Radioactivity , Isotopes and Dating

Lecture 3

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Preamble

- Radioactive decays of certain naturally occurring isotopes are widely used to date terrestrial and meteoritic materials and to trace their evolution.
- Sedimentation and the fossil record are still central to geological history but now the fossil –based geological periods are linked to isotopically dated events.
- The principles of dating by radioactive decay require precise measurement of isotopic abundances.

Preamble

- *Isotopic* methods have become so sensitive that very small variations in isotopic ratios of light elements , arising independently of radioactivity, are also routinely measured.
- *Another* reason for interest in radioactivity is that it is a source of heat. It is the dominant continuing energy source in the Earth.

Radioactive decay

- Atoms of the same element can have different numbers of neutrons; the different possible versions of each element are called *isotopes*. For example, the most common isotope of hydrogen has no neutrons at all; there's also a hydrogen isotope called ***deuterium*** **one** neutron, and another, ***tritium*** , with two neutrons.
- *Radioactive decay* involves the spontaneous transformation of one element into another. The only way that this can happen is by changing the number of protons in the nucleus (an element is defined by its number of protons), and when it does, the atom is forever changed. This process is irreversible.

Radioactive decay

- The rate of radioactivity decay of an isotope is represented by the decay constant , λ , which is the probability per unit time that a constituent particle in an atomic nucleus will escape through the potential barrier binding it to the nucleus.
- The rate of decay of N nuclei is proportional to N :

$dN/dt = -\lambda N$ (1)

Integrating from an initial number N_0 at time $t = 0$ we obtain the decay equation:

$N = N_0 e^{-\lambda t}$ (2)

Radioactive decay

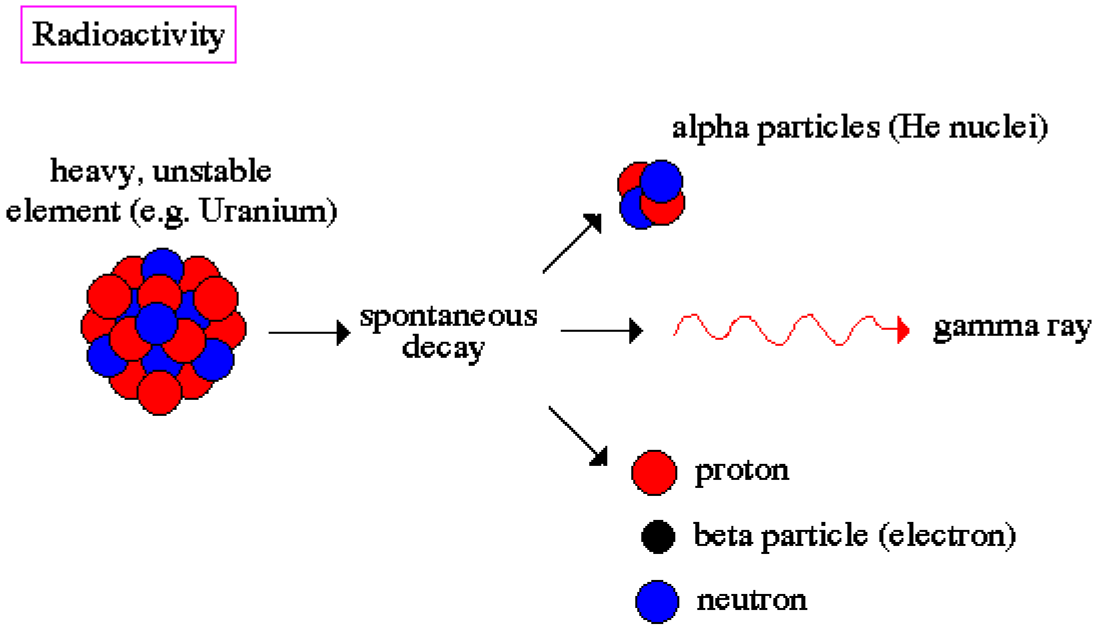
- The relationship between λ and the half life, $T_{1/2}$, of an isotope is obtained by substituting $N_0/2$ at $t = T_{1/2}$,

$T_{1/2} = \ln 2/\lambda = 0.69315/\lambda$ (3)

- Decay by escape of α-particles (^4He nuclei)and β^- or β^+ particles (electrons or positrons) occurs by the penetration of potential barriers that bind these particles to the nucleus.
- The probability of decay by fission , in which a nucleus breaks into two comparable fragments plus neutrons , is also a nuclear property represented by a decay constant.

