Teaching Radioisotope Dating Using the Geology of the Hawaiian Islands

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ABSTRACT

Students and the general public are often told that the chronology of ancient events is known with high confidence, but the methods used to determine how long ago an event occurred are usually not described or even mentioned. This gives the impression that the methods are either not important or that only scientists can understand them. Fortunately, many of the techniques are understandable if properly presented. Here one key method of dating ancient materials, argon/potassium radioisotope dating, is described in detail. In addition, a dramatic example of its calibration is described using the geology of the Hawaiian Islands. Sample lessons used in a high school physics class are described and discussed.

INTRODUCTION

Even though the accuracy of radioisotope dating has been well established (Currie, 2004; Roth and Poty, 1989), polls show that many Americans do not agree with the results. According to one recent poll, 45% of Americans believe that humans were created in their present form only a few thousand years ago, which totally contradicts the evidence from fossils dated using radioisotope dating (Gallup poll, 2004). One major reason for this discrepancy is that the isotope dating method is only rarely explained to the general public. Typically, when a textbook or news report describes a discovery about an ancient species or a human settlement, they will mention the age of the samples but give no clue about how the age was determined or the date's confidence level. This paper is intended to promote discussion of this method by arming teachers with relevant data and graphs for presenting a coherent and convincing picture of the radioisotope dating process. Hopefully the data presented here will be at least partially convincing, even to skeptics.

One likely reason that there have been limited efforts at educating non-scientists about radioisotope dating is that it requires understanding of several different science areas: chemistry, physics, geology, and math. Table 1 is a summary of the ideas that should be understood to have a full appreciation of the argon dating method.

Viewed as a group, this may seem like a challenging set of ideas. However, that is itself a reason for making radioisotope dating lessons a priority in K-12 and college courses. By presenting an example which uses knowledge from a variety of fields, students are exposed to the complexity of the scientific process, and see the importance of equipping themselves with a wide range of scientific knowledge. Applying this effort to understanding one of the most important scientific tools ever invented is a great way of demonstrating interdisciplinary science at its best.

Of the ideas listed in Table 1, the first, that atomic nuclei transform into different types of nuclei, is the foundation of the entire technique. Since students do not observe nuclear decay in their daily lives, it is understandable that they have many misconceptions about it (Prather, 2005). However, teaching students about nuclear decay is achievable, as demonstrated by Freeman et al., who emphasized developing the students' sense of place by connecting the nuclear topics with geology topics

TABLE 1. A LIST OF KEY IDEAS INVOLVED IN UNDERSTANDING ARGON DATING

Domain	Concept
Chemistry	Argon atoms do not bond to any other atoms, and therefore exit rocks far faster than other atoms when heat is applied.
Physics	Nuclei decay into other nuclei very predictably. The end products of nuclear decay, and the relative fractions of those decay products, are known very accurately.
Physics	Nuclear decay rates are known very accurately and observed in many ways to be constant, even in the distant past.
Chemistry	Argon produced by potassium decay stays locked inside a rock as long as it is not heated too much, which leads to larger argon levels in rocks which have not been melted in longer times.
Chemistry	Scientists have very effective methods of measuring argon and potassium isotope concentrations in rocks, with enough precision to enable dating of the rocks.
Math	Exponential decay calculations, along with other mathematical methods, allow the time since last melting to be calculated using the argon and potassium isotope values.
Geology	The existence of hot spots is demonstrated by the existence of numerous trails of islands and seamounts, and by analysis of rocks all over the earth.
Geology	The motion of the earth's tectonic plates has been measured in a variety of ways, with excellent agreement in magnitude and direction of their motions.

