UNIVERSITY OF MINNESOTA

Minnesota Geological Survey

Minnesota at a Glance

Geologic Time

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).

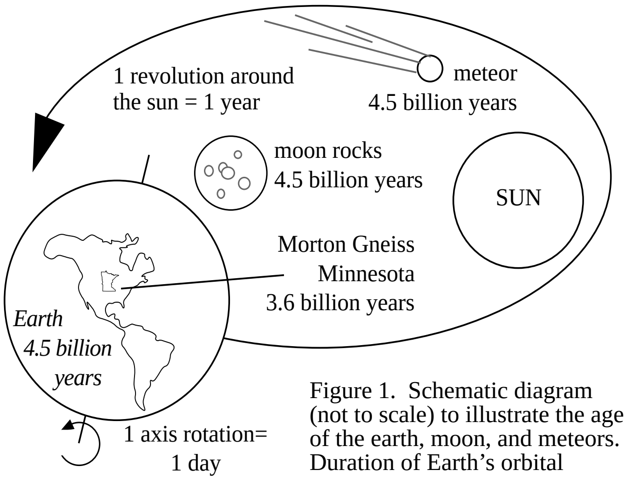


Figure 1. Schematic diagram (not to scale) to illustrate the age of the earth, moon, and meteors. Duration of Earth's orbital revolutions indicated.

Minnesota is host to some of the oldest rocks on earth. Parts of the Morton Gneiss (pronounced "nice") in western Minnesota have been dated at 3,600 million years before present. Rocks as old or older than these are rare on earth because geologic processes on and within our active planet tend to recycle old rocks and produce younger ones. Only in Minnesota, northwestern Canada, Greenland, Siberia, South Africa, and Australia have remnants of very old rocks been preserved. The oldest mineral grains yet identified on earth are about 4,100 million years old; they are in rocks in Australia that represent sediments recycled from even older rocks.

How do we know that the Morton Gneiss is older or younger than some other rock unit? How do we know that any rock is really that old? Actually, geologic age questions are of two kinds—"older-than, younger-than" questions—questions about relative age, and "when, exactly, did it form or happen" questions—questions about absolute age in terms of years, days, or seconds.

To illustrate the concept of relative age, we know that a wrinkled, gray-haired man is older than a smooth-skinned, dark-haired baby girl because we know the physical characteristics of aging in humans. We don't need to know birthdates to reach a conclusion about their relative ages. In a similar way geologists can show that a particular rock unit is older than some other rock unit without knowing exactly how old either one is. Geologists understand the processes by which rocks form, and have developed logical rules based on observable field relationships to establish the relative ages among rock units. The method of determining the relative age of rocks is called chronologic dating.

Returning to our human analogy, someone might want to know how old the baby or the man actually is. To answer this we need a calendar or a clock—some means for measuring the passage of time. Calendars and clocks based on astronomical observations were invented thousands of years ago and have served very well for measuring time on a human scale. Let's say the man is 74 years old. That means he has survived for 74 revolutions of the earth around the sun, or that he was born 74 orbital revolutions ago. The baby is 36 days old. She has survived for 36 rotations of the earth on its axis; she was born 36 earth rotations ago. Ages are determined by counting some physical happening (like an orbital revolution of the earth around the sun) that occurs at a constant rate. Although we may not be used to thinking of them this way, calendars and clocks are simply convenient devices for counting orbital revolutions and earth rotations (Fig. 1). The calibration of human history depends on people who counted and recorded orbital revolutions in some systematic way. For the vast majority of geologic time, however, nobody was keeping track with astronomical calendars and clocks. We must therefore use other kinds of calendars or clocks, based on other kinds of constant rates, to date geological events.

Chronologic Dating

Chronologic dating of rocks means establishing the order in which they were deposited. It depends on the four basic principles, as outlined below.

