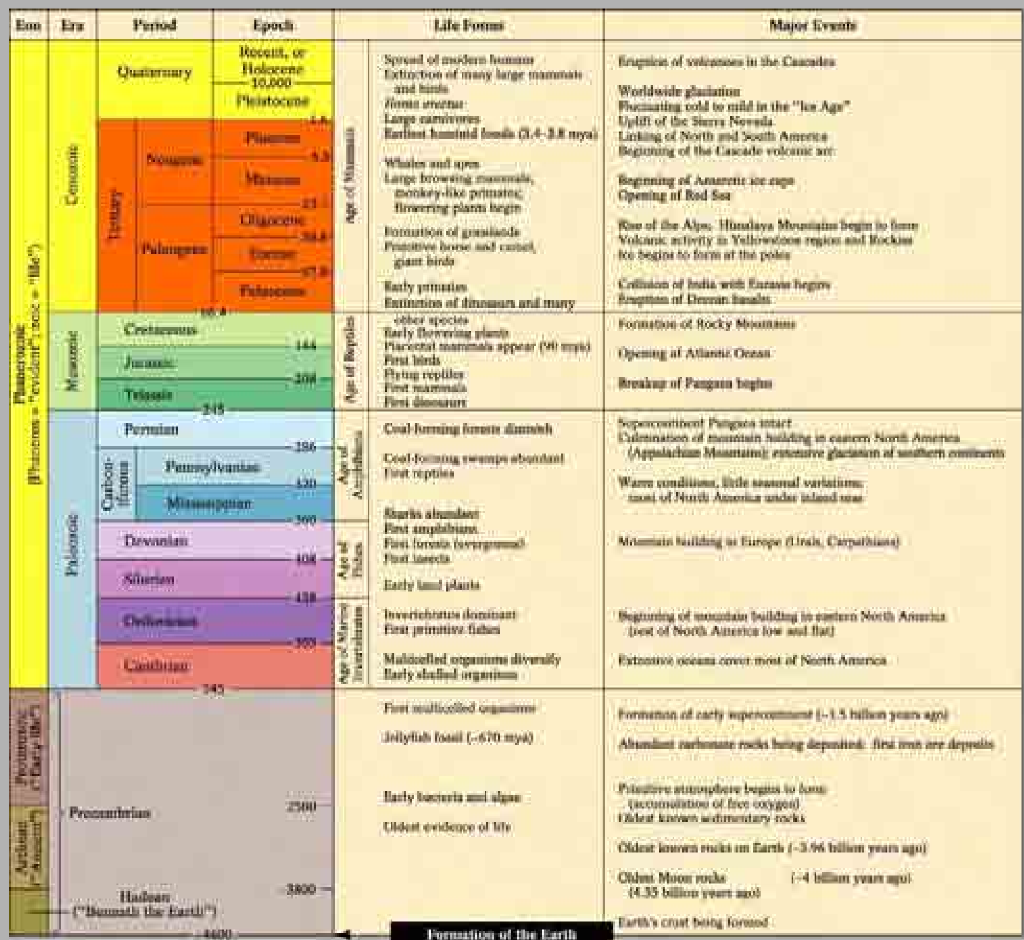
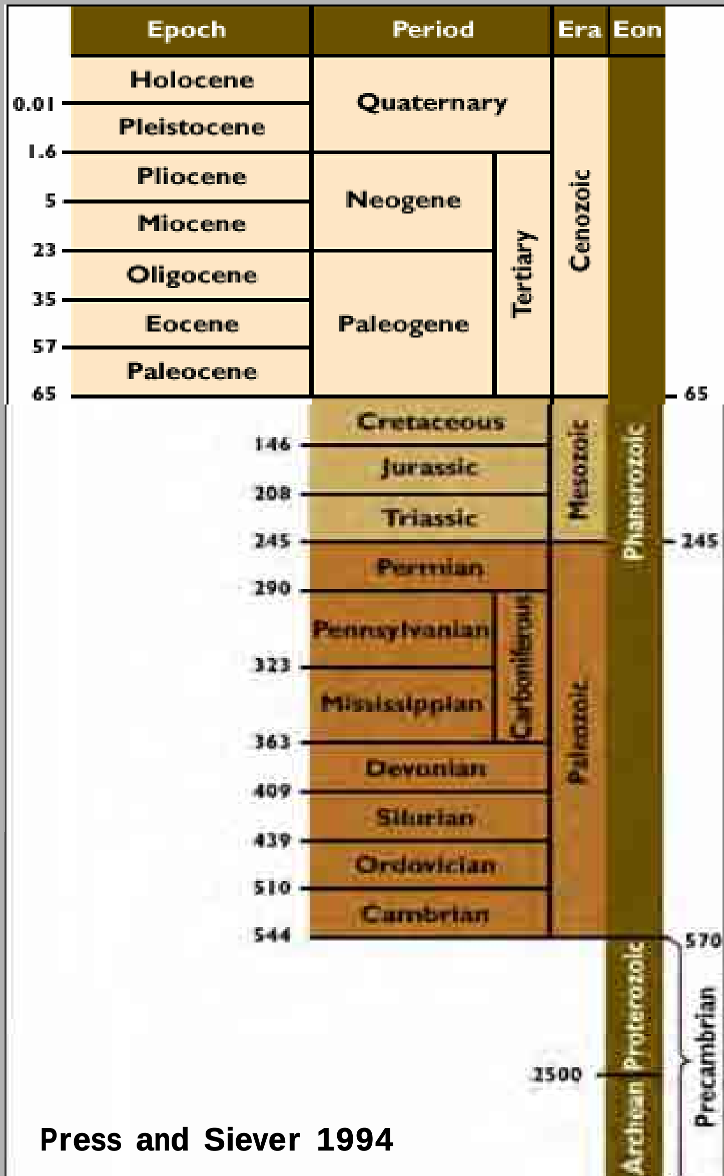
Geological Time



Murck and Skinner, 1999

Geological Time Scale

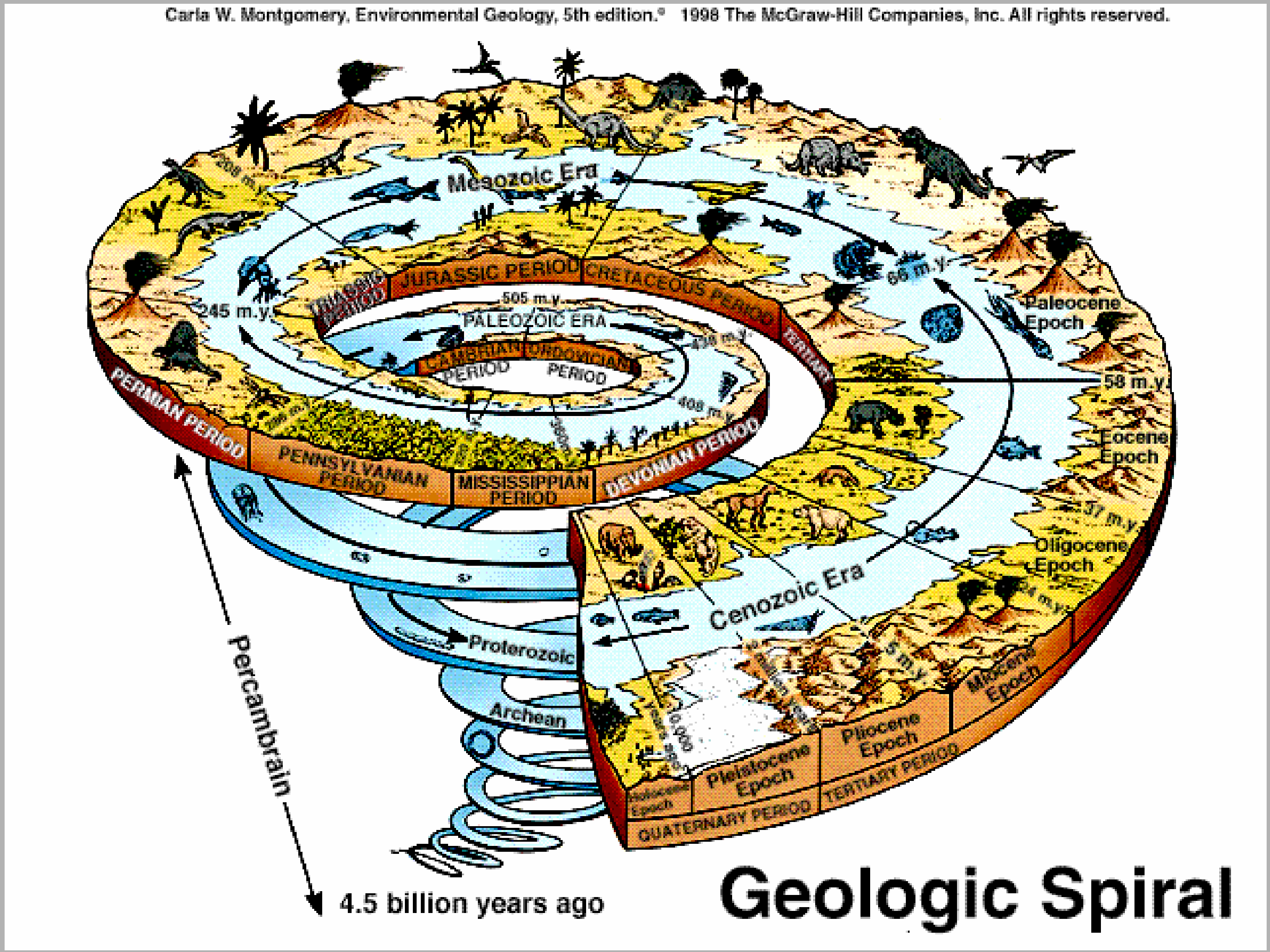


- The Precambrian (Archaean + Proterozoic) covers the first 85% of the geological timescale. Precambrian rocks form the cores of the major continental plates.
- The Phanerozoic Eon is subdivided into three Eras the Palaeozoic (old life), Mesozoic (middle life) and Cenozoic (new life)
- Many boundaries such as the Permian-Triassic and Cretaceous-Tertiary are marked by major extinction events.

Geological Time

- The Earth is approximately 4.6 billion years old
- The oldest rocks found so far are around ~4.3 billion years old
- The oldest fossils are around 545 million years old
- Man has been around for ~100,000 years
- Written records go back a few 1000 years

Geological Time



Montgomery, 2000

Geological Time

- **Many geological processes such as erosion and sedimentation operate over very long timescales (thousands to millions of years)**

- **Some processes, such as earthquakes, landslips or volcanic eruptions occur over very short timescales (seconds - decades)**

Dating the Earth

- Initial attempts to date the earth relied on genealogies found in the bible, came up with ~6000 years (Bishop Usher)
- More ‘scientific’ methods included measuring the cooling rates of iron balls (~75,000 years) and calculating how long it took for sedimentary sequences to form (1-2 billion years)

Geological Time Scale

- **The geological timescale was developed during the first half of the 19th Century based entirely on the outcrop relationships of rock units in Britain and Europe.**
- **The timescale originally was only relative since there was no method for absolute dating of rocks until the 20th century.**

- The relative ages of widely separated exposures of sedimentary rocks could be assessed by comparing their fossil assemblage with that in a continuous section exposed elsewhere.
- The study of fossils is called palaeontology

Relative dating

- Before we could date rocks geologists relied on relative dating
- This relies on a simple concept
  - James Hutton and the Principle of Uniformitarianism
  - Defined the concept that the “present is the key to the past”. Rather than relying on catastrophic event to explain the formation of the earth he recognized that gradual processes occurring over a long period could produce the same results

Uniformitarianism

Ancient and modern mudcracks

Wicander and Monroe, 2001

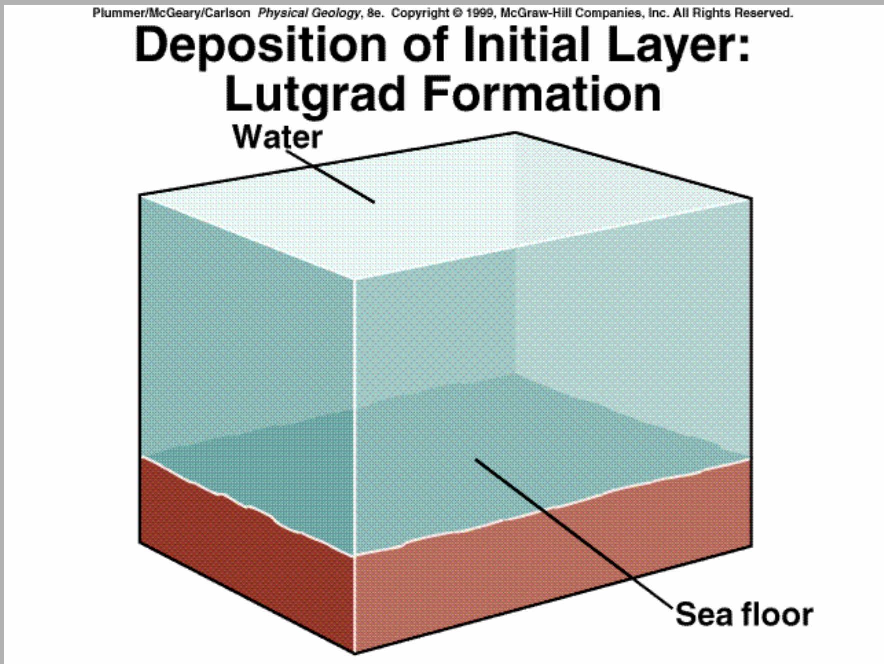
Principles of relative dating

- Principle of superposition
- Principle of original horizontality
- Principle of lateral continuity
- Principle of fossil succession
- Principle of cross-cutting relationships
- Principle of inclusions

Most of these are based on the principles of stratigraphy

Original horizontality

- Individual layers of sediment are called stratum
- The study of strata and stratification is called stratigraphy
- The principle of original horizontality states that water-borne sediments are deposited in horizontal layers



Plummer et al., 2000

Original horizontality

Murck and Skinner

Flinders Ranges, R

Murck and Skinner, 1999

Superposition

- In any undisturbed sequence the oldest strata will be at the bottom and the youngest at the top

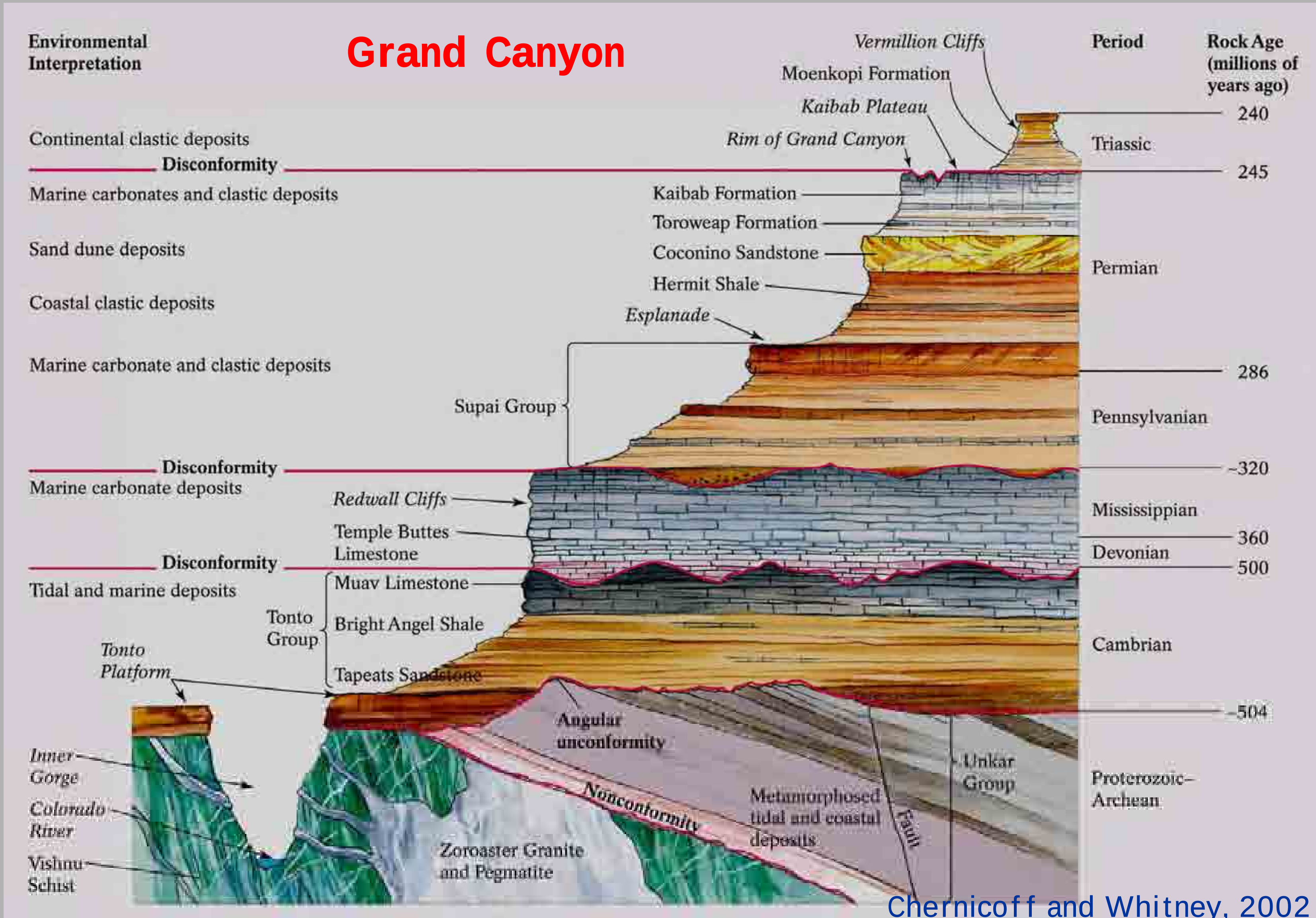
Younger

~300 m.y.

