DEEP TIME

HOW OLD IS THE EARTH? HOW OLD IS THAT FOSSIL? HOW DO WE KNOW?

As we explore the history of life (and the history of our planet), we often talk about events happening millions and even billions of years ago. Some people have heard that the Earth is only about 6-10,000 years old (the ”young earth” idea), so how can geologists and biologists be so confident that the Earth is so much older?

In order to measure deep time, we need some kind of **clock**, something that marks time by changing in some regular way that we can detect, not in seconds or hours, but in millions of years. Our clock must be reliable, unaffected by weather or temperature changes over those millions of years.

As it turns out, we have such a clock; in fact, we have many such clocks. We call them “**radioisotopes**.” They are found abundantly in nature, and extensive studies have shown that their physical properties nicely qualify many of them as clocks for measuring the past. Their behavior follows universal laws of physics which have been confirmed by studies in astronomy. Those studies, carried out over the past half century, have consistently and reliably revealed to us that the Earth is very, very old, and have also provided us with a large number of reliable techniques giving us very close age markers for many events of the distant past.

The following series of statements, activities, and questions will walk you through this field of “Geo-Chronology”, and help you to learn about those techniques and tools, and to understand why scientists are so confident of the reality of “Deep Time”.

INSTRUCTIONS: Read through and think about the background, examples, and other informational items. When you come to an “Activity” or “Question”, do these on the special Worksheet provided. At some point, possibly the next day in class, your teacher will go over the answers and lead you in discussion.

BACKGROUND:

1. All elements have atoms of slightly different forms, called isotopes.
2. All isotopes of the same element act the same chemically, since they each have the same number of protons and electrons; only their neutron numbers differ (which produce their different atomic masses).
3. Most elements exist in nature as a mix of two or more isotopes of the element.
4. Most isotopes give off radiation, so they are called “radio-isotopes” .
5. Many of those radioisotopes are found naturally in the Earth’s crust.
6. Each radioisotope has its characteristic traits (type and energy of radiation, half-life, etc.) which can be measured with considerable accuracy.

7. **HALF-LIFE**: The half-life of a radioisotope is a constant unchanging value for that radioisotope. It’s the amount of time it takes for half of the atoms of a sample to randomly decay into another isotope, with the loss of energy in the form of radiation. Half-lives range widely from fractions of a second for some radioisotopes, to billions of years for others. The “daughter” isotope produced in the decay can be of the **same** element, or a **different** element, depending on its type of decay, and whether or not protons are added or lost.

8. The half-life of a **long**-lived radioisotope is measured by sampling its mass or its radiation for a measured period of time (as both decrease exponentially), then calculate or extrapolate from that to a future point in time at which its mass (and its radioactivity) would be 1/2 of the values when the measurements were started.

8-**EXAMPLE:** As an example, a pure 100 gram sample of radioactive **Uranium 235 (U235)** would decay into 50 grams of **U235** and 50 grams of **non**-radioactive Lead 207 (Pb207) in about 713 million years, and then to 25 grams of **U235** and 75 grams of Pb207 in another 713 million years (a total of 1,426 million years for those two half-lives). (Actually, **U235** decays into Pb207 through a series of intermediate radioisotopes). Therefore, the half-life for **U235** is 713 million years (0.713 billion years).

TIME	**U 235 --->**	Pb 207
crystallized	100 g	0 g
1 half-life	50 g	50 g
2 half-lives	25 g	75 g
3 half-lives	12.5 g	87.5 g

9.. After several half-lives, the amount of the isotope practically disappears (100 grams becomes 0.07 grams in ten half-lives). Our sample, in that time, would now consist of 99.93 grams of non-radioactive lead.

9-Q: How many years would it take for a sample of U235 to decay through 10 half-lives?
ANS.: 10 x 713 million = 7,130 million, or 7.13 **billion** years (7.13 x 10^9 years).

10. ACTIVITY: To help you show your understanding so far, a graph is provided for you on the **worksheet**. On it, the gradual reduction of 100 grams of **U235** to less than 1 gram is plotted over a time span of ten half-lives. Your job is to show, by drawing a curve on that graph, how Pb207 **increases** from less than 1 gram over that same time span. Clearly label your growth curve as "Pb207". For help, see item #8-Example above.