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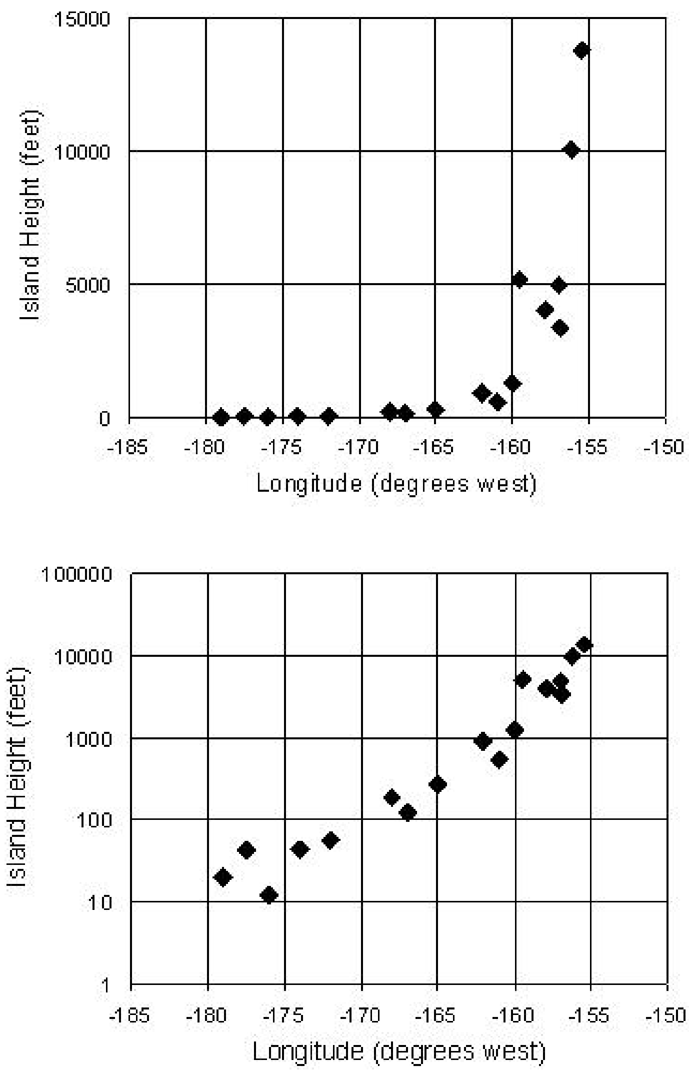

FIGURE 1. Height of Hawaiian Islands vs. longitude, using linear and logarithmic scales for the island height relative to sea level.

(Freeman et al., 2007).

Adding to the challenge, and the opportunity for learning, is the fact that several different types of radioisotope dating exist. Carbon dating is typically used for the study of human civilization, since it is primarily effective for samples less than 50,000 years old. Uranium-lead dating is often used for the study of the early Earth and solar system, since it is effective for samples more than a billion years old. The use of a wide range of dating tools is a point worth emphasizing to students. This paper will discuss argon dating, which is very effective for samples which are several million years old; this means that it is useful for studying genetic evolution, including human evolution.

The Hawaiian islands are a great place to study ancient geology and isotope dating because their history is easy to understand (Hawaiian Center for Vulcanology website). Just looking at a map of the Hawaiian islands suggests that they all must have been formed in a similar way. As a first clue, it is clear that the eastern islands have larger areas. By looking at the peak height data relative to