Older

Murck and Skinner, 1999

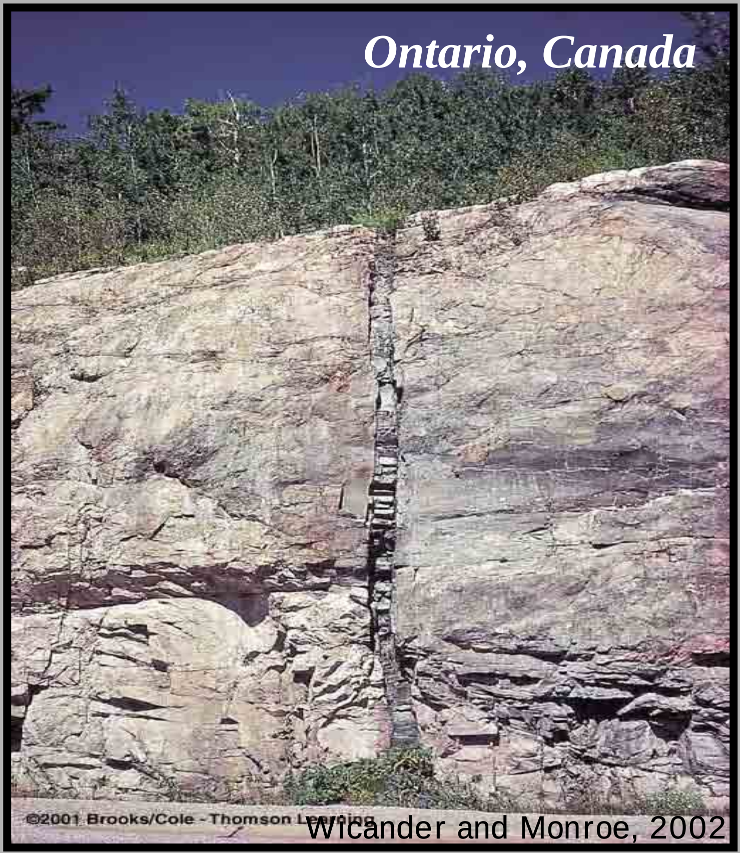
Superposition



Chernicoff and Whitney, 2002

Cross cutting relationships

- **A rock unit must be older than anything that cuts or disrupts it**



Wicander and Monroe, 2002

Murck and Skinner, 1999

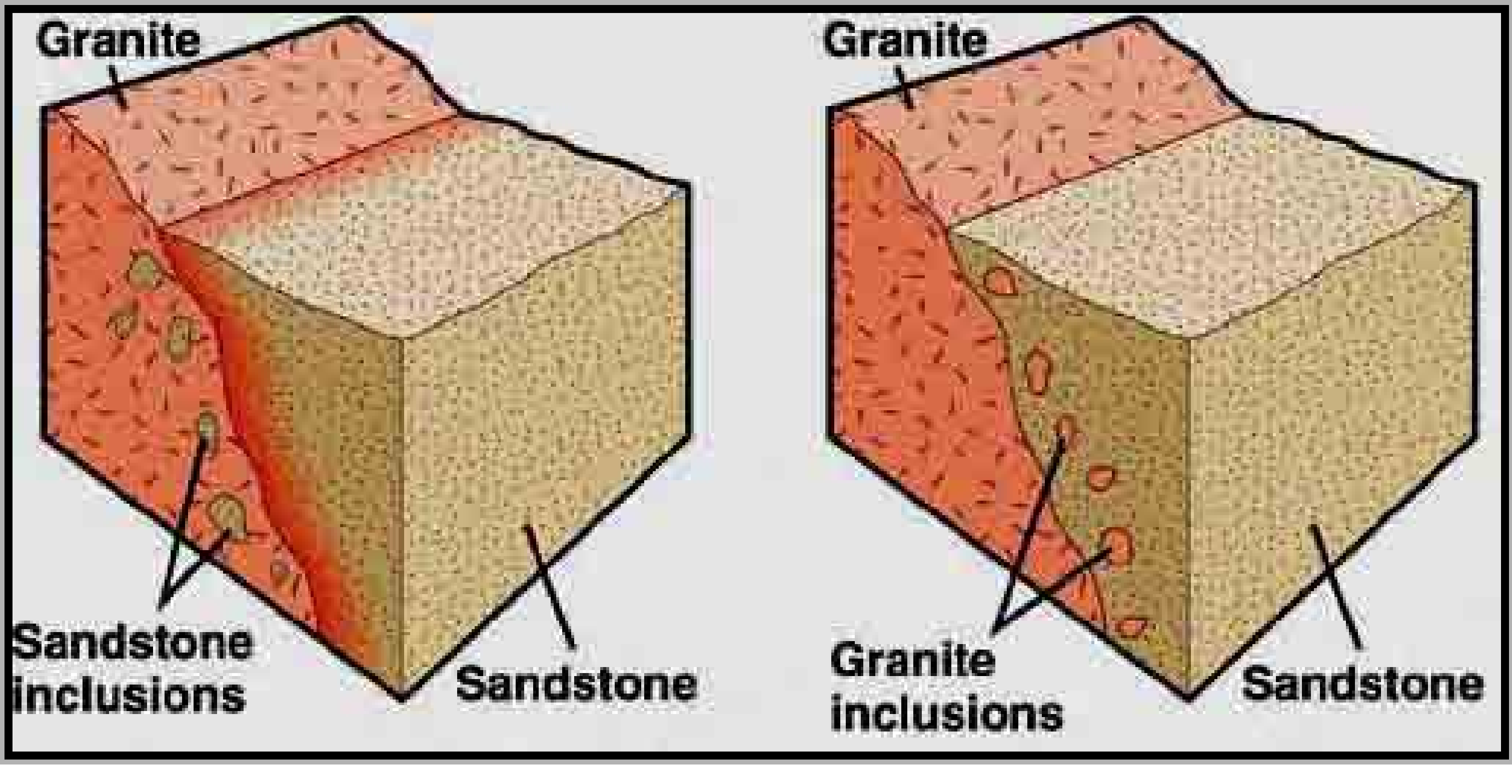
Lateral continuity

- The principle of lateral continuity states that layers of sedimentary rock extend laterally in all directions until they thin and pinch out or terminate at the edge of the depositional basin.

Wicander and Monroe, 2002

Inclusions

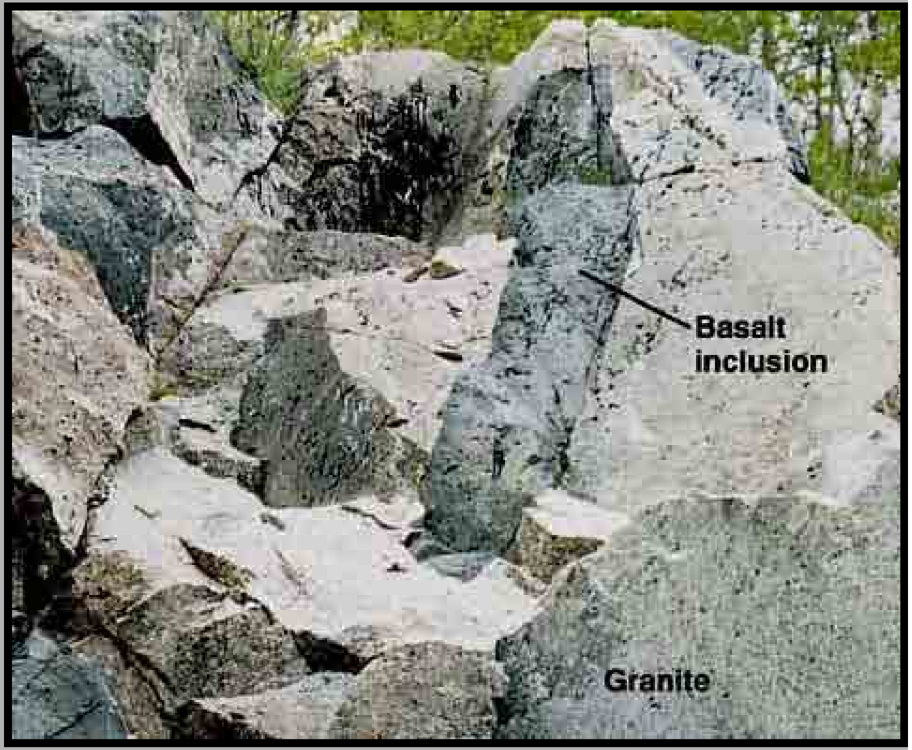
- **The principle of inclusions states that inclusions, fragments of one rock within another, are older than the rock containing them.**



Wicander and Monroe, 2002

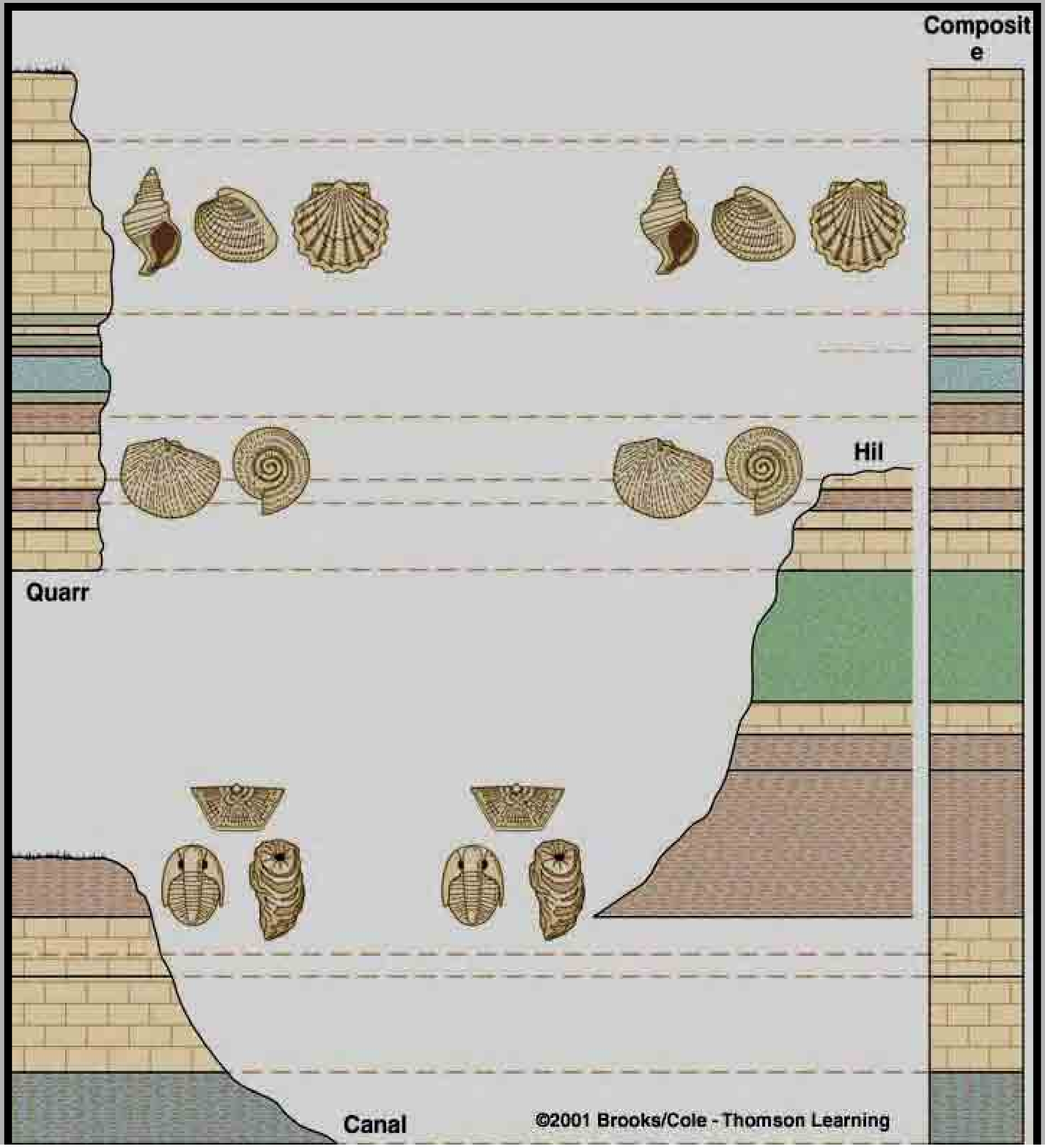
Inclusions

Chernicoff and Whitney, 2002



Wicander and Monroe, 2002

Fossil succession



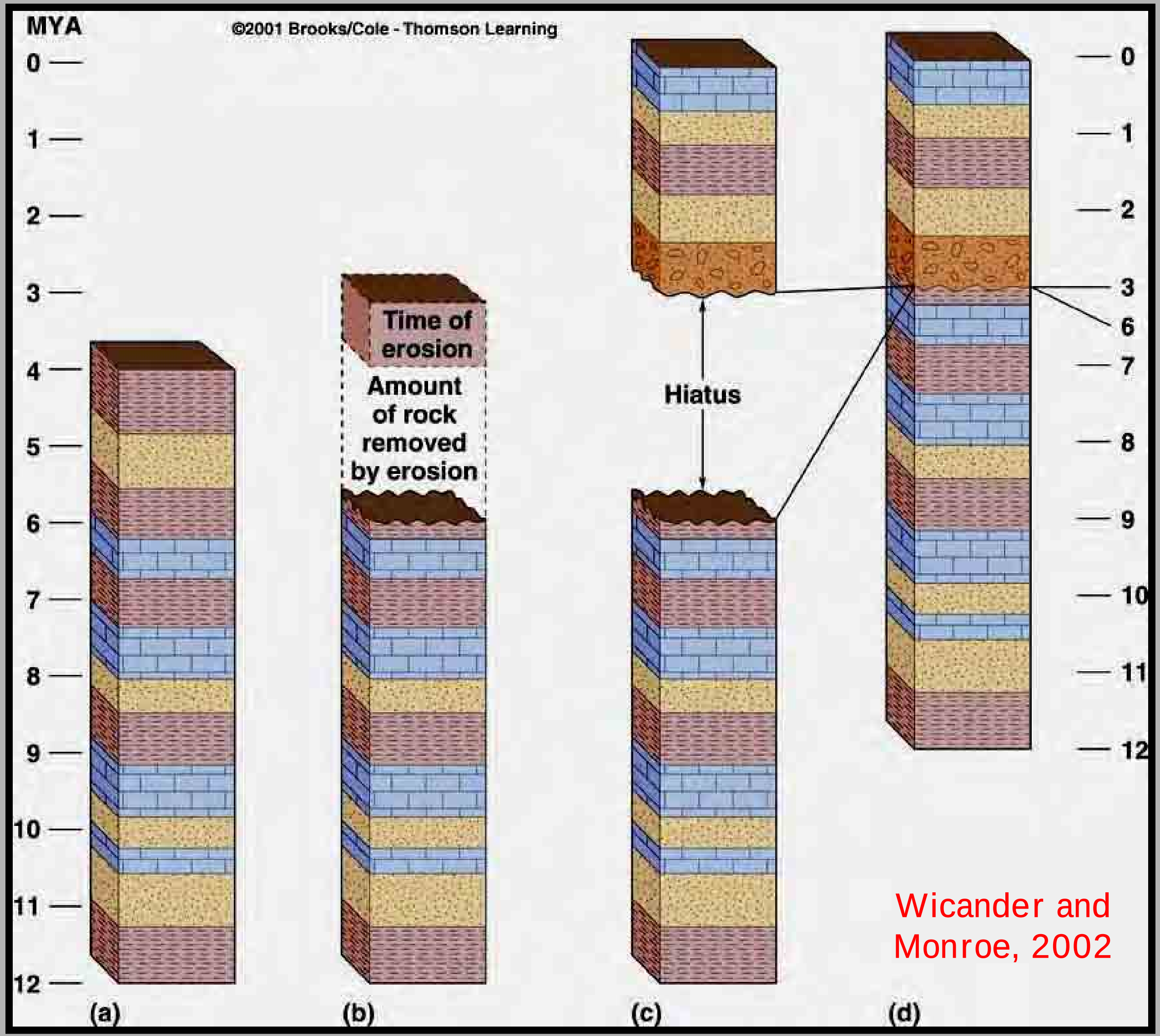
The principle of **fossil succession** reasons that fossils in rock layers at the bottom of a sequence are older than those in layers at the top of a sequence. Thus fossils can be used to identify rocks of the same age in different areas.

