The age of rocks

✶ The rate of geological processes

Different processes, different timescales:

- ***A few minutes or less*** —— Earthquakes, meteorite impacts
- ***Hours to days*** —— Floods, typhoons, volcanic eruptions
- ***Months to years*** —— Δ in sediment discharge, beach erosion
- ***10s to 100s of years*** —— Filling of embayments by sediments
- ***1000s to 10,000s of years*** —— Glacioeustatic sea level changes
- ***1000,000s of years*** —— Speciation, carving of large canyons
- ***10,000,000s of years and longer*** —— Opening of ocean basins, formation of mountain belts

Direct measurements

- Rate of beach erosion
- Seasonal variations in sediment discharge by rivers
- Motion of glacier and tectonic plates using GPS

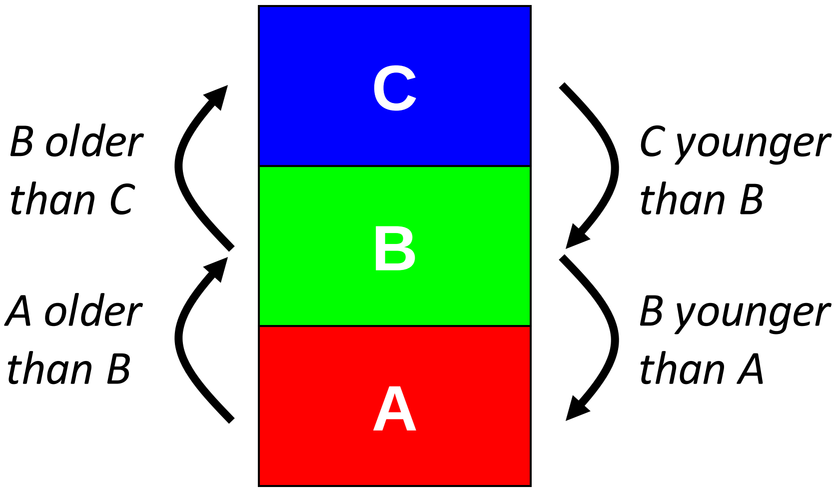
Historical documents

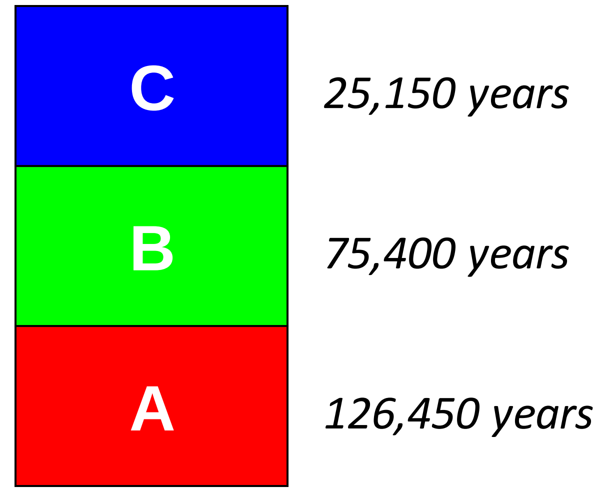
Frequency of *earthquakes, tsunamis, volcanic eruptions*

BUT HOW DO WE KNOW THE PACE OF VERY SLOW PROCESSES AND THE CHRONOLOGY OF GEOLOGIC EVENTS THAT ARE VERY OLD…

…AND HOW DO WE KNOW WHAT “VERY OLD” MEANS?

Relative ages vs. Absolute ages





This information began to be available at the end of the 17th century

This information was not available before the 20th century!

✶ Stratigraphy: the study of sedimentary layers (strata)

https://en.wikipedia.org/wiki/Nicolas_Steno

Nicolas Steno (1638-1686)

Berkeley

- *Glossopetrae* (tongue stones) identical to modern shark teeth.

  → first proof of the **biological origin of fossils**

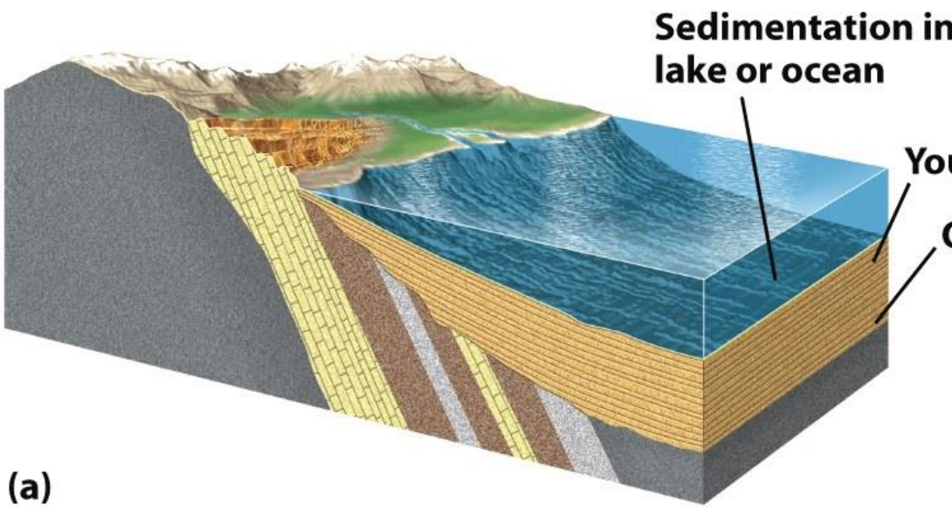
Understanding Earth

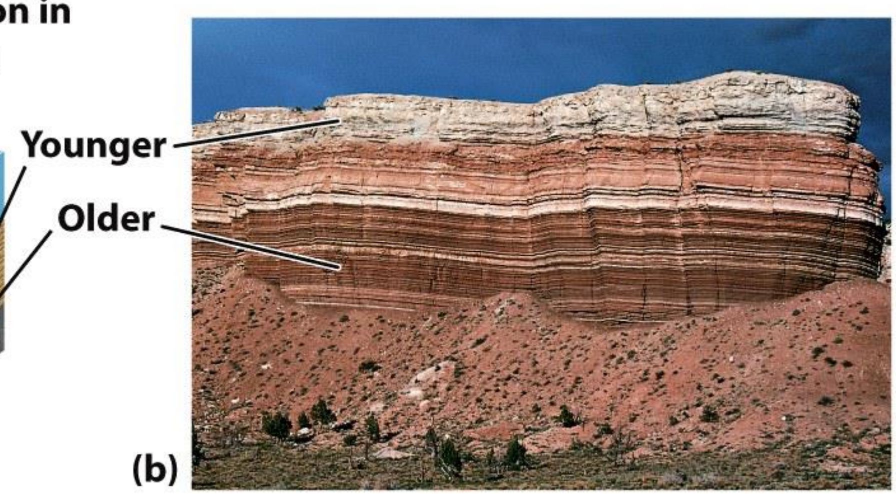
- Fossils can be used to **reconstruct past environments**.

- BASIC PRINCIPLES OF STRATIGRAPHY:

1. Principle of original horizontality

2. Principle of superposition





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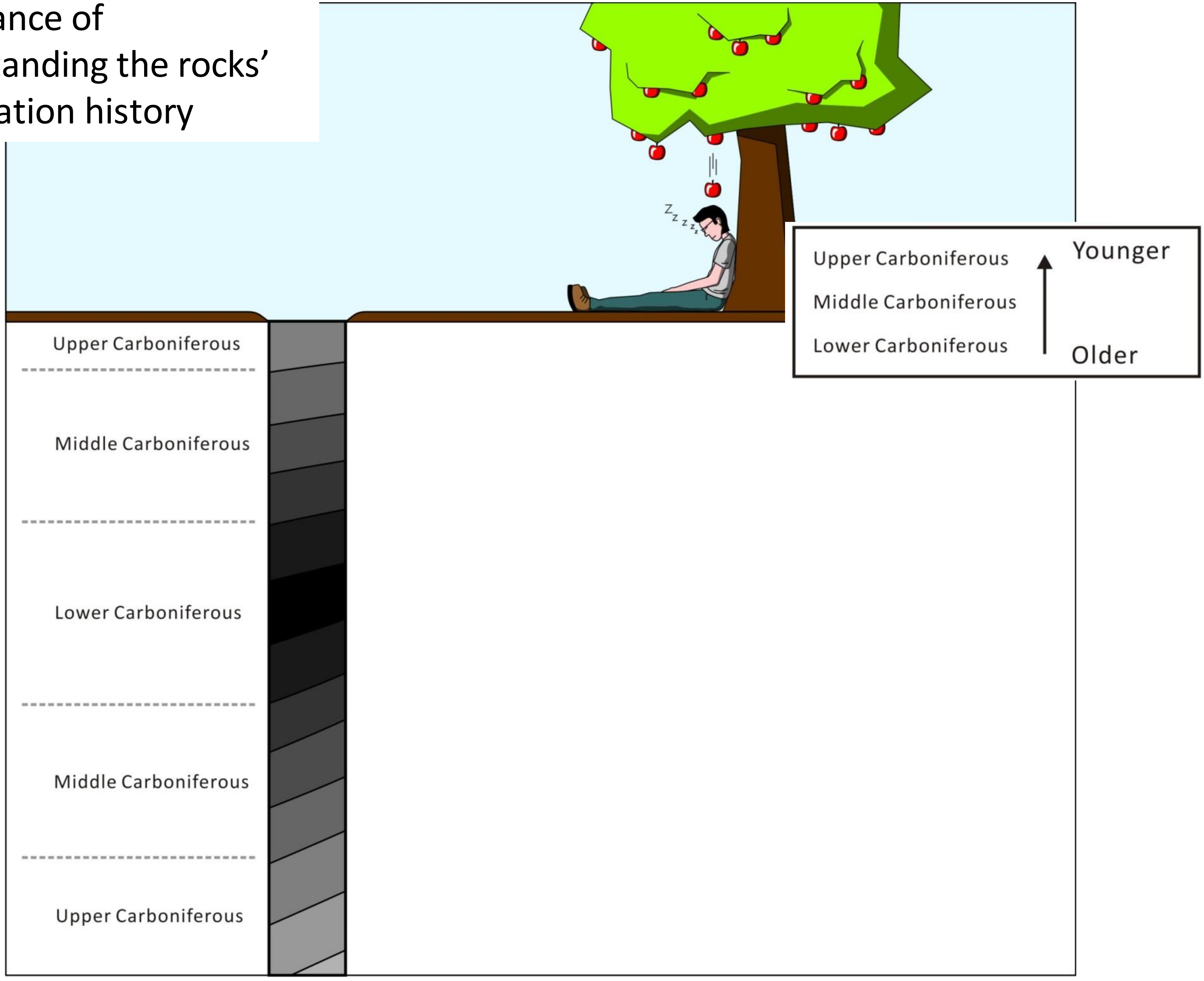
3 IMPORTANT ISSUES

- **TECTONIC DEFORMATION**
- **CORRELATION** BETWEEN LAYERS AT DIFFERENT LOCATIONS
- TIME GAPS (PERIODS OF **NON-DEPOSITION** OR **EROSION**) = **UNCONFORMITIES**

Importance of understanding the rocks' deformation history

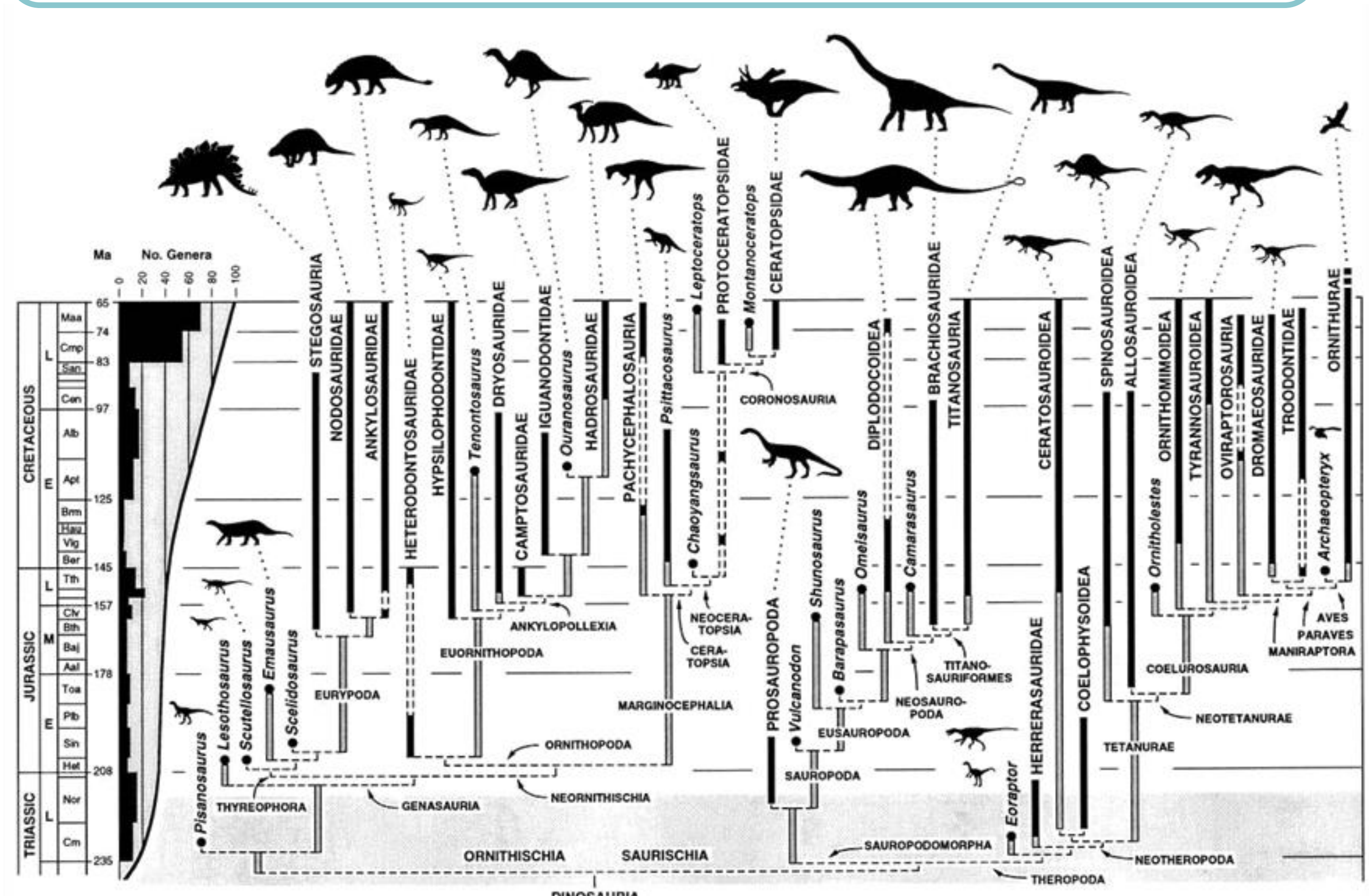


✶ Biostratigraphy

Biostratigraphy: Study of the fossil content of rock layers to find out their relative ages