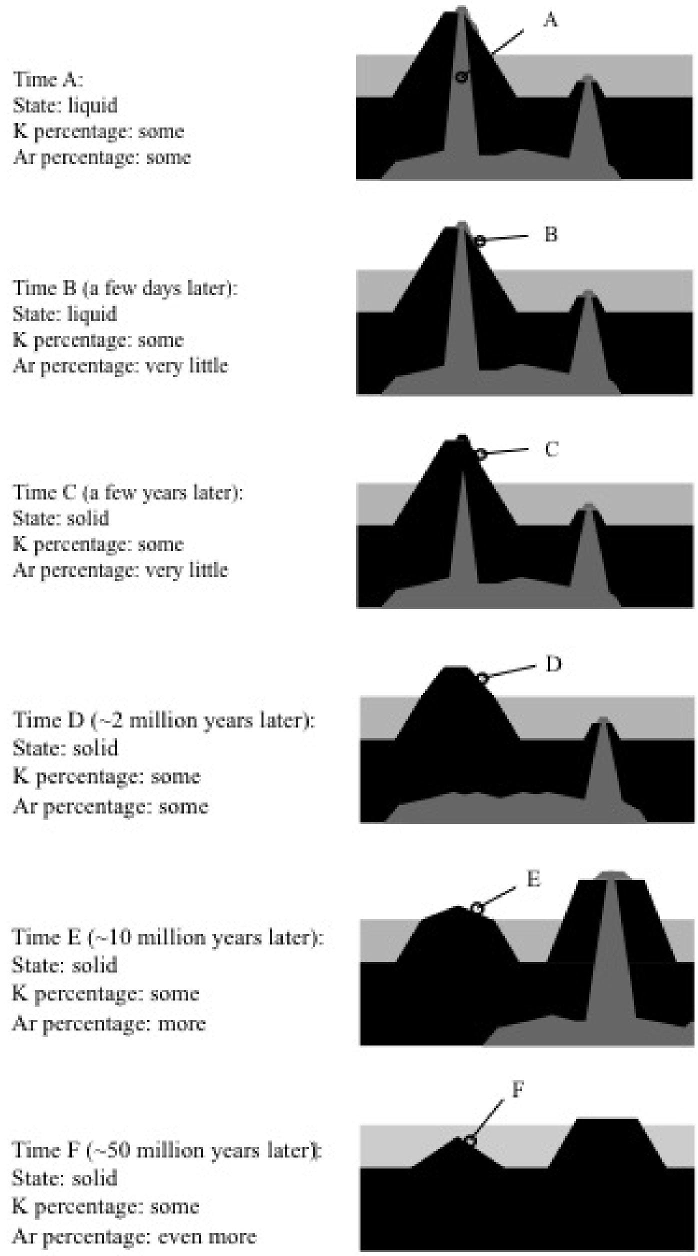

FIGURE 2. Illustration of argon processes that have taken place in Hawaiian Island rocks.

sea level from all of the major islands, it is obvious that the eastern islands also have the tallest peaks relative (Figure 1; Stearns, 1985). Also significant is the fact that the easternmost island, known as the Big Island, is the only one which has produced fresh lava within the last century. Scientists believe that all these observations are related through the mechanism known as the hot spot model.

Under the Pacific Plate there is a source of material called a hot spot. It sends material to the surface, creating islands through multiple eruptions of liquid lava. Meanwhile, the Pacific Plate is moving to the west, which means that after an island is formed, it moves away from the hot spot and stops growing. After it stops growing, the height of the island decreases due to two mechanisms: subsidence and erosion (Hawaiian Center for Vulcanology web site; Dalrymple et al., 1981). Subsidence is the

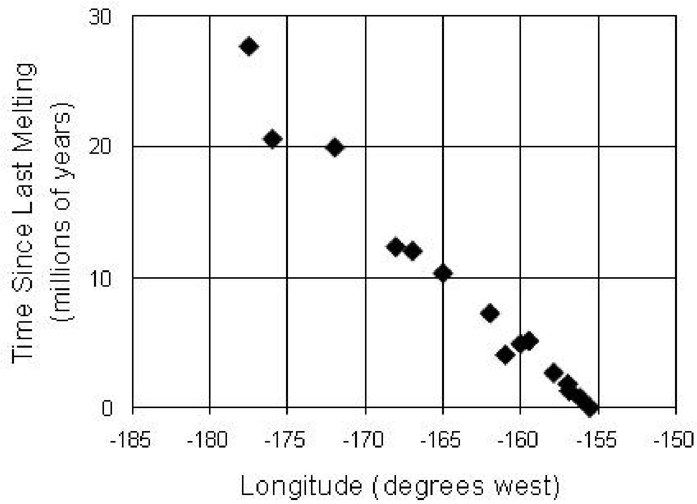

FIGURE 3. Age of Hawaiian Islands vs. longitude. Each data point represents one island.