Wicander and Monroe, 2002

Gaps in the record

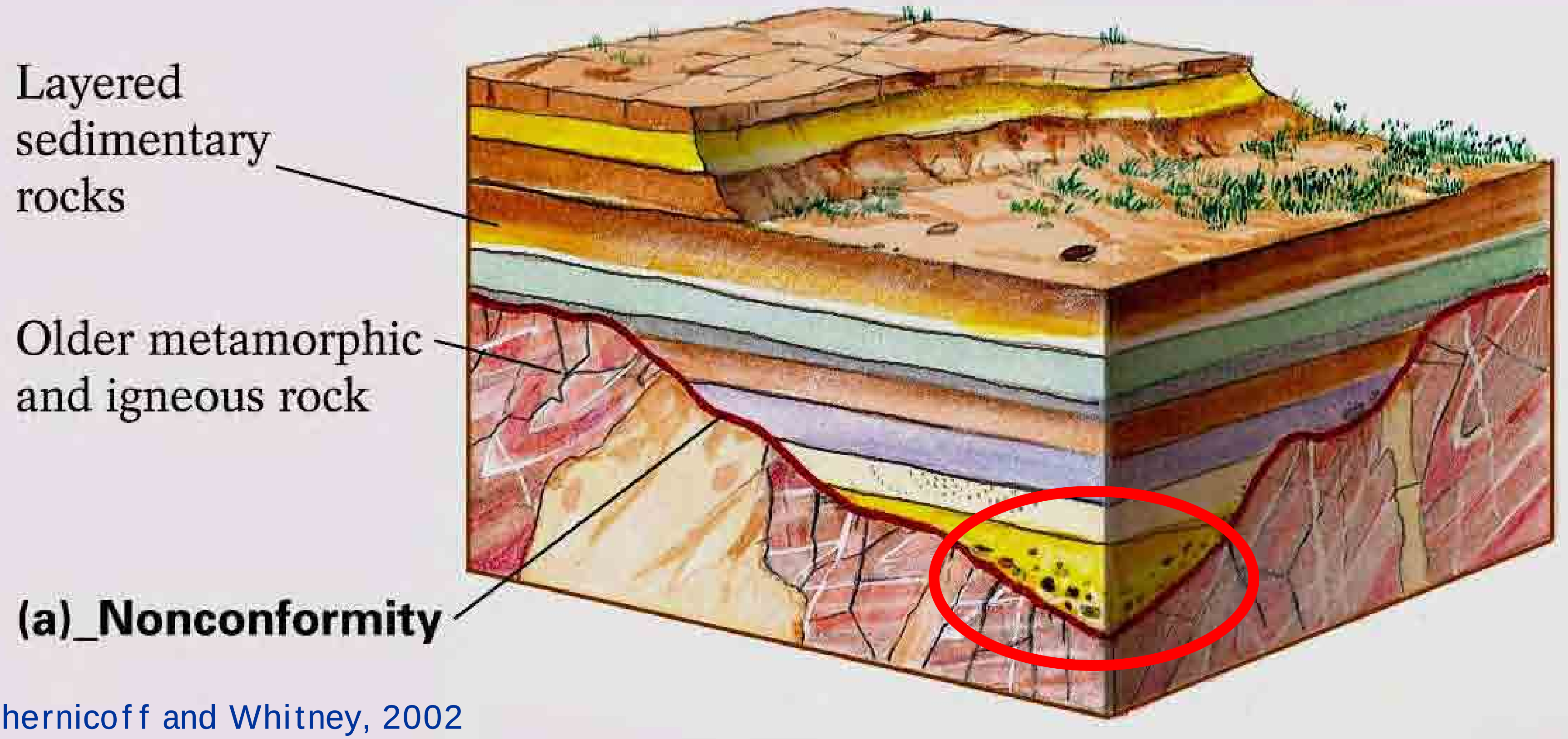
- If the geological record was complete we could determine an absolute age based on the thickness of sediments
- This requires that the sedimentary record is conformable
- However, because sedimentation periodically stopped and there are periods of erosion this is not the case
- These gaps are called unconformities

Unconformities



Wicander and Monroe, 2002

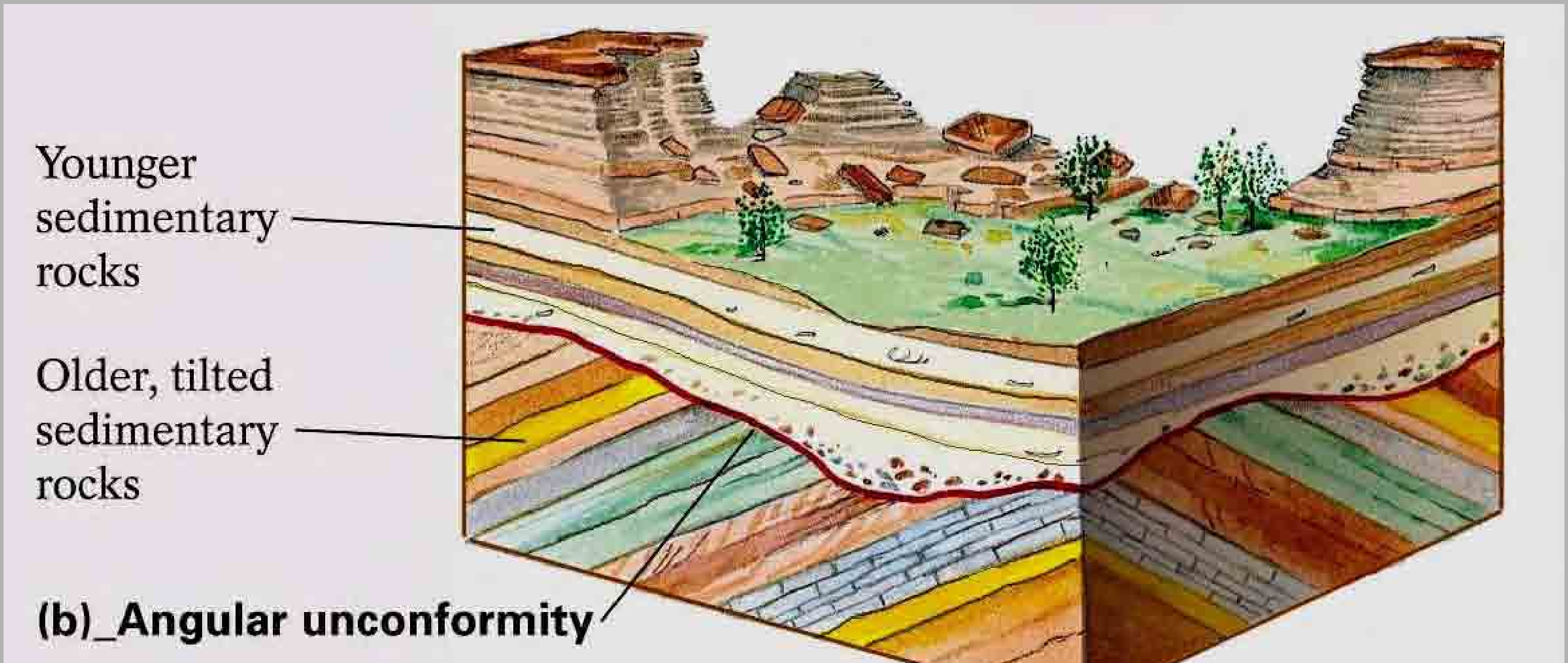
Nonconformity



Chernicoff and Whitney, 2002

Erosional surface cutting into older igneous or metamorphic rocks

Angular unconformity

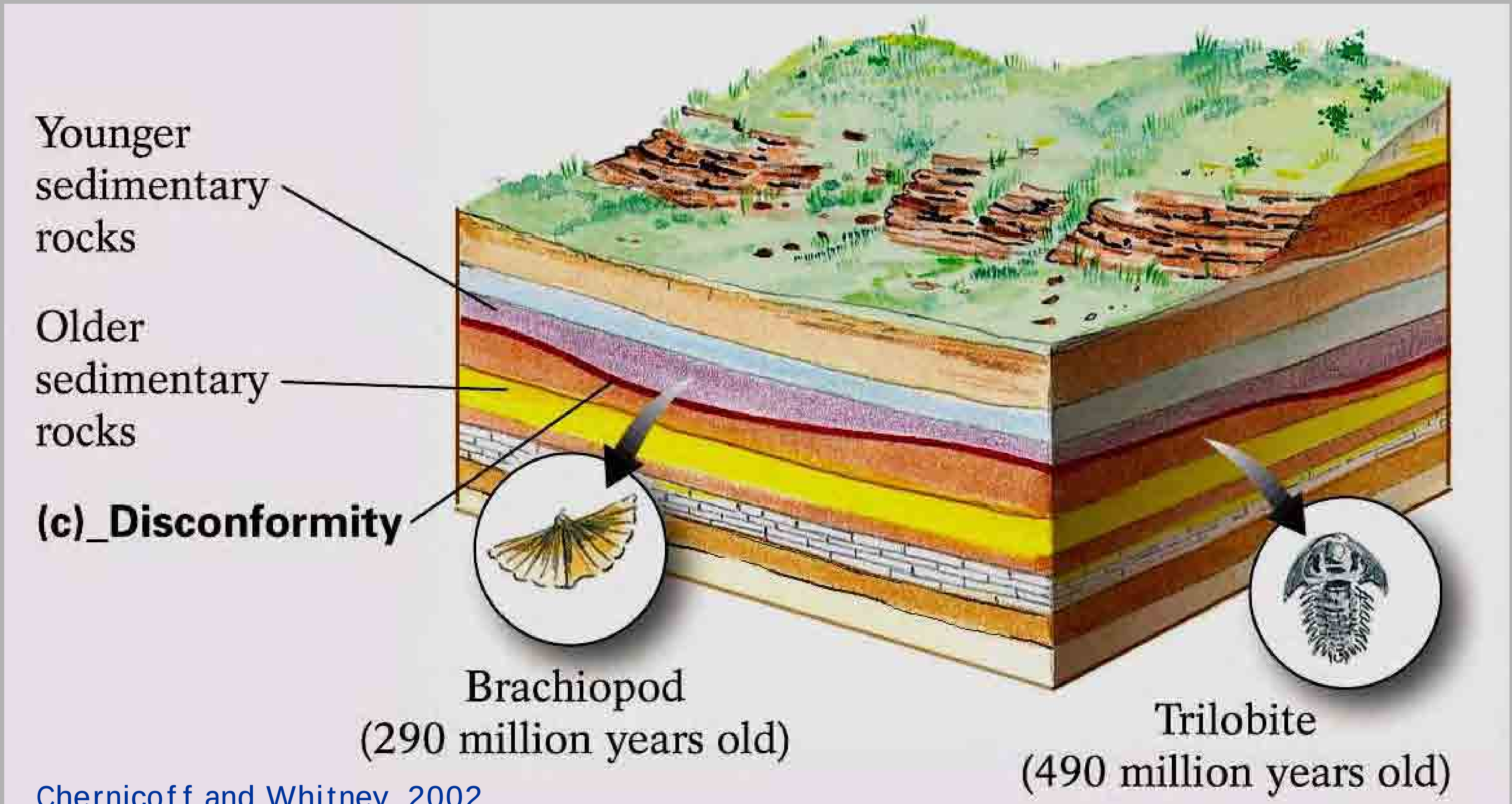


Chernicoff and Whitney, 2002

Strata below are tilted

Siccar Point, Scotland

Disconformity



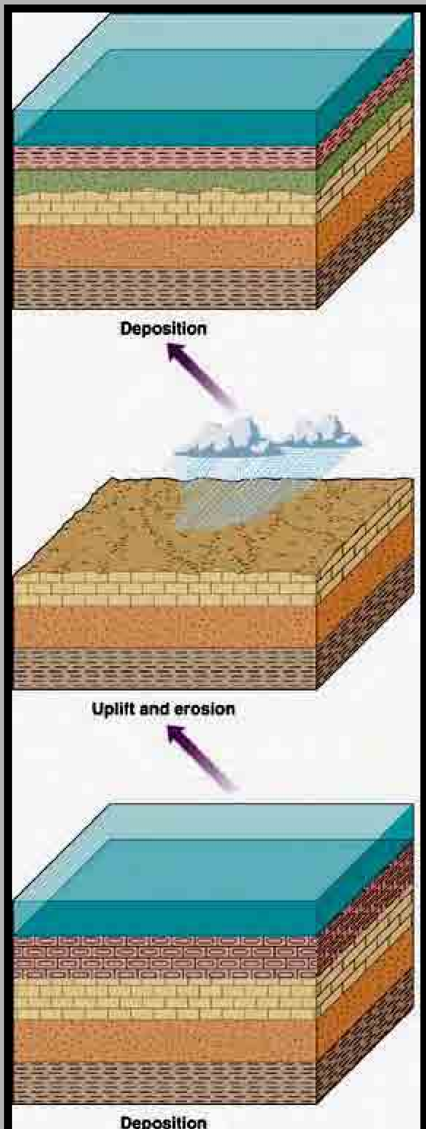
Chernicoff and Whitney, 2002

Apparently conformable but not really

Unconformities

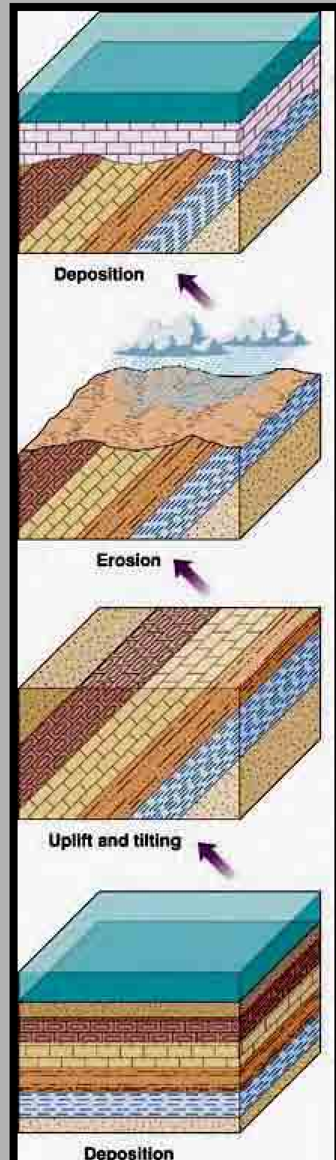
1

Disconformity



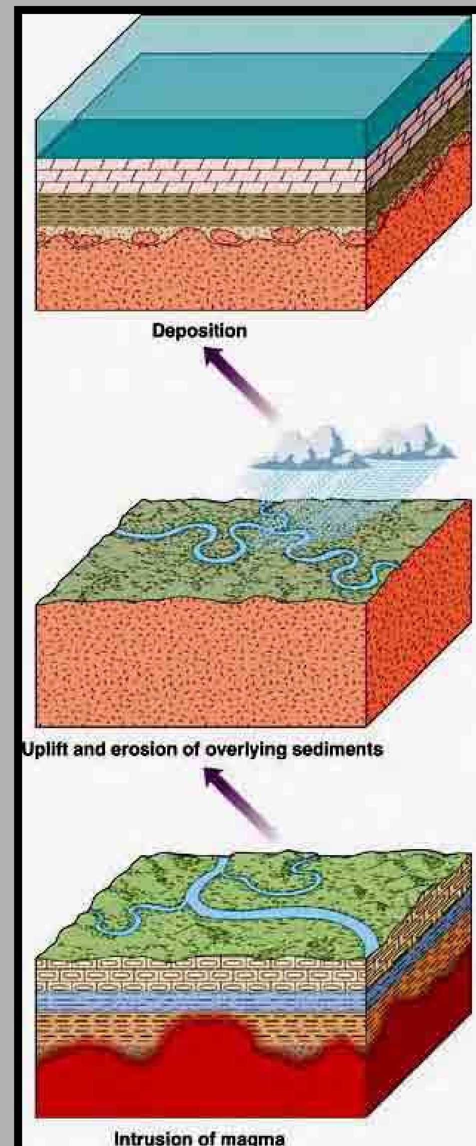
2

Angular unconformity



3

Nonconformity



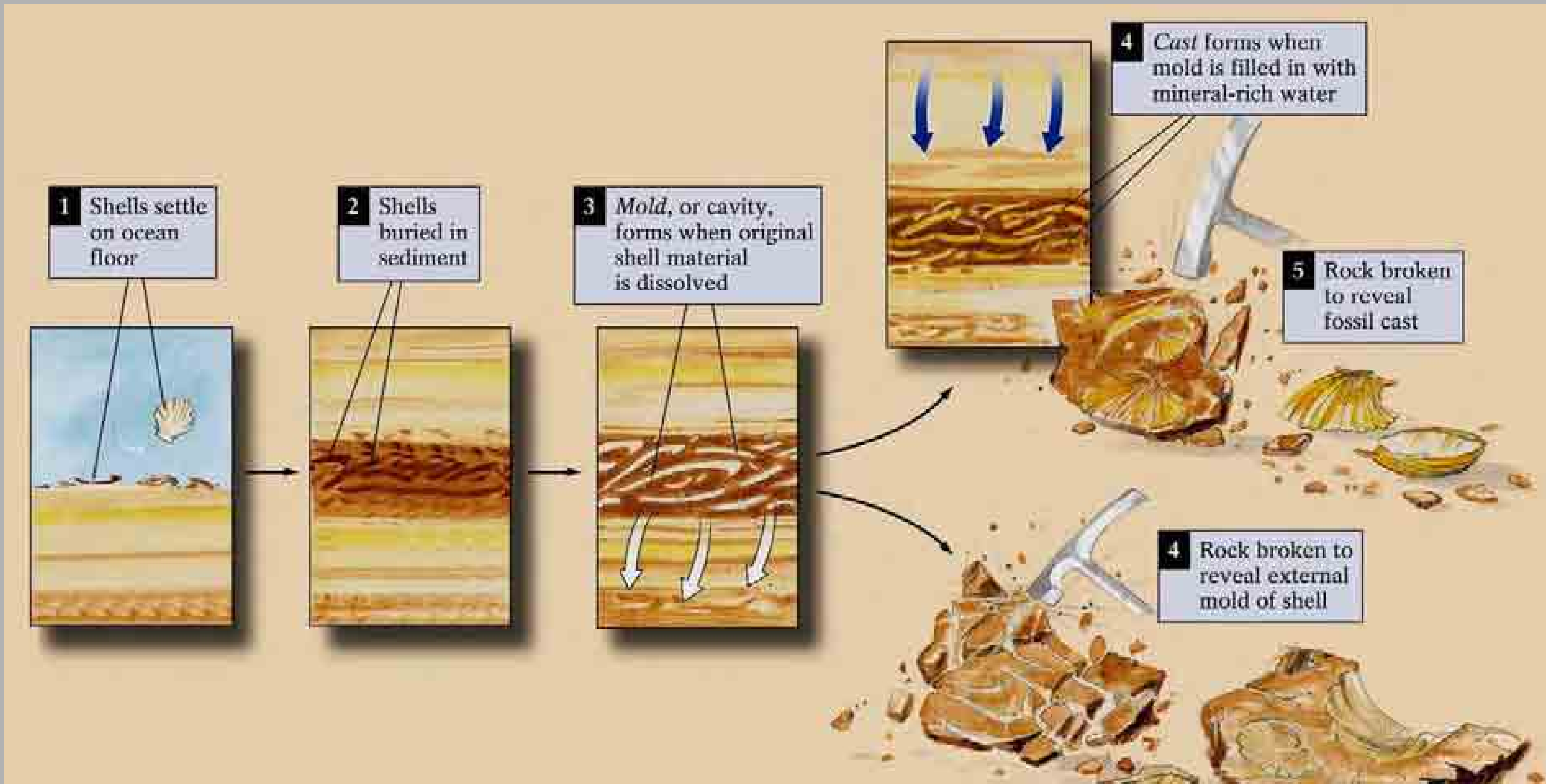
Wicander and Monroe, 2001

Fossils

- This includes any organic matter preserved in the rock record, including coprolites
- May also include tracks and footprints of animals

