9. The age of rocks

9.1. Absolute vs. relative ages

The issue of time is central to earth science. Geologists want to know how old rocks are and how long it takes for geological processes to take place. Until the 20th century and the discovery of radioactivity, geologists could only tell whether a rock was younger or older than another rock. In other words, they could only determine the ***relative age*** of rocks. Knowing the number of years elapsed since a rock has formed, i.e. the ***absolute age*** of the rock, could only be achieved after the development of radiometric dating in the 20th century.

9.2. The relative age of rocks

9.2.1. Fundamental principles of stratigraphy

Stratigraphy is the study of sedimentary layers (or strata). The founder of stratigraphy is a Danish scientist named Nicolas Steno (1638-1686). He is also known for his study of the fossil *Glossopetrae* which he correctly identified as fossilized shark teeth, a notable achievement at a time when the true nature of fossils was poorly understood. His interest for geology led him to study the sedimentary rocks of northern Italy (where he lived) and to enounce two fundamental rules of stratigraphy:

1. **Principle of original horizontality**
Sediments are deposited horizontally (or nearly so) by gravity. This implies that sedimentary layers which are folded or faulted have been subjected to deformation after their deposition.

2. **Principle of superposition**
New sedimentary layers form on top of older layers; therefore, in an undeformed succession of sedimentary layers, layers at the bottom are older than layers at the top.

The principle of superposition is of course very useful to determine the relative age of sedimentary layers. When studying a section of sedimentary rocks, this principle can be used to reconstruct the chronological order of the layers, providing that we understand the deformation history of the rocks studied[*]. What if we have two sections that are very far from each other? How can we know that the rocks of one section are younger or older than the rocks of another section located far away? One way to solve this problem is to study the fossil content of the sedimentary layers. This is the domain of a research field called ***biostratigraphy***.

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[*] Due to folding, a succession of sedimentary layers can be overturned (up-side down) and the chronological order is inverted. If the deformation is not noticed, the chronological reconstruction will be completely wrong!

9.2.2. Biostratigraphy

Biostratigraphy is the branch of stratigraphy which uses fossils to correlate sedimentary rocks found at different geographic locations and to determine their relative age. The technique relies on the fact that life evolves. Some species go extinct while new species appear. As a consequence, fossil assemblages of different geological intervals are not the same. The geological record is characterized by fossil assemblages whose species composition is changing through time. This is the ***principle of faunal succession***. For example, a fossil of Australopithecus[*] is not found in the same layer as a fossil of dinosaur because dinosaurs went extinct 65 million years ago (61 million years before the first Australopithecus appeared!).
Some species are more useful than others when it comes to determine the relative ages of sedimentary rocks. Species which are widespread －with a broad range of distribution－ and which have existed for a relatively short geological time span are excellent biostratigraphic markers. These species are called ***index species***.

NB: The concept of biological evolution was accepted before Charles Darwin (1809-1882) proposed his theory of evolution by natural selection. The roots of biostratigraphy are to be found in the 18th century when scientists noticed that sedimentary rocks of different ages were characterized by different fossils. What Darwin discovered is a mechanism explaining how new species arise, and therefore how evolution can take place.

9.2.3. Unconformities: gaps in the stratigraphic record

The stratigraphic record is not continuous. There are gaps which can result from prolonged lack of deposition or from the erosion of preexisting sedimentary layers. The surfaces corresponding to these gaps are called ***unconformities***.
In many cases unconformities result from an episode of erosion. Sedimentary layers formed in a lake or in the sea can be eroded during a long period of emergence. How do sedimentary layers initially formed under water become emerged? There are two important mechanisms that can cause long periods of emergence: ***sea level fall*** **(1)** and upward ground movement, i.e., ***uplift*** **(2)**.

(1) During ice ages (glacial periods), more ice accumulates on landmasses, meaning that less water remains in the ocean, and sea level falls dramatically. During the maximum of the last ice age, about 20,000 years ago (Last Glacial Maximum = LGM), the sea level was about 120 m lower than today! The continental shelves stood above sea level and sediments were exposed to erosion by wind and rain. New sedimentary layers formed only when the sea re-flooded the continental shelves during the subsequent －and current－ warm period. The surface which separates these

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[*] Australopithecus is an ancient genus of hominids －the family of primate to which we belong－ which appeared around 4 million years ago and went extinct 2 million years later.

new layers from the layers deposited before the LGM is an unconformity and represents a time gap of thousands of years. Many cold －glacial－ and warm －interglacial－ periods preceded the LGM.

