Fundamentals of Earth Sciences (ESO 213A)

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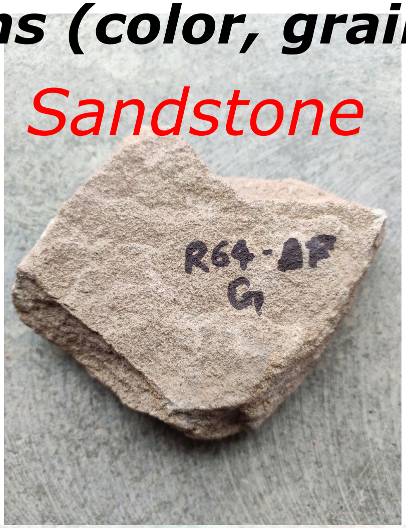
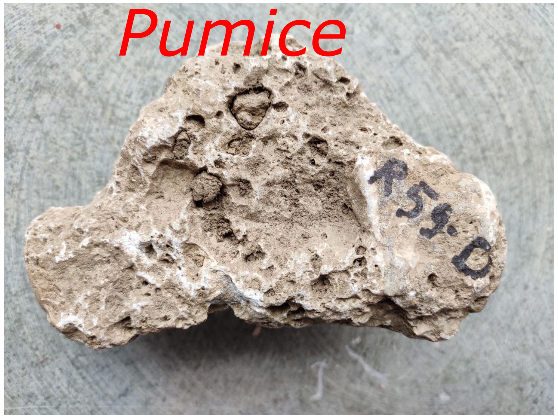
Earth's history and Geological Time Scale

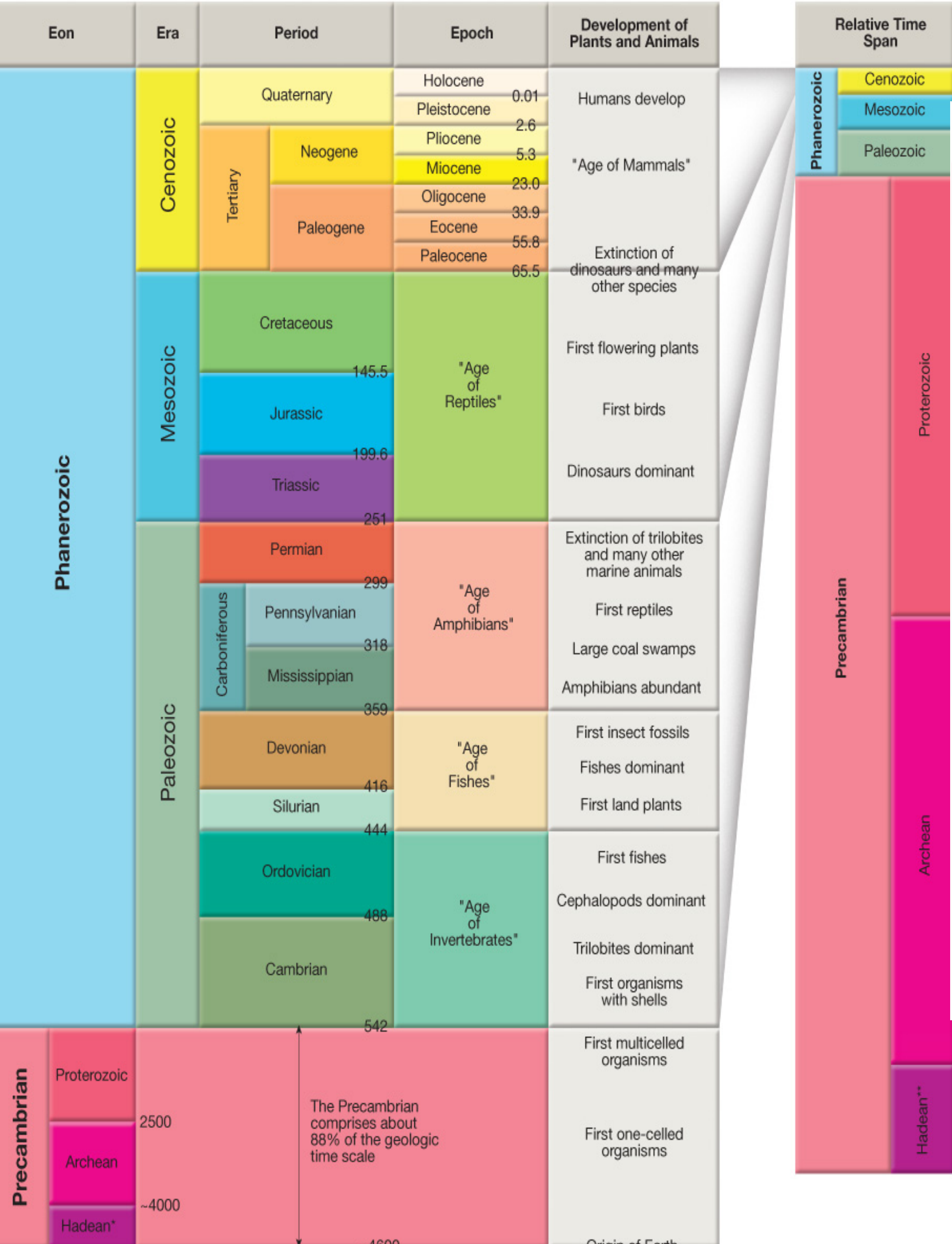
Previous Class: Hand specimen

Identify hand specimens (color, grain size, features, name)

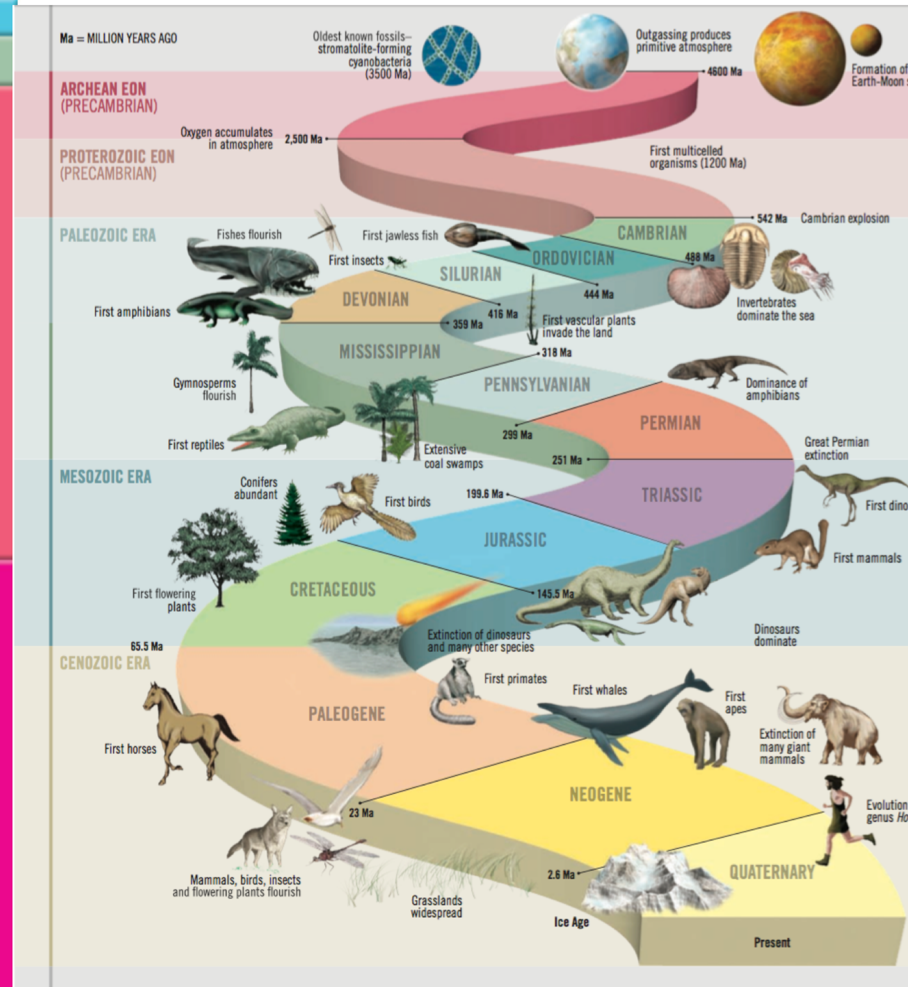




Geologic time scale



*Hadean is the informal name for the span that begins at Earth's formation and ends with Earth's earliest-known rocks.



Snowball Earth

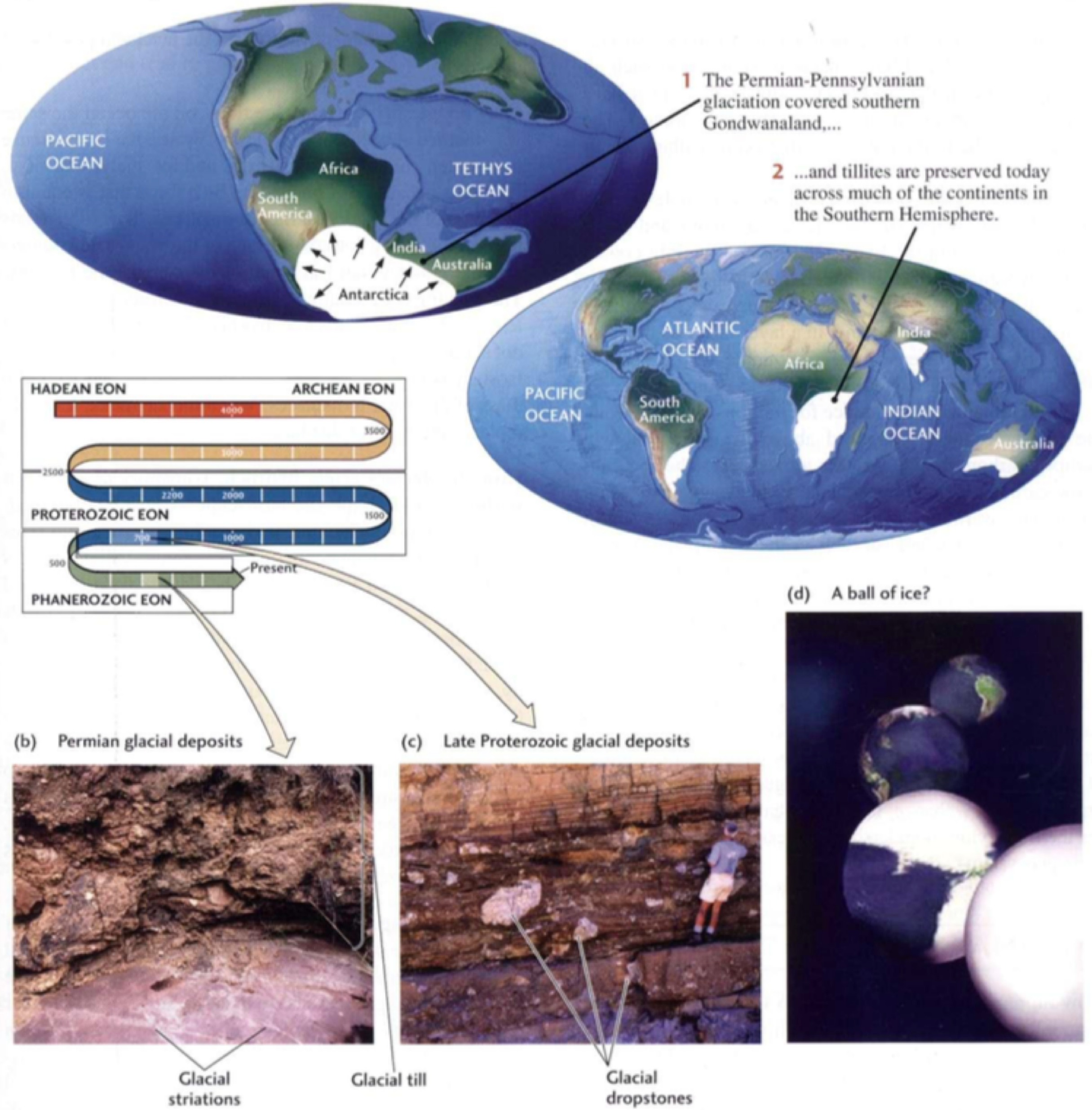


Figure 21.26 Ancient glacial epochs. (a) The first map shows the distribution of Permian-Pennsylvanian glacial deposits, formed more than 350 million years ago. At this time, the continents were assembled as the supercontinent Gondwanaland and the ice was situated in the Southern Hemisphere, centered over Antarctica, as the modern-day ice fields are. The second map shows the distribution of Permian-Pennsylvanian glacial deposits today. (b) Permian glacial deposits from South Africa. [John Grotzinger.] (c) Late Proterozoic glacial deposits. [John Grotzinger.] (d) The development of a late Precambrian Snowball Earth. Geologists debate the extent to which ice covered the globe, but some think even the oceans became frozen.

