Rocks brought back from the moon by astronauts are about 4,500 million years old. Many meteors that fall to Earth are about 4,500 million years old also. Because the moon, the earth, and the meteors probably formed at the same time, when the entire solar system formed, we can logically conclude that the earth itself is about 4,500 million years old even though no earthly rock that old has yet been found (Fig. 1).

Minnesota Geological Survey
Minnesota at a Glance

Geologic Time

Rocks deposited in almost horizontal layers (Fig 2). These principles enable one to recognize depositional order, and also to recognize when originally flat-lying rocks have been deformed by tectonic forces. Tectonism tilts rock layers by folding or faulting them, and may even turn them upside down. In the last case, geologists must find primary features of the rocks, such as ripple marks or crossbeds, that preserve evidence of which way used to be up.

Fossils are powerful indicators of relative age. Earlier generations of geologists noted that the assemblages of fossils contained in thick sedimentary rock sequences changed upward; that is, there were different fossils in lower (older) rocks.
Radiometric Dating

A chemical element is composed of atoms that are made up of particles called protons, neutrons, and electrons. Together, protons and neutrons form the nucleus of the atom. The number of protons determines the kind of element; the number of neutrons determines the isotope of that element. For example, the element carbon has 8 different isotopes, all of which have 6 protons. The number of neutrons may vary from 3 to 10. The isotope carbon-14 has 6 protons and 8 neutrons. Isotopes of the same element have slightly different chemical properties.

Of the 322 naturally occurring isotopes, 62 are radioactive. A radioactive isotope is unstable and will spontaneously change to a more stable isotope at a measurable, constant rate. The original isotope is called the parent; the resulting stable isotope is called the daughter. The transformation from parent to daughter is called radioactive decay. Because the rate of decay is constant for a particular isotope, a geologist can measure the amount of daughter isotopes present in a rock and determine how long it took to accumulate that amount.

The amount of time it takes for half of the parent material to convert to daughter material is called the half-life. For example, potassium-40 has a half-life of 1.3 billion years. In that time, each potassium-40 atom has a 50/50 chance of decaying. In 1.3 billion years, half of the potassium-40 has transformed into its daughter isotopes argon-40 or calcium-40. After two half-lives, or 2.6 billion years, 75 percent of the original potassium-40 has disappeared. The amount of daughter isotopes has increased by the same amount. Some isotopes have short half-lives, on the order of hours to days. However, the isotopes useful for dating geological events have long half-lives (Table 1).

Figure 2. Rock layers along bluffs of Mississippi River illustrate the principles of superposition and faunal assemblages. The Shakopee Dolomite is oldest. Fossils indicated in rocks in the left column are correlated to rocks containing similar fossils on the right.

than in higher (younger) rocks. From this observation the principle of faunal assemblages was deduced; it states that similar fossil assemblages are of similar geologic age and indicate similar ages for rocks that contain them. Fossils are excellent tools for correlating, or matching, rock sequences from one place to another (Fig. 2). To be best for this purpose a fossil must be easily distinguished, widely distributed, and limited in the amount of geologic time during which it lived.

For intrusive igneous rocks such as granite or gabbro, geologists rely on the principle of cross-cutting relations to determine relative age. Intrusive rocks form when molten rock (magma) invades and fills cracks in other rocks and then crystallizes in place. The rock that was cracked and intruded (or "cut") by the magma was there first; therefore, it must be older than the intrusive rock (Fig. 3).

Of course these dating methods yield only the relative age of rock sequences. How much older is unit 2 than unit 4 (Fig. 3)? To estimate the actual age of a rock, geologists must use radiometric dating, or natural radioactive "clocks," to tell geologic time.

Potassium-Argon Dating

Potassium-40 occurs in several common minerals in igneous rocks (Table 1). As a magma cools and crystallizes, potassium-40 is bound into mineral grains of the newly forming rock (Fig. 4A and B). Argon-40, a gas, does not enter mineral crystals and escapes until the system has cooled below a certain temperature. When that temperature is reached, the clock is set; the argon-40 produced from the radioactive decay of potassium-40 begins to accumulate and will keep accumulating until the rock is heated up again. The time since an igneous rock last cooled below the argon-40 “blocking temperature” can be calculated from the measured ratio of argon-40 to potassium-40 (Fig. 4C). This age may be close to the time when the igneous rock first formed, or it may record a later heating event. Other kinds of geologic information can tell a trained geologist which of these interpretations is the more likely.

Radiocarbon Dating (Carbon-14)

The reasoning used in carbon-14 dating differs from that in the potassium-40 example. Instead of measuring the accumulation of daughter isotope since a mineral formed,
Table 1. Principal isotopes used for radiometric dating (modified from Skinner and Porter, 1995).