Wicander and Monroe, 2002

Fossilization

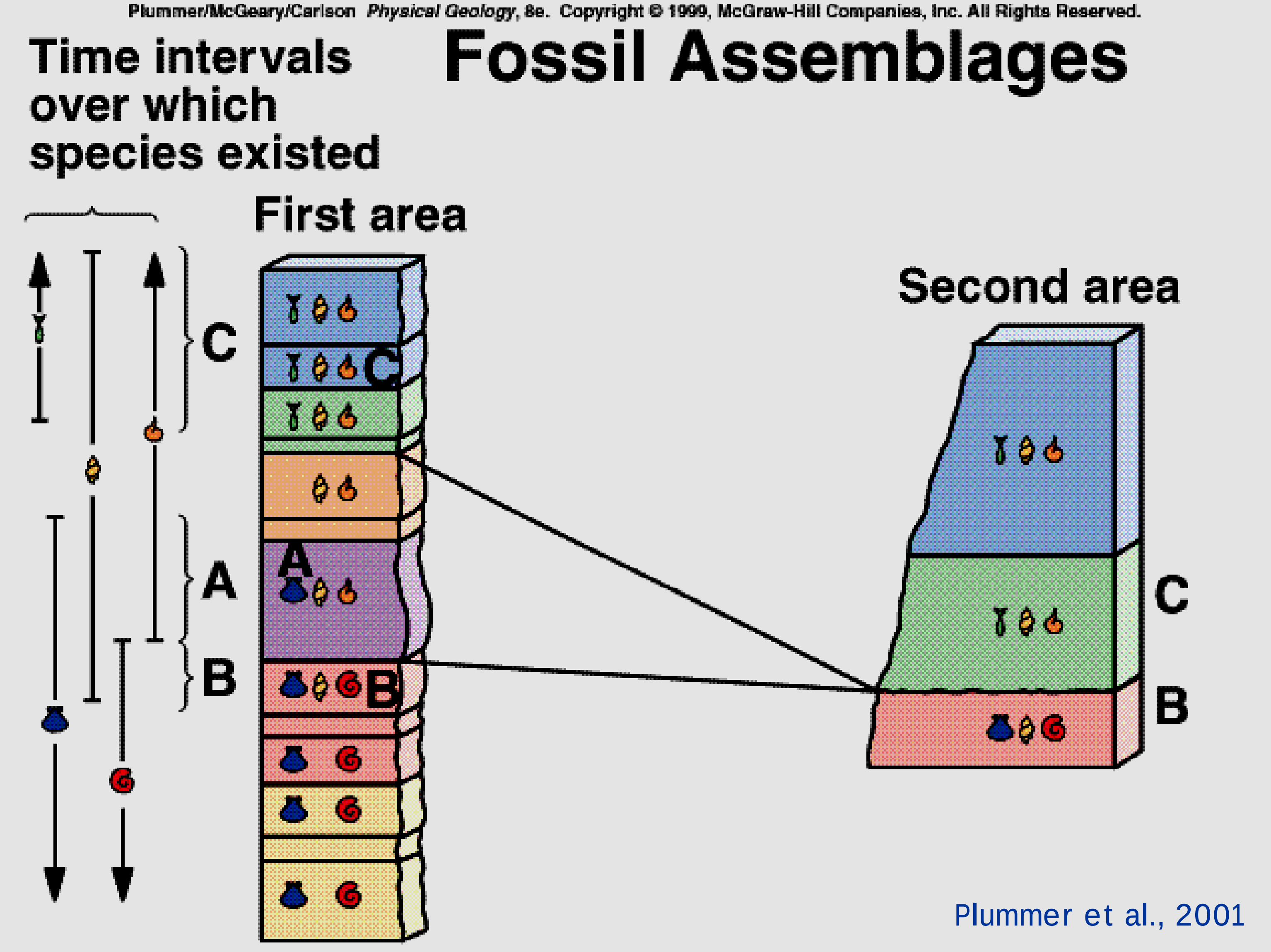


Chernicoff and Whitney, 2002

Fossils and correlation

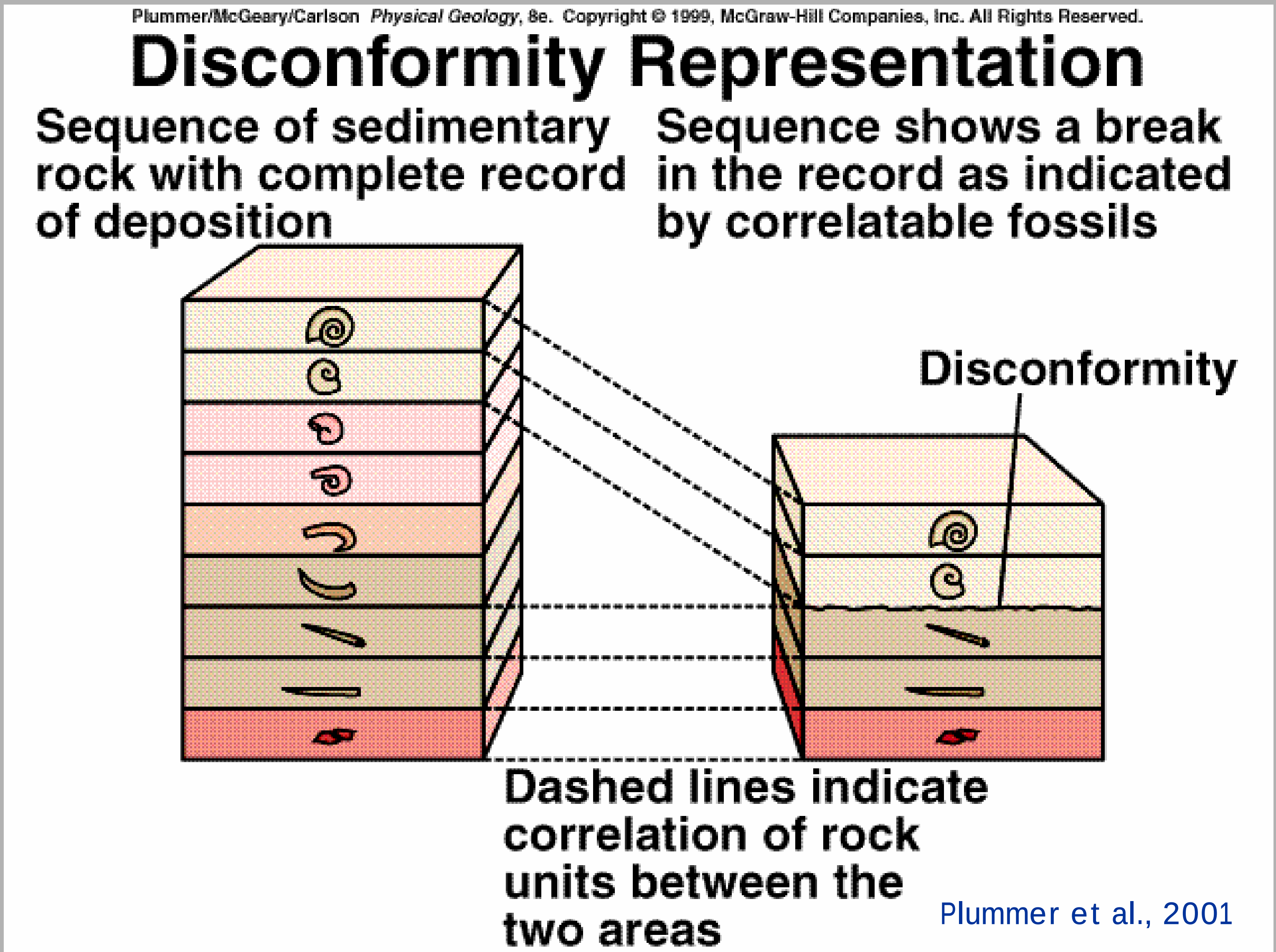
- William Smith - an engineer building canals in England in the early 1700's started cataloguing fossils in the rocks he worked with
- The study of fossils is known as palaeontology
- The stratigraphic ordering of fossils (or fossil assemblages) is known as the faunal succession

Fossil assemblages



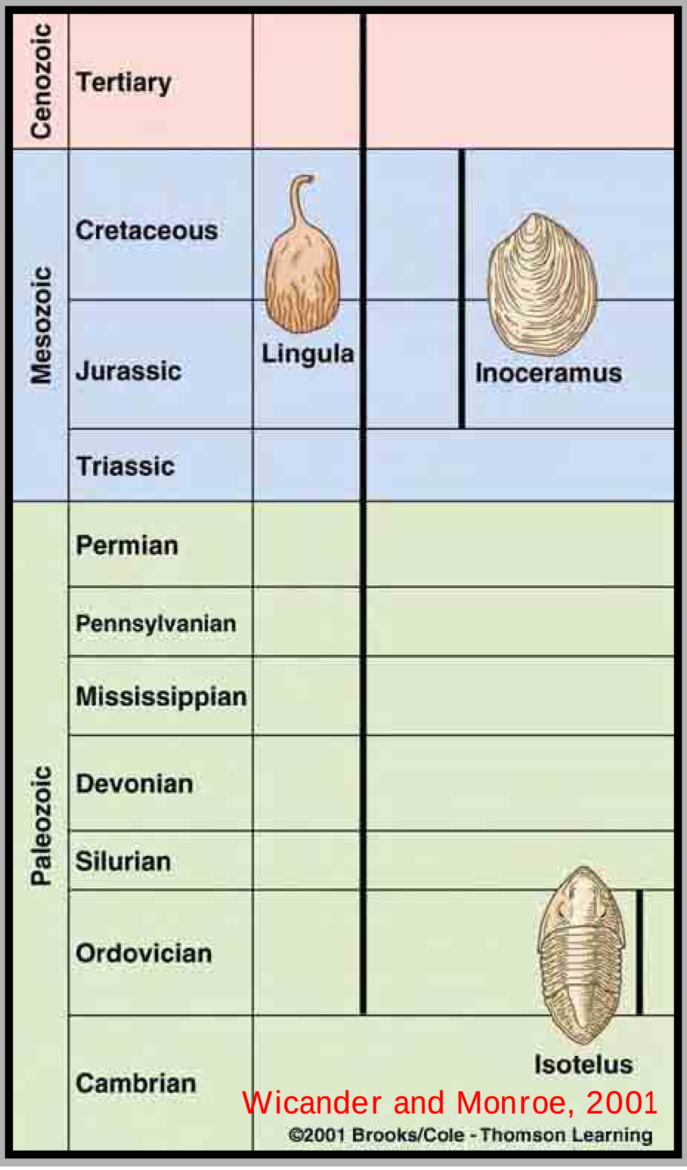
Plummer et al., 2001

Fossil correlation



Plummer et al., 2001

How Do Geologists Correlate Rock Units?



Fossils such as *Inocceramus* or *Isotelus* are the most useful for this purpose

Guide fossils must be:

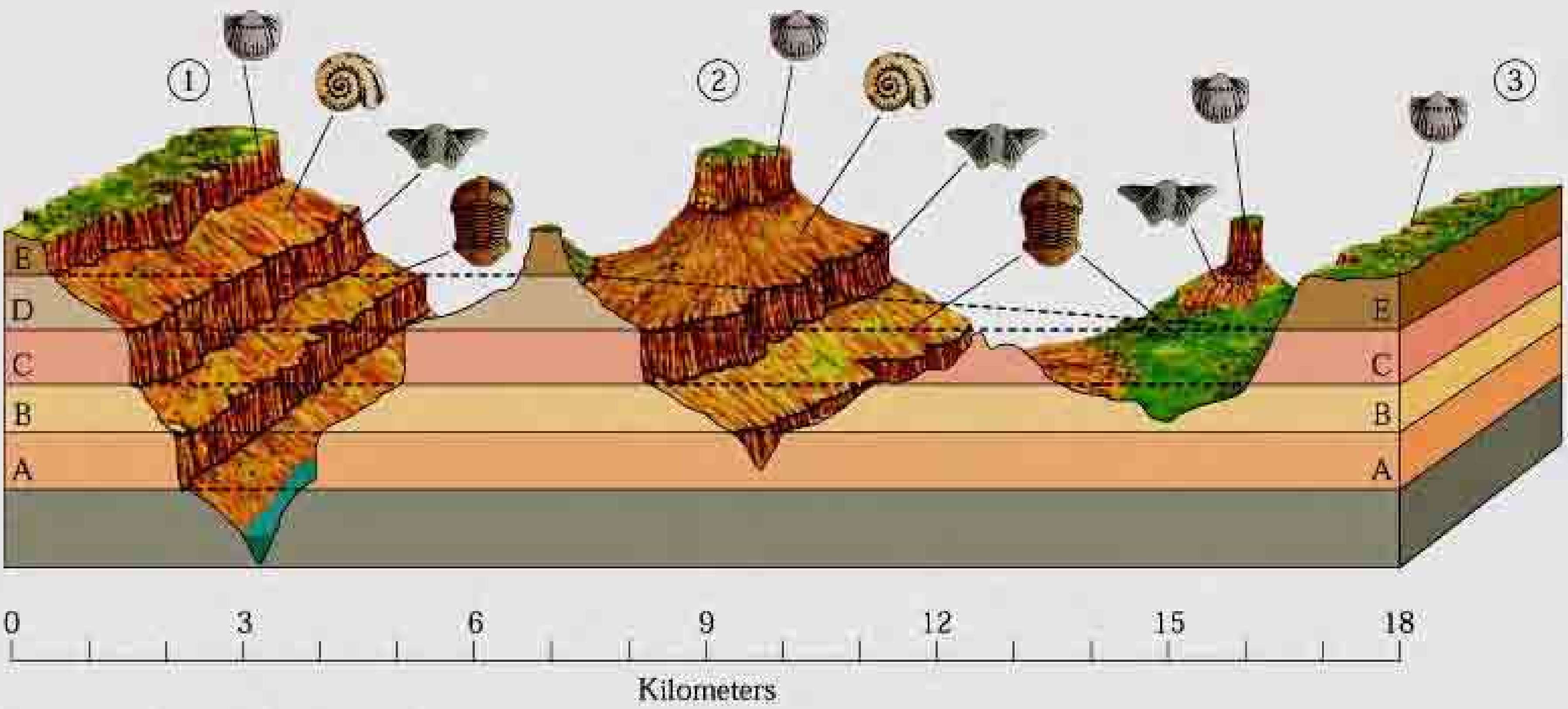
1) organisms that persisted for a short interval of geologic time,

2) easily identified

3) geographically widespread.

Lingula is not a good guide fossils, because they persisted through many geologic periods and were widespread.

Faunal succession

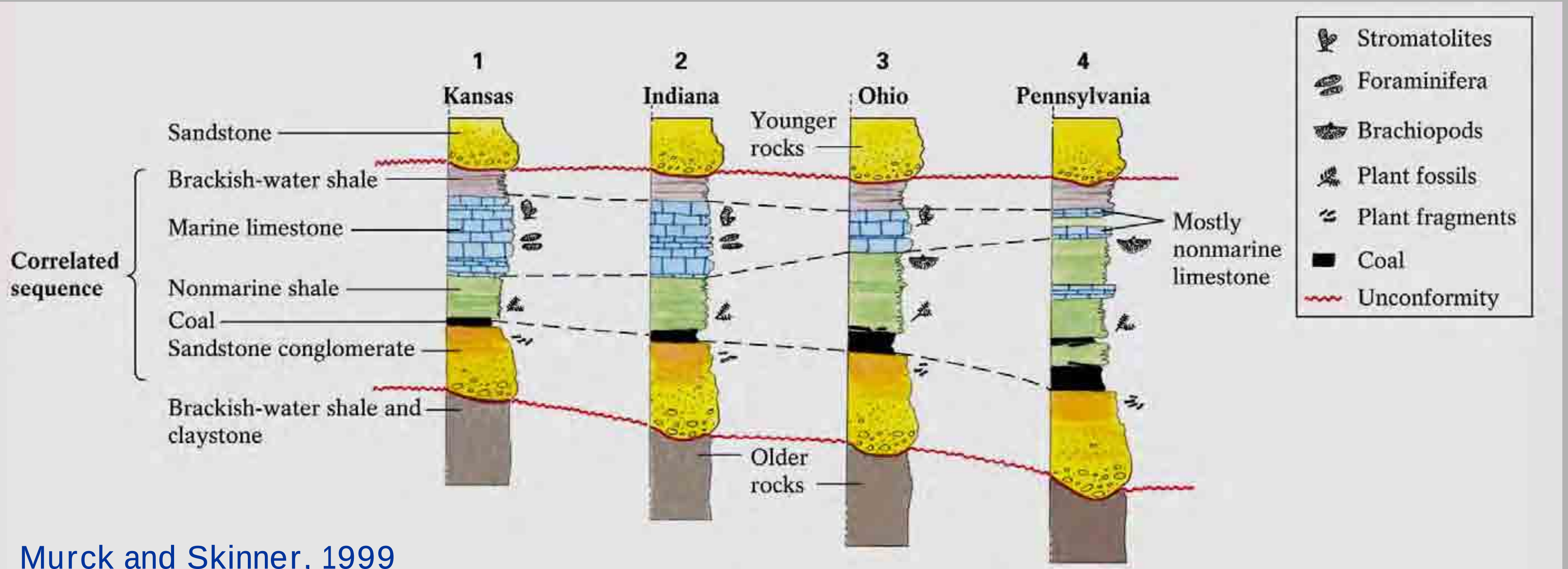


Murck and Skinner, 1999

Sequence stratigraphy

- In the latter part of the 20th century another means of stratigraphic correlation was developed
- Geologists recognized that the geological record preserved instances of global sea level rise and fall
- This left sequences of conformable strata bounded by unconformities