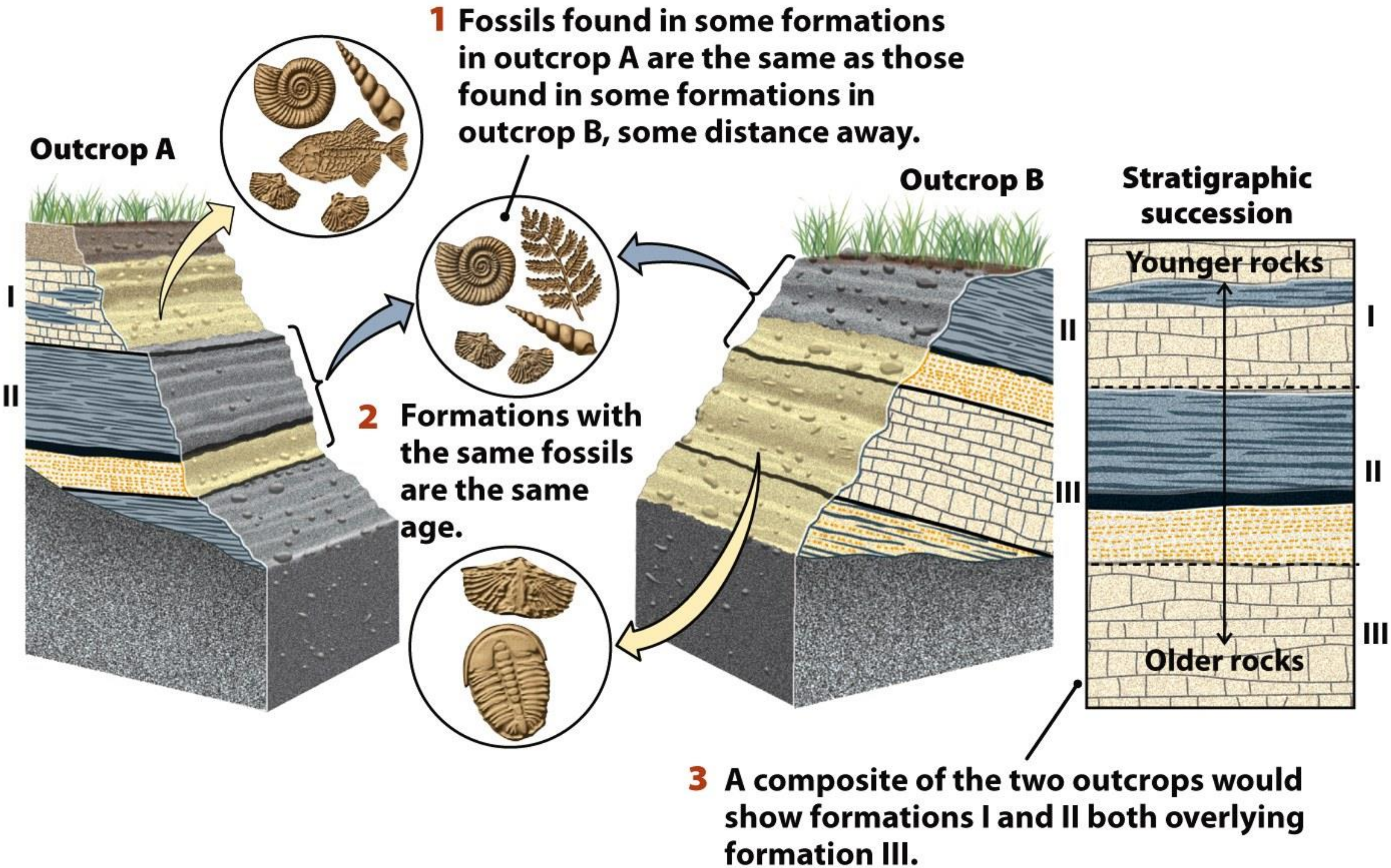
→ Principle of faunal succession

Since life evolves, different organisms have lived at different times.



Sereno (1999)

Fossils are useful to determine the relative age of sedimentary rocks and correlate sections that distant from each other.



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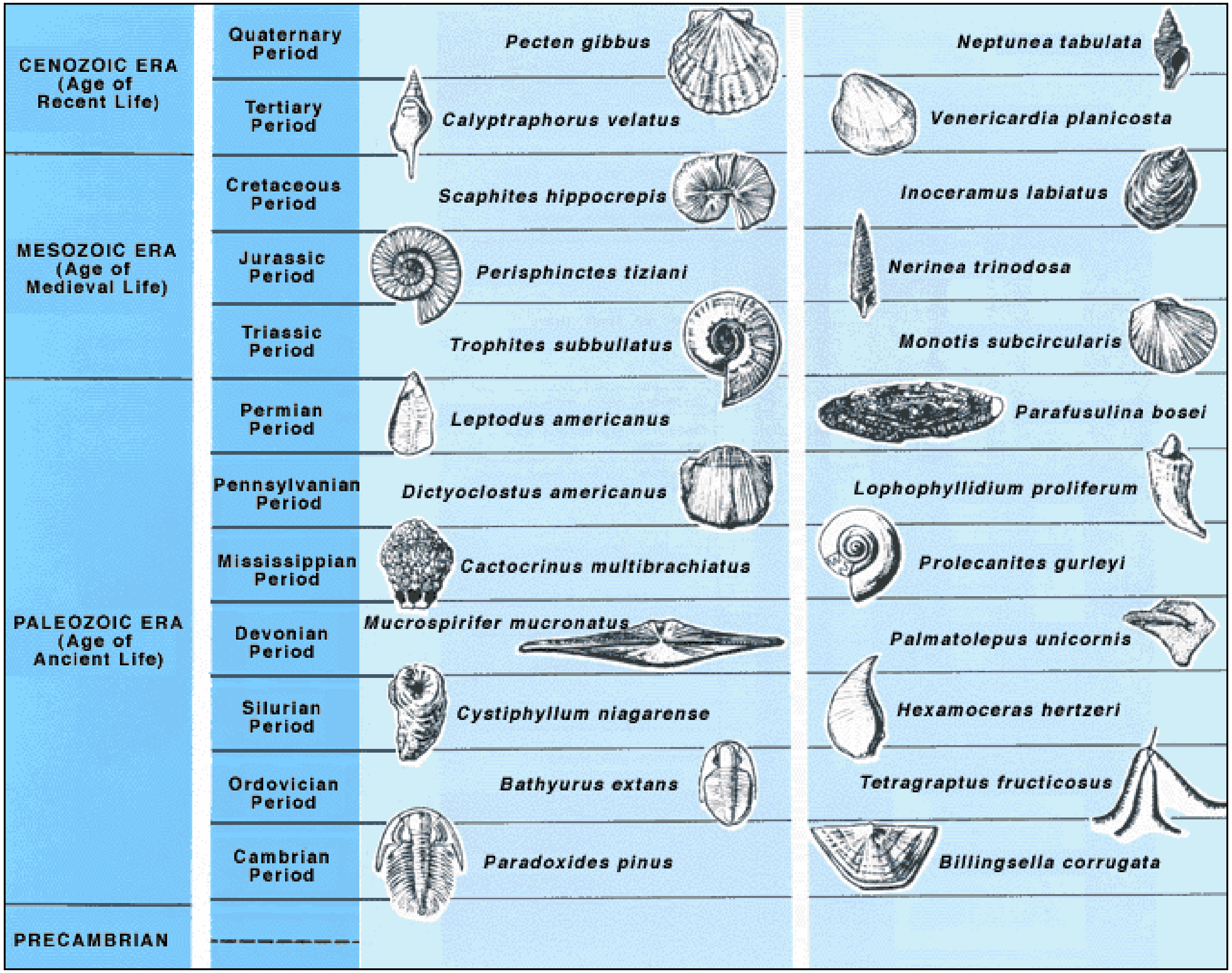
Pioneers in biostratigraphy:

Jean-Andre Deluc (1727-1817); Georges Cuvier (1769-1832); Alexandre Brongniart (1770-1847); William Smith (1769-1839)

Index fossils = "forms of life which existed during limited periods of geologic time and thus are used as guides to the age of the rocks in which they are preserved" (definition of USGS)

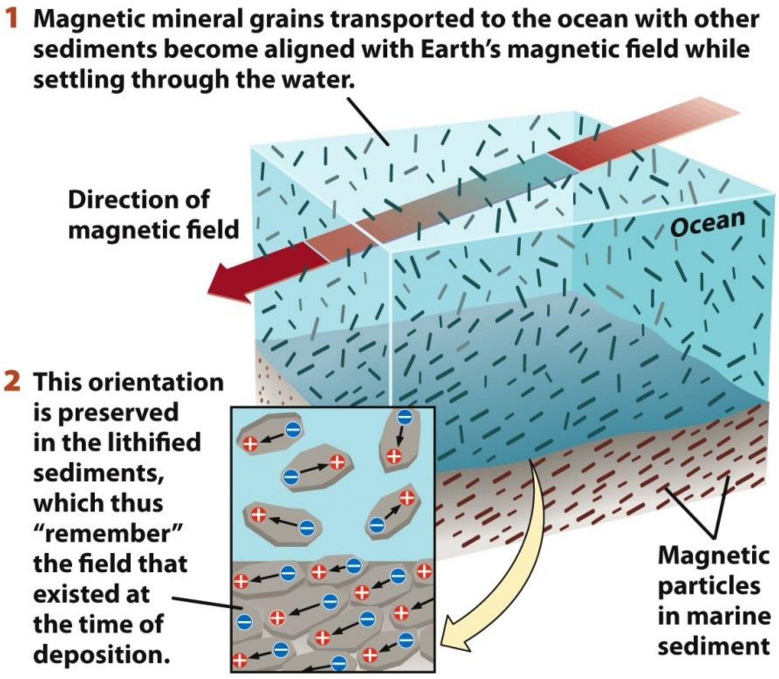


USGS

✶ Other means of stratigraphic correlations

- ***Chemical stratigraphy***
  - Stratigraphic correlations based on the chemical composition of sedimentary rocks (e.g. concentration of Fe, Mn) which reflects the composition of the ocean when sediments were deposited.

- ***Paleomagnetic stratigraphy***
  - The direction of the magnetic field preserved in volcanic rocks and in some sedimentary rocks can be used as a tool for correlation and dating.



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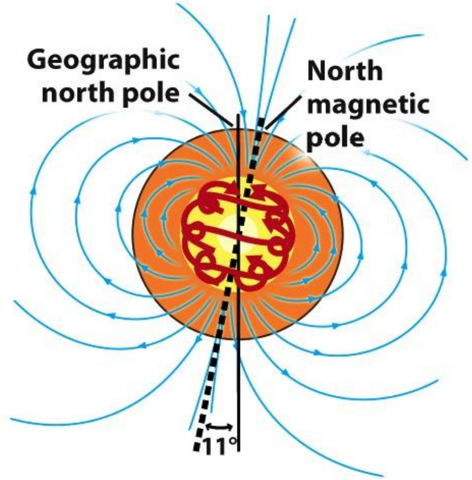
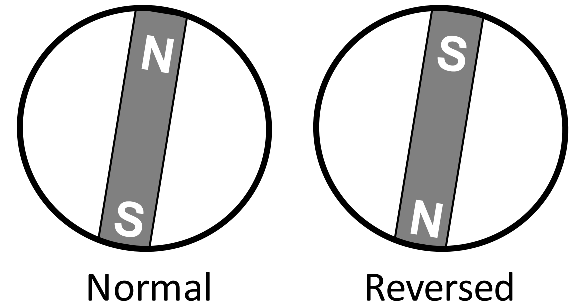
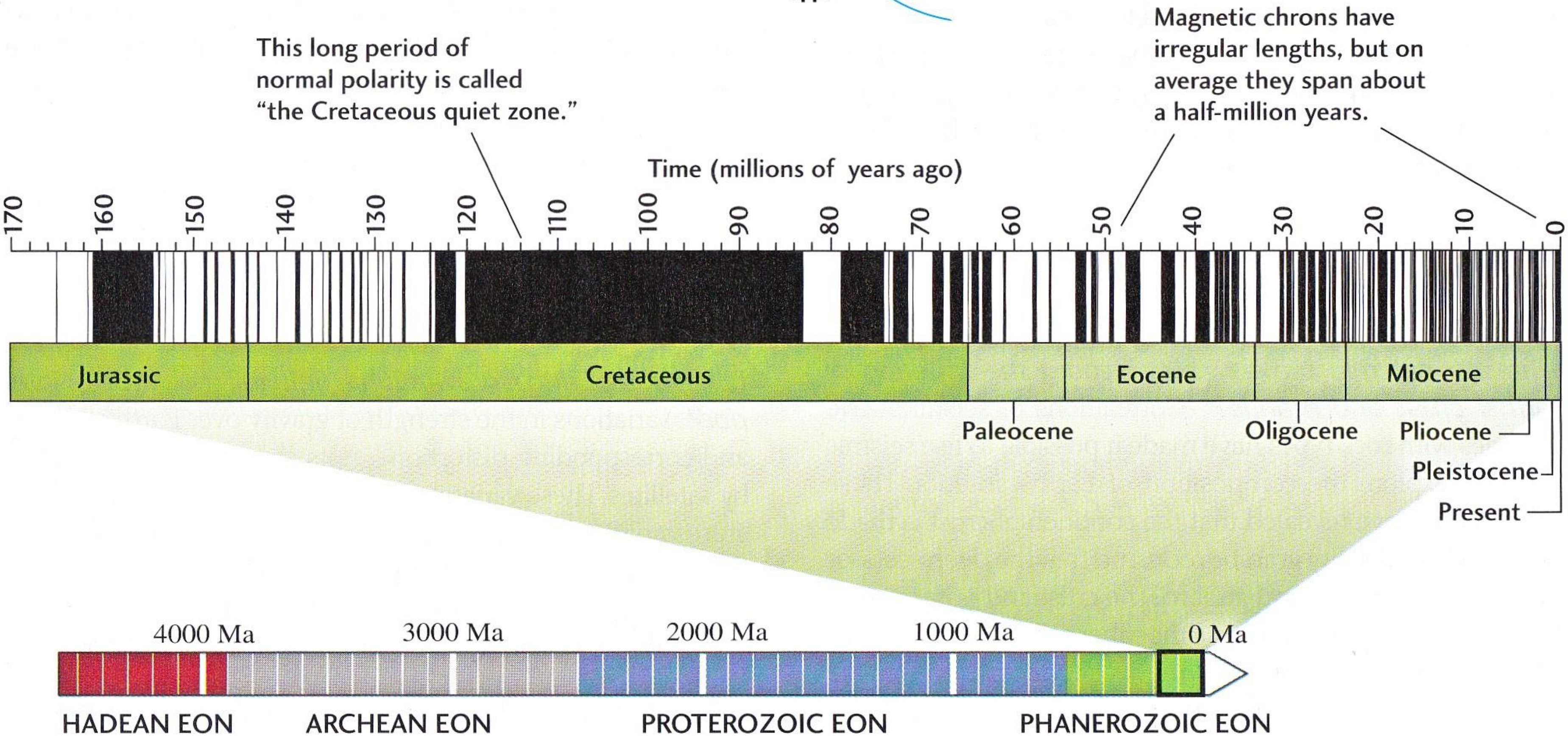
The magnetic polarity time scale







