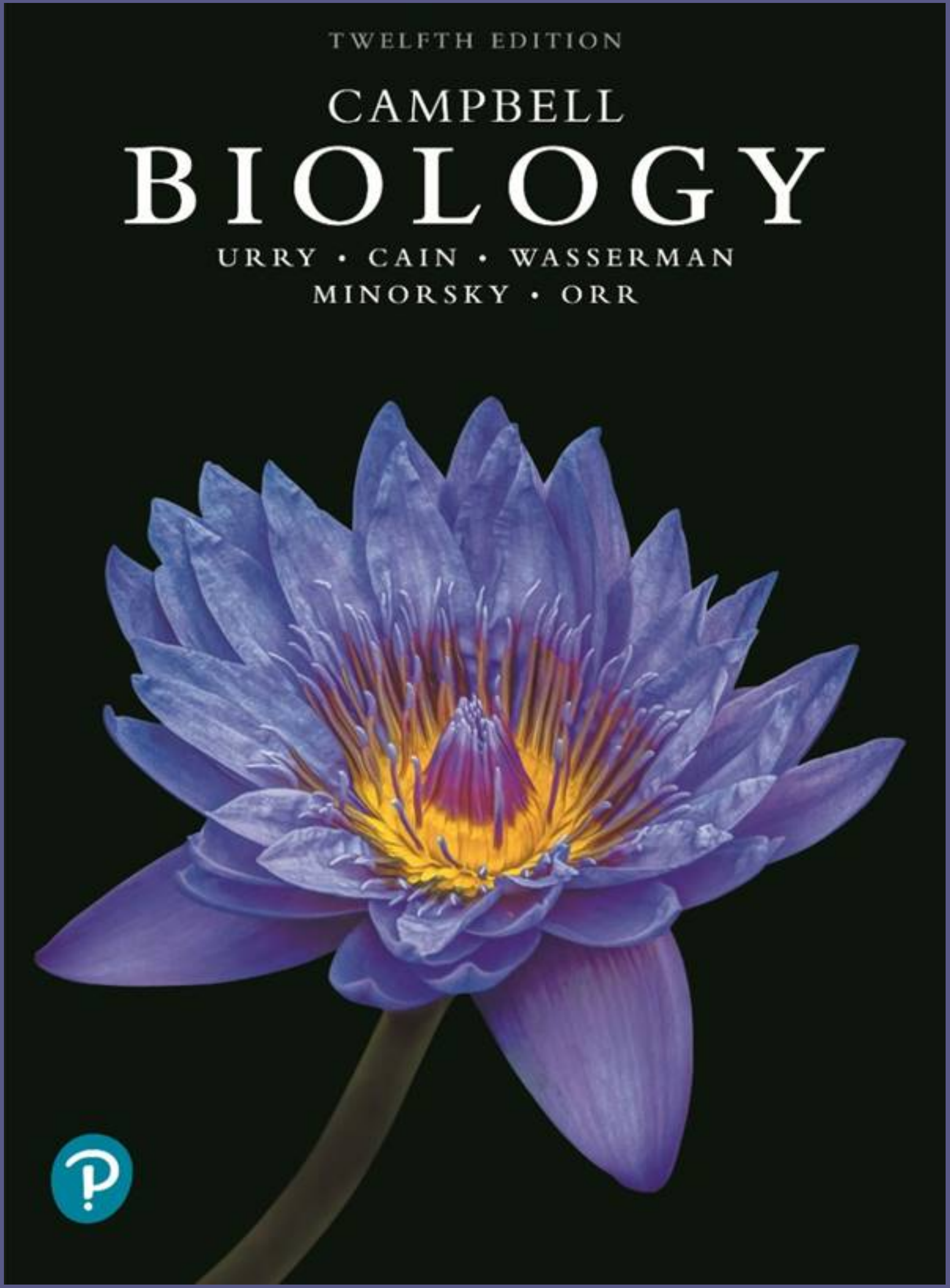


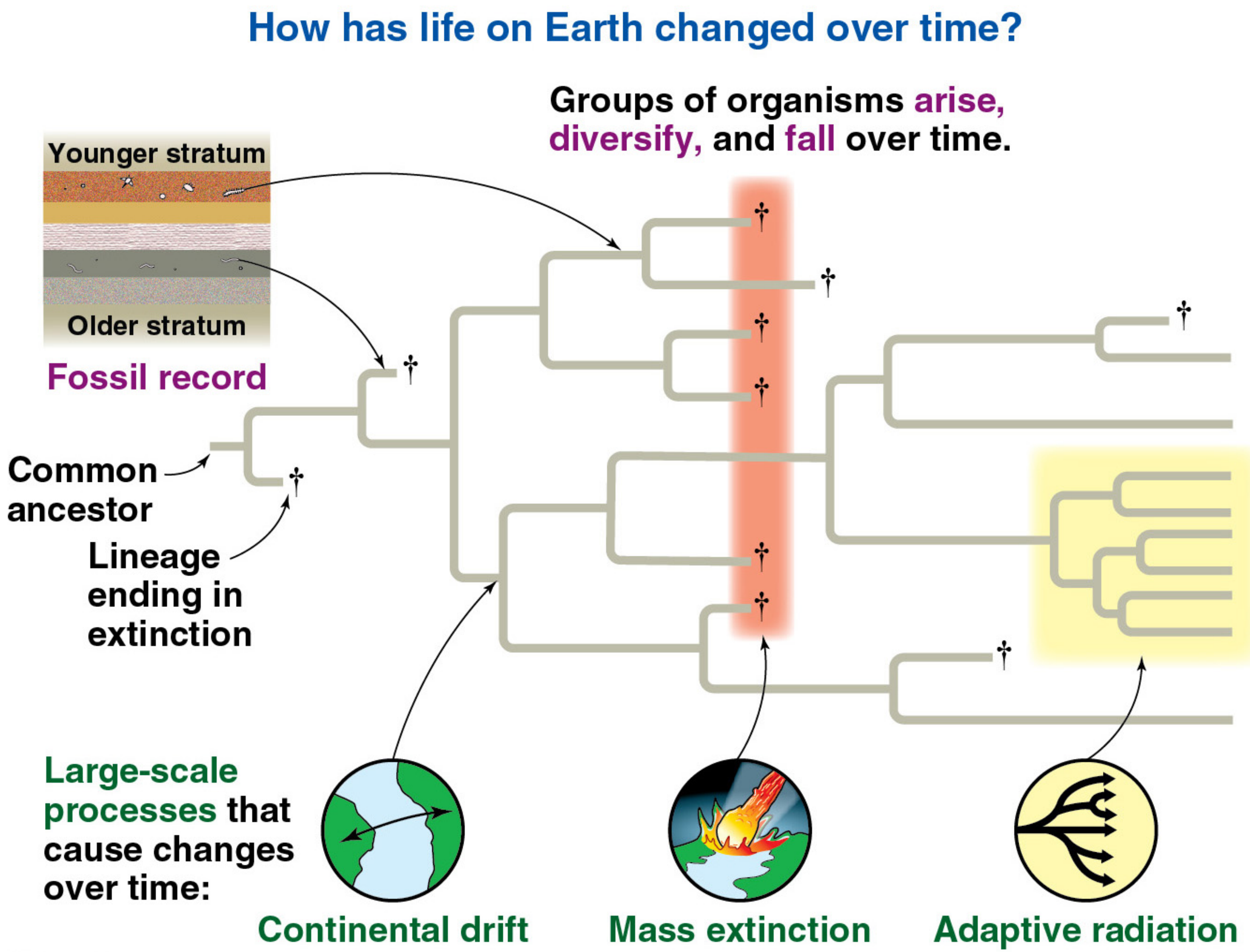
Chapter 25

The History of Life on Earth

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 25.1a

Figure 25.1b


How has life on Earth changed over time?
Groups of organisms arise, diversify, and fall over time.
Younger stratum
Older stratum
Fossil record
Common ancestor
Lineage ending in extinction
Large-scale processes that cause changes over time:
Continental drift
Mass extinction
Adaptive radiation

How has life on Earth changed over time?

- Past organisms were very different from those presently living
  - For example, fossils found in the Saharan Desert document the transition of whales from land to sea

- **Macroevolution** is the broad pattern of evolution above the species level
- The fossil record shows macroevolutionary changes over large time scales, for example:
  – the emergence of terrestrial vertebrates
  – the impact of mass extinctions
  – the origin of key adaptations, such as flight

CONCEPT 25.1: Conditions on early Earth made the origin of life possible

- Chemical and physical processes could produce simple cells through four stages
  1. Abiotic synthesis of small organic molecules
  2. Joining of these small molecules into macromolecules
  3. Packaging of molecules into **protocells**, droplets with membranes that maintain an internal chemistry different from the environment
  4. Origin of self-replicating molecules

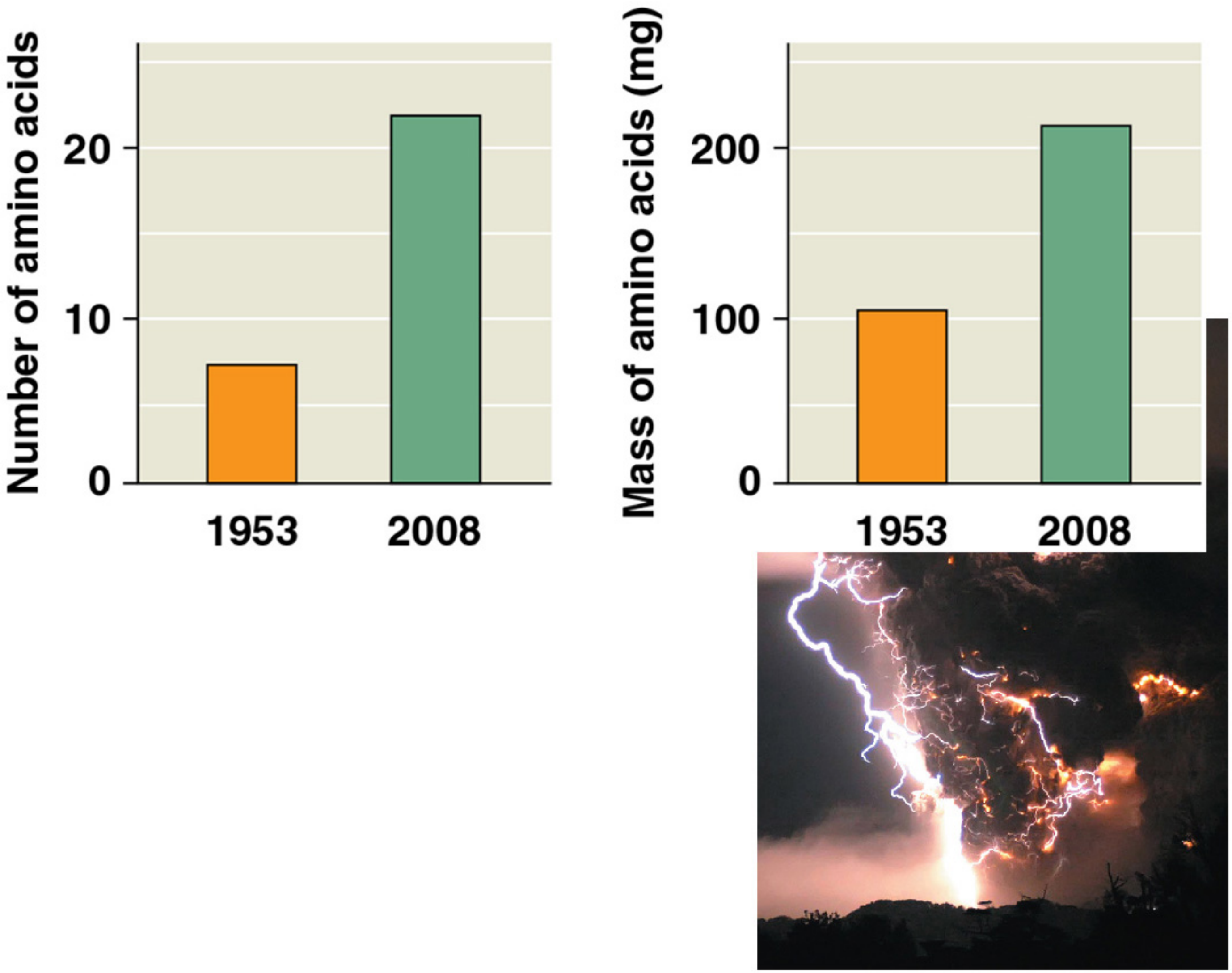
Synthesis of Organic Compounds on Early Earth

- Earth formed about 4.6 billion years ago
- Collisions with rocks and ice vaporized water, and prevented sea formation before 4 billion years ago
- The early atmosphere had little oxygen, but lots of water vapor plus compounds released by volcanic eruptions
  - For example, nitrogen and its oxides, carbon dioxide, methane, ammonia, hydrogen

- In the 1920s, A. I. Oparin and J. B. S. Haldane independently hypothesized that the early atmosphere was a reducing environment
- In 1953, Stanley Miller and Harold Urey demonstrated that abiotic synthesis of organic molecules was possible in a reducing atmosphere

- Some evidence suggests that the early atmosphere was neither reducing nor oxidizing
- The first organic compounds may have formed in reducing conditions near the openings of volcanoes
- In reanalysis of Miller’s results, amino acids were formed under conditions simulating volcanic eruption

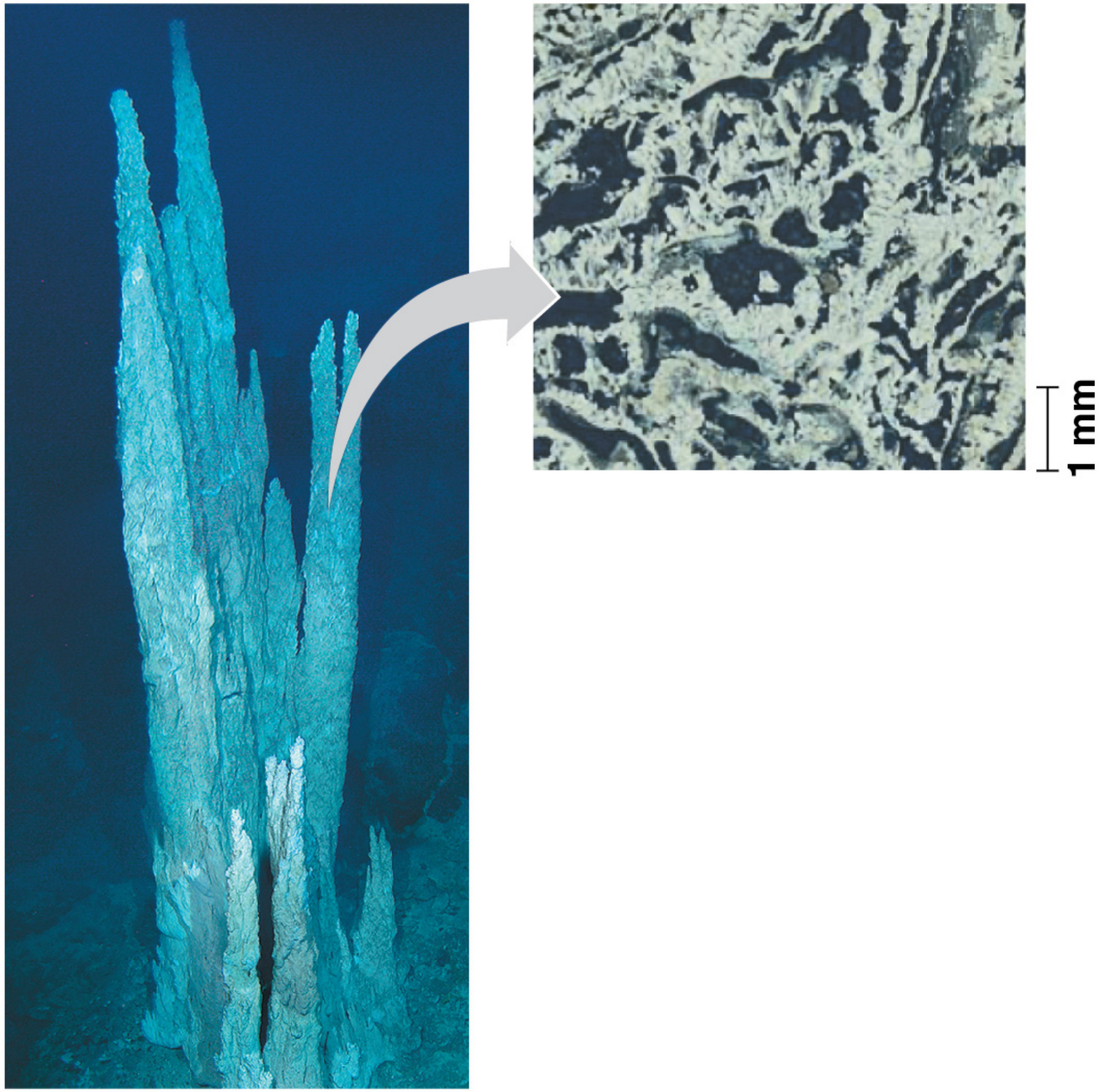
Figure 25.2


Number of amino acids
0
10
20
1953
2008
Mass of amino acids (mg)
0
100
200
1953
2008

- Organic compounds could have been produced in deep-sea **hydrothermal vents**
- Hot water and minerals gush through these vents from beneath the Earth’s surface and into the ocean

- Organic compounds are unstable in the extreme heat (300–400ºC) released by “Black smoker” vents
- Other vents, called **alkaline vents**, release water with high pH (9–11) and warm water (40–90ºC)
- This environment would have been more suitable for the origin of life than that near black smokers

Figure 25.3



Video: Tube Worms

- Meteorites could also have been a source of organic molecules
  - For example, fragments of the 4.5-billion-year-old Murchison meteorite contain amino acids, lipids, simple sugars, and nitrogenous bases

Abiotic Synthesis of Macromolecules

- Spontaneous abiotic synthesis of all four RNA monomers has been demonstrated in lab conditions
- RNA polymers form spontaneously when a solution of monomers is dripped onto hot sand, clay, or rock
- Such abiotically synthesized polymers could have acted as weak catalysts on early Earth

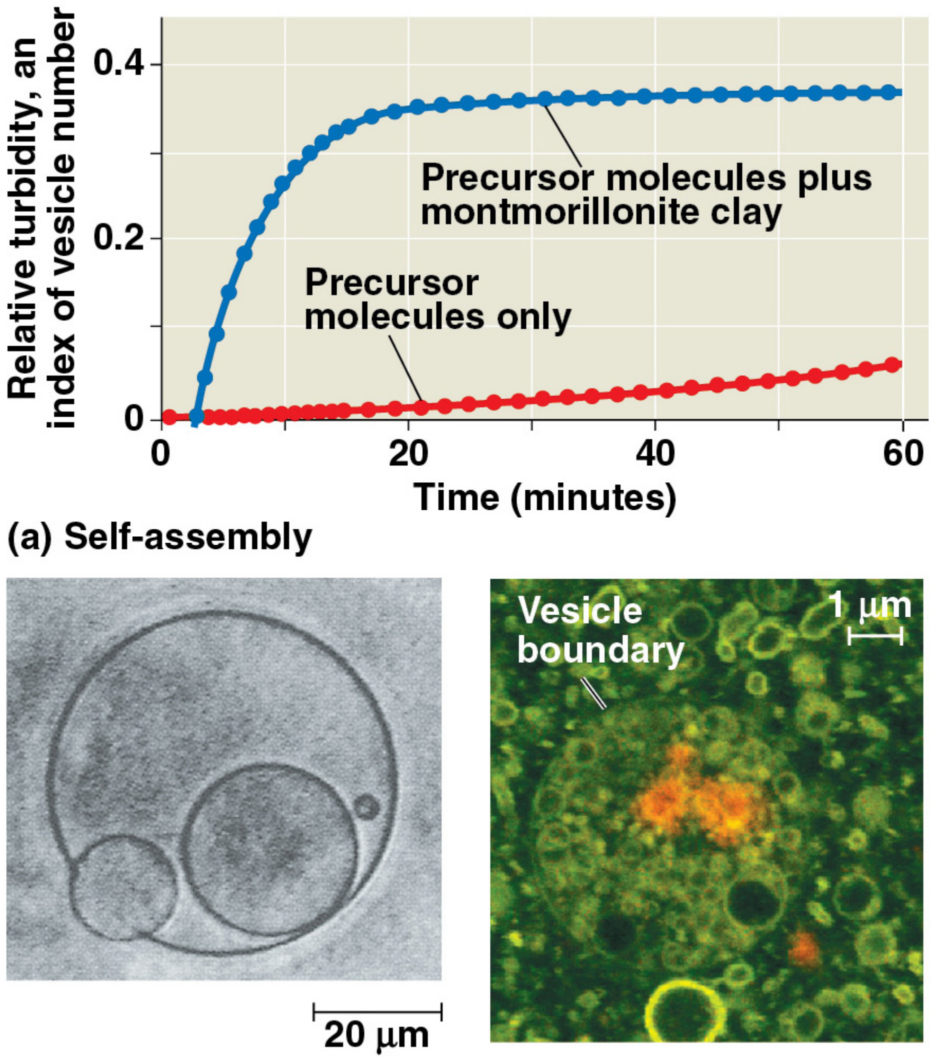
Protocells

- Replication and metabolism are key properties of life and may have appeared together in protocells
- Protocells may have formed from fluid-filled vesicles with a membrane-like structure
- In water, lipids and other organic molecules can spontaneously form vesicles with a lipid bilayer

- Adding montmorillonite, a mineral clay common on early Earth, increases the rate of vesicle formation
- Organic molecules attached to montmorillonite can be absorbed through the vesicle membrane

- Vesicles can exhibit some of the properties of life
  - Simple growth without dilution of contents
  - Reproduction
  - Metabolism
  - Maintenance of internal environment different from surroundings

Figure 25.4



(a) Self-assembly

(b) Reproduction

(c) Absorption of RNA

Self-Replicating RNA

- The first genetic material was likely RNA, not DNA
- RNA plays a central role in protein synthesis
- RNA molecules called **ribozymes** have been found to catalyze many different reactions
  - For example, ribozymes can make complementary copies of short stretches of RNA from nucleotides

