GEOLOGIC TIME
Smith and Pun, Chapter 7

DETERMINING THE ORDER OF EVENTS

Examination of ancient rocks reveals the history of our planet. Sedimentary and volcanic rocks record processes that occur on the surface of the Earth, while plutonic and metamorphic rocks record processes occurring in the interior.

Ordering of geologic features from youngest to oldest determines the relative age of each feature. In other words, this process establishes the age of one feature as being older or younger than another.

When we can actually establish the age at which an event occurred, this is referred to as the absolute age.
DETERMINING THE ORDER OF EVENTS (2)

Geologists have established rules to determine the relative ages of geologic events. These rules, also called principles, provide a systematic method for ordering geologic events. These four principles are the:

- Principle of superposition
- Principle of original horizontality
- Principle of cross-cutting relationships
- Principle of inclusions

DETERMINING THE ORDER OF EVENTS (3)

Principle of Superposition

The principle of superposition tells us that within a sequence of rock layers formed at the Earth’s surface, those lower in the sequence are older than those found above (see Figure 7.2 on page 170).

The principle of superposition was developed in 1669 by the Danish physician Niels Steensenn, who is better known by his Latinized name, Nicolaus Steno.
DETERMINING THE ORDER OF EVENTS (4)

Principle of Original Horizontality

Steno also observed that surfaces where sediment typically accumulates are nearly flat. His principle of original horizontality states that sediment tends to be deposited in horizontal layers.

Therefore, nonhorizontal sedimentary layers require explanation. Such nonhorizontal rocks must have been tilted after the deposited sediment had lithified to rock (see Figure 7.3 on page 171).

DETERMINING THE ORDER OF EVENTS (5)

Principle of Cross-Cutting Relationships

The principle of cross-cutting relationships, applied by James Hutton in Scotland, states that geologic features that cut across rocks must form after the rocks that they cut through (see Figure 7.4 on page 171).

Igneous intrusions are a common cross-cutting feature.

Faults, fractures where rocks are displaced as a result of tectonic forces, are also a common cross-cutting feature, and must develop after the rocks they displace.
DETERMINING THE ORDER OF EVENTS (6)

**Principle of Inclusions**

Steno also developed the principle of inclusions which states that objects enclosed in rock must be older than the time of rock formation (see Figure 7.5 on page 172).

For example, granite pebbles in sedimentary rock reveal that the granite is older than the sedimentary rock (Figure 7.5 top).

In contrast, metamorphosed inclusions of sedimentary rock within granite indicate that the granite is younger than the sedimentary rock (Figure 7.5 bottom).

DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED

In some areas, sedimentary rock layers continue uninterrupted in outcrops for long distances. This is especially true where the climate is dry and rock is not obscured by dense vegetation.

The Grand Canyon is a dramatic example of such continuous exposures. Intervals of sandstone, shale, and limestone can be traced continuously for 200 km in some area of the Grand Canyon (see Figure 7.6 on page 173).
DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (2)

Principle of Lateral Continuity

Steno is also responsible for developing the principle of lateral continuity which states that sedimentary rock layers would be continuous until encountering some obstruction.

For example, sedimentary layers may be eroded or buried beneath younger rock.

Combining the principles of lateral continuity and superposition extends relative age relationships over larger areas (see Figure 7.6).

DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (3)

Principle of Faunal Succession

The principle of faunal succession was developed by William Smith, based on observations he made during the late 1700s and early 1800s. During this time period, Smith was surveying coal mines and canal excavations throughout England.

Smith recognized that the coal seams in different underground mines occurred in predictable positions between other sedimentary layers.
DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (4)

**Principle of Faunal Succession**

Smith reached his conclusion by using superposition to put different rock layers in relative order within each mine. However, Smith also noted that some layers contained unique fossils.

For example, two different coal layers in one mine were each overlain by limestone layers containing distinctly different fossils. When Smith encountered coal and limestone in another mine, he related layers between the two mines by comparing their fossils.

The process of matching rocks found in different places is called correlation.

