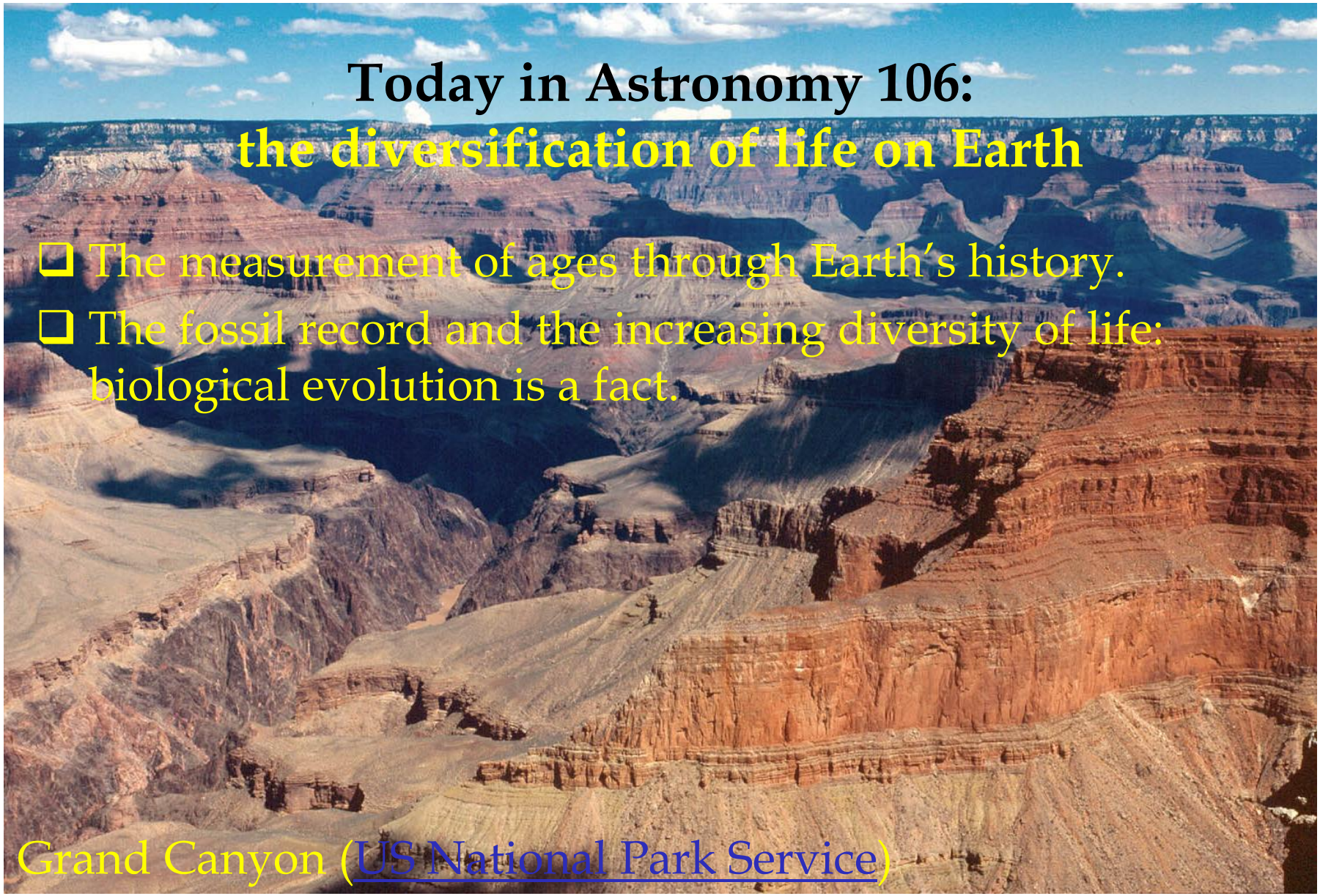


Today in Astronomy 106:
the diversification of life on Earth

- The measurement of ages through Earth's history.
- The fossil record and the increasing diversity of life: biological evolution is a fact.

Grand Canyon (US National Park Service)

Back to Life on Earth: more on age measurement

So now we know how life emerges from organic molecules and water. What happens next?

- This can be determined experimentally by examining the **fossil record**: the state of living things on Earth as a function of time since the formation of the Solar system.
  - As usual the chronology is the most important thing to establish.
- Then the steps can be illuminated in finer detail by **phylogeny**: the classification of different forms of life, and comparison of genetic material among the forms that still exist. (Next lecture.)
  - Measurement of "genetic distance" can be hooked through the fossil record to chronology.

Ages of Earthly objects

We already know how to measure the ages of old igneous rocks and meteorites, using Rb-Sr radioisotope dating of minerals. Several similar methods give redundancy to check each other, or better precision over different age ranges.

Radionuclide	Daughter	Stable reference	Half life (Gyr)
^{147}Sm	^{143}Nd	^{144}Nd	106
^{87}Rb	^{87}Sr	^{86}Sr	50
^{187}Re	^{187}Os	^{186}Os	43
^{176}Lu	^{176}Hf	^{177}Hf	35
^{232}Th	… ^{208}Pb	^{204}Pb	13.9
^{238}U	… ^{206}Pb	^{204}Pb	4.5
^{40}K	^{40}Ca	^{44}Ca	1.5
^{235}U	… ^{207}Pb	^{204}Pb	0.71

Ages of Earthly objects

There are also a couple of interesting methods that do not involve mineral chemistry *per se*.