Radioactive decay

Fig.1



A decay clock : ^{14}C dating

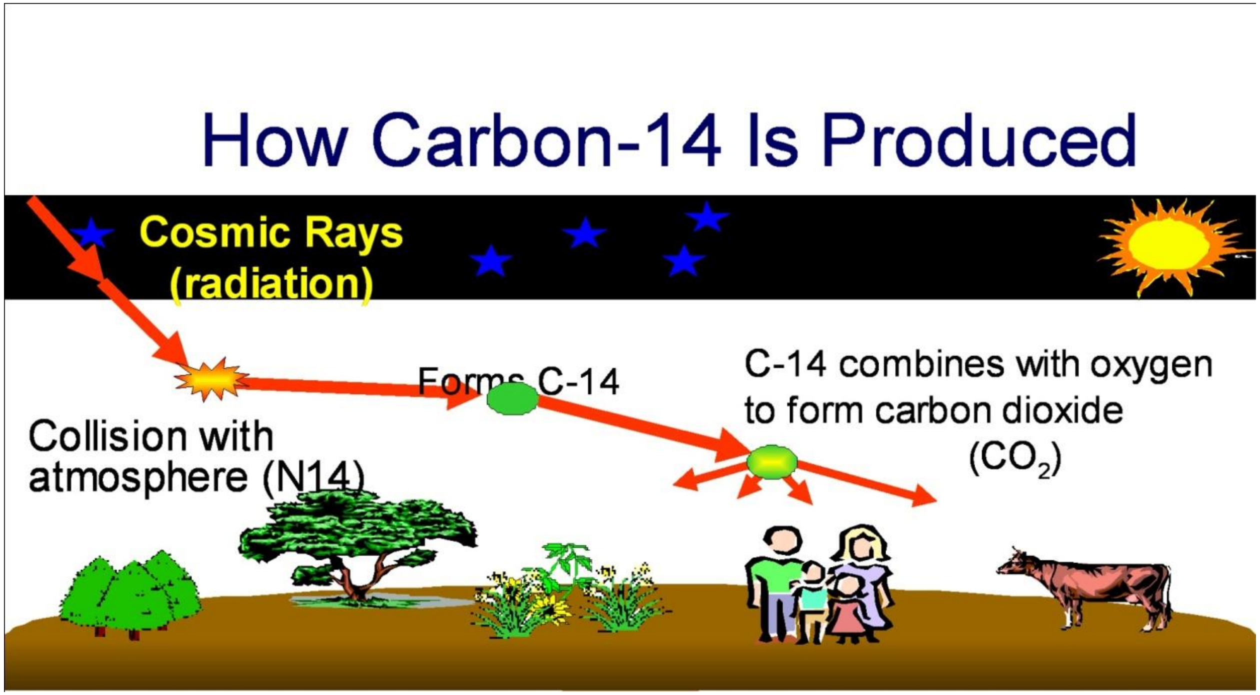
- A decay clock is one that use Eq.(3) .
- The measured abundance , *N* , of a decaying isotope is compared with an assumed initial abundance, N_0 , and *t* is calculated from the ratio.
- The need to know N_0 restricts the usable decay clocks to those that make use of continuously maintained reservoirs of the parent isotopes.

A decay clock : ^{14}C dating

- The most important of these isotopes is ^{14}C, which is produced by reaction of cosmic ray – generated neutrons on atmosphere ^{14}N (Fig.2).
- ^{14}C is incorporated in vegetation by photosynthesis , so that materials of biological origin can be dated by the ^{14}C method.

A decay clock : ^{14}C dating

Fig.2.



A decay clock : ^{14}C dating

- Once the carbon is fixed in a sample of wood or the bones of an animal that dies, the clock is ‘switched on ‘ and the date of fixing of the carbon can be determined by amount of ^{14}C remaining .
- The method is most effective for materials of ages comparable to the half-life , 5730 years, and is progressively less accurate for both younger and older samples.

A decay clock : ^{14}C dating

- Carbon dating has a central role in archeology and has provided a quantitative tool for the study of geological processes in the quaternary period.