(2) Regions of the crust near convergent plate boundaries experience tremendous compressional forces which can cause folding and bring portions of the crust at higher elevations, a process called tectonic uplift*. Uplifted sedimentary layers can be raised above sea level where they are exposed to erosional processes. Once compression stops, subsequent tectonic movements may create a depression in which new sediments can accumulate. The surface between the older folded sedimentary layers and the new sediments is an unconformity which may encompass a huge time lapse of millions of years!

There are three types of unconformities:
Disconformity: the sedimentary layers below and above the unconformity are both undeformed and horizontal. An example of a process that can lead to the formation of a disconformity is the episode of sea level fall presented above [see **(1)**].
Angular unconformity: the sedimentary layers below the unconformity are folded whereas the sedimentary layers above the unconformity are undeformed and horizontal. An example of a process that can lead to the formation of an angular unconformity is the episode of compressional deformation followed by erosion, subsidence, and deposition of new sediments presented above [see **(2)**].
Nonconformity: unconformity between sedimentary rocks (formed at the surface of Earth) and unstratified metamorphic or igneous rocks (formed deep inside the crust). This type of unconformity may represent a very extensive time gap of tens of millions of years or more.

9.2.4. Cross-cutting relationships

The geometrical relationships between sedimentary rock formations, igneous intrusions (e.g. dykes －sheet-like intrusion intersecting rock layers－), faults, and unconformities can be used to reconstruct the chronological order in which these geological features formed. The rule is simple: *younger geological structures cut older ones*. For example, a dyke intersecting sedimentary layers must be younger than these layers, or a fault cutting a dyke must be younger than the dyke.

9.2.5. The geological time scale

Geologists of the 19th century used the principle of superposition and biostratigraphy to divide the geological record into successive intervals characterized by distinct fossil assemblages. This

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* Note that uplift does not necessarily imply folding. Rocks can be uplifted without undergoing much folding (remember the sedimentary rock layers of Miocene age we observed during our field trip to Mizunami).

approach led to the construction of the ***geological time scale***. The basic subdivisions of the geological time scale (from longer to shorter time units) are ***eras*** (e.g. Cenozoic), ***periods*** (e.g. Quaternary), and ***epochs*** (e.g. the current epoch is called Holocene[*]).

The boundary between geological periods is characterized by abrupt changes in fossil assemblages. Several of these boundaries correspond to ***mass extinctions***. A mass extinction event represents a relatively short geological time span (a few million years or less) during which a large proportion of the total number of species living on the Earth (e.g., 75% or more) become extinct (see chapter on the origin and evolution of life).

9.3. The absolute age of rocks

When the geological time scale was established in the 19th century, geologists did not know the duration of each period. Nobody knew precisely how old the Earth was! This issue had implications not only for science but also for religion because of the strongly held religious belief that the Earth could not be older than a few thousands of years based on the rigorous interpretation of religious texts. The solution came only after the discovery of radioactivity in 1896 by a French physicist named Henri Becquerel. At the beginning of the 20th century, the physicist Ernest Rutherford proposed a technique to date rocks based on radioactive decay. The method of ***radiometric dating*** was born. Based on this method, an American geochemist named Clair C. Patterson calculated in the 1950s an age for the Earth of 4.56 billion years[**] by dating samples of meteorites!

The basic principle of radiometric dating is simple. Elements consist of different isotopes with nuclei composed of the same number of protons but with different numbers of neutrons. Some isotopes are not stable; they loose mass (energy) and transform into another chemical element when the number of protons changes. These isotopes are called ***Radioactive isotopes*** (or ***radioisotopes***), and the process of transformation is called ***radioactive decay***. In a rock containing a certain amount of a given radioactive isotope, the concentration of the element produced by radioactive decay increases with time and can be used as a natural clock to determine the age of the rock. This can work only if the rate of radioactive decay is known and does not vary in time.

