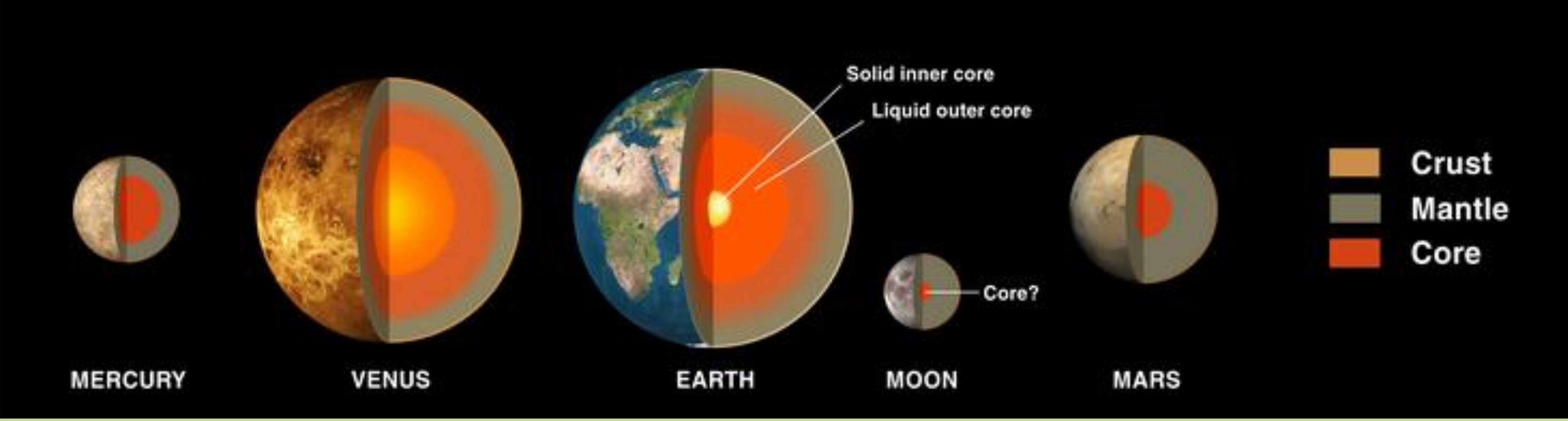
Earth Systems

Dr. Shelley Kauffman
skauffman@alb.edu
Albright College



Terrestrial Planet Interiors

Mercury

Mercury has an average density of 5430 kilograms per cubic meter, which is second only to Earth among all the planets. It is estimated that the planet Mercury, like Earth, has a ferrous core with a size equivalent to two-thirds to three-fourths that of the planet's overall radius. The core is believed to be composed of an iron-nickel alloy covered by a mantle and surface crust.

Venus

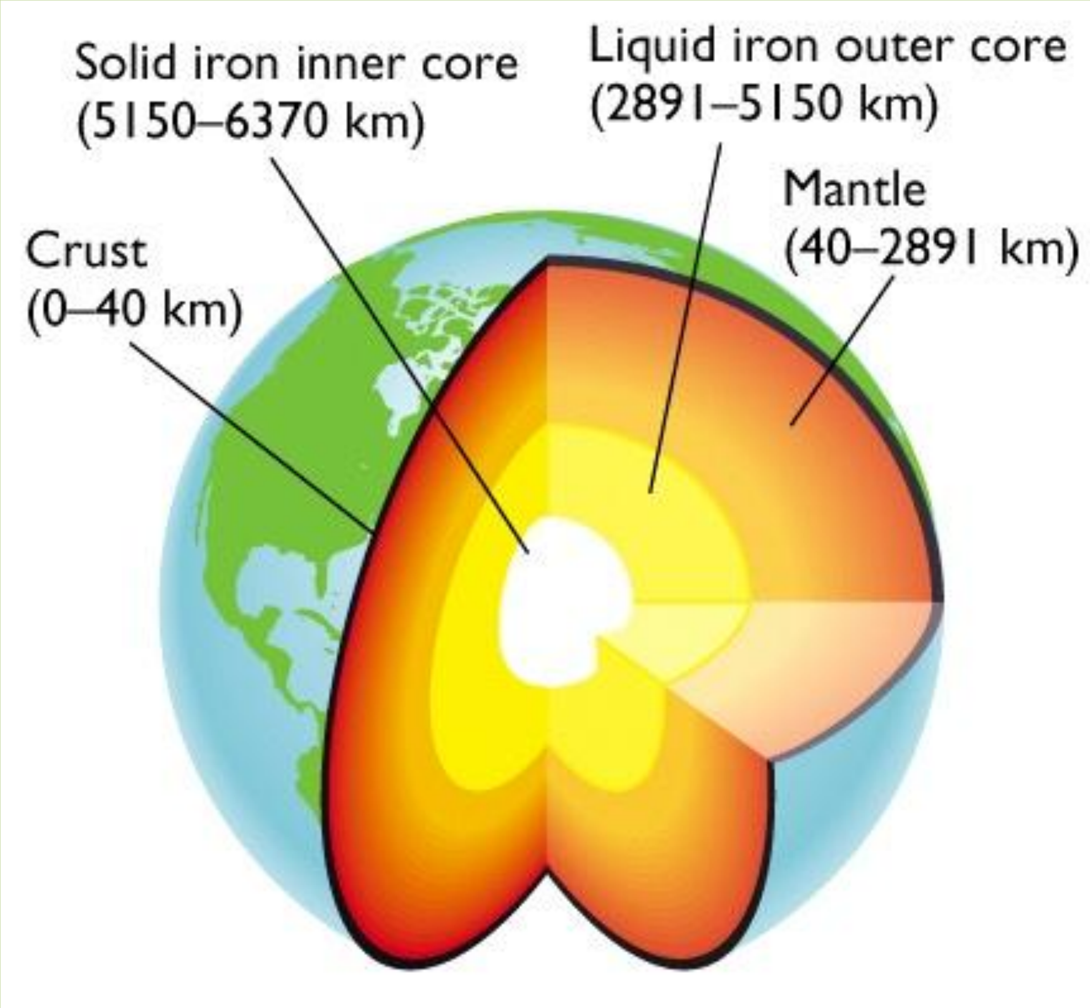
It is believed that the composition of the planet Venus is similar to that of Earth. The planet crust extends to around 10-30 kilometers below the surface, under which the mantle reaches to a depth of some 3000 kilometers. The planet core comprises a liquid iron-nickel alloy. Average planet density is 5240 kilograms per cubic meter.

Earth

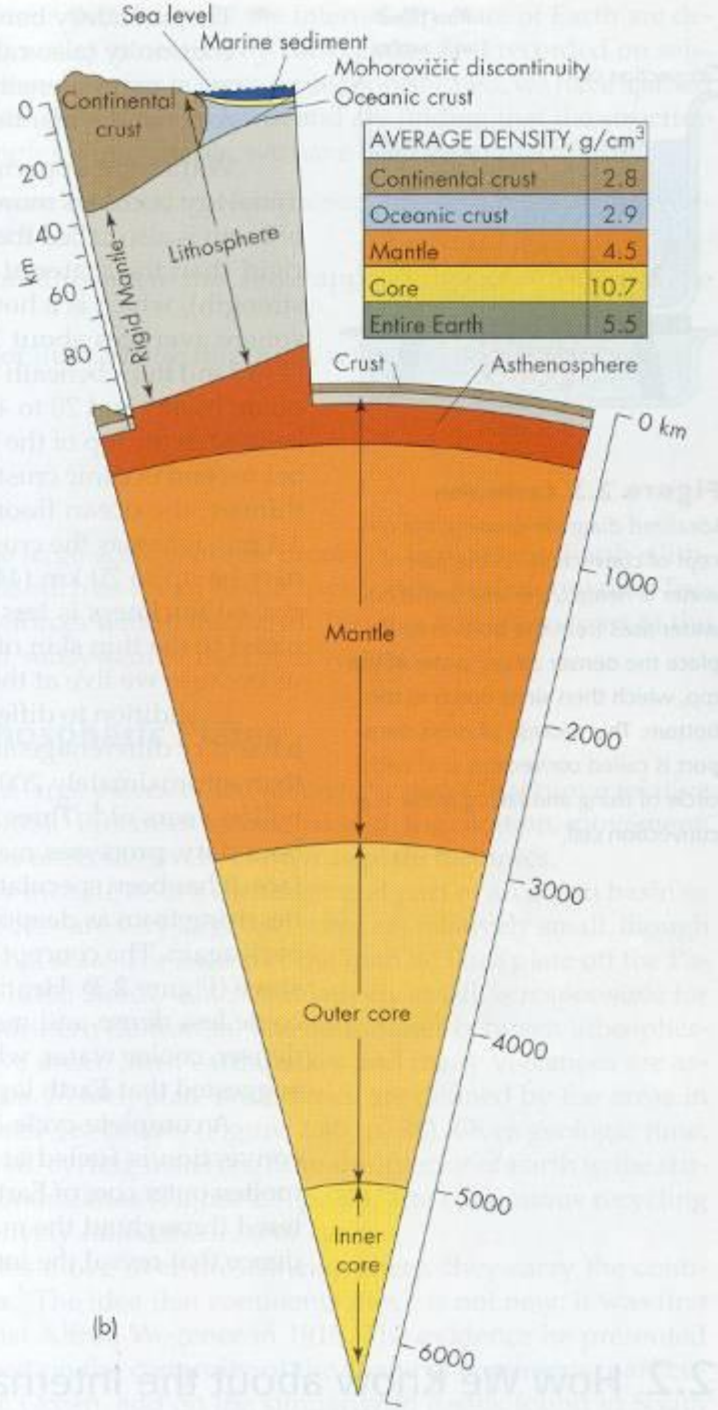
The Earth comprises three separate layers: a crust, a mantle, and a core (in descending order from the surface). The crust thickness averages 30 kilometers for land masses and 5 kilometers for seabeds. The mantle extends from just below the crust to some 2900 kilometers deep. The core below the mantle begins at a depth of around 5100 kilometers, and comprises an outer core (liquid iron-nickel alloy) and inner core (solid iron-nickel alloy). The crust is composed mainly of granite in the case of land masses and basalt in the case of seabeds. The mantle is composed primarily of peridotite and high-pressure minerals. Average planet density is 5520 kilograms per cubic meter.

Mars

Mars is roughly one-half the diameter of Earth. Due to its small size, it is believed that the martian center has cooled. Geological structure is mainly rock and metal. The mantle below the crust comprises iron-oxide-rich silicate. The core is made up of an iron-nickel alloy and iron sulfide. Average planet density is 3930 kilograms per cubic meter.



(c)



(b)

Why are the layers differentiated?

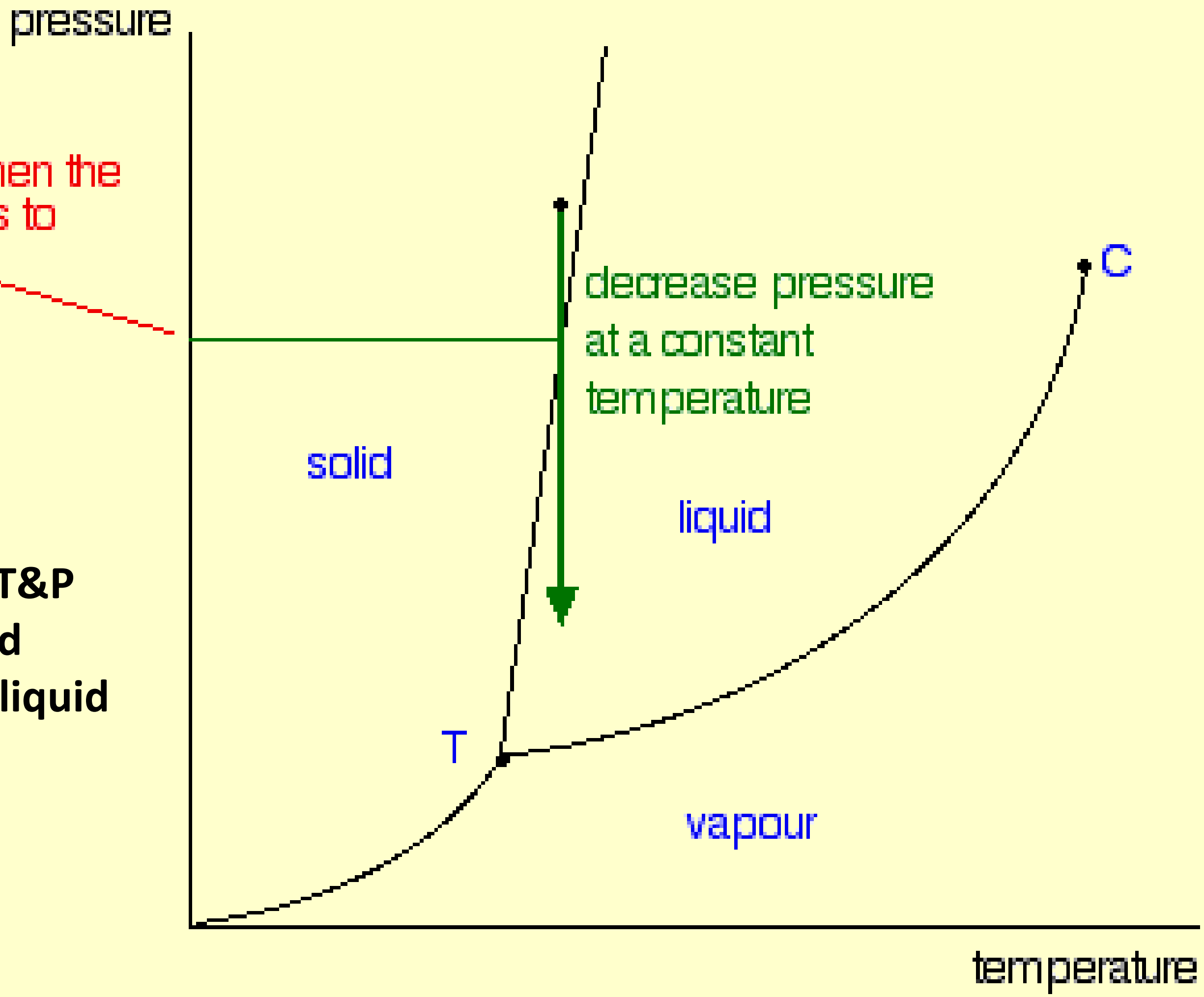
How do we know this?

(deepest borehole, in Russia, is 12km…)

Solid/liquid/gas state is dependent upon ***temperature*** **and *pressure***

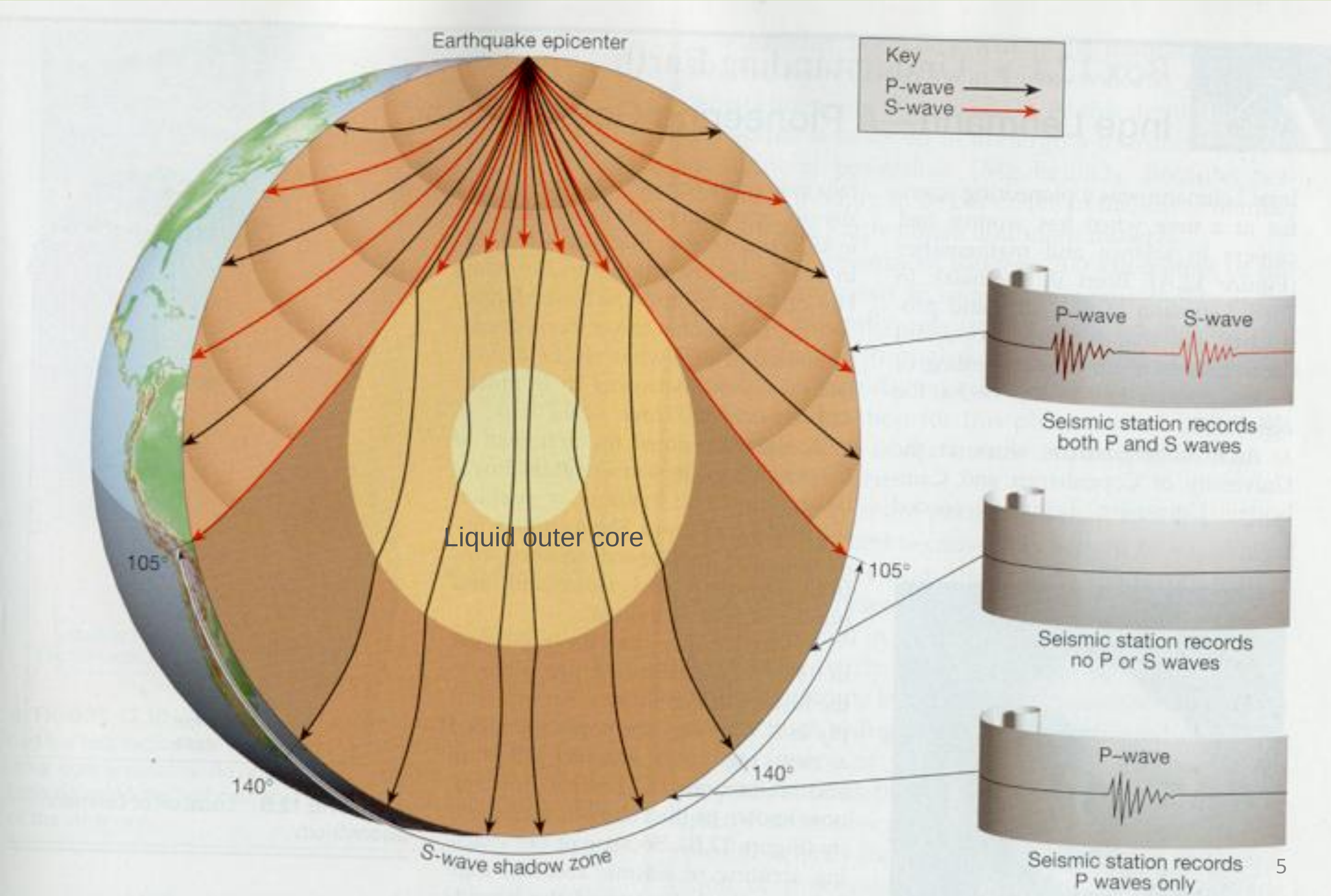
.

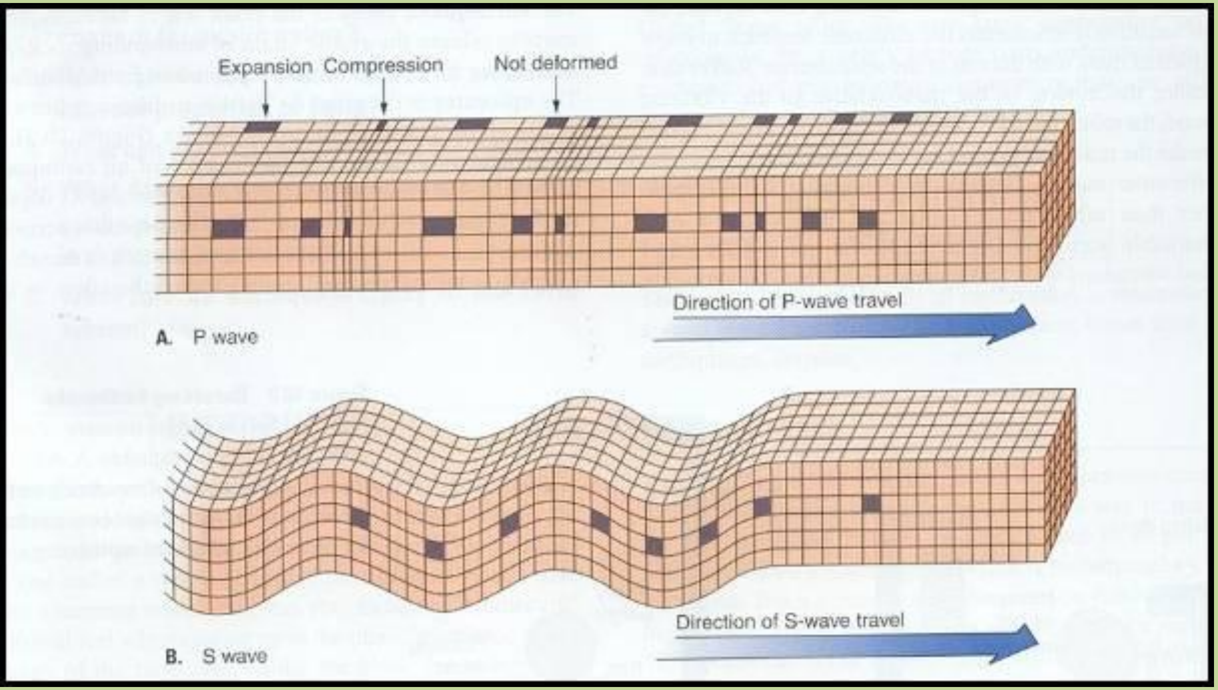
Solid melts when the pressure drops to this value.