Understanding Earth (p. 389)

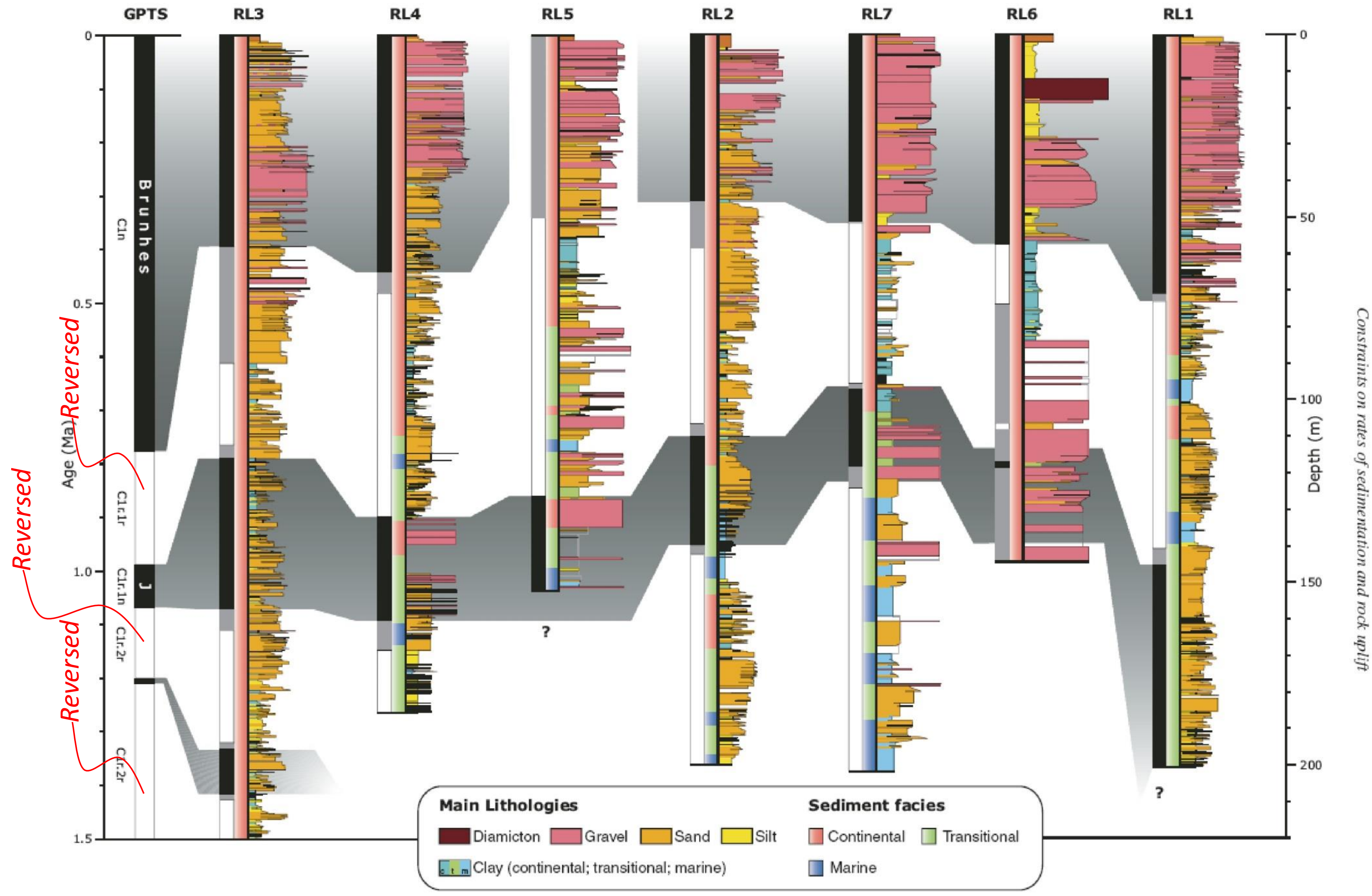


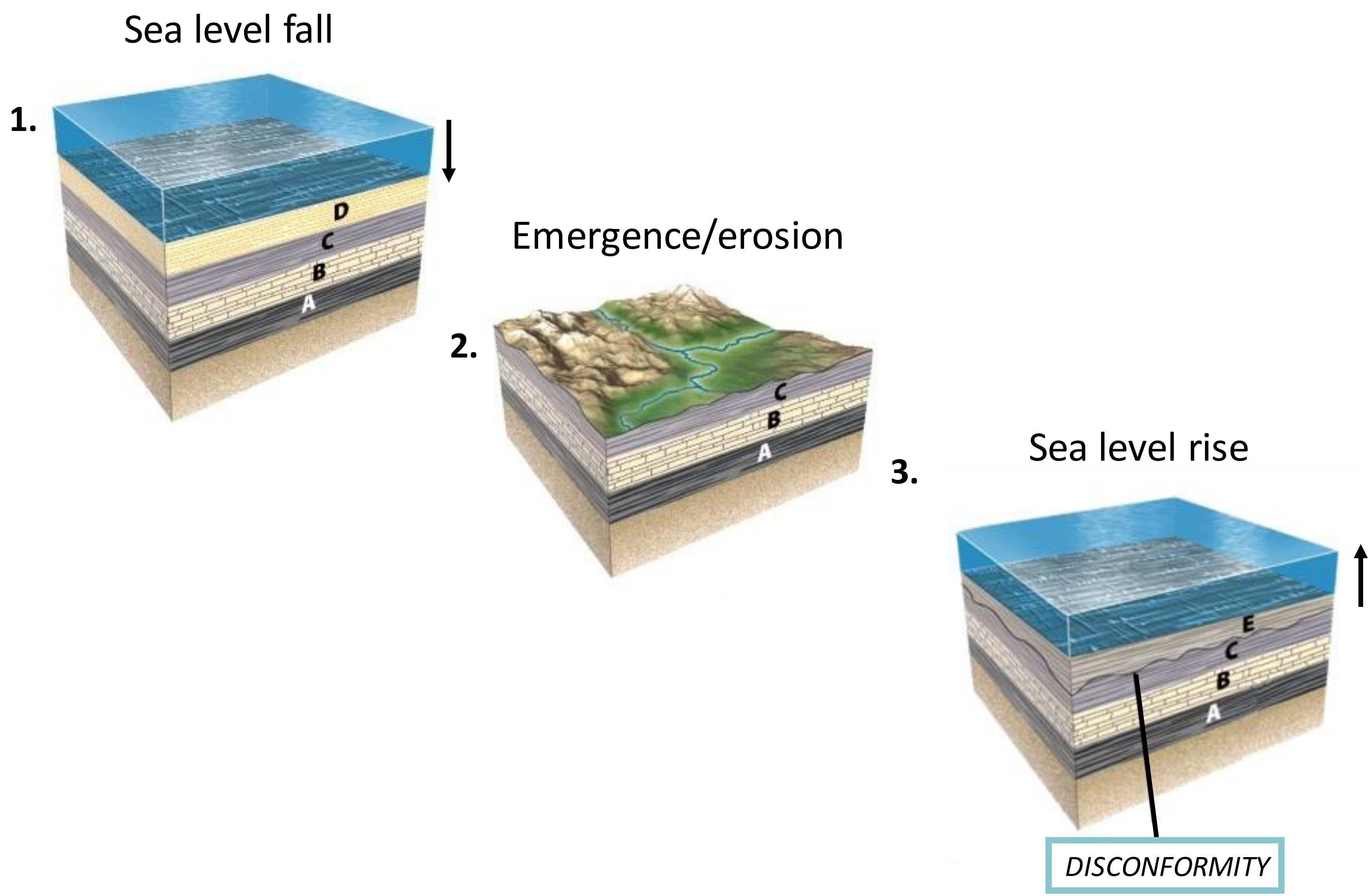
Figure 6. Magnetostratigraphic correlations of the studied cores ordered longitudinally from the west (Cilavegna RL3) to the east (Ghedi RL1). Datum is referred to the ground surface. The geomagnetic polarity time scale (GPTS) adopted for polarity interpretation is that of Cande and Kent (1995).

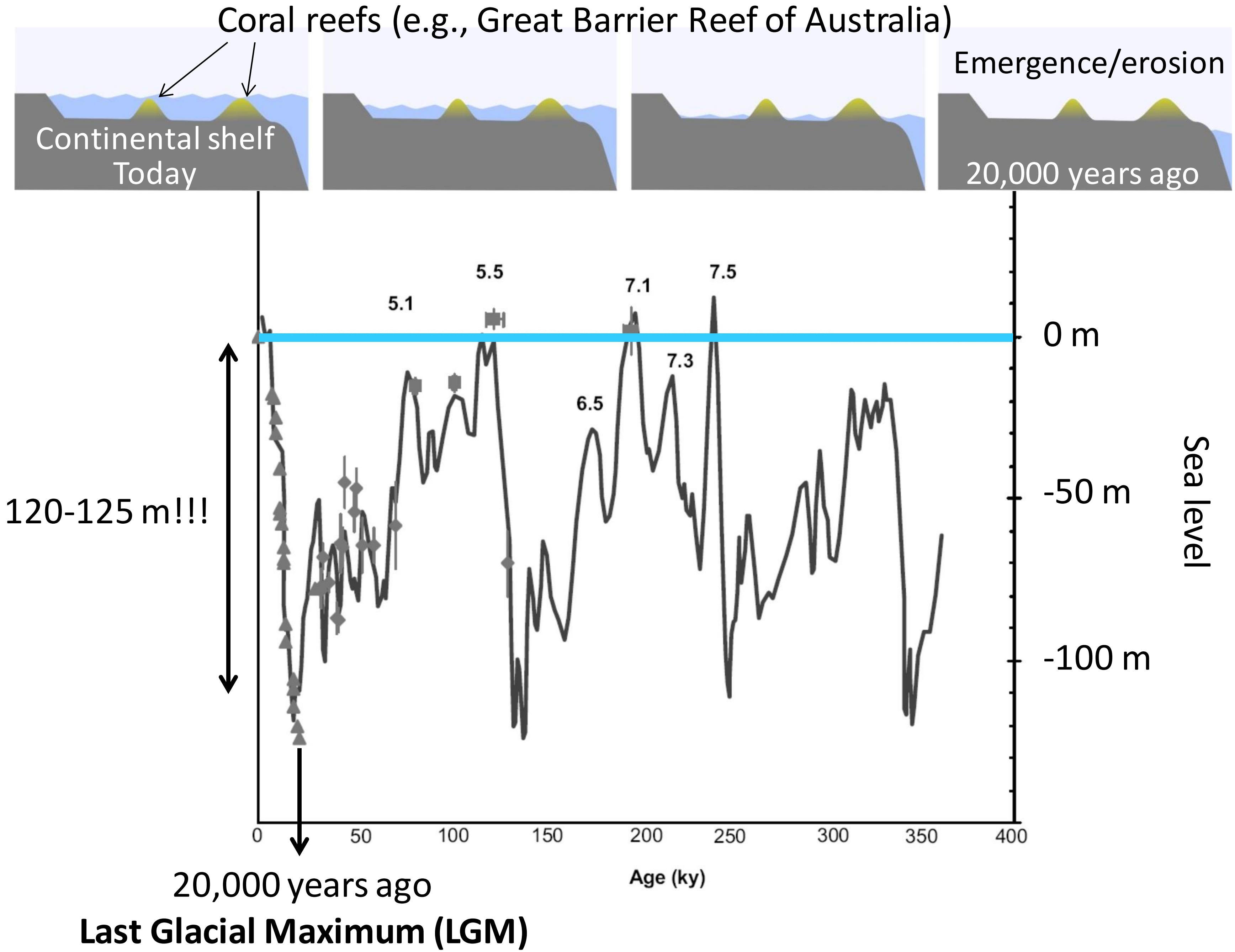
Scardia et al. (2006)

- ***Tephrostratigraphy***
  - Method for correlating geological rock sequences based on volcanic ash layers (*tephra* means ashes in Greek). This method requires to be able to recognize specific ash layers using criteria such as their mineralogical and chemical compositions (used as “fingerprints”).