- Self-replicating ribozymes have been produced through natural selection in laboratory experiments
- RNA molecules with different nucleotide sequences fold into different shapes
- Copying errors occasionally produce new shapes that enable faster replication with fewer errors
- The RNA molecule with the greatest replication ability leaves the most descendent molecules

- Researchers recently built a vesicle within which copying of a template strand of RNA could occur
- Protocells could form on early Earth from vesicles that grew, split, and passed RNA to their “daughters”
- Natural selection could act on such protocells, making more successful forms over generations

- RNA could have provided the template for the assembly of DNA nucleotides
- Double-stranded DNA is more chemically stable and can be replicated more accurately than RNA

CONCEPT 25.2: The fossil record documents the history of life

- The fossil record reveals changes in the history of life on Earth

The Fossil Record

- The fossil record is based on the accumulation of fossils in sedimentary rock layers, called strata
- Other types of fossils, such as insects captured in amber, also provide useful information

Figure 25.5a

(a) Plant fossil, about 300 million years old

(b) Petrified tree in Arizona, about 215 million years old

(c) 150-million-year-old dinosaur tracks in Colorado

(e) A 50,000-year-old wolf pup found in frozen soil in Yukon, Canada

(d) Insect in amber, about 40 million years old

Sedimentary rock

- Most fossils are found in sedimentary rock

(a) Plant fossil, about 300 million years old

Mineralized organic matter

- Some fossils form as minerals seep into and replace organic matter

(b) Petrified tree in Arizona, about 215 million years old

Trace fossils

- Footprints, burrows, or other traces of an organism's activities can be preserved in the fossil record

Figure 25.5d

(c) 150-million-year-old dinosaur tracks in Colorado

Amber

- Entire organisms can be found preserved in hardened resin from a tree

Figure 25.5e

(d) Insect in amber, about 40 million years old

Frozen soil, ice, and acid bogs

- Bodies of larger organisms can rarely be preserved in frozen soil, ice, or an acid bog

Figure 25.5f

(e) A 50,000-year-old wolf pup found in frozen soil in Yukon, Canada

Video: Grand Canyon

- The fossil record shows the great changes in the types of organisms on Earth over time
  - Many past organisms were unlike those living today
  - Many organisms once common are now extinct
  - New groups arose from previously existing ones

- The fossil record is an incomplete chronicle of evolution because
  - Few organisms were preserved as fossils
  - Many fossils were destroyed by geologic processes
  - Only a fraction of fossils have yet been discovered

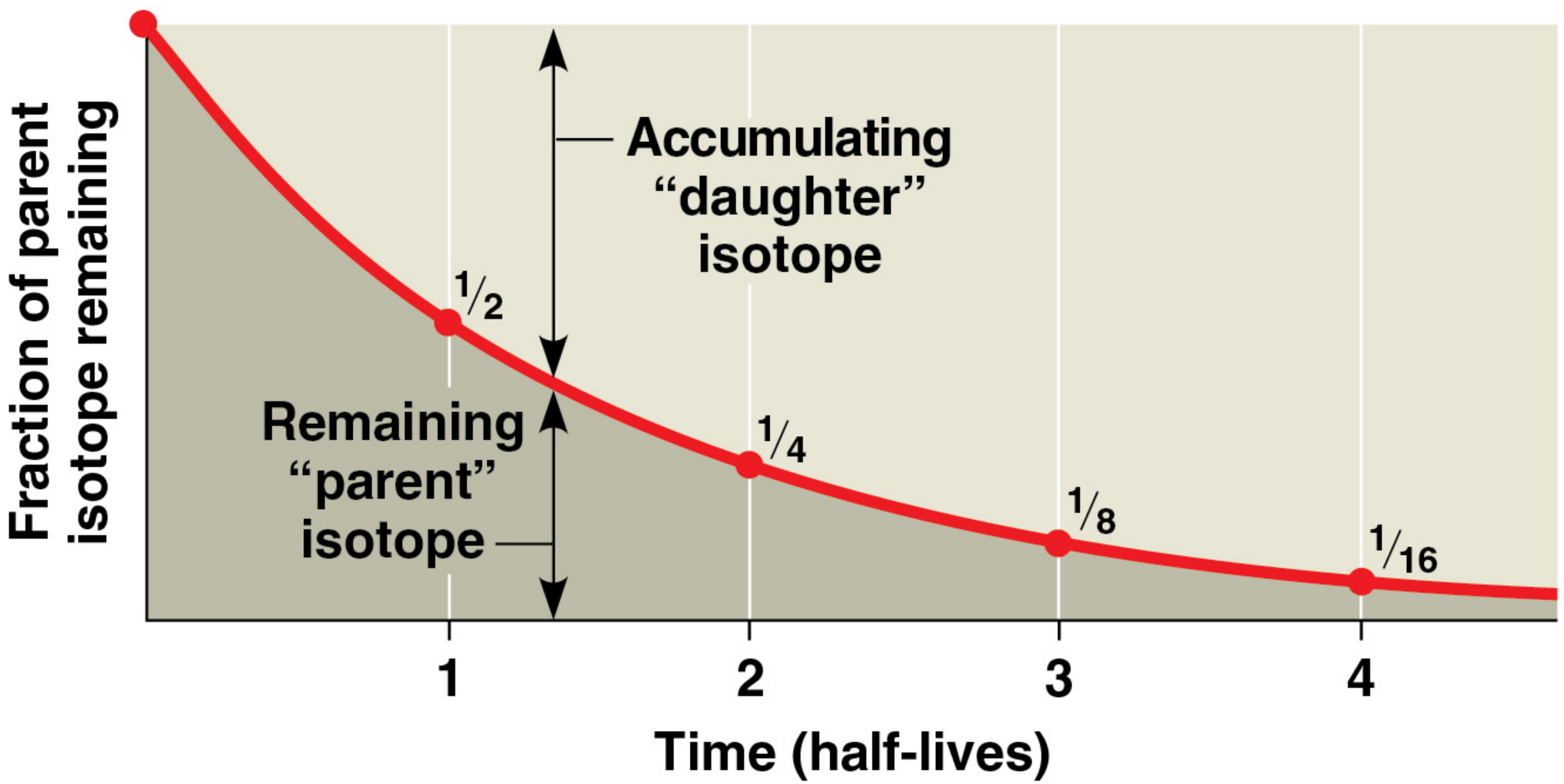
- The known fossil record is biased in favor of species that
  - Existed for a long time
  - Were abundant and widespread
  - Had hard parts, such as shells or skeletons

How Rocks and Fossils Are Dated

- The order of fossils in rock strata tells us the sequence in which they were formed
- We can infer relative ages of fossils using this method, but not their actual ages

- **Radiometric dating** is used to determine the age of fossils based on the decay of radioactive isotopes
- A radioactive “parent” isotope decays to a “daughter” isotope at a characteristic rate
- Each isotope has a known **half-life**, the time required for 50% of the parent isotope to decay

Figure 25.6



Fraction of parent isotope remaining
Accumulating "daughter" isotope
Remaining "parent" isotope
1/2
1/4
1/8
1/16
1
2
3
4
Time (half-lives)

- Fossils contain isotopes that accumulated in the organisms when they were alive
- A fossil’s age can be estimated based on the ratio of carbon-14 to carbon-12 isotopes it contains
  - Carbon-12 is stable; the amount in the organism does not change after its death
  - Carbon-14 is radioactive; it slowly decays to nitrogen-14 after the organism’s death

- Carbon isotopes can be used to date fossils up to 75,000 years old
- Dating older fossils requires the use of radioactive isotopes with longer half-lives
- Organisms do not use radioisotopes with long half-lives to build bones or shells
- Older fossils are dated using radioisotopes with long half-lives found in surrounding layers of volcanic rock

- The study of fossils is used to establish the geologic record: a standard time scale dividing Earth’s history into four eons and further subdivisions

Table 25.1

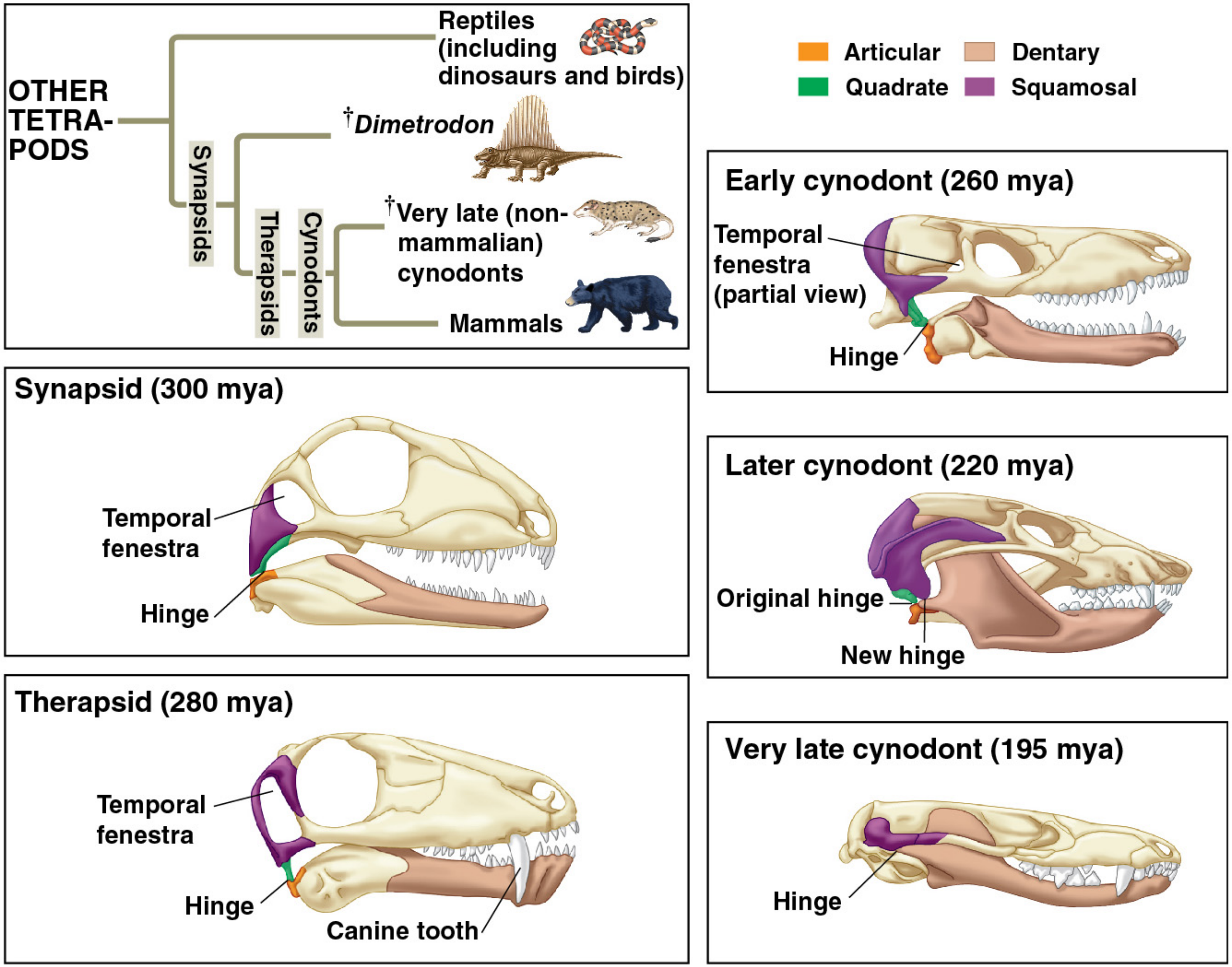
Table 25.1 The Geologic Record

Eon	Era	Period	Epoch	Age (Millions of Years Ago)
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01
			Pleistocene	2.6
		Neogene	Pliocene	5.3
			Miocene	23
		Paleogene	Oligocene	33.9
			Eocene	56
			Paleocene	66
	Mesozoic	Cretaceous		145
		Jurassic		201
		Triassic		252
	Paleozoic	Permian		299
		Carboniferous		359
		Devonian		419
		Silurian		444
		Ordovician		485
		Cambrian		541
Proterozoic	Neoproterozoic	Ediacaran		635
				1,000
				2,500
Archaean				4,000
Hadean				Approx. 4,600

The Origin of New Groups of Organisms

- Mammals belong to the group of animals called tetrapods, named for having four limbs
- The evolution of unique mammalian features can be traced in the fossil record
  - For example, mammalian jaws and teeth evolved gradually over time, in a series of steps

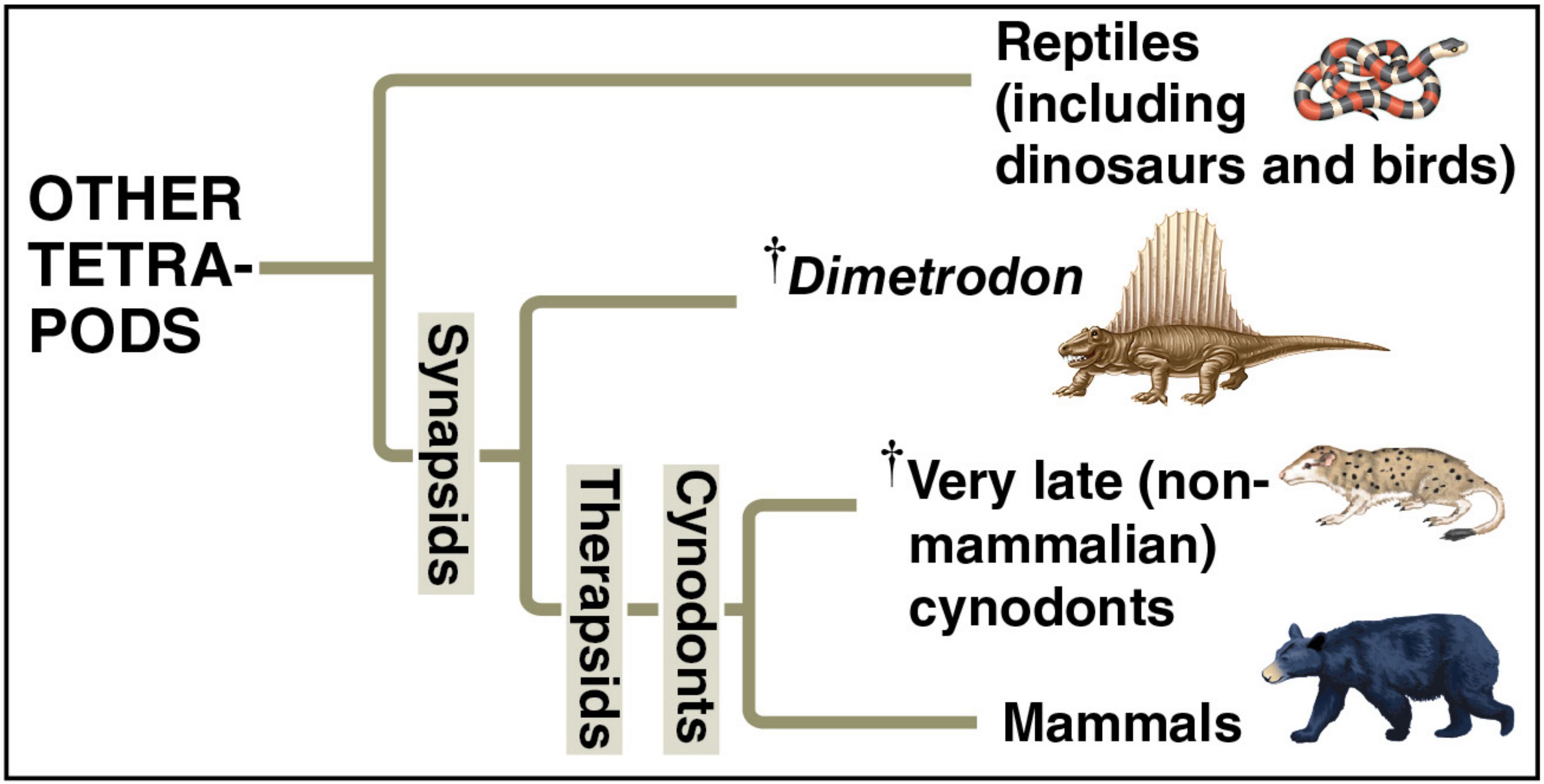
Figure 25.7a



OTHER TETRA-PODS
Synapsids
Therapsids
Cynodonts
Reptiles (including dinosaurs and birds)
†Dimetrodon
†Very late (non-mammalian) cynodonts
Mammals
Articular
Dentary
Quadrate
Squamosal
Synapsid (300 mya)
Temporal fenestra
Hinge
Therapsid (280 mya)
Temporal fenestra
Hinge
Canine tooth
Early cynodont (260 mya)
Temporal fenestra (partial view)
Hinge
Later cynodont (220 mya)
Original hinge
New hinge
Very late cynodont (195 mya)
Hinge

- Mammals originated gradually from a group of tetrapods called synapsids

Figure 25.7b



Reptiles (including dinosaurs and birds)
†*Dimetrodon*
†Very late (non-mammalian) cynodonts
Mammals
OTHER TETRA-PODS
Synapsids
Therapsids
Cynodonts

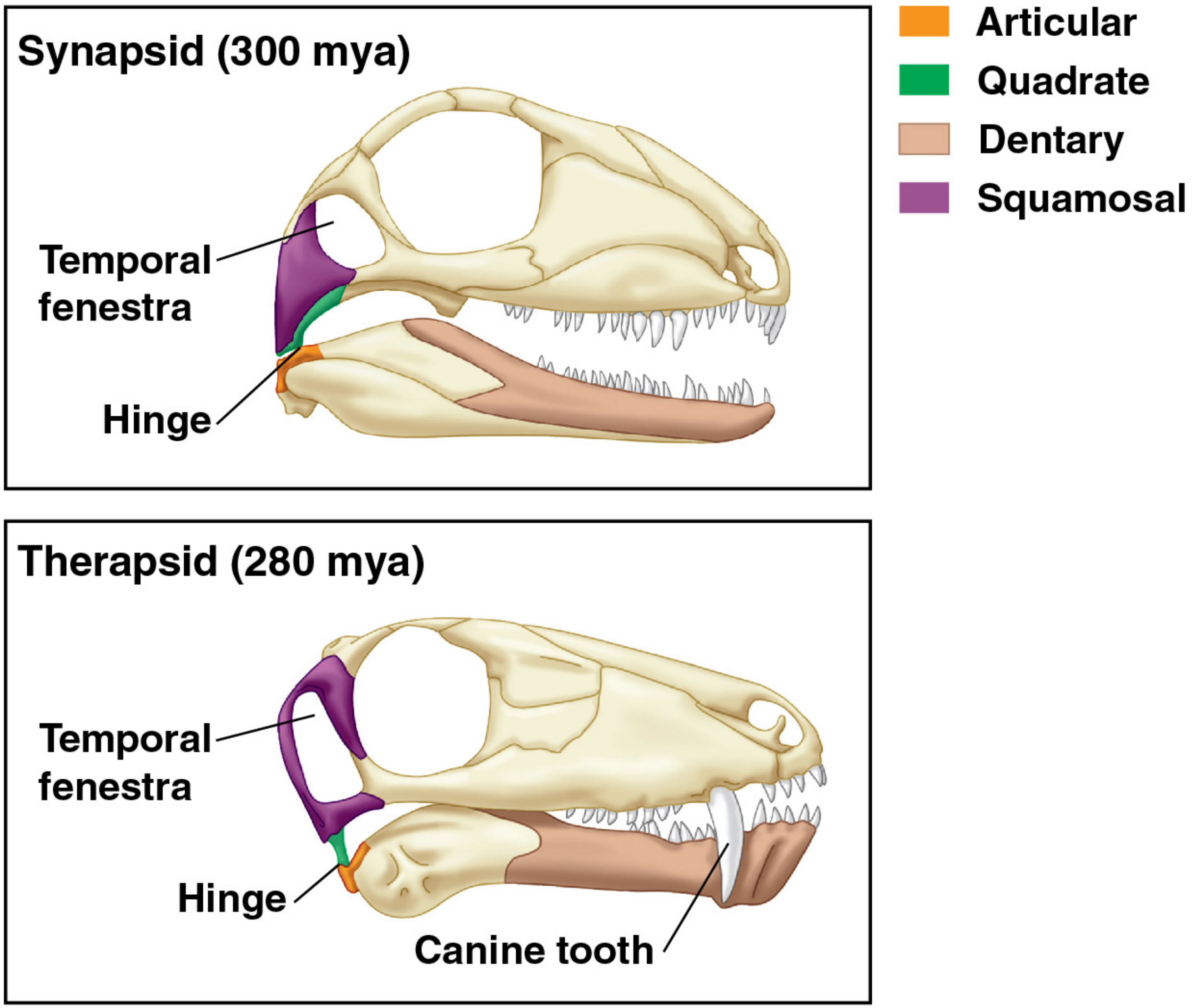
Synapsid (300 mya)

- Early synapsids had multiple bones in the lower jaw, a hinge between the articular and quadrate bones, single-pointed teeth, and temporal fenestra

Therapsid (280 mya)

- Therapsids had large dentary bones, long faces, and specialized teeth, including large canines

Figure 25.7c



Synapsid (300 mya)
Temporal fenestra
Hinge
Therapsid (280 mya)
Temporal fenestra
Hinge
Canine tooth
Articular
Quadrate
Dentary
Squamosal

Early cynodont (260 mya)

- Early cynodont therapsids had large dentary bones, large temporal fenestra in front of the jaw hinge, and teeth with several cusps