Balance of T&P creates solid inner core, liquid outer core

An accidental discovery thanks to the use of seismometers: a liquid outer core!





P waves = change in volume

(solid-liquid-gas)

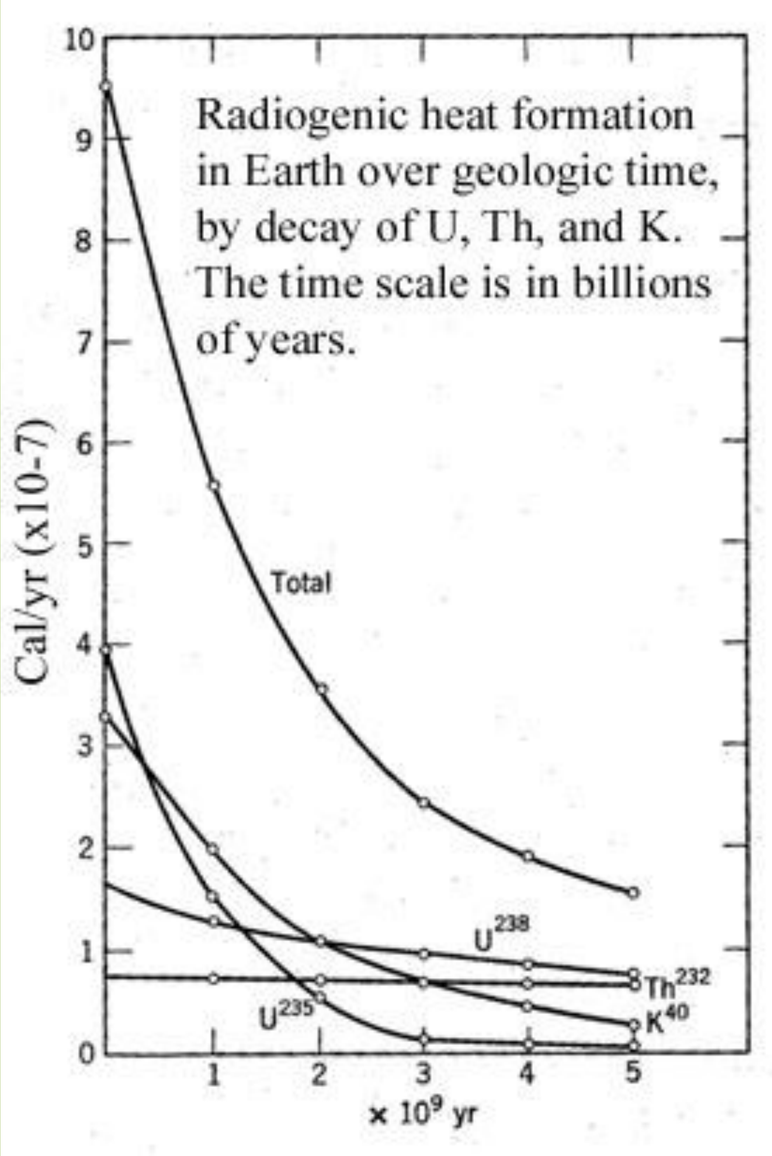
S waves = change in shape

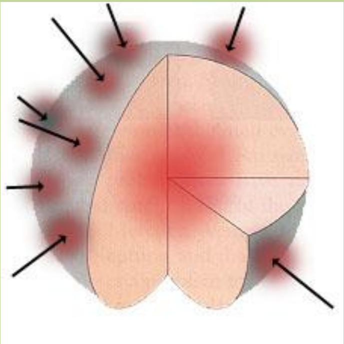
(only solid)

Heat within the Earth comes from two main sources:
radioactive decay **and** ***residual heat from its formation.***

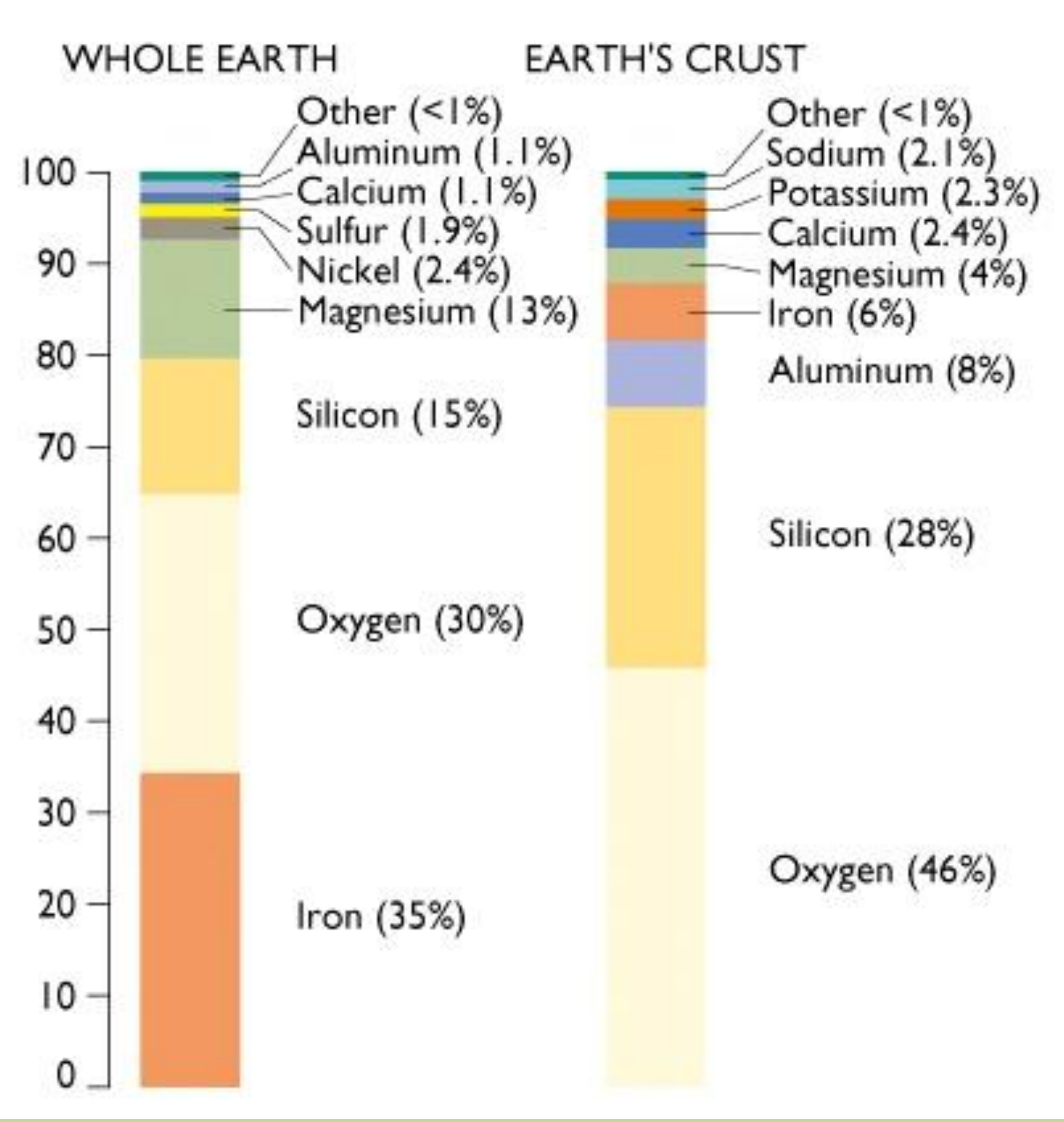
The radioactive decay of naturally occurring chemical elements -- most notably uranium, thorium, and potassium -- releases energy in the form of heat, which slowly migrates toward the Earth's surface (accounts for about 90% of heat generated).

Residual heat is gravitational energy left over from the formation of the Earth -- 4.6 billion years ago -- by the compression of cosmic debris (accounts for about 10% of heat generated).





(While the heat energy produced inside Earth is enormous, it’s some 5,000 times less powerful than what Earth receives from the sun!)



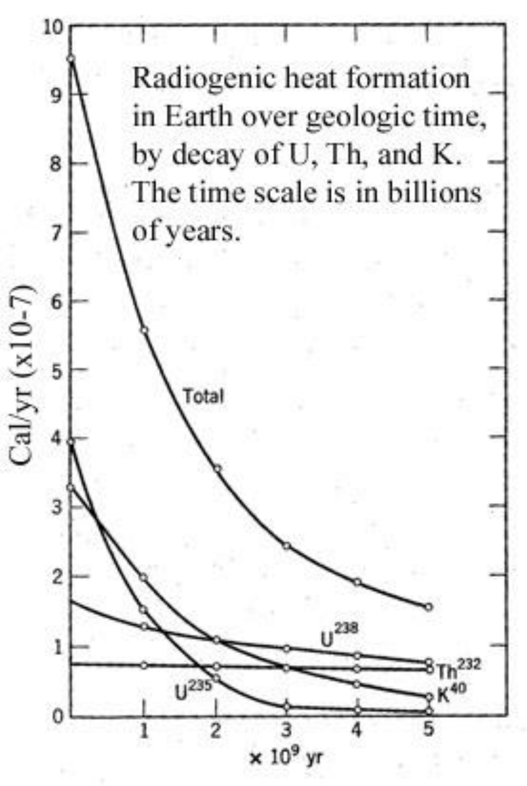
Earth differentiated chemically. More dense elements concentrated in the core, more lighter elements in the crust.

Convection

Convection is the transfer of heat by the movement of a heated fluid.

During convection, heated particles of a fluid begin to flow, transferring heat energy from one part of the fluid to another.

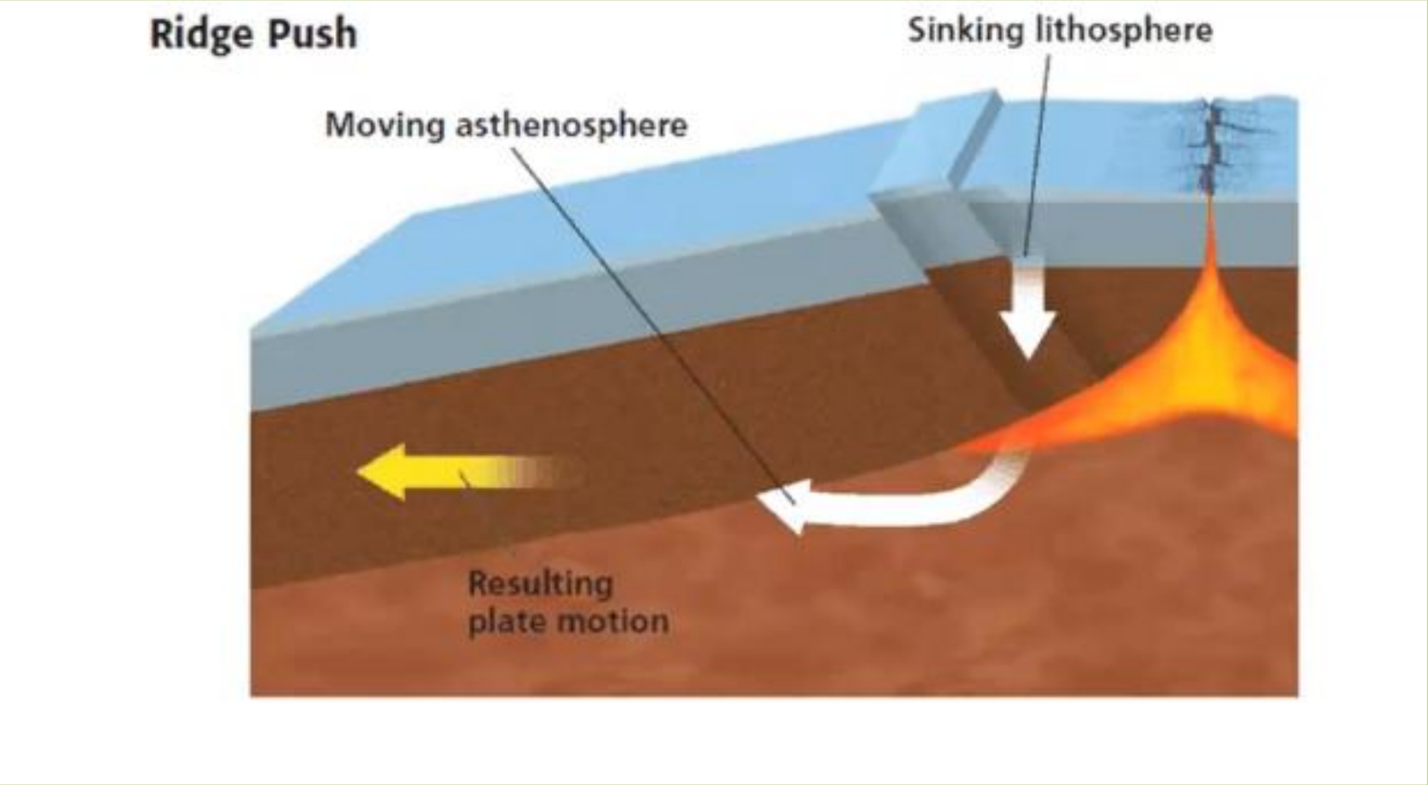
Convection currents continue as long as heat is added to the fluid.



ridge push

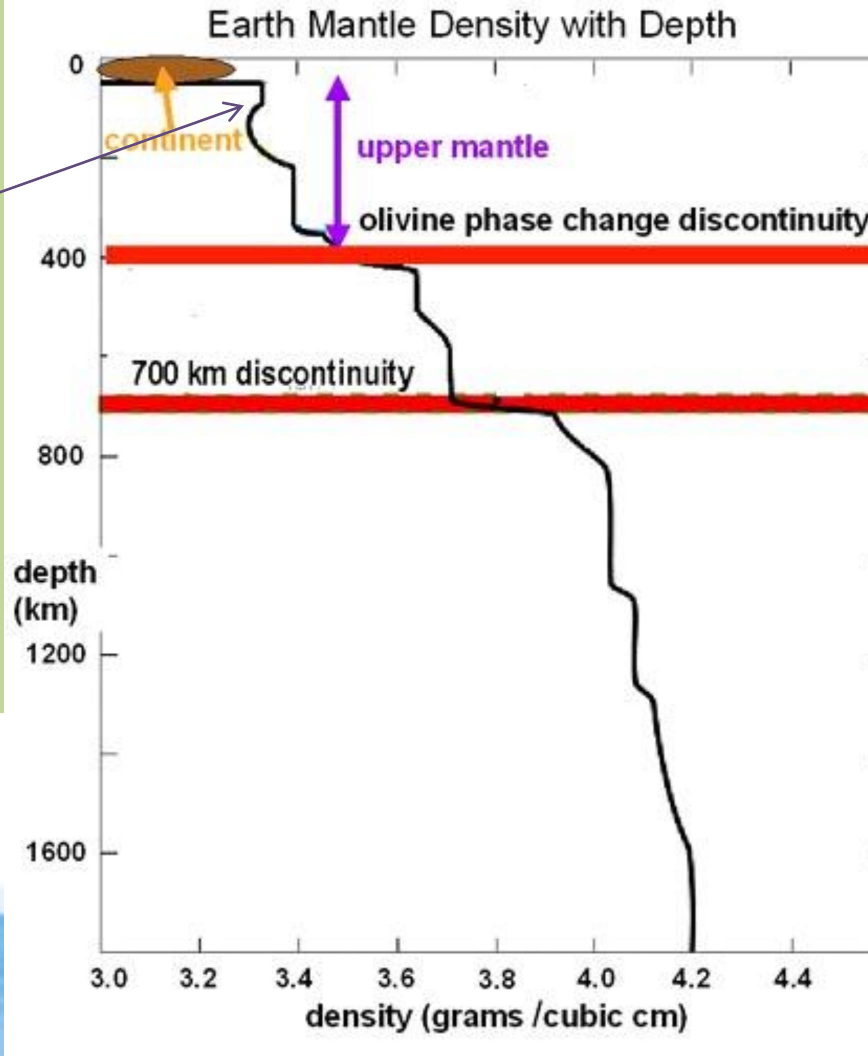
"gravity sliding" off of spreading ridges

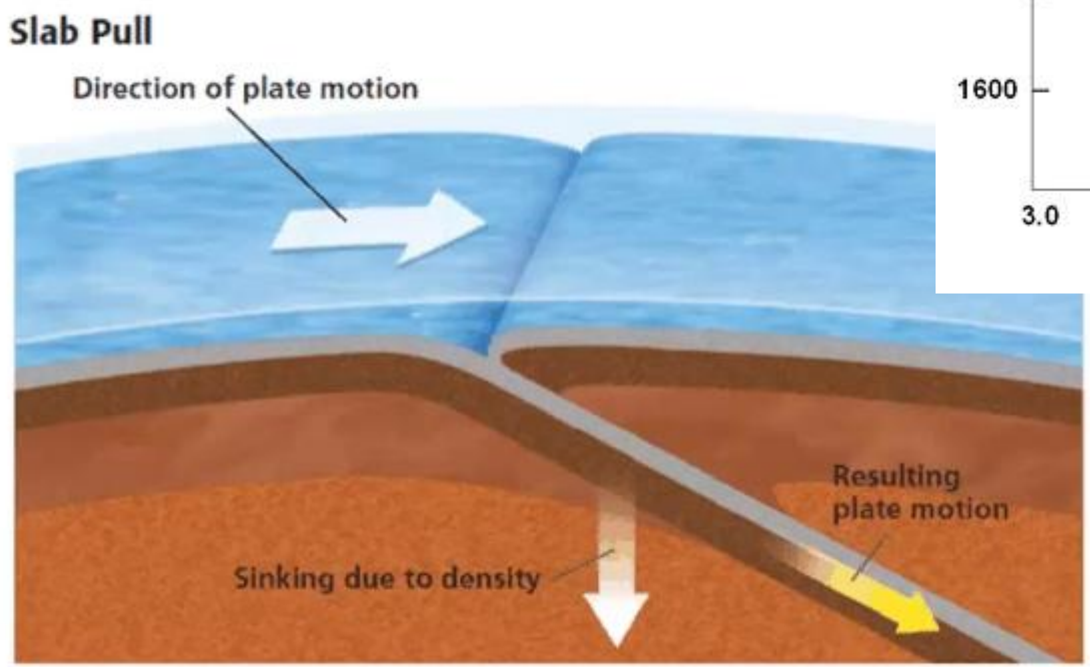
The lithosphere/asthenosphere boundary slopes away from the ridge. The weight of the lithosphere on this sloping surface produces a downslope force.



slab pull

As lithospheric plates move away from midocean ridges they cool and become slightly more dense than the underlying hot mantle. After subducted, cool, dense lithosphere sinks into the mantle under its own weight. This helps to pull the rest of the plate down with it.