Mass extinctions & reefs

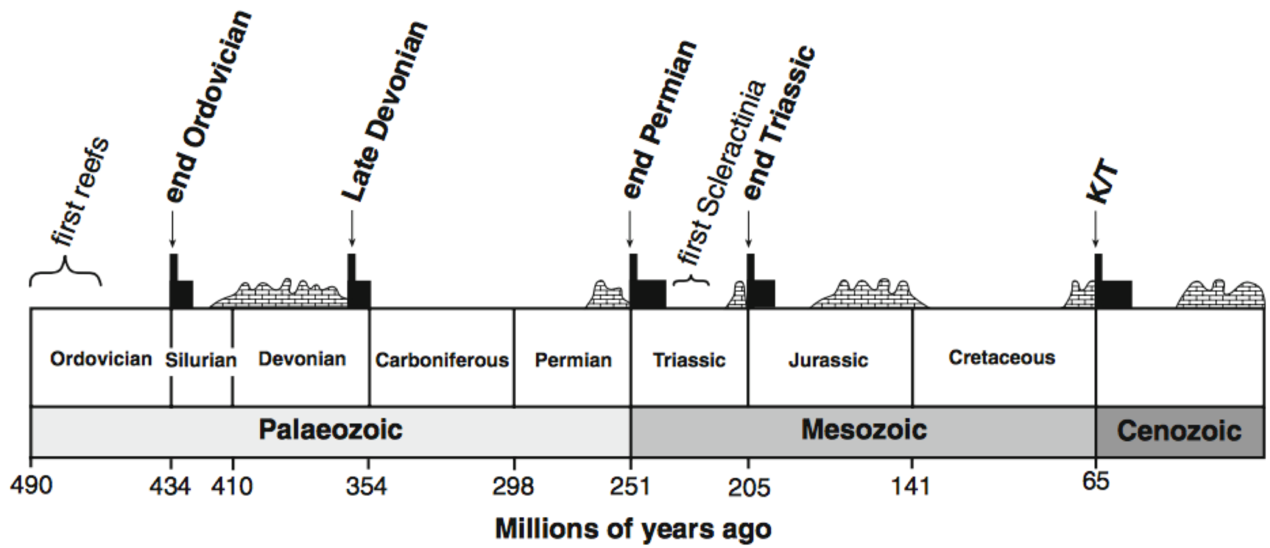
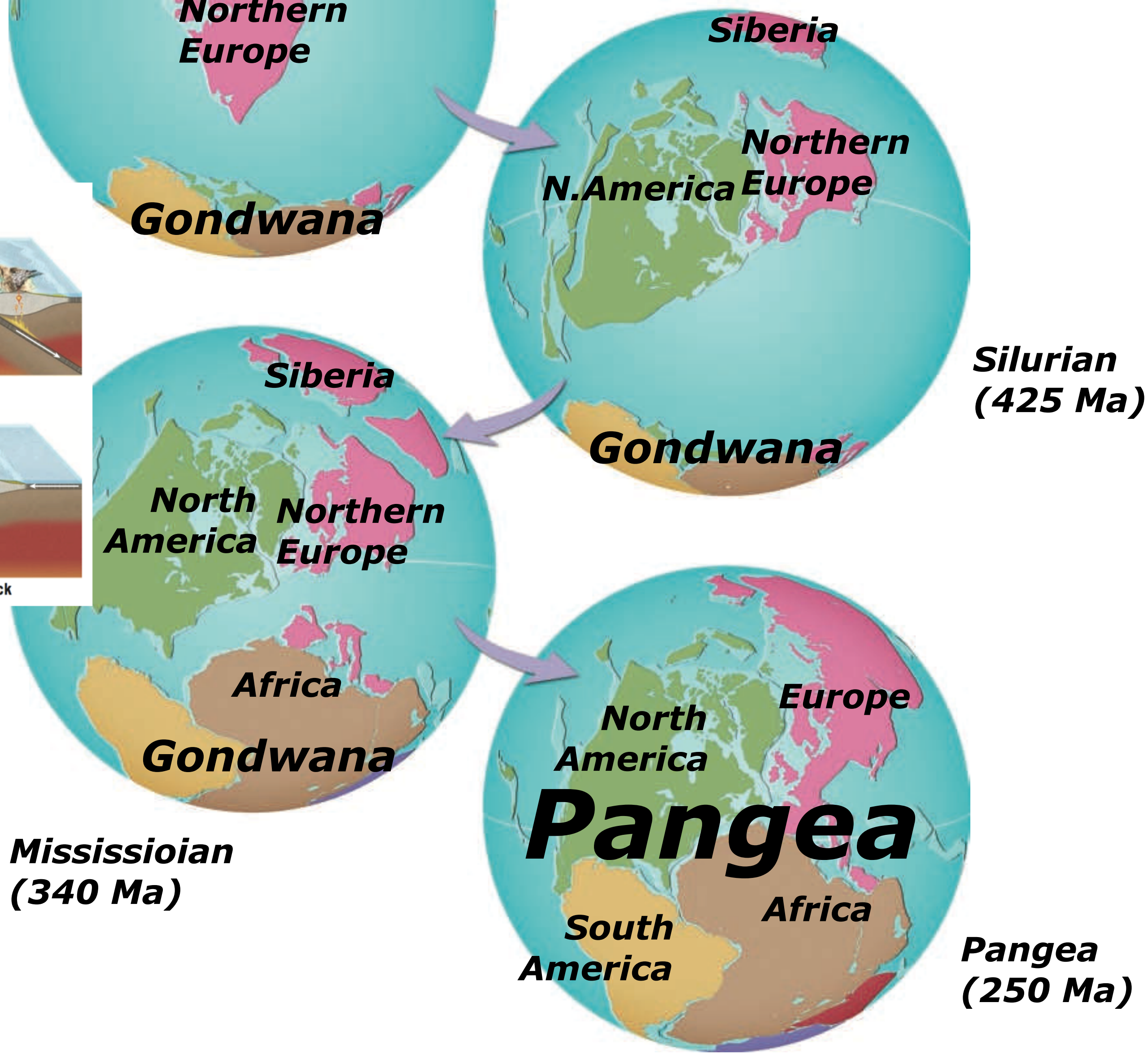
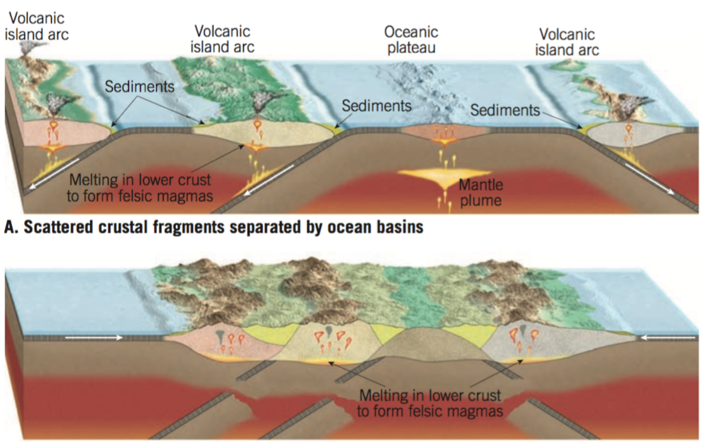


Fig. 1 Timeline of mass extinction events. The five named vertical bars indicate mass extinction events. Black rectangles (drawn to scale) represent global reef gaps and brick-pattern shapes show times of prolific reef growth. At other times reef growth appears to have been between these extremes, although there were many gaps not associated with mass extinctions and there were intervals of prolific growth in limited geographic regions not indicated here (after Veron 2008)

Formation of Pangaea

During the late Paleozoic, Earth's major landmasses joined to produce the supercontinent of Pangaea. (After P. Hoffman, J. Rogers, and others)





A. Scattered crustal fragments separated by ocean basins

B. Collision of volcanic island arc and oceanic plateau to form a larger crustal block

Pangea broke ~ 185 Ma and formation of Atlantic Ocean initiated

Relative and Radiometric Dating

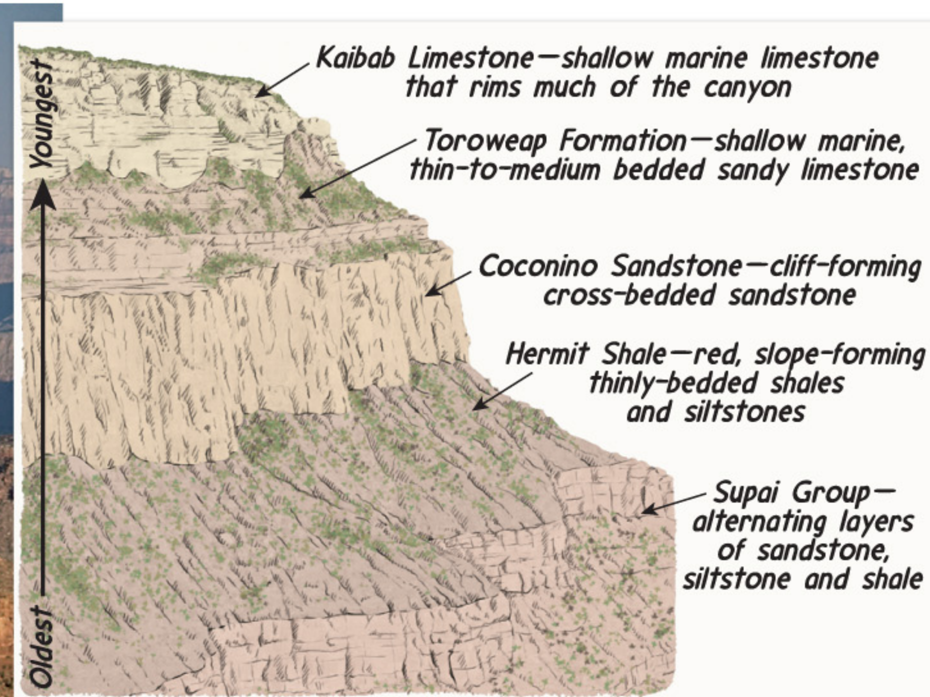
- **Relative Dating**
  - **Rocks are placed in their proper sequence of formation**
  - **Numerical values are not assigned to rocks**
- ***Radiometric / Numerical Dating***
  - ***Specifies the actual number of years that have passed since an event occurred***
  - ***Radioactivity***

Relative Dating

- **Follows a few principles / rules**

I. *Law of superposition*

- **Developed by Nicolaus Steno in 1669**
- **In an undeformed sequence of sedimentary rocks (or layered igneous rocks), each rock is older than the one above and younger than the one below**