The principle of superposition notes that rocks deposited on the earth's surface are laid down in order of age, with the oldest (first deposited) at the bottom. This principle applies to sedimentary rocks and lava flows. The related principle of original horizontality notes that sedimentary and volcanic rocks are 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

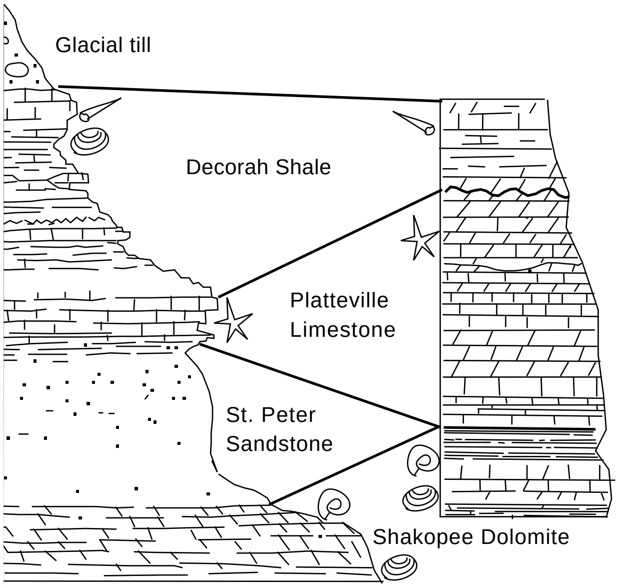


Figure 2. Rock layers along bluffs of Mississippi River illustrate the principles of superposition and faunal assemblages. The Shakopee Dolomite is oldest. Fossils indicated in rocks in the left column are correlated to rocks containing similar fossils on the right.

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.

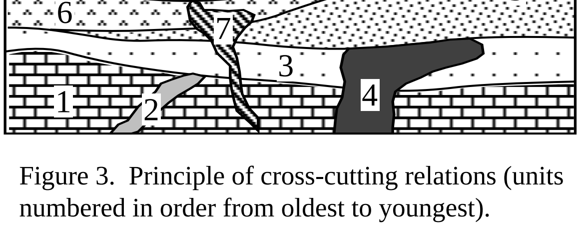


Figure 3. Principle of cross-cutting relations (units numbered in order from oldest to youngest).

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).

Potassium-Argon Dating

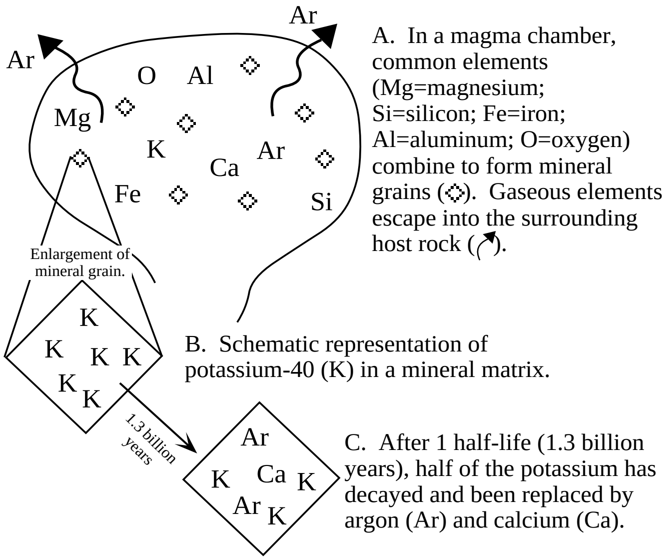
Potassium-40 occurs in several common minerals in igneous rocks (Table 1). As a magma cools and crystallizes, potassium-40 is bound into mineral grains of the newly forming rock (Fig. 4A and B). Argon-40, a gas, does not enter mineral crystals and escapes until the system has cooled below a certain temperature. 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).

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



A. In a magma chamber, common elements (Mg=magnesium; Si=silicon; Fe=iron; Al=aluminum; O=oxygen) combine to form mineral grains (◇). Gaseous elements escape into the surrounding host rock (↗).

B. Schematic representation of potassium-40 (K) in a mineral matrix.

C. After 1 half-life (1.3 billion years), half of the potassium has decayed and been replaced by argon (Ar) and calcium (Ca).

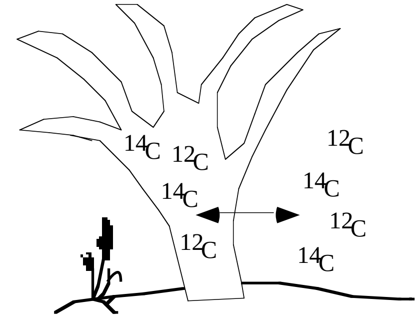
Figure 4. Schematic representation of mineral formation and radioactive decay.