Potassium-argon. Normal potassium is ^{39}K. About 0.01% of potassium exists as ^{40}K, which can decay radioactively by two means, ordinary beta decay and electron capture:

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \overline{\nu_e} \quad 88.8\% \text{ of decays}$$

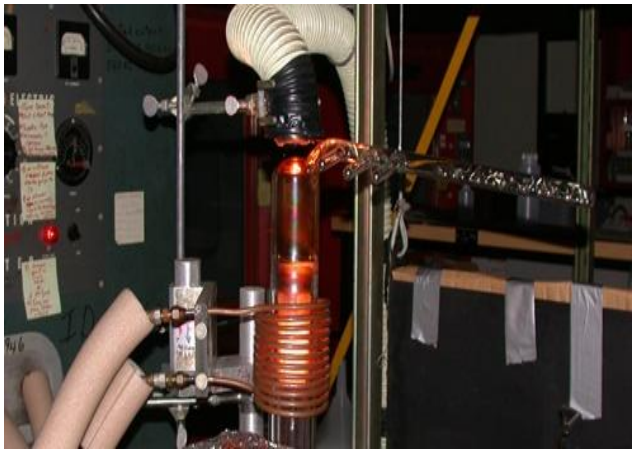
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e \quad 11.2\% \text{ of decays}$$

The halflives are 1.5 Gyr (see previous page) and 11.9 Gyr.

- Argon, though a gas and not chemically bound to the mineral, does not escape from the site it occupied as a K atom unless the rock is heated sufficiently.
- The rock would otherwise contain no argon.

Ages of Earthly objects (continued)

- Thus counting the trapped argons gives accurately the number of decays since the rock was formed, and this can be done by baking the rock to release the gas.
- One must still count the potassium. The slickest way to do that is to subject the sample to a neutron beam from a nuclear reactor. This quickly converts all the ^{39}K to ^{39}Ar, which can be baked out and counted along with the ^{40}Ar.
- Analysis works thenceforth like Rb-Sr.



The Dartmouth K-Ar lab.

This gives accurate ages in the 50,000 year – 1 Gyr range, nicely extending the reach of Rb-Sr to younger ages.

Ages of Earthly objects (continued)

Carbon-14. In the atmosphere, cosmic rays transmute a tiny fraction of the normal isotope of nitrogen, ^{14}N, into the radioactive form of carbon ^{14}C.

- The half-life of ^{14}C is shorter than any of the radioactive clocks considered hitherto: **5730 years**. Thus it's only good for measuring young ages, ~100 - 60,000 years.
- The atmospheric concentration of ^{14}C is roughly constant through time: **$^{14}C/\text{total C} = 1.18\times10^{-12}$**.
- The carbon in plants comes from atmospheric CO_2, so live plants have this same fraction of their carbon in ^{14}C.
- The carbon in animals comes from plants, so live animals also have their ^{14}C in the atmospheric abundance.

Ages of Earthly objects (continued)

- As soon as the plant or animal stops photosynthesizing or eating, the ^{14}C stops being replenished: dead things have less ^{14}C than the atmosphere, by amounts directly related to how long they have been dead.
- Caveats: the atmospheric concentration of ^{14}C does vary with such things as the Solar sunspot cycle. Thus for high accuracy ^{14}C dates must be corrected by comparison to other methods.
  - e.g. ^{14}C dates of tree rings, which go back about 9000 years.

Bristlecone pine, White Mountain, CA (Wikimedia Commons)

Calculating ^{14}C ages

Ignoring corrections, the concentration of ^{14}C is given by the master equations for radioactive decay:

$$\text{Concentration:} \quad n(t) = n_0 e^{-t \ln 2 / t_{1/2}}$$

$$\text{Decay rate:} \quad r(t) = \frac{\ln 2}{t_{1/2}} n(t)$$

which can be rearranged to yield

$$t = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{n_0}{n(t)}\right) = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{r_0}{r(t)}\right)$$

, where

You need to understand how to use this formula.

$n_0 = 1.18 \times 10^{-12}$

$r_0 = 13.56$ decays per minute per gm of C

The ^{14}C concentration in a prehistoric corpse is ¼ that of the atmosphere. How long ago did it die?