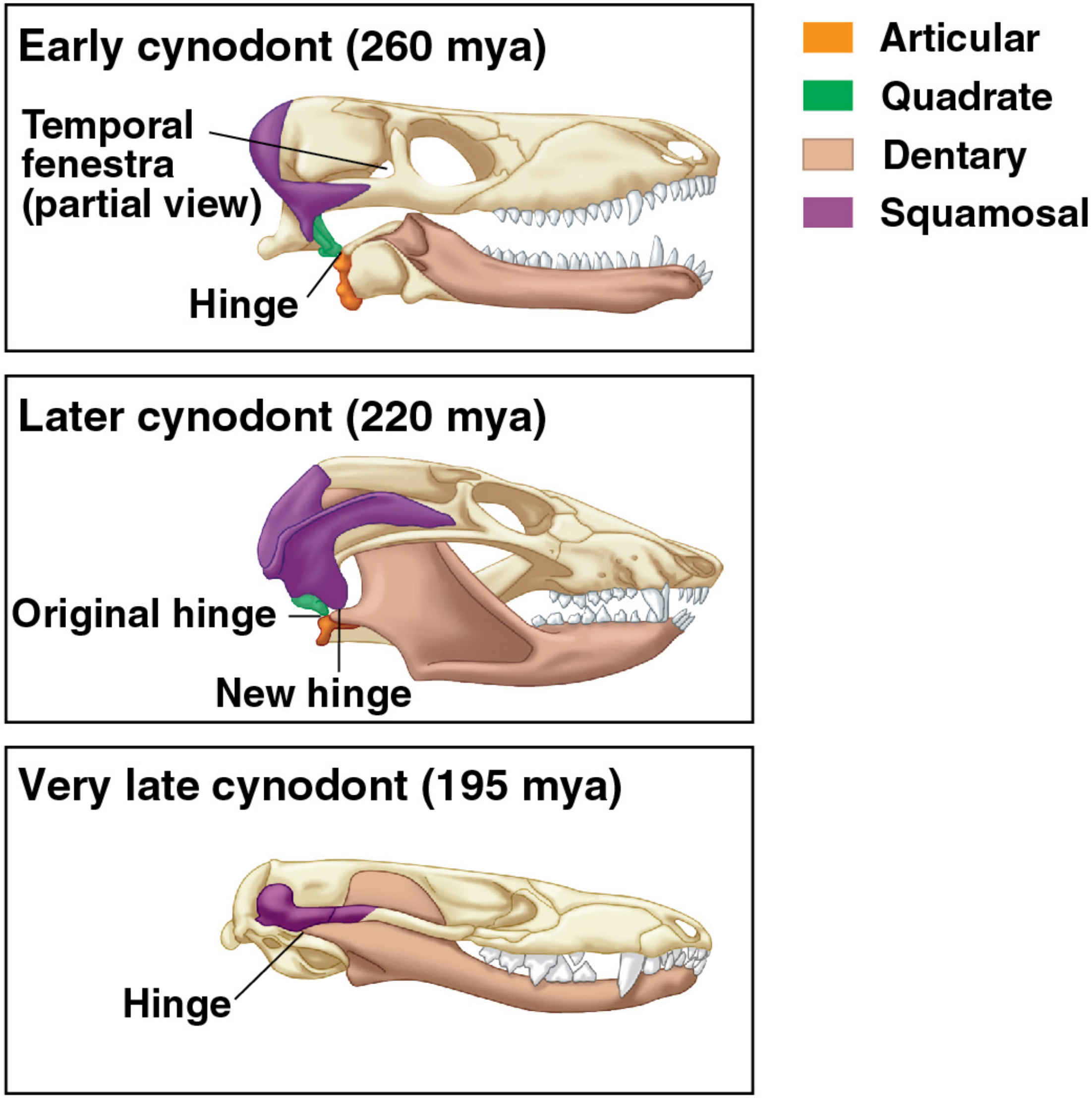
Later cynodont (220 mya)

- Later cynodonts had teeth with complex cusp patterns and jaws hinged in two locations

Very late cynodont (**195 mya**)

- Some very late cynodonts and early mammals lost the original articular-quadrate jaw hinge
- The articular and quadrate bones formed inner ear bones that functioned in transmitting sound
- In mammals, these bones evolved into the hammer (malleus) and anvil (incus) bones of the ear

Figure 25.7d



Early cynodont (260 mya)
Temporal fenestra (partial view)
Hinge
Later cynodont (220 mya)
Original hinge
New hinge
Very late cynodont (195 mya)
Hinge
Articular
Quadrate
Dentary
Squamosal

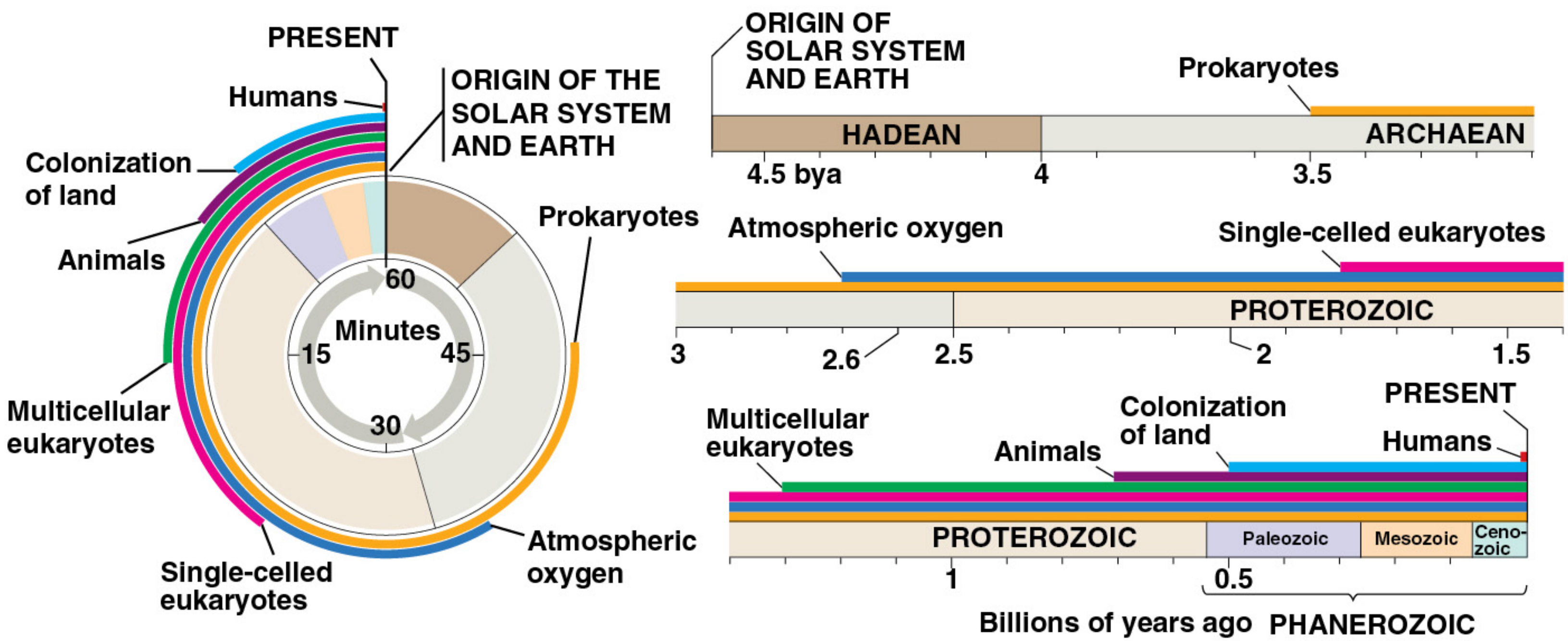
- Most tetrapods have undifferentiated, single-pointed teeth
- Mammalian teeth are specialized for their function
  - Incisors are used for tearing
  - Canines are used for piercing
  - Molars are used for crushing and grinding

CONCEPT 25.3: Key events in life's history include the origins of unicellular and multicellular organisms and the colonization of land

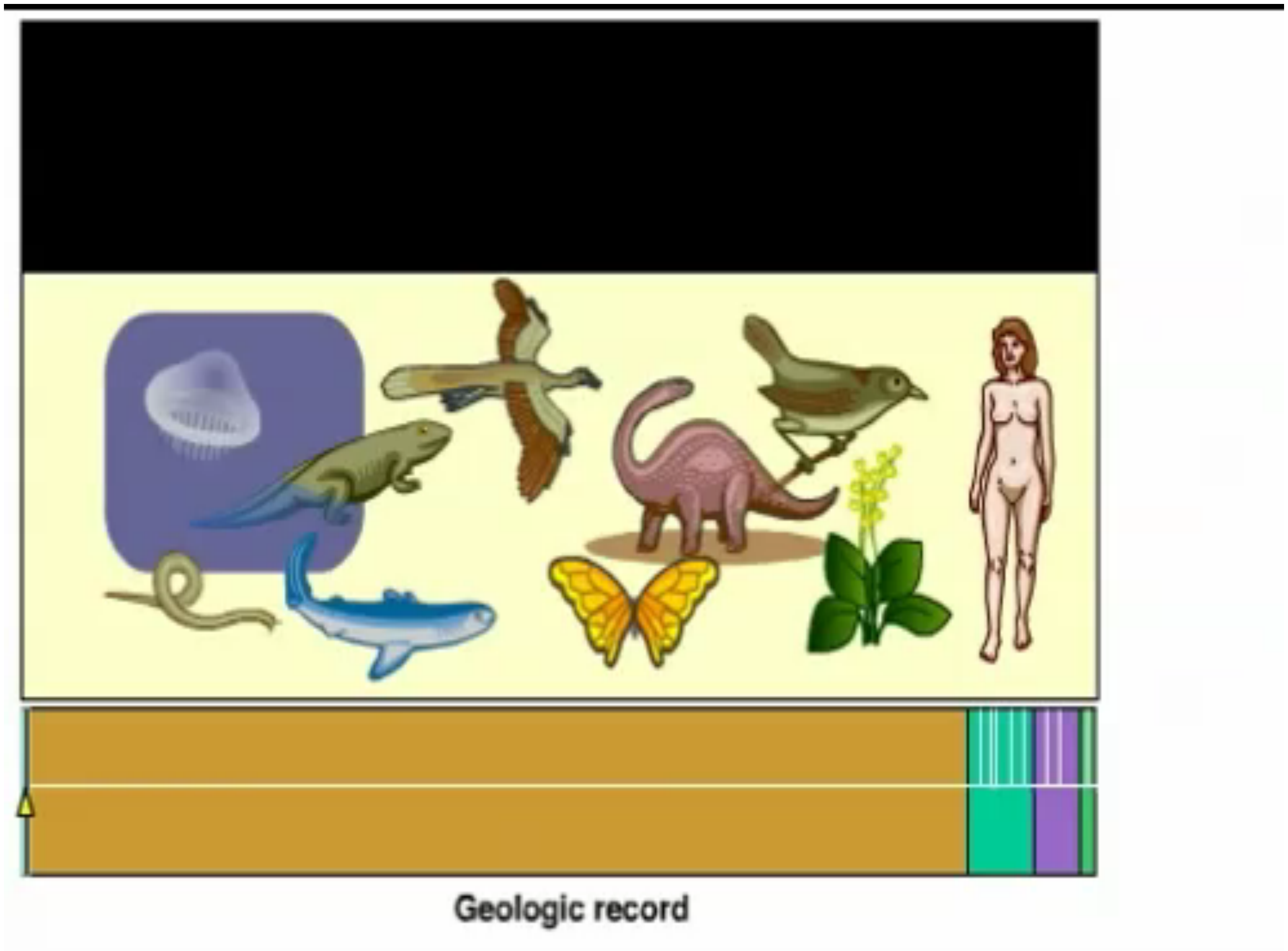
- The geologic record is divided into the Hadean, Archaean, Proterozoic, and Phanerozoic eons
- The most recent eon, the Phanerozoic, includes the Paleozoic, Mesozoic, and Cenozoic eras
- Major boundaries between these eras correspond to major extinction events in the fossil record

- The analogy of a 1-hour countdown timer can be used to relate geologic time to a familiar time scale
  - For example, on a 1-hour time scale, animals originated about 9 minutes ago, while humans appeared less than 0.2 second ago

Figure 25.8


PRESENT
Humans
Colonization of land
Animals
Multicellular eukaryotes
Single-celled eukaryotes
ORIGIN OF THE SOLAR SYSTEM AND EARTH
Prokaryotes
Atmospheric oxygen
60
Minutes
15
45
30
ORIGIN OF SOLAR SYSTEM AND EARTH
Prokaryotes
HADEAN
ARCHAEAN
4.5 bya
4
3.5
Atmospheric oxygen
Single-celled eukaryotes
PROTEROZOIC
3
2.6
2.5
2
1.5
Multicellular eukaryotes
Colonization of land
PRESENT
Animals
Humans
PROTEROZOIC
Paleozoic
Mesozoic
Ceno-zoic
1
0.5
Billions of years ago
PHANEROZOIC

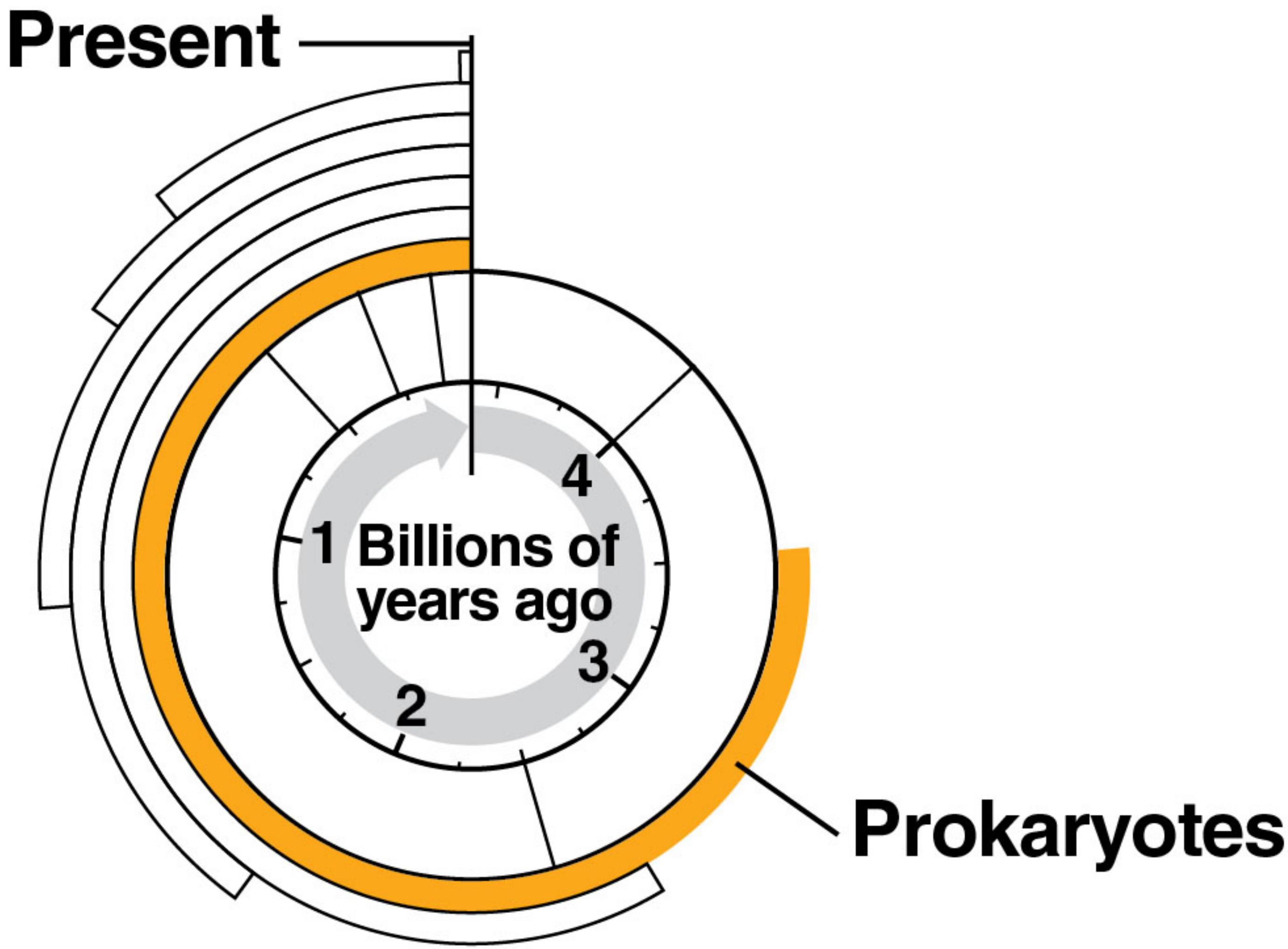
Animation: The Geologic Record



The First Single-Celled Organisms

- **Stromatolites** are layered rocks that form when prokaryotes bind thin films of sediment together
- Fossilized stromatolites dating from 3.5 billion years ago are the earliest evidence of life on Earth
- Prokaryotes were Earth’s sole inhabitants for more than 1.5 billion years

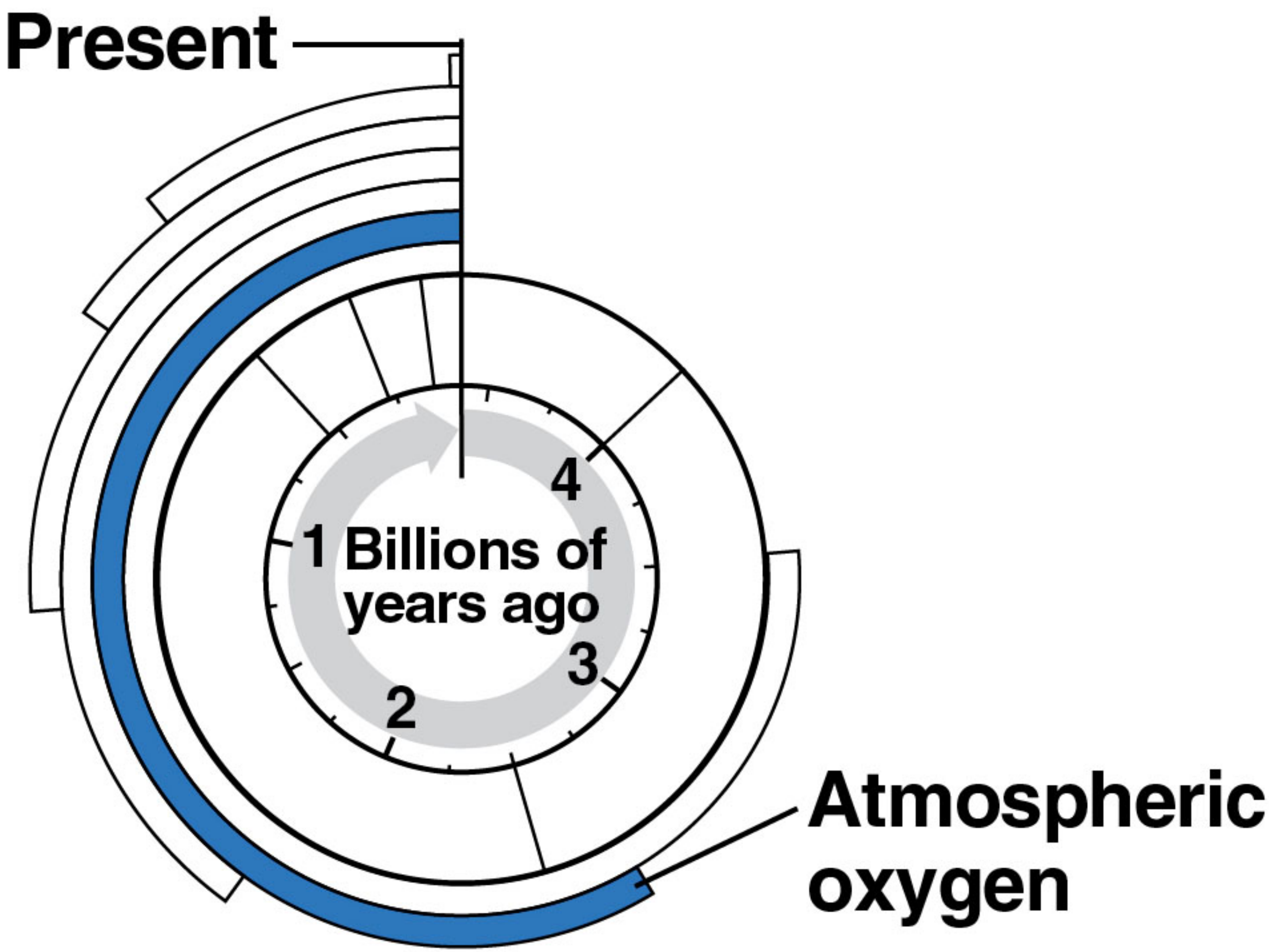
Figure 25.UN01



Photosynthesis and the Oxygen Revolution

- Most atmospheric oxygen (O_2) is of biological origin
- On early Earth, O_2 produced by photosynthesis likely first reacted with dissolved iron in the sea and precipitated out to form iron oxide sediments
- These sediments were compressed to form banded iron formations, red layers of rock