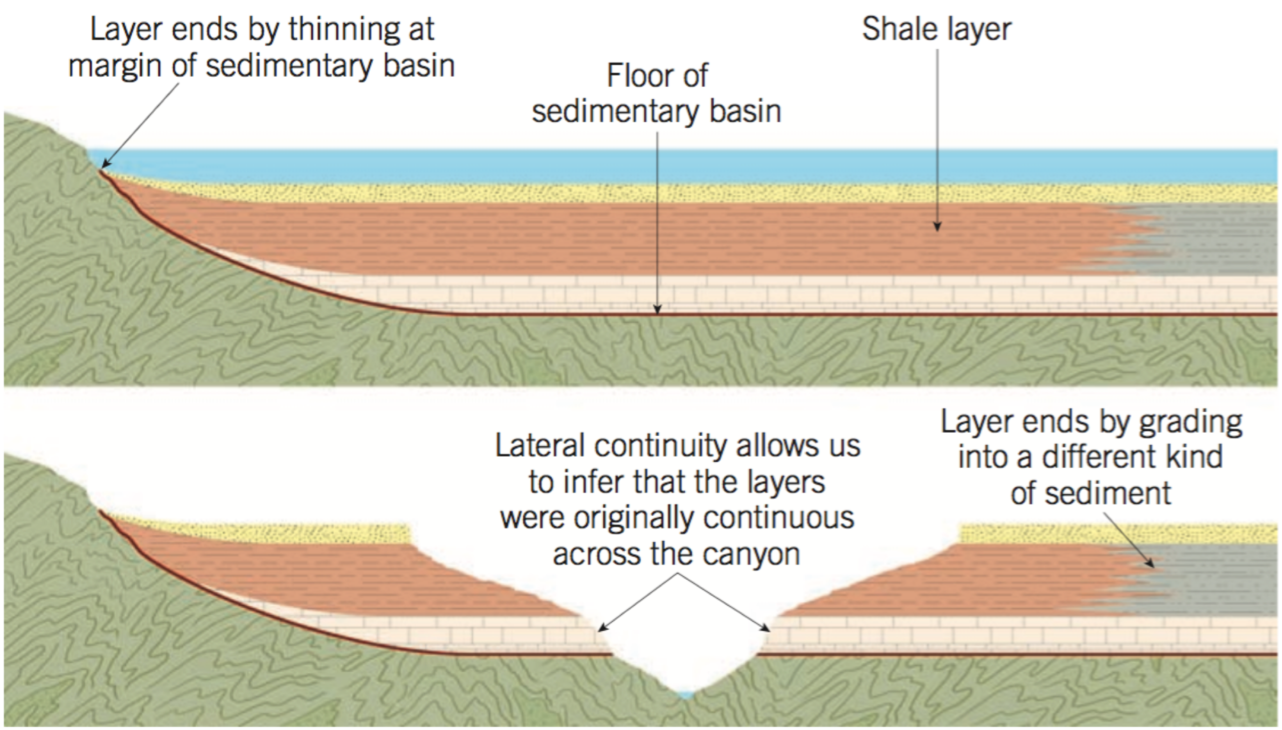
Geologist's Sketch

Superposition Is Well Illustrated by the Strata in the Grand Canyon

Relative Dating

II. Principle of original horizontality

- ***Originally*, layers of sediment are deposited in a horizontal position.**
- **Rock layers that are flat have not been disturbed.**
- **Rocks that are folded or inclined at a steep angle must have been moved into that position by crustal disturbances *after* their deposition.**

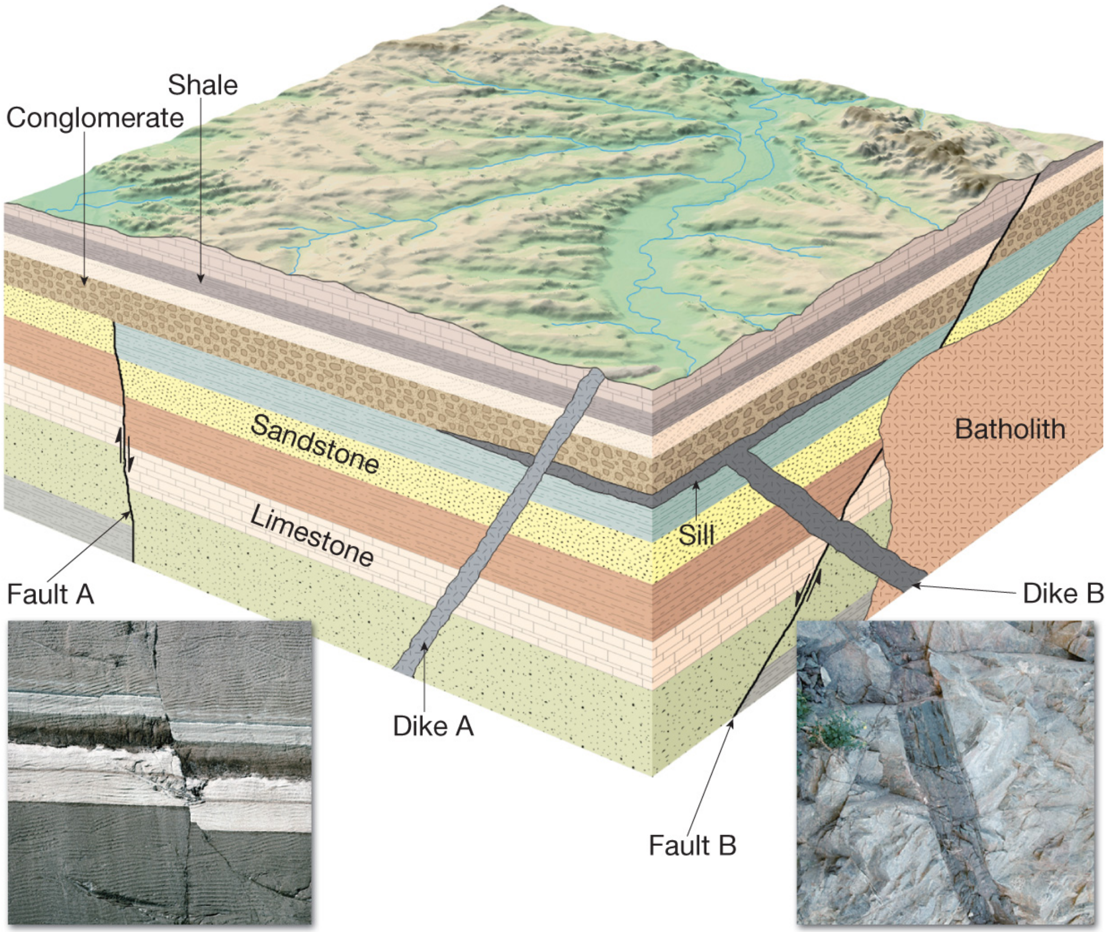


Folded Layers on the Island of Crete

Relative Dating

III. Principle of cross-cutting relationships

- **Younger features cut across older features.**

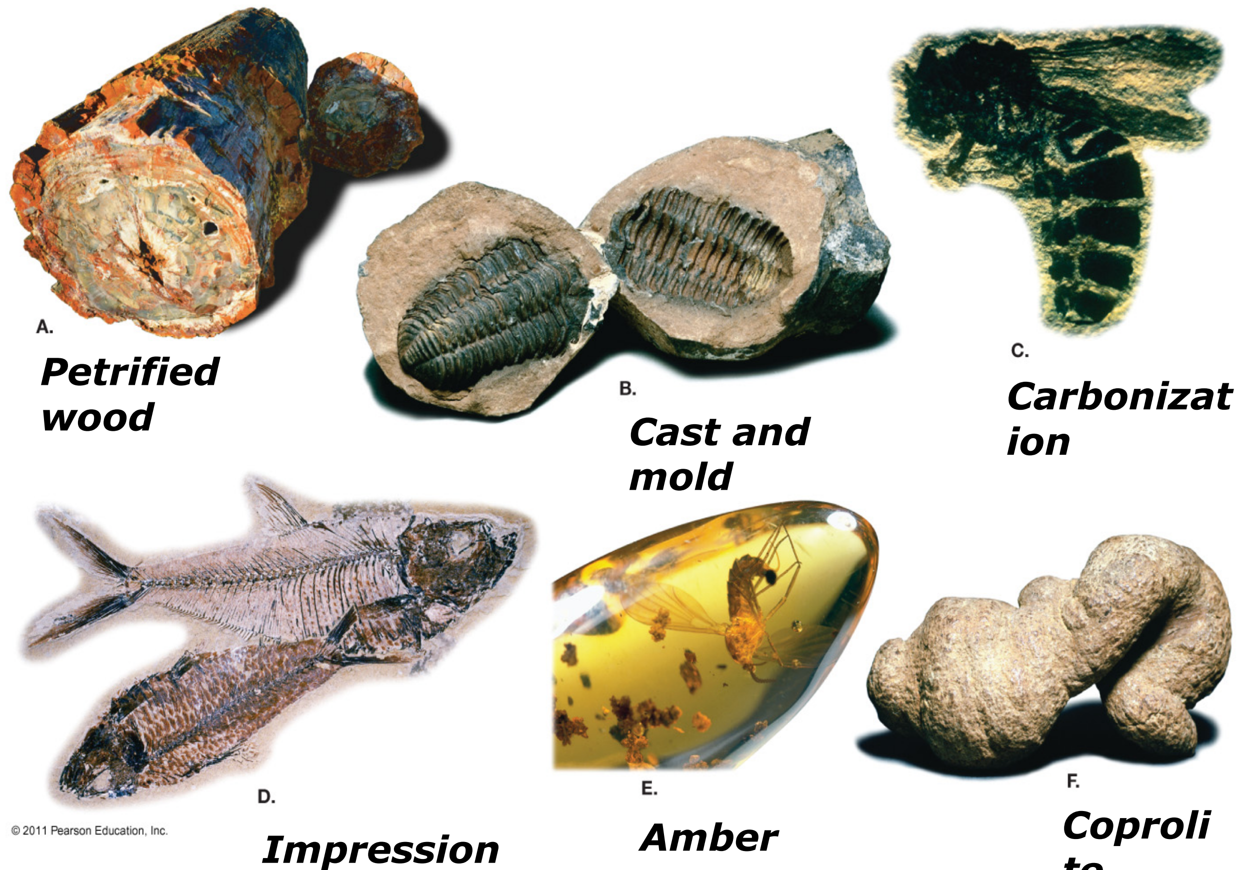


Relative Dating

IV. Principle of fossil succession

***Fossils* are traces or remains of prehistoric life that are now preserved in rock.**

Fossil organisms succeed one another in a definite and determinable order, and therefore any time period can be recognized by its fossil content



Fossils—Evidence of Past Life

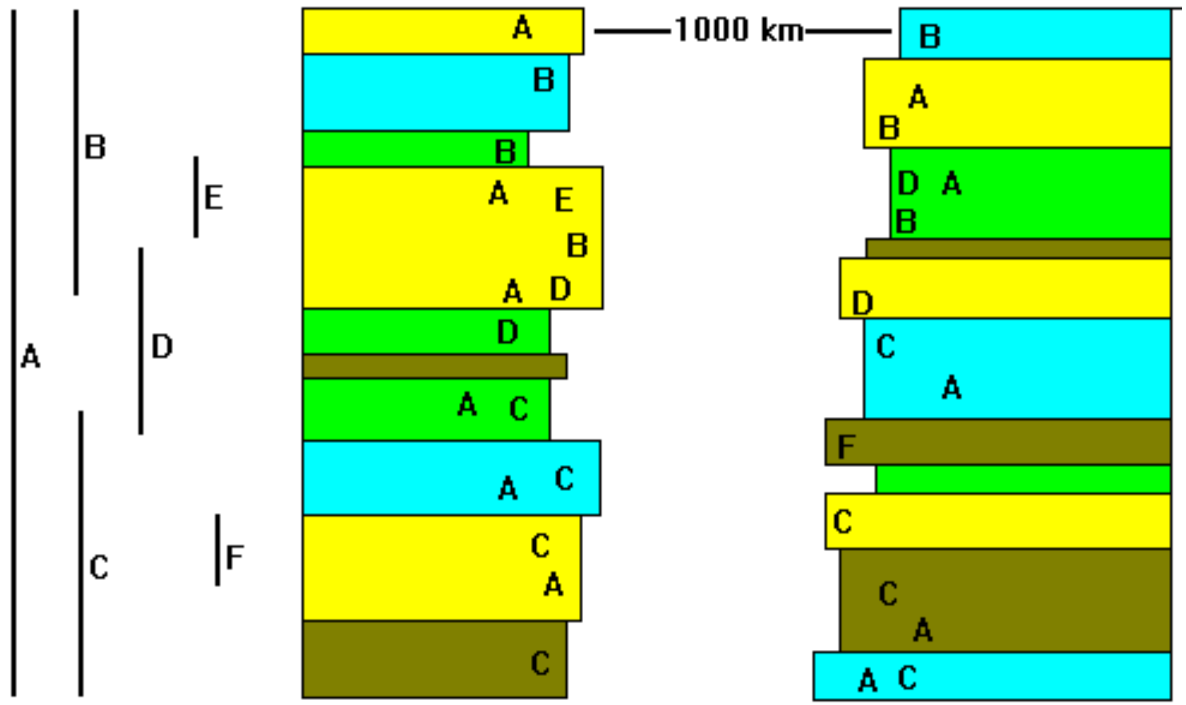
- **Fossils are generally found in sedimentary rock (rarely in metamorphic and never in igneous rock).**
- **Paleontology is the study of fossils.**
- ***Geologically fossils are important because they:***
    - ***Aid in interpretation of the geologic past***
    - ***Serve as important time indicators***
    - ***Allow for correlation of rocks from different places***