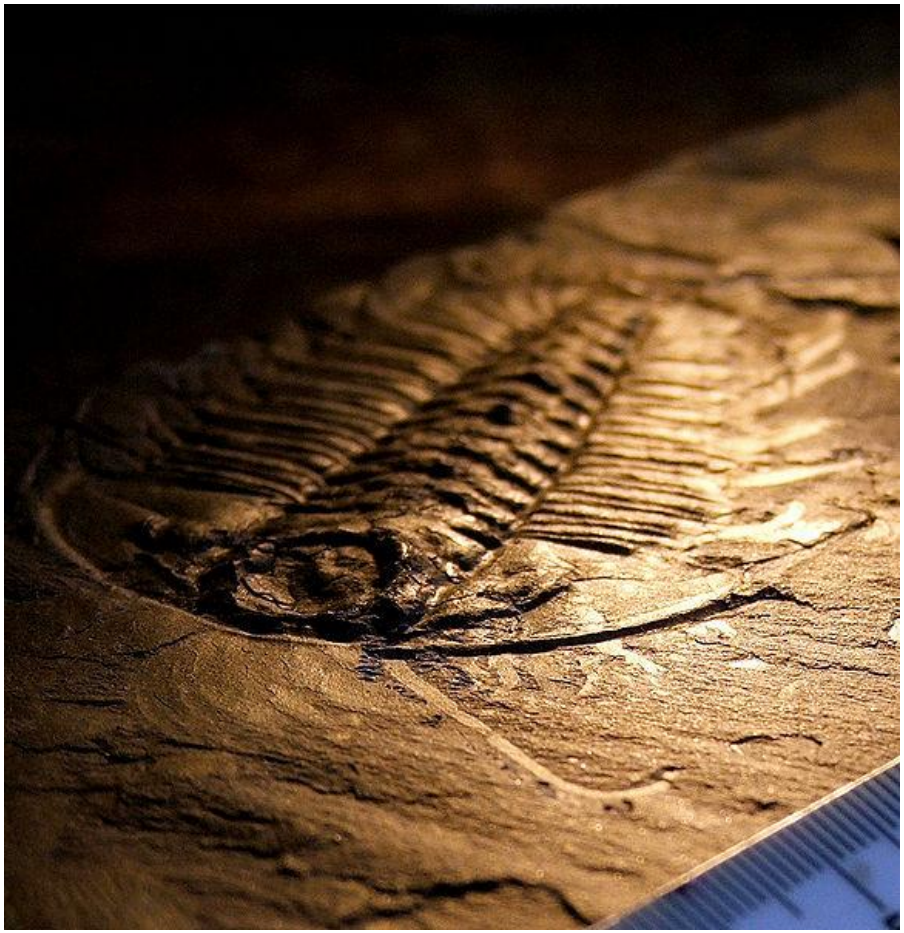
A. 1146 years B. 11460 years C. 57300 years
D. 4.6×10^9 years E. Can't be determined from the info given.

The ^{14}C decay rate from a prehistoric corpse is measured to be 3.39 decays per minute per gram of C from the corpse. How long ago did it die?

A. 1146 years B. 11460 years C. 57300 years
D. 4.6×10^9 years E. Can't be determined from the info given.

Mid-lecture Break

- Homework #3 is on WeBWorK; due Thursday by Midnight.
- Exam #2 is Friday, 10 June 2011 in a 75-minute span of your choice between 10 AM and 6 PM. Preceded as usual by a practice exam and office hours.



Burgess Shale trilobite: the archetypal Cambrian fossil (Wikimedia Commons)

The dating of sedimentary-rock strata

So we have good ways of measuring ages of

- igneous rocks of just about any age;
- corpses of plants and animals that died within the last 60,000 years.

Unfortunately

- fossils are not organic: their material has been replaced by inorganic minerals. So ^{14}C dating wouldn't work even if it could reach very old.
- fossils are only found in sedimentary rocks. Sedimentary rocks are made of granules of other sorts of rock whose solidification ages bear no natural resemblance to one another.

The dating of sedimentary-rock strata (cont'd)

Fortunately the Earth is volcanic, and there are sheets of sedimentary rock hundreds of miles across that have been horizontal since formation on ancient oceanic floors.

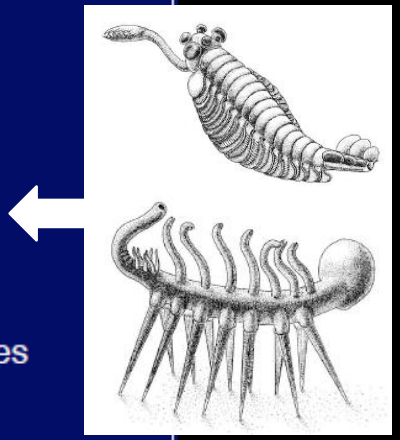
- Thus sedimentary strata are overlain and underlain with igneous rocks whose ages can be measured by radioisotope means (most frequently K-Ar or K-Ca).
- Sediments build from the bottom up, so older sediments were buried by newer ones, and now lie at lower elevation or greater depth. Paleontologists call this the **principle of superposition**.

So fossil ages can in fact be measured with few-percent accuracy, and we can construct the **fossil record**: the census of living things through the last few Gyr.