Accumulation clocks: K–Ar and U–He dating

– An alternative to direct knowledge of the initial concentration , N_0 , of a radioactive parent is a measurement of the concentration , D^* , of a daughter product because

$$D^* = N_0 - N = N_0 (1 - e^{-\lambda t}) \qquad (4)$$

Dividing Eq.(4) by Eq.(2) , the unknown N_0 is eliminated ,

$$D^* / N = e^{\lambda t} - 1 \qquad (5)$$

– For a decay scheme with no initial daughter or other complications , Eq.(5) could be used directly in determination of ages.

Accumulation clocks: K-Ar dating

- The K-Ar dating is based on the decay of a minor isotope of potassium , ^{40}K to ^{40}Ar.
- It is that only 10.5% of ^{40}K decays yield ^{40}Ar , the remainder being β^- decays to ^{40}Ca .
- Argon is almost completely lost by outgassing from cooling lava.
- When an extrusive igneous rock solidifies , with no ^{40}Ar , its clock is set to zero .

Accumulation clocks: K-Ar dating

- For K- Ar dating the clock equation is a simple modification of Eq.(5),

$$^{40}Ar = (\lambda_{Ar} / \lambda) \, ^{40}K \, (e^{\lambda t} - 1) \qquad (6)$$

- Estimation of the age of a rock or mineral by Eq.(6) requires a determination of the ratio $^{40}K / ^{40}Ar$. There are two methods to obtain the ratio $^{40}K / ^{40}Ar$:

Accumulation clocks: K-Ar dating

I. The most used method relies on independent measurements of argon and potassium . This means carefully dividing a sample into two halves that contain equal concentrations of K and Ar, and then K is measured in one half and Ar in the other.

- The argon measurement is made with mass spectrometer and potassium is commonly determined by a flame photometer .

Accumulation clocks: K-Ar dating

II. An alternative method of obtaining the ratio ^{40}K / ^{40}Ar in a sample is to expose it to a neutron flux in a nuclear reactor.

- The K-Ar method is well suited to dating igneous rocks with simple histories , especially materials that are relatively young geologically .

Accumulation clocks: U-He dating

- Another accumulation clock with a gaseous daughter product is the decay of uranium and thorium , which produce ^{4}He .
- The He/U method was used in the first dating of rocks by Ernest Rutherford .
- Accumulation of ^{4}He has been measured in the mineral apatite.
- This method has been used to show that the San Gabriel Mts, in California , have been rising at about 0.3mm/yr for the last 5 million years.

The Rb – Sr “isochrons “Method

- The Rb-Sr method is based on the radioactivity of ^{87}Rb, which undergoes simple beta decay to ^{87}Sr with a half-life of 48.8 billion years .
- Rubidium is a major constituent of very few minerals, but the chemistry of rubidium is similar to that of potassium and sodium, both of which do form many common minerals, and so rubidium occurs as a trace element in most rocks .

The Rb – Sr “isochrons “Method

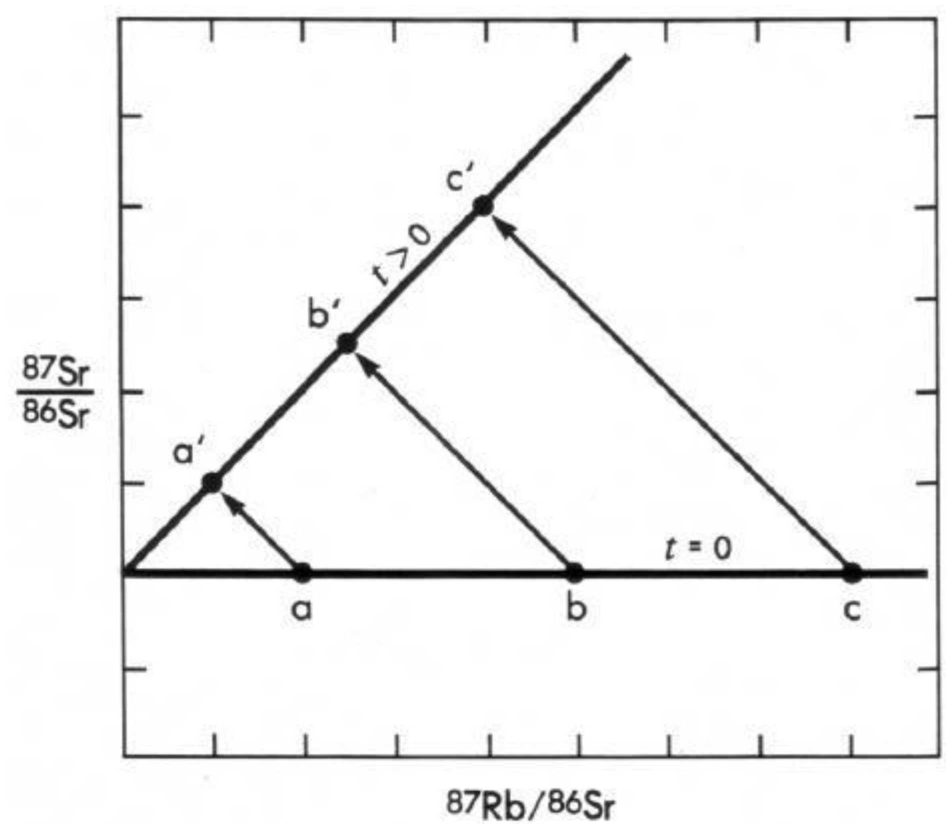
- Because of the very long half-life of ^{87}Rb, Rb-Sr dating is used mostly on rocks older than about 50 to 100 million years.
- This method is very useful on rocks with complex histories because the daughter product, strontium, does not escape from minerals nearly so easily as does argon.
- Unlike argon, which escapes easily and entirely from most molten rocks, strontium is present as a trace element in most minerals when they form. For this reason, simple Rb-Sr ages can be calculated only for those minerals that are high in rubidium and contain a negligible amount of initial strontium. In such minerals, the calculated age is insensitive to the initial strontium amount and composition.