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DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (5)

**Principle of Faunal Succession**

Smith observed long, high rock exposures while surveying canals excavated to transport coal from mines into the cities. He noted the succession of rock types and the fossils occurring in each natural and excavated exposure. Smith then used the fossils to correlate the rocks from different locations and established a chronological sequence of the beds (see Figure 7.8 on page 174).

Smith used this knowledge to establish the principle of faunal succession.
DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (6)

**Principle of Faunal Succession**

The principle of faunal succession states that fossil plants and animals appear in the rock record according to definite chronological patterns:

- Fossils of different organisms first appear at different times.
- Fossils of related organisms change in the same manner in progressively younger rocks everywhere that they occur.

DETERMINING RELATIVE AGES WHEN ROCKS ARE WIDELY SEPARATED (7)

**Principle of Faunal Succession**

- Fossil species disappear from the rock record everywhere when they become extinct and do not reappear in younger rocks.

Each type of fossil represents a distinct interval of geologic time, which means that the relative ages of fossil-bearing rocks are defined by the included fossils.
THE GEOLOGIC TIME SCALE

Since fossil assemblages characterize each interval of geologic history, then the relative ages of rocks in distant locations can be determined by comparing their fossils.

The time intervals represented by different fossil associations are named periods.

The geologic time scale is a chronological listing of time intervals of varying duration; periods are the fundamental time interval (see Figure 7.9 on page 175).

THE GEOLOGIC TIME SCALE (2)

The geologic time scale was constructed gradually during the 19th century, largely based on fossil-bearing sedimentary rocks. Sedimentary rocks anywhere in the world can be assigned to a specific time interval based on the fossils present in the rock.

Periods are grouped into eras, which further group into eons. Periods consist of shorter intervals called epochs.

Fossils contained in sedimentary rocks define each Phanerozoic (eon) time interval. Age boundaries between Precambrian time intervals are adopted by international convention.
GAPS IN THE ROCK RECORD

Gaps in the rock record, when erosion occurred rather than deposition, are called **unconformities**. Unconformities are significant because:

1. It is important to know what part of the rock record is missing to construct the geologic history of an area.

2. Identification of the event or series of events that caused the break in the rock record is also part of the geologic history.

Three types of unconformities are generally recognized.

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GAPS IN THE ROCK RECORD (2)

An **angular unconformity** is present between intervals of layered rocks (sedimentary beds or lava flows) that are inclined at different angles (see Figure 7.11 on page 177).

When an angular unconformity is present, there must be a time interval when the lower layers of rock were tilted and eroded at Earth’s surface prior to the deposition of the overlying rocks.
GAPS IN THE ROCK RECORD (3)

A **disconformity** is also present between intervals of layered rock, but where all layers are either horizontal or inclined at the same angle (see Figure 7.12 on page 178). An erosional surface, which might be a deeply eroded channel or a subtle and nearly planar feature, marks a disconformity.

The geologic record is incomplete across the disconformity because no rock exists to show the time interval of erosion or nondeposition separating the deposited layers.

GAPS IN THE ROCK RECORD (4)

A **nonconformity** is present where sedimentary or volcanic rocks accumulate on top of eroded plutonic igneous or metamorphic rocks (see Figure 7.13 on page 179).

This contact must be an unconformity because plutonic igneous and metamorphic rocks form beneath Earth’s surface, whereas sedimentary and volcanic rocks accumulate on the surface.

When metamorphic and plutonic rocks form, there is other rock above that extends to the surface. All of that other rock, possibly several km in thickness, must be eroded to expose the metamorphic and plutonic rocks at the surface, before these rocks can be covered by sediment or volcanic debris.
THE AGE OF THE EARTH

The discovery of radioactivity in the 1890s was a major scientific breakthrough that allowed for more accurate calculations of the age of the Earth to be made. Two significant implications for calculating the age of the Earth based on radioactivity are:

1. Radioactivity provides a persistent heat source inside the Earth. Therefore, earlier assumptions by Lord Kelvin that all of the heat remains from the initial formation of Earth are wrong.

2. Radioactivity provides a method for measuring the absolute ages of rocks and reveals that the Earth is about 4.5 billion years old.