- **Conditions favoring preservation**
    - **Rapid burial**
    - **Possession of hard parts (skeleton, shell, bone, teeth, etc.)**

Dinosaur Tracks, Texas

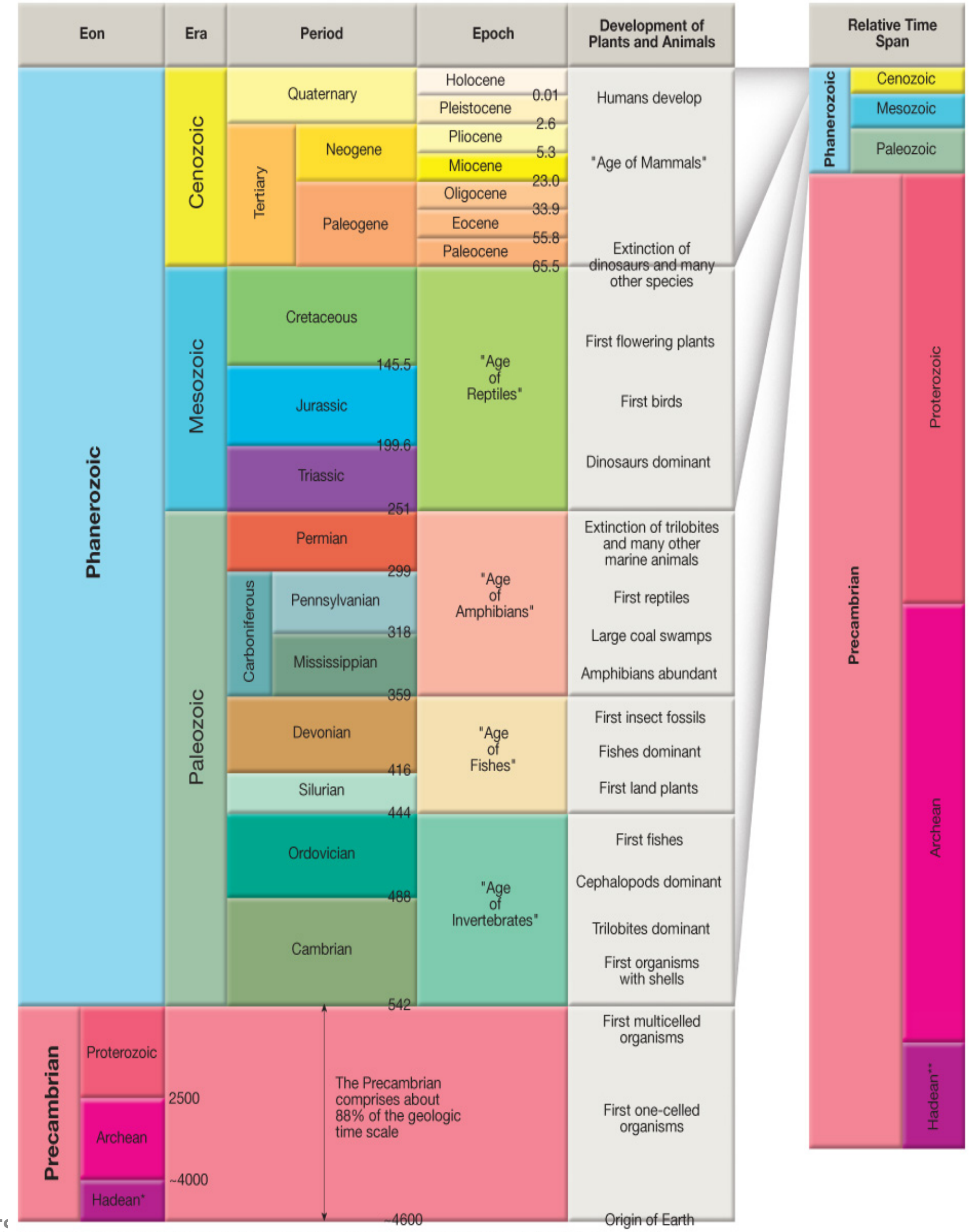
Fossils and Correlation

- **Matching of rocks of similar ages in different regions is known as correlation.**
- **Correlation often <u>relies upon fossils</u>.**
    - **William Smith (in the late 1700s) noted that sedimentary strata in widely separated areas could be identified and correlated by their distinctive fossil content.**



Fossils and Correlation

- **Principle of fossil succession**—fossil organisms succeed one another in a definite and determinable order. Therefore, <u>any time period can be recognized by its fossil content.</u>
- Fossils document the evolution of life through time (Age of Trilobites, Age of Fishes, Age of Coal Swamps, Age of Reptiles, Age of Mammals)
- An **index fossil** is a geographically widespread fossil that is limited to a short span of geologic time.



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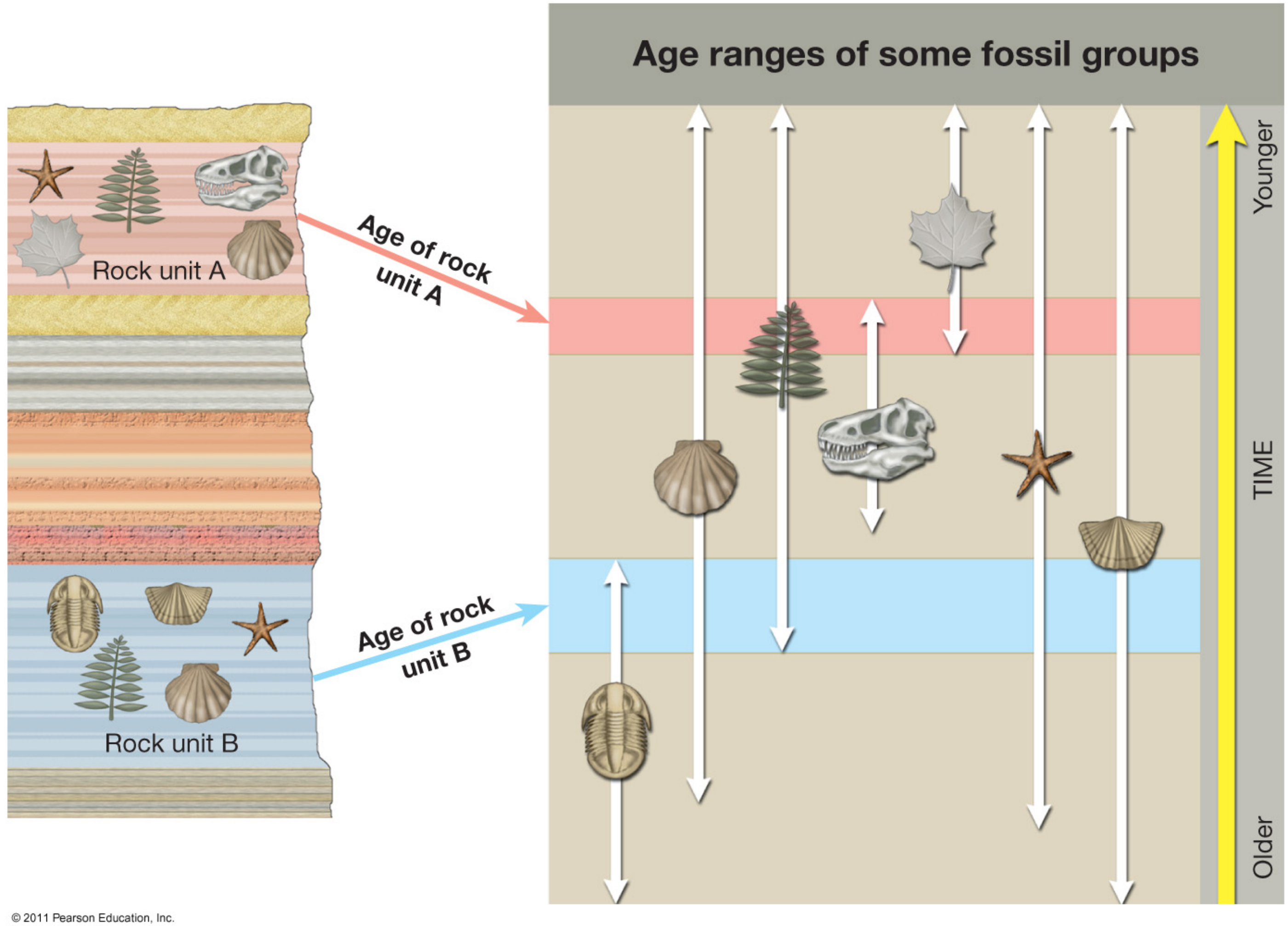
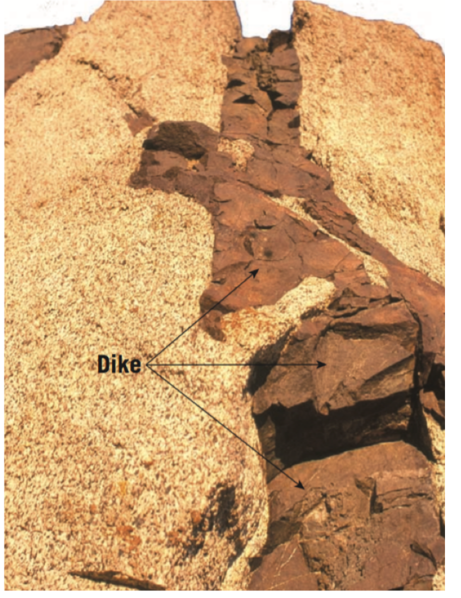
Dating Rocks Using Overlapping Fossil Ranges

Overlapping ranges of fossils help date rocks more exactly than using a single fossil.