✶ Unconformities: time gaps in the stratigraphic record

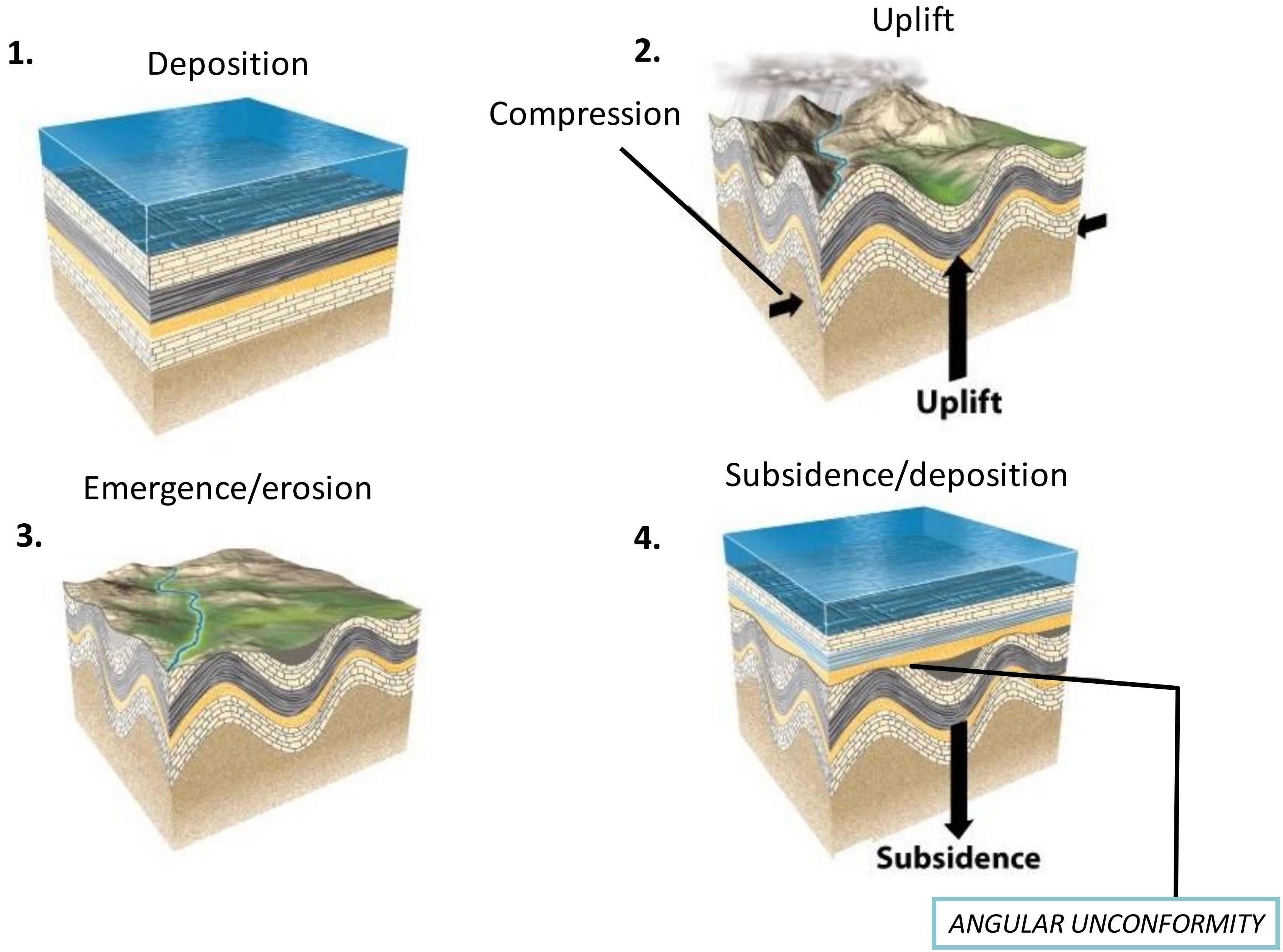
(1)





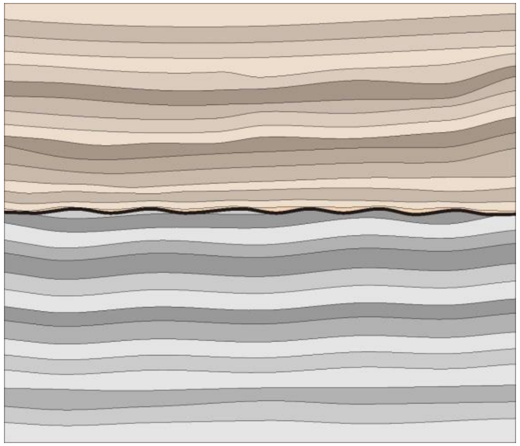
Lea et al. (2002)

(2)



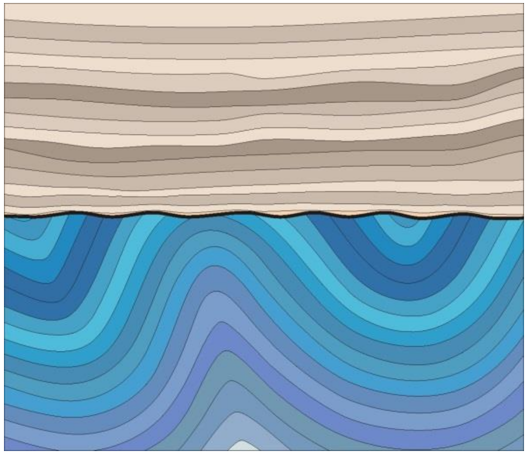
Understanding Earth (modified)

DISCONFORMITY



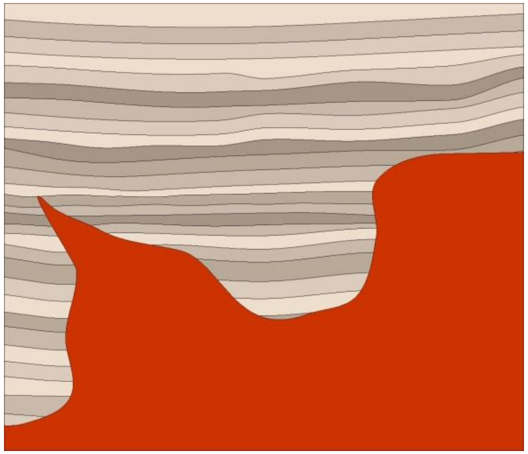
Rock strata above and below the unconformity are **parallel**.

ANGULAR UNCONFORMITY



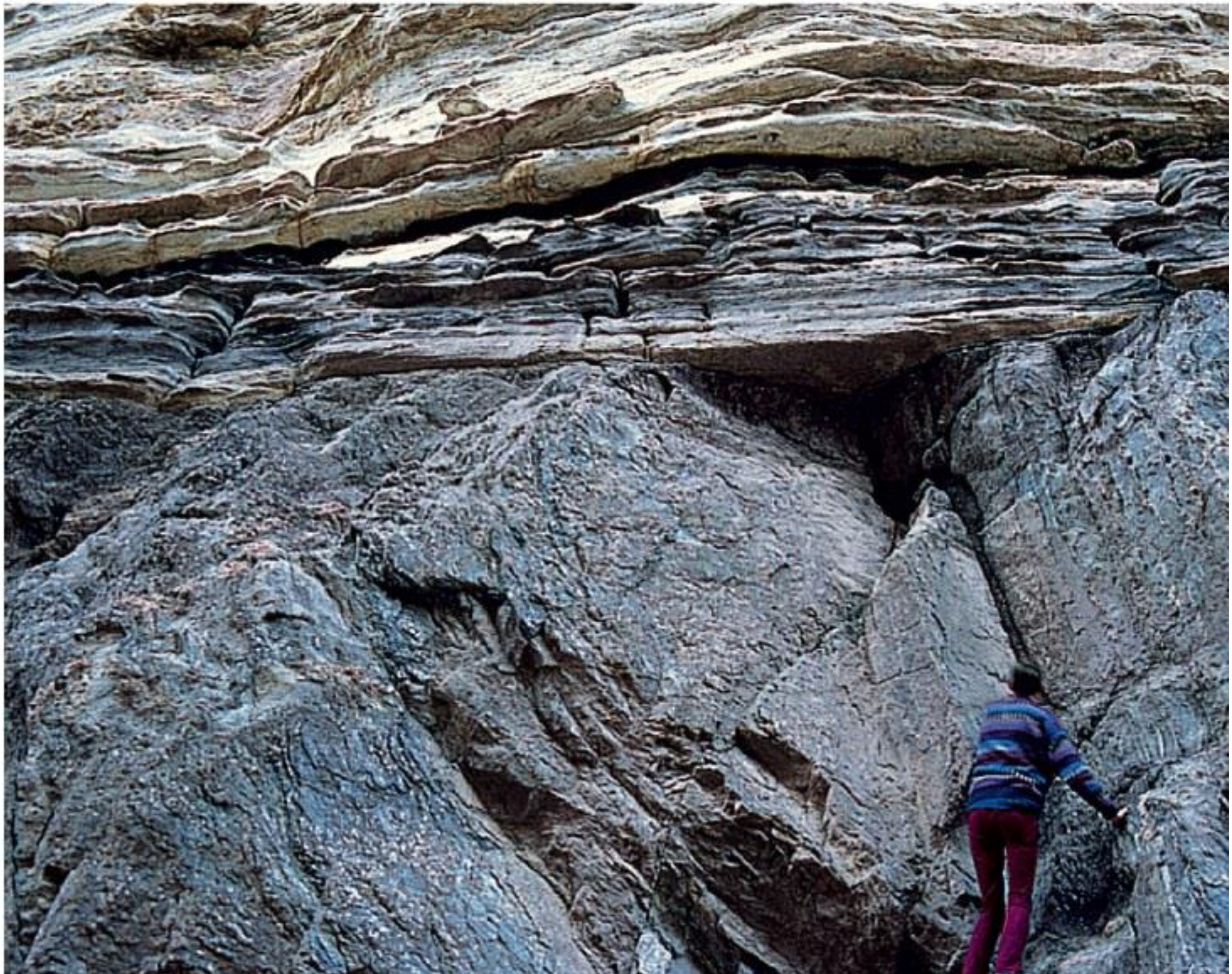
Rock strata above and below the unconformity are **not parallel**.

NONCONFORMITY



Sedimentary rock strata in contact with unstratified **metamorphic** or **igneous** rocks.

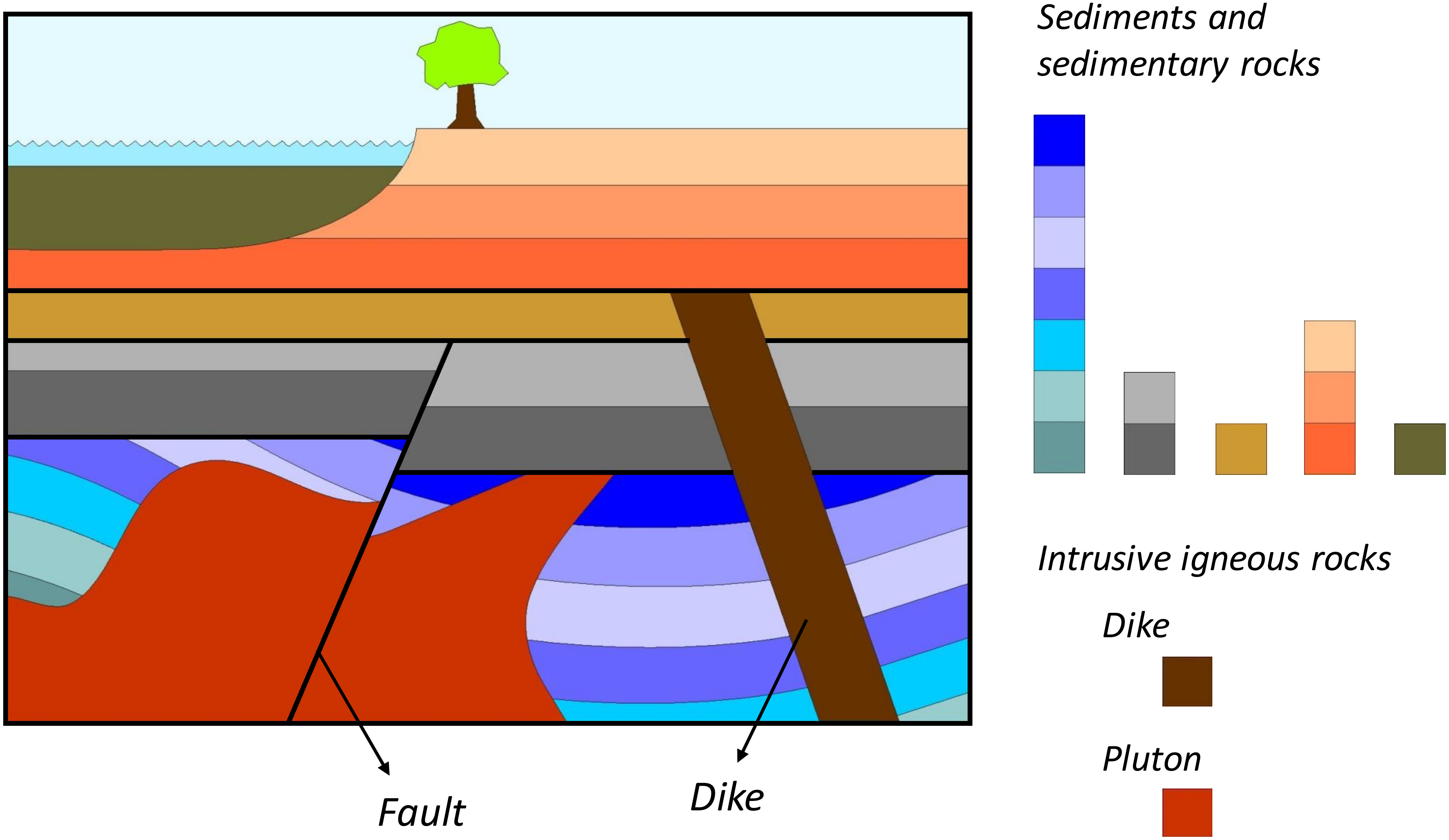
John Grotzinger & Thomas H. Jordan (2010) *Understanding earth* 6th edition W H Freeman & Co