THE AGE OF THE EARTH (2)

Radioactivity is the energy and subatomic particles released when atoms of one element transform into atoms of another element by processes that change the number of protons and neutrons in the nucleus.

Remember that each element is defined by a specific number of protons (see Figure 7.16 on page 183).

Isotopes are atoms of the same element that have the same number of protons but a different number of neutrons.

Therefore, all isotopes of the same element have the same atomic number (the number of protons) but different atomic mass numbers (the number of protons plus the number of neutrons).
THE AGE OF THE EARTH (3)

Only certain combinations of the number of protons and neutrons in an atomic nucleus are stable.

Radioactive decay is a change in the number of protons, neutrons, or both that transforms an unstable isotope to a stable one.

Scientists have identified 339 isotopes among the 84 naturally occurring elements. Only 70 of the 339 natural isotopes are unstable, or radioactive, isotopes.

DETERMINING THE ABSOLUTE AGE OF ROCKS

Geologists use the natural radioactive decay of elements commonly found in rock-forming minerals to determine the “birth date” of many minerals.

This date provides the basis for establishing the absolute age of rocks.
DETERMINING THE ABSOLUTE AGE OF ROCKS (2)

Measuring Isotope Abundances

The absolute age of a geologic sample may be determined by measuring the changing abundance of selected isotopes (see Figure 7.17 on page 184).

Although the sample contains atoms of many elements, it is simpler to focus on just the abundance of a particular radioactive parent isotope that decays through time to produce a daughter isotope of another element.

At time t=0, no daughter isotope is present; the number of daughter isotopes increases over time because of radioactive decay while the number of parent isotopes decreases.

DETERMINING THE ABSOLUTE AGE OF ROCKS (3)

Measuring Isotope Abundances

Each daughter atom originates from the decay of a parent atom. Therefore, the sum of daughter and parent isotopes remains the same.

The ratio of daughter isotope to parent isotope is directly related to the amount of time since radioactive decay began in the sample.

The greater the number of parent atoms, the more decays that occur. As the number of parent atoms decreases, progressively fewer decays occur.
DETERMINING THE ABSOLUTE AGE OF ROCKS (4)

Measuring Isotope Abundance

Referring to Figure 7.17, notice that at \( t=0 \), 64 million parent atoms are present.

After 1 month, 54 million parent atoms are present; 10 million parent atoms have undergone decay.

After 4 months, 32 million parent atoms are present; \( \frac{1}{2} \) or 32 million parent atoms have undergone decay.

The half-life of the radioactive decay process is the time interval during which the number of parent isotope atoms decreases by \( \frac{1}{2} \). Therefore, the half-life for the decay depicted in Figure 7.17 is four months.

DETERMINING THE ABSOLUTE AGE OF ROCKS (5)

Measuring Isotope Abundance

The two key factors in determining the absolute age of a rock are:

1. Measuring the abundance of parent and daughter isotopes, and

2. Knowing the half-life value for the rate of decay of parent to daughter.

These measurements can be made with high precision and accuracy in specially equipped geochemical laboratories.
DETERMINING THE ABSOLUTE AGE OF ROCKS (6)

Measuring Isotope Abundance

Four radioactive decay schemes are routinely used by geologists for dating geologic samples (see Figure 7.18 on page 185). These methods are:

1. $^{14}$C method
2. $^{40}$K-$^{40}$Ar method
3. $^{238}$U-$^{206}$Pb method
4. $^{87}$Rb-$^{87}$Sr method

DETERMINING THE ABSOLUTE AGE OF ROCKS (7)

Radioactive Decay Methods

Each isotope system has its own time range of usefulness depending on the duration of the half-life.

The radioactive decay of $^{14}$C is useful for dating relatively young samples; it is especially useful for dating materials up to about 50,000 years old (see Figure 7.19a on page 186).
DETERMINING THE ABSOLUTE AGE OF ROCKS (8)

Radioactive Decay Methods

For dating materials older than approximately 50,000 years, geologists use isotope decay systems with longer half-lives. In some cases, the half-lives of two or more methods are utilized to date the same sample.