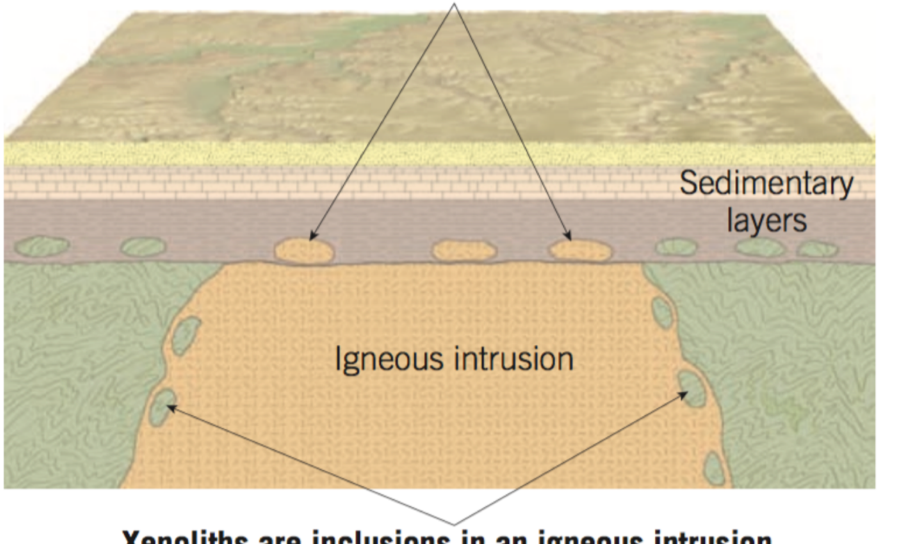


Relative Dating

- **Inclusions**
  - **An inclusion is a piece of rock that is enclosed within another rock.**
  - **The rock containing the inclusion is younger.**
- **Unconformity**
  - **An unconformity is a *break in the rock record*: deposition ceased, erosion removed previously formed rocks, and then deposition resumed**
  - **Uplift, erosion → Subsidence, renewed deposition**

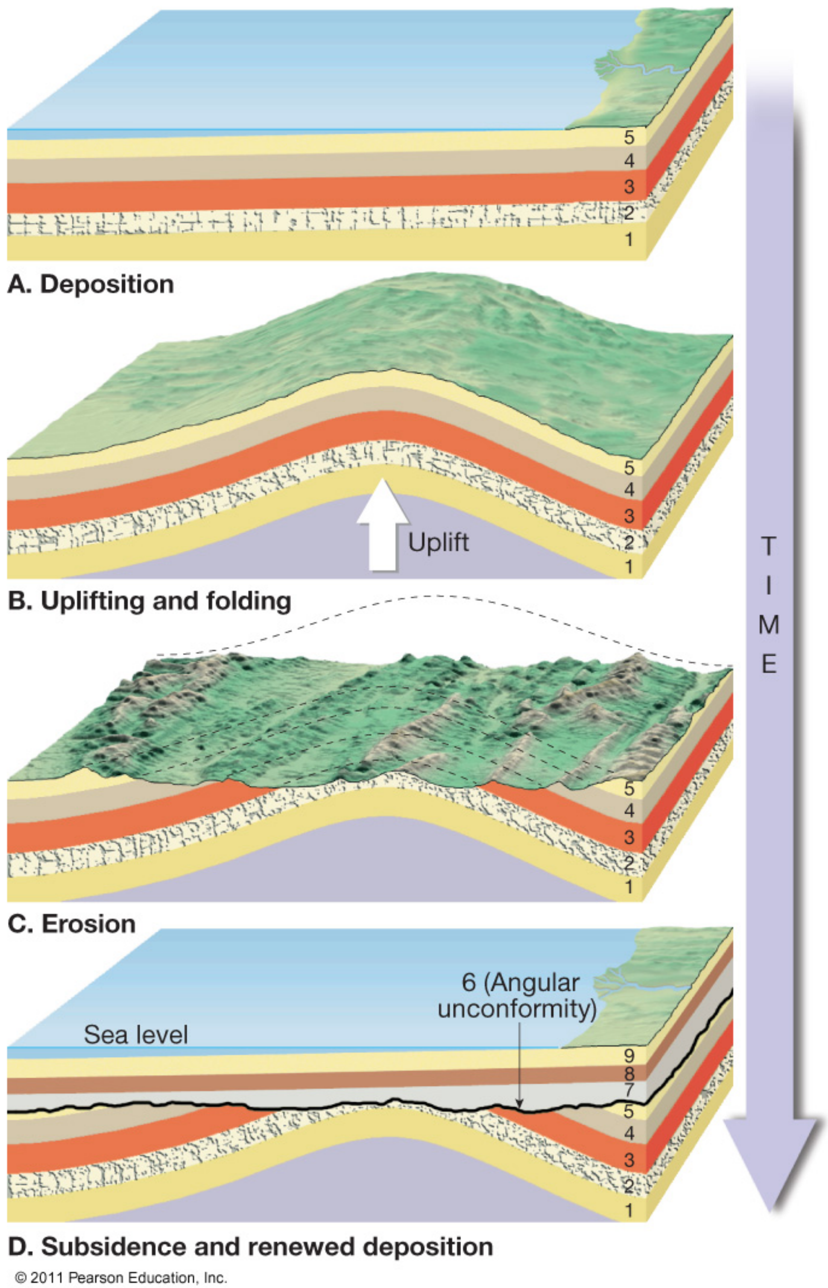


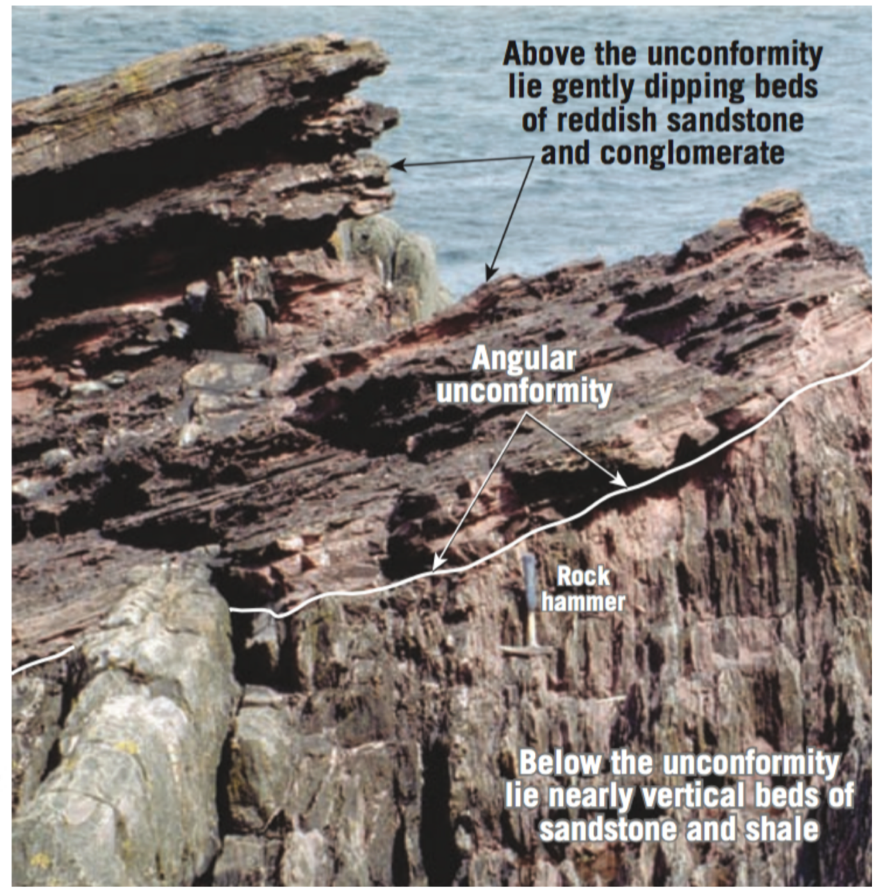
These inclusions of igneous rock contained in the adjacent sedimentary layer indicate the sediments were deposited atop the weathered igneous mass and thus are younger.



Xenoliths are inclusions in an igneous intrusion that form when pieces of surrounding rock are incorporated into magma.

Formation of an Angular Unconformity



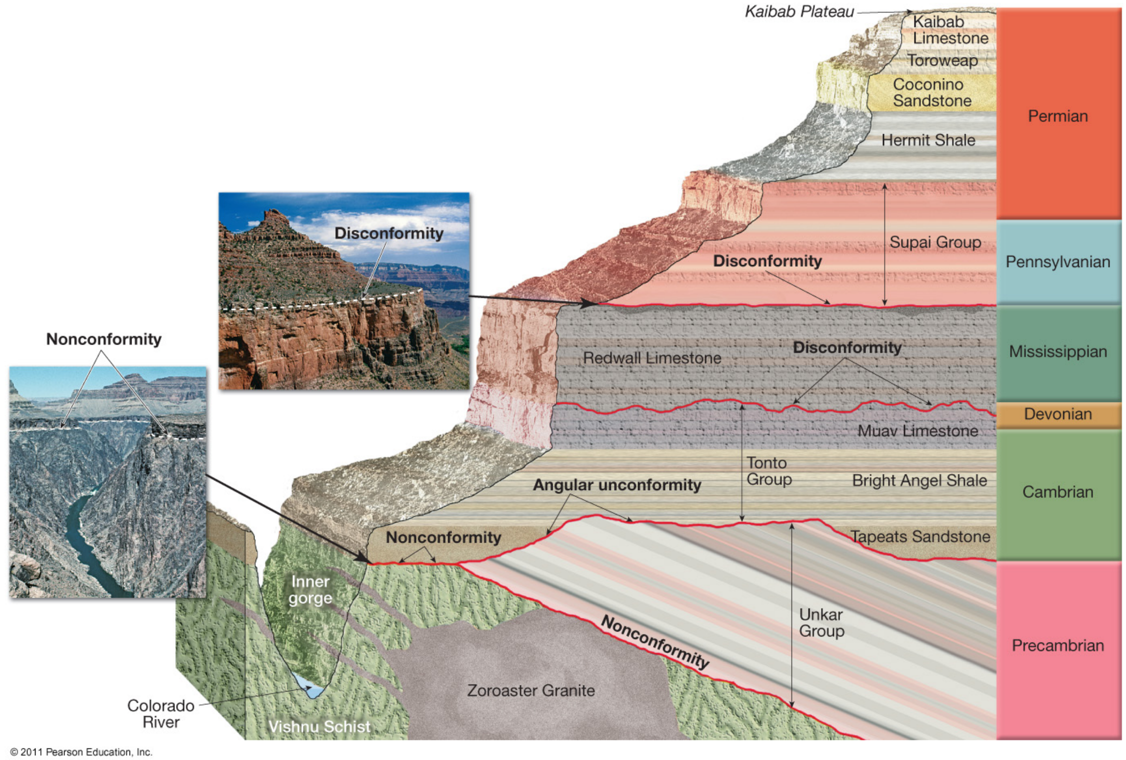


Relative Dating

Unconformity

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



Unconformities in the Grand Canyon

Arrange A to K in terms of oldest to youngest!