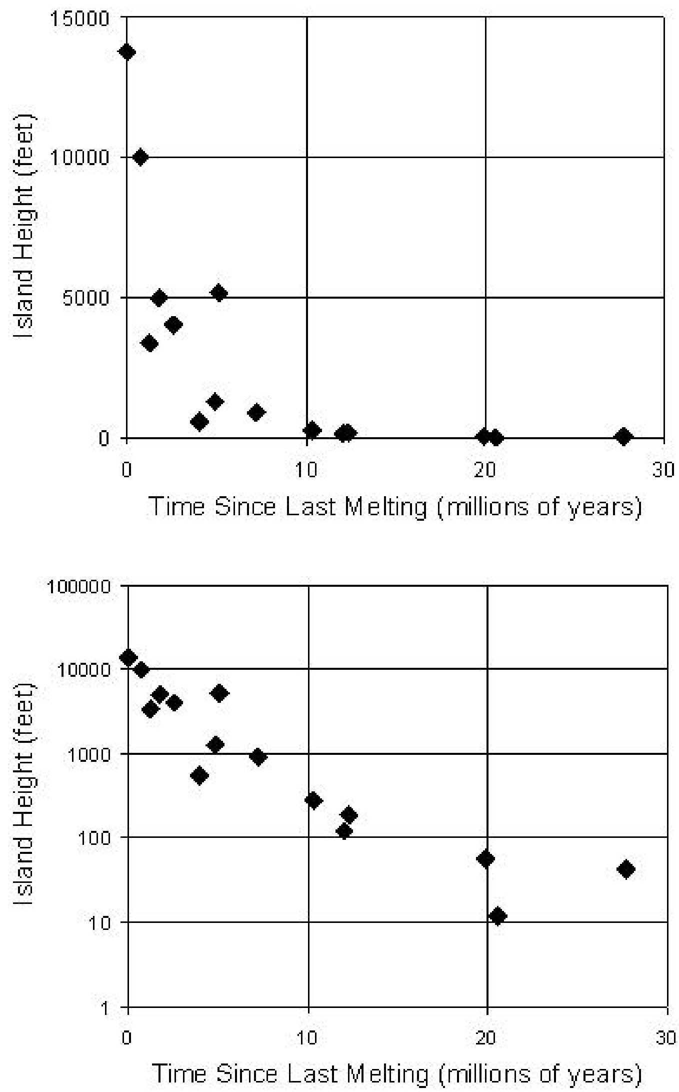

FIGURE 4. Height of Hawaiian Islands vs. age, using both linear and logarithmic scales for the island height.

lowering of the ocean floor related to the motion away from the warm hot spot, while erosion is the wearing away of material due to weathering. Together with the motion of the plate, the subsidence and erosion mechanisms explain the relative peak heights and areas of the islands very well. Since the Pacific Plate is moving to the west, the volcanic rocks on the western islands should be older than rocks on the eastern islands, since it has been longer since they were converted from liquid into solid rock. Fortunately, scientists have invented ways of determining the length of time since a particular rock has melted.

One of the most important of these age measurement methods is argon isotope dating. The element argon is very useful for dating because it does not attach strongly to any kind of material. This is because argon does not form chemical bonds with atoms commonly found in rocks. Because of this, when a rock is heated argon leaves the rock material very quickly compared to other the principal elements in the rock, especially if the rock is melted. Therefore, rock which has been recently melted typically contains essentially zero argon.

One isotope of another element, potassium, is known to decay into a certain argon isotope very slowly over millions of years. Although this radiogenic argon, which has been transformed from potassium, is not attached strongly to the atoms in the rock, it does stay trapped between the atoms inside the rock, as long as the temperature does not rise too high. That means that after a long time, a rock that at one time contained some potassium and zero argon will accumulate argon inside of it. Therefore, by measuring the amounts of the argon isotopes and the potassium isotopes inside such a rock, it is possible to calculate the amount of time since the rock was last heated. The process is described in this Figure 2, which illustrates the history of island rock material.

The argon and potassium isotope concentration measurements must be done very carefully, but after much work scientists have invented reliable methods for doing so. Using dating results from analyzing argon and potassium concentrations, Figure 3 shows that the western islands are older than the eastern islands, which agrees with the model above (Dalrymple et al., 1981). Figure 4 displays the dating results together with island heights, showing that the older islands have lower peak heights, which is due to the long-term subsidence and erosion of the islands. By looking at the slope of the data in graphs of island ages vs. position, scientists calculate that the Pacific Plate is moving relative to the hot spot with a speed of about 9 cm/year, in a direction about 30 degrees north of due west.

If the velocity of the islands has been approximately constant for millions of years, and there is still fresh lava being produced, it is expected that the islands should still be moving to the west today. Fortunately, there are several methods of measuring the relative velocities of different locations on the earth. One method uses the same technology which enables Global Positioning System (GPS) location devices. Handheld GPS devices work by measuring the arrival times of signals from various satellites. Since the speed of light is known, and the orbital positions of the satellites can be calculated, a handheld

GPS device can determine its location. By using more sophisticated receivers which are attached to solid ground, the movement of the earth's plates can be measured with very high accuracy. Using GPS measurements of dozens of sites for more than five years, scientists have calculated that Hawaii is moving to the west at the rate of about 7 cm/year relative to other parts of the earth's surface (Larson et al., 1997).

Notice that the island velocities determined from recent motion measurements and from argon dating measurements agree very well. The excellent agreement between the modern (GPS) and ancient (argon isotope dating) velocity measurements provides strong evidence that the hot spot model is correct.

Here is a summary of some of the evidence for the hot spot model of the formation of the Hawaiian Islands:

- The areas of the eastern islands are larger.
- The eastern island peaks are taller relative to sea level (see Fig. 1).
- According to argon and potassium content measurements of rock samples, the eastern islands are younger (see Fig. 3).
- Stated another way, the island peak heights are taller for the younger islands (see Fig. 4).
- According to the argon and potassium measurements, the islands are moving west relative to the hot spot at a rate of about 9 cm/year, in a direction about 30 degrees north of due west.
- According to radio-based GPS measurements, the islands are moving west relative to other parts of the earth's surface at a rate of about 7 cm/year, in a direction about 30 degrees north of due west.
- Numerous laser-based and magnetism-based measurements confirm both the short term (GPS) and the long term (argon) measurements described above.
- The Pacific Ocean contains many other chains of islands and undersea mountains which are aligned from northwest to southeast, easily visible using Google satellite maps. The measured ages of these chains indicate they were produced by other hot spots which have been less productive than the Hawaiian hot spot. These chains give extra support to the hot spot model, and to the radioisotope dating method (Clouard and Bonneville, 2005).