The rate at which a radioactive isotope (parent atom) disintegrates into another element (daughter atom) is expressed by its ***half-life***. The half-life of a radioactive isotope is the time it takes for half of the initial amount of parent atoms to decay into daughter atoms (Figs. 1 & 2).
The half-life of a given radioisotope is constant. It is not affected by changes in physico-chemical conditions, such as variations in temperature and pressure. This is of fundamental importance

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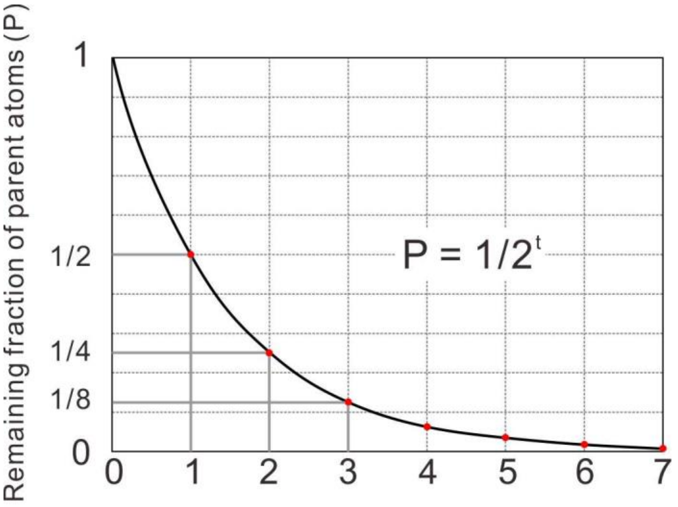
[*] Note that geologists are now discussing the creation of a new epoch: the Anthropocene. The beginning of the Anthropocene would mark the time when human activities began to have a pervasive and significant impact on the Earth's global environment.

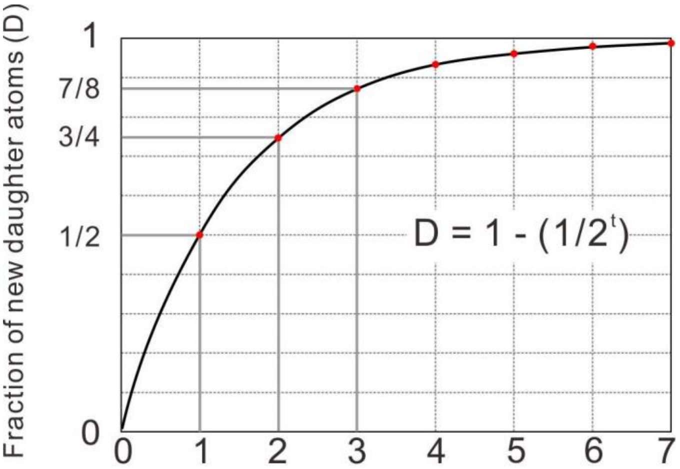
[**] This is still the accepted age of the Earth and the Solar System today.

because, if the half-life of radioactive isotopes were dependent on external factors and varied in time, radiometric dating would not be possible.



Time t (in half-lives)

Figure 1



Time t (in half-lives)

Figure 2

Different isotopes have different half-lives. For example, ^{14}C (carbon-14) disintegrates into ^{14}N and has a half-life of 5730 years. Another example is ^{87}Rb which disintegrates into ^{87}Sr and has a half-life of 49 billion years. Therefore, if one wants to measure the age of a rock that is hundreds of millions of years old or more, one can use the rubidium-strontium system, but not the radioactive isotope of carbon. The ^{14}C method is used to measure the age of much younger materials (<50,000 years). For example, you can use ^{14}C to measure the age of corals which were growing several thousands of years ago, or wooden structures unearthed during archeological excavations.

In order to understand how the age of a rock can be measured, let's take the example of the rubidium-strontium system. In this case, the parent atom is ^{87}Rb and the daughter atom is ^{87}Sr. The evolution of the fraction of parent atoms remaining and new daughter atoms formed as the process of radioactive decay goes on is illustrated in figure 1 and 2, respectively.

Let's say we collected a sample of igneous rock and we want to know its age. The age of the sample in this case is the time elapsed since it crystallized from a cooling magma. The crystals forming in the cooling magma have trapped a certain amount of parent atoms $[^{87}\mathrm{Rb}]_{t=0}$. We assume the crystals have behaved as closed systems since they formed. It means that no exchange of matter took place with the surroundings, and that variations in the amount of parent and daughter atoms in the sample are the result of radioactive decay alone.