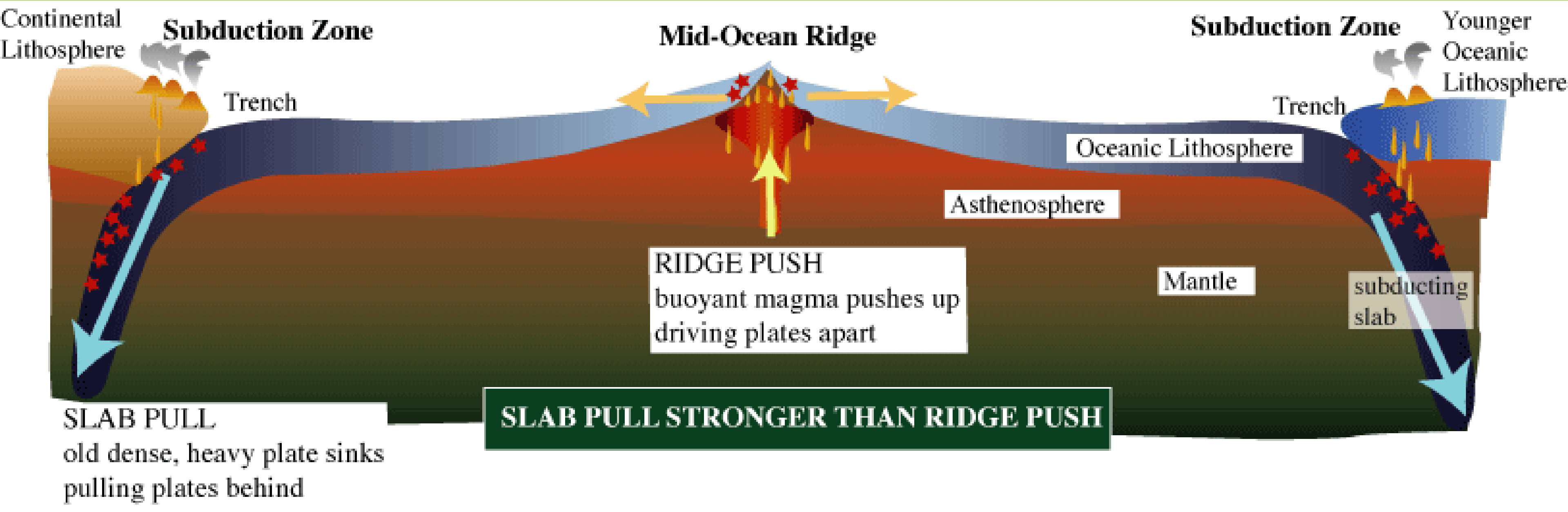




Ridge Push vs. Slab Pull

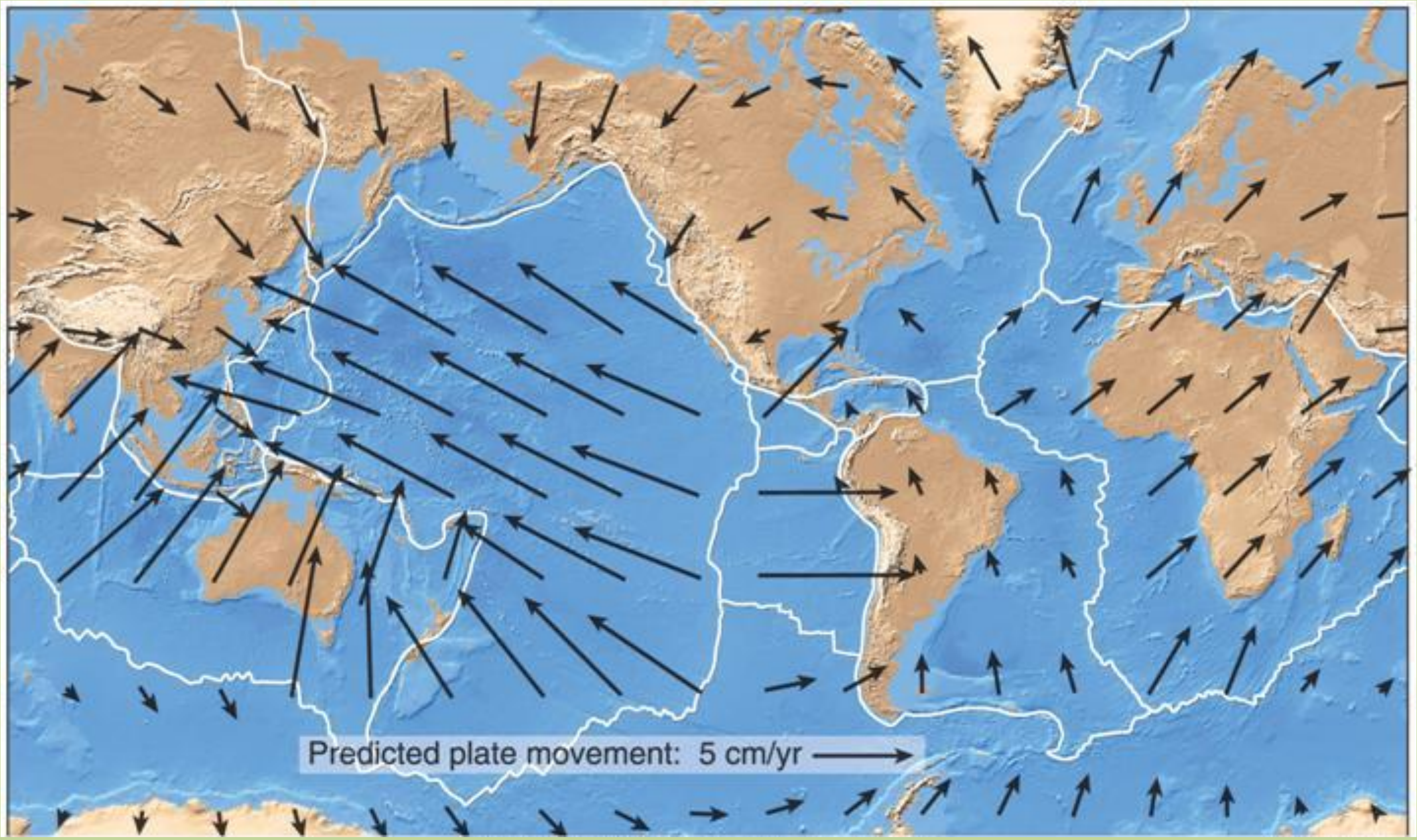
Plates move and convection occurs. But which drives the other?

This is not a resolved question.



Convection currents DO act on the mantle to bring less dense material toward the surface – this continually transfers heat from the interior to the exterior of the planet.

We often think of the mantle moving like silly putty – which will act as a fluid over long time periods.



Velocity of a plate is strongly related to the proportion of its margin that is subducting.

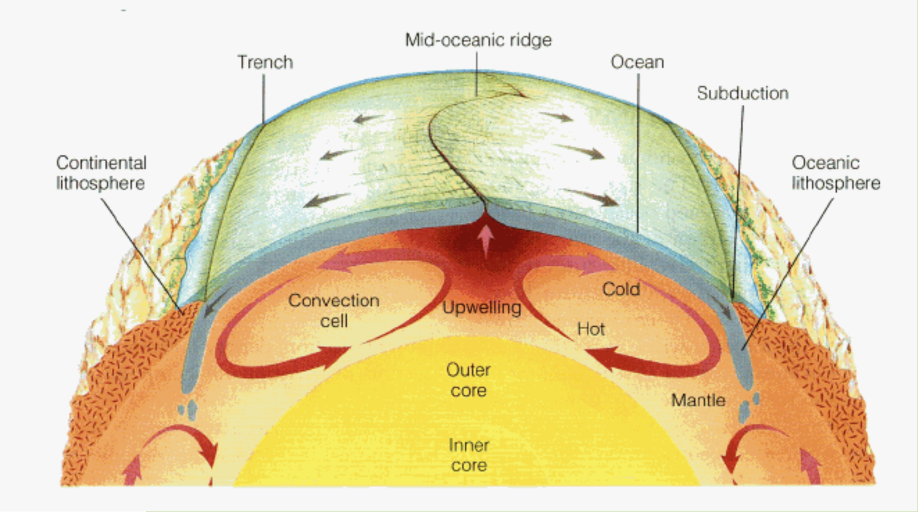
Pacific and Cocos plates - more of the margin is represented by subduction zones
– leads to high plate velocities (greater than 5 cm/yr).

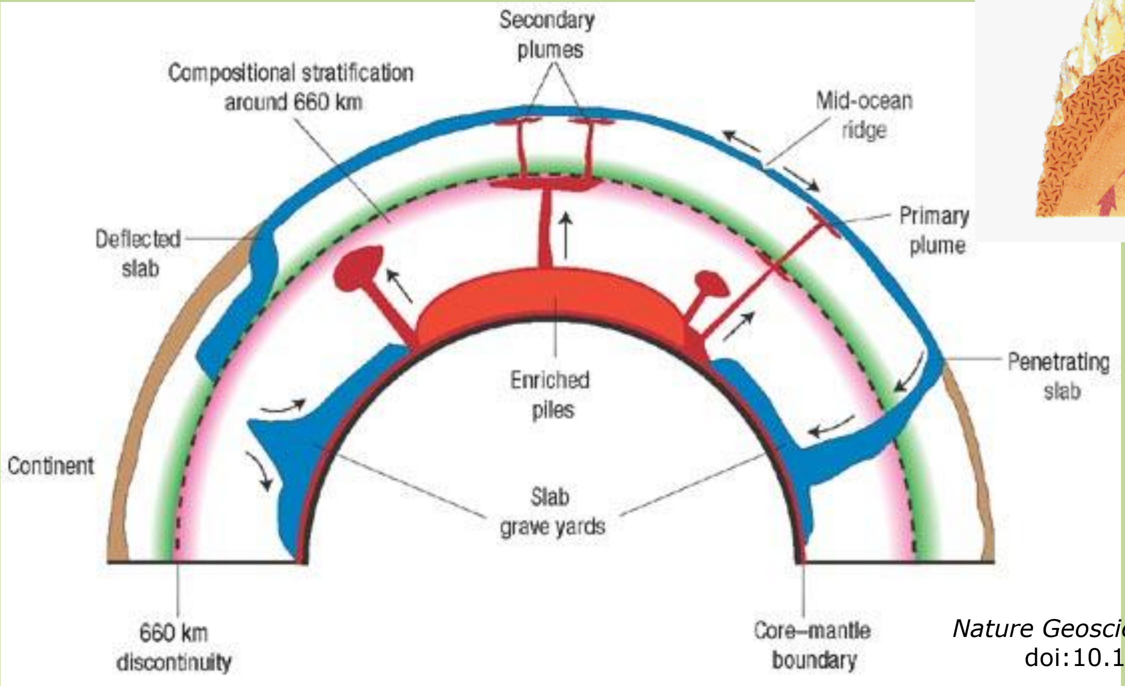
North American plate (and others) – less of the margins are represented by subduction zones
- move more slowly (1 to 3 cm/yr).

Hence, many researchers have concluded that SLAB PULL is the major driving force

“subduction . . . plays a more fundamental role than seafloor spreading in shaping the earth's surface features" and "running the plate tectonic machinery." The gravity-controlled sinking of a cold, denser oceanic slab into the subduction zone (called "slab pull") -- dragging the rest of the plate along with it -- is now considered to be the driving force of plate tectonics. -Seiya Uyeda (Tokai University, Japan)

Convection cells or mantle plumes?



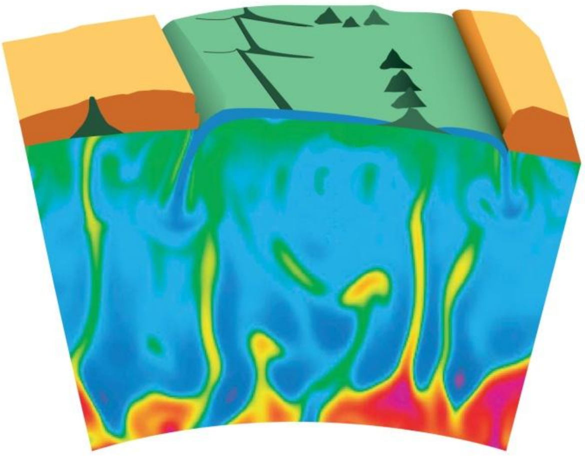


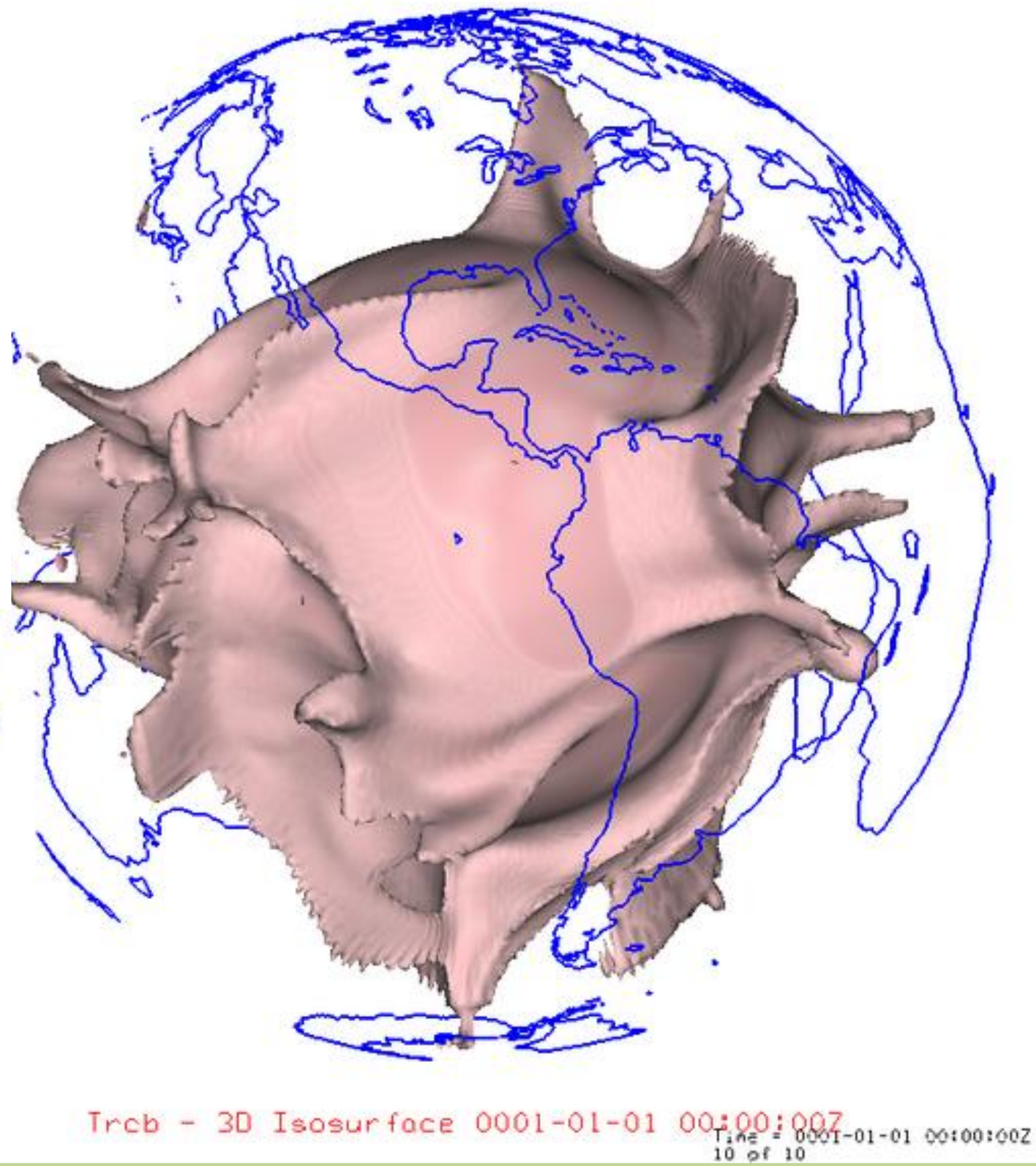
Nature Geoscience **1**, 157 - 158 (2008)
doi:10.1038/ngeo134

Are the convection cells whole mantle or layered?

This, again, is under debate. The emerging model suggests a less uniform model than we typically envision.

Mantle plumes according to the modelers





EarthViewer

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By Howard Hughes Medical Institute

Open iTunes to buy and download apps.

View In iTunes

Free

Category: Education
Released: Jan 31, 2013
Version: 1.0
Size: 161 MB
Language: English
Seller: Howard Hughes Medical Institute

Rated 4+

Requirements: Compatible with iPad. Requires iOS 4.0 or later.

Customer Ratings

Current Version:
★★★★½ 78 Ratings

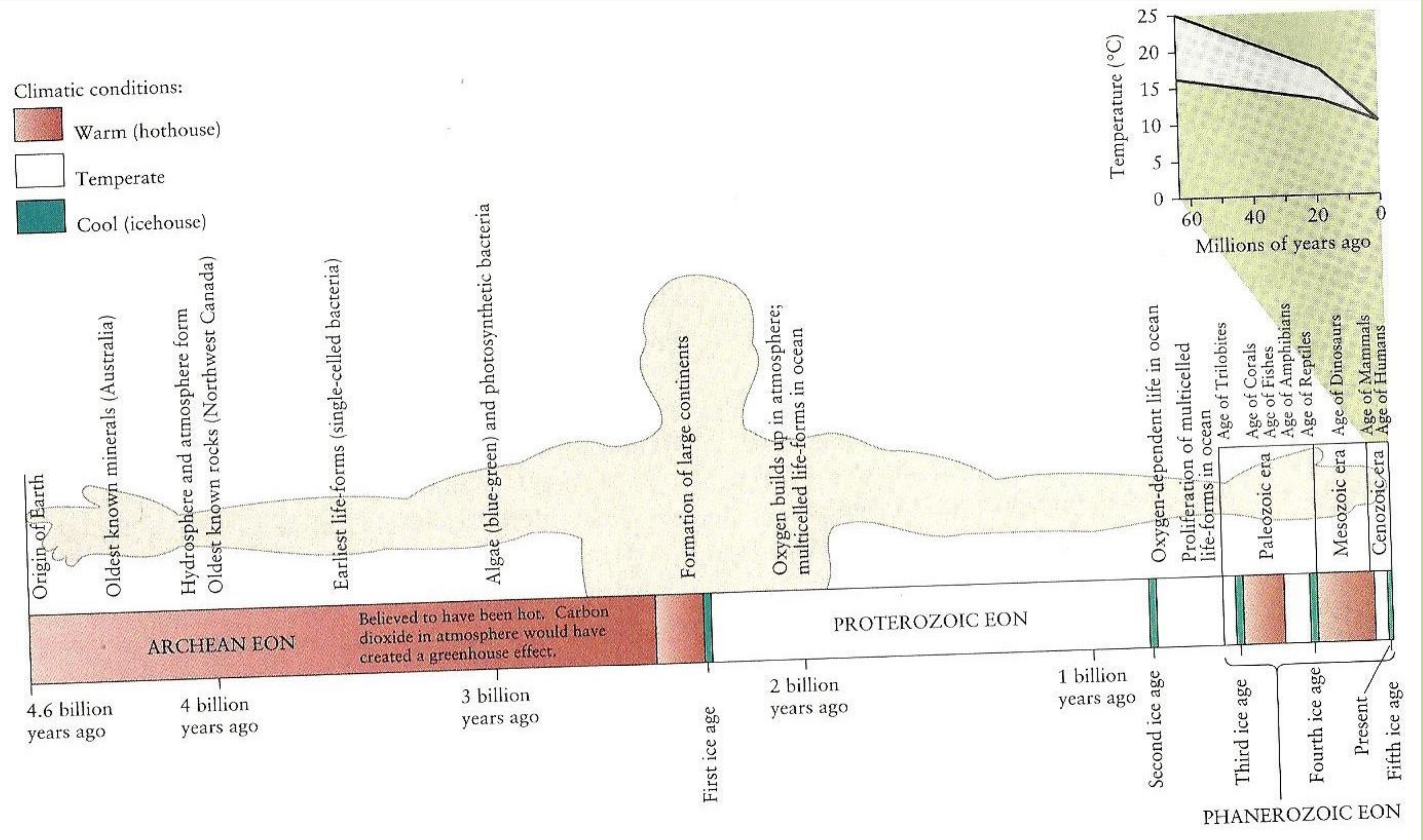
Description

What did Earth's continents and oceans look like 250 million years ago, or 1 billion years ago for that matter? Can we say anything about Earth's climate as far back as our planet's origin?