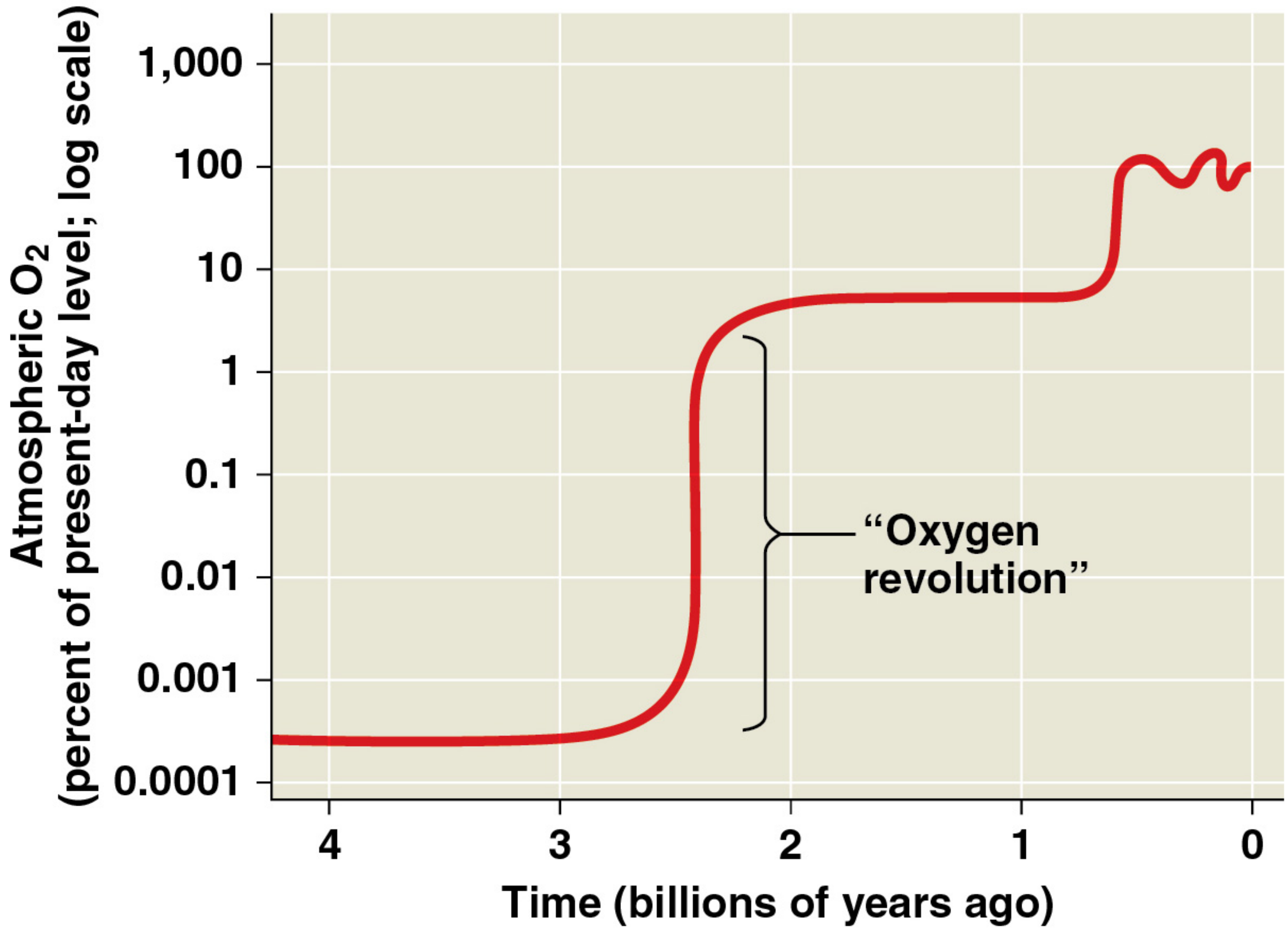
Figure 25.UN02



- Once all the dissolved iron had precipitated, O_2 dissolved into the water
- When the seas and lakes became saturated, O_2 began to “gas out” and enter the atmosphere
- O_2 accumulated gradually in the atmosphere from about 2.7 to 2.4 billion years ago

- After 2.4 billion years ago, atmospheric O_2 shot up rapidly to between 1% and 10% of its present level
- This period is referred to as the “oxygen revolution”

Figure 25.9



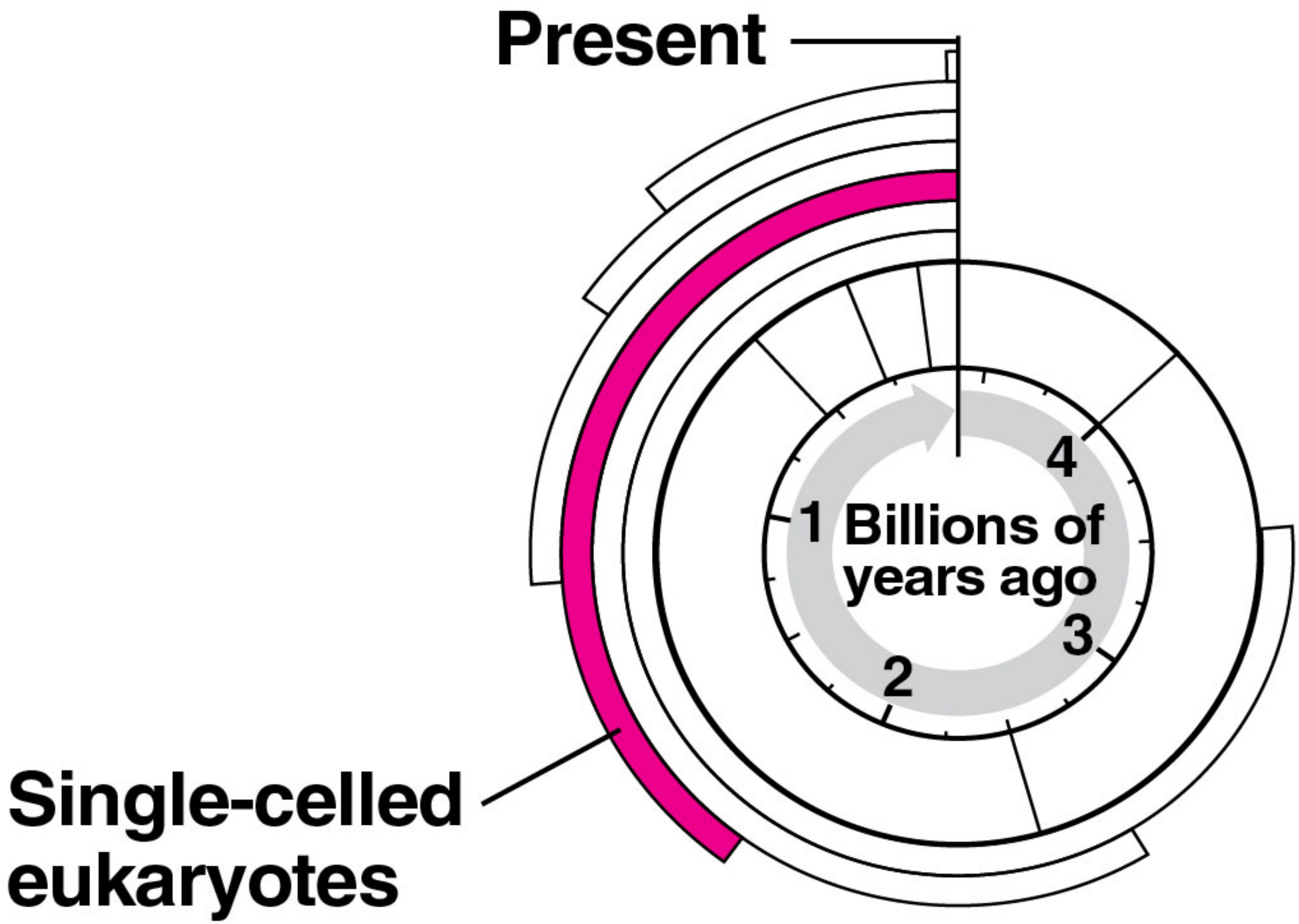
Atmospheric O_2
(percent of present-day level; log scale)
1,000
100
10
1
0.1
0.01
0.001
0.0001
4
3
2
1
0
Time (billions of years ago)
"Oxygen revolution"

- Oxygen can attack chemical bonds, inhibiting enzymes and damaging cells
- The oxygen revolution likely drove many prokaryotic groups to extinction
- Some survivors found refuge in anaerobic habitats; others adapted to use O_2 for cellular respiration

The First Eukaryotes

- The oldest eukaryote fossils are from single-celled organisms that lived 1.8 billion years ago
- Unlike prokaryotes, eukaryotic cells have a nucleus, membrane-bound organelles, and a cytoskeleton
- The cytoskeleton allows eukaryote cells to change shape and engulf other cells

Figure 25.UN03

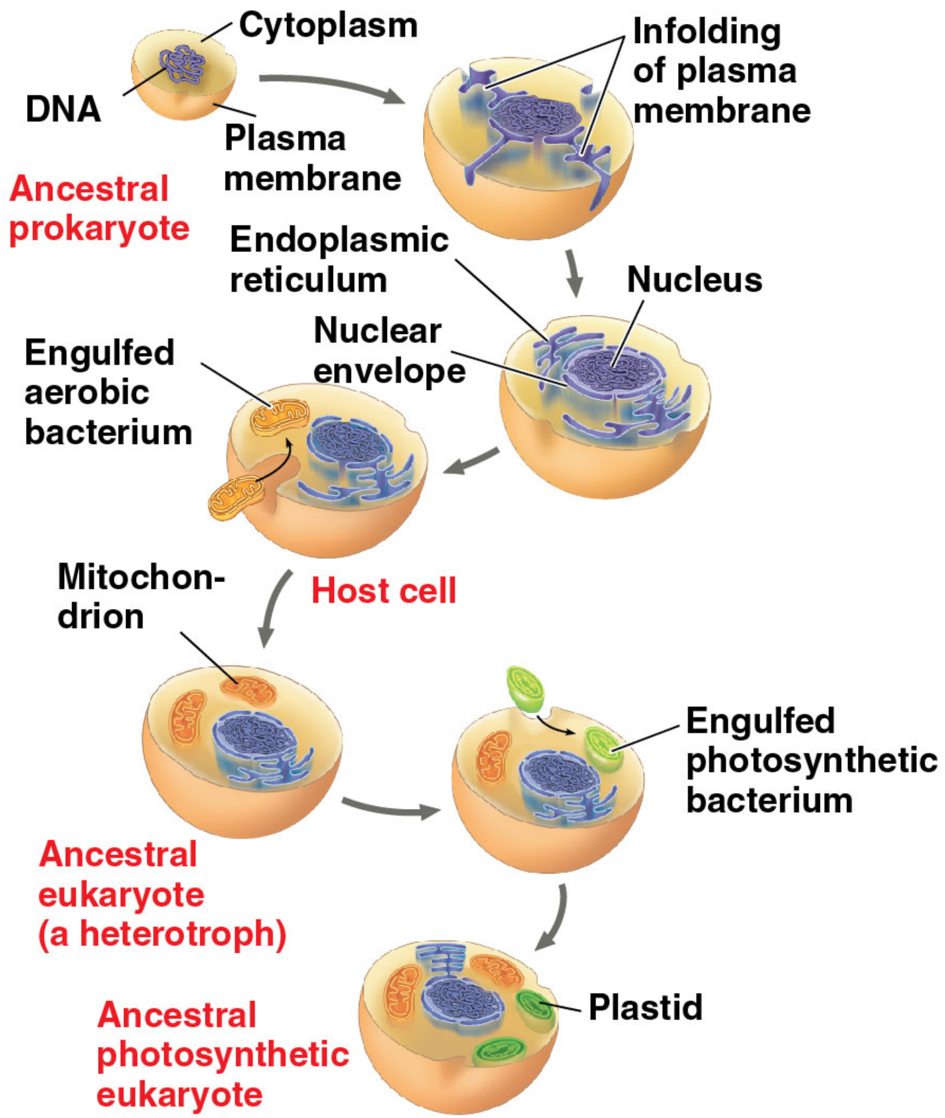


- Eukaryotes likely originated by **endosymbiosis** when a prokaryotic cell engulfed a small cell that would evolve into a mitochondrion
- The small engulfed cell is an endosymbiont; it lives within the host cell

- Anaerobic host cells would benefit from aerobic endosymbionts as O_2 built up in the atmosphere
- Over time, the host and endosymbiont would become interdependent, forming a single organism

- All eukaryotic cells have mitochondria, but not all have plastids (chloroplasts and related organelles)
- **Serial endosymbiosis** is the hypothesis that mitochondria evolved before plastids through a sequence of endosymbiotic events

Figure 25.10



Cytoplasm
DNA
Plasma membrane
Ancestral prokaryote
Infolding of plasma membrane
Endoplasmic reticulum
Nucleus
Nuclear envelope
Engulfed aerobic bacterium
Mitochon-drion
Host cell
Engulfed photosynthetic bacterium
Ancestral eukaryote (a heterotroph)
Plastid
Ancestral photosynthetic eukaryote

- Both mitochondria and plastids are thought to have descended from bacterial cells
- The original host cell is thought to be an archaean or close relative of the archaea

- Several points of evidence support an endosymbiotic origin of mitochondria and plastids:
  - Some of their membrane proteins are homologous to those found in bacterial membranes
  - Replication is similar to bacterial cell division
  - Chromosome and DNA structure is similar to bacteria
  - Both transcribe and translate their own DNA
  - Their ribosomes are similar to those of bacteria in size, RNA sequence, and antibiotic sensitivity

The Origin of Multicellularity

- The origin of eukaryotic cells sparked the evolution of greater morphological diversity of unicellular forms
- The evolution of multicellularity drove the diversification of algae, plants, fungi, and animals

Early Multicellular Eukaryotes

- The oldest fossils of multicellular eukaryotes are of small red algae from about 1.2 billion years ago
- Larger, more diverse multicellular organisms appear in the fossil record from about 600 million years ago
- These fossils, called the Ediacaran biota, include algae, soft-bodied animals, and some unknown taxa

Figure 25.UN04

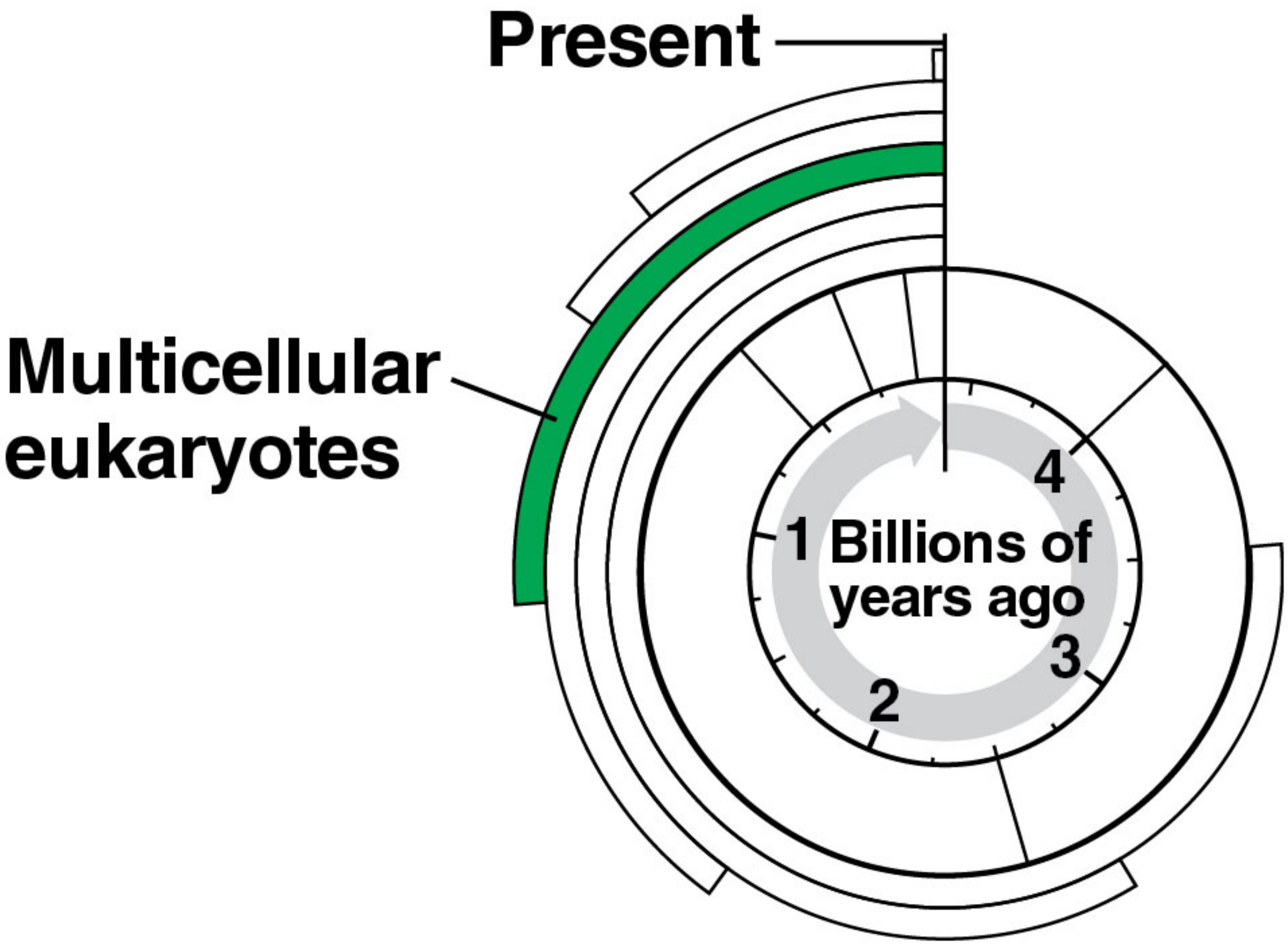
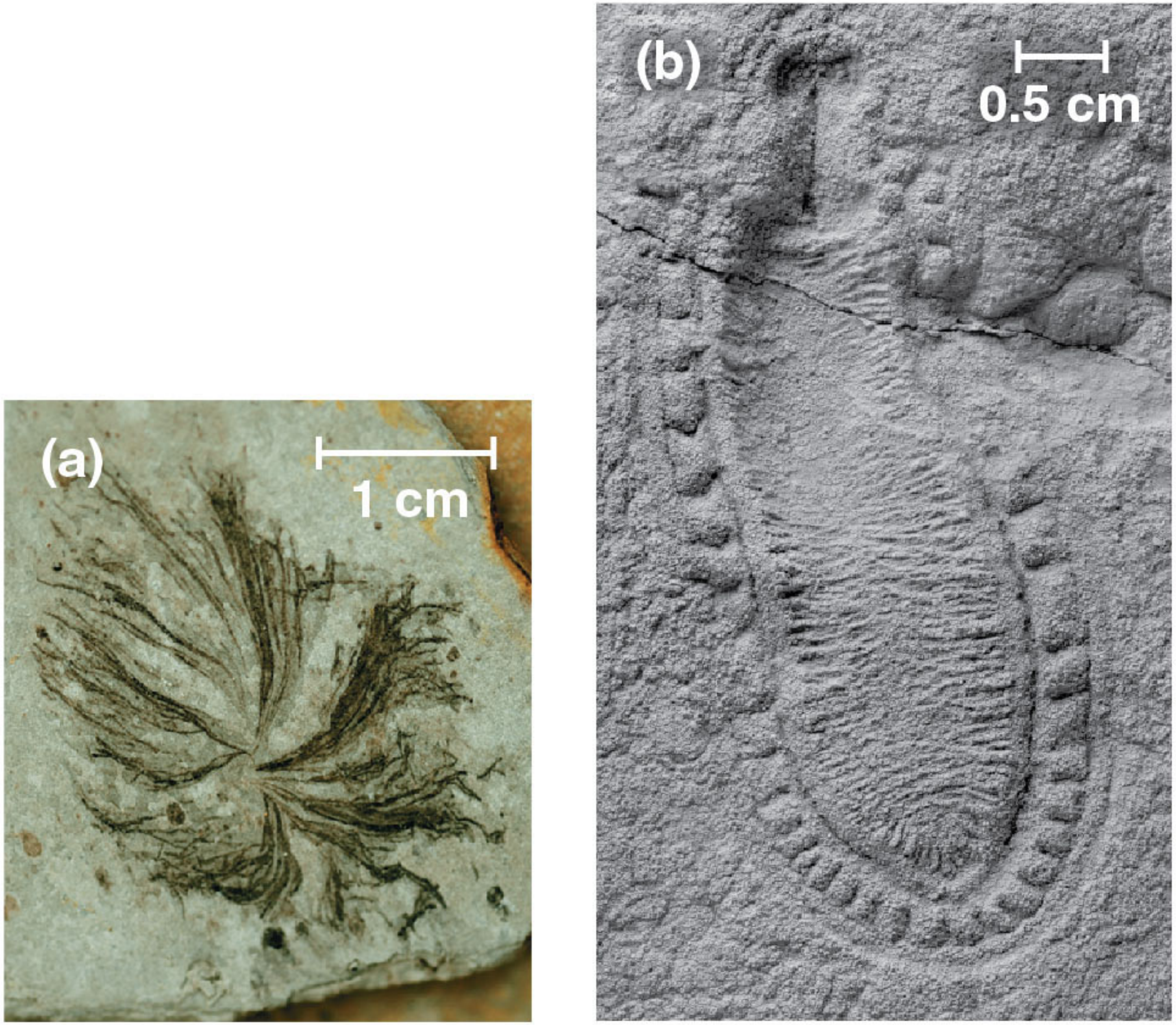


Figure 25.11



The Cambrian Explosion

- Many animal phyla appear suddenly in the fossils of the Cambrian period (535–525 million years ago)
- This phenomenon is called the **Cambrian explosion**
- Fossils of sponges, cnidarians, and molluscs appear in older rocks from the late Proterozoic

