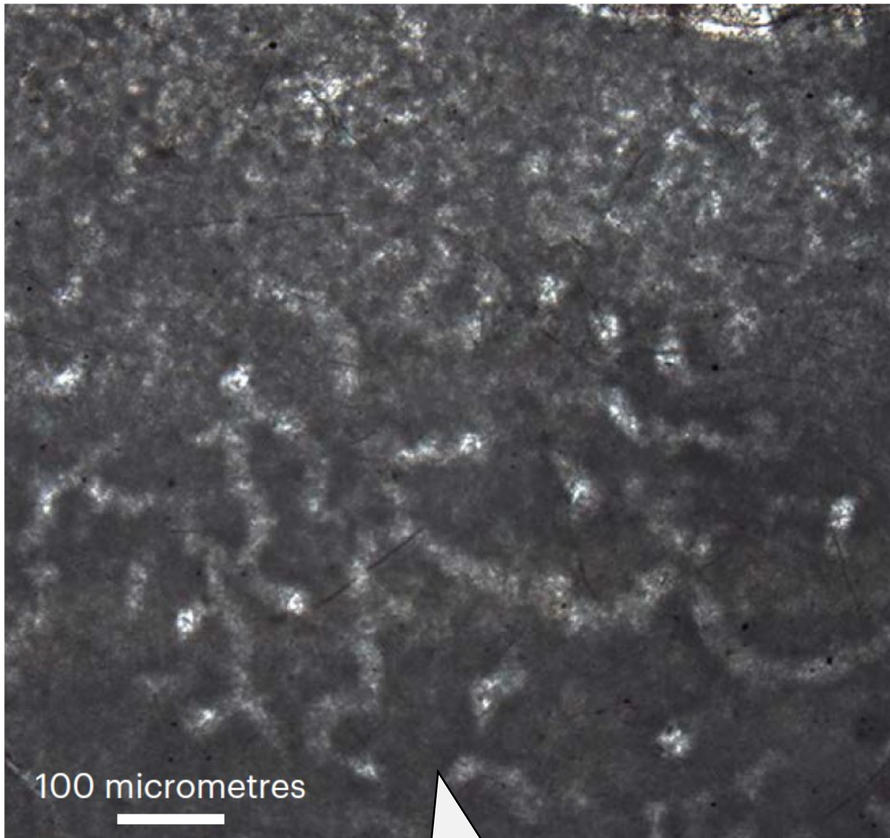
Doushantuo formation (S China), 590–560 M: many species

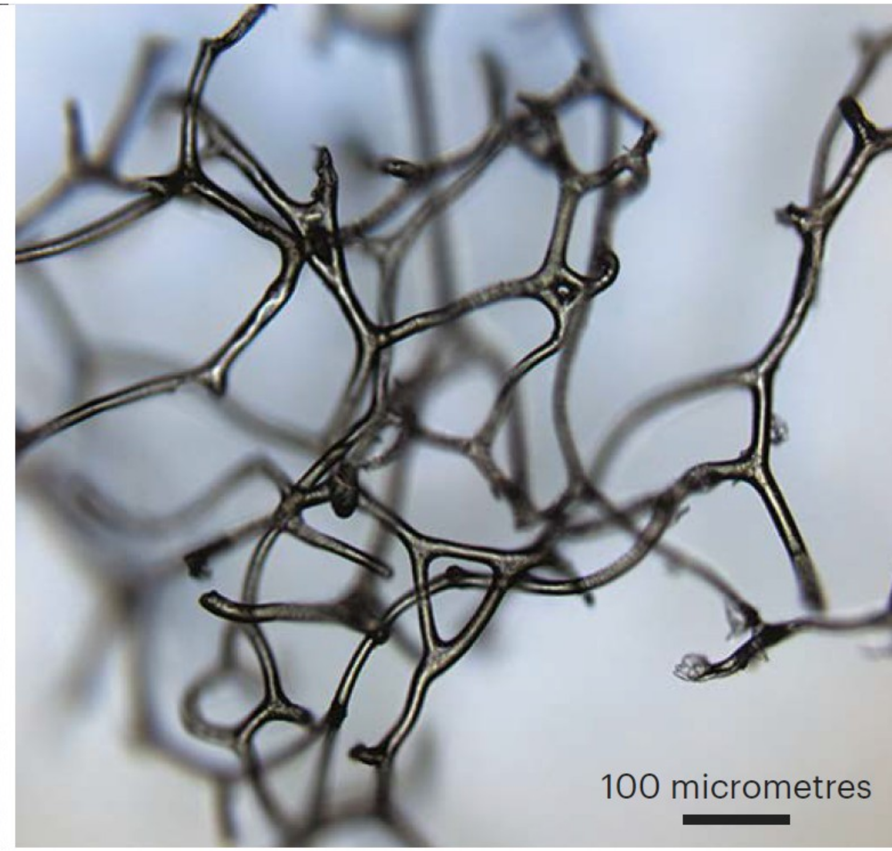
early embryonic stages?