The fossil record, 0-800 Myr ago

Era	Period	Myr Ago	Life Forms	Events
Cenozoic	Quaternary	2	H. sapiens	Ice Ages
	Tertiary	65	Primates	Extinction of Dinosaurs
Mesozoic	Cretaceous	136	Birds	South Atlantic open to 1900 miles.
	Jurassic	190		North Atlantic open to 600 miles
	Triassic	225	Mammals	Continental Drift
Paleozoic	Permian	280	Reptiles	Pangaea breaks up
	Carboniferous	345	Amphibians	Formation of coal
	Devonian	395	Insects	
	Silurian	430	Land Plants	
	Ordovician	500	Fish (Chordata)	Burgess Shale forms
	Cambrian	543	Trilobites	
Precambrian		545	Small Shelly fossils	
		580	Ediacarans	
		600–800		Snowball Earth episodes
			Multicellular life	

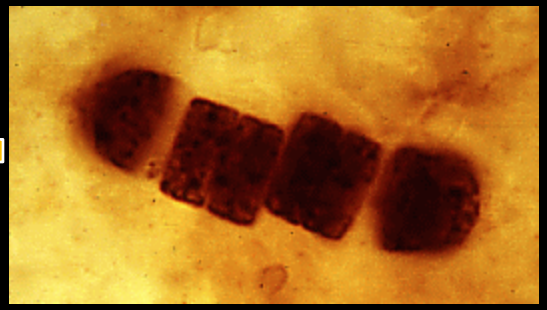
Burgess Shale fossil reconstructions by Marianne Collins and Stephen Jay Gould, *Wonderful life*



The fossil record, complete

Myr Ago	Era	Fossil Group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic Life
		Ediacara	
			Snowball Earth
	Precambrian		
1000		Bitter Springs	Worm tracks (?)
			Multicellular Algae
		Beck Spring Dolomite	
			Eukaryotes certain
		McArthur Group	Sexual Reproduction (?)
2000		Gunflint Chert	Eukaryotes possible
	Proterozoic		Oxygen-Rich Atmosphere
			Snowball Earth
			Formation of continents
3000		Bulawayan	
		Fig Tree	
		Onverwacht	
		Warrawoona	Autotrophs–Stromatolites
	Archean		Life Begins (?)
			(Prokaryote Heterotrophs)
4000			Formation of oceans
			Bombardment decreases
			Frequent impacts
	Hadean		Formation of Earth
5000			

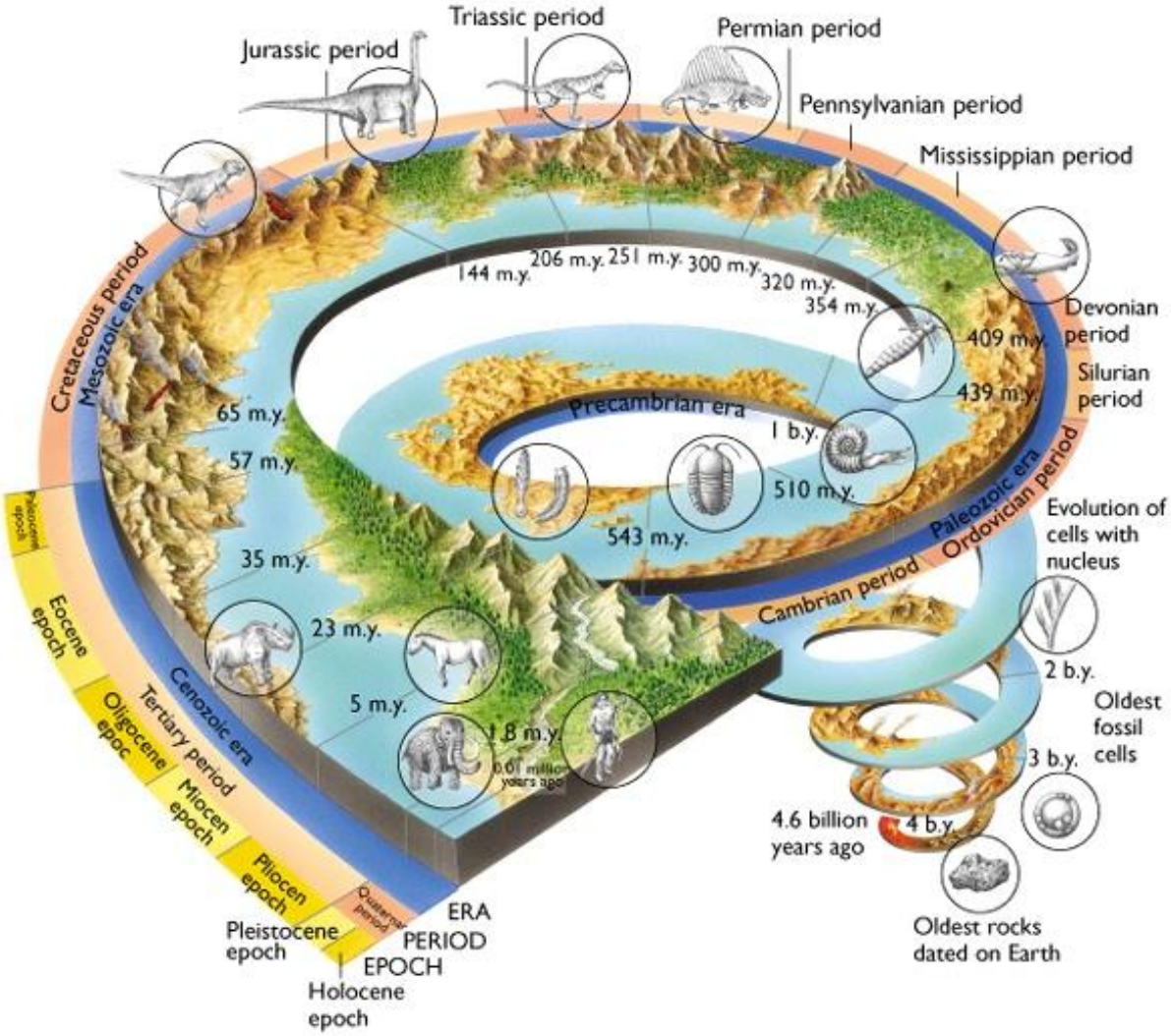
Fossil microbes



Schopf 1992

Tables borrowed from Neal Evans's AST 309L lecture notes.

