Rocks as time machines: principles of geologic time

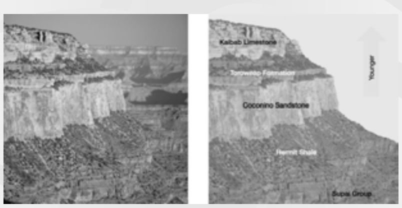
Determining geological ages

• Relative dating – placing rocks and events in their proper sequence of formation

• Numerical (absolute) dating – specifying the actual number of years that have passed since an event occurred (known as absolute age dating)

Principles of relative dating

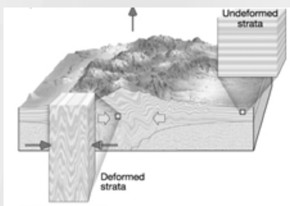
- Law of superposition
  - Developed by Nicolaus Steno in 1669
  - In an undeformed sequence of sedimentary rocks (or layered igneous rocks), the oldest rocks are on the bottom



Superposition is well illustrated by the strata in the Niagara Gorge

Principles of relative dating

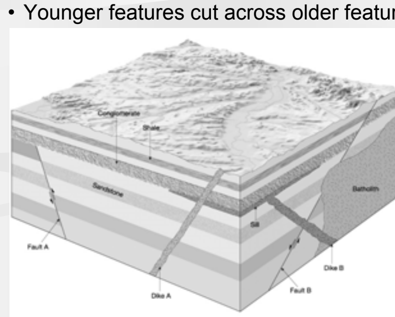
- Principle of original horizontality
  - Layers of sediment are generally deposited in a horizontal position
  - Rock layers that are flat have not been disturbed



Undisturbed (flat-lying)

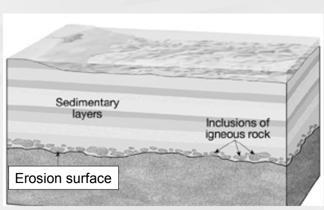
Highly disturbed (deformed)

- Principle of cross-cutting relationships
  - Younger features cut across older features



(e.g. fault B is younger than fault A, which is younger than the layer labelled “sandstone”)

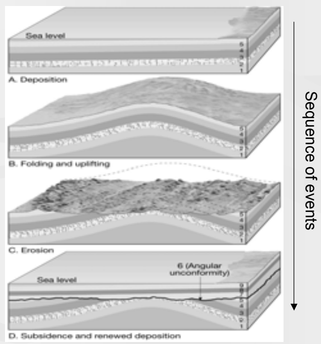
- Inclusions
  - An inclusion is a piece of rock that is enclosed within another rock
  - Rock containing the inclusion is younger



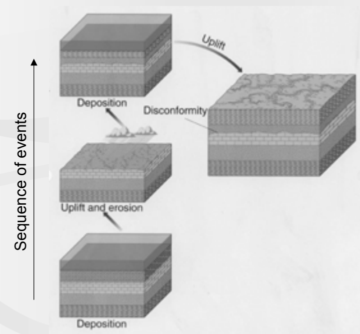
Unconformity

- An unconformity is a break in the rock record produced by erosion and/or nondeposition of rock units
- Represents “lost time”
- Types of unconformities
  - Angular unconformity – tilted rocks are overlain by flat-lying rocks
  - Disconformity – strata on either side of the unconformity are parallel
  - Nonconformity – metamorphic or igneous rocks in contact with sedimentary strata