Haikouichthys ercaicunensis
525 M

ca. 890 mil., Little Dal reefs, Stone Knife Formation, SZ Canada





Sponges (Porifera)?

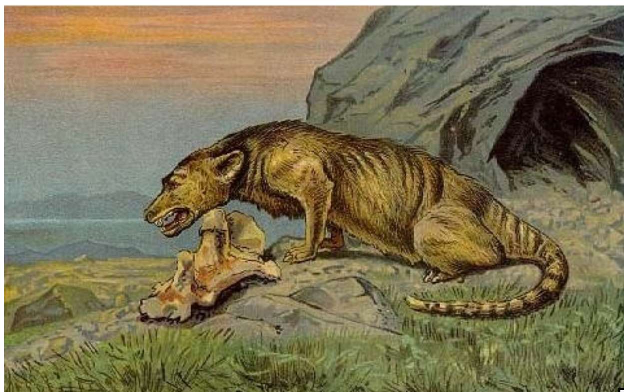
Elizabeth Turner, *Nature* 2021

Paleontological vs. molecular data

When have animal phyla and mammalian/bird orders emerged?

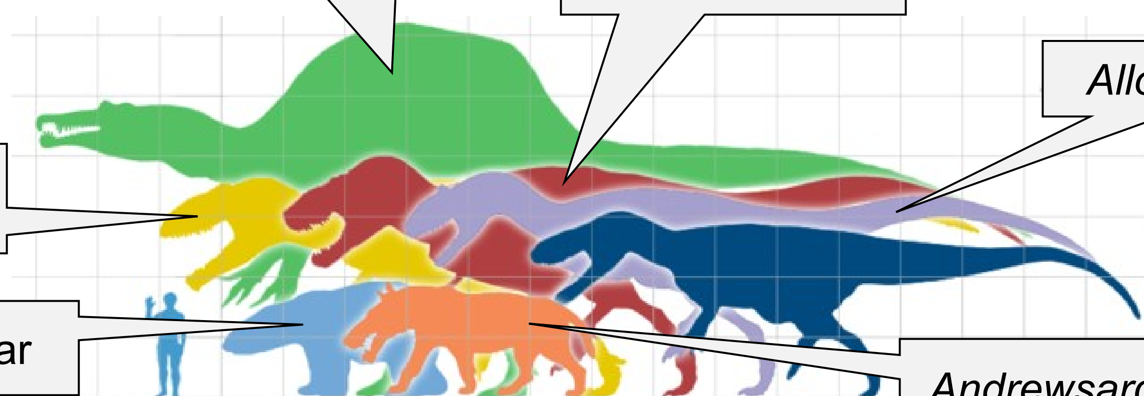
recent groups of mammals and birds and the K/T boundary

