Using Melting Ice to Teach Radiometric Dating

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ABSTRACT

Radiometric dating is extremely difficult to teach in an interesting, practical way to elementary geology classes. A teaching exercise can use the measurable transition of ice to water as a substitute for radioactive decay. The students are challenged to a Sherlock Holmes mystery in which they construct their own decay curves of melting ice to determine time zero. In the process, the analogies to radiometric dating and some elementary thermodynamics are explained. The fact that students can do their own dating to derive a reasonably accurate time of origin is a great aid in helping convince them of the validity of geologic dating.

Key words: ice, dating, geologic time, thermodynamics

INTRODUCTION

Time and the establishment of geologic age are central themes with which almost every elementary geology class must deal. Unfortunately the subjects of isotopic dating, decay curves, rate phenomena, and parent/progeny relationships (mother/daughter products in earlier eras of sexist age dating) are far removed from students' ordinary thought patterns. At first mention of a decay curve, their eyes glaze over and any further discusson remains forever a mystery about which they care nothing.

A far more concrete and memorable coverage of the same subject can be taught as a kind of mystery involving the students in a lecture/lab. On arrival at lab, the students find a number of funnels full of melting ice as in Figure 1. They are told that Sherlock Holmes' arch enemy, the evil Professor Moriarity, has come in at some time in the past, put ice cubes in all the funnels, and left the time of the crime written on a folded note. The students' task is to use Holmes-type reasoning to find this time from their own observations. Finally, they will check their deduction by looking at Moriarity's note.

The students should record immediately the time and volume of water in the cylinders and plot these as a point on the time versus volume graph. These observations should continue until a reasonably linear plot emerges, usually about an hour. (This time can be compressed as described below.) The waiting time while the decay curve is being determined is ideal for a discussion of: A) how any dating system can work by projection of the product versus time curve back to the time of zero progeny; B) what assumptions are involved in this system (room temperature remains constant, closed system, and so forth); C) what can go wrong and; D) how most of the factors in this melting experiment have direct analogies in isotopic dating. As the melting curve begins to evolve on the plot, discussion can deal with the reasons for this curve being relatively linear whereas isotopic decay curves are exponential. As described below, many interesting aspects of thermodynamics also can be sneaked into the discussion.

Unlike the glassy-eyed audience common to these kinds of lectures, most of the students are now likely to be very eager to consider basic principles of dating and how these can be applied to their particular mystery. It is then a much
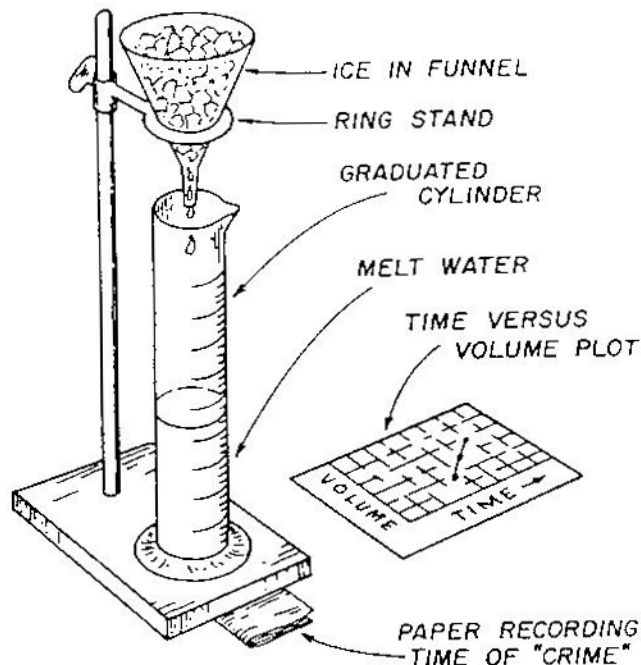

Figure 1. Experimental set-up. If the meltwater was spiked, the note should also record the volume of salt water added. The experiment should be started about 40 minutes before class time. Class time can be saved by adding a note from a police inspector who visited the scene about 15 minutes before class and recorded the time and volume of water in each cylinder.

easier matter to move on to the mysteries of isotopic dating of geologic events.

PRACTICAL CONSIDERATIONS

The most important requirement in students' eyes for this to be a successful lab is the ability to project the "decay curve" back to time-zero with ease and accuracy. To arrange this, some practical thermodynamics is required in the lab set-up. The same physics can be discussed with the students as an interesting follow-on to factors affecting the age determination.