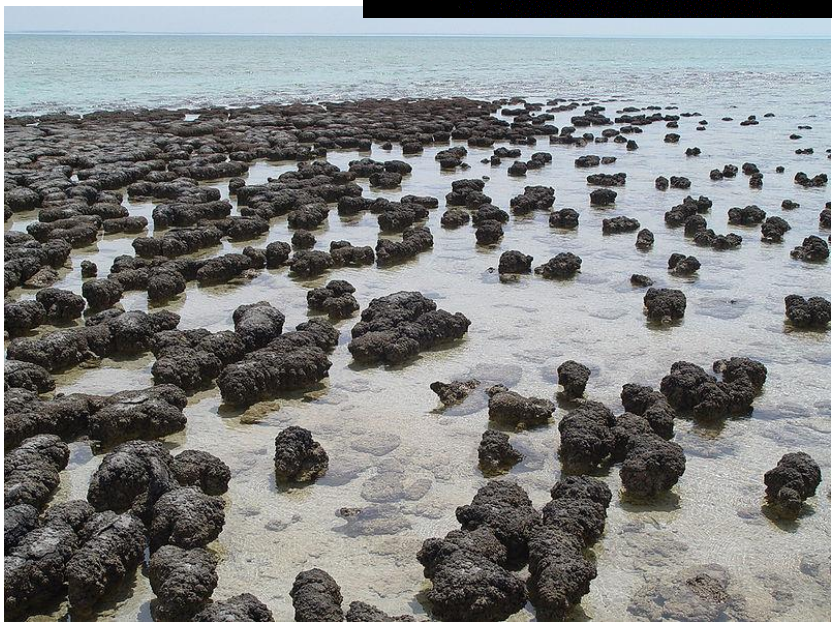
The fossil record, more complete



Summary of fossil record

- Microfossils – single fossilized cells date conservatively to 3 Gyr, and controversially 3.5 Gyr
- Cellular life has been around for at least 3 Gyr.
- Mats of microbes layered with sediments called **stromatolites** date back to 3.5 Gyr
- Photosynthetic organisms have been around 3.5 Gyr

Ancient stromatolite, layers of sediment, calcium carbonate and photosynthetic bacteria. UC Berkely



Modern stromatolites in Australia.

Summar of fossil record (con't)

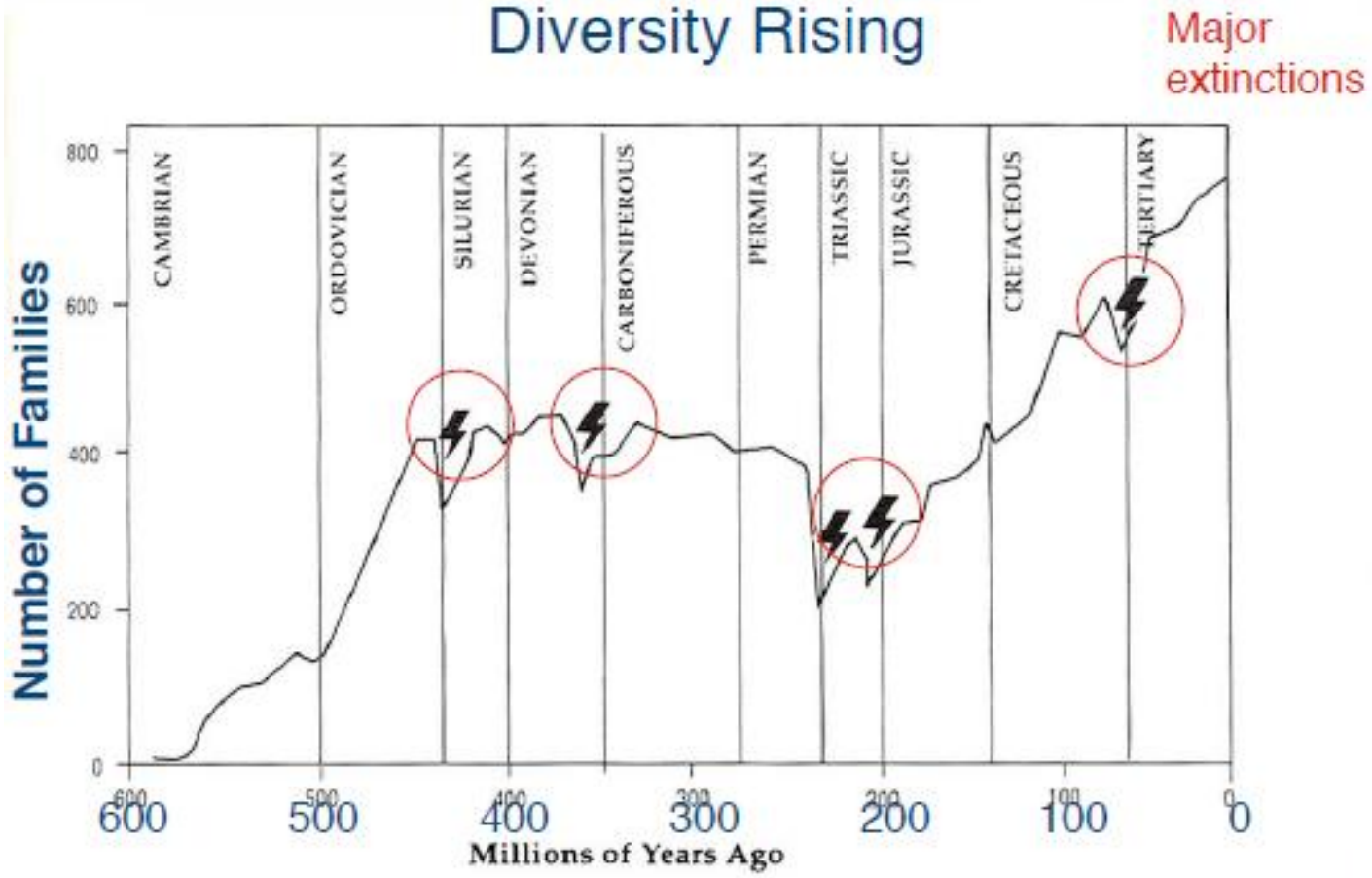
- Simple organisms developed first, more complex ones later: prokaryotes, then eukaryotes, then multi-cellular ones
- Multicellular organisms developed 1.2 Gyr ago (henceforth Gya)
- Deterministic "progress" of families is not always observed:
  - many organisms develop and become extinct with no links to successors.
  - some families develop greater complexity, but many stay about the same (e.g. bacteria).