Understanding Earth

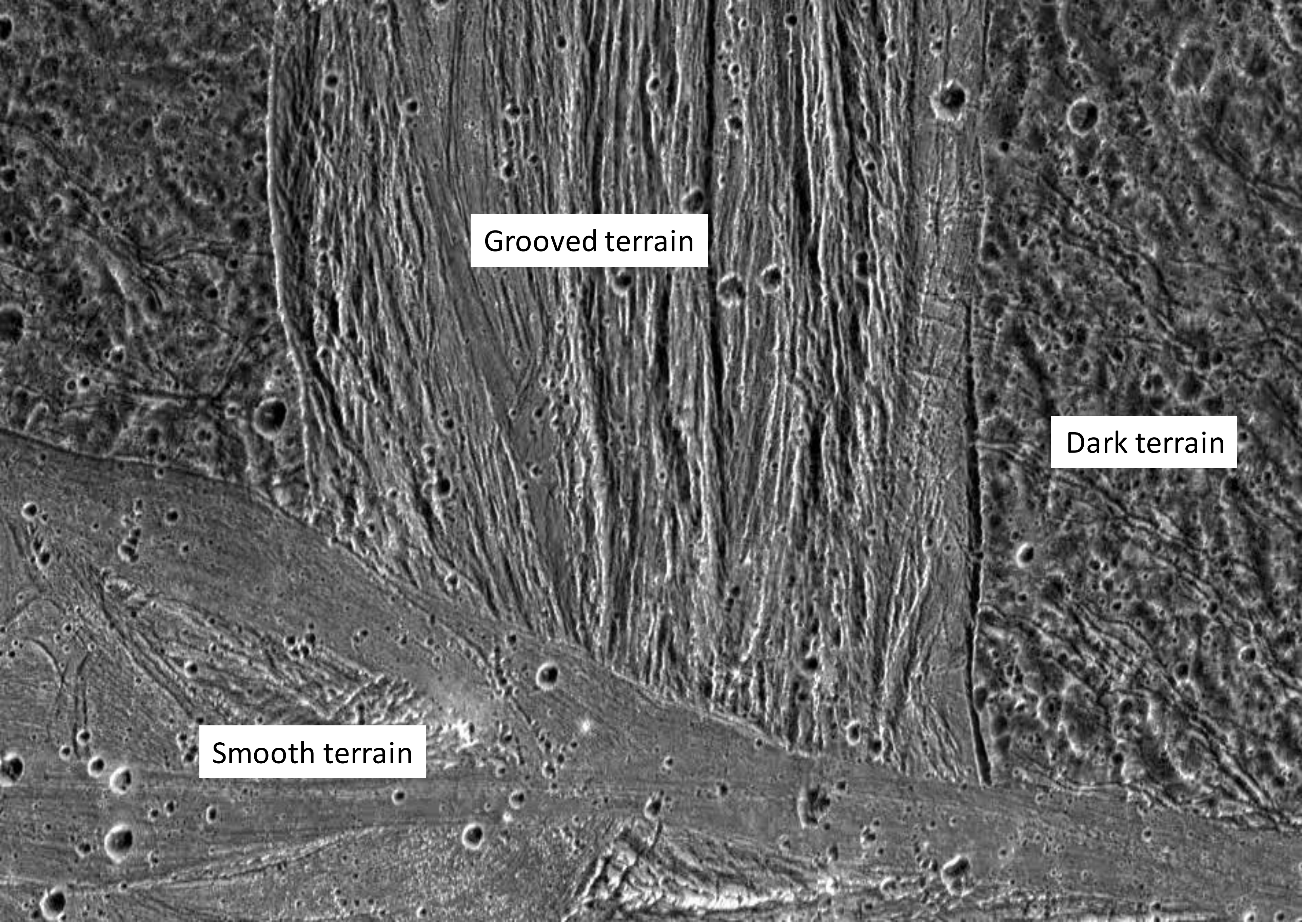
✶ Cross-cutting relationships

Younger geologic features cut older ones



East Aichi Prefecture (Touei-chou,東栄町)

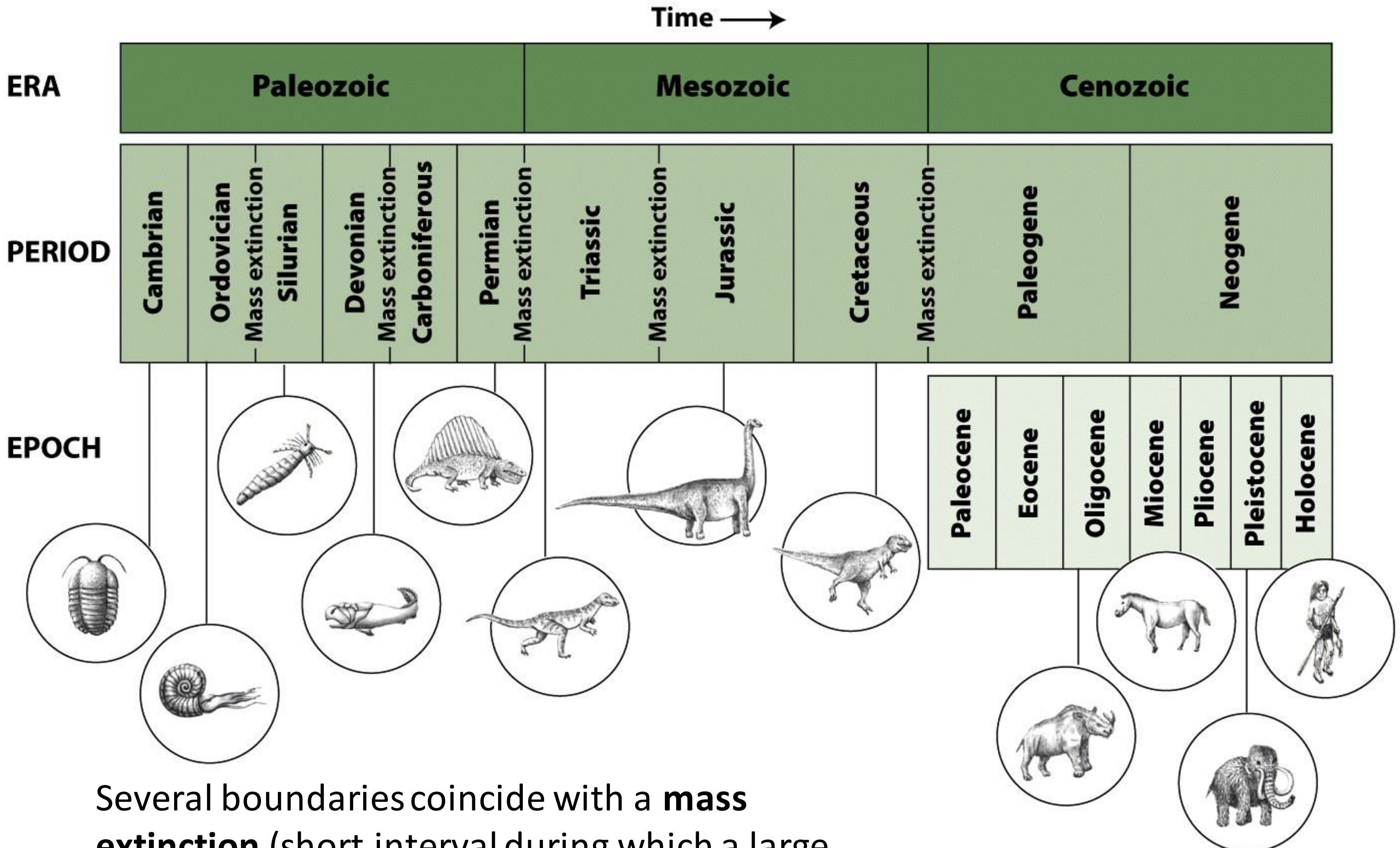

Sill
Sedimentary rocks
Sedimentary rocks



NASA (Galileo image of Ganymede)

✶ The geologic time scale based on relative ages

The **geologic time scale** « divides Earth History into intervals marked by distinct sets of fossils »



Several boundaries coincide with a **mass extinction** (short interval during which a large proportion of species disappears)

Understanding Earth

✶ The absolute age of rocks

- ***How old is the Earth?***

- ***Age based on religious believes***

*Archbishop James Ussher (1581-1656): **6000** yrs, based on a careful study of the Old Testament*

- ***Early scientific calculations***

*Comte de Buffon (1707-1788): **75,000** yrs, based on the time it takes for red-hot cannon balls to cool down extrapolated to an iron ball the size of the Earth*

*Jean Fourier (1768-1830): **100,000,000** yrs, based on a set of mathematical equations taking into account the insulating effect of the Earth's crust*

*Lord Kelvin (1824-1907): between **20,000,000** and **400,000,000** yrs, based on more advanced calculations in thermodynamics*

*John Joly (1857-1933): between **80,000,000** and **90,000,000** yrs for the oceans, based on their sodium content and assuming a constant supply rate by rivers*

- ***Radiometric dating and the correct age of the Earth***

Henri Becquerel (1852-1908) discovers radioactivity in 1896.

*Ernest Rutherford (1871-1937) came up with a technique to measure the age of rocks based on radioactive decay. He was the first to date a mineral and came up with an age of **500,000,000** years.*

*Clair C. Patterson (1922-1995): **4,550,000,000** yrs, currently accepted age of the Earth based on the age of meteorites*

TABLE 8.1 Major Radioactive Elements Used in Isotopic Dating

Isotopes: Parent	Isotopes: Daughter	Half-Life of Parent (years)	Effective Dating Range (years)	Examples of Minerals and Materials That Can Be Dated
Rubidium-87	Strontium-87	49 billion	10 million–4.6 billion	Muscovite, biotite, orthoclase feldspar
Uranium-238	Lead-206	4.5 billion	10 million–4.6 billion	Zircon, apatite
Potassium-40	Argon-40	1.3 billion	50,000–4.6 billion	Muscovite, biotite, hornblende
Uranium-235	Lead-207	0.7 billion	10 million–4.6 billion	Zircon, apatite
Carbon-14	Nitrogen-14	5730	100–70,000	Wood, charcoal, peat; bone and tissue; shells and other calcium carbonates

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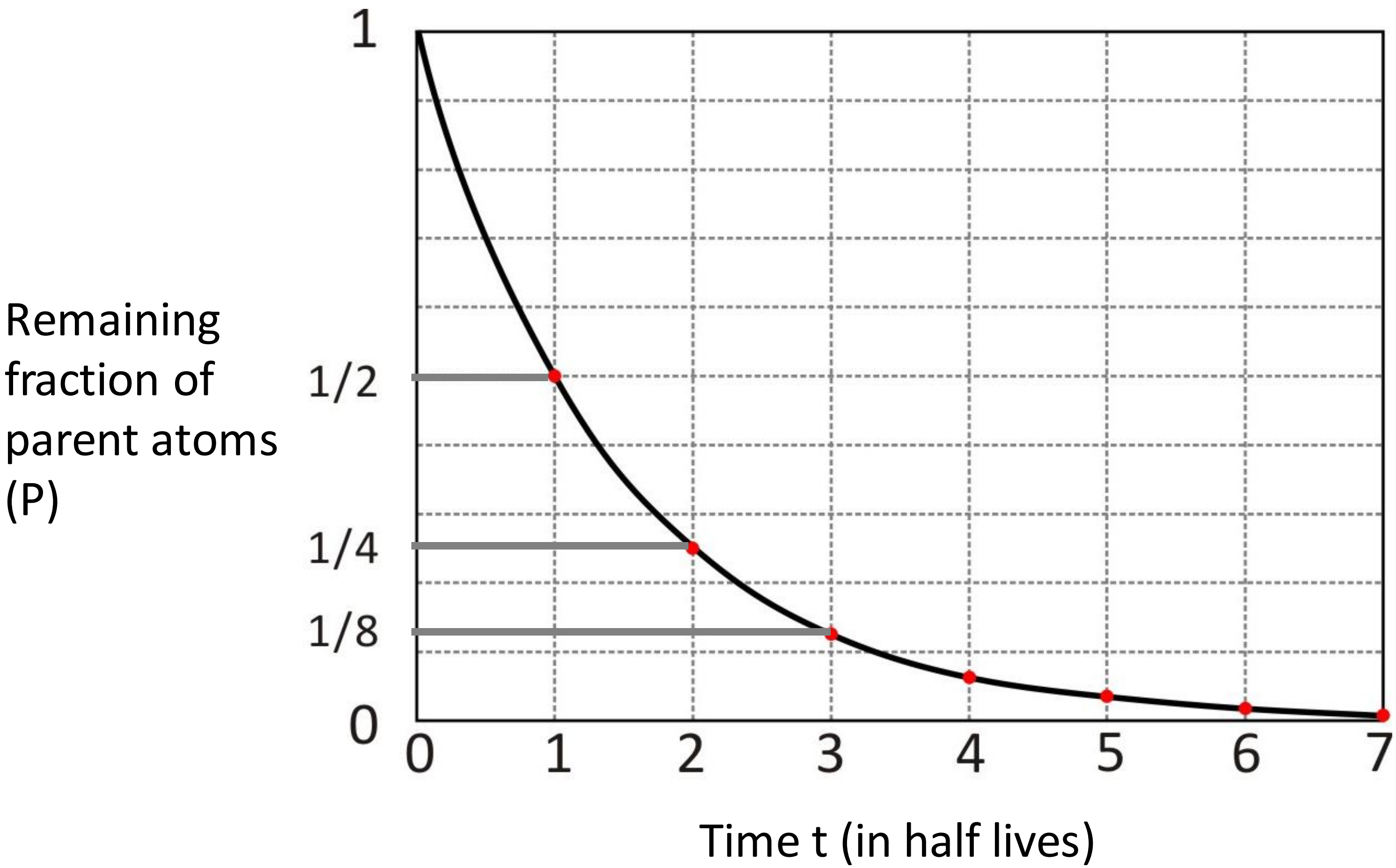
Half-life = time it takes for one half of the parent atoms to be transformed into daughter atoms