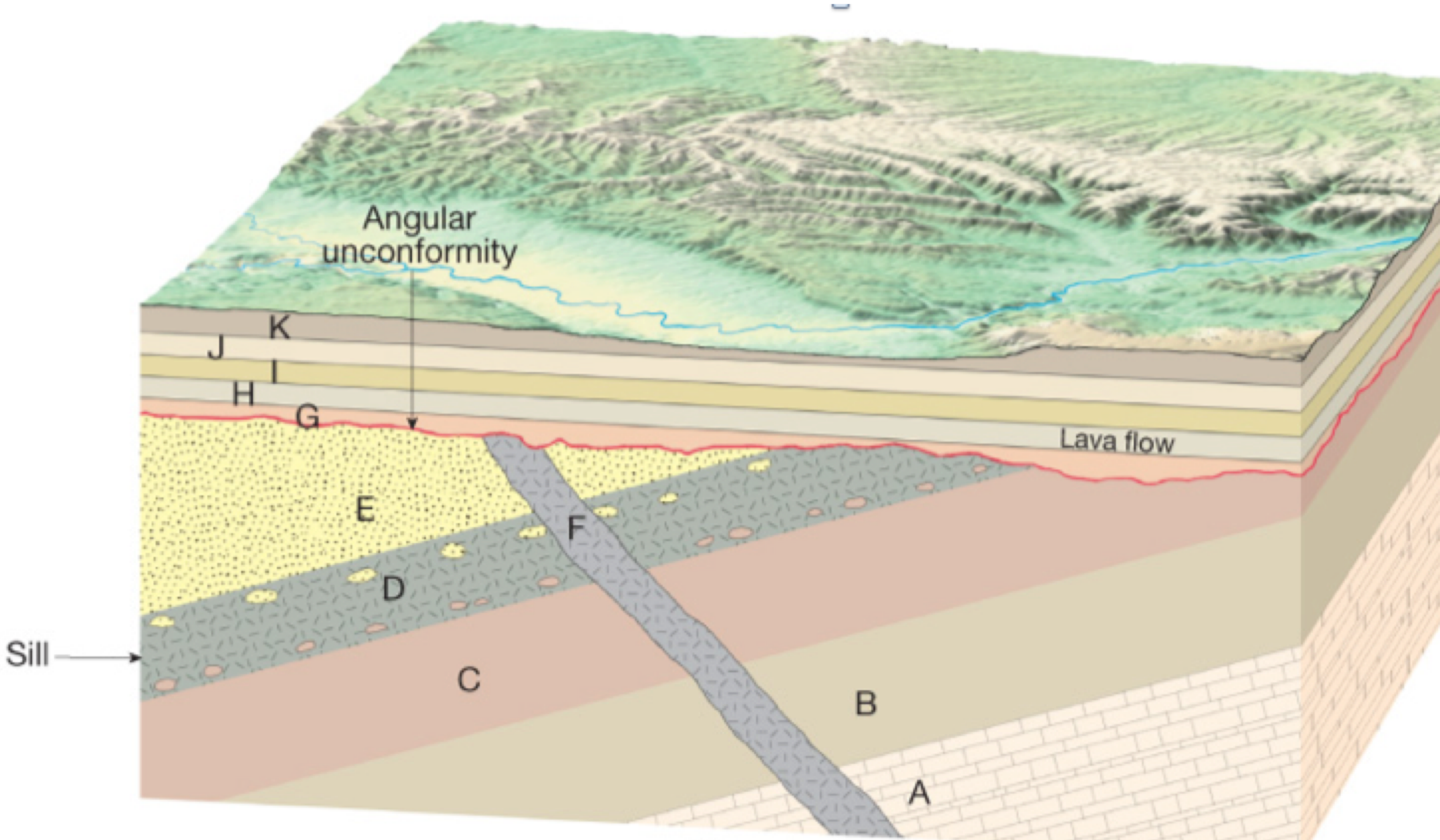
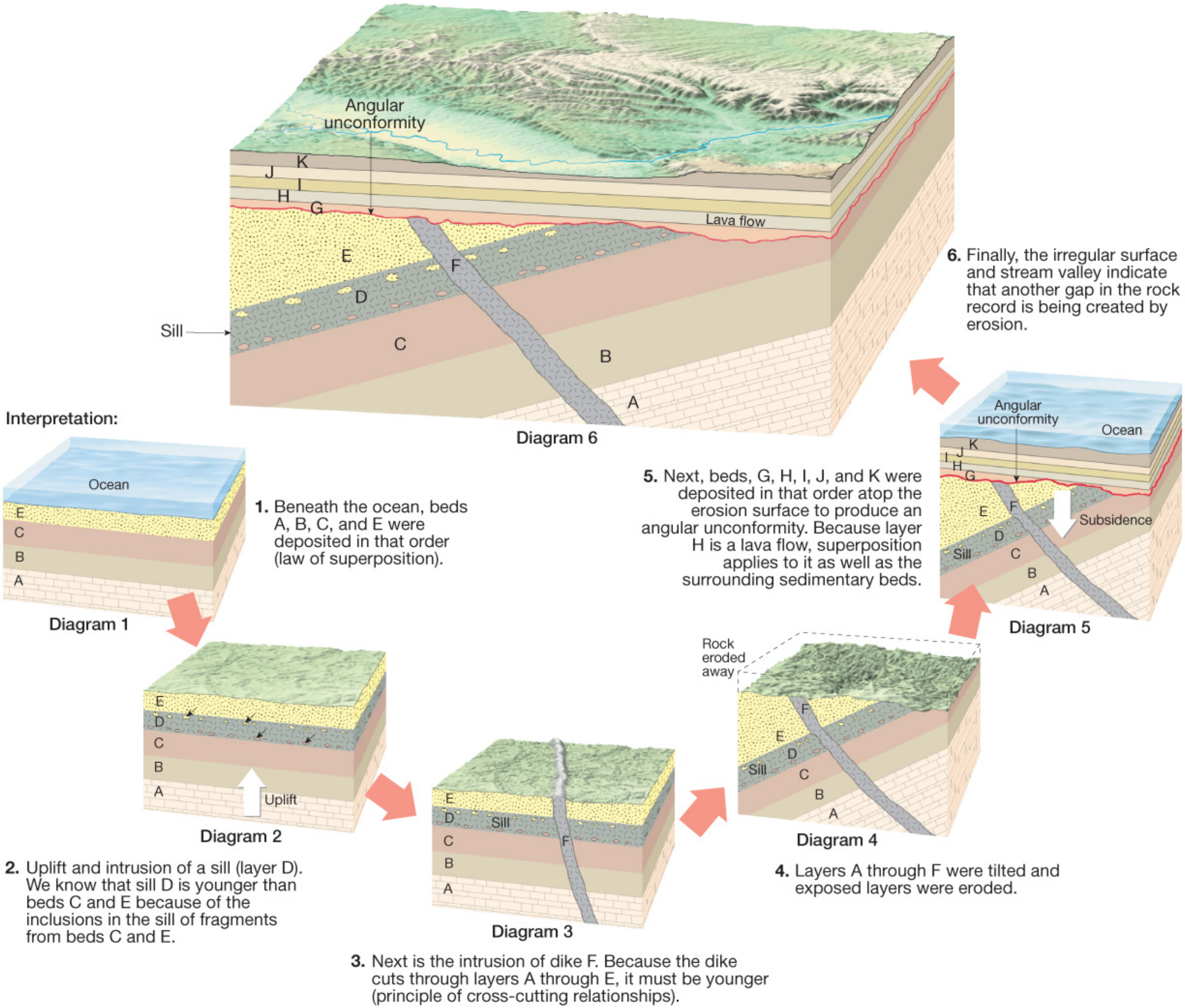
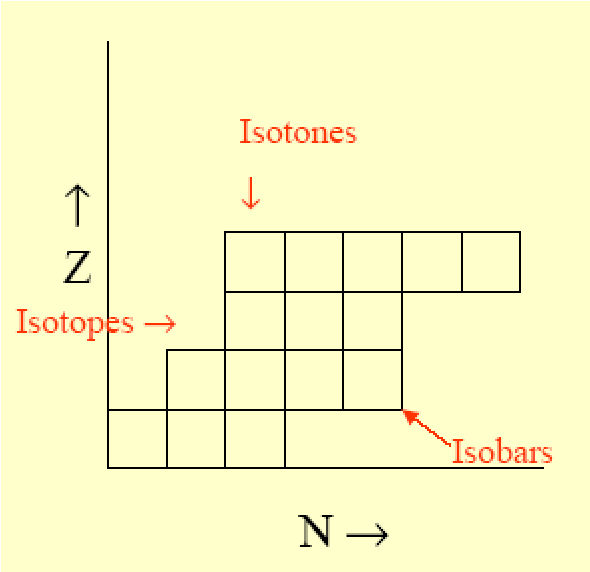


Diagram 6


Angular unconformity
K
J
I
H
G
Lava flow
E
F
D
Sill
C
B
A
Diagram 6
6. Finally, the irregular surface and stream valley indicate that another gap in the rock record is being created by erosion.
Interpretation:
Ocean
E
C
B
A
Diagram 1
1. Beneath the ocean, beds A, B, C, and E were deposited in that order (law of superposition).
Angular unconformity
Ocean
K
J
I
H
G
E
F
D
Sill
C
B
A
Subsidence
Diagram 5
5. Next, beds, G, H, I, J, and K were deposited in that order atop the erosion surface to produce an angular unconformity. Because layer H is a lava flow, superposition applies to it as well as the surrounding sedimentary beds.
E
D
C
B
A
Uplift
Diagram 2
2. Uplift and intrusion of a sill (layer D). We know that sill D is younger than beds C and E because of the inclusions in the sill of fragments from beds C and E.
E
D
Sill
C
B
A
F
Diagram 3
3. Next is the intrusion of dike F. Because the dike cuts through layers A through E, it must be younger (principle of cross-cutting relationships).
Rock eroded away
F
E
D
Sill
C
B
A
Diagram 4
4. Layers A through F were tilted and exposed layers were eroded.

Absolute dating: Dating with Radioactivity

Z = proton number = No. of protons in the nucleus; defines an element
N = neutron number = No of neutrons in the nucleus
A = mass number = Z + N;
Notation: ${}^{A}_{Z}X$



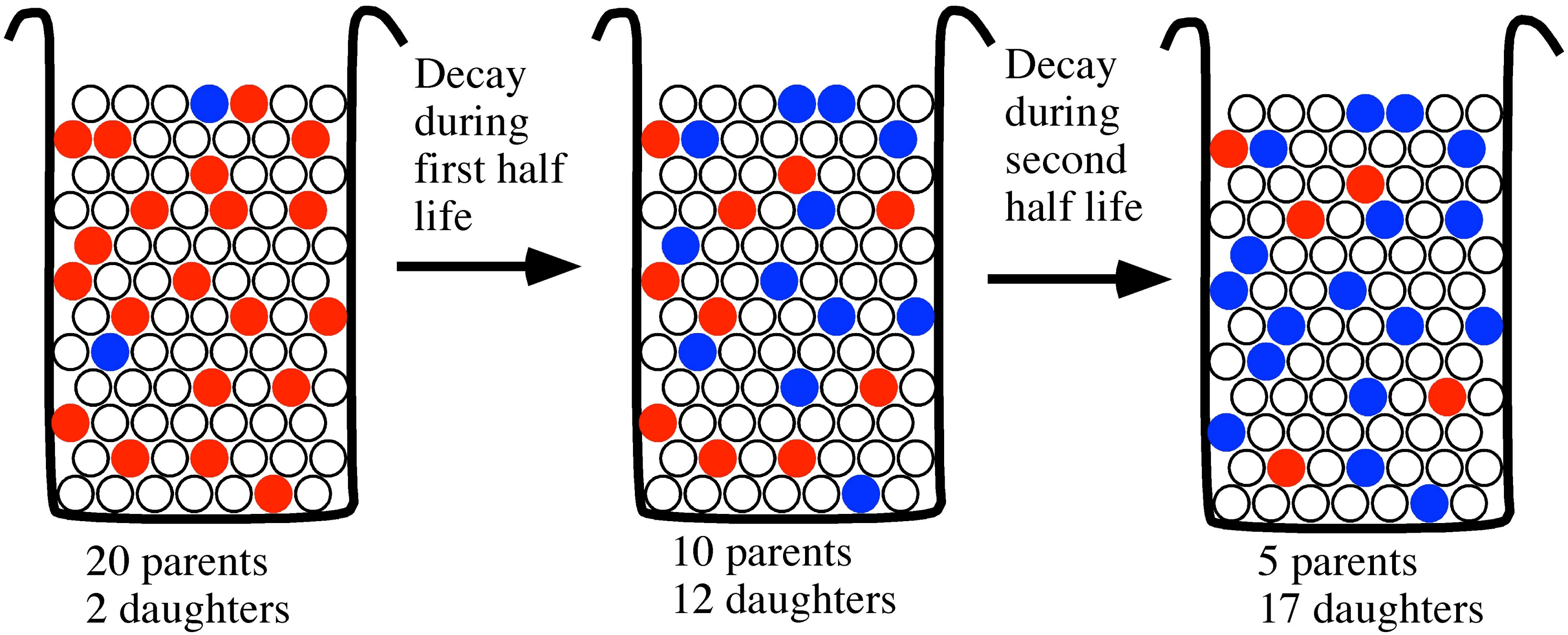
Isotope = line of equal Z (no. of proton);
nuclides with the same No. of protons (therefore they are the same element), but variable N;
e.g. ^{12}C, ^{13}C, ^{14}C are isotopes

Isotone = line of equal N (no. of neutrons);
nuclides with the same # of neutrons, but variable Z;
e.g. ^{37}Cl & ^{39}K are isotones (both have 20 neutrons)

Isobar = Equal mass;
nuclides with the same mass number, but variable N and Z;
e.g. ^{12}C, ^{12}B, ^{12}Be are isobars

- **Parent—an unstable radioactive isotope**
- **Daughter product—the isotopes resulting from the decay of a parent**
- **Half-life—the time required for one-half of the radioactive nuclei in a sample to decay**

Dating with Radioactivity



The actual number of atoms that decay (radioactive parent) continually decreases and the number of stable daughter atoms (radiogenic daughter) increases.