Utilization of multiple age determinations provides a further test of the approach. Additionally, consistency of relative and absolute ages validates the radioactive isotope method.

DETERMINING THE ABSOLUTE AGE OF ROCKS (9)

Radioactive Decay Methods

To accurately apply radioactive dating, it is essential that the following conditions are met:

1. No daughter isotopes are present when the rock forms
2. No parent isotopes are gained or lost after the rock forms, and
3. No daughter atoms are lost or gained from the rock once it forms and radioactive decay begins.
DETERMINING THE ABSOLUTE AGE OF ROCKS (10)

Radioactive Decay Methods

Condition 1 (no daughter isotopes present) is not always met. This requires additional measurements and calculations to determine how much of the daughter isotope was present prior to the decay of the parent.

Conditions 2 and 3 are met in most cases, but may be impacted by weathering or metamorphism. These two processes can add or remove atoms of parent isotopes, daughter isotopes, or both.

DETERMINING THE ABSOLUTE AGE OF ROCKS (11)

Potassium – Argon Dating

Several common minerals contain abundant K, including K-feldspar, muscovite, and biotite. Other minerals, including plagioclase feldspar and amphibole, contain measurable amounts of K.

K-bearing minerals commonly form by crystallization of magma or during metamorphism; therefore the $^{40}\text{K} - ^{40}\text{Ar}$ method applies to dating igneous and metamorphic rocks (See Figure 7.20 on page 187).

Ar is a pure gas that does not readily bond to other elements to form compounds. Therefore, Ar is not incorporated into growing mineral structures.
DETERMINING THE ABSOLUTE AGE OF ROCKS (12)

Dating Sedimentary Rocks

The distribution of fossils within sedimentary rocks defines the geologic time scale. This scale was established decades before the discovery of radioactivity and nearly 100 years before geologists began to routinely use radioactive decay for dating.

Obtaining absolute ages for the boundaries between periods and eras on the time scale is problematic, because radioactive isotope methods are used to determine ages of igneous and metamorphic rocks, but the time scale is based on fossils found in sedimentary rocks.

DETERMINING THE ABSOLUTE AGE OF ROCKS (13)

Dating Sedimentary Rocks

Direct isotope dating of sedimentary rocks is problematic.

1. Clastic grains eroded from older rocks yield the absolute age of the original source rock, and not the age the sediment was deposited.

2. Cementing minerals provide the age of cementation, which occurs after deposition.

3. Calcite in limestone often contains some U, which allows application of U-Pb dating methods. However, calcite is prone to recrystallization and reaction with pore water, which changes the abundance of both the parent and daughter isotopes.
DETERMINING THE ABSOLUTE AGE OF ROCKS (14)

**Dating Sedimentary Rocks**

The age of sedimentary rocks is often estimated by combining the absolute and relative ages (see Figure 7.21 on page 188).

The principles of superposition and cross-cutting relationships relate the relative age of sedimentary rocks to igneous rocks; igneous rocks provide absolute time measurements.

DETERMINING THE ABSOLUTE AGE OF ROCKS (15)

**Dating Sedimentary Rocks**

The same approach may be utilized for to obtain ages for boundaries on the time scale (see Figure 7.22 on page 189).

It is very unusual to find igneous rocks right at the boundary between two periods defined by different fossil assemblages, so the age of the boundary is estimated.

The ages on the time scale boundaries are revised as more information on absolute dates relevant to establishing boundary ages is obtained.
The oldest rock found to date is gneiss resulting from metamorphism of a tonalite intrusion in northwestern Canada. The gneiss contains the zirconium-silicate mineral zircon, which incorporates radioactive U when it crystallizes.

U-Pb isotope measurements reveal a 4.03 billion year age for the centers of the zircon crystals in the gneiss and are interpreted to represent the original crystallization age of the tonalite prior to metamorphism.

Sandstone in Australia contains zircon sand grains as old as 4.4 billion years, and although no rock this age has been found, the source of these zircon grains may be concealed beneath younger rocks.

These sand grains are the oldest dated minerals on Earth.