HOW OLD IS THE EARTH? Three check-questions to answer on your answer sheet:

11. If the Earth has always been here (for an infinite time), how much **U235** would we have in our crust now?
a. none
b. a small but measurable amount
c. a large amount

12. If the Earth had a beginning in the not-too-distant past, how much **U235** would we have in our crust now?
a. none
b. a small but measurable amount
c. a large amount

13. Since there are still substantial amounts of **U235** in our crust (we are still mining and extracting it for nuclear power plants), this tells us that the Earth ...
a. has always been here.
b. had a beginning billions of years ago
c. had a beginning only a few thousands of years ago

14. Right! If the Earth had been here forever, the **U235** would have been gone long ago. But is it **billions** of years old, or only some **thousands** of years old? How can we tell? Let's take a look at ALL the known natural-occurring radioisotopes.

15. **INFORMATION:** Of the 34 known radio-isotopes with half-lives of a million years or more, only 23 are found in detectable amounts in nature, and of these 23, only 18 have persisted since our planet was formed, while 5 are continuously being produced as decay products from other decay series. (To simplify, we will omit these 5 radioisotopes in the following acitvity, and work with only 29).

15. ACTIVITY: Take the envelope provided, remove the 29 radioisotope strips from it, and arrange them from the longest half-life to shortest half-life. [An uncut strip of 17 of these, already sequenced, may be provided to save you some time.] Look for a **pattern** of "Yes's" and "No's" in the sequence. "No" = "not found in nature"; "Yes" = "found in nature". In case you aren't familiar with "scientific notation", a number times 10^9 is greater than the same number times 10^8, by a factor of 10.

NOTE: Those "not found in nature" have simply not been detected in our solar system. However, they HAVE been detected in our analyses of the light spectra of younger distant stars. We know that all but the lightest atomic nuclei are formed in stars and/or stellar explosions. Physicists have a good understanding of how atomic nuclei form, and would fully expect the "not found" isotopes to be here if our solar system were only several thousand years old.

[To save time, your teacher might may simply show you a table with all these radioisotopes already sorted as described.]

15. QUESTIONS: Examine the list of radioisotopes which you've sequenced, and answer the following questions on your worksheet:

16. What is common to all the radioisotopes with half-lives of **more** than 80 million years that is NOT true of those with half-lives of **less** than 80 million years? (80 million = 8 x 10^7)

17. What has probably happened to **all** the radioisotopes with **shorter** half-lives? (Remember that it takes only about 10-20 half-lives for most radioisotopes to disappear, depending on their abundance. Twenty half-lives of 80 million years for each half-life takes about 1.6 billion years).

18. **Why** do we still find **all** the radioisotopes with **longer** half-lives in nature?

19. About **how old** does all this suggest our solar system must be?

DATING A ROCK

The evidence for a very old Earth (billions of years) is very compelling, just by looking at all the known radioisotopes and seeing how their half-lives sort out. But what if we find a rock... or a fossil, and we want to know how old it is? As it turns out, there are many different ways of doing this, depending generally on the material being examined. Even with the same material, several different methods can often be used, and where these methods work independently of each other, they can be used to check each other, to see if they agree.

Let's go back to our discussion of **Uranium 235** decaying to Lead 207. [You might want to review items #8-10 before proceeding].

20-Q. In order to estimate the age of a rock sample from all this information, what would we need to know?
- a. the amount of original Pb207 (lead 207) in the rock when it was formed
- b. the amount of new Pb207 produced by radioactive decay of **U235**
- c. both a and b

MORE BACKGROUND:

21. Unfortunately, we can't tell original and new Pb207 apart; they are chemically and physically identical. This raises a seemingly insurmountable problem. How can we deal with that? Continue:

22. Fortunately, another common isotope of lead (Pb204) is never formed by radioactive decay, so all of the Pb204 in the rock is original. Also, these two isotopes of lead (Pb204 and Pb207) are chemically identical, so, as the rock sample cooled and crystallized from its molten state during its formation, they would have formed compounds in the rock in the **same ratio** (proportions) as they were found on the surface of the earth **at that time**. From that point on, the **U235** would continue to decay into **additional** Pb207 at a steady rate, while the amount of stable Pb204 would remain the same.

22-ACTIVITY: On the previous graph showing **U235** decay (and Pb207 increase) over 10 half-lives, add a line (in a different color, e.g. blue or green) showing the amount of Pb204 over that time. Choose a small starting amount, say about 10 grams, since Pb204 is not very abundant.