Summary of fossil record (con't)

- General increase in diversity of lifeforms, though:
  - A few **mass extinctions**
  - A few booms or explosions in diversity
- Large amount of Cyanobacteria aka "blue-green algae" around 2.7 Gya
- "Great Oygenation Event" 2.35 Gya
- Cambrian Explosion – 530 Gya
  - Profound increase in diversity
  - Development of the 30 different phyla of Animalia
  - Thought to be caused by a variety of factors including increase in O_2, optimal complexity, climate change and lack of predators

Summary of fossil record (con't)

- Plants move to land around 475 Mya
- Amphibians and insects follow 75 Myr later
- By 360 Mya there are vast forests abundant with insects
    - This is the time coal was created



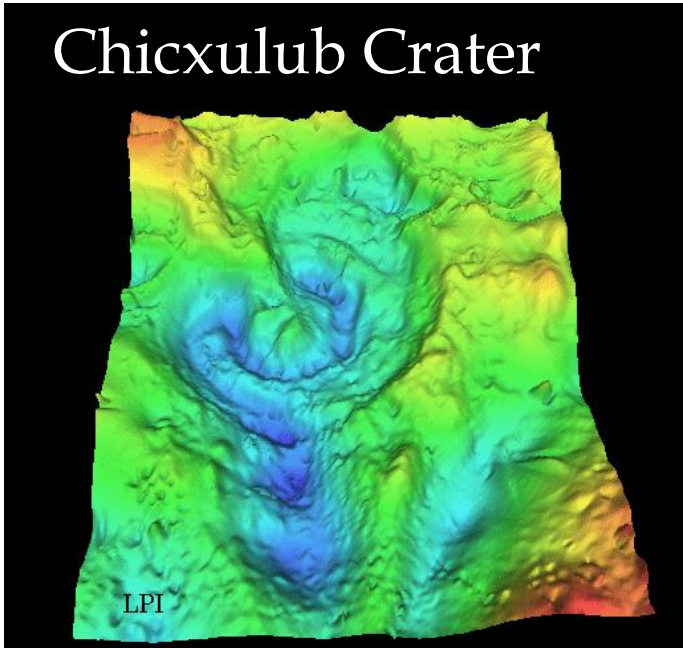
Biological diversity has increased slowly over geological time, with occasional setbacks through mass global extinctions. There have been five such extinctions so far, indicated here by lightning flashes. The data given are for families (groups of related species) of marine organisms. A sixth major decline is now underway as a result of human activity.