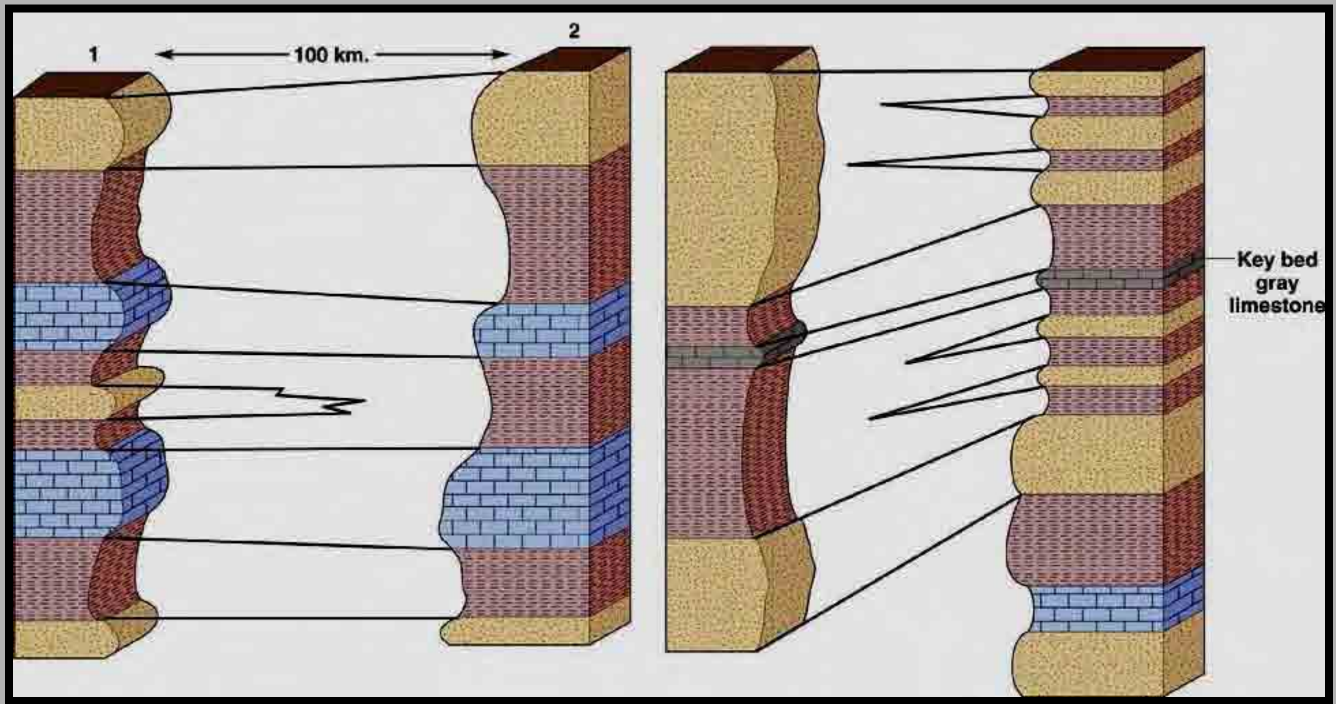
Correlating sediments



Murck and Skinner, 1999

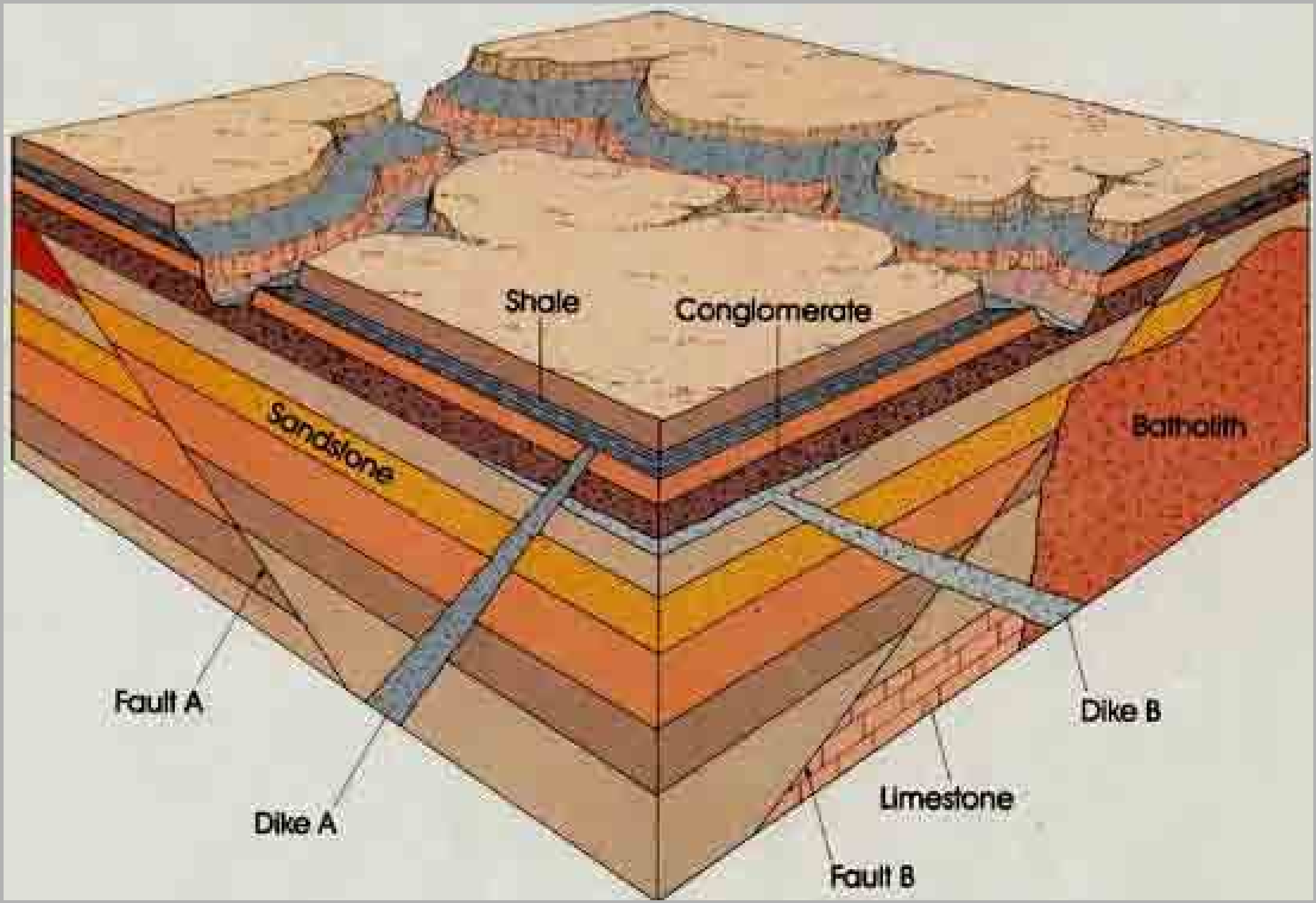
How Do Geologists Correlate Rock Units?

- **Geologists must correlate rocks from location to location to reconstruct the complete geologic history of a region. Similarity of rock type, position in a sequence, fossils, and key beds are all useful for correlation. Key beds are distinctive units that can be recognized at several locations.**



Wicander and Monroe, 2001

More examples

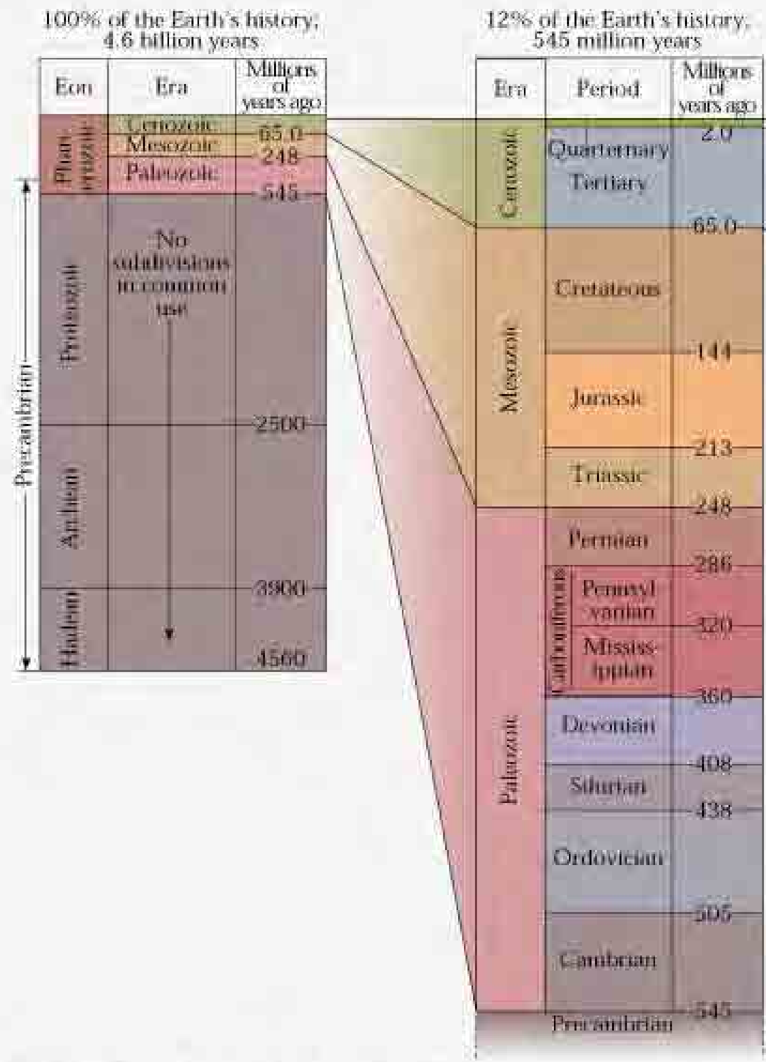


Macmillan Publishing Co., 1993

What does all this mean?

- Geologists, initially in Europe but later globally, were able to use the concepts of relative dating and stratigraphy to develop a relative time scale
- Units were placed in the order they were deposited and given names

The Geologic Column



Murck and Skinner, 1999

How do we measure absolute age?

- Early attempts included
  - The “begat” method
    - ~6000 years ☹
    - Relies on the literal translation of bible
  - Measuring the cooling rates of iron balls and extrapolating to a sphere the size of the Earth
    - ~75,000 years ☹
    - Assumes the earth is a uniform composition

How do we measure absolute age?

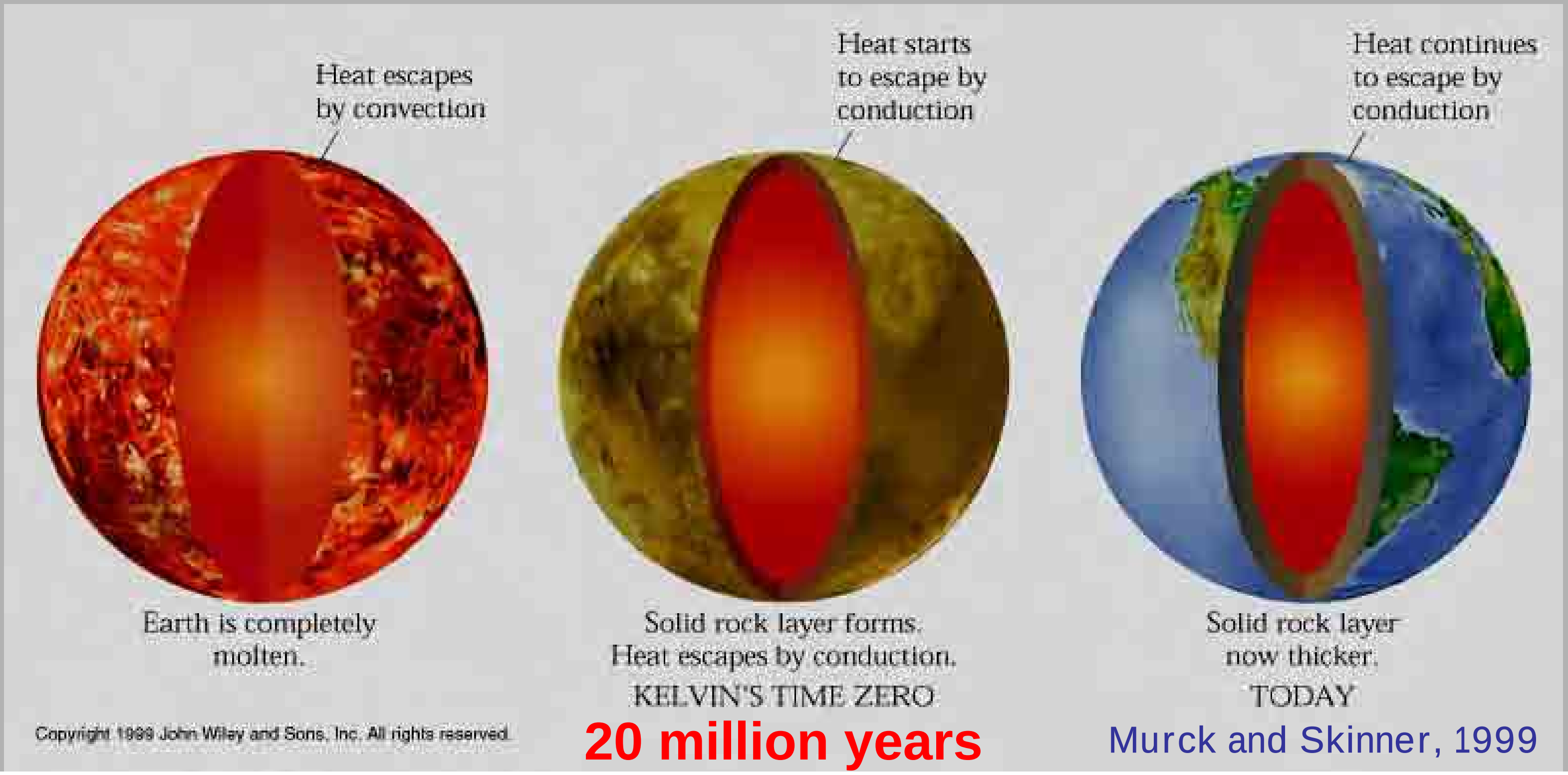
- **Estimating rates of sedimentation**
  - **3 million to 1.5 billion** ☹
  - **Rates of sedimentation were not uniform**
- **The age of the oceans (as sediments were deposited in oceans). Halley (1715) suggested measuring the rate at which salts are added to the oceans and calculating how long it would take to to reach present levels**
  - **90 million years**
  - **The ocean is an open system, therefore, salt was also removed** ☹

The drive for an answer

- Darwin's ***'On the Origin of the Species'*** **sparked considerable debate in the 1800's**
- **Natural selection was a very slow process**
- **Darwin was opposed by the renowned physicist Lord Kelvin who measured the thermal properties of rocks and estimated how long the Earth would have taken to cool by conduction**
  - **20 million years** ☹

Kelvin's hypothesis

- **Kelvin assumed that no heat had been added to the Earth**
- **In fact heat is added by radioactivity**



So how old is the Earth?

- **Generally accepted that the Earth is 4.6 billion years old**
- **~~The oldest rocks on Earth are the Acasta gneisses in the NWT~~**
- **~~Dated at 3.96 Ga~~**
- **Older detrital zircons**

Acasta gneiss, Chernicoff and Whitney, 2002

“The geological world is buzzing with news that the oldest rocks on Earth are sitting on a windswept, barren shore in northern Quebec.” Margaret Munro, Canwest News Service (Sept 2008)

The Earth’s oldest rock- from the eastern shore of Hudson Bay

4.28 Ga

- At 4.28 Ga, earth was being attacked by meteors, comets and asteroids
- The rocks in Quebec may also carry a “biosignature”, meaning there might be evidence of primordial life….which would be the earliest life to emerge from the primordial seas…
- Occurs on the Nuvvugittuq greenstone belt
- Under debate b/c of geological resetting..

Canada's next tourist hotspot!

Science 26 September 2008:
Vol. 321. no. 5897, pp. 1828 - 1831
DOI: 10.1126/science.1161925

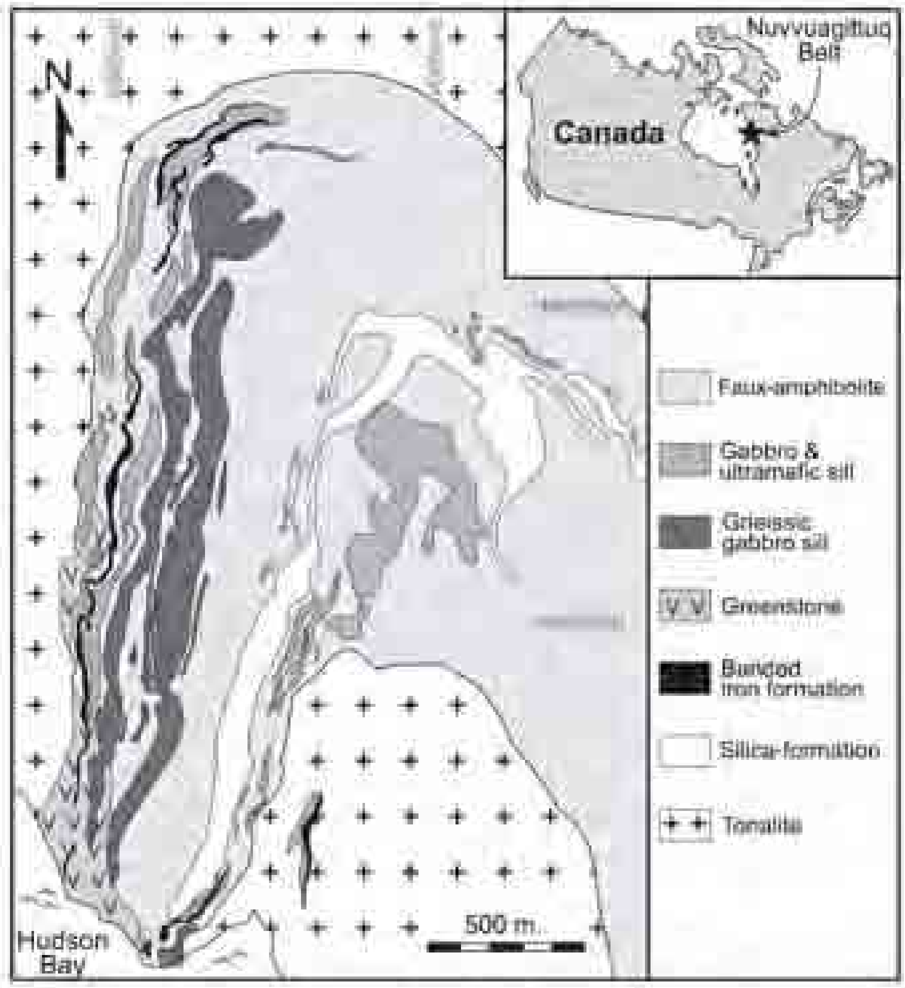


Fig. 1. Simplified geological map of the Nuvvuagittuq greenstone belt. The geology of the belt is described in more detail in (8). Coordinates are in universal transverse mercator zone 18 NAD 27.