TIME	**U 235 --->**	new Pb 207	Pb 204
crystallized	100 g	0 g	10 g
1 half-life	50 g	50 g	10 g
2 half-lives	25 g	75 g	10 g
3 half-lives	12.5 g	87.5 g	10 g

23-**INFO:** If our rock is **young**, its Pb204 to Pb207 ratio (Pb204 / Pb207) will be nearly **identical** to the current ratio in our crust. But if billions of years have passed, there will be two differences:
- it will contain relatively little **U235**, and
- the ratio of Pb204 to Pb207 will be **lower** than the current ratio, because of the increase of Pb207 (from the decay of **U235** over time). In other words, the amount of Pb204 (unchanged), divided by the amount of Pb207 (increased) will give us a smaller number.

Using a mass spectrometer, the amounts of these isotopes in a sample can be measured with high precision, and from these data, the approximate time when the rock formed can be calculated.

23-Q. If there was a different method for determining the age of a rock, and the results agreed essentially with the Uranium-Lead method already described, how should this influence our confidence in the accuracy of the age determination?
- a. no influence; could just be coincidence
- b. possibly increase our confidence, with this additional evidence
- c. definitely increase confidence in the age, with this independent method
- d. would provide absolute proof that the age was correct

24- **INFO:** As it happens, there are several independent methods for dating a rock:

- a couple of methods based on the decay of **potassium-40** into argon-40
- three methods based on three different isotopic series of uranium and thorium
- four other methods based on decay of samarium (Sm), lutetium (Lu), rhenium (Re) and rubidium (Rb)

Each method has its own advantages and limitations, but in essence, they can all give about the same age when used on the same rock sample, each with a small range of error (depending on various factors), thereby giving us very strong support for the accuracy of the age.

25- **INFO:** The potassium-argon (K-Ar) method: **Potassium-40 (K40)** is a radioisotope of a common element which decays into argon (Ar40), a rare inert gas. In a particular mineral of potassium, its chemistry requires a specific number of potassium atoms at fixed positions in its crystal structure, but no initial argon. As time passes, atoms of **K40** decay into Ar40, which are then trapped within the crystal. A newly formed volcanic rock will have almost no argon (it's rare in the atmosphere), but an ancient rock will show a loss of **K40** exactly balanced by an equal increase in the amount of trapped Ar40. A mass spectrometer can tell us the precise amounts of these isotopes in a sample, which can, with the known half-life of **K40**, be translated into an age for the rock.

25-Q. The only serious source of error in this method occurs when the rock has been disturbed by heating, releasing some of the argon gas. How would this affect the resulting age calculation?
a. make the rock appear older than it is
b. make the rock appear younger than it is
c. could be a or b, depending on the sample
d. no effect.

26-Q. Potentially, radioisotopic analysis of rocks...
a. could provide strong confirmation of a very **young** Earth (6-10 thousand years old).
b. could provide strong confirmation of a very **old** Earth (billions of years old)
c. could provide strong confirmation of a moderately old Earth (say 100s of millions of years old)
d. none of the above.
e. any of the above

26-**INFO:** The situation addressed in question #26, is an example of a "**Fair Test**" question. This is one of the strongest, most critical tests to which scientific questions can be subjected. The strength of a scientific idea can sink or swim, depending on the results of a Fair Test question being resolved. In this case, different results are possible, and what we actually find depends on the actual age and the validity of the methods used.

27-Q. If all suitable rocks had very small amounts of argon in its crystals, this would indicate....
a. the earth must be very young
b. the earth must be very old
c. no clear picture of this (depends on the rock)

28- **INFO:** When all the radiometric efforts to determine the age of the Earth are compared, using several independent methods, involving the dating of the oldest crustal rocks on Earth, Moon rocks, and meteorites, the overwhelming conclusion is that the Earth is very close to 4.5 billion years old. This agrees with the conclusions of astronomers, based on cosmic measurements and the universal speed of light, pointing to a universe of about 13 billion years in age.

29. Those who claim that the Universe is only about 6-10 thousand years old face the challenge of explaining why the data and conclusions in literally thousands of studies by as many physicists and geologists are totally wrong. There have been a few attempts by some to meet that challange by using isolated data or poorly selected samples. From their conclusions (or premises?), we would have to conclude that virtually all science is unrelible and that everything we call reality is a total illusion. In response to that, it needs to be said that there are a number of natural illusions we all experience, but it has been science which has revealed them as illusions, and given us deeper understanding about deep time and many other "mysteries" of the universe.