Figure 25.UN05

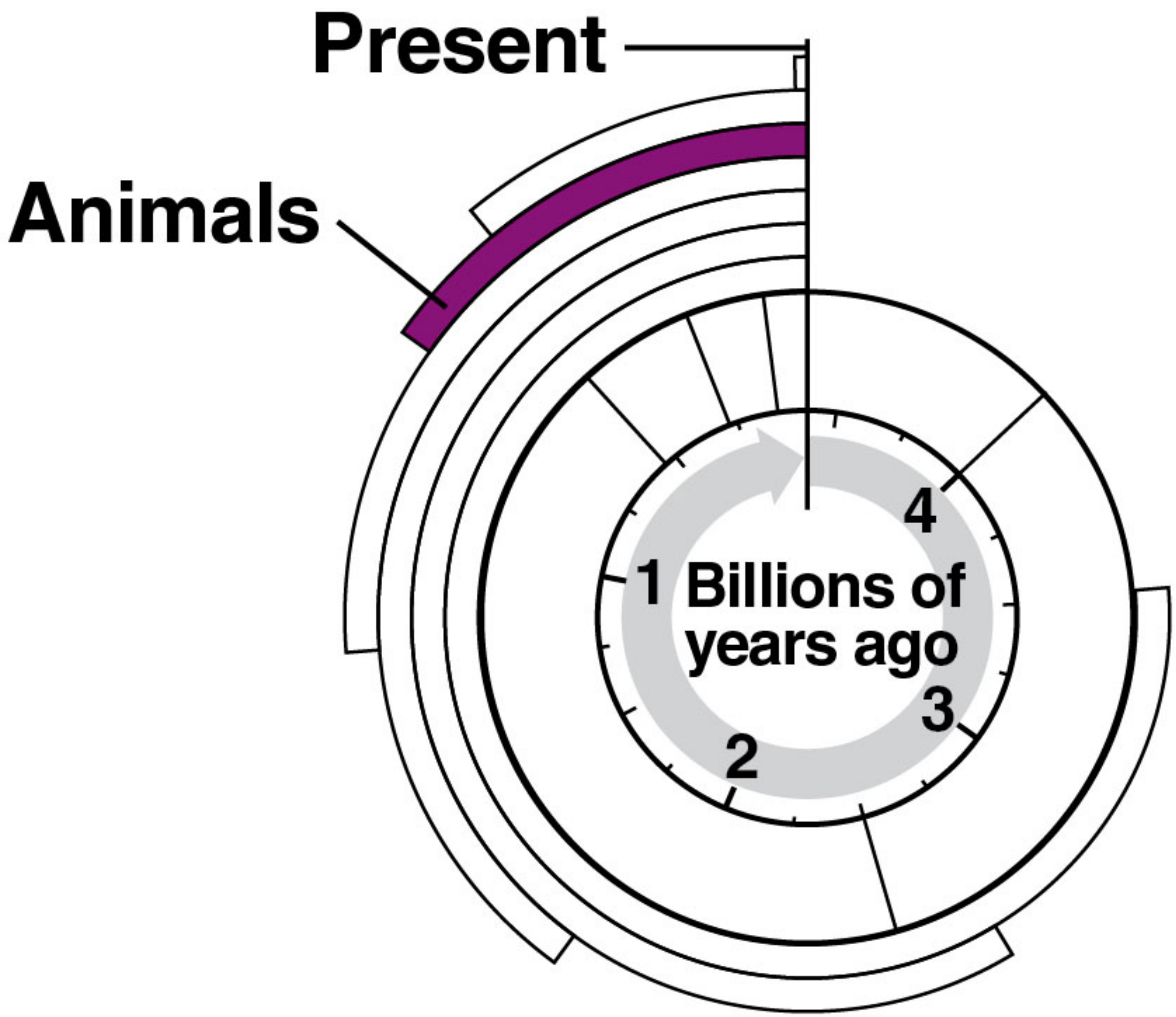
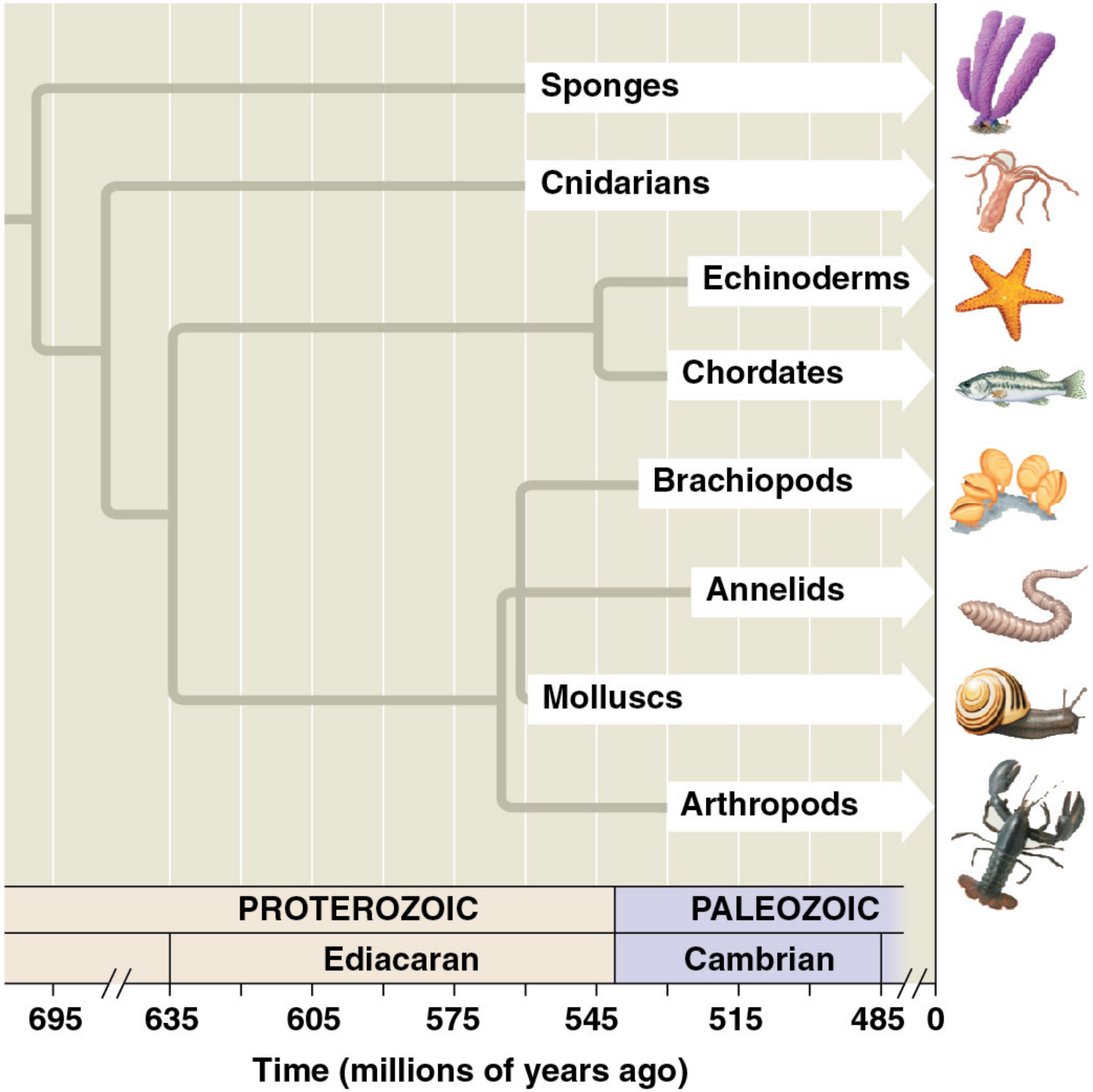


Figure 25.12



Sponges
Cnidarians
Echinoderms
Chordates
Brachiopods
Annelids
Molluscs
Arthropods
PROTEROZOIC
PALEOZOIC
Ediacaran
Cambrian
695
635
605
575
545
515
485
0
Time (millions of years ago)

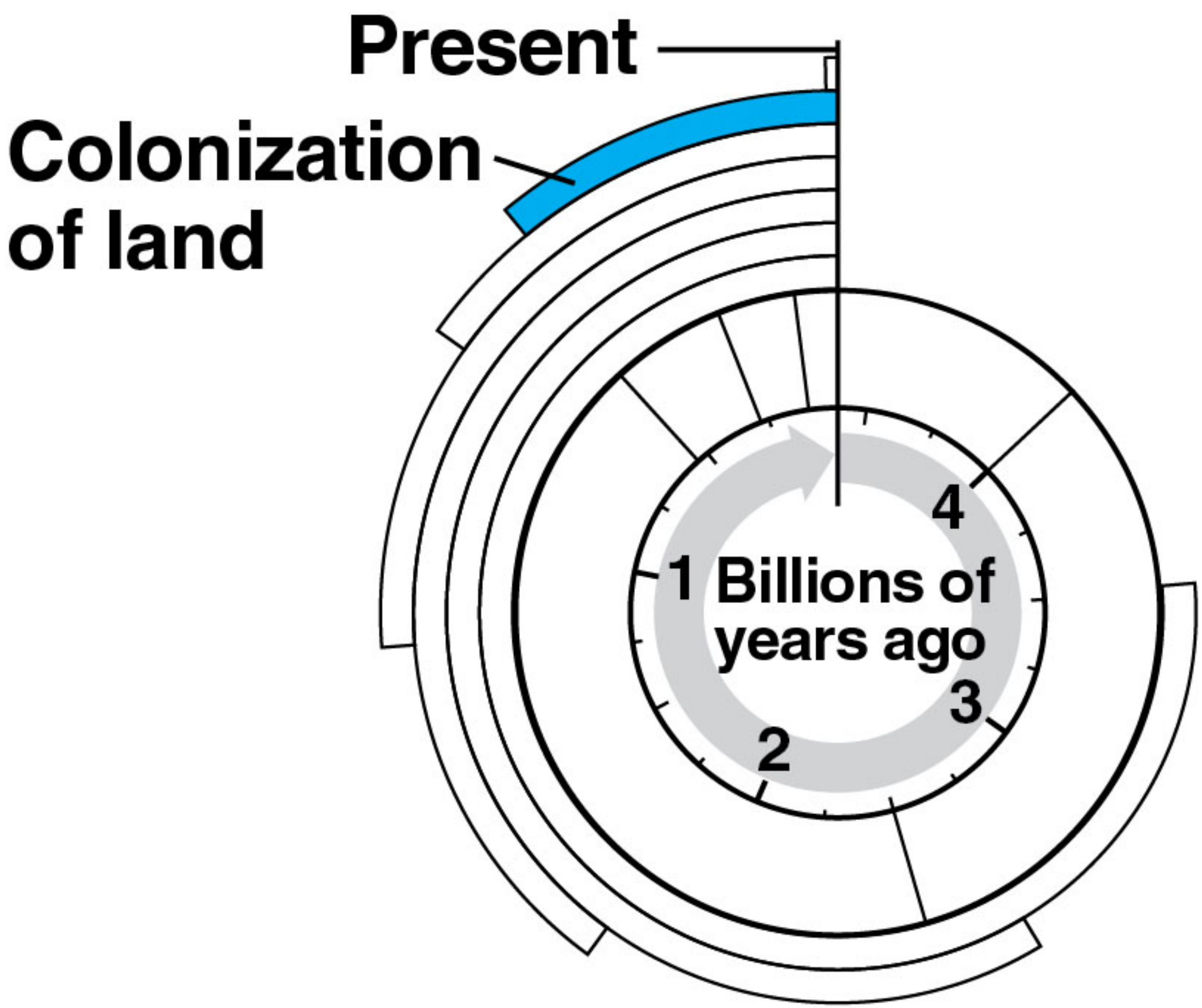
- Little evidence of predation appears in fossils formed prior to the Cambrian explosion
- Adaptations for predation, including large bodies and claws appeared within 10 million years
- New defense adaptations, including sharp spines and heavy body armor, appeared in prey species

- DNA analyses suggest the common ancestor of animal phyla lived about 670 million years ago
- Animals originated about 700 million years ago and remained small for over 100 million years
- They diversified explosively during the Cambrian

The Colonization of Land

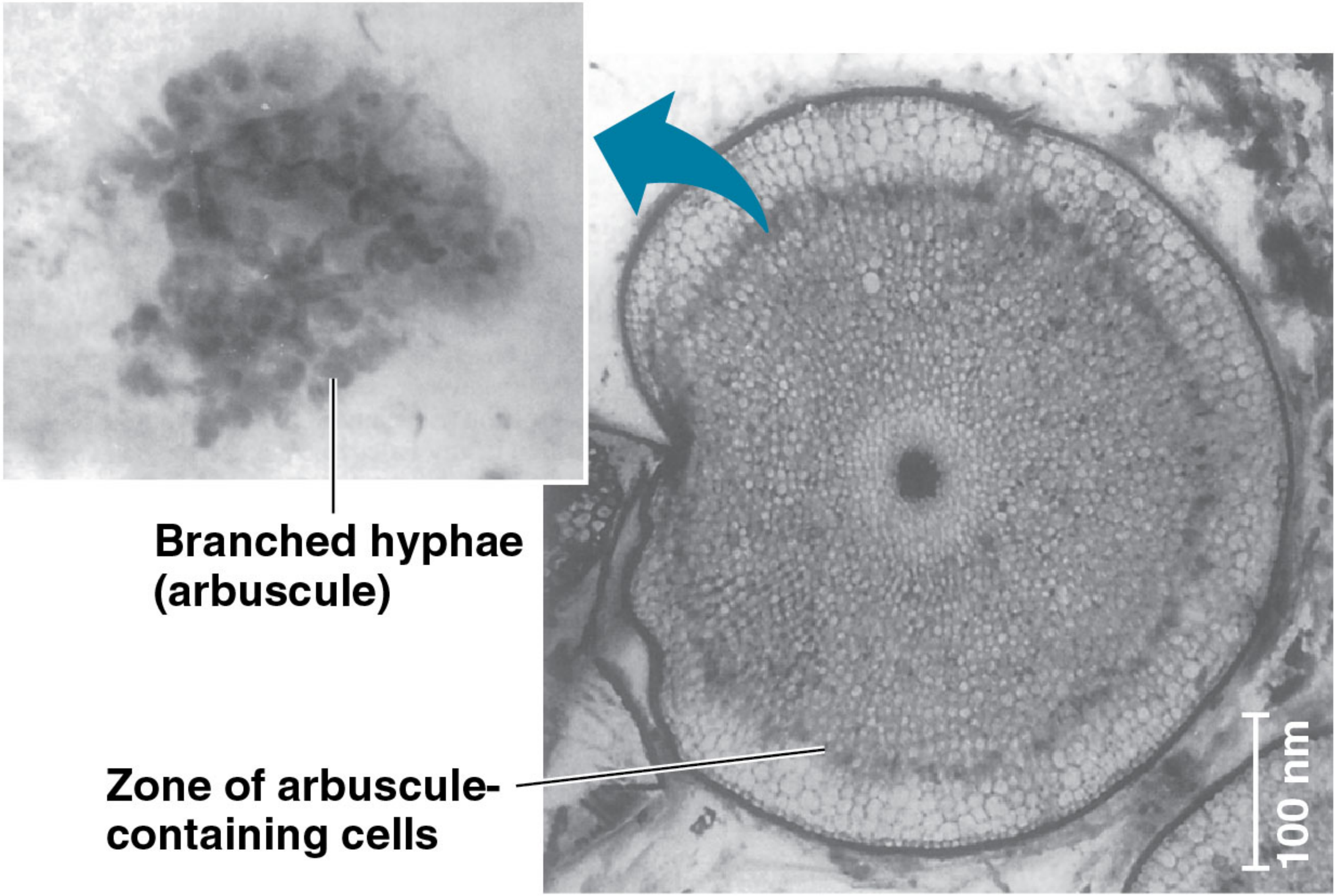
- Prokaryotes lived on land 3.2 billion years ago
- Fungi, plants, and animals began to colonize land about 500 million years ago

Figure 25.UN06



- Adaptations for reproduction on land and prevention of dehydration arose with the move to land
  - For example, early signs of a wax coating on leaves and vascular system for internal transport appeared in plants by 420 million years ago

- Plants and fungi likely colonized land together
- Mutualisms between plants and fungi (mycorrhizae) are seen in the oldest fossilized plants

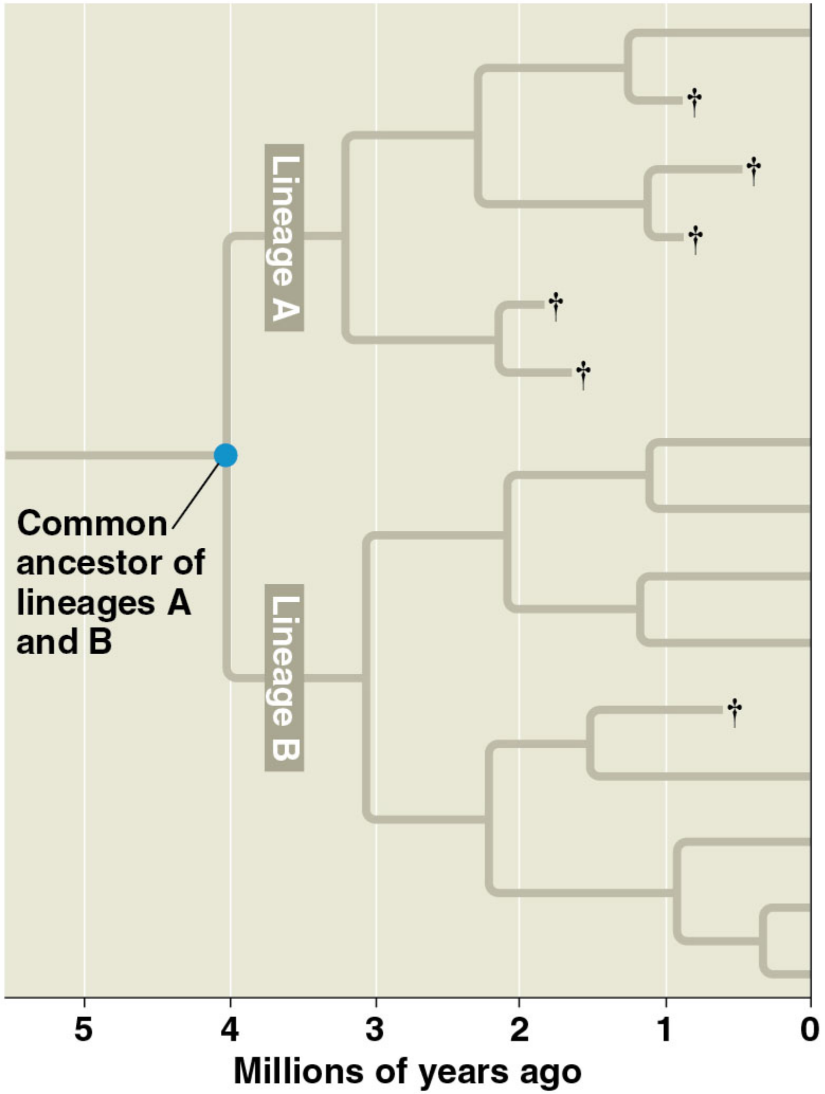

Branched hyphae (arbuscule)
Zone of arbuscule-containing cells
100 nm

- Arthropods and tetrapods are the most widespread and diverse land animals
- Arthropods were among the first animals to colonize land about 450 million years ago
- Tetrapods evolved from lobe-finned fishes around 365 million years ago
- The human lineage diverged from other primates 6–7 million years ago
- Modern humans originated only 195,000 years ago

CONCEPT 25.4: The rise and fall of groups of organisms reflect differences in speciation and extinction rates

- The rise and fall of many groups of organisms have occurred in the history of life
- The rise and fall of any particular group depends on speciation and extinction rates of its member species
- These changes are affected by processes including plate tectonics, mass extinction, and adaptive radiation

Figure 25.14

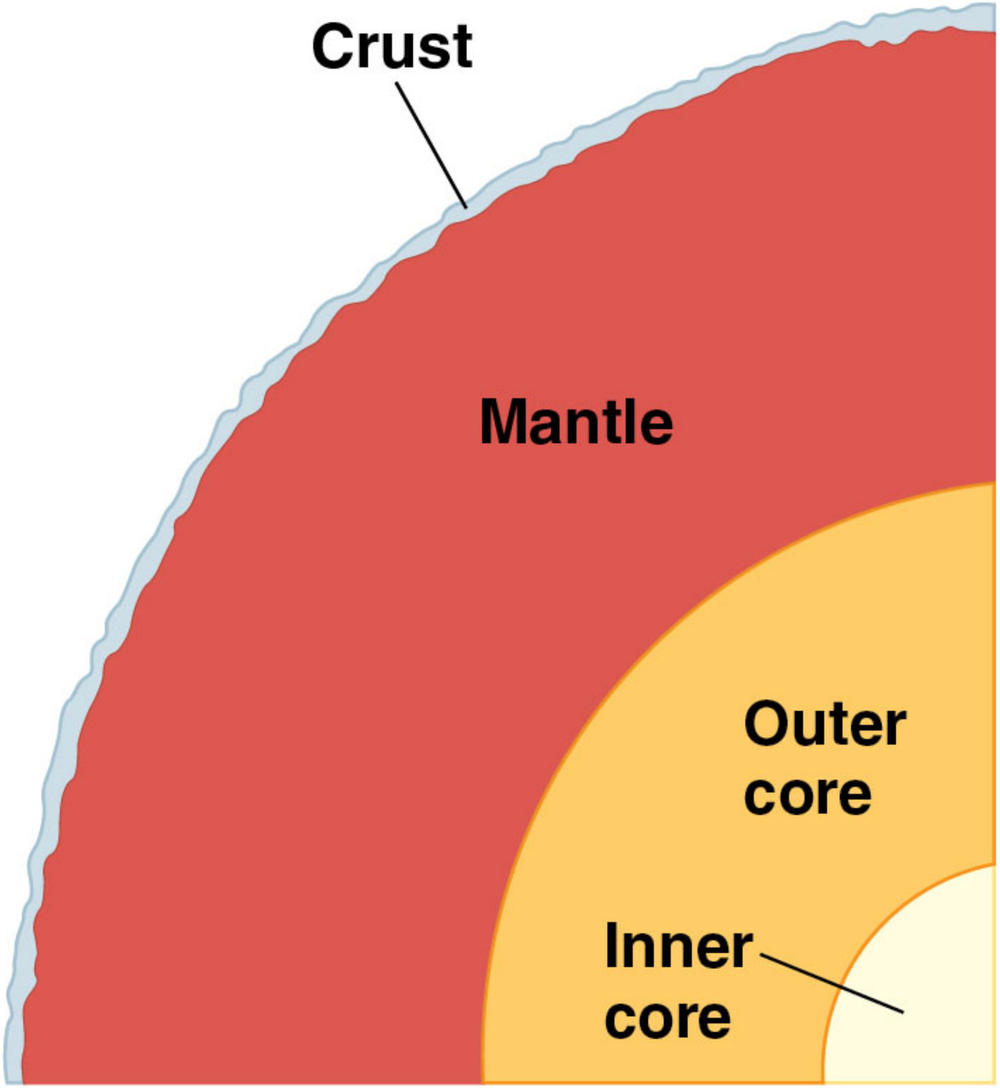


Lineage A
Lineage B
Common ancestor of lineages A and B
5
4
3
2
1
0
Millions of years ago