So how do we measure age?

- Unlike early methods we need a process that
  - Has run continuously
  - Is non reversible
  - Is immune to high temperatures and chemical reactions
  - Does not leave gaps such as those found in the stratigraphical record
- It turns out that the same radioactivity missed by Kelvin could provide the answer

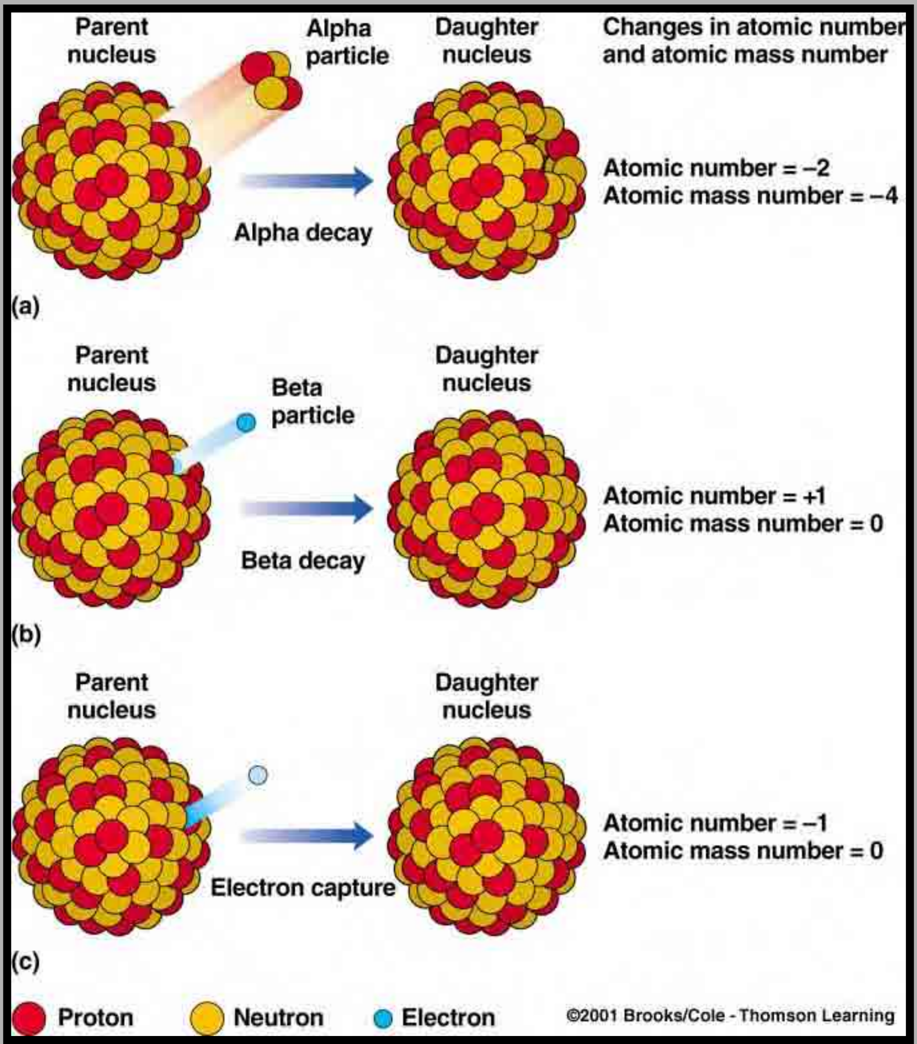
Radioactivity

- In an earlier lecture we discussed the concept of isotopes
- Most elements have isotopes (same number of protons but different numbers of neutrons)
- The majority of these are stable isotopes, which although geologically useful cannot be used for dating

Unstable or radiogenic isotopes

- The discovery of radioactivity in 1903 by Marie and Pierre Curie facilitated radiometric dating, a powerful new tool to accurately date geologic events
- Radioactivity refers to the spontaneous decay of one isotope to another more stable isotope.
- For example, carbon has three isotopes. All carbon atoms have six protons, but C^{12} atoms have six neutrons, whereas C^{13} atoms have seven neutrons and C^{14} atoms have eight.

Radioactive decay

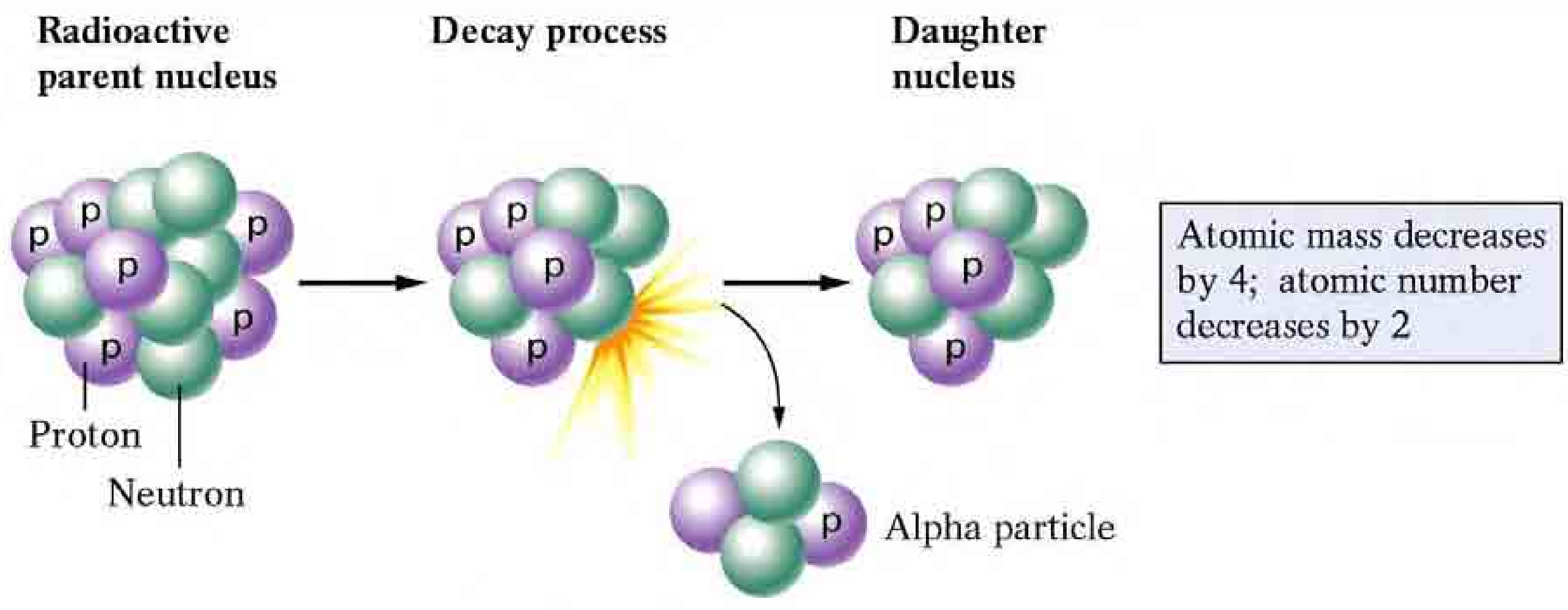


Wicander and Monroe (2002)

- There are three processes by which radioactive decay occurs
  - Alpha decay
  - Beta decay
  - Electron capture

Radioactive decay

- **Alpha decay** emits two protons and neutrons from the nucleus, reducing the atomic mass number by 4 and the atomic number by 2.

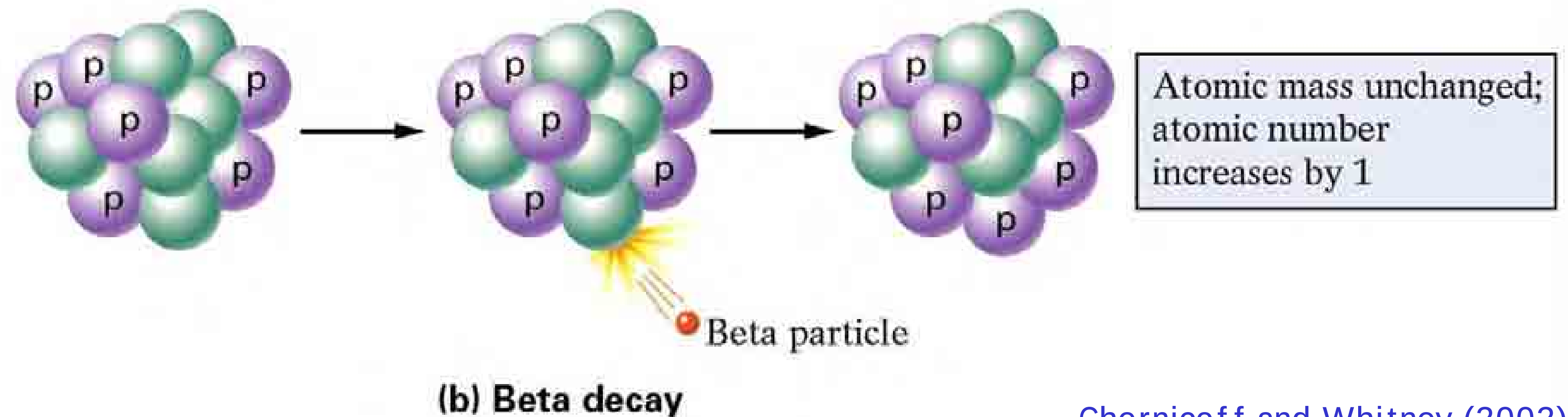


(a) Alpha decay

Chernicoff and Whitney (2002)

Radioactive decay

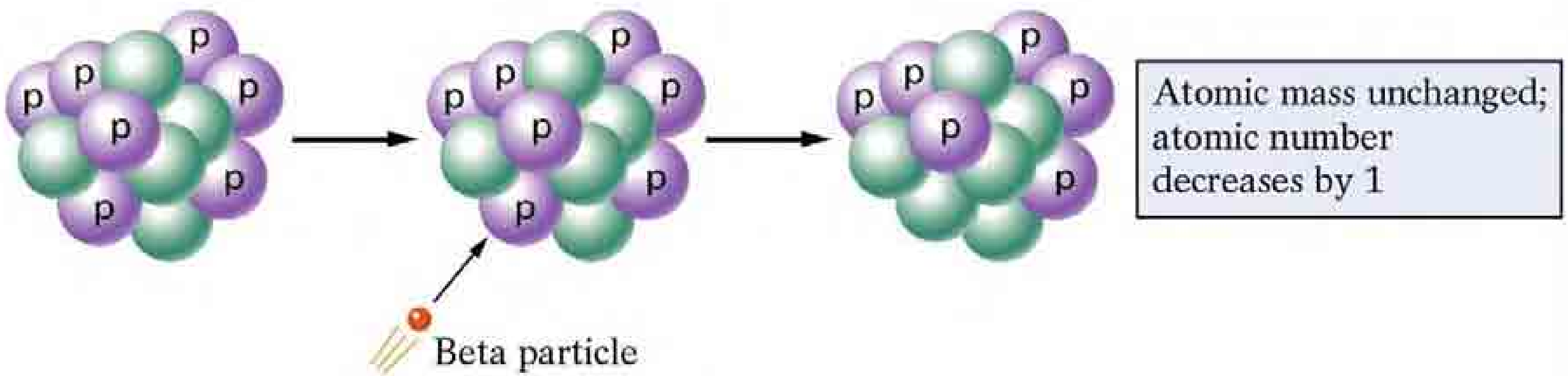
- **Beta decay** emits an electron as a neutron becomes a proton increasing the atomic number by 1.



Chernicoff and Whitney (2002)

Radioactive decay

- **Electron capture** changes a proton to a neutron, reducing the atomic number by 1.

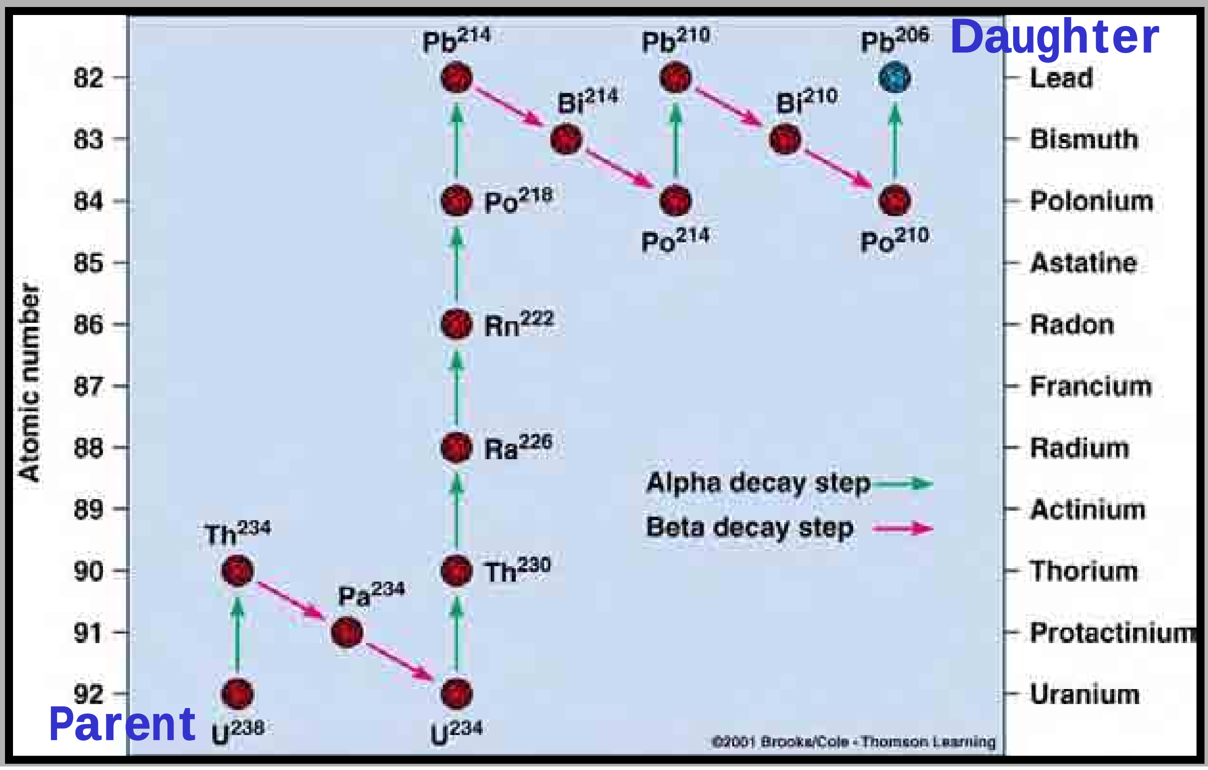


(c) Electron capture

Chernicoff and Whitney (2002)

Radioactive decay

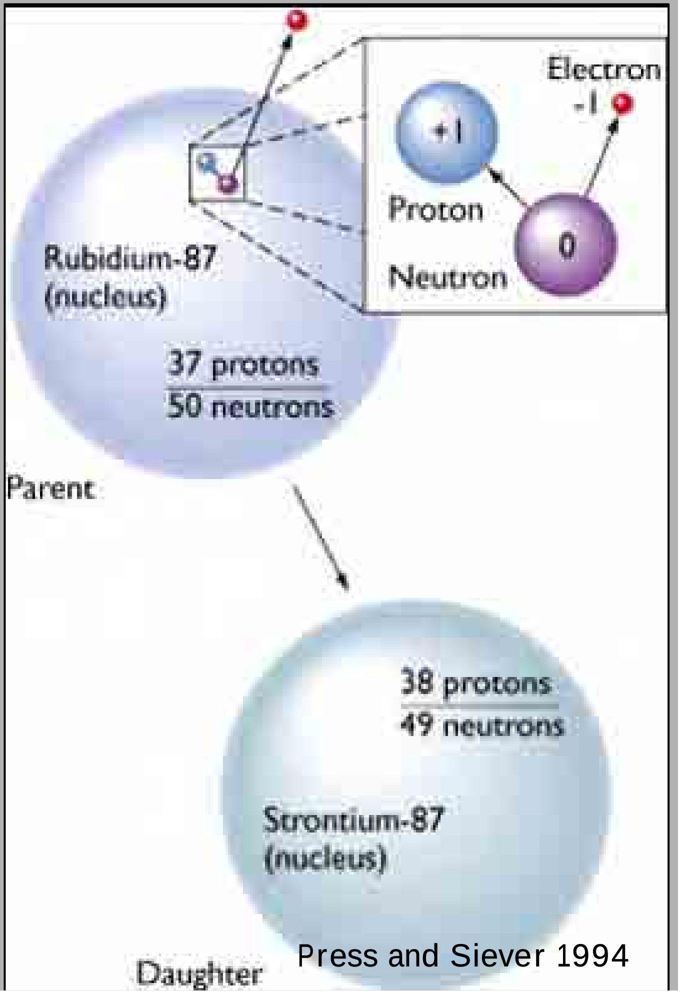
- Some radioactive isotopes undergo only one decay step to achieve a stable form, such as rubidium 87 decaying to strontium 87 by a single beta emission.
- Many radioactive isotopes undergo multiple decay steps. For instance, uranium 238 decays to lead 206 by eight alpha and six beta decay steps.



Wicander and Monroe (2002)

Why do we care?