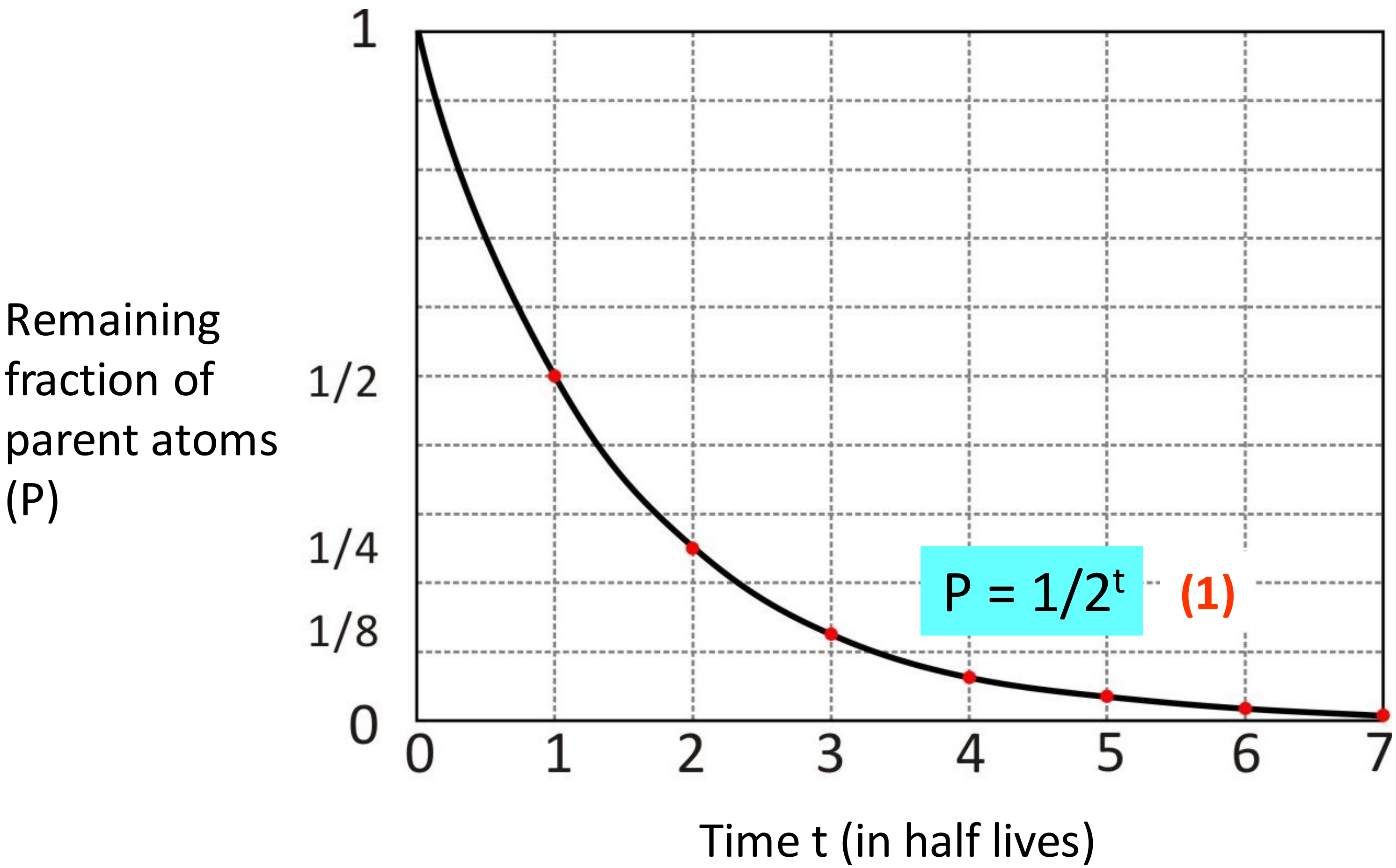
The rate of radioactive decay is **constant** (independent of T, P, chemistry)

Example: Rubidium-Strontium system

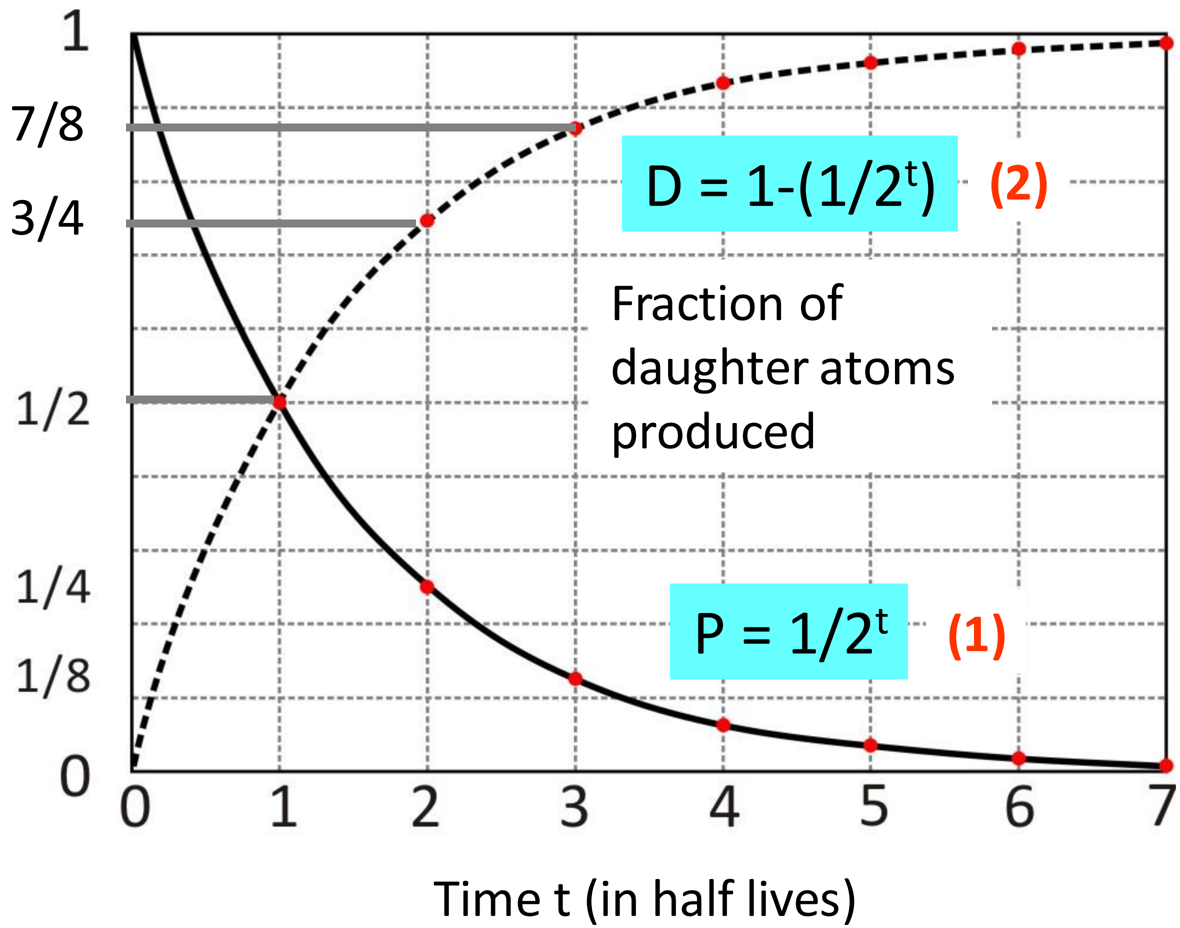
Parent atom: ^{87}**Rb** Daughter atom: ^{87}**Sr**



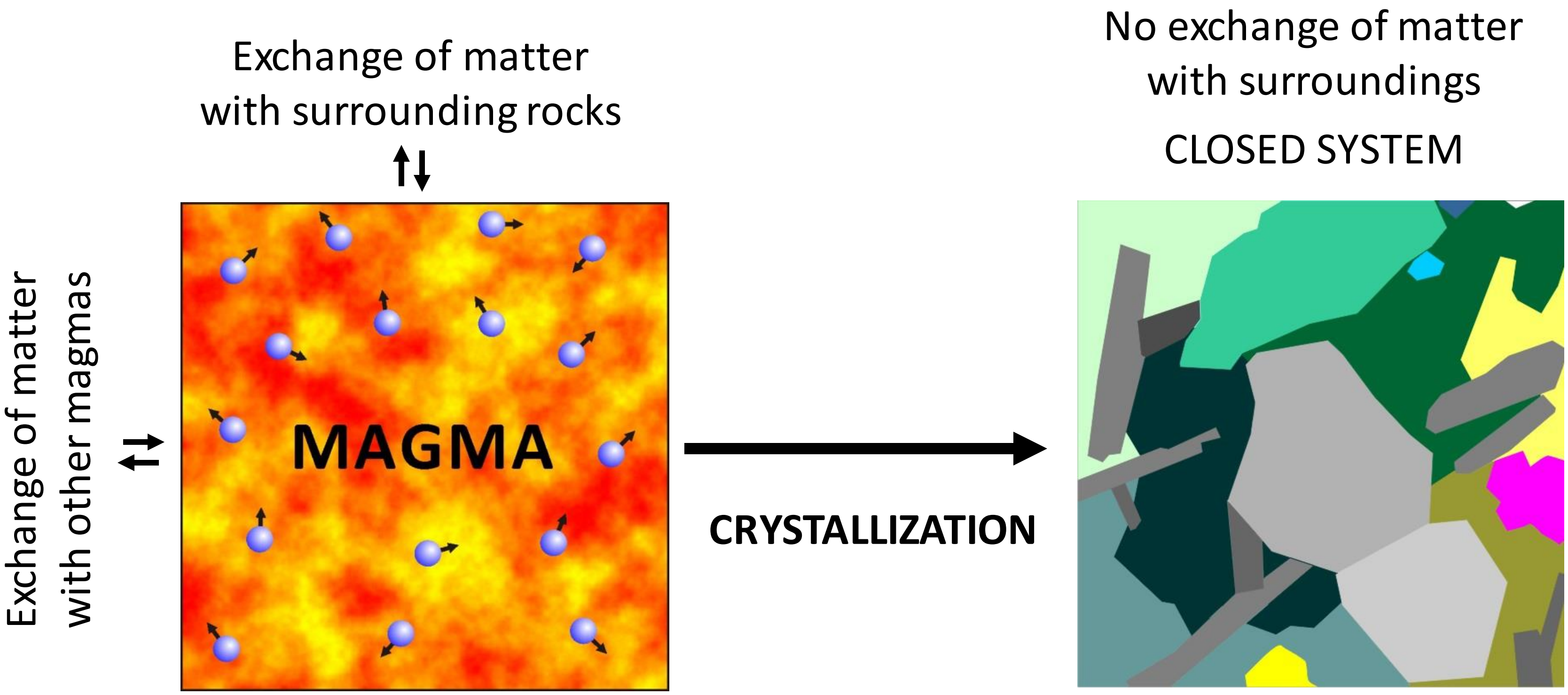
Parent atom: ^{87}**Rb** Daughter atom: ^{87}**Sr**



Parent atom: ^{87}**Rb** Daughter atom: ^{87}**Sr**



Example: the age of an igneous rock



The age of the rock is the time elapsed since crystallization

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What we can measure is the concentration (number of atoms) of ^{87}Rb and ^{87}Sr present in our sample at the present time t: $[^{87}Rb]_t$ and $[^{87}Sr]_t$

We need an equation that links $[^{87}Rb]_t$ and $[^{87}Sr]_t$ with time:

Let's assume there is NO daughter atoms in the system at time t=0

$$[^{87}Sr]_t = [^{87}Rb]_{t=0}\ [1 - (1/2^t)] \quad \textbf{(2)}$$

Amount of daughter atoms produced = initial amount of parent atoms minus the amount of parent atoms remaining