Howard Hughes Medical Institute Web Site ▸ EarthViewer Support ▸ ...More

iPad Screenshots

A geologic time scale you can carry with you.

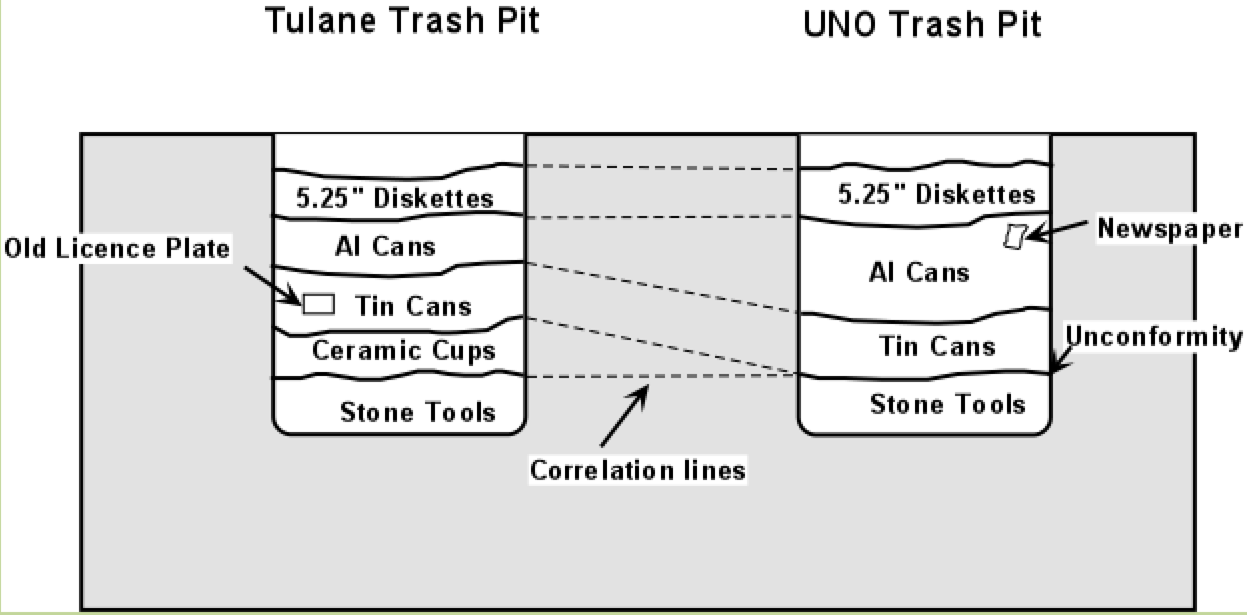


(it would take about 2 additional people to show the time since the Big Bang!)

TABLE 1.1 Geologic Time with Important Events

Era	Period	Epoch	Million Years before Present	Events: Life	Events: Earth	Million Years before Present	True Scale (Million Years before Present)
Cenozoic	Quaternary	Holocene	0.01	• Extinction event • Modern humans	Ice Age Formation of Transverse Ranges, CA		Cenozoic
		Pleistocene	1.65	• Early humans		1.65	
	Tertiary	Pliocene	5.2		Formation of Andes Mountains		
		Miocene	23	• Grasses	Collision of India with Asia forming Himalayan Mountains and Tibetan Plateau		
		Oligocene	35	• Whales			
		Eocene	56	• Extinction event • Mammals expand	Rocky Mountains form		
		Paleocene	65			65	
Mesozoic	Cretaceous		146	• Dinosaur extinction[1], extinction event • Flowering plants	Emplacement of Sierra Nevada Granites (Yosemite National Park)		Mesozoic
	Jurassic		208	• Birds	• Supercontinent Pangaea begins to break up		
	Triassic		245	• Mammals • Dinosaurs		245	
Paleozoic	Permian		290	• Extinction event • Reptiles	• Ice Age		Paleozoic
	Carboniferous		363	• Trees (coal swamps) • Extinction event	Appalachian Mountains form		
	Devonian		417				
	Silurian		443	• Land plants • Extinction event			
	Ordovician		495	• Fish			
	Cambrian		545	• Explosion of organisms with shells		545	
Precambrian			2500	• Multicelled organisms • Free oxygen in atmosphere and ozone layer in stratosphere	• Ice Age • Ice Age		Precambrian
			3500	• Primitive life (first fossils)			
			4000		• Oldest rocks		
			4600		• Age of Earth	4600	4600

Relative vs. Absolute Dating



<u>Relative</u>

5.25" Disk Layer - Youngest
Al Cans Layer
Tin Cans Layer
Ceramic Cups Layer
Stone Tools Layer - Oldest

Observational - qualitative

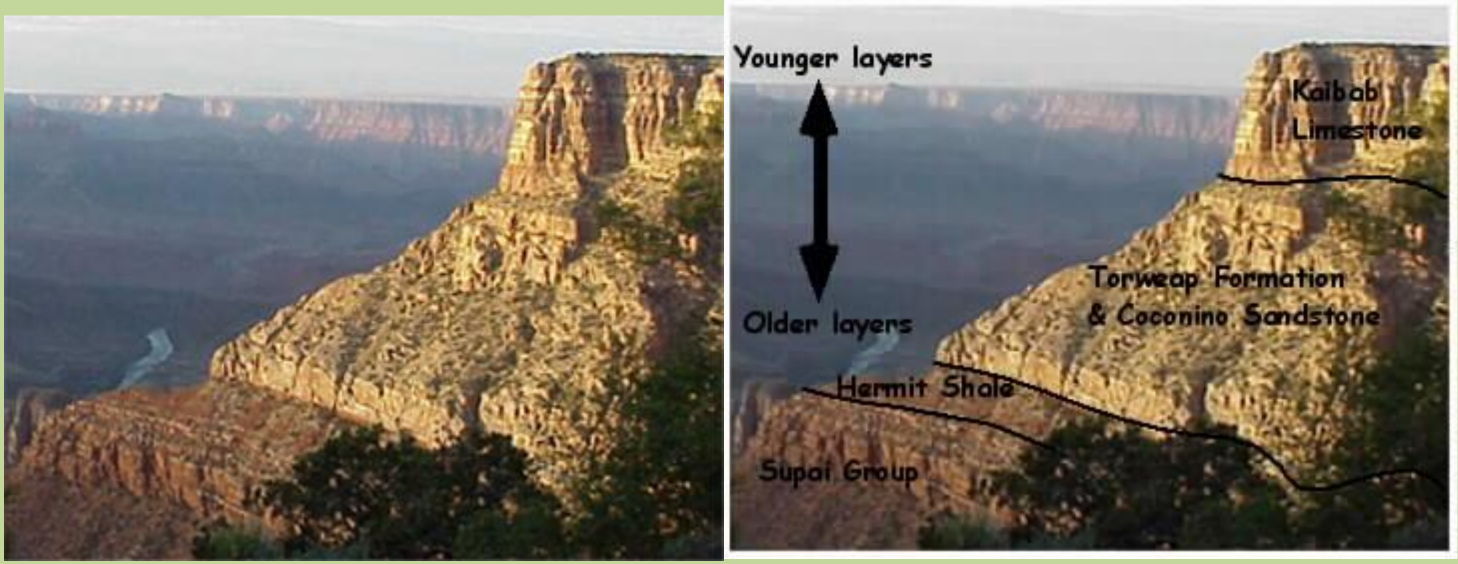
<u>Absolute</u>

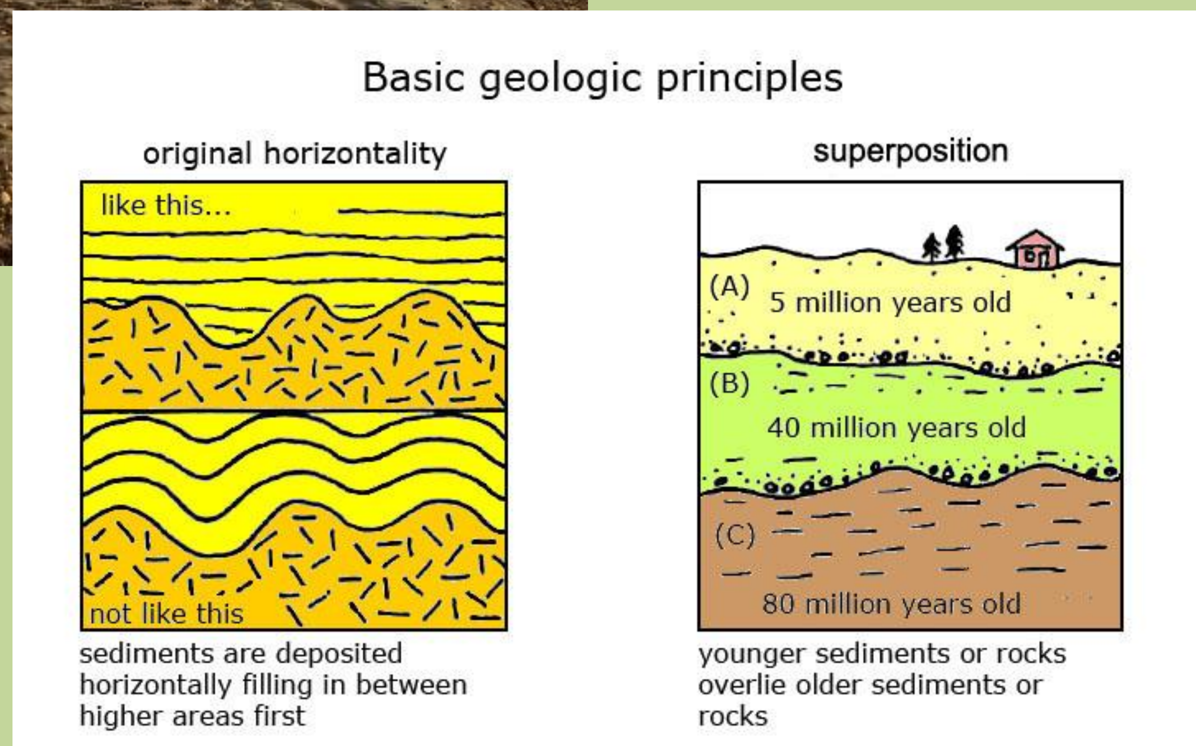
Al Cans Layer – 1978 Newspaper
Tin Cans Layer – 1950 License plate

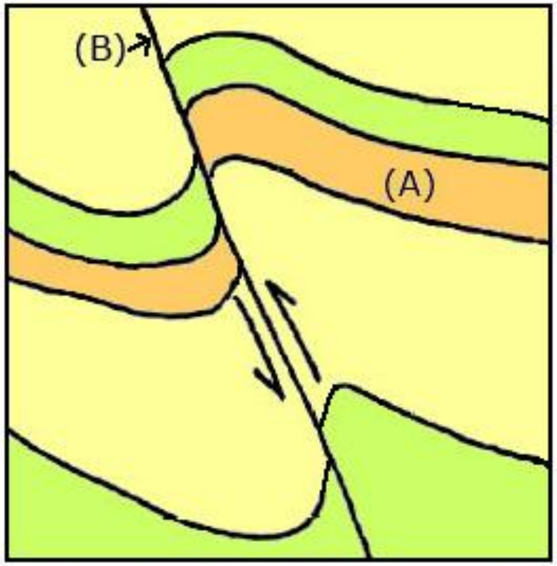
Measurable - quantitative

Principle of superposition

oldest units are on the bottom, youngest on the top

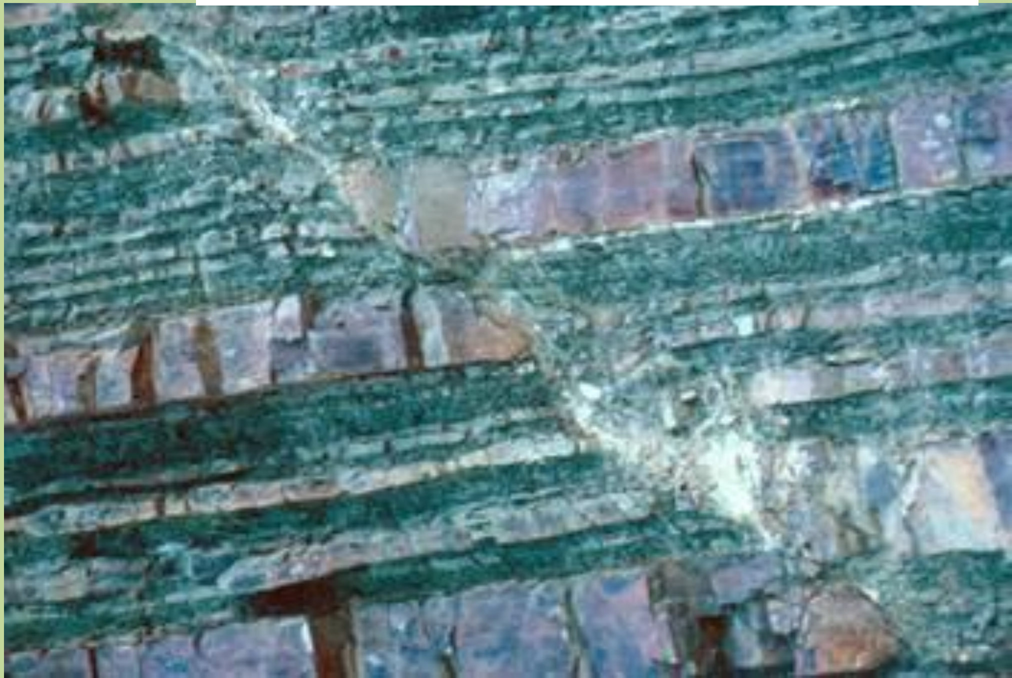



Basic geologic principles
original horizontality
like this...
not like this
sediments are deposited horizontally filling in between higher areas first
superposition
(A)
5 million years old
(B)
40 million years old
(C)
80 million years old
younger sediments or rocks overlie older sediments or rocks



rocks are older than the forces
that deform them: the rock (A)
is older than the fold or fault (B)

Rule of cross-cutting

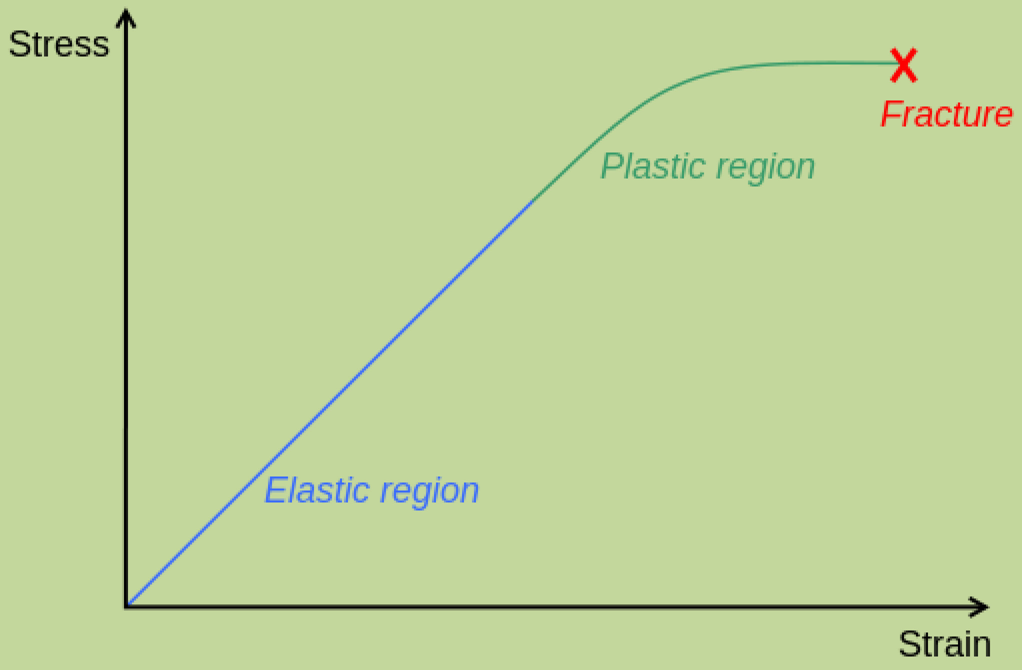


It may be useful to have a little bit of materials science interjected here.

Geologists estimate that when a relatively soft rock like limestone is buried at 1 km depth it will have the same 'strength' as toothpaste.

TABLE 11.1 Relative Rock Strength at Surface Temperature and Pressure

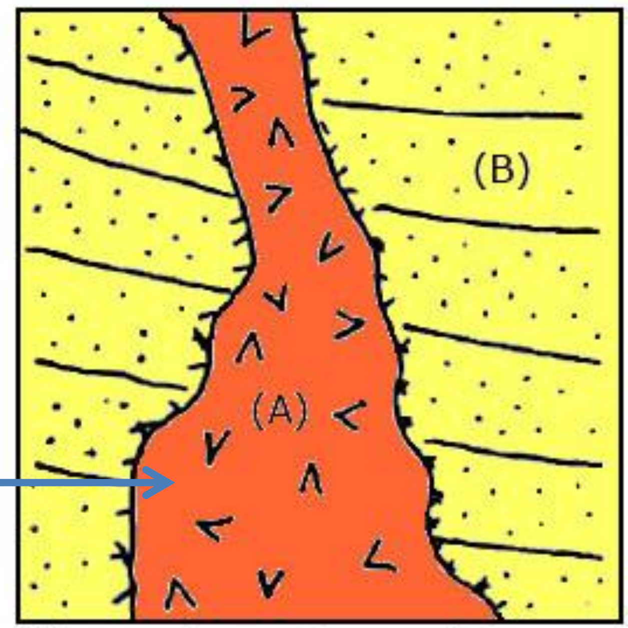
Strength and deformation	Rock type
High strength, brittle deformation	
↑	Quartzite
	Granite
	Quartz-cemented sandstone
	Basalt
	Limestone
	Calcite-cemented sandstone
	Schist
	Marble
	Shale and mudstone
↓	Rock salt
Low strength, plastic deformation	



Elastic behavior: earth can bounce back (like a rubber band)
Plastic behavior: rocks strained beyond the point of no return and can’t bounce back into original shape

How a rock behaves depends upon the internal strength of the rock and corresponding temperature and pressure.