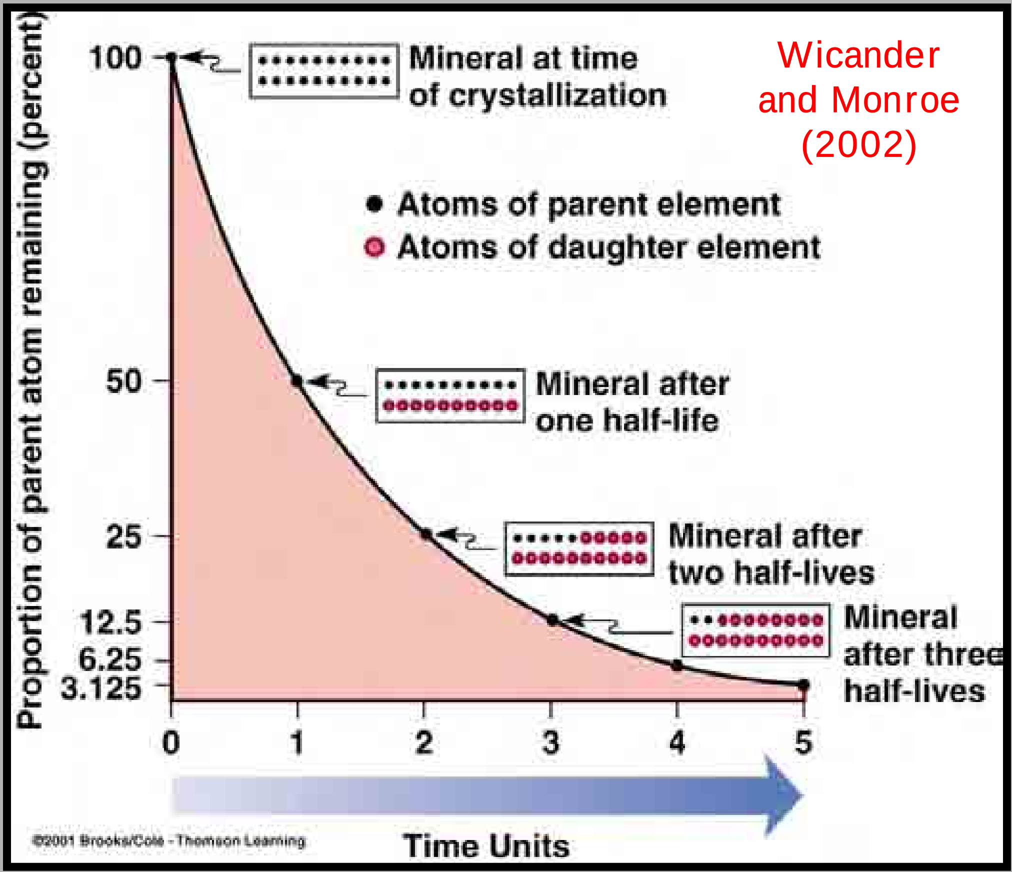
- Radioactivity can be hazardous to your health
- More importantly for geologists each radioactive isotope decays at a constant and measurable rate
- Because the decay rate is different for each element a single rock will contain many ‘clocks’



Press and Siever 1994

Decay rates

For a given radioactive element, decay rate is constant and can be precisely measured. The concept of half-life is used to describe decay rates

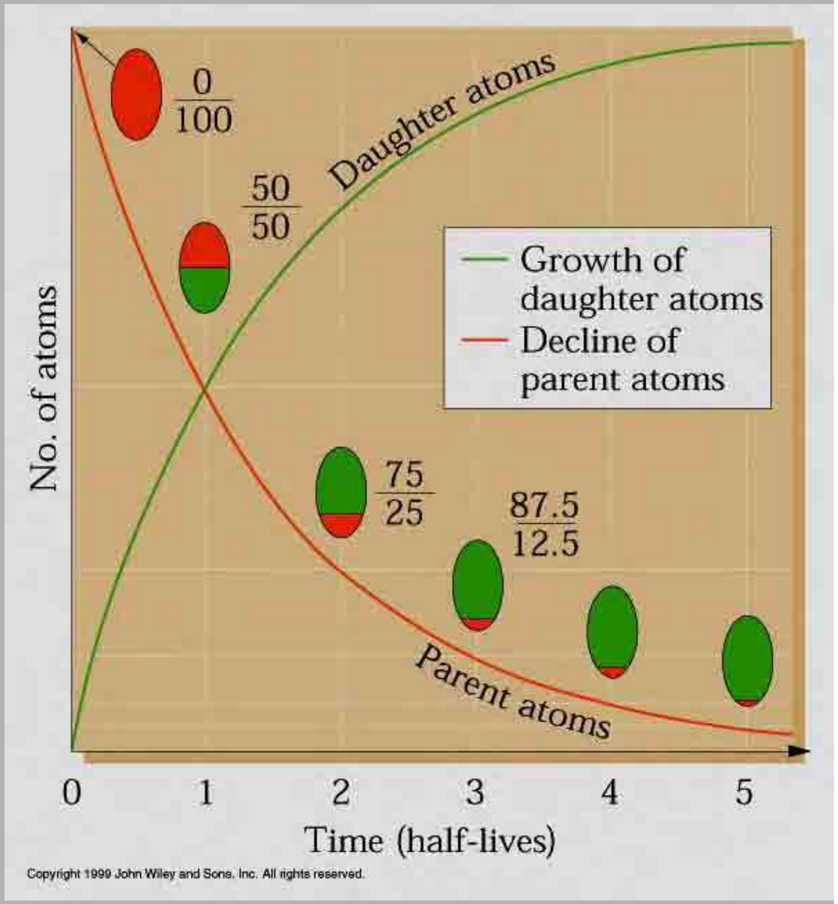


Wicander and Monroe (2002)

Half-life refers to the amount of time required for one-half of the atoms of an unstable parent element to decay to a stable daughter element. Half-lives range from less than one billionth of a second to 49 billion years

Decay rates

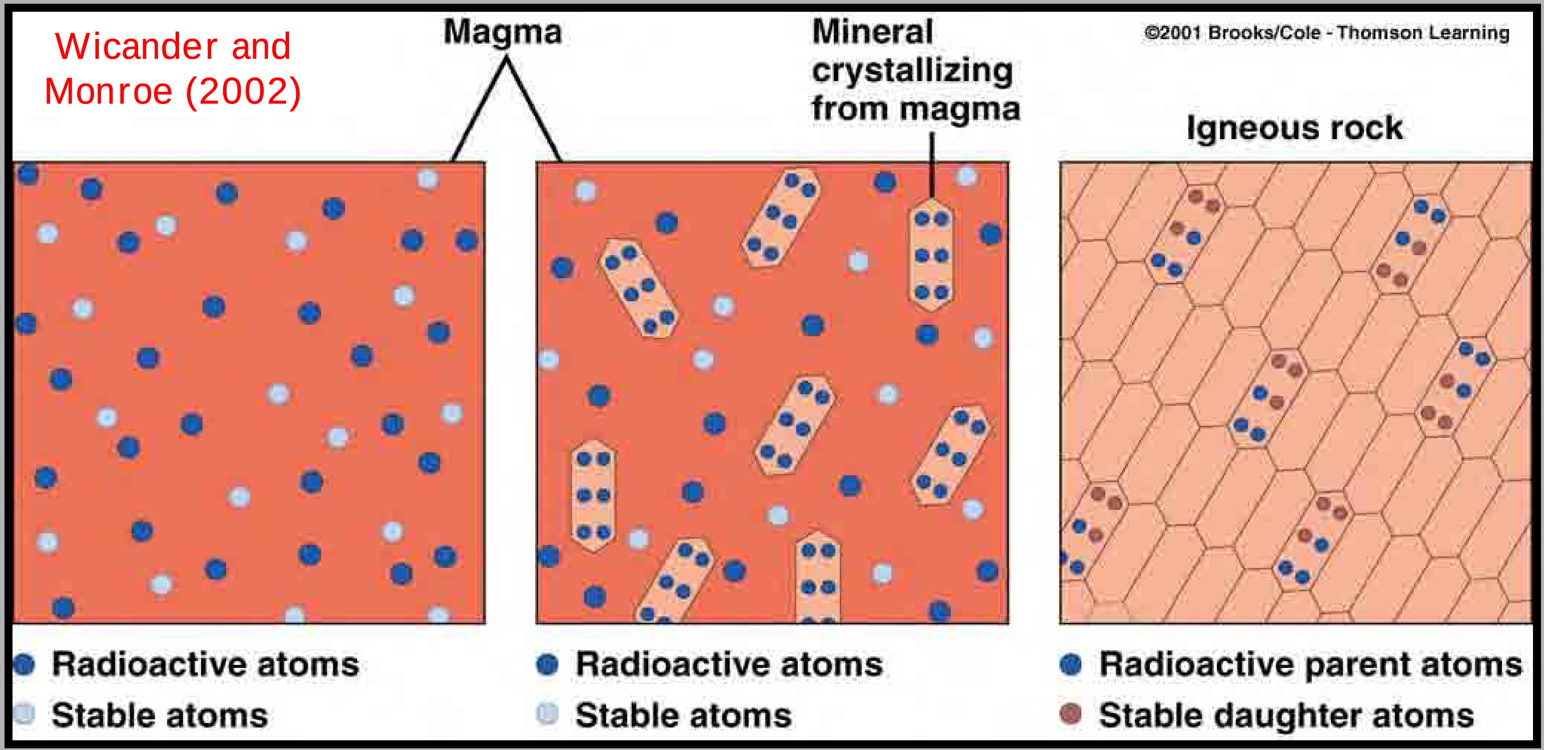
- Many isotopes present when the Earth formed have decayed away
- However, we know that decay rates are not affected by chemical or physical environments
- The rates are not affected by geological processes



Murck and Skinner, 1999

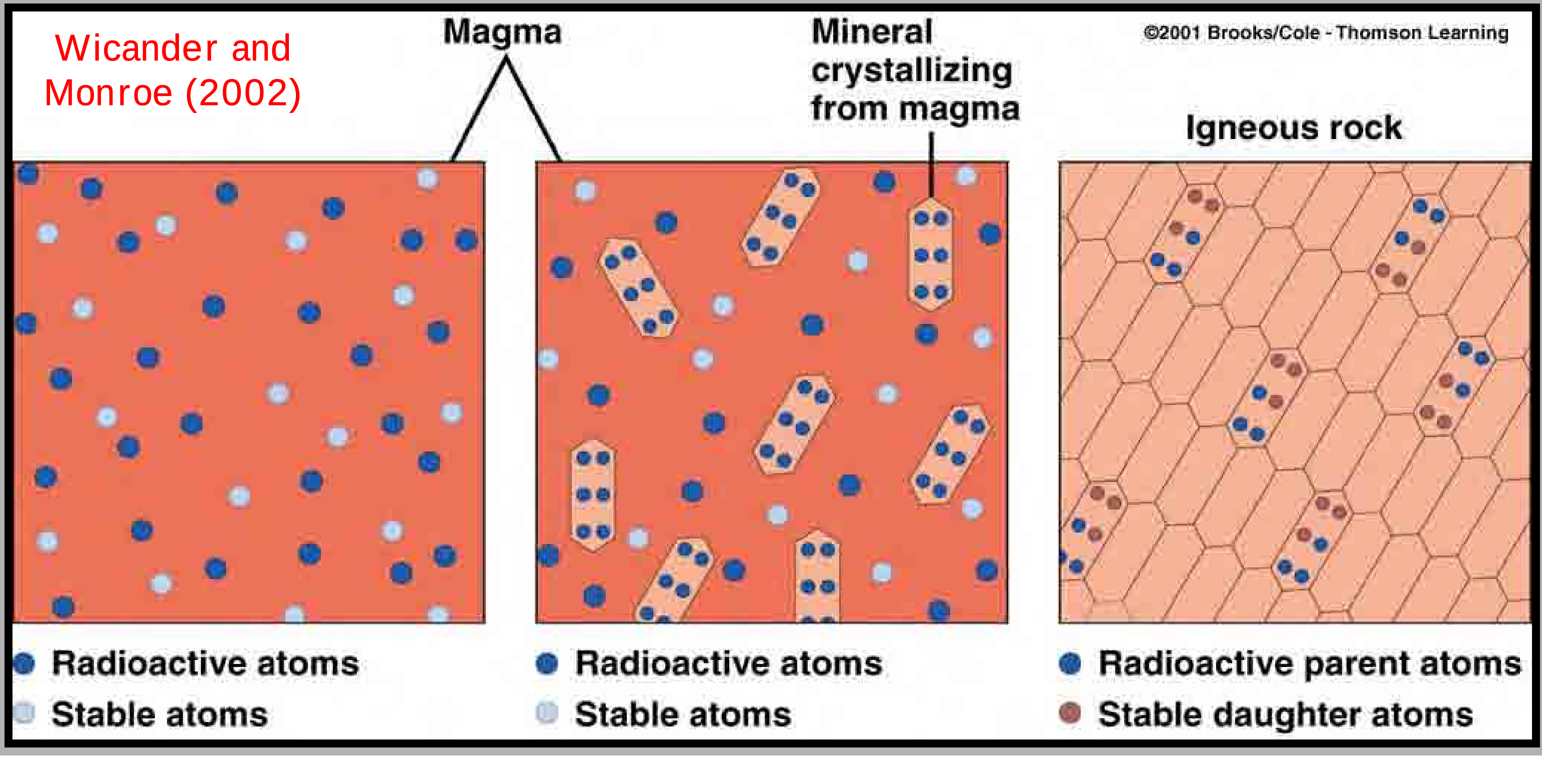
Dating igneous rocks

- **The most accurate radiometric dates are for the time of mineral crystallization in igneous rocks.**
- **Radioactive parent elements are incorporated into minerals as they crystallize because of their size.**

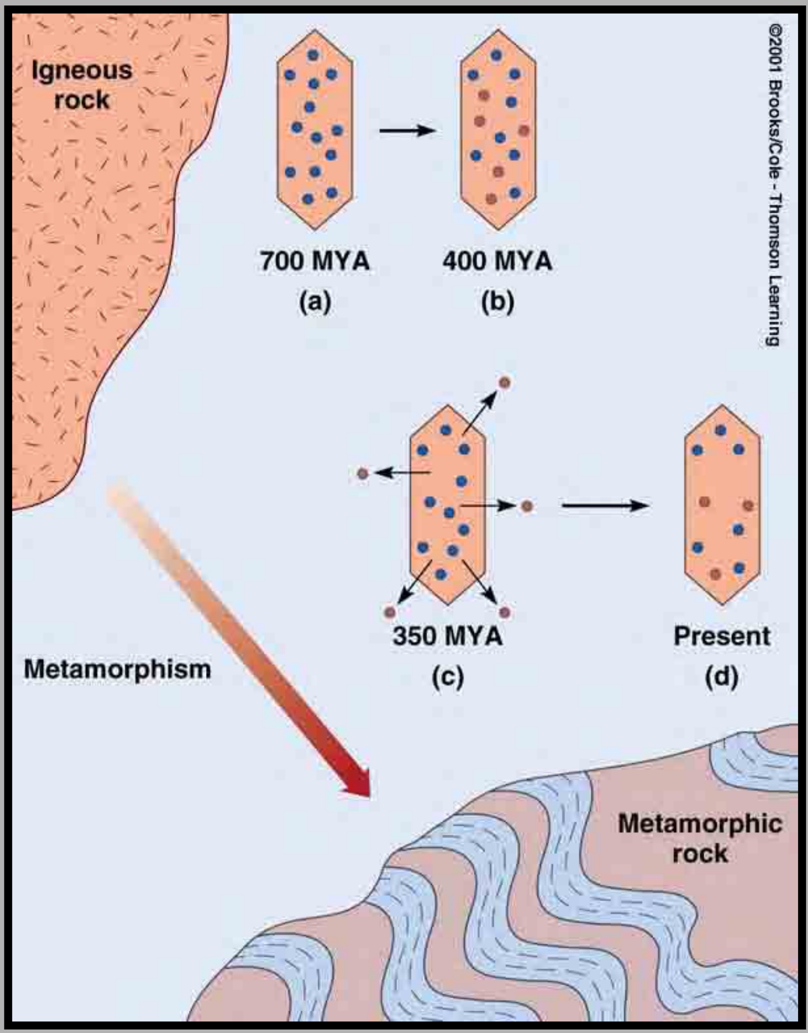


Dating igneous rocks

- Stable daughter atoms are usually not incorporated into the mineral because the atoms were too large
- As the parent atoms decay, the crystal structure of the mineral is deformed to accommodate the newly formed daughter atoms



Sources of Uncertainty



Wicander and Monroe (2002)

- **A closed system is required for accurate dating.**
- **Neither parent nor daughter can be added or removed**
- **If daughter atoms leak, the calculated age will be too low, and if parent atoms leak, the age will be too great.**
- **The intense heat and pressure of metamorphism can sometimes cause leakage**
- **If all the daughter atoms leak during metamorphism, then the date obtained will be for the metamorphic event**