Plate Tectonics

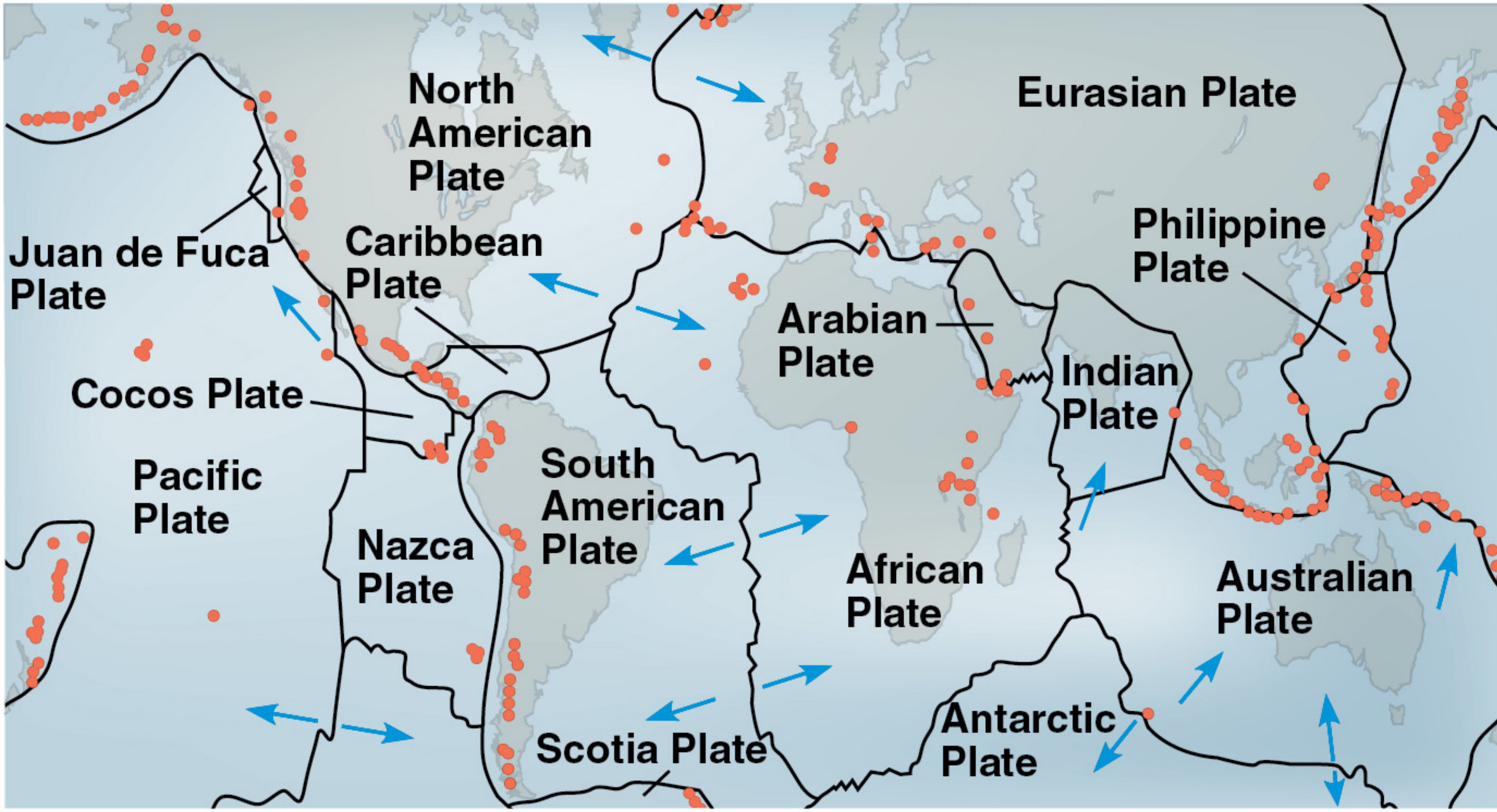
- Earth's land masses have formed a supercontinent and then broken apart three times: 1 billion, 600 million, and 250 million years ago
- **Plate tectonics** theorizes that the Earth's crust is composed of plates floating on the underlying mantle

Figure 25.15



- Movements in the mantle cause the plates to gradually shift in a process called continental drift
- Tectonic plates can drift apart, collide (forming mountains), or slide past each other (causing earthquakes)
  - For example, the Himalayan mountains formed 45 million years ago when tectonic plates collided

Figure 25.16


North American Plate
Eurasian Plate
Juan de Fuca Plate
Caribbean Plate
Philippine Plate
Arabian Plate
Cocos Plate
Indian Plate
Pacific Plate
South American Plate
Nazca Plate
African Plate
Australian Plate
Antarctic Plate
Scotia Plate

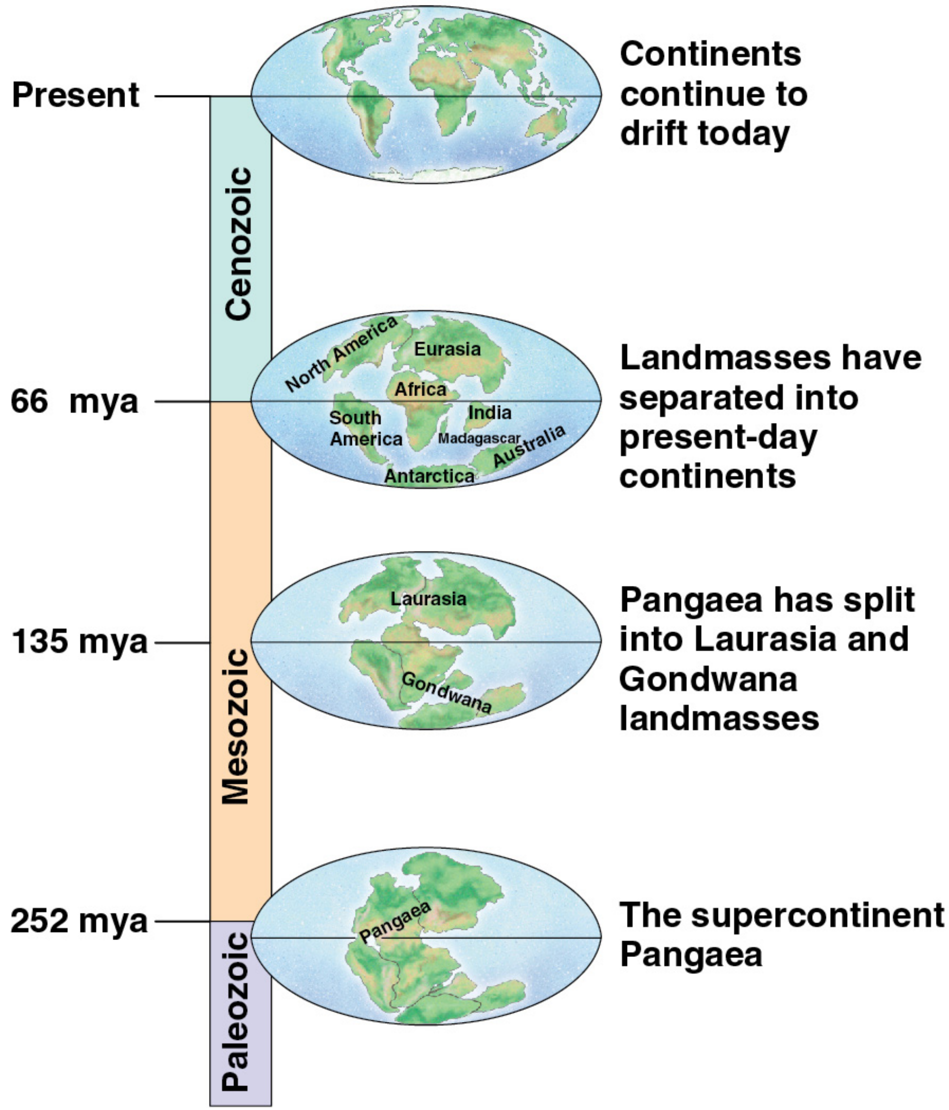
Animation: Plate Tectonics

Video: Animated Life: Pangea, Wegener, and Continental Drift

Consequences of Continental Drift

- Formation of the supercontinent **Pangaea** about 250 million years ago altered many habitats:
  - Ocean basins became deeper
  - Most shallow-water habitat was destroyed
  - The interior of the continent became colder and drier

Figure 25.17



Present
66 mya
135 mya
252 mya
Cenozoic
Mesozoic
Paleozoic
North America
Eurasia
Africa
South America
India
Madagascar
Australia
Antarctica
Laurasia
Gondwana
Pangaea
Continents continue to drift today
Landmasses have separated into present-day continents
Pangaea has split into Laurasia and Gondwana landmasses
The supercontinent Pangaea

- Major changes in climate occur when a continent shifts toward or away from the equator
  - For example, Labrador, Canada, was located in the tropics 200 million years ago
- Organisms must adapt to the changing climate, move to a new location, or face extinction

- When supercontinents break apart, regions that were once connected become isolated
- As a result, organisms on the new continents diverge and allopatric speciation occurs on a grand scale
  - For example, marsupials fill ecological roles in Australia analogous to those filled by eutherians on other continents

- The distribution of fossils and living groups reflect the historic movement of continents
  - For example, fossils of the same species of Permian reptiles are found in Brazil and West Africa
  - These parts of the world were joined during the Permian, but are now separated by 3,000 km of ocean

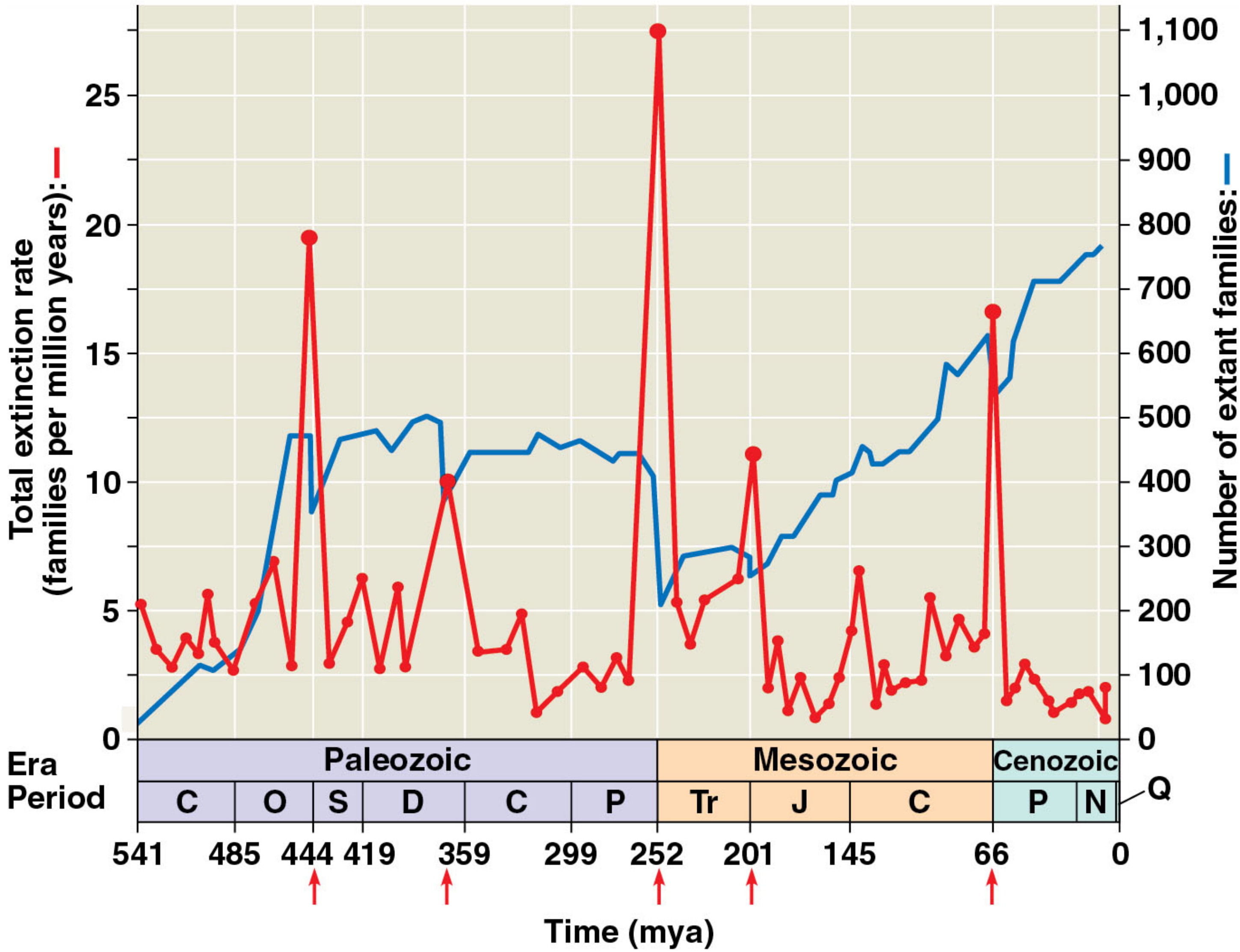
Mass Extinctions

- The fossil record shows that most species that have ever lived are now extinct
- Extinction can be caused by changes to a species' biotic or abiotic environment
- **Mass extinctions** occur when large numbers of species rapidly become extinct worldwide

The "Big Five" Mass Extinction Events

- Mass extinctions are triggered by disruptive global change
- Five mass extinctions have been documented in the fossil record over the past 500 million years
- More than half of all of marine species became extinct in each event

Figure 25.18



Total extinction rate
(families per million years):
Number of extant families:
25
20
15
10
5
0
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Era
Period
Paleozoic
Mesozoic
Cenozoic
C
O
S
D
C
P
Tr
J
C
P
N
Q
541
485
444
419
359
299
252
201
145
66
0
Time (mya)

- The Permian extinction (252 million years ago) divides the Paleozoic from the Mesozoic era
- About 96% of marine species became extinct in less than 500,000 years during this mass extinction
- It occurred during an extreme episode of volcanism
  - For example, about 1.6 million km^2 in Siberia was covered with lava hundreds of meters thick

Video: Volcanic Eruption

Video: Lava Flow

- The volcanic eruptions triggered a series of catastrophic events resulting in mass extinction
  - Atmospheric CO_2 rose dramatically
  - The global climate warmed by about 6°C
  - Ocean acidification reduced calcium carbonate for reef-building corals and shell-building species
  - Nutrient enrichment of oceans caused microbial blooms, leading to anoxic conditions

- The Cretaceous mass extinction occurred about 66 million years ago
- More than 50% of marine species, many families of terrestrial plants and animals, and all dinosaurs (except birds) went extinct during this event

- The presence of iridium in sedimentary rocks from the time suggests a massive meteorite collision
- Debris clouds from the impact would block the sun, causing a rapid, enduring drop in global temperature
- Such an impact occurred off the Mexican coast 66 million years ago, forming the Chicxulub crater

Figure 25.19

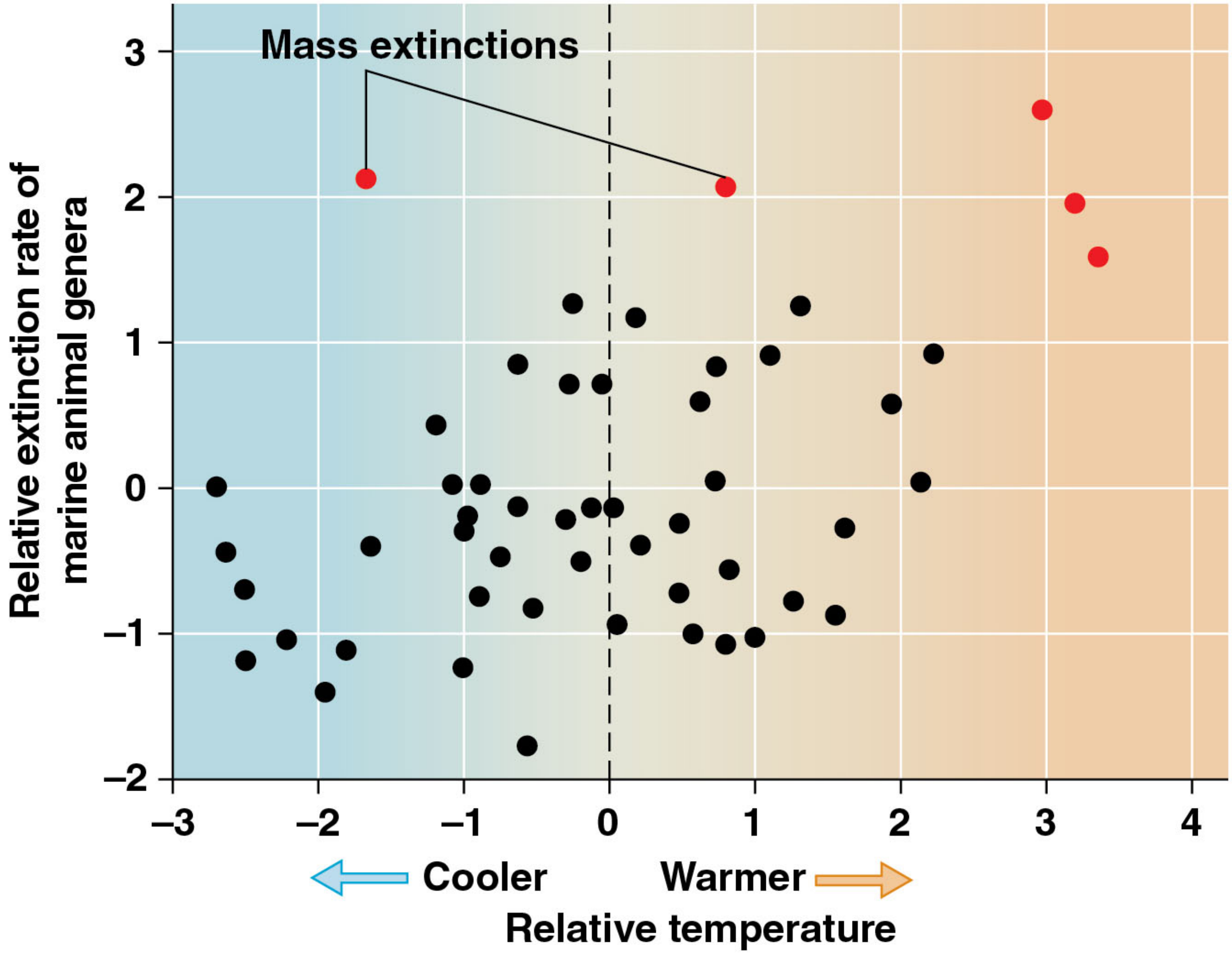
- Large-scale volcanic eruptions, prior to the meteor impact, left many species vulnerable to extinction
- Wildfires resulting from the impact contributed to rising CO_2 and 100,000 years of global warming

Is a Sixth Mass Extinction Under Way?

- The current extinction rate is estimated at 100 to 1,000 times the background rate of the fossil record
- It is hard to say if we are in a sixth mass extinction, due to challenges in documenting current extinctions
  - For example, the rapid destruction of tropical rainforest is driving many unknown species extinct, before they are even discovered

- Species losses to date have not yet reached the level of the “big five” mass extinctions, however
  - Habitat loss, introduced species, and overharvesting are factors contributing to rapid species decline
  - The global climate is warming and, historically, extinction rates increase with high global temperature

Figure 25.20



Mass extinctions
Relative extinction rate of marine animal genera
3
2
1
0
–1
–2
–3
–2
–1
0
1
2
3
4
Cooler
Warmer
Relative temperature

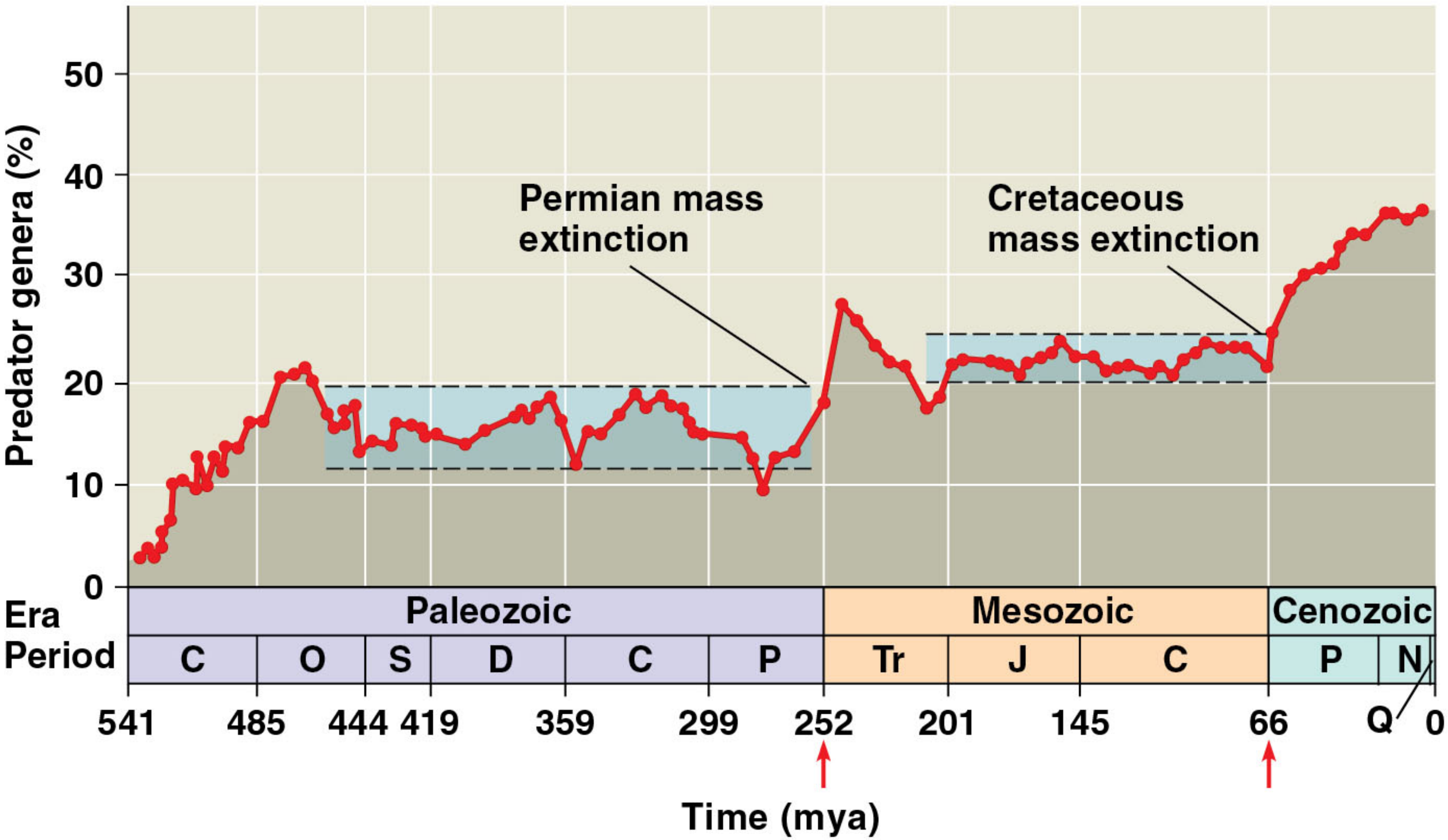
- Unless dramatic actions are taken, a sixth, human-caused mass extinction is likely to occur within the next few centuries