The Rb – Sr "isochrons "Method

- For most rocks, however, initial strontium is present in significant amounts, so dating is done by the isochron method, which completely eliminates the problem of initial strontium.
- In the Rb-Sr isochron method, several (three or more) minerals from the same rock, or several cogenetic rocks with different rubidium and strontium contents, are analyzed and the data plotted on an isochron diagram(Fig.3).

The Rb – Sr “isochrons “Method

Fig.3. Rb-Sr isochron diagram, showing the time-dependent evolution of Rb and Sr isotopes in a closed system.



The Rb – Sr "isochrons "Method

- The ^{87}Rb and ^{87}Sr contents are normalized to the amount of ^{86}Sr, which is not a radiogenic daughter product.
- When a rock is first formed, say from a magma , the ^{87}Sr /^{86}Sr ratios in all of the minerals will be the same regardless of the rubidium or strontium contents of the minerals, so all of the samples will plot on a horizontal line (a-b -c in Fig.3).

The Rb – Sr “isochrons “Method

- The intercept of this line with the ordinate represents the isotopic composition of the initial strontium. From then on, as each atom of ^{87}Rb decays to ^{87}Sr, the points will follow the paths shown by the arrows.
- At any time after formation, the points will lie along some line a’-b’-c (Fig.3) , whose slope will be a function of the age of the rock.

The Rb – Sr “isochrons “Method

– The intercept of the line on the ordinate gives the isotopic composition of the initial strontium present when the rock formed. Note that the intercepts of lines a-b-c and a'-b'-c' are identical, so the initial strontium isotopic composition can be determined from this intercept regardless of the age of the rock.

The U – Pb Method

- The U–Pb method relies on the decays of ^{235}U and ^{238}U. These two parent isotopes undergo series decay involving several intermediate radioactive daughter isotopes before the stable daughter product , Lead is reached.
- Two simple independent "age" calculations can be made from the two U–Pb decays: ^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb .

The U – Pb Method

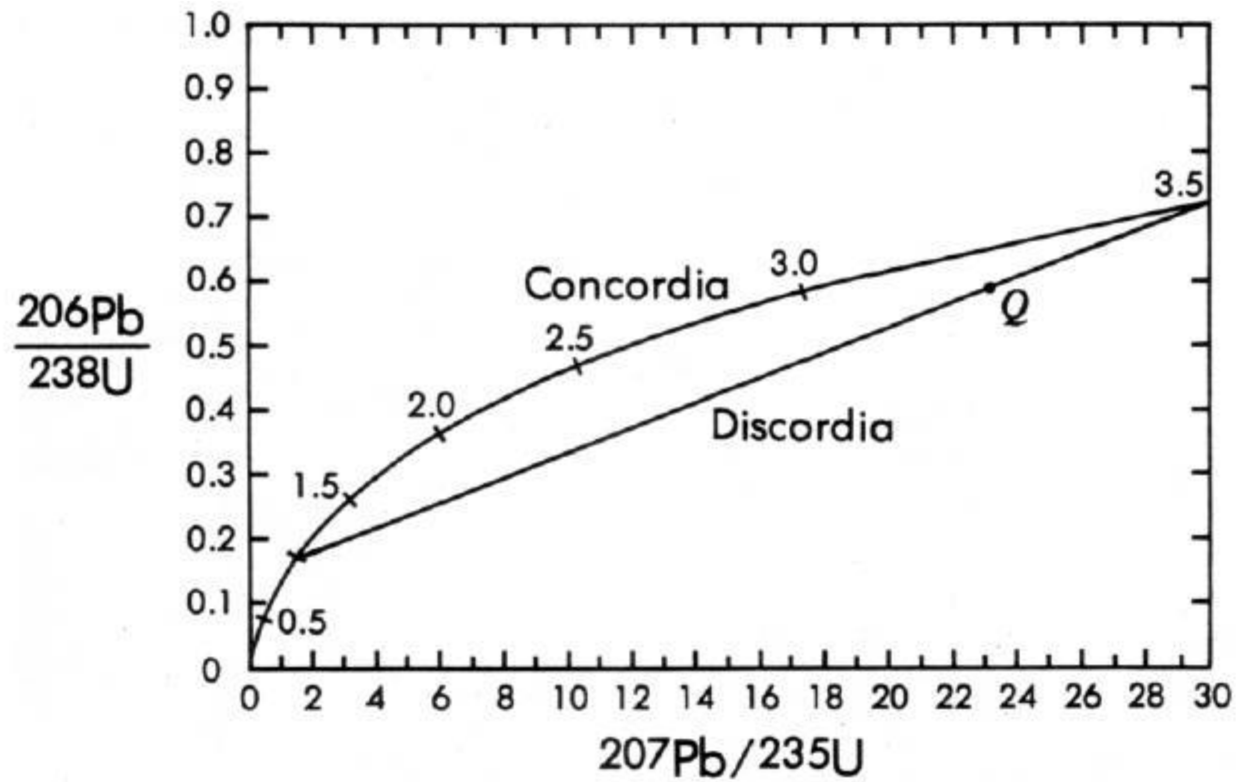
- In addition, an “age” based on the ^{207}Pb / ^{206}Pb ratio can be calculated because this ratio changes over time.
- If these three age calculations agree, then the age represents the true age of the rock.
- Lead is a volatile element, and so lead loss is commonly a problem. As a result, simple U–Pb ages are often discordant.

The U – Pb Method

- The U–Pb concordia – discordia method circumvents the problem of lead loss in discordant systems and provides an internal check on reliability.
- This method involves the ^{235}U and ^{238}U decays and is used in such minerals as zircon, a common accessory mineral in igneous rocks, that contains uranium but no or negligible initial lead. This latter requirement can be checked, if necessary, by checking for the presence of ^{204}Pb , which would indicate the presence and amount of initial lead.

The U – Pb Method

Fig.4.U-Pb concordia-discordia diagram showing the evolution of a system that is 3.5 billion years old and underwent episodic lead loss 1.0 billion years ago.



The U – Pb Method

- In a closed lead-free system, a point representing the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios will plot on a curved line known as concordia (Fig.4).
- The location of the point on concordia depends only on the age of the sample. If at some later date (say, 2.5 billion years after formation) the sample loses lead in an episodic event, the point will move off of concordia along a straight line toward the origin.

The U – Pb Method

- At any time after the episodic lead loss (say, 1.0 billion years later), the point Q in (Fig.4) will lie on a chord to concordia connecting the original age of the sample and the age of the lead loss episode.
- This chord is called discordia. If we now consider what would happen to several different samples, say different zircons, from the same rock, each of which lost differing amounts of lead during the episode, we find that at any time after the lead loss, say today, all of the points for these samples will lie on discordia.

The U – Pb Method

- The upper intercept of discordia with concordia gives the original age of the rock, or 3.5 billion years in the example shown in (Fig 4.).
- The U-Pb concordia -discordia method is one of the most powerful and reliable dating methods available. It is especially resistant to heating and metamorphic events and thus is extremely useful in rocks with complex histories.

References

–Stacey F. and Davis P., Physics of the Earth, Cambridge University Press, 2008.

–Lowrie, W., Fundamentals of Geophysics, Cambridge University Press, 2007.