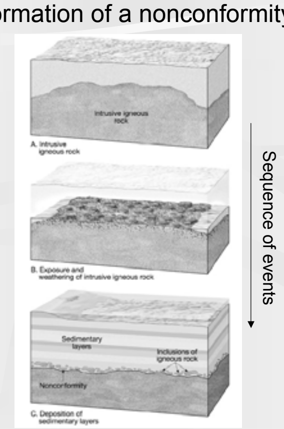
Formation of an angular unconformity



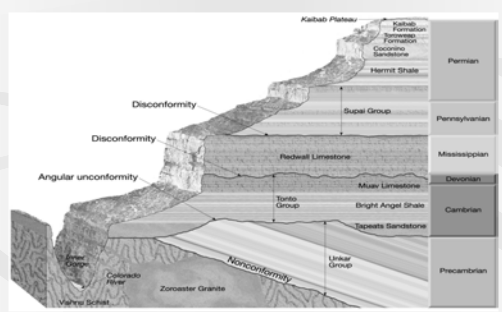
Formation of a disconformity



Formation of a nonconformity



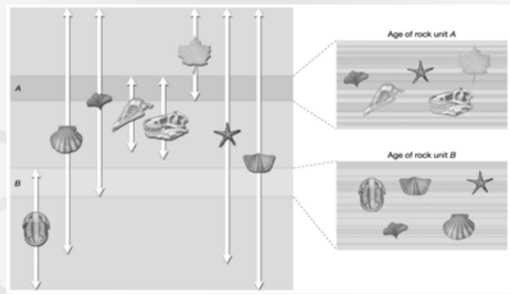
Several unconformities are present in the Grand Canyon



Correlation of rock layers

- Matching of rocks of similar ages in different regions is known as correlation
- Correlation often relies upon fossils
    - William Smith (late 1700s) noted that sedimentary strata in widely separated area could be identified and correlated by their distinctive fossil content
    - Principle of fossil succession – fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content

Determining the ages of rocks using fossils



Note that each fossil has its own range of occurrence, and so strata of a particular age can be recognized from its fossils

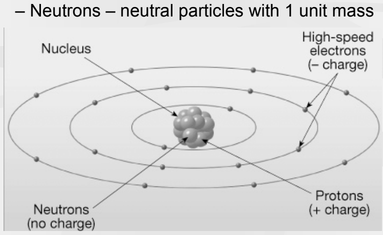
Principles of numerical (absolute) dating

- To understand this, we must look at the basic structure of an atom

Nucleus (a cluster of protons and neutrons)

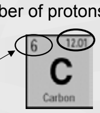
– Protons – positively charged particles with 1 unit mass

– Neutrons – neutral particles with 1 unit mass



plus Electrons - negatively charged particles with no mass that orbit the nucleus

- Basic atomic structure
    - Atomic number
        - An element's identifying number
        - Equal to the number of protons in the atom's nucleus
    - Mass number
        - Sum of the number of protons and neutrons in an atom's nucleus



Atomic mass (12 = 6 protons + 6 neutrons)

Atomic number (6 protons)

This is Carbon-12, as seen in the standard periodic table

- Isotope
    - Variant of the same parent atom
    - Differs in the number of neutrons
    - Results in a different mass number than the parent atom
    - For example, carbon-12 has 6 protons and 6 neutrons, whereas carbon-14 has 6 protons and 8 neutrons

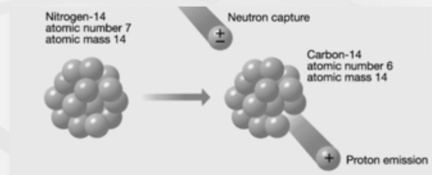
- Radioactive decay
  - A process in which parent atoms spontaneously change in structure to produce daughter atoms and energy
  - In some cases, this decay produces a different isotope (atoms of the same element with a different number of neutrons)
  - In other cases, this decay produces an entirely different element via loss or gain of protons, neutrons or electrons

A Familiar Example: Carbon-14

Carbon-12 (with 6 protons and 6 neutrons) is the most common isotope of carbon.

Carbon-14 is an rarer isotope of carbon that is produced by the bombardment of nitrogen-14 (with 7 protons and 7 neutrons) by rogue neutrons

Nitrogen-14 gains 1 neutron but loses 1 proton, changing it to carbon-14 (atomic mass stays the same, but atomic number changes)

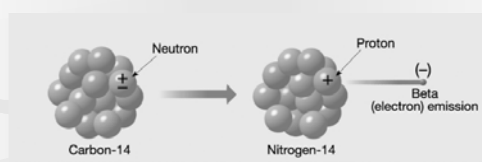


Carbon-14 becomes incorporated into carbon dioxide, along with the more common carbon-12, which circulates in the atmosphere and is absorbed by living things (all organisms, including us, contain a small amount of carbon-14)

As long as the organism is alive, the proportions of carbon-12 and carbon-14 remain constant due to constant replacement of any carbon-14 that has decayed