Rule of cross-cutting



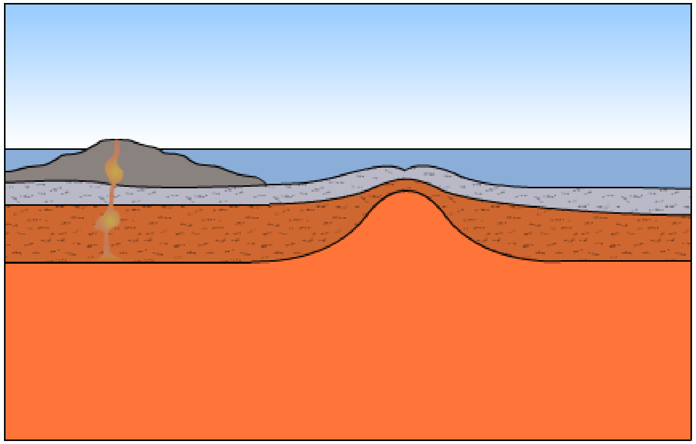
older rocks are bisected by younger rocks; intrusion (A) is younger than the older sandstone formations (B)

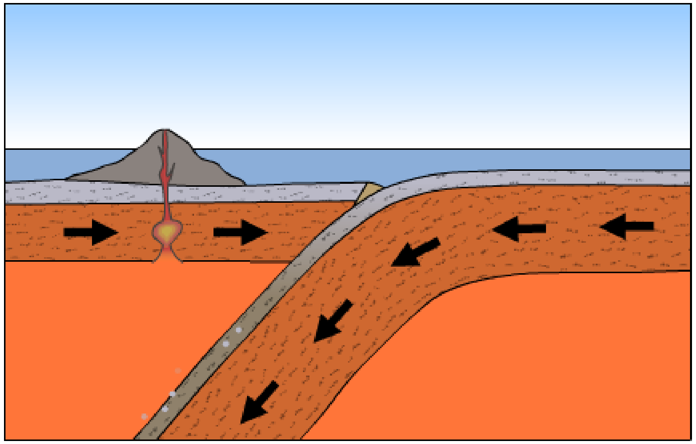
This is an igneous intrusion

Know where the magma comes from?
(Hint: not the liquid outer core!)

License Credits

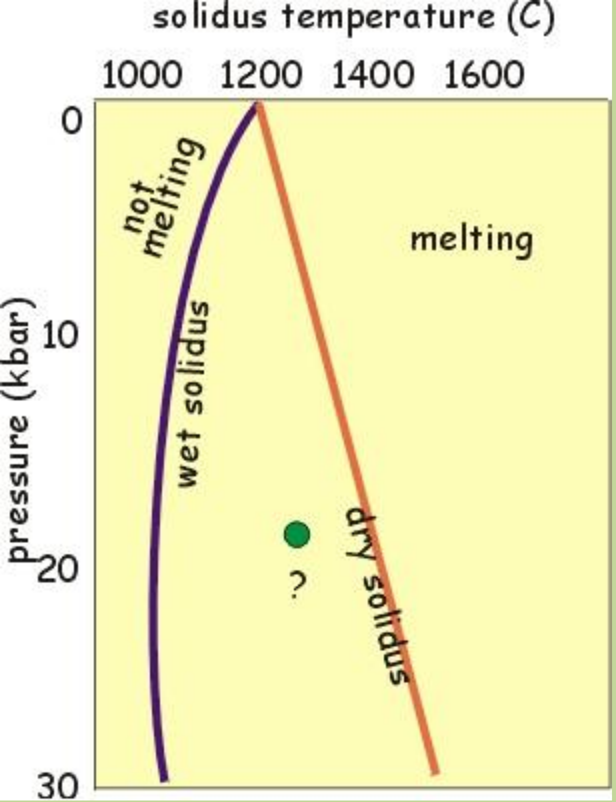
Plate Tectonics and mantle melting





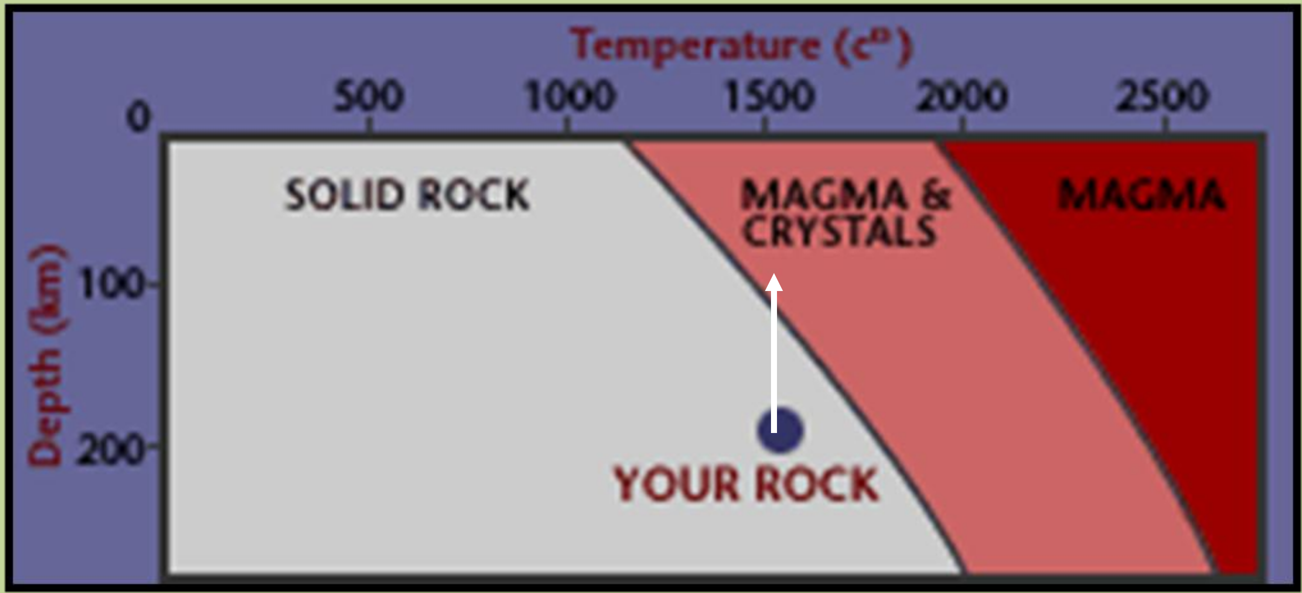
Decompression melting

Wet melting



Addition of water to minerals decreases melting point in the mantle (this is counterintuitive to many but has to do with altered geochemistry of hydrated minerals).

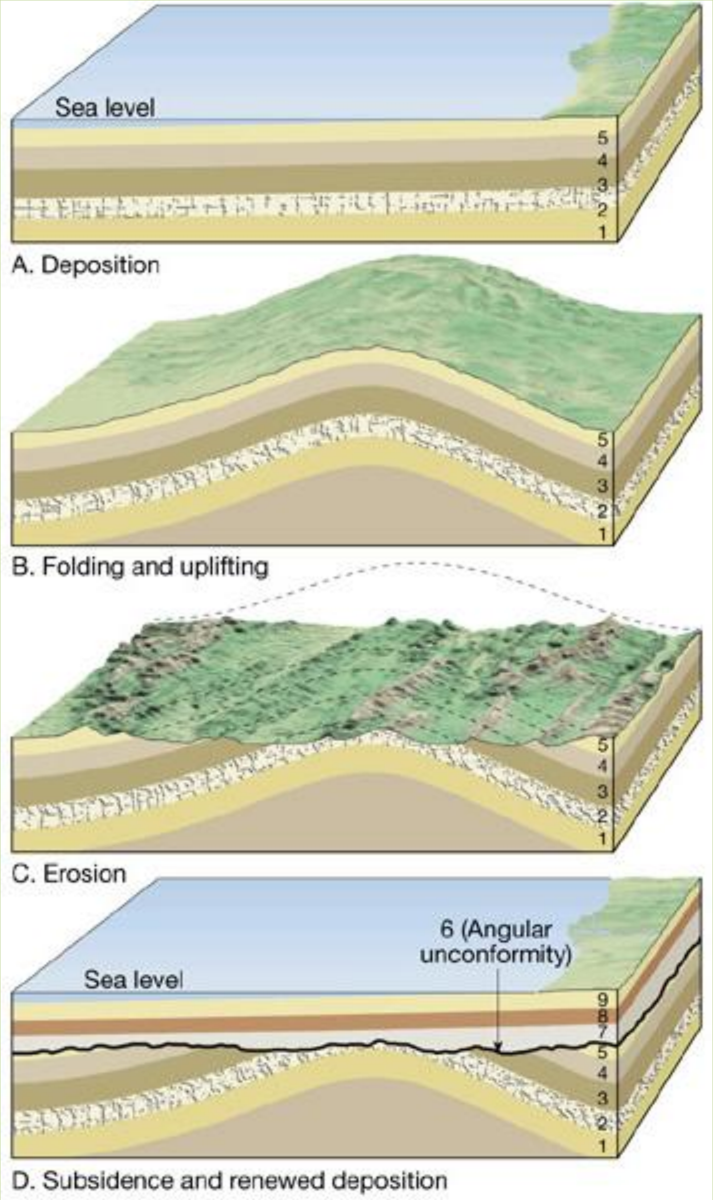
Decrease in pressure will also decrease melting point.



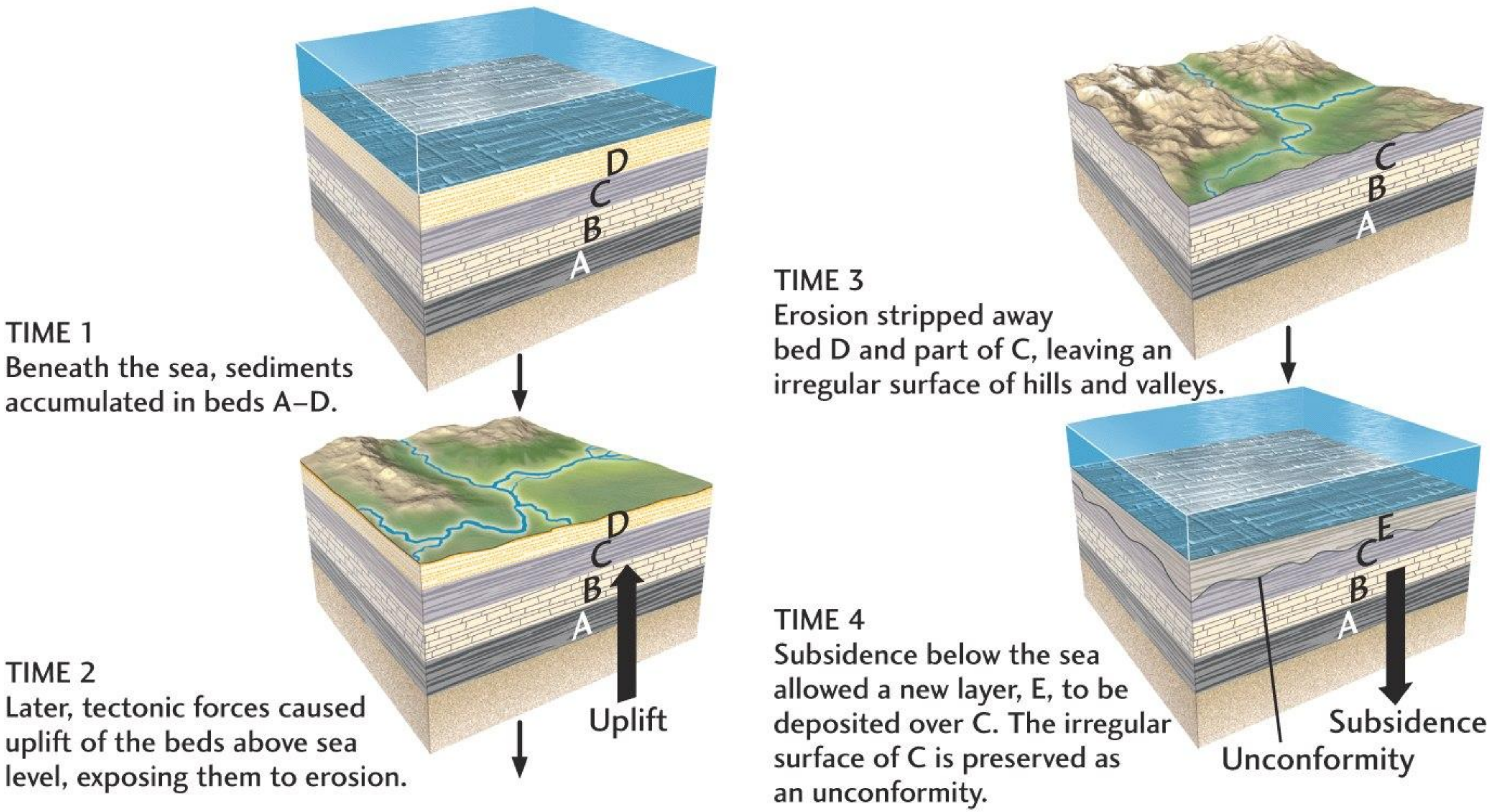
Unconformities

gaps in the geologic record that may indicate episodes of crustal deformation, erosion, and sea level variations.

(The individual names associated with each aren't as important to remember as the forensic evidence they provide of past events.)



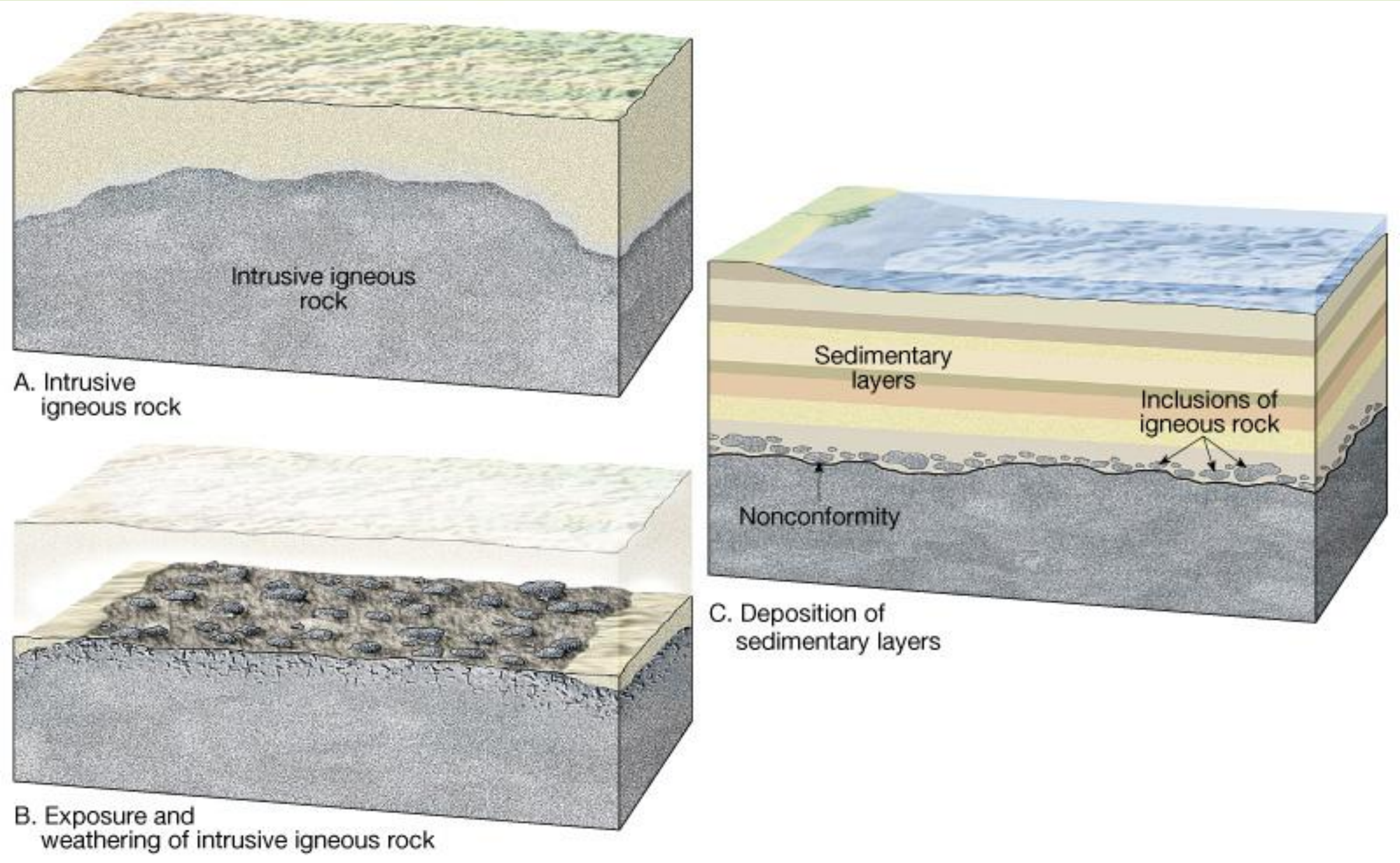
Angular unconformity



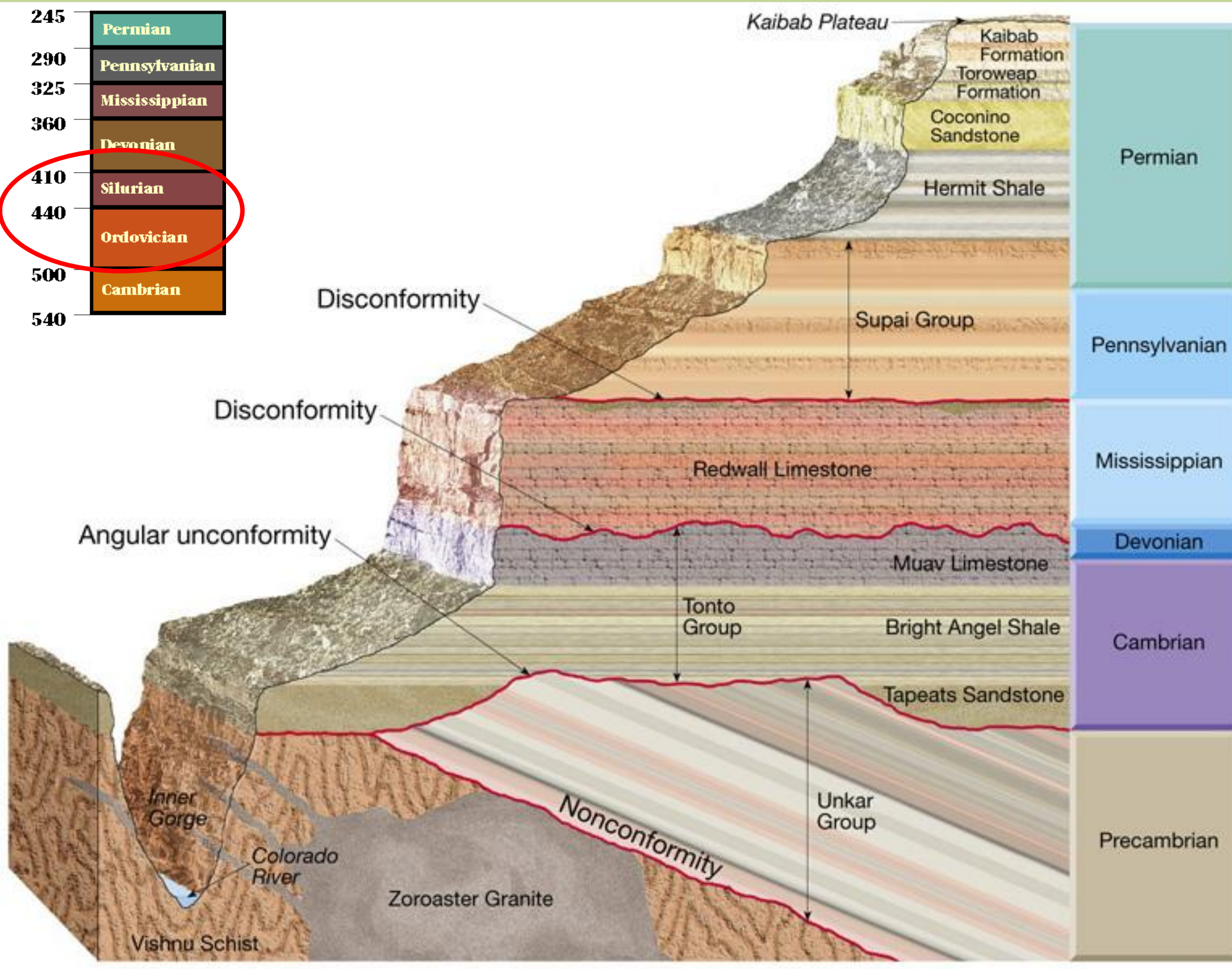
Disconformity – evidence of erosion by gap in time and erosional surface – unit D has been erased from the geological record