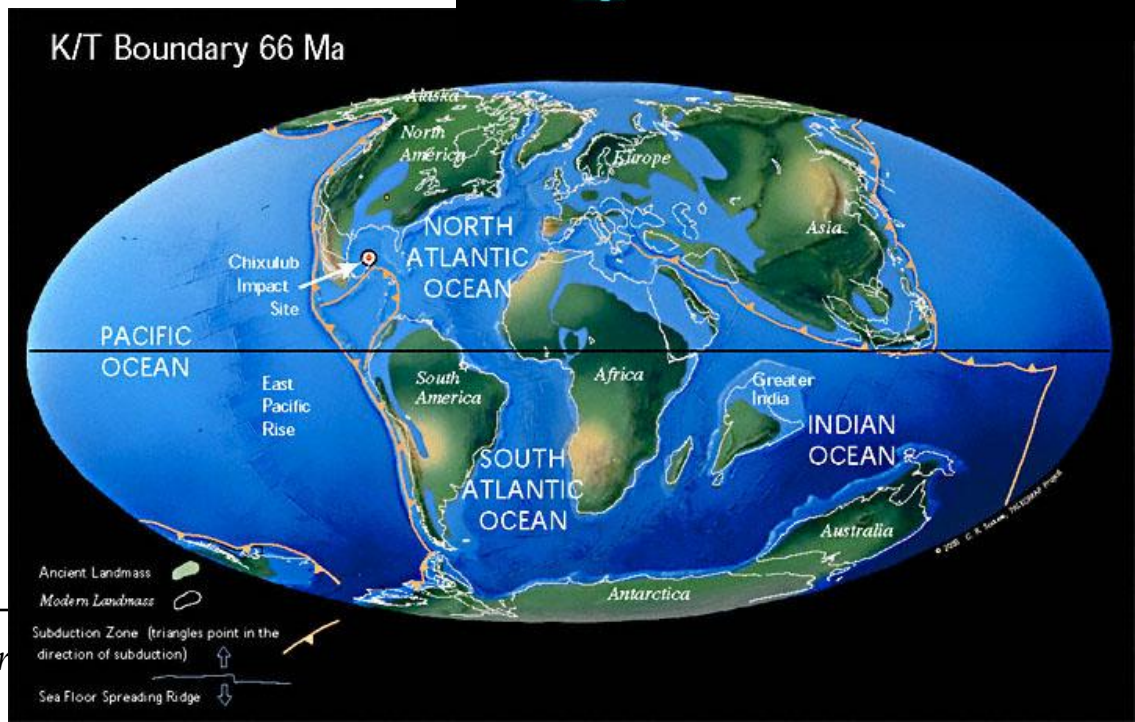
E. O. Wilson:
The Diversity of Life

Borrowed from [Neal Evans's AST 309L lecture notes](#).

Rocks from space!

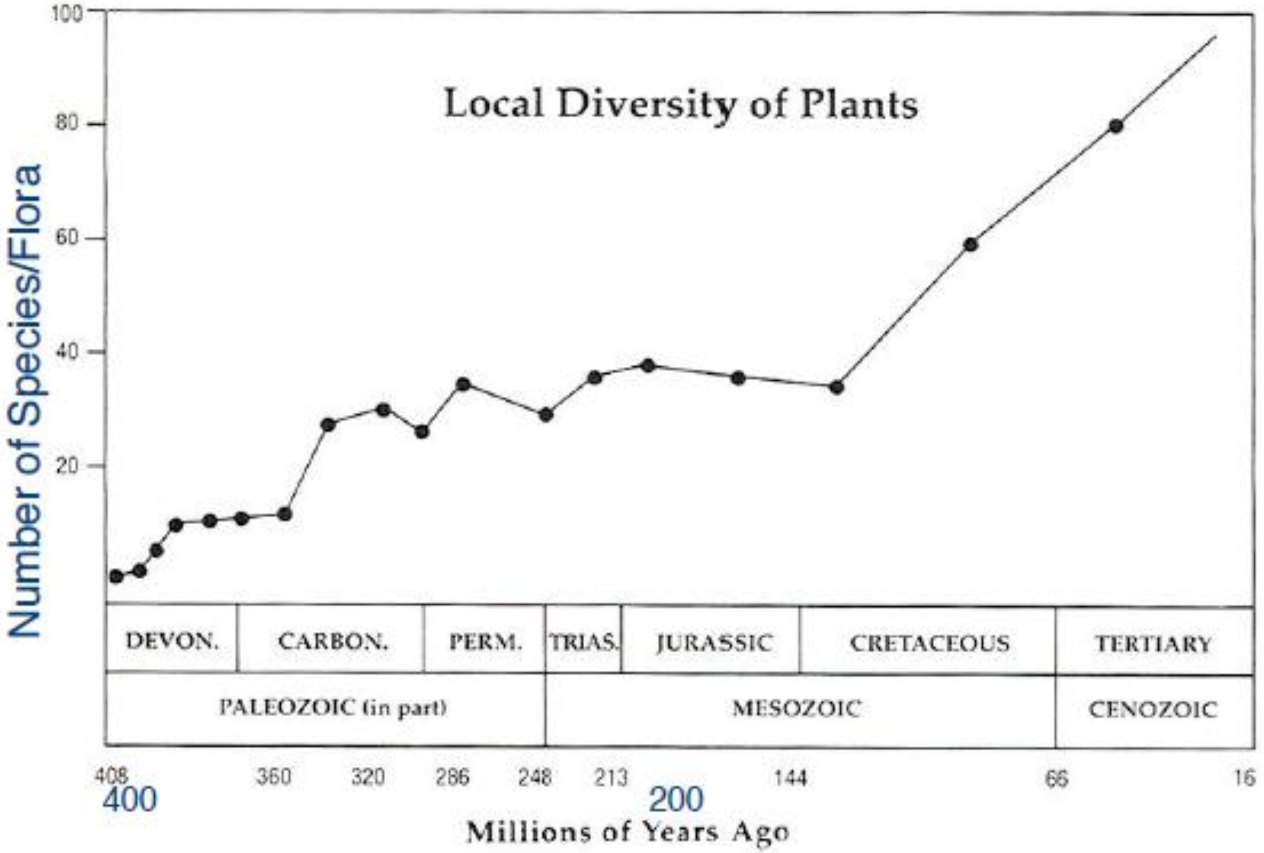
- Evidence:
  - high abundance if iridium (1978)
  - shocked quartz
  - spherical rock droplets
  - soot layers from forest fires
  - crater
- 99% of all plants and animals died
- 75% of all plant and animal species went extinct
- The amazing part:
  25% made it, rise of the mammals