First let's suppose that there are no daughter atoms ^{87}Sr incorporated in the crystals when they formed (though unrealistic!). We can express the amount of ^{87}Rb and ^{87}Sr present in our sample as a function of time using the following relationship:

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

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

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

$$\boxed{[^{87}\mathrm{Sr}]_t = (2^t - 1)\ [^{87}\mathrm{Rb}]_t} \qquad \text{(A)}$$

Equation (A) represents a straight line with a slope equal to (2^t-1) (Fig. 3). Measuring the amount of ^{87}Sr and ^{87}Rb in our sample would therefore enable us to calculate the age of the rock.

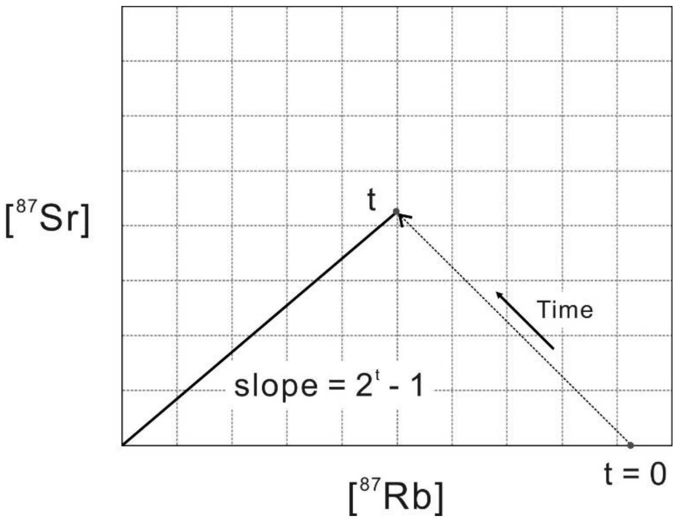


Figure 3

In reality, there is always a certain amount of daughter atoms ^{87}Sr which is incorporated in the crystals when the rock forms. In such case, equation (A) becomes (Fig. 4):

$$\boxed{[^{87}\mathrm{Sr}]_t = (2^t - 1)\ [^{87}\mathrm{Rb}]_t + [^{87}\mathrm{Sr}]_{t=0}} \qquad \text{(B)}$$

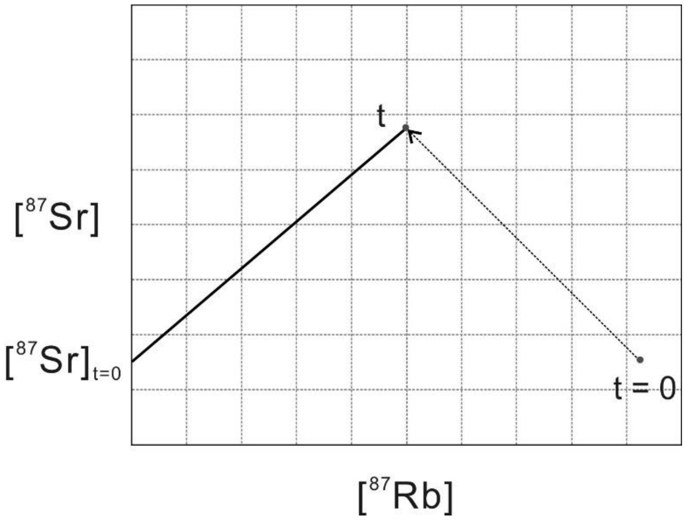


Figure 4

In this more realistic case, measuring the amount of parent atoms and daughter atoms in our sample is not enough to calculate the age of the rock because we don't know how much daughter atoms have been trapped initially in the crystals of our rock sample (Fig. 5). Each crystals of our rock sample can incorporate any amount of ^{87}Rb and ^{87}Sr at the time of crystallization.

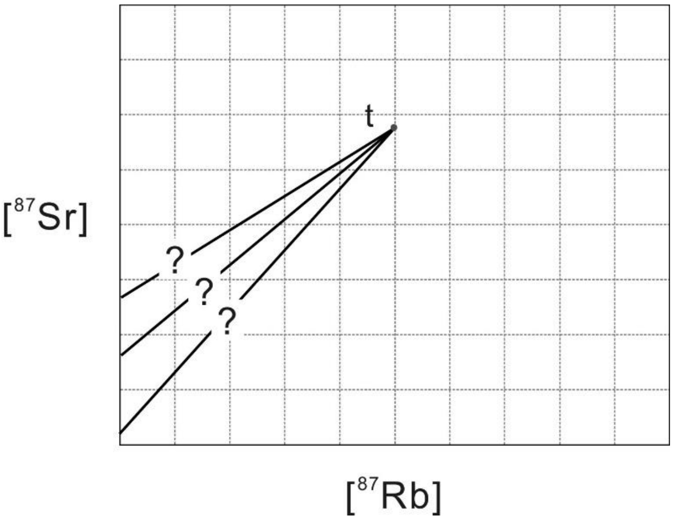
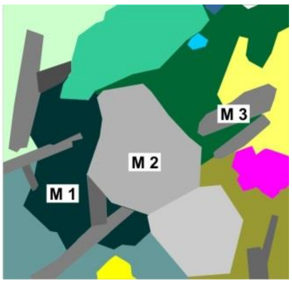