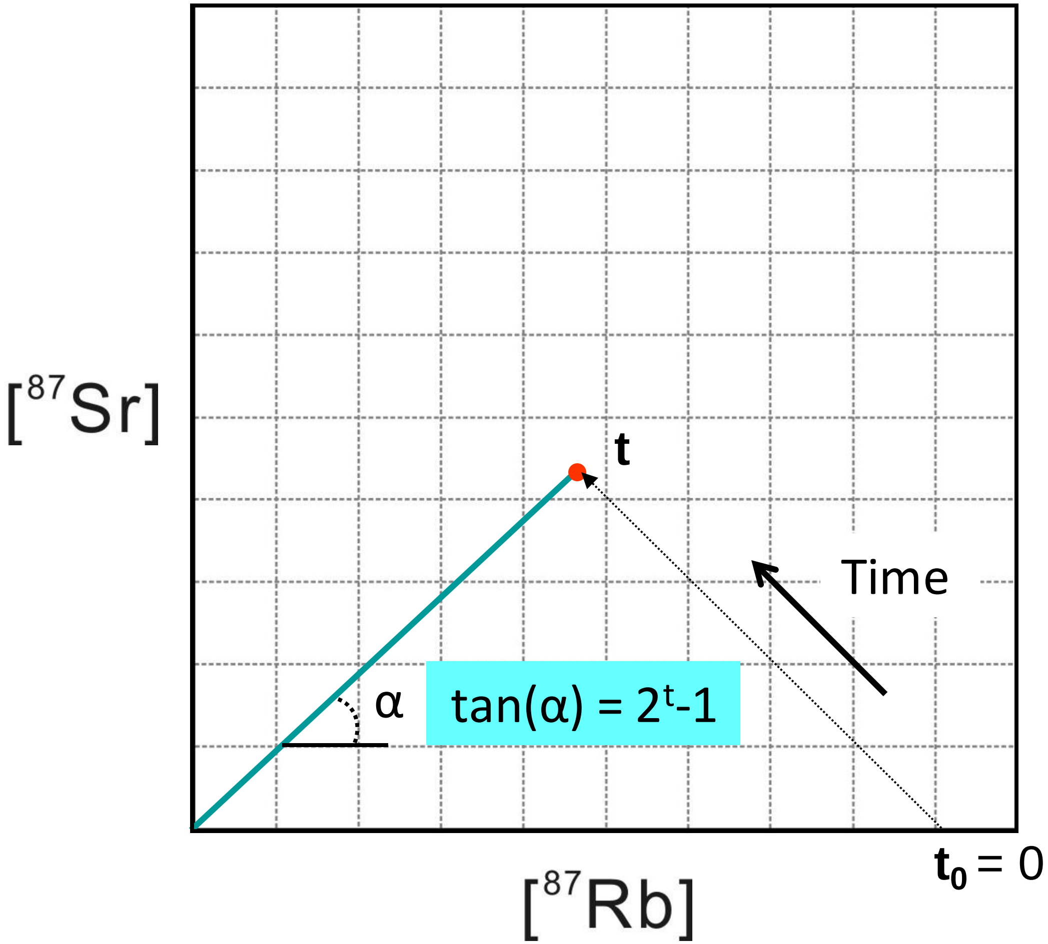
$$[^{87}Rb]_t = [^{87}Rb]_{t=0}\ (1/2^t) \quad \textbf{(1)}$$

Amount of parent atoms remaining

$$\frac{[^{87}Sr]_t}{[^{87}Rb]_t} = \frac{[^{87}Rb]_{t=0}}{[^{87}Rb]_{t=0}} \frac{[1 - (1/2^t)]}{1/2^t} = \frac{[1 - (1/2^t)]}{1/2^t} = \frac{1}{1/2^t} - \frac{1/2^t}{1/2^t} = 2^t - 1$$

$$[^{87}Sr]_t = (2^t - 1)\ [^{87}Rb]_t \quad \textbf{(3)}$$

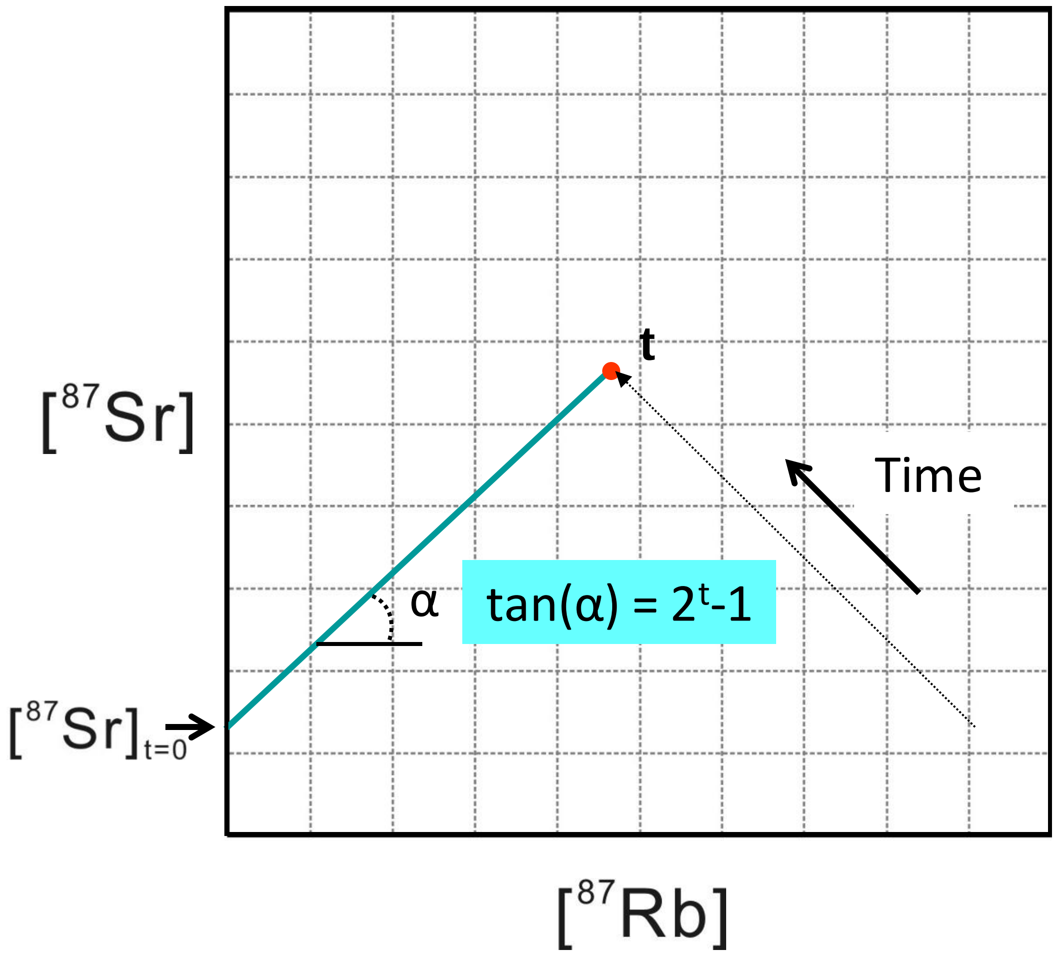
This is the equation of a straight line independent of $[^{87}Rb]_{t=0}$ with a slope = 2^t-1

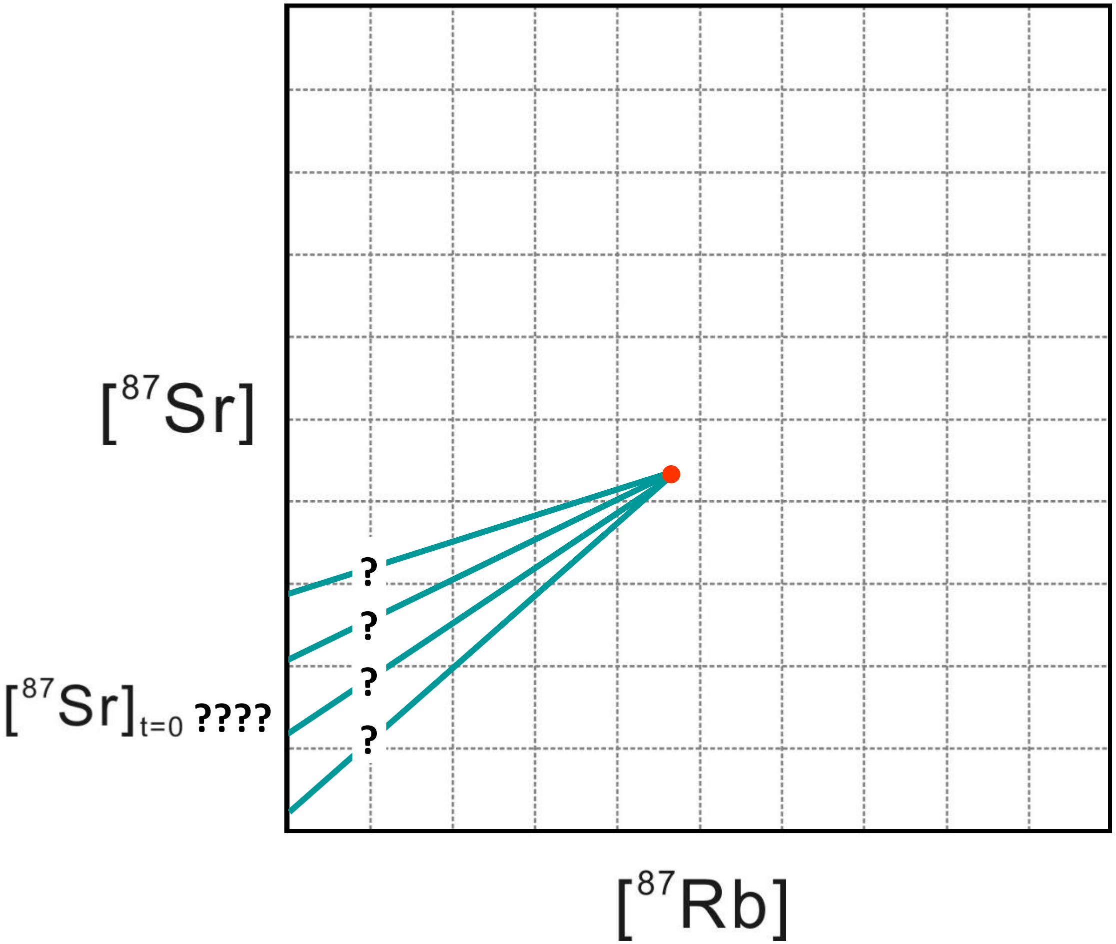


[87Sr]
t
Time
α
tan(α) = 2t-1
[87Rb]
t0 = 0

PROBLEM: Daughter atoms were likely incorporated in the minerals when they crystallized…

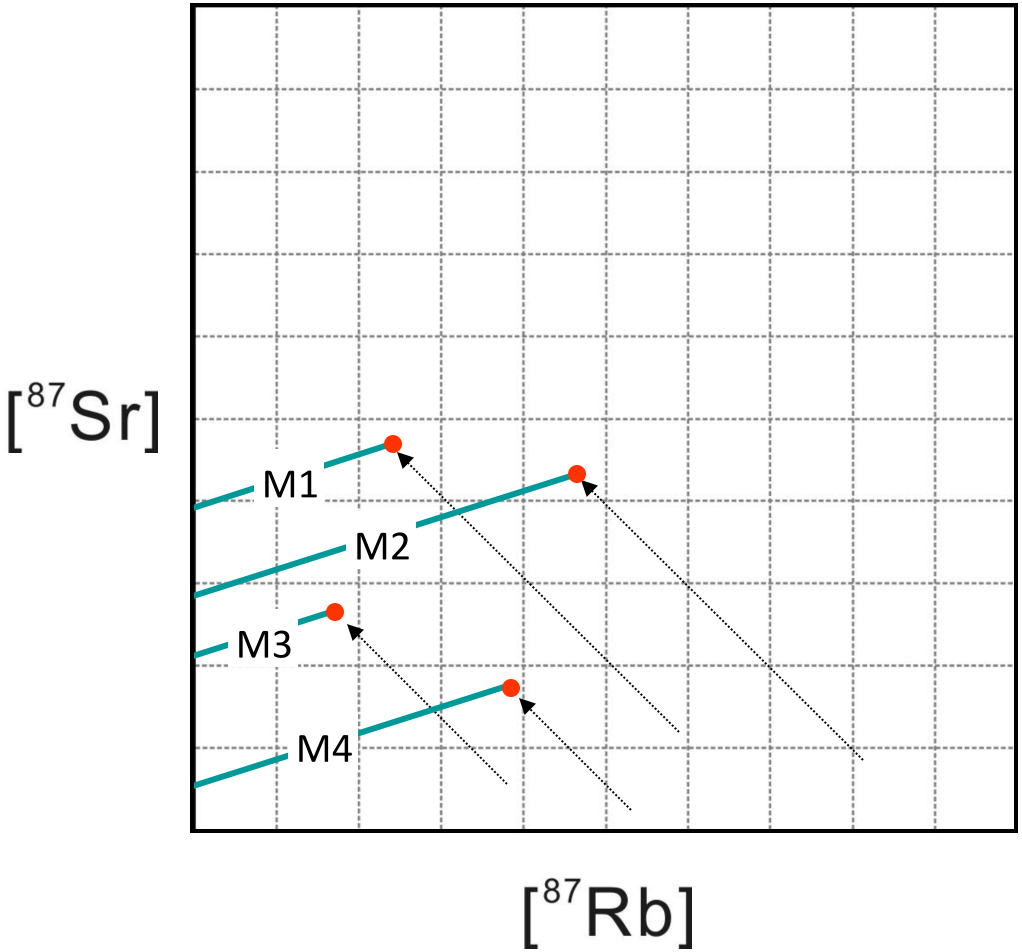
$$[^{87}Sr]_t = (2^t - 1)\,[^{87}Rb]_t + \underline{[^{87}Sr]_{t=0}} \quad (4)$$





[87Sr]
[87Sr]t=0 ????
?
?
?
?
[87Rb]

Each minerals of our rock sample can incorporate any amount of Sr and Rb at time t=0



We need a stable (non-radioactive) isotope that has properties similar to ^{87}Sr so that their initial ratio is the same in all the minerals of the rock sample.