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

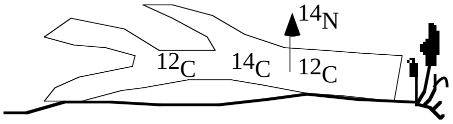
Carbon-14 is being created constantly in the atmosphere, where it easily diffuses and mixes with non-radioactive carbon-12 and carbon-13. The daughter product of carbon-14, nitrogen-14, also diffuses easily in the atmosphere.

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 is 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.



A. Constant exchange of gas maintains the ratio of carbon-14 and carbon-12 in a living organism.



B. Upon death, the gas exchange ceases and carbon-14 is depleted through radioactive decay.

Figure 5. Schematic representation of gas exchange and decay of carbon-14.

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

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Skinner, B.J., and Porter, S.C., 1995, The dynamic earth: an introduction to physical geology, 3rd edition: New York, Wiley, 541 p.

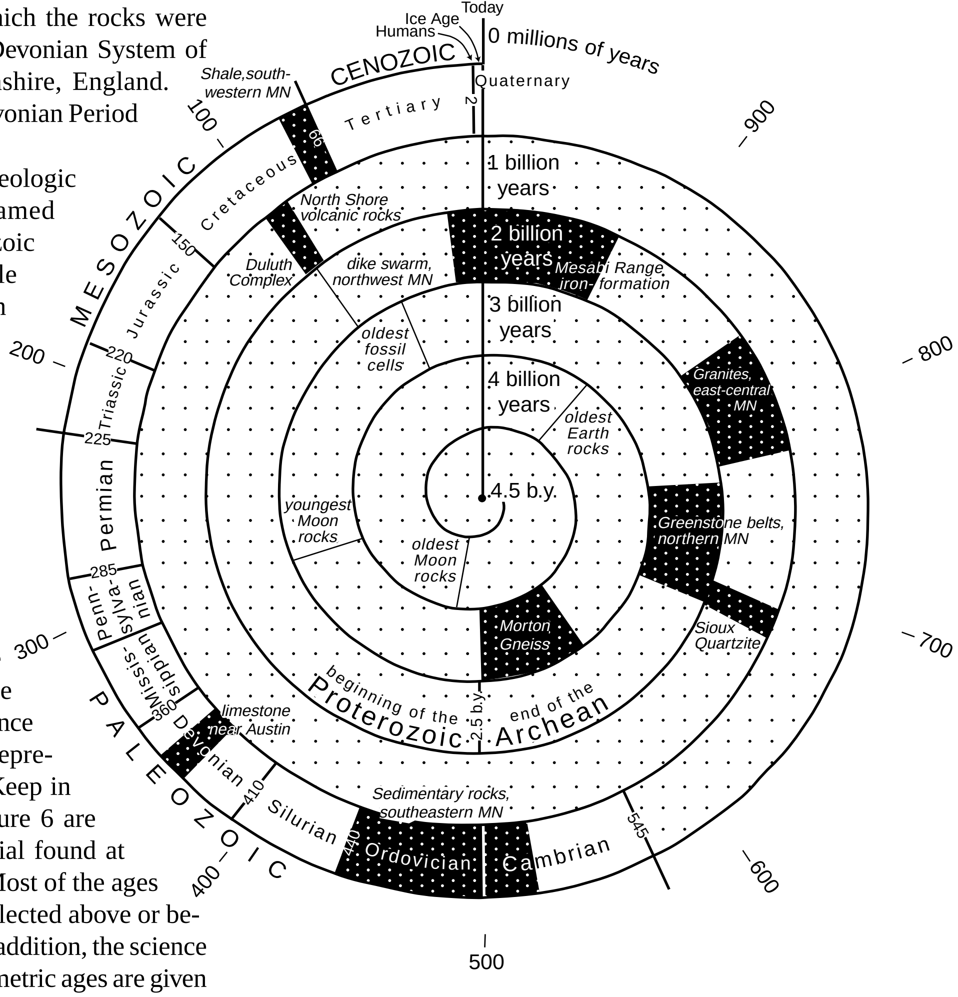

Figure 6. Geologic time scale. The beginning of the Earth is at the center of the spiral. Present day is at the outer edge at the top. Each revolution equals 1 billion years. Lightly stippled area =Precambrian (Archean and Proterozoic eons); dark stippled area =rocks present in Minnesota (modified from Press and Siever, 1974).

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