cetacean evolution: mesonychids → moving to water → cetaceans



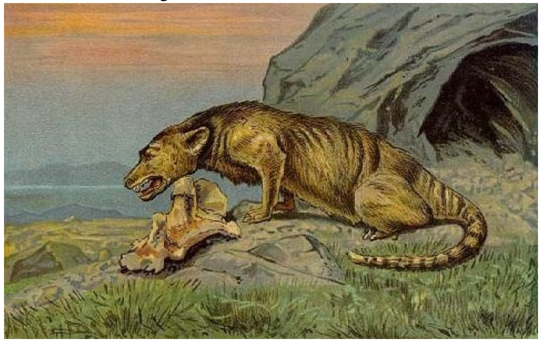
Mesonyx

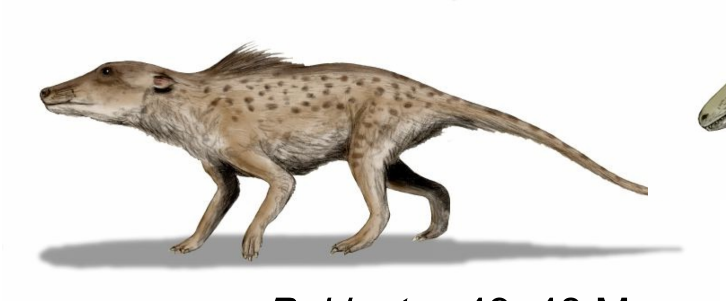
Andrewsarchus mongolicus



cetacean evolution

mesonychids ~ 56 M



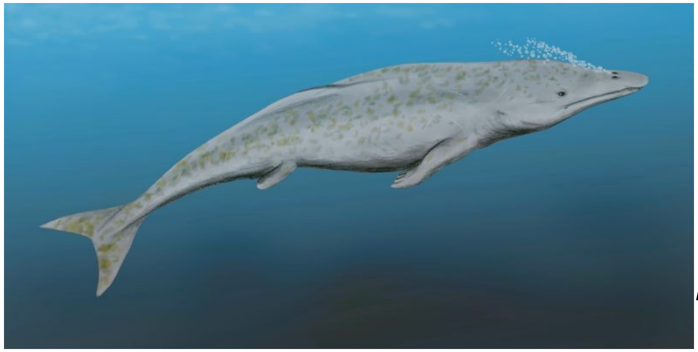


Pakicetus 49–48 M

Ambulocetus 50-48 M

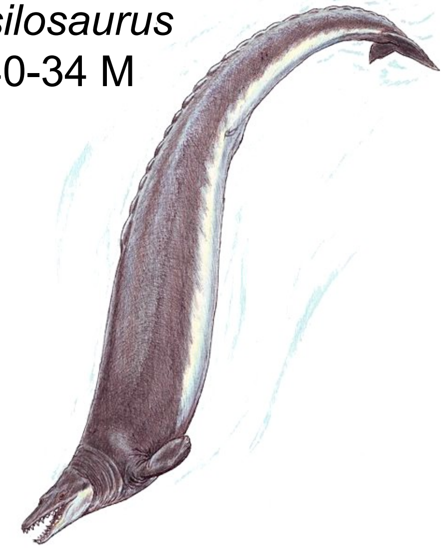
Dorudon 41-33 M

Rodhocetus 47 M

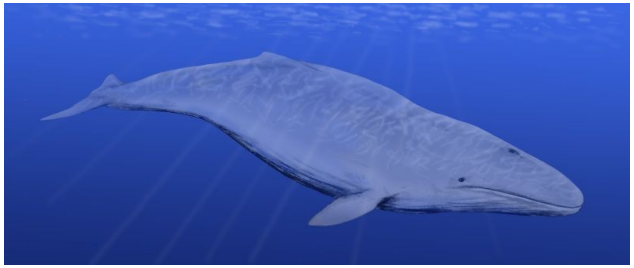


Protocetus 45 M

Basilosaurus 40-34 M



Peregocetus 43 M



Cetotherium 15 M

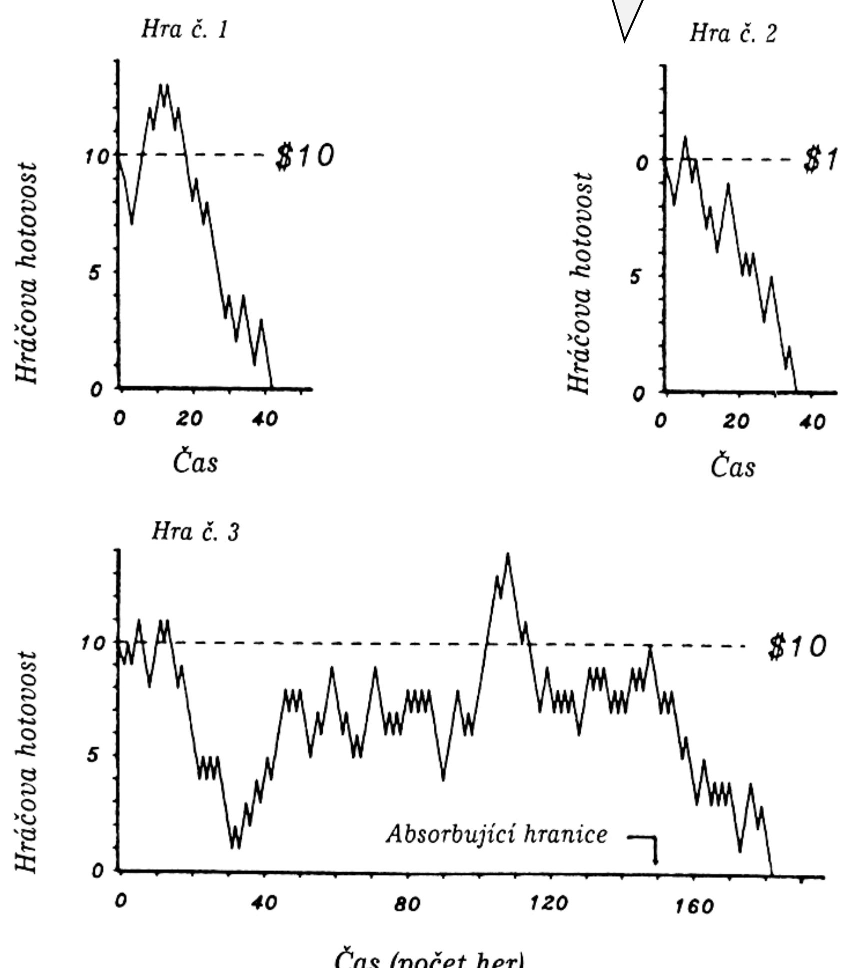
General principles

diversity: stock market analogy

extinction: foot soldier model

lifetime of lineages: gambler´s bankruptcy model

random walk



David Raup, Jack Sepkoski:

periodicity? (26 M – Nemesis)

now 62 M („inner clock“)?

D. Raup

J. J. Sepkoski