But…

When the organism dies, the amount of carbon-14 gradually decreases as it decays to nitrogen-14 by the loss of an electron (so one neutron is changed to a proton)



Number of protons: 6
Number of neutrons: 8

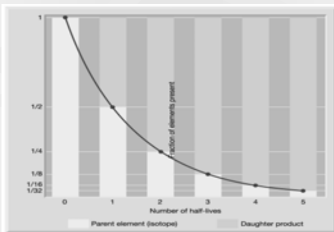
Number of protons: 7
Number of neutrons: 7

By comparing the proportions of carbon-14 and carbon-12 in a sample of organic matter, and knowing the rate of conversion, a radiocarbon date can be determined

Rate of radioactive decay

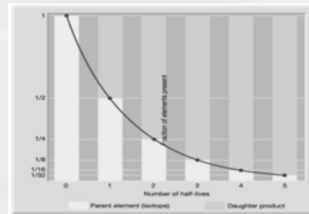
Rates of decay are commonly expressed in terms of half-life

Half life is the time required for half of the atoms in a sample to decay to daughter atoms



Half-life of carbon-14 is 5,730 years

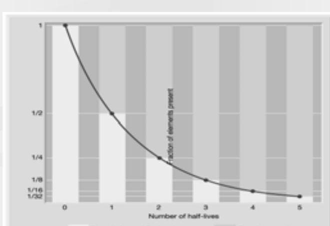
This means:



If parent:daughter ratio is 1:1 (1/2 original amount of parent remaining) one half-life has passed
If parent:daughter ratio is 1:3 (1/4 original amount of parent remaining) two half-lives have passed
If parent:daughter ratio is 1:7 (1/8 original amount of parent remaining) three half-lives have passed
If parent:daughter ratio is 1:15 (1/16 original amount of parent remaining) four half-lives have transpired

In other words, each half-life represents the "halving" of the preceding amount of parent isotope

So:
1. If the half-life of carbon-14 is 5730 years
2. If 1/16 of the original amount of parent remains…



Then we can deduce that…
1. 4 half lives have passed
2. The age of the sample is 4 X 5730 years = 22, 920 years !

Other useful radioisotopes

In addition to Carbon-14, other radioisotopes can be used for dating (very old samples must rely on radioisotopes with longer half lives).

Radioactive Parent	Stable Daughter Product	Currently Accepted Half-life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	713 million years
Thorium-232	Lead-208	14.1 billion years
Rubidium-87	Strontium-87	47.0 billion years
Potassium-40	Argon-40	1.3 billion years

All of the above radioisotopes occur in minerals found in rocks (generally igneous rocks).

Example: Potassium-Argon

89% of potassium-40 decays to calcium-40
(by electron loss)
11% of potassium-40 decays to argon-40
(by electron gain)

Calcium-40 is not useful in dating (can't be distinguished from other isotopes of calcium that may have been present when the rock formed)

But

Argon-40 is a gas that doesn't combine with other elements and becomes trapped in crystals (so amount produced by decay can be measured)

Potassium-argon clock starts when potassium-bearing minerals (e.g. some feldspars) crystallize from a magma

The minerals that have crystallized from magma formed will contain potassium-40 but not argon-40

Potassium-40 decays, producing argon-40 within the crystal lattice

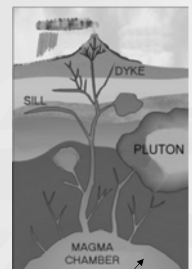
All daughter atoms of argon-40 come from the decay of potassium-40

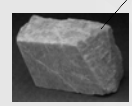
Datable minerals preserved in:

Ash deposits

Lava flows

Igneous intrusions (dykes, sills, plutons)





Argon-40, produced by decay of potassium-40 accumulates in mineral crystals

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Igneous rocks, both intrusive and extrusive, come from magma- potassium minerals can be dated

To determine age, the potassium-40/argon-40 ratio is measured and the half life of K-40 is applied

So now, we have a means of bracketing periods of time in rock sequences, and can apply absolute dates to important events in earth history