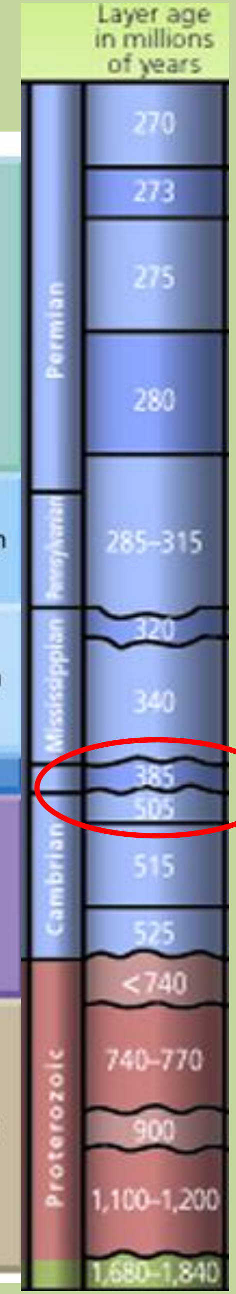
Nonconformity

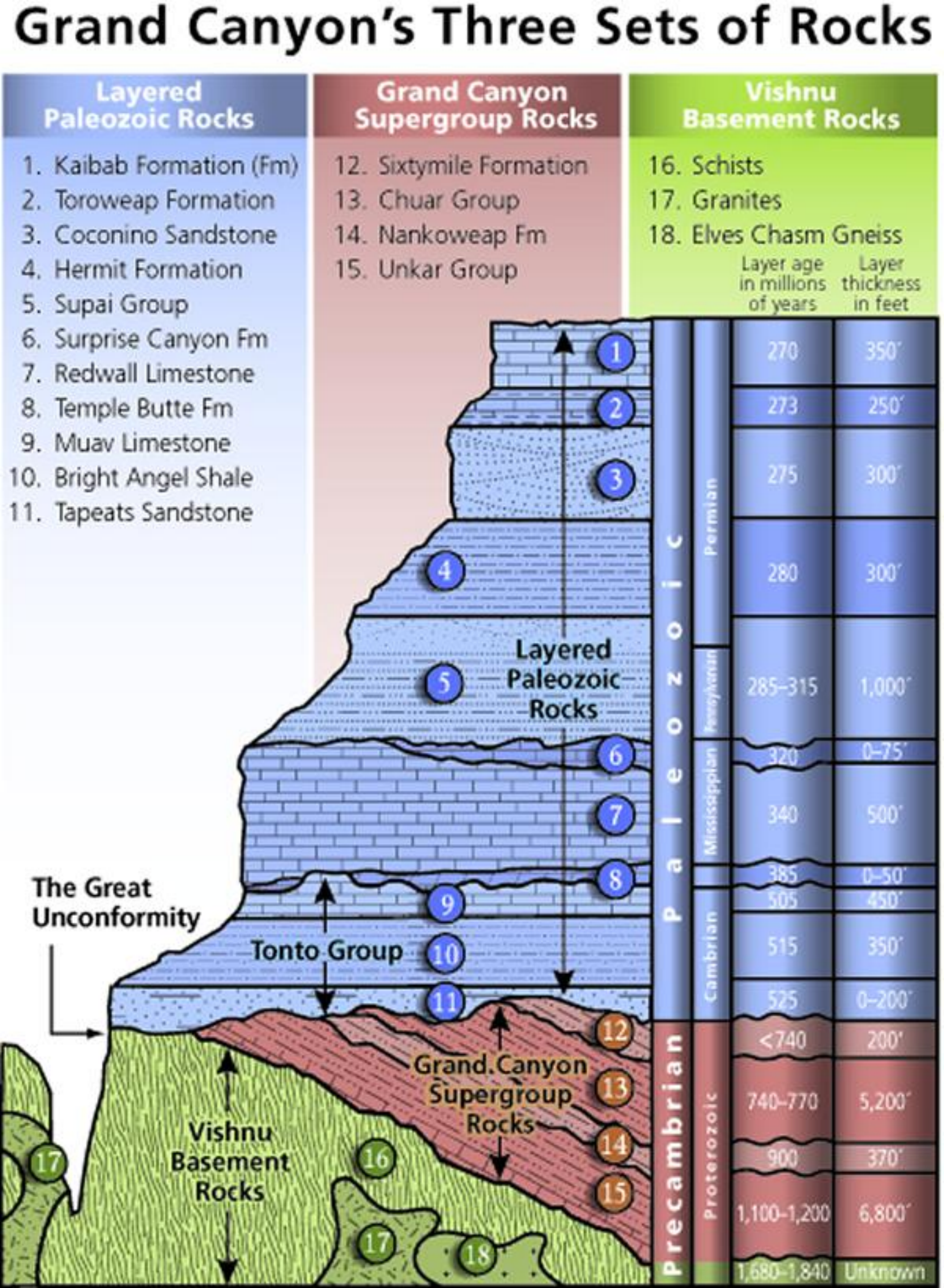
unconformities that separate igneous or metamorphic rocks from overlying sedimentary rocks



Simple layer cake geology…
at least for the last 500 MY







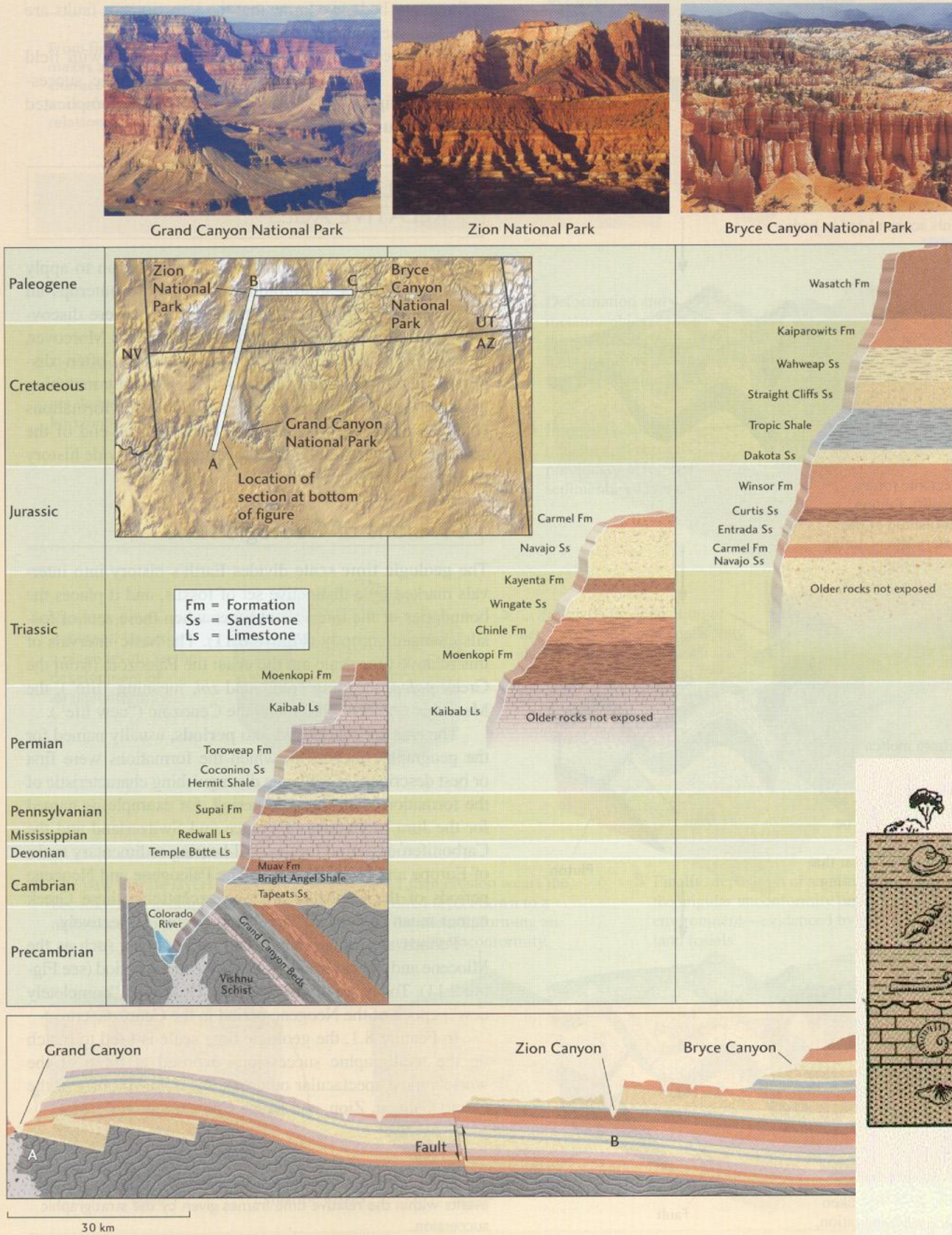
Really nice (lengthy) piece on the historical geology of the grand canyon – speaks to the challenges of absolute dating of sedimentary rocks and the elegant calibration of relative and absolute age dating:

http://www.nature.nps.gov/geology/parks/grca/age/

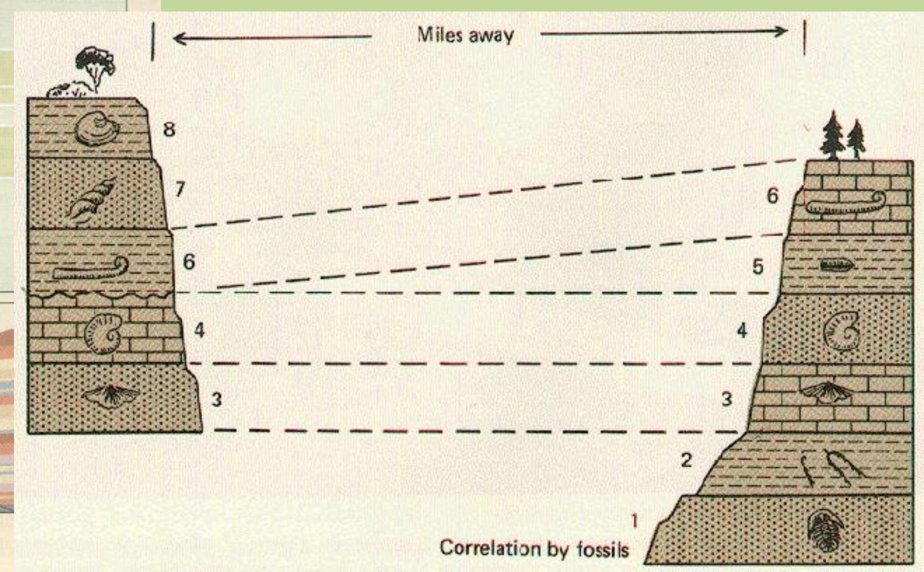
http://www.tectonics.caltech.edu/outreach/animations/sandbox_youtube.html

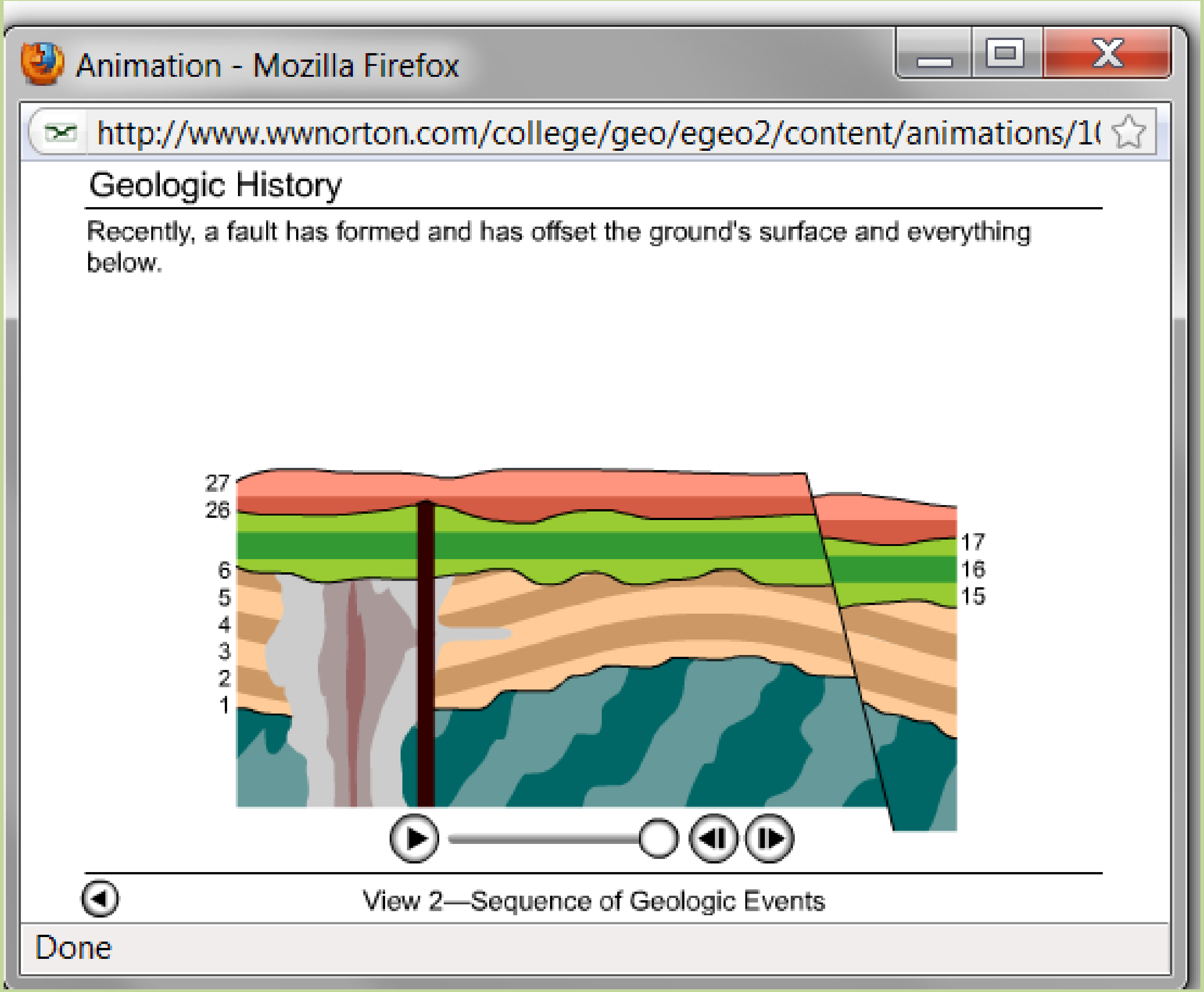
http://www.google.com/culturalinstitute/worldwonders/grand-canyon/

Can you see how Bryce, Zion and Grand Canyons are correlated?

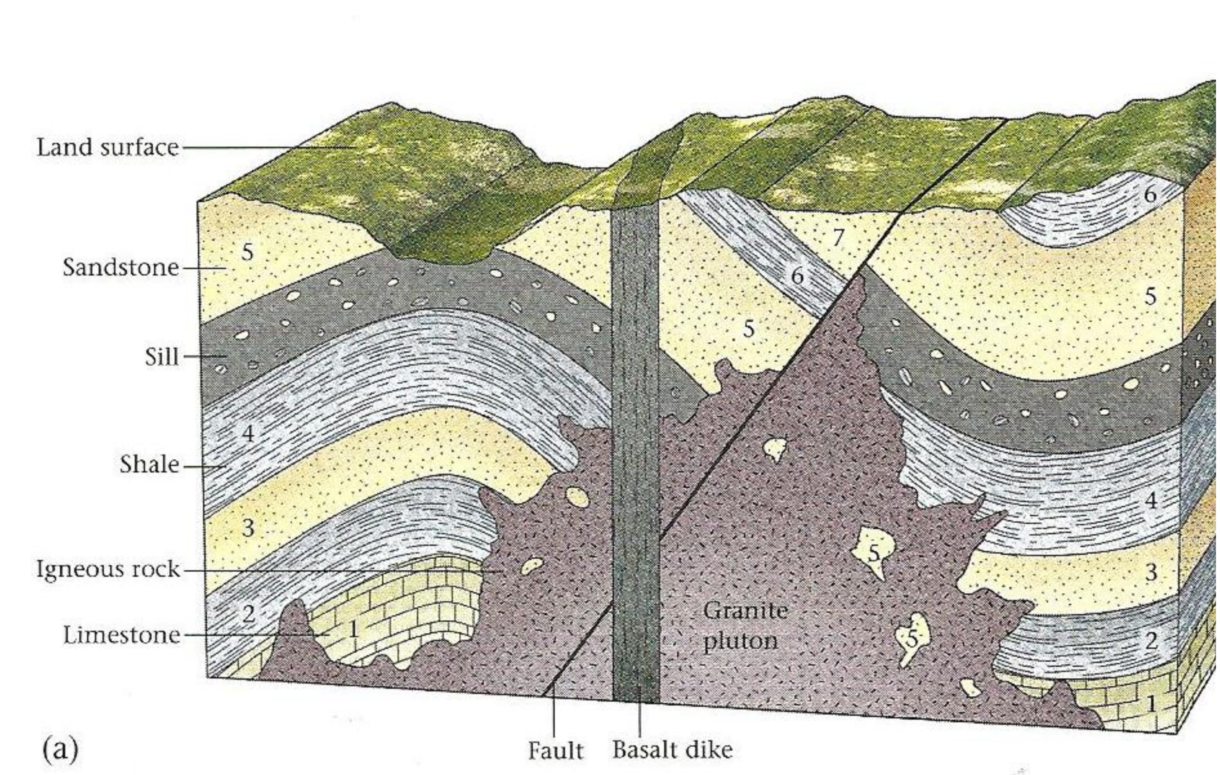


Correlation = filling in the gap between rock units in different geographic areas.