WHAT ABOUT THOSE OTHER METHODS? WHAT ABOUT THE ISOCHRON METHOD?

30-**INFO:** Using a number of those long-lived radioisotopes, a very clever technique has been developed which is fairly precise, and solves two critical problems in age-dating:

- not knowing the original amounts of parent and/or daughter isotopes (when the sample was molten);
- possible contamination or other compromising factors.

The procedure is called the **isochron method**. By solving these two problems, it gives us much greater confidence in the age calculations. In this method, a graph is produced in which a single line is formed through the plotted ratios of several different minerals containing the same isotopes of interest, all crystallized at about the same time while cooling from the molten state. The time when those rocks cooled can be calculated from the slope of that line, the “isochron”, or line of “equal time”.

31-EXAMPLE: In a situation similar to the one described for the **U235**-Pb207-Pb204 system (see #22), we find that **rubidium-87** (**Rb87**) decays into strontium-87 (Sr87), with a half-life of 48.8 billion years. There is another non-radioactive isotope of strontium (Sr86) but this one is NOT produced by decay.

31-Q1. As the **Rb87** in a mineral decays into Sr87, the Sr87 will **increase** by the exact amount that **Rb87** decreases, so in a very old rock, what will have happened to the **ratio** (proportion) of **Rb87** over Sr86?

a) increased; b) decreased; c) remained the same; d) impossible to tell.

31-Q2. What will have happened to the **ratio** of Sr87 to Sr86 in that same mineral?

a) increased; b) decreased; c) remained the same; d) impossible to tell.

32-**INFO:** When a typical igneous or metamorphic rock forms from its molten or near molten state, it will be composed of several different minerals, all crystallizing as they cool, but each with different proportions of rubidium and strontium (for example). The minerals which cool fast have little Rb but lots of Sr (a low Rb/Sr ratio). Those which cool slowly have lots of Rb but very little Sr (a high Rb/Sr ratio). Those with intermediate rates of cooling will have intermediate ratios. At the same time, the ratios of any two isotopes of strontium to each other would be the same (they’re the same element), no matter what mineral they were in, since they behave the same chemically. At the moment a rock is formed from its molten state, we can represent the ratios of selected isotopes as shown in **Fig. 1**, where four different mineral compounds (A,B,C,D) have **different** ratios of **Rb87** to Sr86 (because they cooled at different rates), but all have the **same** ratio of Sr87 to Sr86, as expected Consequently, the mineral plots would form a straight horizontal line (isochron), as shown.

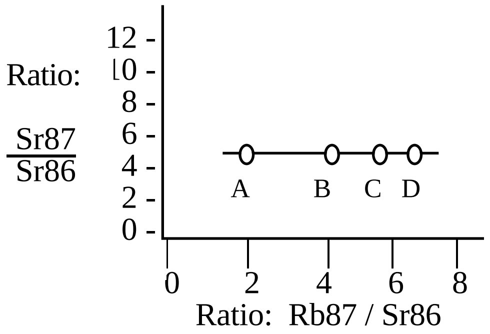

Fig. 1. Rubidium - strontium ratios in four different minerals (A,B,C,D), plotted as they might appear in a newly formed rock. The line through the four plots is the isochron. Figures adapted from Miller, 1999

As the minerals age, and **Rb87** decays into Sr87, the **Rb87**/Sr86 ratio gets smaller for each mineral (as the **Rb87** decays), and the Sr87/Sr86 ratio gets larger for each mineral (as the Sr87 builds up), but these amounts are always directly proportional to their original amounts in the mineral. As you can see in **Fig. 2**, the plotted ratios for those minerals after a long period of time have shifted **upward** (increasing Sr87/Sr86), and to the **left** (decreasing **Rb87**/Sr86), but proportional to the original amounts of the isotopes, so they remain aligned, the net shift is upwards and to the left, and their alignment therefore slopes upwards (the a,b,c,d **isochron**). The more time that has passed, the steeper the slope. With careful measurements, usually of a dozen or more different minerals in the rock sample, the ratios of those isotopes in those minerals can be plotted, and the slope of their collective plots can be used to accurately calculate the age of the rock containing those minerals.