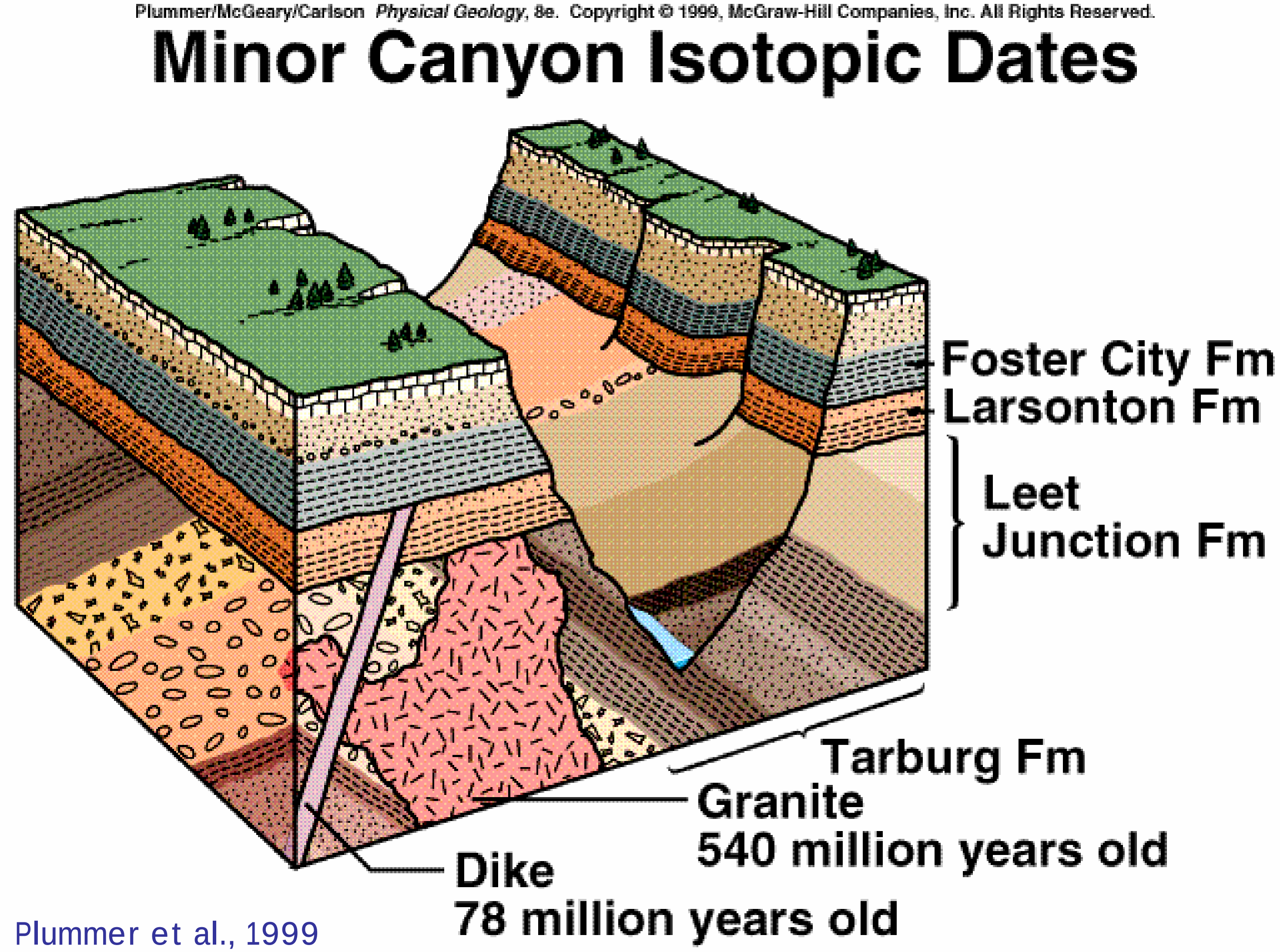
Principle Radioactive Isotopes

Parent	Daughter	Half life	Range	Materials
U-238	Pb-206	4.5 Ga	10 Ma - 4.6 Ga	Zircon, Perovskite
U-235	Pb-207	710 Ma	10 Ma - 4.6 Ga	Uraninite
Th-232	Pb-206	14 Ga	10 Ma - 4.6 Ga	
K-40	Ar-40	1.3 Ga	50,000 - 4.6 Ga	Mica, amphibole & volcanics
Rb-87	Sr-87	4.7 Ga	10 Ma - 4.6 Ga	Mica, feldspar, igneous & metamorphic
C-14	N-14	5730	100 - 70,000	C-bearing material

The dating systems

- Uranium-thorium-lead
  - Rocks that contain uranium such as granite or the mineral zircon can be dated three ways
- Potassium-argon
  - Found in biotite, mica & K-feldspars. Easily disturbed by metamorphism because the argon leaks
- Rubidium-strontium
  - Occurs in plagioclase and garnet, used for igneous and metamorphic rocks

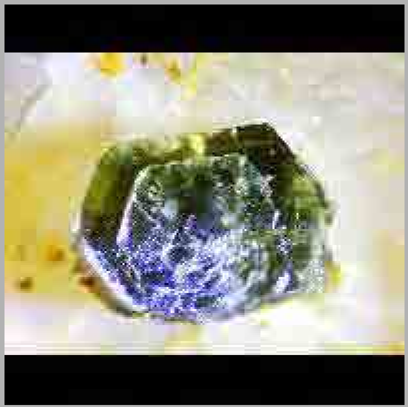
How can we use this?



Plummer et al., 1999

So what is the physical process of dating a rock?

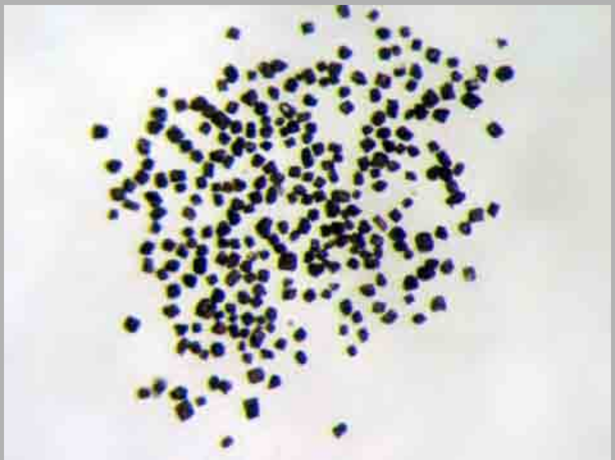
- Collect your sample
- Identify and classify
- Some minerals that are used for dating can be "plucked" off the rock, ex. Phlogopite micas



www.mindat.org//

So what is the physical process of dating a rock? [2]

- Most of the time, minerals are too small, and have to be separated from the host rock in a variety of steps.
- Example: Zircon grains can be 150 µm in length.. Perovskite can be 25 µm…



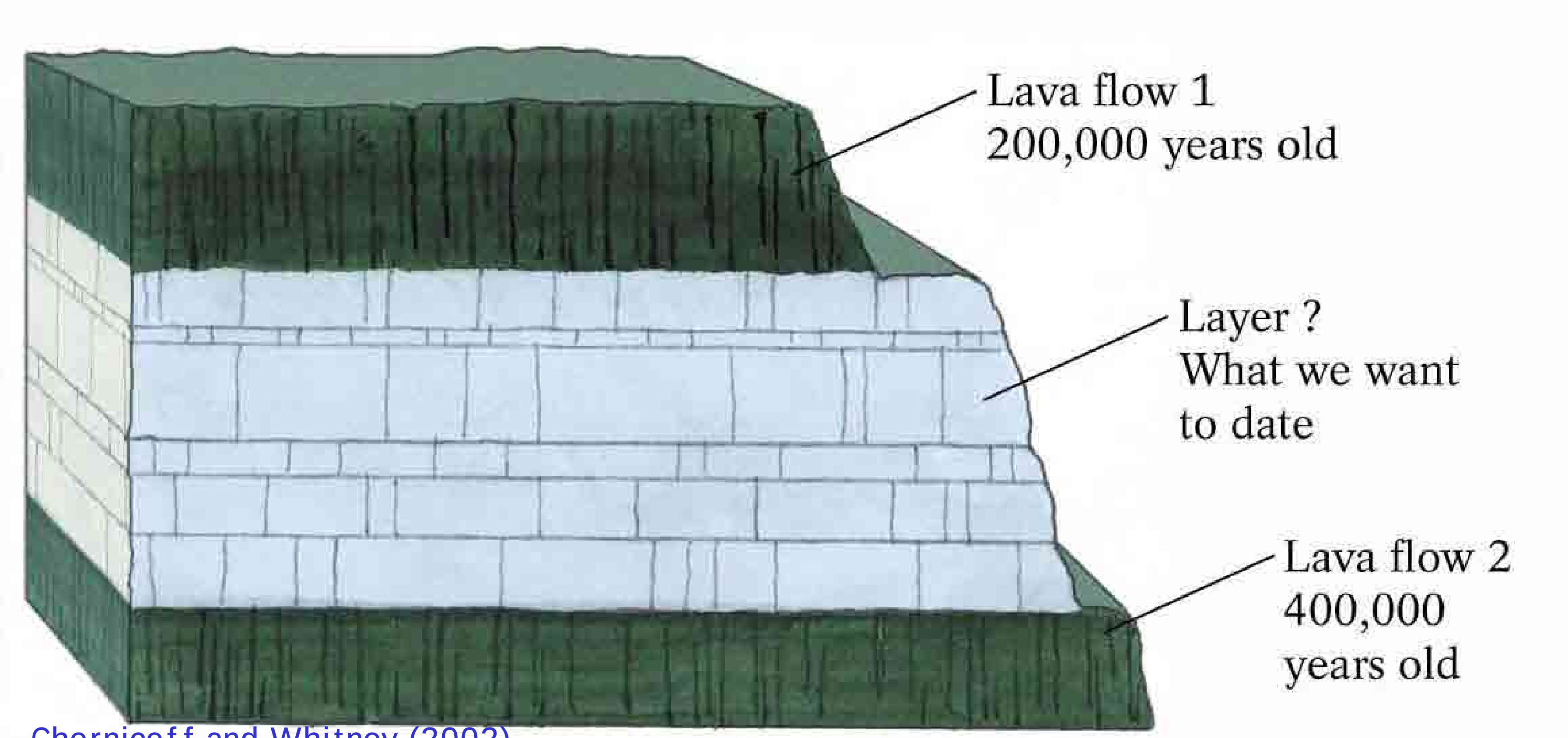
Entire Field of View: 2 mm

So what is the physical process of dating a rock? [3]

- Jaw crushing, disk mills, shatter boxes and hand crushing
- Wifley tables: Vibrating water tables (remove clays)
- Sifting, magnetic separations (variety)
- Chemical techniques
- Hand picking grains suitable for analyses
- Cleaning grains, weighing grains
- “Clean lab” chemistry methods
- Mass spec analyses
- Data analyses
- Very costly and lengthy process
- In-situ analyses becoming more popular

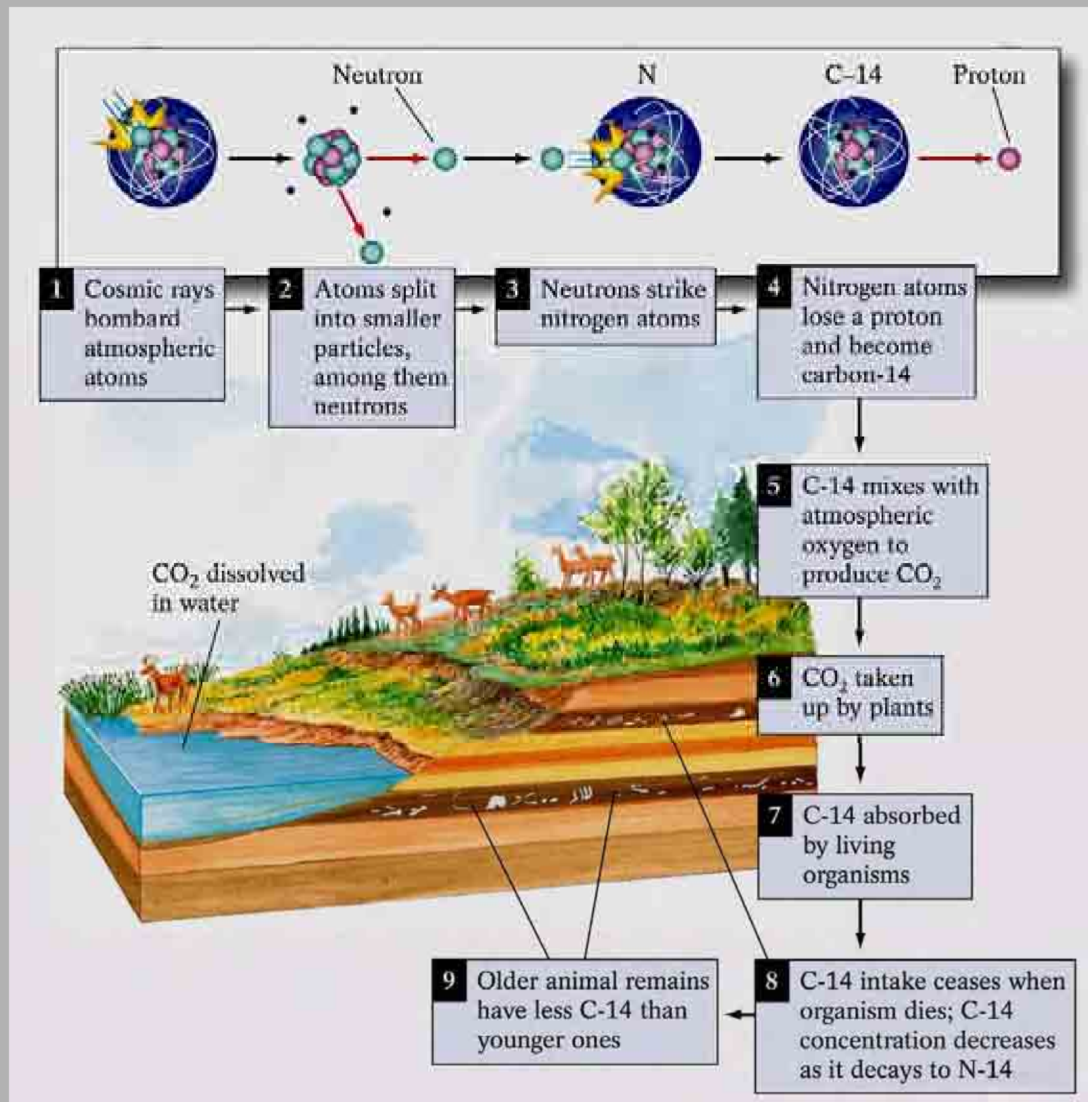
Dating sedimentary rocks

- **Grains in sedimentary rocks will not record the age of sedimentation**



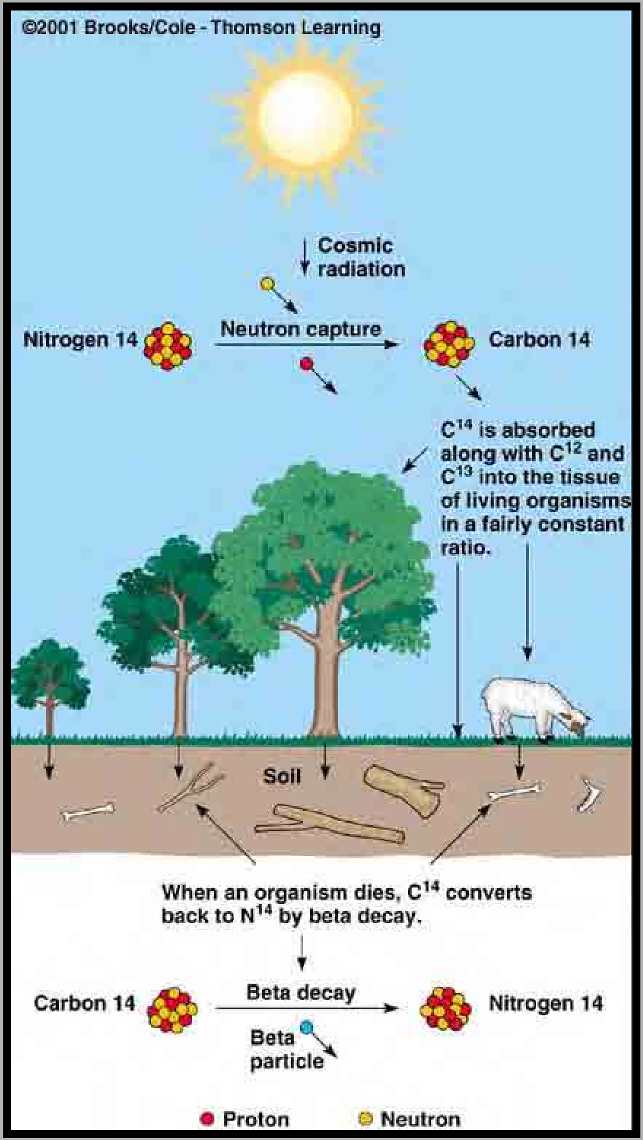
Chernicoff and Whitney (2002)

Carbon-14.



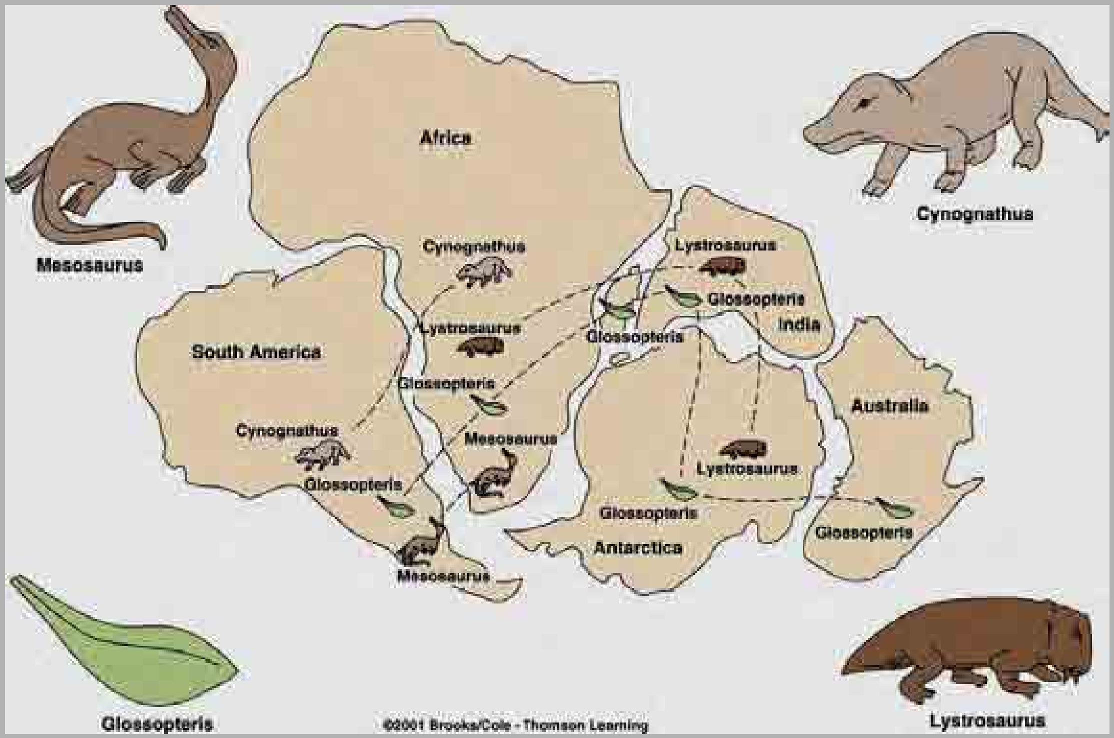
Chernicoff and Whitney (2002)

Carbon 14 Dating Method



- Generally applied to once living things.
- Widely used in archaeology.
- It has to be recognized that the ratio of C^{14} to C^{12} production has varied somewhat over the past several thousand years.
- Dates obtained using this technique have been corrected to reflect these variations.

Wicander and Monroe, 2002



Wicander and Monroe (2002)