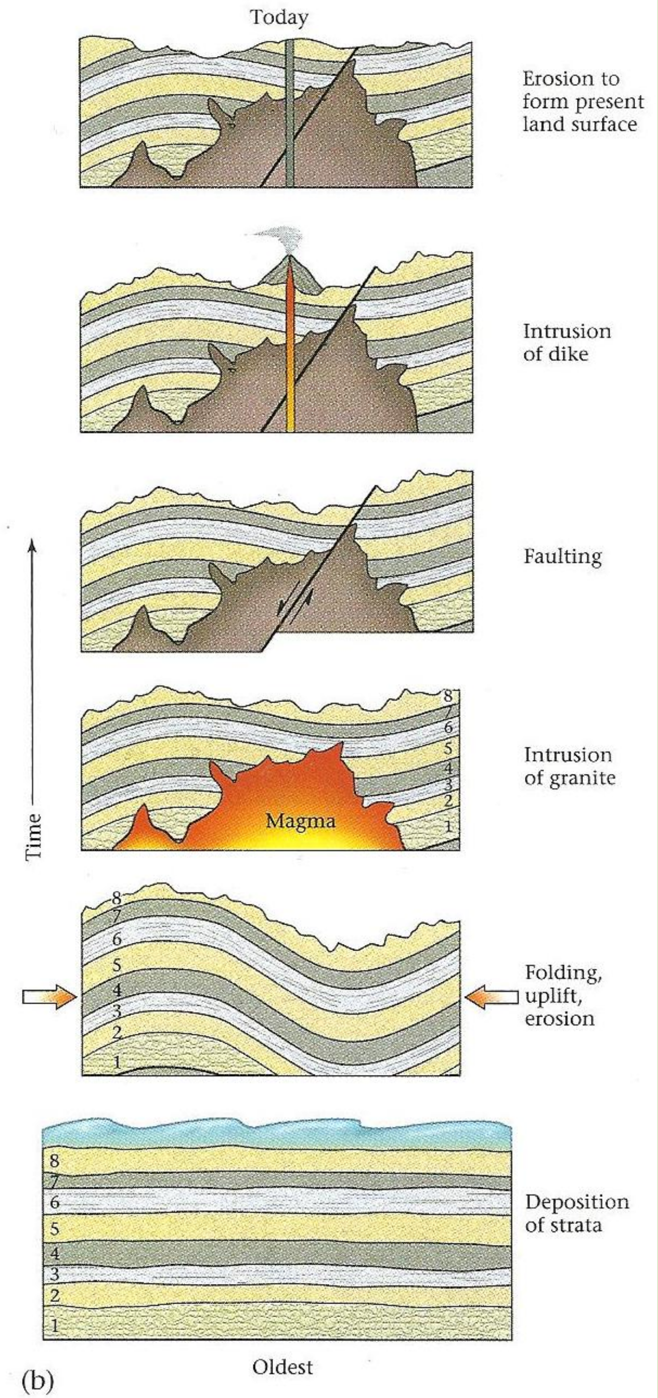




http://www.wwnorton.com/college/geo/egeo2/content/animations/10_1.htm

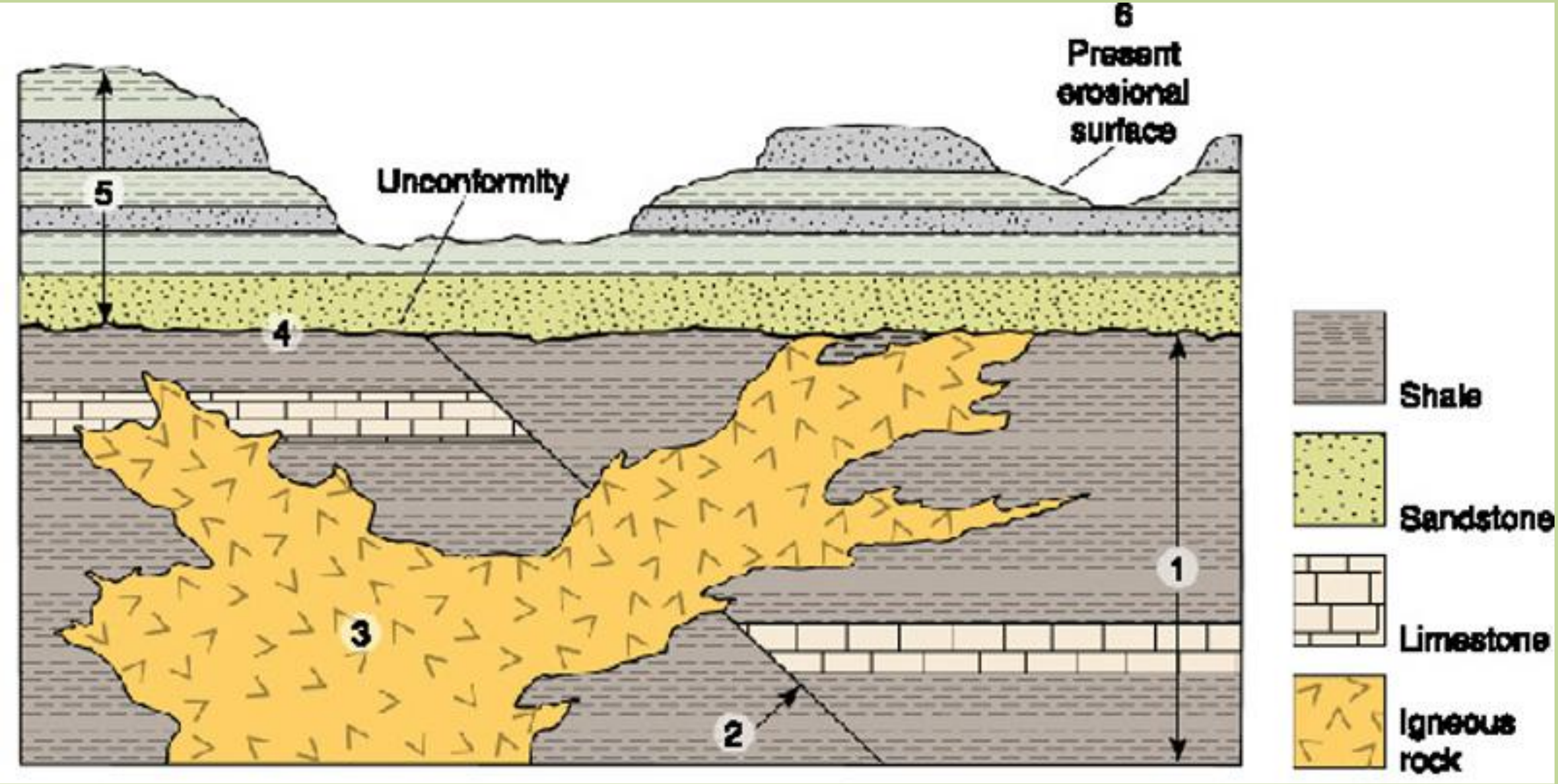


(a)



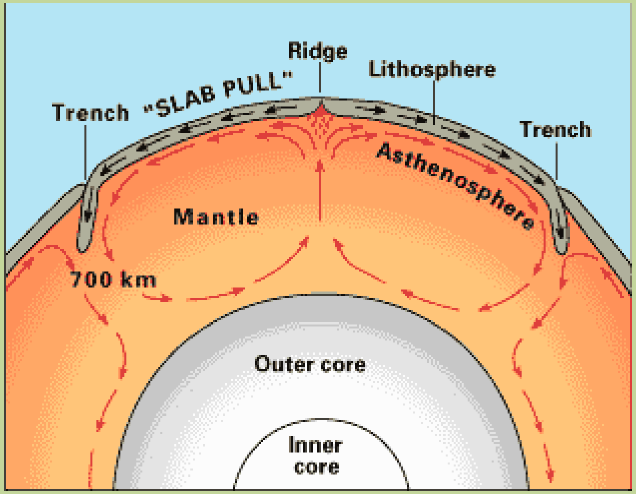
(b)

What happened here?

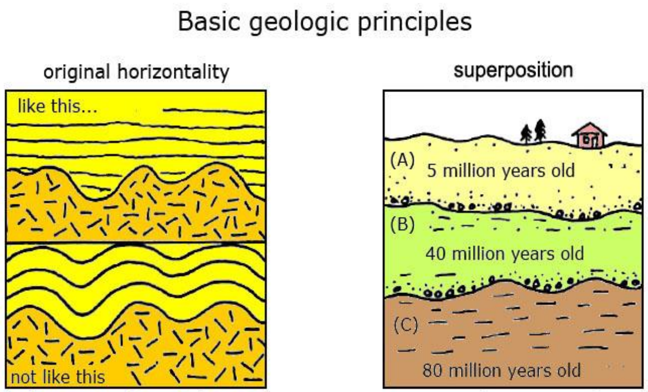

6
Present
erosional
surface
Unconformity
5
4
1
3
2
Shale
Sandstone
Limestone
Igneous
rock

EARTH in summary

•Convection in the mantle is necessary for plate tectonics to occur. We now believe that 'SLAB PULL' is the mechanism that sets the plates in motion.

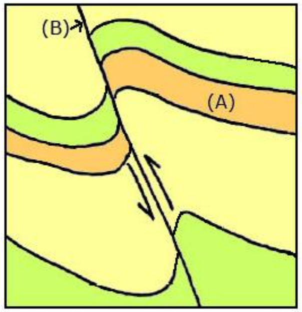


•Rocks are generally deposited in horizontal layers. Any fold/fault/intrusion/erosion that affects a layer or layers is younger than that layer.

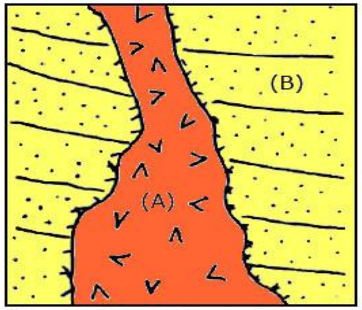


sediments are deposited horizontally filling in between higher areas first

younger sediments or rocks overlie older sediments or rocks

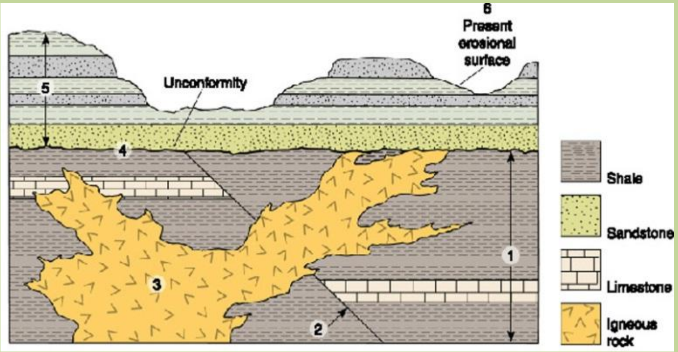


rocks are older than the forces that deform them: the rock (A) is older than the fold or fault (B)



older rocks are bisected by younger rocks; intrusion (A) is younger than the older sandstone formations (B)

•We know that #4 (unconformity) is younger than the #3 intrusion because the surface of the intrusion seems to have been eroded.



•We understand the age of the earth with the help of radiometric dating (not ^{14}C, it's half-life is too short), but with other long-lived radioisotopes such as ^{238}U - ^{206}Pb and ^{40}K - ^{40}Ar.

How do we know the earth's age?

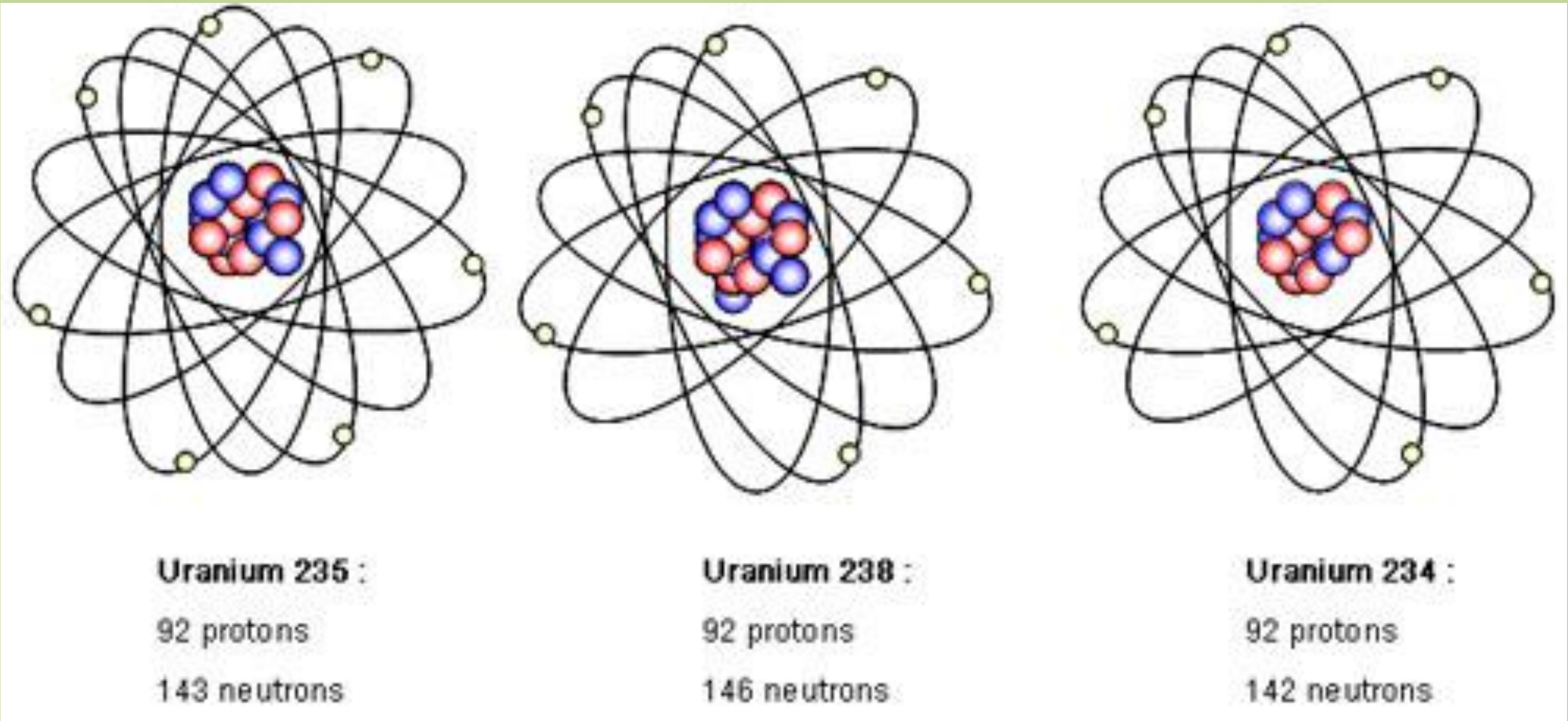
With the discovery of radioactive elements we finally have a way to determine the age of earth materials (absolute dating)

late 1800's —Henri Becquerel discovers radioactivity
Marie and Pierre Curie discover radioactive elements

It is radioactive decay that results in heat still being lost from earth's interior – the source of error in early calculations of earth's age suggested by Newton in the 1600's!

Image of Becquerel's photographic plate that was fogged by exposure to radiation from uranium salts. The shadow of a metal Maltese Cross placed between the plate and the uranium salts is clearly visible.

Isotopes of Uranium

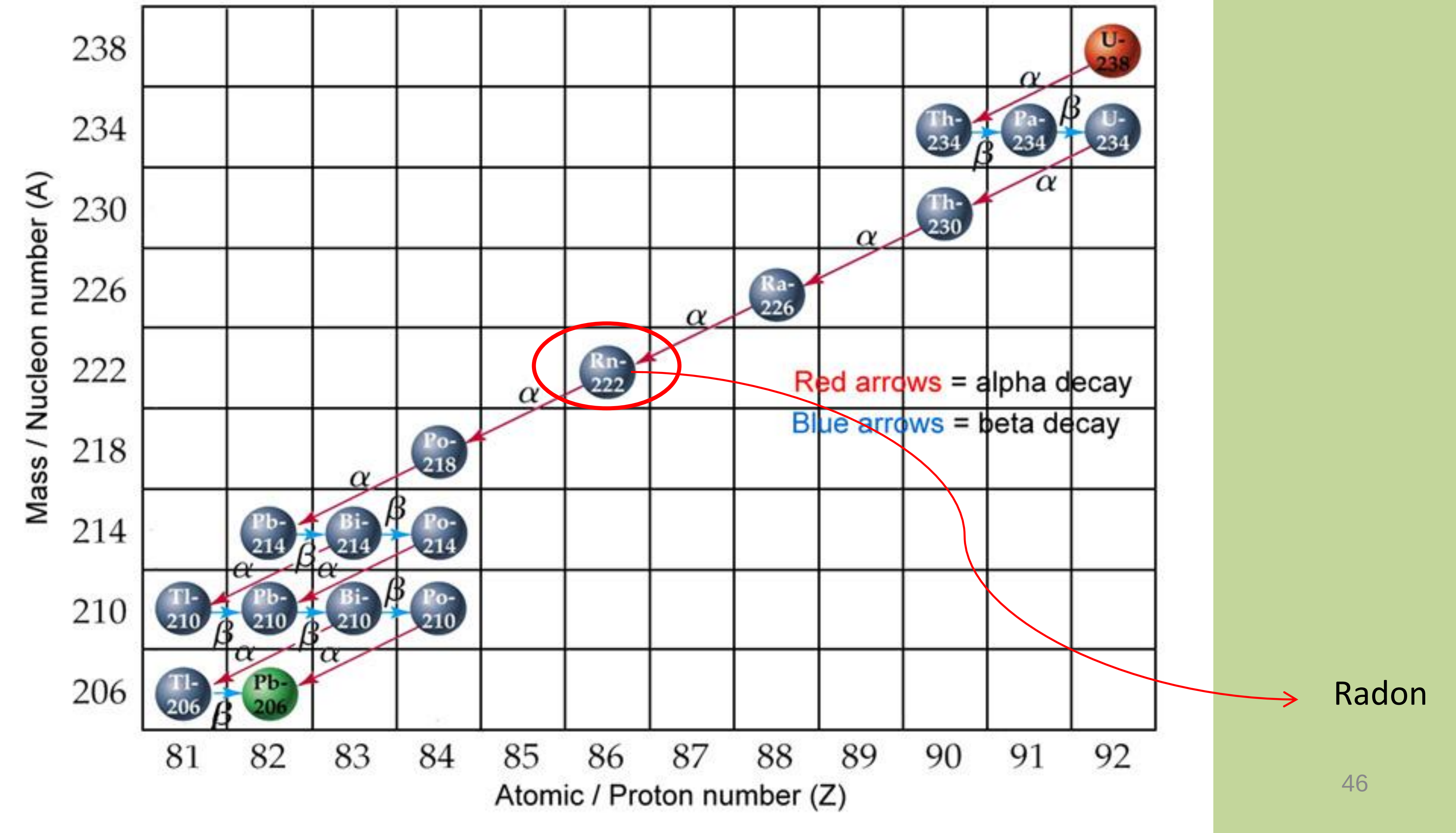


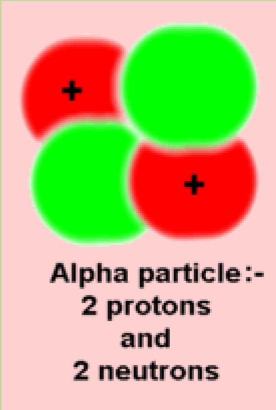
Uranium always has 92 protons (thus atomic # 92)

neutrons vary, creating ***isotopes***:
U-235, U-238, U-234

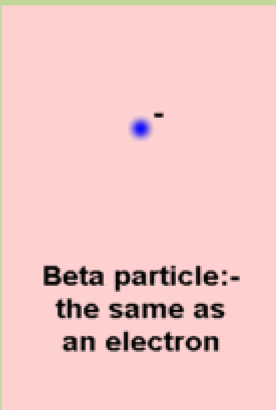
Radioactive Decay of Uranium

As an unstable atom tries to reach a stable form, energy and matter are released from the nucleus. This spontaneous change in the nucleus is called **radioactive decay**.