Notice that the measured values for the Hawaiian samples span a range from the recent past to more than 20 million years ago. Therefore, if properly performed, argon/potassium radioisotope dating of other rock samples should be accurate over at least that range. In other words, these graphs act as a powerful calibration of the entire dating process.

The author has taught this material during the 2006-2007 and 2007-2008 school years in high school physics classes. The lesson started with a video of Hawaiian lava meeting the ocean water to show how new land is being built in modern times. Student handouts which included the material in the Appendix combined with Figures 1-4 were distributed and discussed. Later, multiple-choice questions similar to the questions in the Appendix were used on tests, which indicated that at least some students were able to understand the material.

Armed with these graphs, teachers have a great opportunity to address the methods of science and the interpretation of data. While the graphs shown here support the argon dating method, the data points do not match any perfect curve. However, as my advisor would say, the data is always right, which in this case means that to understand the mechanisms we need to accept that even though data is not perfect, we can still learn from it. Note also Figure 1 and Figure 4, which show data using both linear and logarithmic graphs. Students can see that using a variety of methods to show the same data can be very useful.

The accuracy of radioisotope dating is very important for the study of evolution (Bobrowsky, 2000). Argon dating is frequently used to determine the ages of fossils, especially mammal fossils. This is done by analyzing potassium-rich rocks found near the fossils. If argon dating is reliable, that means that there are many examples of species becoming extinct at a time very close to when similar, yet slightly different, species appear.

Since radioisotope dating involves many different fields (nuclear decay, atomic bonding of argon, plate tectonics, etc.) it is both an exciting and difficult subject to teach. However, its importance in understanding our planet is so important that teachers should make extra efforts at making these topics understood by a wide audience. Courses such as physics, chemistry, and earth science are excellent forums for discussing these topics.

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APPENDIX. STUDENT HANDOUT AND QUESTIONS

Element	Isotope	Protons	Neutrons	Stable?
carbon	C12	6	6	yes
carbon	C14	6	8	no (half-life=6000 years)
potassium	K39	19	20	yes
potassium	K40	19	21	no (half-life=1.3 billion years)
argon	Ar40	18	22	yes

ARGON DATING

- An “isotope” is a type of nucleus with a certain number of protons and neutrons. Most elements have several isotopes.
- After one half-life, half of a radioactive isotope will decay (transform into other atoms).
- K40 atoms decay into Ar40 atoms and other isotopes with a decay half-life of 1.3 billion years.
- Ar40 is a very useful isotope to measure because it does not bond tightly to other elements and easily evaporates. Therefore, when rock material is melted, usually all of the Ar40 evaporates, leaving a rock with zero Ar40.
- If a rock currently has 2 g of K40 today and zero argon, 1.3 billion years from today it will have 1 g of K40, while a corresponding amount of Ar40 will be locked in the rock. In 2.6 million years from today it will have 0.5 g of K40 remaining, and twice as much Ar40 locked in the rock.
- This predictability makes it possible to use K40 and Ar40 amounts as a type of timer. For example, if rock X is found to have a higher ratio of Ar40/K40 than rock Y, then rock X has been solid for a longer time than rock Y.
- These date results have been compared to the geography of the Hawaiian islands and found to be very accurate. Newer islands, which are larger and taller, have smaller Ar40 fractions than older, smaller islands to the west.

QUESTIONS

(1) Is Ar40 stable or not?
(2) Is C14 stable or not?
(3) How many protons are in a K40 atom?
(4) How many protons are in a Ar40 atom?
(5) How many neutrons are in a K39 atom?
(6) How many neutrons are in a K40 atom?
(7) What happens to K40 atoms during long periods of time?
(8) What happens to K39 atoms during long periods of time?
(9) Which Hawaiian Islands are the largest?
(10) Which Hawaiian Islands are the shortest?
(11) According to the atomic measurements, which Hawaiian Islands have rock which has been recently melted?
(12) Do Ar40 atoms stay inside rock for a long time?
(13) How can Ar40 accumulate inside a rock?
(14) How can Ar40 be removed from a rock?
(15) Maui and Oahu are Hawaiian islands. Maui is east of Oahu. Which island is older?
(16) What is the age of the oldest Hawaiian Island in the data shown?