Figure 5

The solution to this problem is to consider the ratio of ^{87}Sr to a stable isotope of the same element which has the same properties. In this case the stable isotope in question is ^{86}Sr. Since ^{87}Sr and ^{86}Sr have a similar behavior during physico-chemical reactions, they will incorporate different minerals always in the same proportion[*]. Let's say we have 1000 atoms of ^{87}Sr and 1200 atoms of ^{86}Sr initially present in the magma. The table below shows their distribution in three different minerals. The initial ratio ^{87}Sr/^{86}Sr is independent of the amount of ^{87}Sr trapped in the minerals when they crystallized (a similar example is presented in the textbook *Understanding Earth*).

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



If we divide equation (B) by $[^{86}\mathrm{Sr}]_t$, we obtain the following relationship:

$$\boxed{\left(\frac{[^{87}\mathrm{Sr}]}{[^{86}\mathrm{Sr}]}\right)_t = (2^t - 1)\left(\frac{[^{87}\mathrm{Rb}]}{[^{86}\mathrm{Sr}]}\right)_t + \left(\frac{[^{87}\mathrm{Sr}]}{[^{86}\mathrm{Sr}]}\right)_{t=0}} \qquad \text{(C)}$$

We can thus determine the age of our sample by measuring the ratio of ^{87}Sr and ^{87}Rb to ^{86}Sr in several minerals in order to obtain a straight line from which we can derive the age t (Fig. 6). In addition to the age, we can also find out the initial ratio of ^{87}Sr to ^{86}Sr.

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[*] Note that the isotopic composition of the magma should be uniform when crystallization occurs. We also assume that there are no variations in the initial ratio of ^{87}Sr to ^{86}Sr due to isotope fractionation taking place during the process of crystallization. The concept of isotope fractionation will be explained in the chapter on the origin and evolution of life.

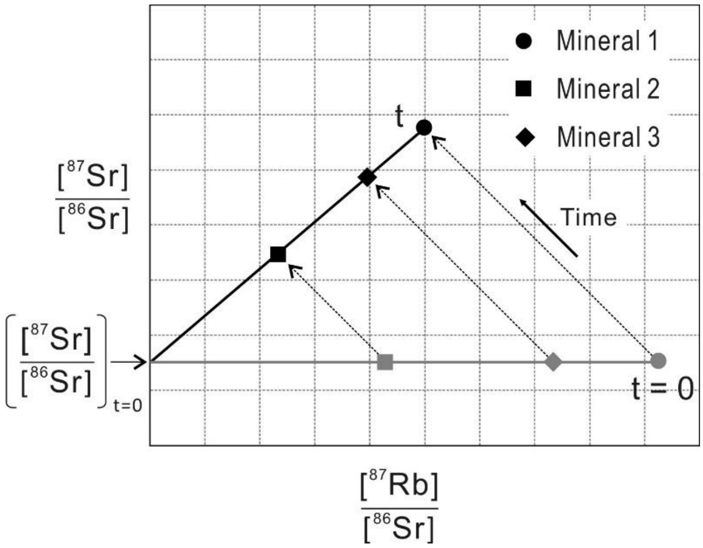

Figure 6

The slope of the line defined by the three minerals in the graph above is a function of the time elapsed since crystallization. This method is valid only if the minerals did not exchange elements with the surrounding environment after they crystallized. Each mineral must have remained a ***closed system****. For metamorphic rocks, the age obtained corresponds to the time since the last phase of crystallization. We can also measure the age of biominerals, like coral skeletons or algal crusts made of $CaCO_3$. In this case, we measure the time elapsed since the organism secreted the mineral assuming that the system remained closed afterward.

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[*] Note that there are techniques that enable geologists to deal with open systems.