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Parent</th>
<th>Daughter</th>
<th>Half-life of parent (years)</th>
<th>Effective range (years)</th>
<th>Materials used for dating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion</td>
<td>10 million–4.6 billion</td>
<td>Zircon, Uraninite and pitchblende</td>
<td></td>
</tr>
<tr>
<td>Uranium-235</td>
<td>Lead-207</td>
<td>710 million</td>
<td>50,000–4.6 billion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorium-232</td>
<td>Lead-208</td>
<td>14 billion</td>
<td>100–70,000</td>
<td>Muscovite, biotite, hornblende, igneous rock</td>
<td></td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.3 billion</td>
<td>100–70,000</td>
<td>Muscovite, biotite, postassium feldspar, metamorphic igneous rock</td>
<td></td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>47 billion</td>
<td>10 million–4.6 billion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon-14</td>
<td>Nitrogen-14</td>
<td>5730 ±30</td>
<td>100–70,000</td>
<td>Wood, charcoal, peat, bone, tissue, animal material, cloth, shell, ground and ocean water, ice</td>
<td></td>
</tr>
</tbody>
</table>

Radiocarbon dating measures the change in isotope ratio since an organism died.

Carbon-14 is being created constantly in the atmosphere, where it easily diffuses and mixes with non-radioactive carbon-12 and carbon-13. The daughter product of carbon-14, nitrogen-14, also diffuses easily in the atmosphere.

The dating logic works like this. Every living organism breathes, eats, and otherwise ingests carbon isotope into its tissues in the exact ratio in which those isotopes exist in the atmosphere (Fig. 5A). The ratio of carbon-14 to carbon-12 in a living tree is exactly the same as the ratio in the atmosphere at the present time. When an organism dies, however, it no longer exchanges carbon isotopes with the atmospheric reservoir. Its dead remains become a closed system with respect to carbon, and the ratio of carbon-14 to carbon-12 begins to change (Fig. 5B). The radioactive carbon-14 decreases in amount because it steadily decays to nitrogen-14, which escapes into the atmosphere. The measured ratio of carbon-14 to carbon-12 in a dead organism decreases with time, and this ratio can therefore be used to estimate the time elapsed since death.

A key assumption in radiocarbon dating is that the production of carbon-14 in the atmosphere has been constant over the past 70,000 years (the effective time span of the method), or that its variation over that length of time can be estimated closely. We know the production rate has not been strictly constant; however, we also know with improving accuracy just how it has changed in the past 70,000 years. With that knowledge, radiocarbon dates can be interpreted with confidence.

Dating Sedimentary Rocks

Sandstone, shale, and many other sedimentary rocks are made up of mineral grains eroded from other rocks. If radiometric methods were used to date those mineral grains, one would learn the time when the minerals formed in the source rock, not the time when the sedimentary rock was deposited.

Some geologically young sedimentary rocks contain fossils which can be dated using carbon-14. The radiocarbon date records the time since the organism died and was buried by sediments which make up the rock.

Commonly, the depositional age of a sedimentary rock cannot be determined directly. Instead, it may be narrowed down to a time range by dating igneous rocks which occur above or below the sedimentary unit. For example, in Figure 3, the igneous intrusions numbered 2, 4, and 7 could be dated radiometrically. If unit 4 is 100,000 years old and unit 2 is 300,000 years old, using the principle of cross-cutting relations, we know that unit 3 is younger than unit 2 and older than unit 4, or between 300,000 and 100,000 years old.
Geologic Time

Before radiometric dating methods were developed, geologists relied upon chronologic dating methods to group rocks of similar age. They created a worldwide classification system called the geologic time scale that relates rocks to time. Rock units, identified by physical characteristics—primarily fossils—serve as reference sections for all rocks formed during the same span of time. The length of time was not originally known. The reference rock unit and the corresponding time interval were generally named for the area in which the rocks were originally described. For example, the Devonian System of rocks was defined at outcrops in Devonshire, England. These rocks were deposited during the Devonian Period of time.

The largest time increments of the geologic time scale are called eons: they are named Archean (Greek for "ancient"), Proterozoic ("earlier life"), and Phanerozoic ("visible life"). Eras within the Phanerozoic Eon are distinguished and named on the basis of life forms as preserved as fossils: Paleozoic ("old life"), Mesozoic ("middle life"), and Cenozoic ("recent life"). Eras are divided into Periods, most of which are named for the location of definitive rock outcrops. Periods are still further subdivided into Epochs and Ages (not shown in Fig. 6).

With radiometric dating, geologists can now date the rocks used to define the named time intervals of the geologic time scale. The Archean and Proterozoic eons, once lumped together as the "pre-Cambrian," represent almost 85% of the earth's history! Keep in mind, though, that the ages listed in Figure 6 are approximations. Rarely is datable material found at the exact boundary in a rock sequence. Most of the ages must have been interpolated from data collected above or below the defined stratigraphic boundary. In addition, the science of radiometric dating is not perfect. Radiometric ages are given with ranges which may span several hundreds or even thousands of years! Thus, the "time" in the geologic time scale is constantly being debated and revised.

Simply putting numbers on a geologic time unit does not convey the magnitude of the time represented. Compare the age of the earth to the length of an ordinary 24 hour day. Consider that the earth formed at midnight—the beginning of the day. In this scheme, insects first appeared on the scene at about 10:15 at night; dinosaurs lived and died in about a half hour between 10:45 and 11:15 pm; and the first homo sapiens, or modern humans, appeared about 30 seconds before midnight at the end of the day!

References