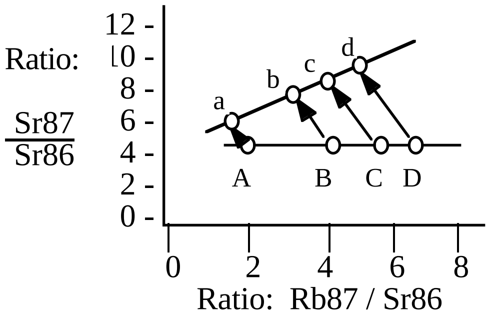

Fig. 2. Rubidium - strontium ratios as time passes. The plots of the four minerals shift upwards and to the left, proportional to their original amounts. The sloping angle of the resulting alignment a,b,c,d (isochron) can be used to calculate the age of the sample.

Any loss or addition of minerals at some time after initial crystallization, or any partial re-melts, would show up as plotted points out of alignment, and those data would either be discounted, or correction factors used, depending on the extent and nature of the deviations. This self-checking feature is one of the great strengths of the isochron method.

33. **VIRTUAL AGE DATING TUTORIAL:** There is an excellent interactive online tutorial program which will vividly help you to understand how **isochron** dating is done. It is memory intensive, however, and works best with a high-speed access (e.g. DSL), and using Explorer 5.0 (or later version) works better than using Netscape. Try it at <http://sciencecourseware.com/VirtualDating/> When you successfully complete the tutorial, be sure to show your **Certificate of Completion** to your teacher.

34. **CARBON-14 METHOD:** Finally, we need to say a word about the classic Carbon-14 method of age dating. It is one of the few methods which can be used on **organic** materials directly (e.g. ancient wood or bone). It is based on the fact that radioactive **Carbon-14 (C14)** is constantly being formed in our atmosphere from Nitrogen-14 (N14) by the action of cosmic radiation. The **C14** then slowly decays back to N14. At any given time, there is a dynamic balance between the **C14** and the more common non-radioactive C12 in the atmosphere and in living organisms (which are constantly taking in and giving off carbon compounds during thier life processes.) When the organism dies, there is no more dynamic exchange, and the **C14** slowly decays to N14, leaving less and less **C14** in the sample (measured by detecting its level of radioactivity, as compared with **C14** levels in modern tissues.) There is a correction factor reflecting differences in carbon dioxide levels over past ages.

The accuracy of the method has been calibrated with the very precise tree ring dating of samples from ancient trees. However, the half life of **C14** is only 5,730 years, and the initial amount of **C14** is so small that the method is good for only about 9 half-lives. This means that it cannot be used to date anything older than about 50,000 years.

There is also an excellent online interactive tutorial for the carbon-14 method of dating (and the half-life concept) on the same **Virtual Age Dating** site described above (#33.) Try it. You'll like it.

34-Q1: What kind of materials is the C14 method used on?
34-Q2: How far back in time is the C14 method used for?

35. **CHANGING NUMBERS:** Very often, when you check the numerical (or "absolute") times that various geological periods began or ended, you may find slightly different numbers on different charts. Why is this? Usually, this is because those ages are constantly being refined and updated with new studies using equipment with greater sensitivity and precision, or based on better samples taken closer to the critical times when fossil types reveal major changes, which the era or period names actually represent. Consequently, recently published charts will often have slightly different ages than earlier charts. The differences are not usually critical, but you should generally use the more recent charts when possible.

In addition, radiometric dating, due to its inherent statistical nature, has minor built in sources of error. Therefore, all geological age dates come with measured levels of plus-or-minus error, e.g. the Cenozoic began 65 mya ± 1 million years, meaning that it started between 64 and 66 mya (million years ago). That's an accuracy of 99.98%... not bad for measuring millions of years of Deep Time!

36. **ASSESSMENT:** Now that you have completed this activity, reflect on your understanding of and confidence in the geological age measurements. Are you more confident or less confident in the ages than before, and why? What further information would help your understanding and confidence in the numbers of deep time? Please place your answers and comments on your answer sheet.

37. **RESOURCES:** This activity was based largely on the presentation by Miller, 1999.

The Age of the Earth: <http://www.talkorigins.org/faqs/faq-age-of-earth.html#dal01>
Geological Time Scale: <http://www.talkorigins.org/faqs/timescale.html>
Miller, Kenneth R. 1999. *Finding Darwin's God*. Cliff Street Books. Chapter 3
Dalrymple, G. Brent. 1991. *The Age of the Earth*. Stanford University Press.

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