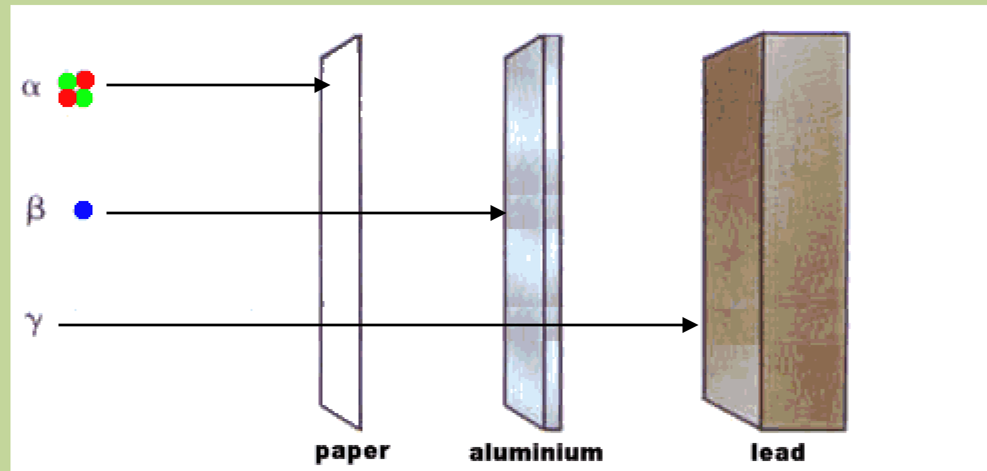


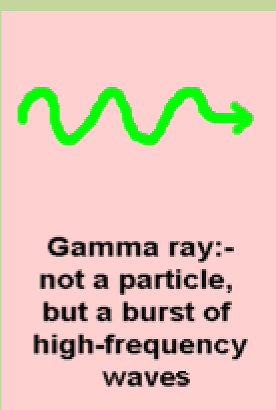


Slow & heavy
Stopped by piece of paper
(e.g. Radon)



Fast & light
Stopped by piece
of Al foil (e.g. C-14)





Waves rather than
particles, takes a
thick sheet of lead
to reduce them
(e.g. I-131, Cs-137)

Measuring ratios of parent/daughter isotopes in rocks enabled geologists to accurately date the earth at 4.6 BY!

TABLE 3-1 Useful Isotopes for Radiometric Dating

Radioactive parent isotope	Product of decay	Approximate half-life (years)	Useful range for dating (years)*
Rubidium 87	strontium 87	48.6 billion	10 million – 4.6 billion
Thorium 232	lead 208	14.0 billion	10 million – 4.6 billion
Uranium 238	lead 206	4.5 billion	10 million – 4.6 billion
Potassium 40	argon 40	1.3 billion	100,000 – 4.6 billion
Uranium 235	lead 207	0.7 billion	10 million – 4.6 billion
Carbon 14†	nitrogen 14	5730	50,000

*In general, the effective dating range for a radioactive isotope is 10 to 15 times its half-life.

†The carbon isotope is useful for dating organic matter and precipitates, such as bones and shells.

For example:

Zircon incorporates U and Th atoms into its crystalline structure, but strongly rejects Pb. Therefore we can assume that the entire Pb content of the zircon is formed by radioactive decay process.

Argon can escape molten magma, but cannot escape the crystal lattice once crystallized, so any argon present is formed by a radioactive decay process.

But HOW were the half-lives of each parent/daughter originally determined?

Decay rates have been directly *measured* over the last 40-100 years.

-In some cases a batch of the pure parent material is weighed and then set aside for a long time and then the resulting daughter material is weighed.

-In many cases it is easier to detect radioactive decays by the energy burst that each decay gives off. For this, a batch of the pure parent material is carefully weighed and then put in front of a Geiger counter or gamma-ray detector. These instruments count the number of decays over a period time.

For example, one gram of material contains over 10^{21} (1,000,000,000,000,000,000,000) atoms. Even if only one trillionth of the atoms decay in one year, this is still millions of decays, each of which can be counted by a radiation detector!

Uranium = 238 g/mol

Avogadro number or 6.02 * 10^23 atoms/mol

(6.02 * 10^23 atoms/mol) * 1 mol/238 g =

=2.53 * 10^21 atoms in a gram of Uranium

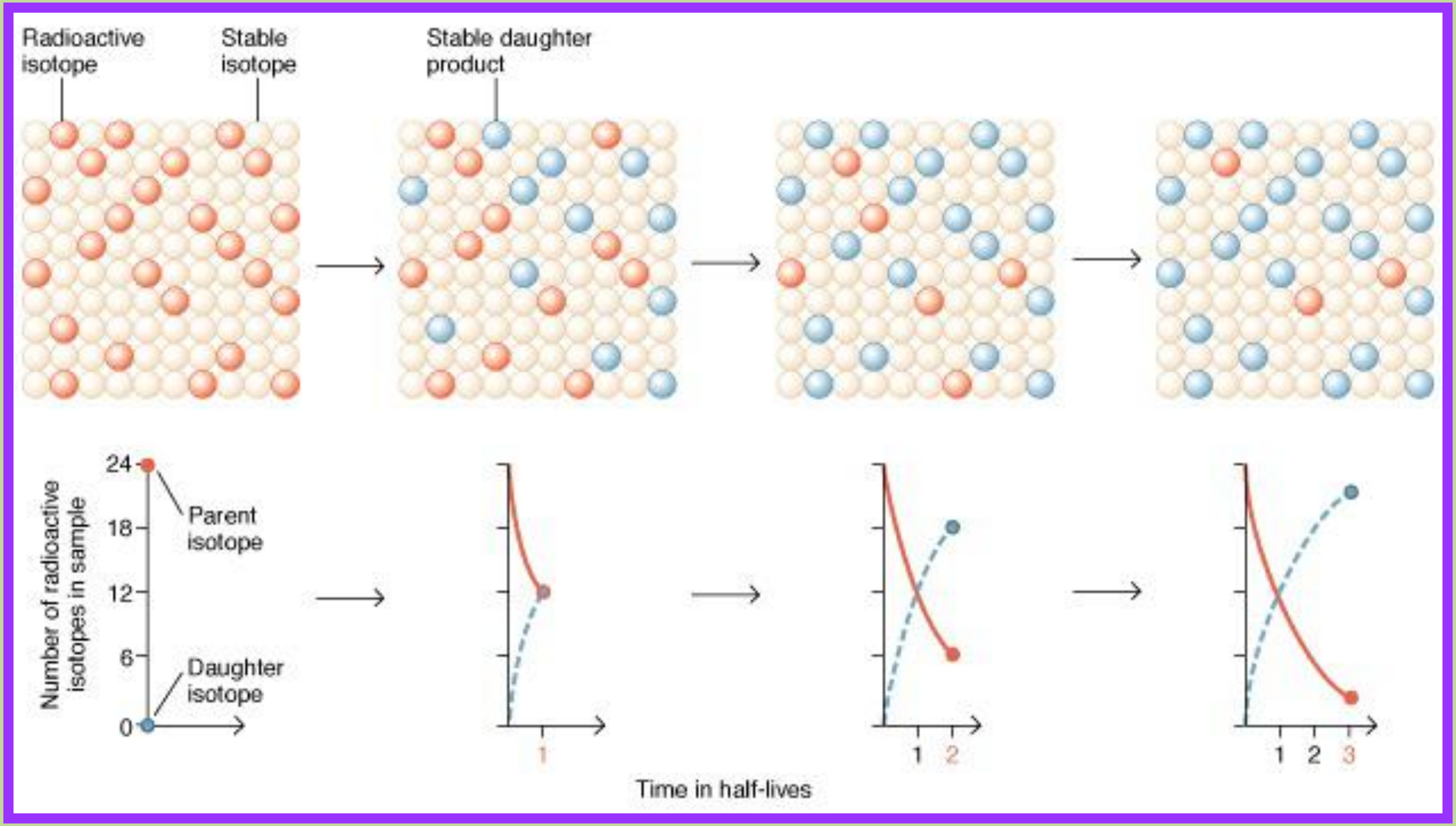
An 8-milligram sample of uranium decays at a rate of about 100 atoms per second.

To be sure of accuracy, dating results must be *reproducible* and so correlation between different isotope pairs confirm the age of a sample. For example, a study of the Amitsoq gneiss from western Greenland used five different radiometric dating methods to examine twelve samples and achieved agreement to within 22 Ma (million years) on an age of 3.64 BY.

Description	**Technique**	**Age (in billions of years)**
Amitsoq gneisses (western Greenland)	Rb-Sr isochron	3.70 +- 0.12
Amitsoq gneisses (western Greenland)	207Pb-206Pb isochron	3.80 +- 0.12
Amitsoq gneisses (western Greenland) (zircons)	U-Pb discordia	3.65 +- 0.05
Amitsoq gneisses (western Greenland) (zircons)	Th-Pb discordia	3.65 +- 0.08
Amitsoq gneisses (western Greenland) (zircons)	Lu-Hf isochron	3.55 +- 0.22
Sand River gneisses (South Africa)	Rb-Sr isochron	3.79 +- 0.06

Good science is *measurable and reproducible*. Radiometric dating meets both of these criteria.

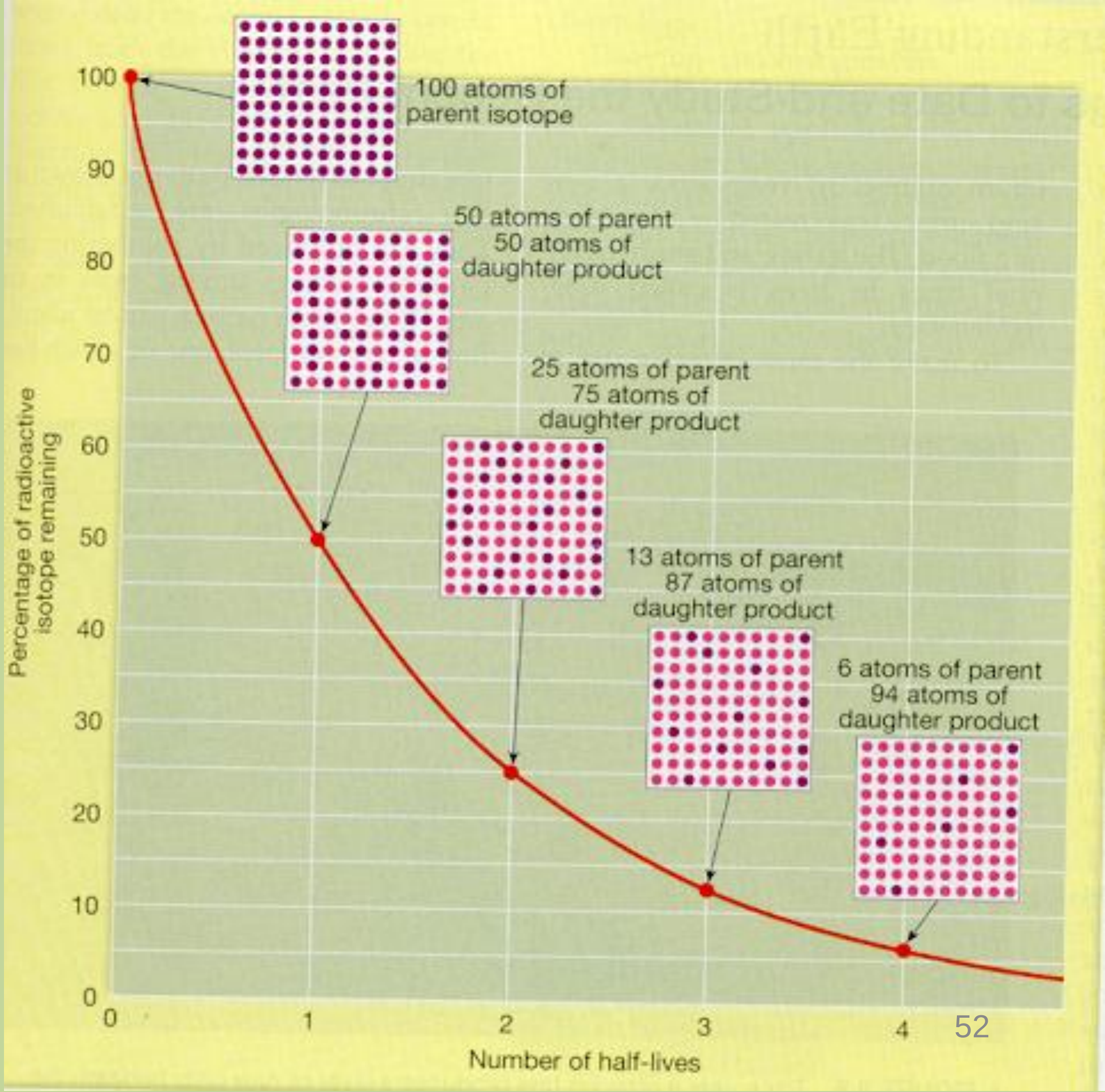
A half-life is the time it takes half of the parent isotopes to decay to daughter isotopes



How do we date rocks based on known half-lives?

Determine ratio of parent/daughter

50/50	= 1 half life
25/75	= 2 half lives
13/87	= 3 half lives

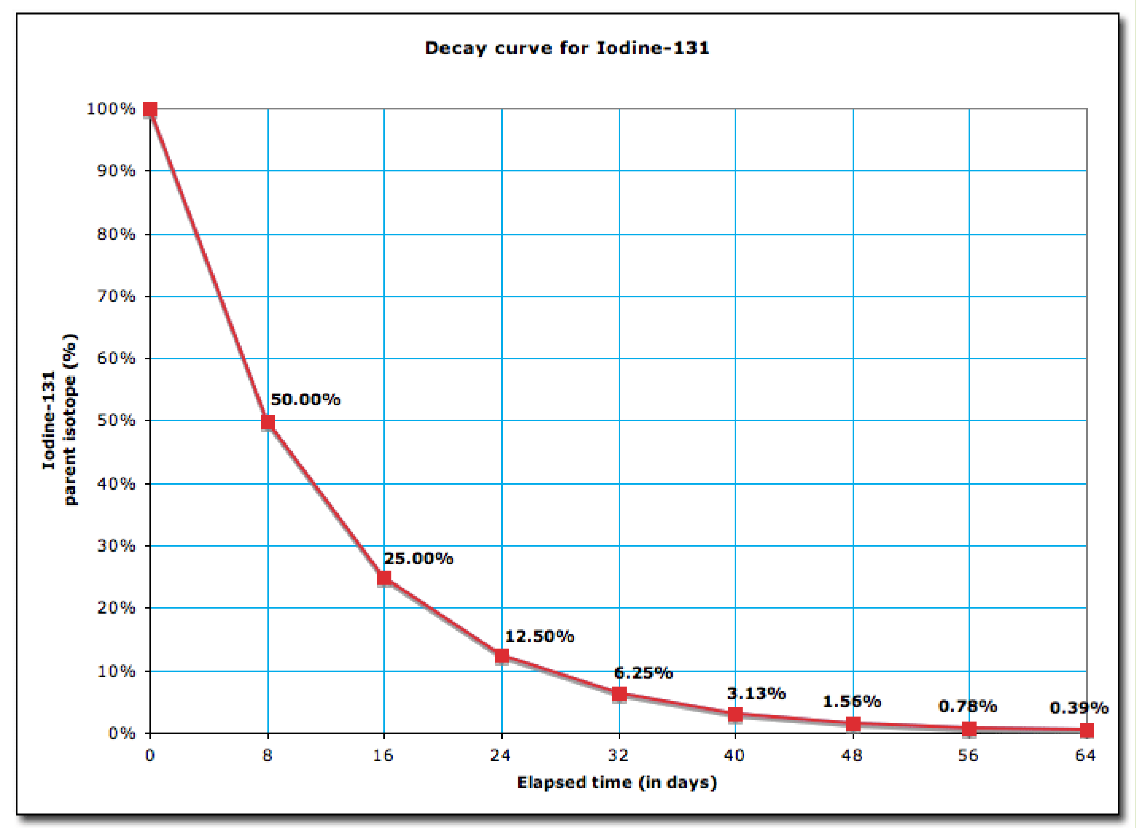


Example:

A radioactive element has a half life of 1 MY currently contains 13 % parent and 87 % daughter. How old would this sample be?

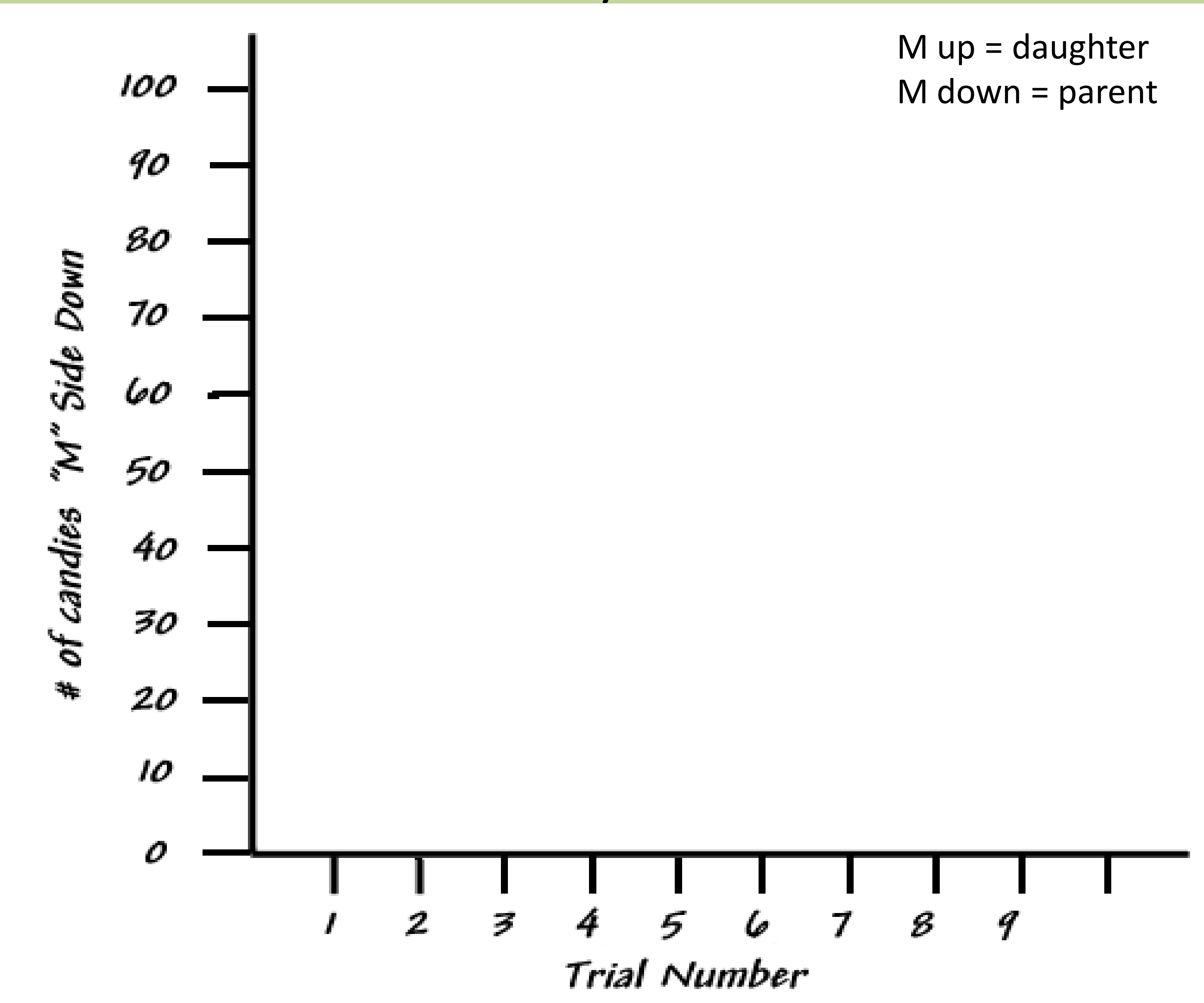
In the aftermath of the Honshu earthquake and Fukushima nuclear power plant meltdown, the news media talked quite a bit about radioactive isotopes of iodine (I-131) and cesium (Cs-137) which were released during the meltdown.

a. According to the figure below, what is the half-life of I-131?



b. Cs-137 has a half life of 30 years (figure does not include data on Cs-137, only I-131). How long would it take to reach a concentration that is 12.5% parent Cs-13 and 87.5% daughter?

Radioactive decay of m&mium



http://serc.carleton.edu/NAGTWorkshops/time/activities/60525.html