Linear Melting Plot. Most people looking at the apparatus of Figure 1 would expect the amount of ice to have a major effect on melting rate. Consequently, they would predict a markedly non-linear plot of meltwater versus time. In reality, most of the curves for various funnels are comparatively linear throughout much of their length (Figure 2). With proper selection of apparatus by the instructor, it is comparatively easy to obtain nearly linear plots which are easily projected to the correct time-zero.

The key factor determining the rate of melting is the rate of heat transfer from the surroundings through the funnel to the ice. Once the system has reached thermal equilibrium, the
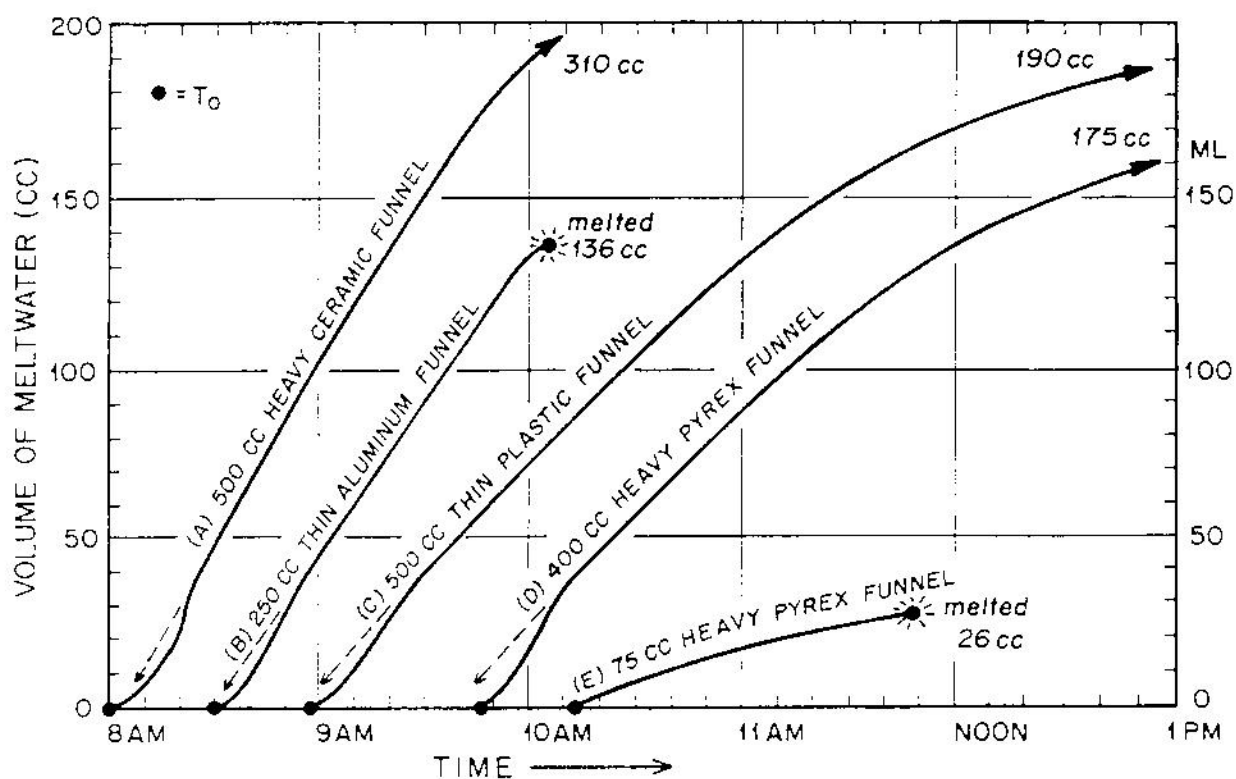
Figure 2. "Decay curves" of volume of meltwater produced as a function of time. The ice was supercooled by being taken directly from the refrigerator. Nearly linear portions of the curves have been projected to zero volume to obtain an estimate of the time of origin (time-zero). Note the sigmoidal shape of the early parts of the curves, reflecting the time needed for the entire system, including the supercooled ice mass, to reach thermal equilibrium.

areas and conductivities will remain essentially constant and produce a nearly linear melting curve. Only late in the melting process, when too little ice remains to keep the funnel at constant temperature, does the temperature of the funnel rise and the rate of heat transfer to the surroundings drop. Thus, contrary to what many might expect, the final small amount of ice in the warmer funnel will melt more slowly than did the larger ice mass when the funnel was colder. Again, the key factor is the rate at which the funnel transfers heat to the surroundings. With a smaller temperature difference, the rate of melting decreases.