Consequences of Mass Extinctions

- It typically takes 5–10 million years for diversity to recover following a mass extinction, but rates vary
  - For example, it took about 100 million years for marine families to recover after the Permian mass extinction

- Mass extinctions can change the types of organisms found in ecological communities
  - For example, after the Permian and Cretaceous mass extinctions, the percent of marine predators increased

Figure 25.21



Permian mass extinction
Cretaceous mass extinction
Predator genera (%)
50
40
30
20
10
0
Era
Period
Paleozoic
Mesozoic
Cenozoic
C
O
S
D
C
P
Tr
J
C
P
N
541
485
444
419
359
299
252
201
145
66
Q
0
Time (mya)

- Mass extinctions can also curtail lineages with novel and advantageous features
  - For example, gastropods that could drill through the shells of their prey were lost in the extinction at the end of the Triassic
  - This ability did not reappear for 120 million years

- By eliminating so many species, mass extinctions pave the way for adaptive radiations, and the proliferation of new groups of organisms

Adaptive Radiations

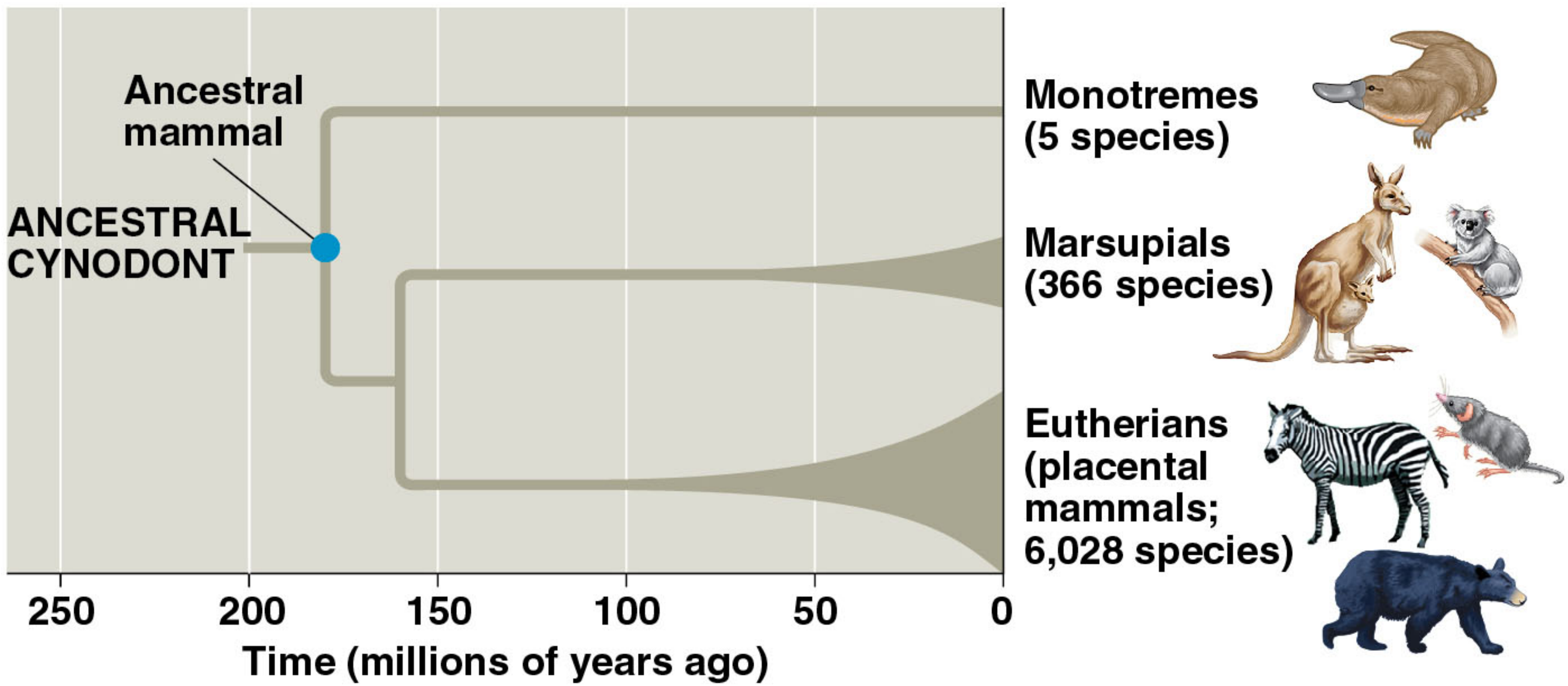
- **Adaptive radiation** is a rapid period of evolutionary change where many new species arise and adapt to different ecological niches

- Adaptive radiations can occur in response to
  - The opening of niches following mass extinctions
  - The evolution of novel characteristics that enable the exploitation of new resources or habitats
  - The colonization of new regions with few or weak competitors

Worldwide Adaptive Radiations

- Prior to 66 million years ago, the size and diversity of mammals was restricted by predation and competition from dinosaurs
- After the extinction of terrestrial dinosaurs, mammals underwent an adaptive radiation
- They diversified and filled the ecological niches left open following the mass extinction

Figure 25.22



Ancestral mammal
ANCESTRAL CYNODONT
Monotremes (5 species)
Marsupials (366 species)
Eutherians (placental mammals; 6,028 species)
250
200
150
100
50
0
Time (millions of years ago)

- Several adaptive radiations have occurred in response to the evolution of major innovations
  - The rise of photosynthetic prokaryotes
  - The evolution of large predators in the Cambrian explosion
  - The colonization of land by plants, insects, and tetrapods

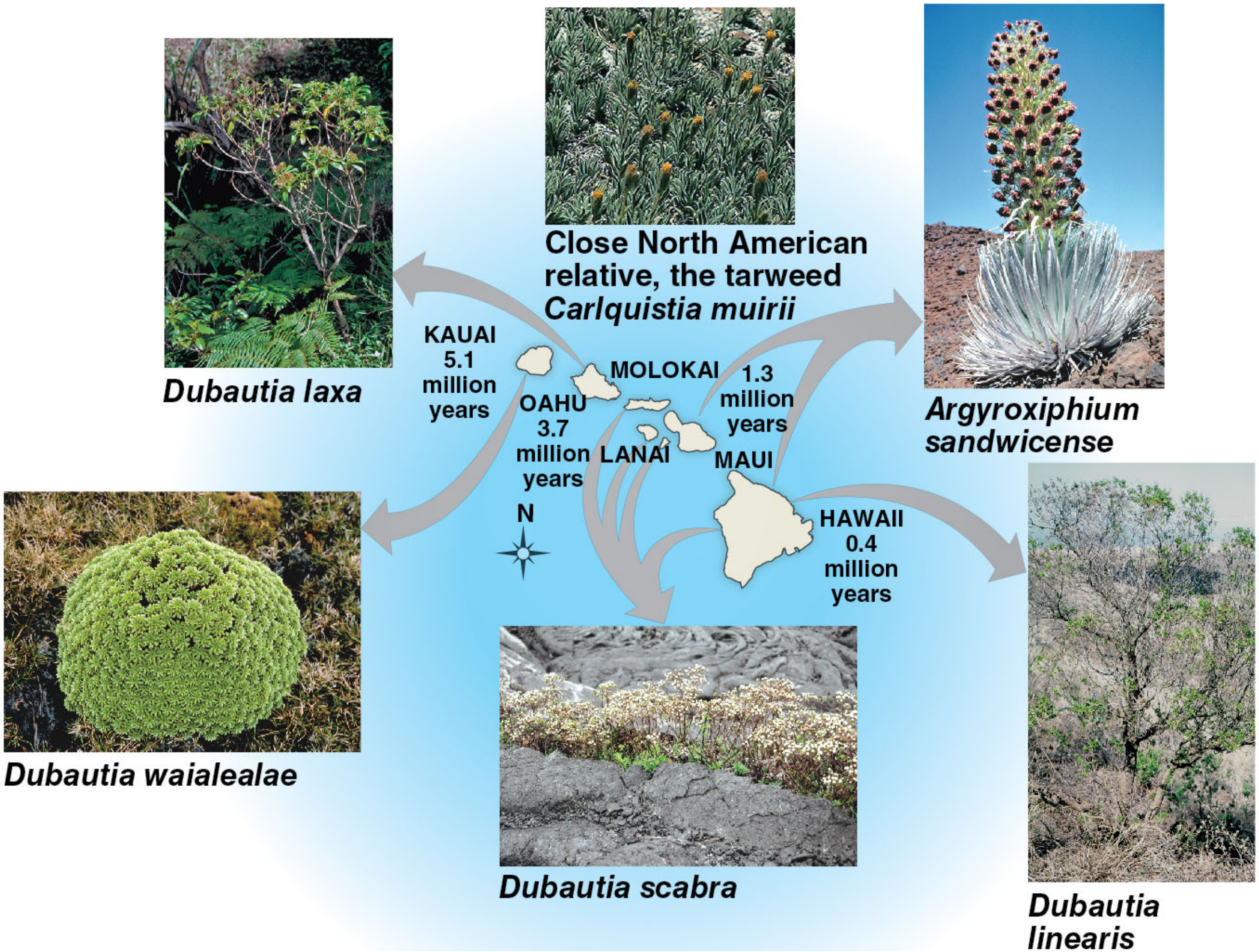
- Adaptive radiations by plants, insects, and tetrapods followed the evolution of key adaptations for survival on land
  - For example, the evolution of supportive stems and a water-protective coat enabled the diversification of plants on land

- Some groups diversified as adaptive radiations in other groups provided new food sources
  - For example, the adaptive radiation of insects followed the diversification of the plants they ate and pollinated

Regional Adaptive Radiations

- Adaptive radiations can be limited to small regions if a few organisms colonize isolated environments with little competition
  - For example, the “silversword alliance” of the Hawaiian archipelago descended from an ancestral tarweed that arrived about 5 million years ago

Figure 25.23


Close North American relative, the tarweed *Carlquistia muirii*
Dubautia laxa
KAUAI 5.1 million years
OAHU 3.7 million years
MOLOKAI
1.3 million years
LANAI
MAUI
N
HAWAII 0.4 million years
Argyroxiphium sandwicense
Dubautia waialealae
Dubautia scabra
Dubautia linearis

- The Hawaiian islands were formed by volcanic eruptions, 3,500 km from the nearest continent
- Each was initially devoid of life and populated slowly by stray organisms from the mainland
- Multiple invasions were followed by speciation events as organisms adapted to the diverse habitats
- Thousands of species are unique to these islands

CONCEPT 25.5: Major changes in body form can result from changes in the sequences and regulation of developmental genes

- Studying genetic mechanisms of change can provide insight into large-scale evolutionary change

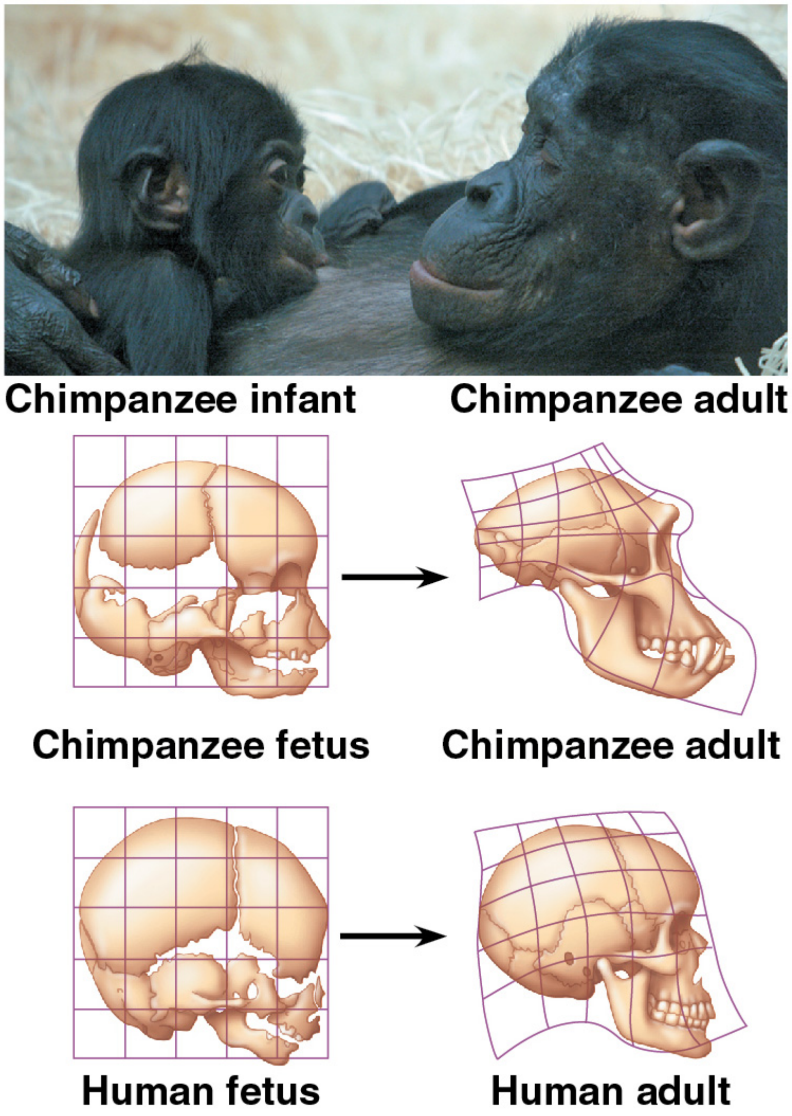
Effects of Developmental Genes

- Genes that program development control the rate, timing, and spatial pattern of changes in an organism's form as it develops to adulthood

Changes in Rate and Timing

- **Heterochrony** is an evolutionary change in the rate or timing of developmental events
- It can have a significant impact on body shape
  – For example, the contrasting shapes of human and chimpanzee skulls are the result of small changes in relative growth rates of different body parts

Figure 25.24



Chimpanzee infant
Chimpanzee adult
Chimpanzee fetus
Chimpanzee adult
Human fetus
Human adult

Animation: Allometric Growth

- Heterochrony can alter the relative timing of reproductive to nonreproductive development
- In **paedomorphosis**, development of reproductive organs accelerates relative to other organs
- Sexually mature individuals retain features that were juvenile structures in an ancestral species

Figure 25.25

Changes in Spatial Pattern

- Changes in genes that control the placement and organization of body parts can drive evolution
- **Homeotic genes** are master regulatory genes that determine where an organism’s features will develop
  - For example, they determine the location of a bird’s wings or the arrangement of a plant’s flower parts

- *Hox* genes, a class of homeotic genes, provide positional information in animal embryos
- If the location of *Hox* gene expression changes, the position of the corresponding body part changes
  - For example, in crustaceans, a change in *Hox* gene expression produces a swimming appendage where a feeding appendage should be

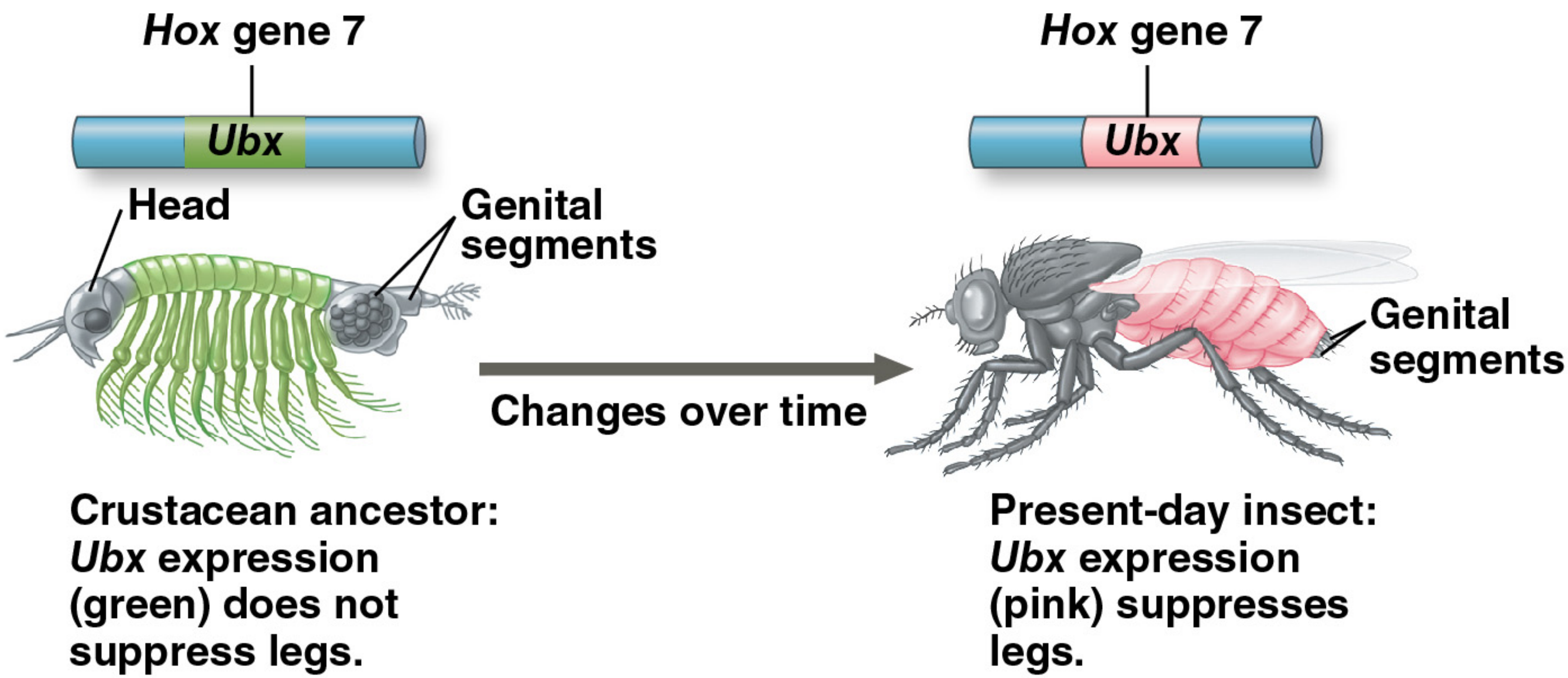
The Evolution of Development

- New morphological forms can arise from changes in sequence or regulation of developmental genes
- Developmental genes likely played an important role in diversification during the Cambrian explosion

Changes in Gene Sequence

- Duplication events producing new developmental genes can give rise to new morphological forms
- Experiments have revealed a mechanism by which six-legged insects could evolve from crustaceans
- In insects, the *Hox* gene *Ubx* suppresses leg formation where it is expressed

Figure 25.26



Hox gene 7
Ubx
Head
Genital segments
Changes over time
Hox gene 7
Ubx
Genital segments
Crustacean ancestor: *Ubx* expression (green) does not suppress legs.
Present-day insect: *Ubx* expression (pink) suppresses legs.

- Fruit fly embryos were genetically engineered to express the *Ubx* gene from either *Drosophila* (an insect) or *Artemia* (a crustacean)
- The *Drosophila Ubx* suppressed 100% of limb development; the *Artemia Ubx* suppressed only 15%
- The nucleotide changes responsible for suppressing limb development in insects have been identified

Changes in Gene Regulation

- Many morphological changes are caused by mutations affecting developmental gene regulation
  - For example, threespine sticklebacks in lakes have fewer spines than their marine relatives
  - The sequence of the *Pitx1* developmental gene is the same, but regulation of its expression differs between lake and marine groups

Figure 25.27

Results

Hypothesis A:
Differences in sequence

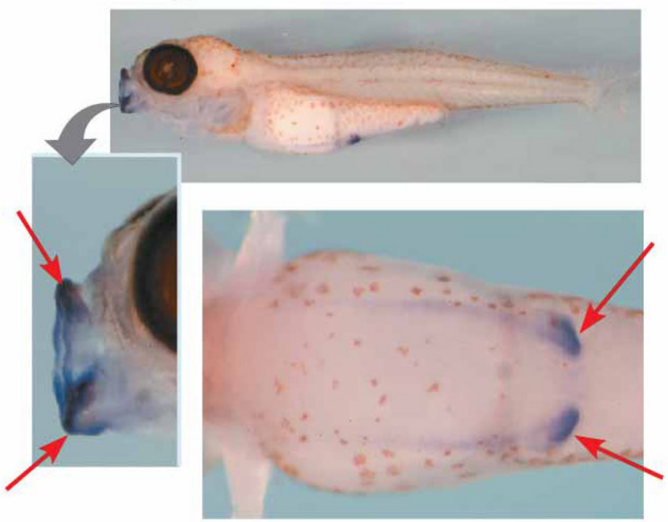
Result: No
The 283 amino acids of the *Pitx1* protein are identical.