Simple Radioactive Decay

Radioactive decay is a stochastic process linked to the stability of nuclei. The rate of change in the number of radioactive nuclei is a function of the total number of nuclei present and the decay constant λ.

$$- dN / dt = \lambda N$$

The sign on the left hand is negative because the number of nuclei is decreasing. Rearranging this equation yields

$$- dN / N = \lambda dt$$

and integrating yields

$$- \ln N = \lambda t + C$$

C is the integration constant. We solve for C by setting $N = N_0$ and $t = t_0$. Then

$$C = - \ln N_0$$

Substituting for C gives

$$- \ln N = \lambda t - \ln N_0$$

We rearrange

$$\ln N - \ln N_0 = - \lambda t$$

Rearrange again

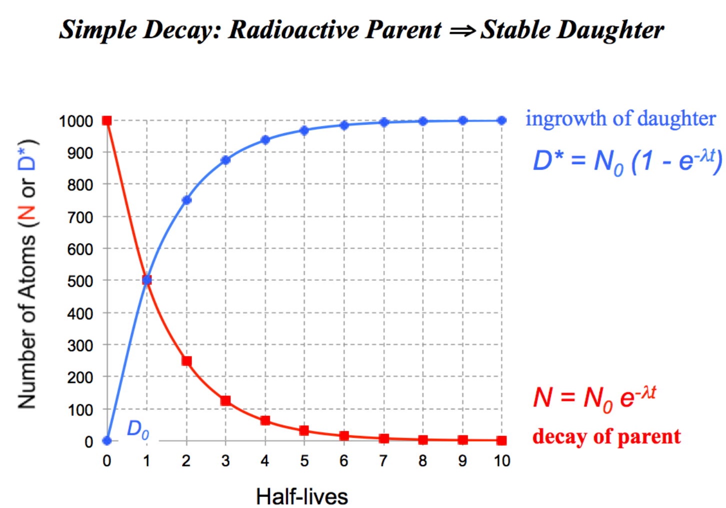
$$\ln N/N_0 = - \lambda t$$

Eliminate the natural log

$$N/N_0 = e^{-\lambda t}$$

And rearrange

$$N = N_0 e^{-\lambda t}$$



…continue…

Unfortunately, we don't know N_0 a priori, but decayed N have produced radiogenic daughters D*.

Therefore $$D^* = N_0 - N$$

Replacing N_0 with $N\,e^{\lambda t}$ yields $$D^* = N\,e^{\lambda t} - N$$

Rearranged $D^* = N\,(e^{\lambda t} - 1)$ or, for small λ t, $D^* = N\,\lambda\,t$,

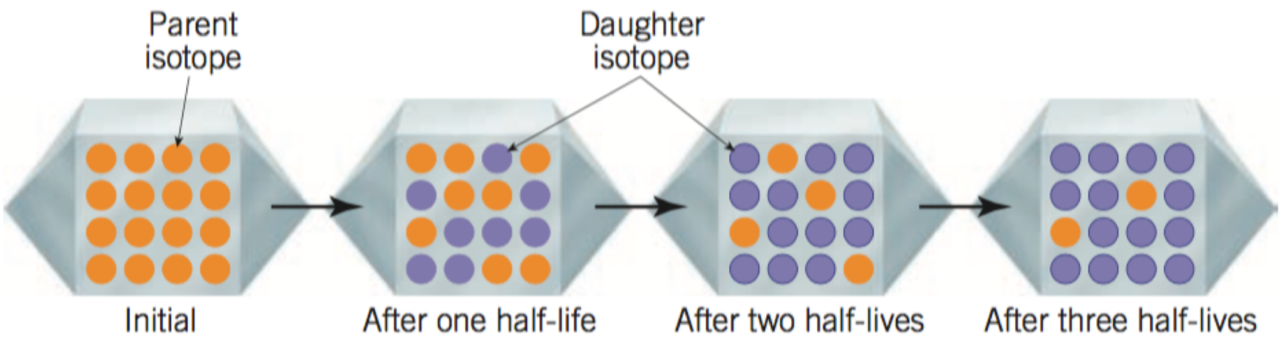
The number of daughter isotopes is the sum of those initially present plus those radiogenically produced.

$$D = D_0 + D^*$$

Therefore, $D = D_0 + N\,(e^{\lambda t} - 1)$ or, for small λ t, $D = D_0 + N\,\lambda\,t$,

This is the basic radioactive decay equation used for determining ages of rocks, minerals and the isotopes themselves. D and N can be measured and λ has been experimentally determined for nearly all known unstable nuclides. The value D_0 can be either assumed or determined by the **isochron method**.

CALCULATE IT Measurement of zircon crystals from a granite yield parent/daughter ratios of 25 percent parent (uranium-235) and 75 percent daughter (lead-206). The half-life of uranium-235 is 704 million years. How old is the granite?



Radioactive Parent	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 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

Isotopes Frequently Used in Radiometric Dating

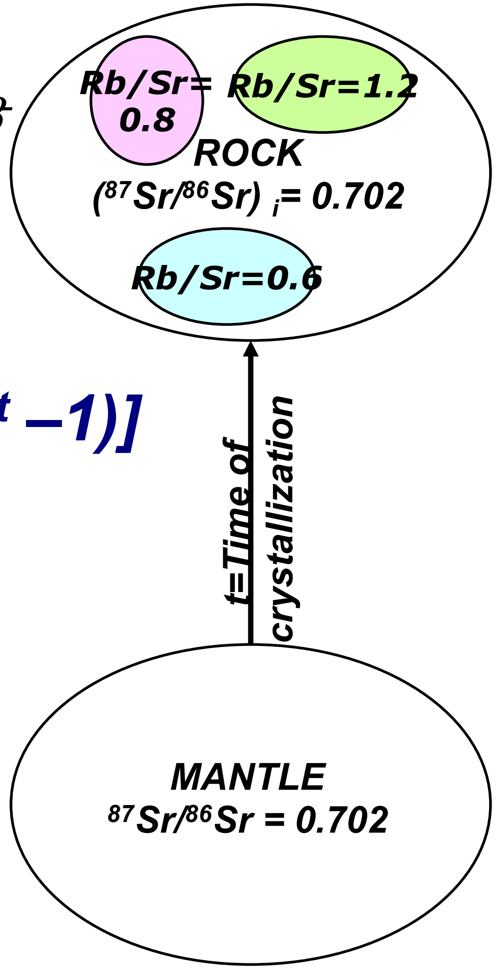
The only equation you have to memorize

$$D = D_0 + N\,(e^{\lambda t} - 1)$$

D = radiogenic daughter, N daughter atoms produced by radioactive decay of a parent, D_0=initial daughter atoms

^{87}Rb-^{87}Sr decay equation (Isochron equation)

Divide by a stable, non-radiogenic isotope of the daughter element to get ratios e.g. for $^{87}Rb \rightarrow {}^{87}Sr + \beta^-$



$$\frac{^{87}Sr}{^{86}Sr} = \left(\frac{^{87}Sr}{^{86}Sr}\right)_i + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right)$$

$$[D = D_0 + N\,(e^{\lambda t} - 1)]$$

measured ***measured***

when you crystallize a rock, you will always have some Sr present

<u>So how do you determine the initial $^{87}Sr/^{86}Sr$ ratio?</u>

Because igneous rocks are so heterogeneous, different mineral phases will have different Rb/Sr ratios, even though they have the same crystallization age and the same $^{87}Sr/^{86}Sr$ initial.

The Isochron

The radioactive decay equation is in the form of a line:

$$D = D_0 + P(e^{\lambda t}-1) \;\dots\; y = b + xm$$

Plot D ratio vs. P/D for several comagmatic or cogenetic samples and draw a best fit line through the data

y-intercept = initial D ratio, slope is related to t

This line is called an "Isochron"

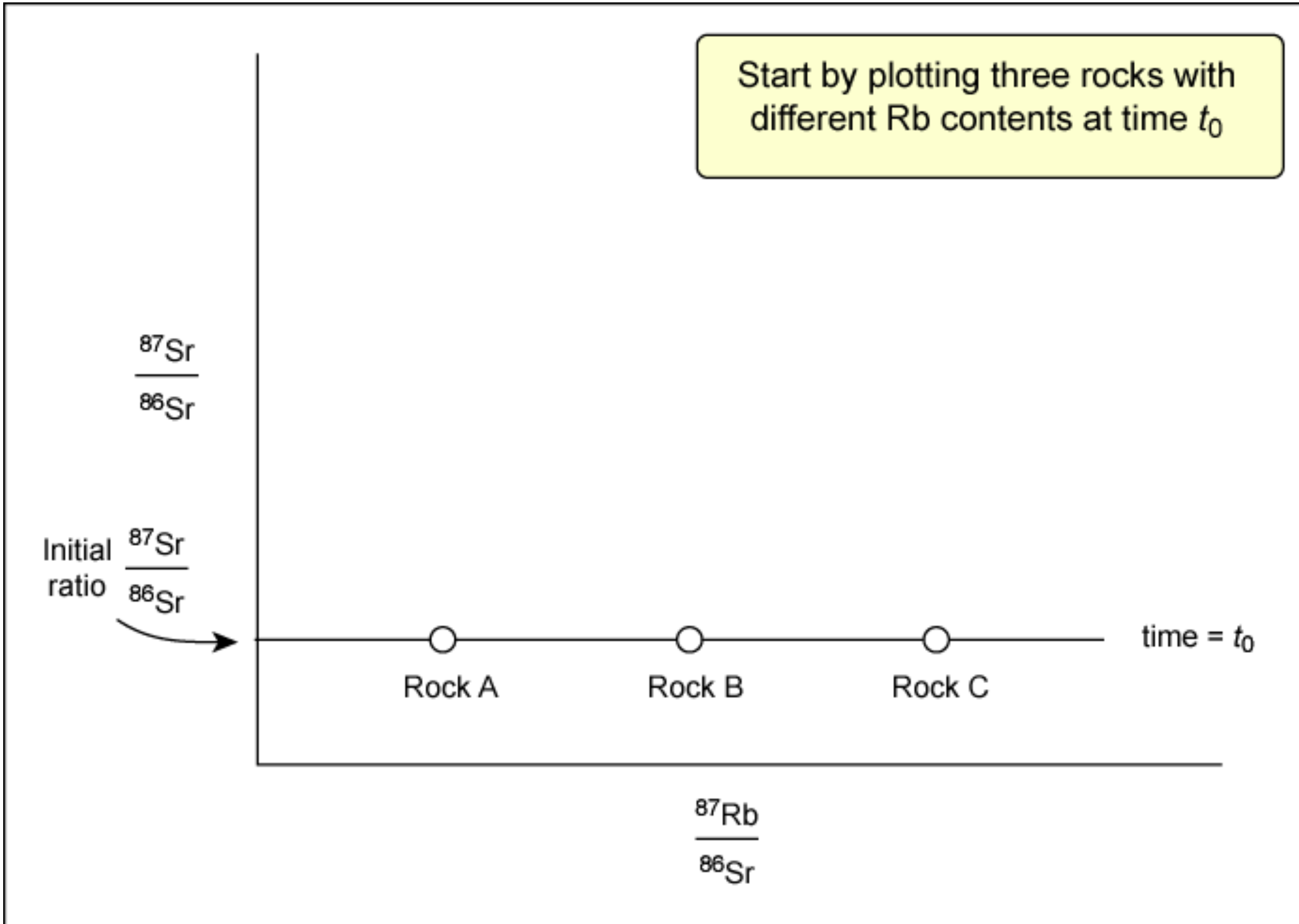
Represents true age if:

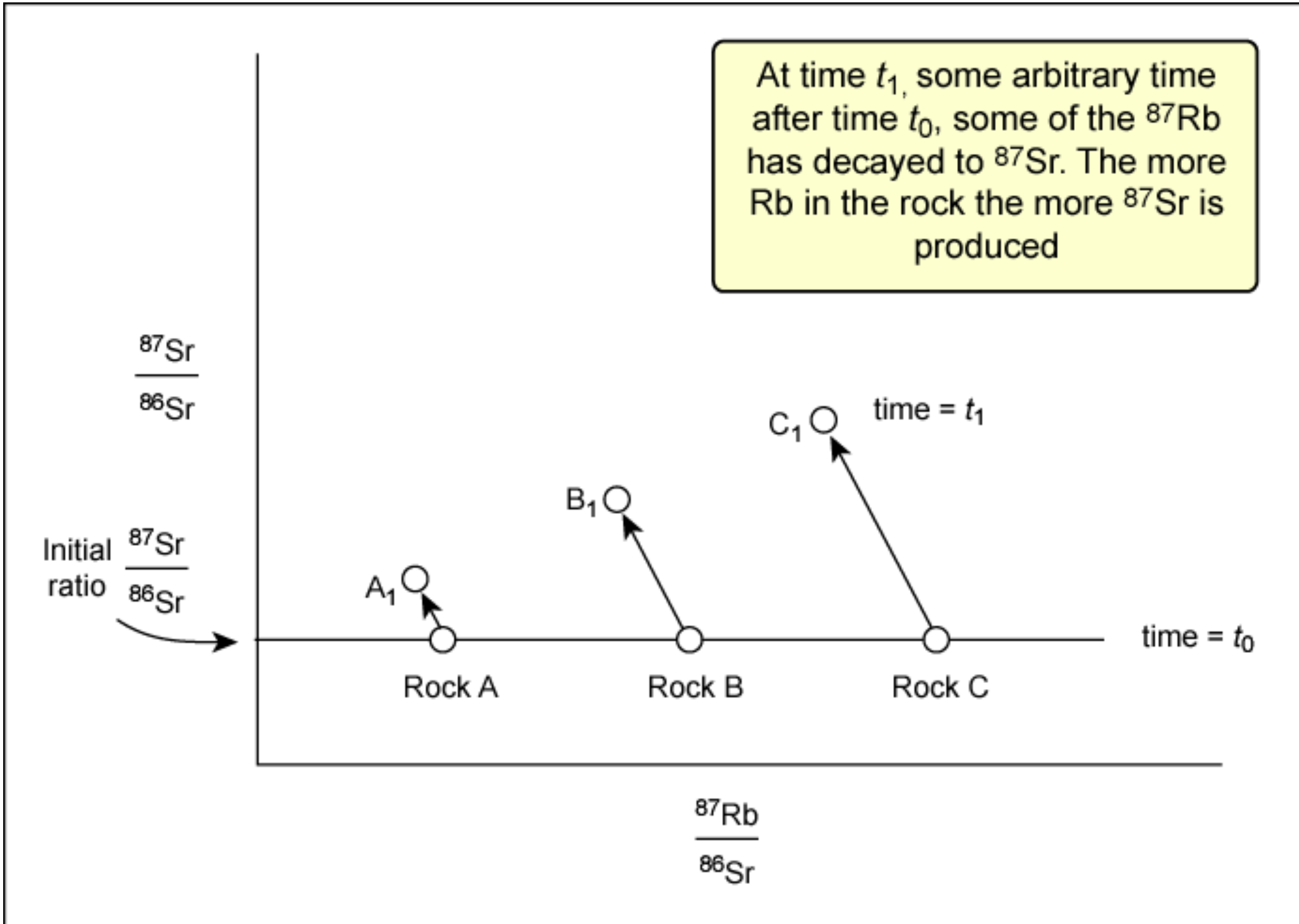
(1) The system was at isotopic equilibrium at time t = 0. I.e. all the samples formed with the same initial daughter isotope ratio

(2) Closed system since formation

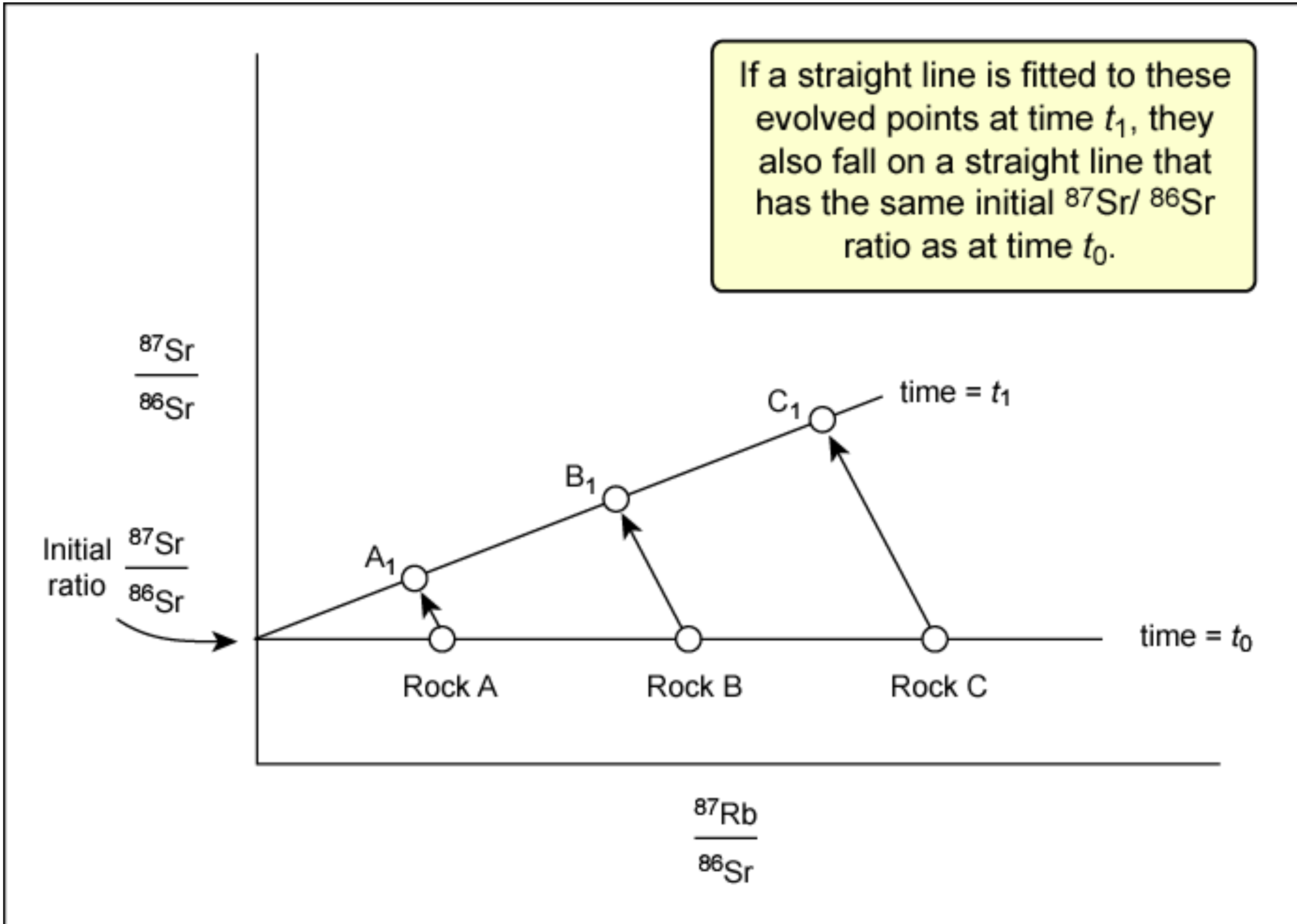
Whole-rock isochron represents age of formation

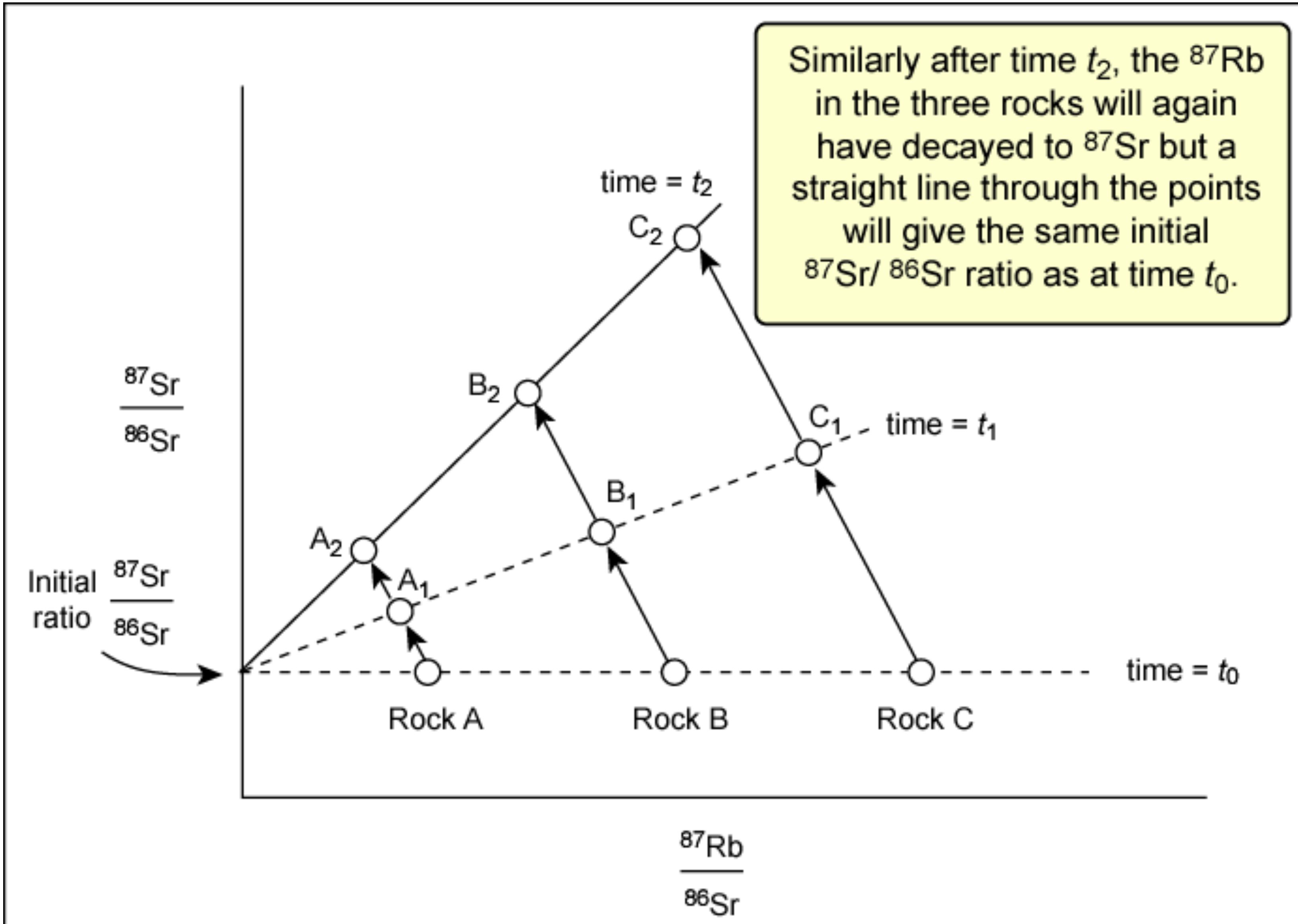
Mineral isochron represents age of last metamorphosis


Start by plotting three rocks with different Rb contents at time t_0
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$



At time t_1, some arbitrary time after time t_0, some of the ^{87}Rb has decayed to ^{87}Sr. The more Rb in the rock the more ^{87}Sr is produced
$\frac{^{87}Sr}{^{86}Sr}$
C_1
time = t_1
B_1
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
A_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$


If a straight line is fitted to these evolved points at time t_1, they also fall on a straight line that has the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
C_1
B_1
A_1
time = t_1
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$



Similarly after time t_2, the ^{87}Rb in the three rocks will again have decayed to ^{87}Sr but a straight line through the points will give the same initial $^{87}Sr/^{86}Sr$ ratio as at time t_0.
time = t_2
C_2
B_2
C_1
time = t_1
B_1
A_2
A_1
$\frac{^{87}Sr}{^{86}Sr}$
Initial ratio $\frac{^{87}Sr}{^{86}Sr}$
time = t_0
Rock A
Rock B
Rock C
$\frac{^{87}Rb}{^{86}Sr}$