For this reason, the metal funnel with its high thermal conductivity will remain at a constant temperature and produce a linear curve until almost the last piece of ice is gone (Figure 2, curve B). Conversely, the less conductive glass, ceramic, and plastic funnels show this effect much earlier in their melting cycles. The small, thick-walled glass funnel (Figure 2, curve E) begins this pattern so early that the curve is almost useless.

Thermal Equilibrium. Most of the plots of Figure 2 show a steep slope for 10 to 15 minutes prior to establishment of the linear portion of the curve. This represents a higher rate of heat transfer from the funnel to the ice as the funnel cools from room temperature to to its new equilibrium temperature.

Supercooled Ice. From the above discussion of thermal equilibrium, the very first portions of the curves of Figure 2 might also be expected to start at a steeper slope than the equilibrium one. This would result in a projected age considerably older than the correct one. In reality, there is almost no melting at time-zero and the curves increase their slopes

steadily for 10 to 20 minutes before shallowing to the equilibrium slope (Figure 2). Ice in most refrigerators is kept at a few degrees below freezing. Thus, ice in contact with the funnel must be heated to the freezing point before melting can begin. Then, the remainder of the ice mass will heat slowly by conduction as the experiment progresses.

Apparatus. Several factors should be remembered in attempting to produce a linear melting plot projecting to the correct time. Fortunately, the initial higher temperature of the funnel and supercooling of the ice act in opposite directions to minimize many of the early thermal disequilibrium effects.

To insure that the students derive approximately the correct answer, the following factors should be considered. 1) Large volume, thin-walled and thermally conductive funnels are ideal; small, thick-walled glass funnels are poor. To assure success, it might be worth the instructor's effort to find several sets of metal funnels of various sizes. For more sophisticated treatment of thermal effects, glass and other kinds of funnels can be used to demonstrate various characteristics of the curves as discussed above. 2) Some supercooling of the ice is desirable. Do not allow too much time between removal of ice from the refrigerator and filling the funnels. 3) Choose a large enough vertical scale on the graph to produce a steep slope capable of easy projection to time-zero. 4) Having "Moriarity do his deed" about 40 minutes before class time avoids the early disequilibrium problems as well as late stage changes in funnel temperatures. 5) To compress the observation time for an adequate plot into an hour lecture, a few time and volume measurements might be supplied from the notes of a police detective who visited the crime scene prior to the start of class.

DISCUSSION TOPICS

Once the basic discussion of how to use the time versus progeny plot is completed, the class can turn to the assumptions being made and the analogous assumptions required to date a uranium mineral having radiogenic lead in it. Some of these assumptions for class discussion are listed below.

1) Parent and progeny represent a direct transition of one form to another. Ice converts to water and uranium converts to lead (through many intermediate radioactive elements).

2) Closed system. Nothing escaped and nothing was added to the system. Only with these assumptions is it possible to calculate time-zero when no progeny were present.

   A) All the water in the cylinder came from melting of the ice. Initially there was a dry cylinder (or there was no initial lead in the mineral). In this experiment, condensation on the outside of the funnel commonly drips into the cylinder. How significant was this?

   B) Evaporation and sublimation of ice and water are negligible, the cylinder did not leak, and nobody removed any of the melt water or any of the ice. (For uranium/lead mineral dating, this requires that none of the uranium or lead was dissolved or diffused out of the mineral.)

3) Rate of change from parent to progeny can be determined. As noted above, the rate of melting of the ice is likely to be relatively linear whereas radioactive decay is exponential. The half-lives of some typical elements used for isotopic dating are given in Table 1.

Showmanship

As any good teacher knows, a bit of healthy competition among students to get the right result and a bit of showmanship often enhance the learning process. The class may well be challenged to find the best possible zero time by considering all the different curves derived from a variety of kinds and sizes of funnels. Initial suspicion may focus on whether everyone was doing the reading and plotting correctly but should soon turn to questions of real scientific merit involving principles of thermodynamics and assumptions having direct analogy to isotopic dating of geologic materials. Finally, when all but one of the good curves yield about the same time zero, it may be discovered that Moriarity played an additional trick by invalidating one of the basic assumptions for that anomalous curve (see below).