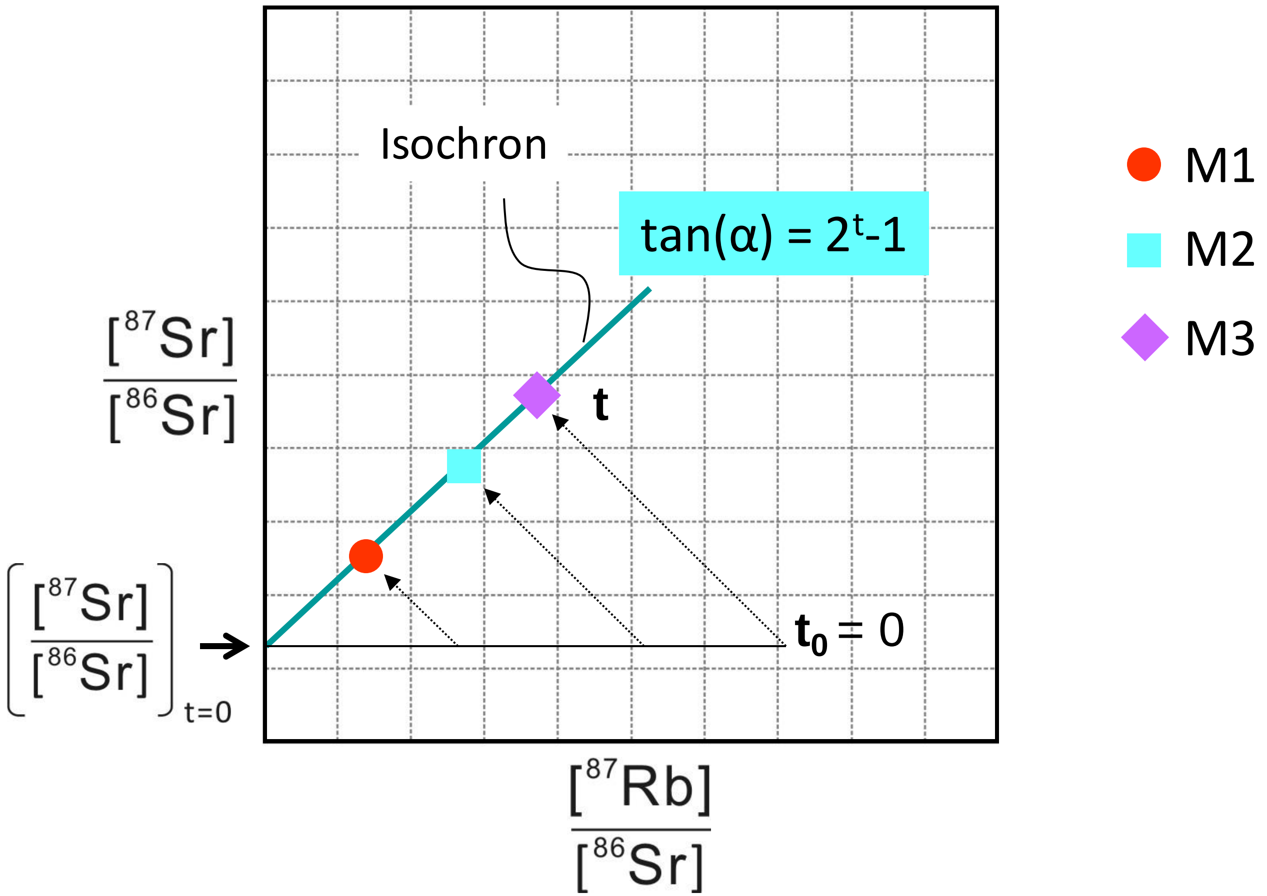
For the rubidium-strontium system, the stable isotope is **^{86}Sr**

We assume that all the minerals of the sample we want to date have crystallized from a melt with a uniform Sr isotope ratio and that all minerals have incorporated Sr with the same initial ratio $[^{87}Sr]/[^{86}Sr]$.

Say we have 1000 atoms of ^{87}Sr and 1200 atoms of ^{86}Sr initially present in a magma:

	Mineral 1 (M1)	Mineral 2 (M2)	Mineral 3 (M3)
$[^{87}Sr]_{t=0}$	500	100	400
$[^{86}Sr]_{t=0}$	600	120	480
$\left(\frac{[^{87}Sr]}{[^{86}Sr]}\right)_{t=0}$	0.83	0.83	0.83

$$\left[\frac{[^{87}Sr]}{[^{86}Sr]}\right]_t = (2^t - 1)\left[\frac{[^{87}Rb]}{[^{86}Sr]}\right]_t + \left[\frac{[^{87}Sr]}{[^{86}Sr]}\right]_{t=0} \quad (5)$$



Important condition: each minerals must have remained a closed system since the time of magma crystallization

Radiometric dates of moon rocks

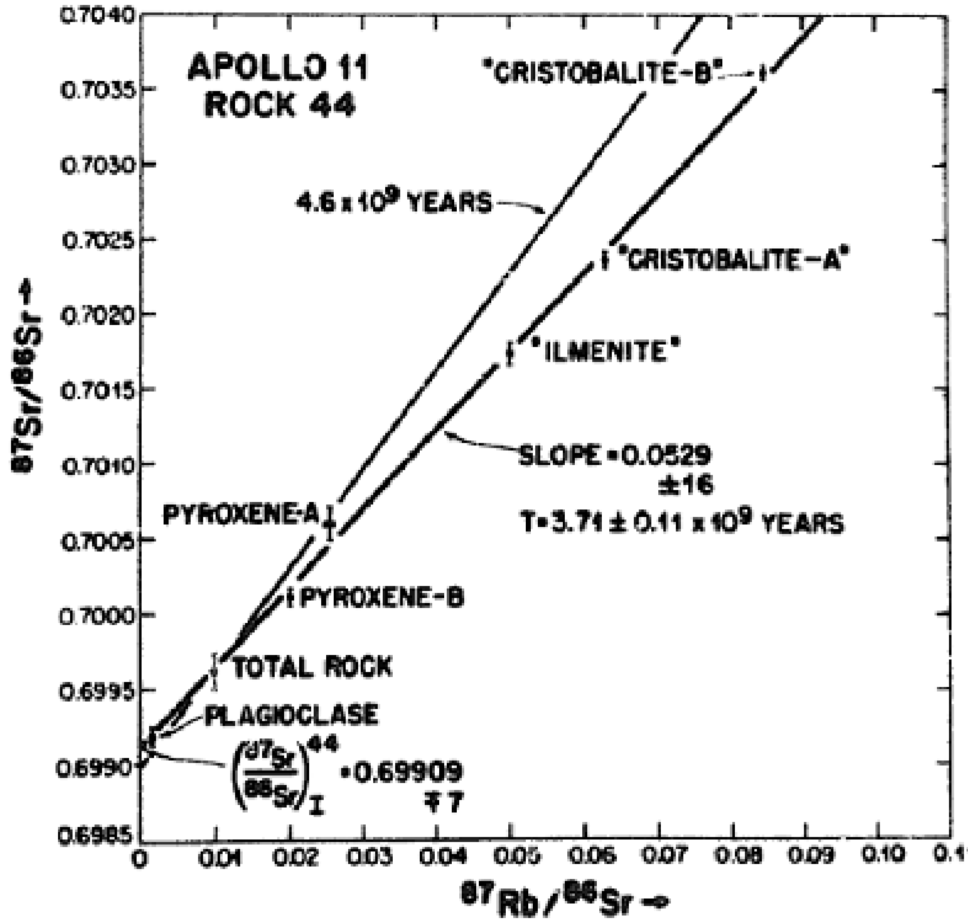


Fig. 3. Rb-Sr evolution diagram for low-K rock # 44. Best fit isochron and parameters shown; 4.6×10^9 yr reference isochron also shown. Range of enrichment of ($^{87}Sr/^{86}Sr$) is 0.6%.

Papanastassiou et al. (1970)

Mass spectrometer

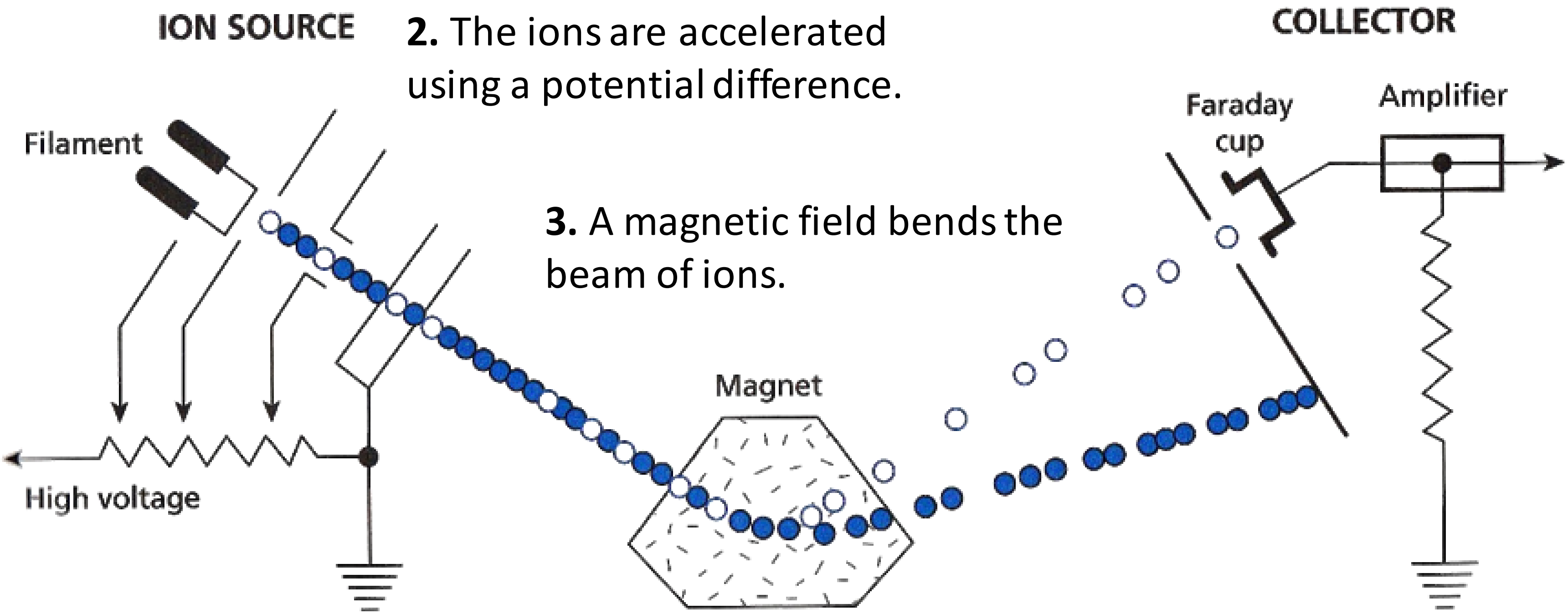
1. The sample is ionized.

2. The ions are accelerated using a potential difference.

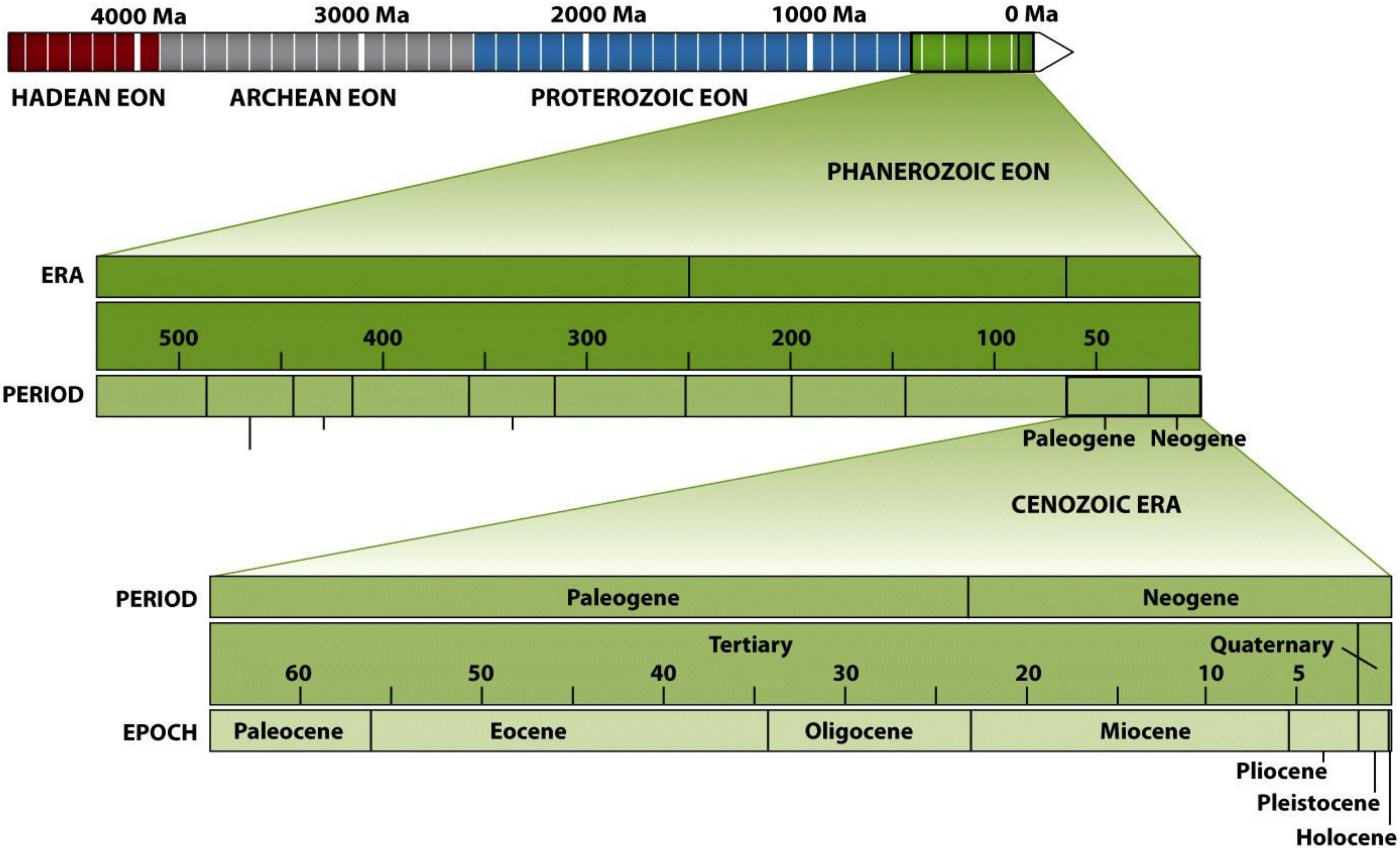
3. A magnetic field bends the beam of ions.

4. The lighter ions are deflected more than the heavier ones.

5. The relative abundance of each isotope can be measured from the intensity of the current produced by each stream of ions.



✶ The geologic time scale based on absolute ages



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