Mass extinctions

- 5 major mass extinctions in the fossil record
  - Spanning the last 500 Myr
- Large rock from space should hit about once every 100 Myr
- What else could cause a mass extinction?
  - Large scale volcanism
  - Combination of factors deemed "sick earth" hypothesis
  - Change in mutation rate
  - Nearby Gamma Ray Burst (?!)

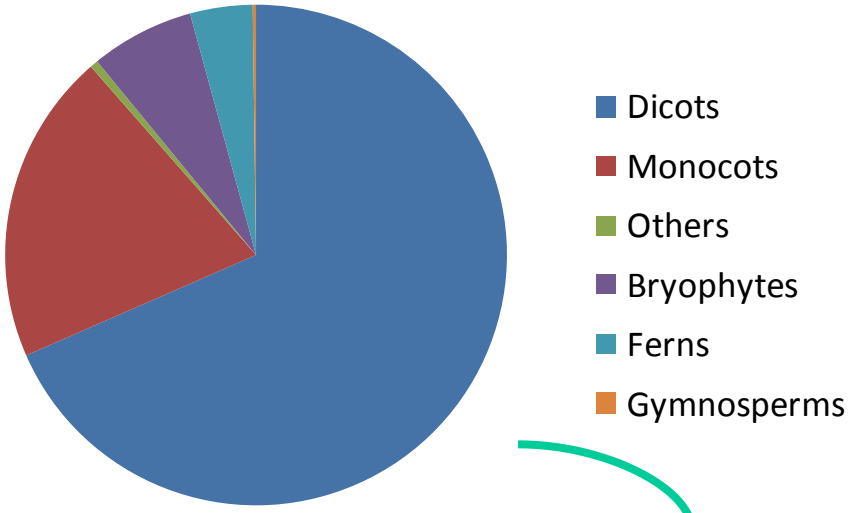


The average number of plant species found in local floras has risen steadily since the invasion of the land by plants 400 million years ago. The increase reflects a growing complexity in terrestrial ecosystems around the world.

E. O. Wilson:
The Diversity of Life

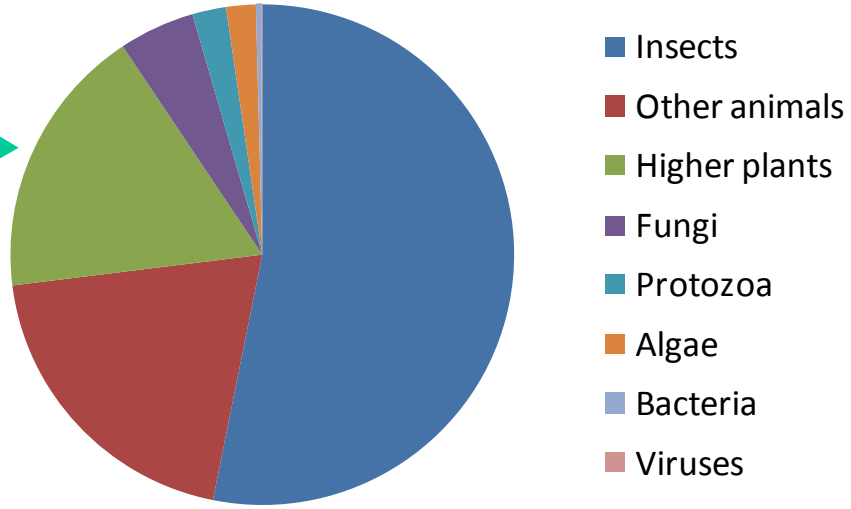
Borrowed from [Neal Evans's AST 309L lecture notes](#).

Biodiversity today



Higher plants on land: about 300,000 species total

All known species: about 2,000,000, mostly on land. Vast numbers remain to be discovered, particularly among the small wedges.



Biological evolution

These features of the fossil record:

- change of Earth's population with time over billions of years;
- development of greater complexity as time goes on;
- clear developmental linkages among species within many families as time goes on;

The Burgess Shale formation in British Columbia, the richest source of Cambrian-era (500-550 Myr ago) fossils.

are experimental facts. Thus **biological evolution is also an experimental fact**, to go with all the other cosmic evolutions we have found so far. We will discuss further evidence of this tomorrow.