Hypothesis B:
Differences in expression

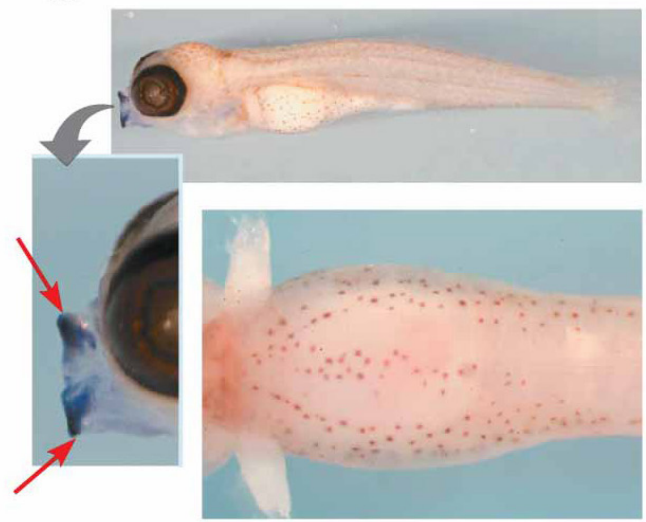
Result: Yes

Red arrows indicate regions of *Pitx1* expression.

Marine stickleback embryo: expression in ventral spine and mouth regions



Lake stickleback embryo: expression only in mouth regions



CONCEPT 25.6: Evolution is not goal oriented

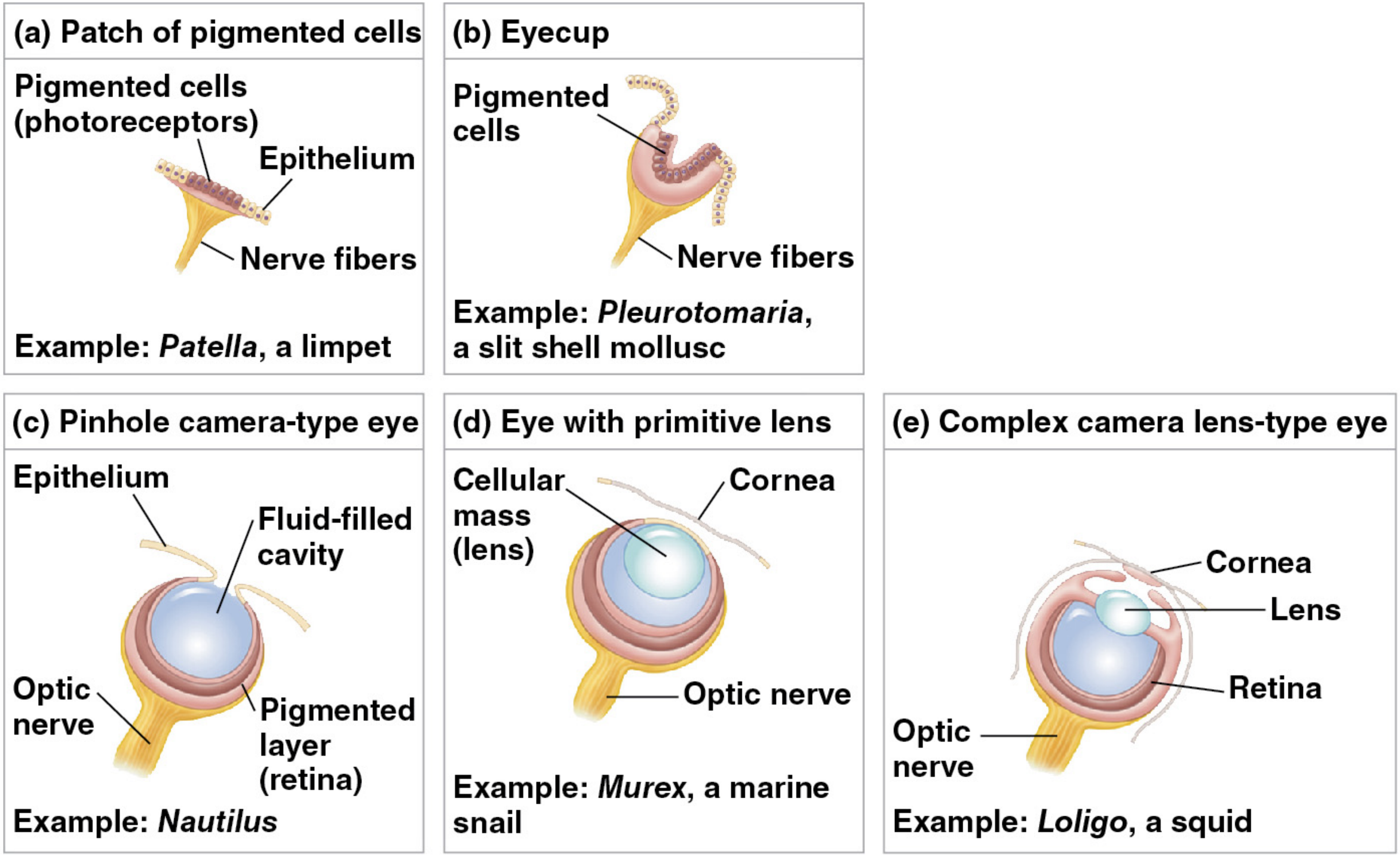
- Evolution is like tinkering—new forms arise by the slight modification of existing structures or developmental genes

Evolutionary Novelties

- Most novel biological structures evolve in many stages from simpler ancestral structures
  - For example, complex eyes have evolved from simple photosensitive cells independently many times
  - Such “simple” eyes are found in molluscs called limpets

Figure 25.28

Figure 25.29



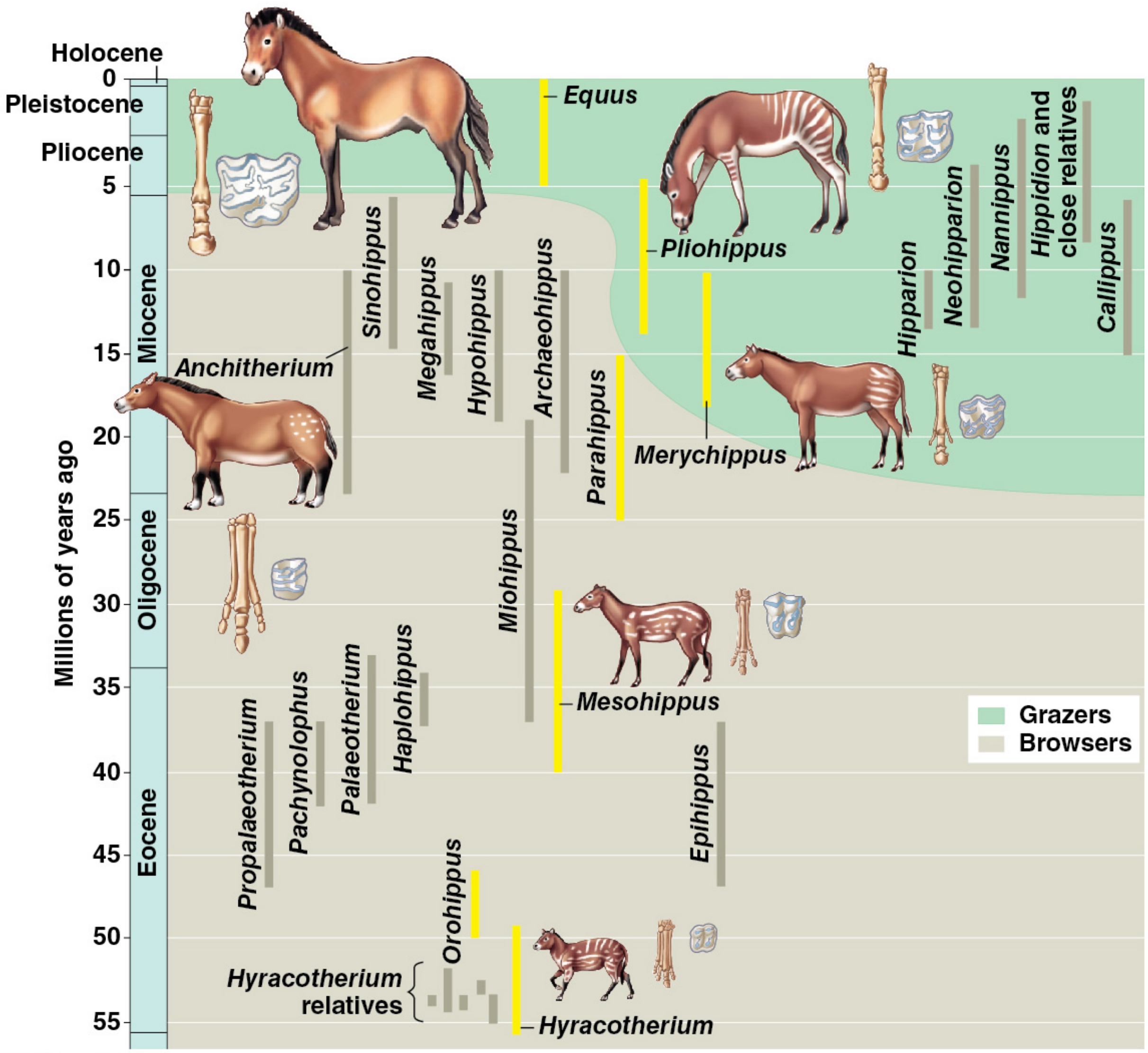
(a) Patch of pigmented cells
Pigmented cells (photoreceptors)
Epithelium
Nerve fibers
Example: *Patella*, a limpet
(b) Eyecup
Pigmented cells
Nerve fibers
Example: *Pleurotomaria*, a slit shell mollusc
(c) Pinhole camera-type eye
Epithelium
Fluid-filled cavity
Optic nerve
Pigmented layer (retina)
Example: *Nautilus*
(d) Eye with primitive lens
Cellular mass (lens)
Cornea
Optic nerve
Example: *Murex*, a marine snail
(e) Complex camera lens-type eye
Cornea
Lens
Retina
Optic nerve
Example: *Loligo*, a squid

- Exaptations are structures that evolve in one context but become co-opted for a different function
- Structures do not evolve in anticipation of future use; natural selection can only improve a structure in the context of its current utility

Evolutionary Trends

- The fossil record can reveal trends in evolution
  - For example, present-day horses have teeth suitable for grazing, larger body size, and fewer toes per foot compared to their ancestor, *Hyracotherium*

Figure 25.30



Holocene
0
Pleistocene
Pliocene
5
10
15
20
25
30
35
40
45
50
55
Miocene
Oligocene
Eocene
Millions of years ago
Equus
Pliohippus
Merychippus
Anchitherium
Sinohippus
Megahippus
Hypohippus
Archaeohippus
Parahippus
Miohippus
Mesohippus
Epihippus
Propalaeotherium
Pachynolophus
Palaeotherium
Haplohippus
Orohippus
Hyracotherium relatives
Hyracotherium
Hipparion
Neohipparion
Nannippus
Hippidion and close relatives
Callippus
Grazers
Browsers

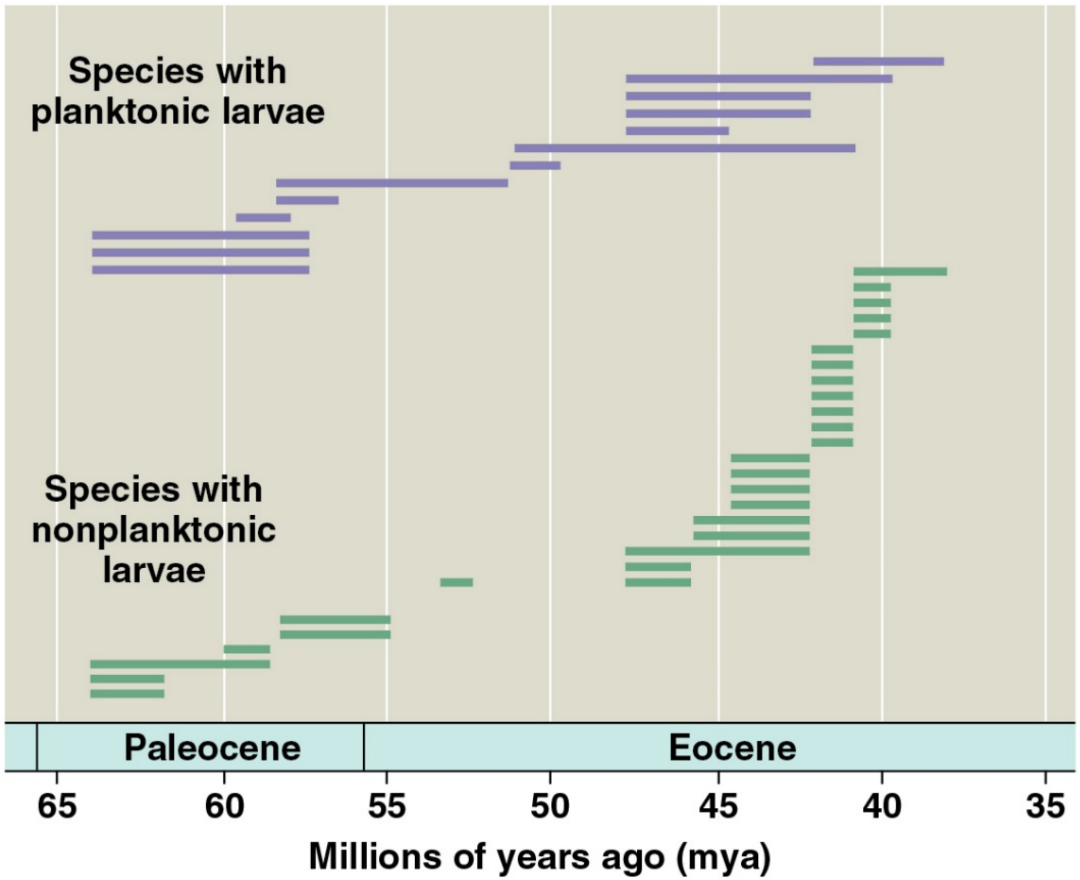
- Because species are often missing, using the fossil record to infer evolutionary trends can be misleading
  - For example, the trend toward large-bodied, single-toed grazers in the horse lineage disappears when all extinct species in the fossil record are considered

- One model of long-term trends views species as analogous to individuals
  - Speciation is their birth
  - Extinction is their death
  - New species that arise are their offspring

- As populations undergo natural selection, species undergo species selection
- Species that endure the longest and generate the most new species determine the direction of evolutionary trends

- Evolutionary trends do not imply an intrinsic drive toward a particular phenotype
- Evolution results from interactions between organisms and their current environment; if conditions change, the trend will cease or change

Figure 25.UN07a



Data from T. A. Hansen, Larval dispersal and species longevity in Lower Tertiary gastropods, *Science* 199:885–887 (1978). Reprinted with permission from AAAS.

Figure 25.UN07b

Figure 25.UN08

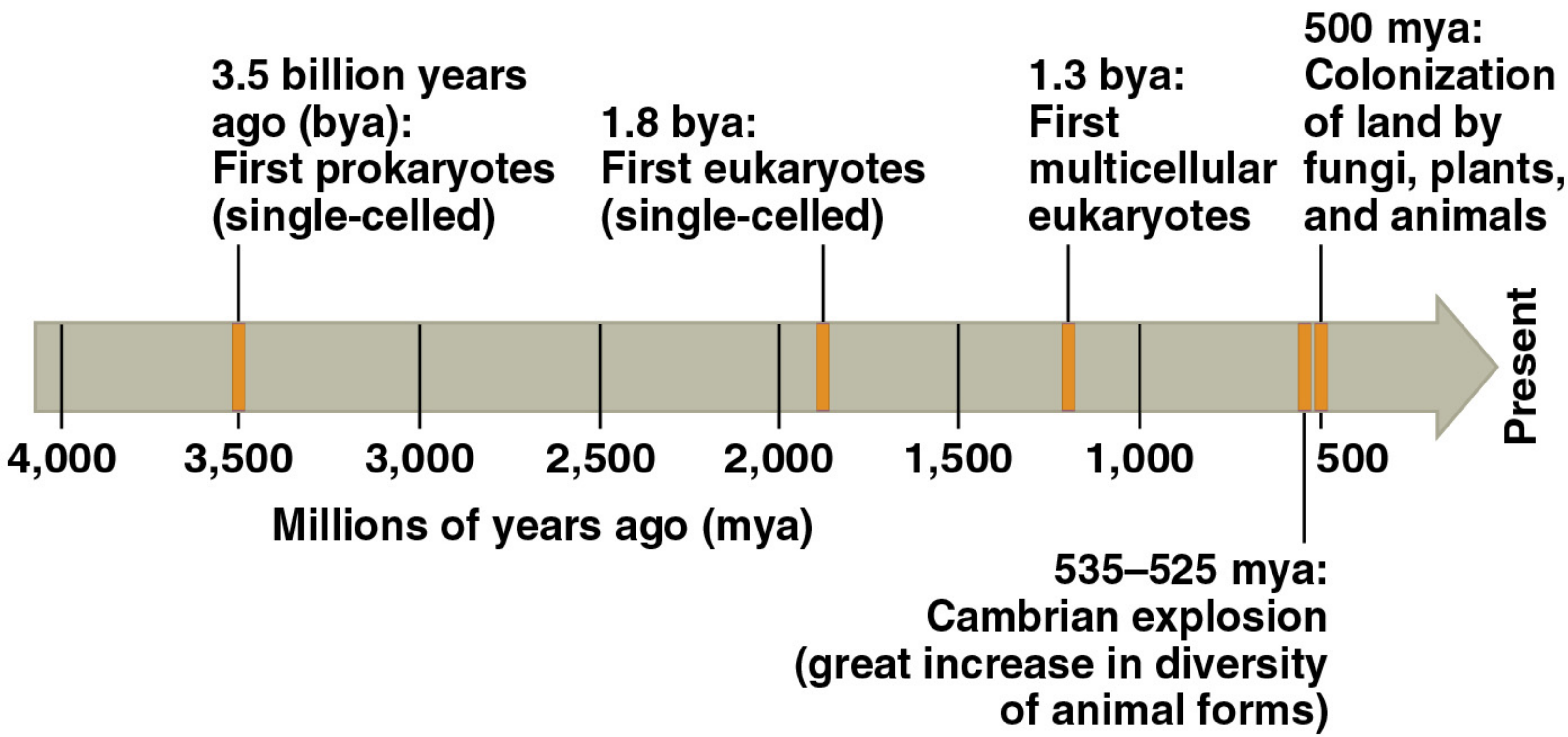


Figure 25.UN09

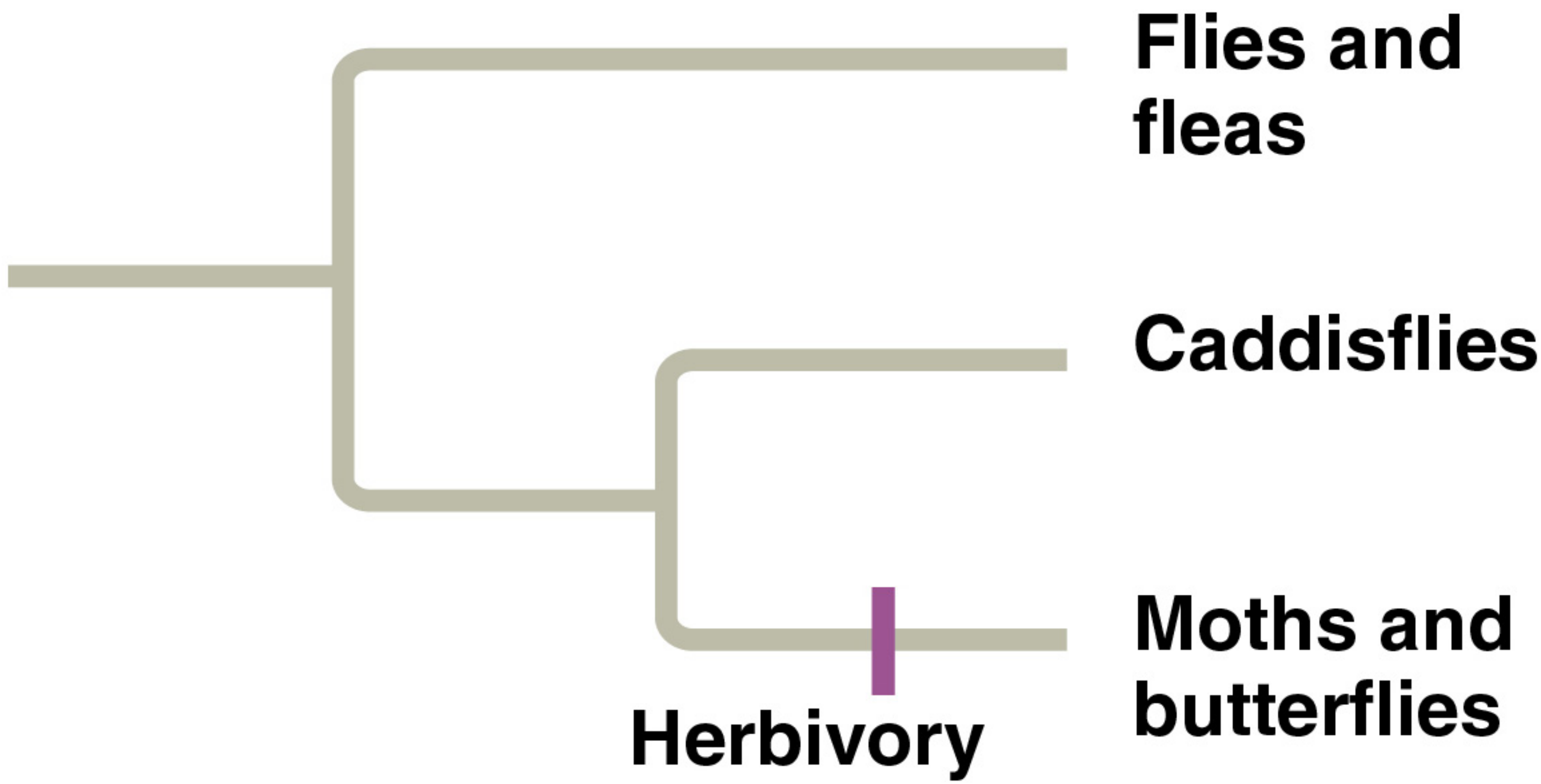


Figure 25.UN10