Use of many different sizes and kinds of funnels will result in a variety of decay curves. Some small funnels may have gone to complete melting before class started, analogous to the disappearance of short half-life elements in the early history of the rock. Conversely, a huge volume of ice in a funnel made from a cut-off plastic milk container may not have risen completely to freezing temperature in the elapsed time. The resulting concave upward curve will be difficult to use. In a very crude sense, this is analogous to trying to use very long half-life elements for dating very young materials. One must select a proper decay system in either ice or mineral to obtain useful results.

With students using different funnels, the resulting different melting curves reinforce the concept of multiple clocks ticking in the same rock, add spice to the class in the competition for accuracy, and ultimately provide material for a discussion of which sets of curves are likely to yield the best results. Should all the dates be averaged with equal weight or should only those curves showing the closest approximation to linearity be used? Should the results of these most linear plots be averaged?

Parent	Progeny	Half-Life
Uranium 238	Lead 206	4.51 billion years
Uranium 235	Lead 207	0.713 billion years
Potassium 40	Argon 40	1.3 billion years
Rubidium 87	Strontium 87	47 billion years

Table 1. Some isotopic decay relations commonly used in dating of minerals and rocks.

What if one of the good plots yields an age much older than the cluster of other good dates? What might have happened? Could Moriarity have spiked the system with additional water in that cylinder? Discovery of a beaker of salt water and box of salt on one side of the lab suggests that he might have done the spiking with salt water. A quick taste test reveals that only the cylinder yielding the anomalously old age date has salty water in it. Using the average age from the other good determinations, it is possible to calculate how much extra water was added. Moriarity's note under the anomalous cylinder announces not only the time but also that he has added X milliliters of salt water to the cylinder. . . . "Take that, Sherlock!"

Spiking of the experiment is far more than just showmanship; it has a direct analogy in uranium-lead dating. If the distinction among the kinds of lead was overlooked in the analysis, any incorporation of non-radiogenic or primordial lead into the mineral at the time of its formation would lead to an overestimate of the mineral age. Just like the salt water, this represents a violation of the basic assumption of a closed system for parent and progeny. Fortunately, primordial lead has a different isotopic mass (204 amu) than lead produced by uranium decay (206 or 207 amu). The ratios of these various kinds of lead are easily determined in a mass spectrometer and, like the salt water example, the amount of contamination in the original system can be found and a correct age calculated.

Some Elementary Thermodynamics

The same experiment can be set up for a second lab in which the students plot the melting-rate curves very accurately, starting with their own observations from time zero. The details of supercooling and thermal equilibrium responsible for the changing shapes of the curves can be discussed as done in the sections above. Once equilibrium is reached, the rate of heat transfer to the surroundings by each funnel can be calculated by the students using the heat of fusion of 80 calories for each cc of water produced. In effect they have a calorimeter; any changes to the system should result in a new slope to the curve, reflecting a new rate of heat transfer. Use of differing colors of identical plastic funnels should allow numerical determination of this effect on heat transfer. Putting a fan or a heat lamp near the funnels should produce a change in slope and allow calculations of the consequent changes in rate of heat transfer. Adding metal strips or copper wires into the ice mass should allow calculation of the amount of heat being transferred by conduction. This second lab may not be typical geology but it can certainly be good science teaching.

Conclusions

Much of geology involves a detective-like approach to problems but the excitement of this kind of chase is very hard

to convey to elementary classes. Running class as a "Whodunit" with a final moment of truth revealing exactly when the evil Professor Moriarity put out the ice to melt and how he tried to fool the unsuspecting student investigators with salt water is not quite up to the style of Sir Arthur Conan Doyle. Nevertheless, it can be good theater and excellent teaching of basic science while conveying some of the excitement of geologic dating.

Convincing students of the reality and magnitude of geologic time is always difficult, particularly in an era when strong elements of our society are trying to legislate teaching of a creation only 10,000 years ago. Thus, it is increasingly vital that we show and convince students of the validity of methods of geologic dating. The fact that students can actually derive their own accurate date of past events using these methods is a powerful tool for convincing them of the reality of geologic time and methods.

"Elementary, my dear Watson, ... "Elementary Geology!"

ABOUT THE AUTHOR

The author has been professor of structural geology at the University of Massachusetts at Amherst since 1970 after having taught a dozen years at Franklin and Marshall College. He served as Chief Scientist and Deputy Director of NASA's Lunar Exploration Office at the time of the first landings. He was the founding chairman of the Geological Society of America's Structure and Tectonics Division and also served as chairman of the Planetary Geology Division. His research includes Appalachian and Laramide tectonics, planetary geology, and brittle fracture behavior on all scales.