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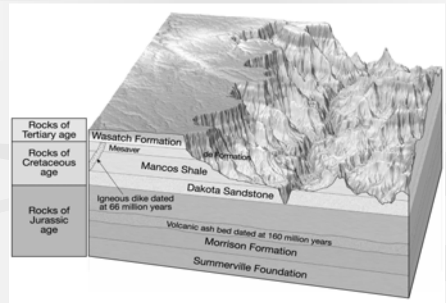
Using radioactivity in dating

- Difficulties in dating the geologic time scale
  - Not all rocks can be dated by radiometric methods
    - Grains comprising clastic sedimentary rocks are not the same age as the rock in which they formed (have been derived from pre-existing rocks)
    - The age of a particular mineral may not necessarily represent the time when the rock formed if daughter products are lost (e.g. during metamorphic heating)
    - To avoid potential problems, only fresh, unweathered rock samples should be used

Importance of radiometric dating:

- Rocks from several localities have been dated at more than 3 billion years
- Confirms the idea that geologic time is immense

Dating sedimentary strata using radiometric dating



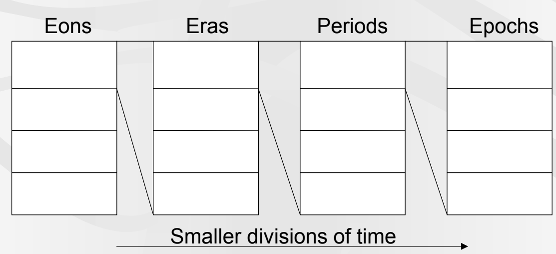
Dating of minerals in ash bed and dyke indicates that the sedimentary layers of the Dakota Sandstone through to the Mesaverde Formation are between 160 and 60 million years old

Geologic time scale

- A product of both relative and absolute dating is the geological time scale
- The geologic time scale is a “calendar” of Earth’s 4.5 billion year history
  - Subdivides geologic history into units for easy reference
  - Originally created using relative dates
  - Absolute dates later applied with development of radiometric dating techniques

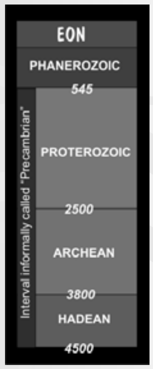
Structure of Geologic Time Scale

- Eon – the greatest expanse of time
- Era – subdivision of Eon
- Period – subdivision of Era
- Epoch – subdivision of Period

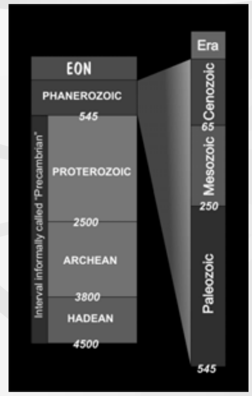


Geologic time scale

- Eons
  - Phanerozoic ("visible life") – the most recent eon, began about 545 million years ago
  - Proterozoic
  - Archean
  - Hadean – the oldest eon



Geologic time scale



Era – subdivision of an eon

Eras of the Phanerozoic eon

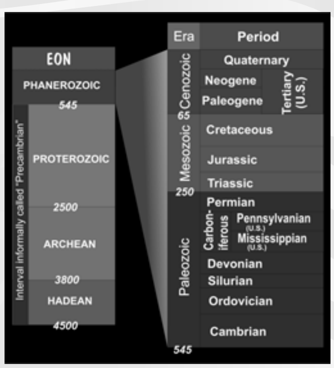
Cenozoic ("recent life")
Mesozoic ("middle life")
Paleozoic ("ancient life")

Period – subdivision of an era

Names derived from:

1. "Type" localities (e.g. Jurassic, named after Jura Mountains)
2. Rock characteristics (e.g. Carboniferous, coal-rich rocks in the UK)
3. From various whims (e.g. Silurian, named after Celtic tribe of Wales)

-in other words, a big mess !



Know this !

Importance of Dating Rocks

Rocks contain valuable information on physical, chemical, and biological processes in the Earth's past

It is only through relative and numerical dating that we can put these processes in the context of time

Bottom line: Theories can be made on what might have happened in the Earth's past, but it is geology that tells us what did happen. Rocks are our only basis for interpreting the Earth's history !

End of Lecture