

Relative Age-dating -- Discovery of Important Stratigraphic Principles

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Background

Physical Geology and Historical Geology are the two introductory level Geology classes taught at most colleges and universities. Physical Geology is the study of Earth materials (minerals, rocks, sediment and soil) and the processes that affect those materials, including processes associated with oceans and shorelines, rivers, glaciers, groundwater, the wind, downslope movement and tectonic forces. Historical Geology is the study of the Earth through time, emphasizing the origins of and changes in the Earth's surface and subsurface, atmosphere, biosphere, and hydrosphere (water).

Historical Geology is, as the name implies, essentially a history class. As in any other history class, we wish to know what happened, and when those particular events occurred. Of equal importance to learning these facts is an understanding of *how* we know what we claim to know about the history of the Earth. I believe it is critically important to establish that all of our geological knowledge about the Earth and its history has a firm, scientific foundation, and is based on important principles and concepts.

In piecing together the history of the Earth, geologists rely on several key principles that allow us to determine the ages of rocks and the timing of significant events. There are two very different approaches to age-dating geological materials and events. *Actual age-dating* is the determination of the precise, numerical age of rocks and the geologic events that have affected those rocks for a particular area. It is often considered to be synonymous with radiometric age-dating, in which the occurrence and radioactive decay of natural, radioactive isotopes within minerals and rocks can be used as a type of very accurate clock to determine their age, although not all actual age-dating methods are radiometric. Obtaining accurate age-dates of rocks and geologic events has been possible only since the early-to-mid-twentieth century, with the perfection and widespread use of the mass spectrometer and other equipment.

Another, much older age-dating technique used by geologists is called *relative age-dating*. Relative age-dating is the determination of the correct chronologic sequence in which rocks formed and geologic events occurred, and is really the first step toward understanding the geologic history of an area. No numbers (actual ages of rocks and events) are involved.

Approximately eight relative age-dating principles are recognized and used by geologists, and taught in Historical Geology classes (see Appendix for a list of the principles and their definitions). These relative age-dating principles were discovered by just a few researchers during the early stages of the development of the science of geology itself, from the late 1600's until the early 1800's.

Understanding Relative Age-Dating: The Traditional Approach

Nicolaus Steno (1638-1686), based on his observations of geological processes in northern Italy, was the first person to understand that the Earth has a history

which can be discerned by careful studies of rocks, and to publish these insights. He noted the manner in which layers of sediment were deposited in river beds, lakes, and in the sea, and realized that sedimentary rocks and the fossils within them are ancient counterparts of these processes.

Steno is credited with discovering three relative age-dating principles. By far the most important is known as the Principle of Superposition, which simply states that in a stack of rocks, especially sedimentary rocks, the layer on the bottom formed first and is therefore the oldest, with layers becoming progressively younger toward the top of the sequence. The youngest layer would, of course, be the layer at the very top. In 1669 Steno wrote, "At the time when any given stratum was being formed, all the matter resting upon it was fluid, and therefore, at the time when the lowest stratum was being formed, none of the upper strata existed." I like to compare this concept to a stack of pancakes placed on a plate one at a time--the pancake that was first to hit the plate is the one on the bottom of the stack, and the last, the pancake on top. Although this discovery may seem, from our present perspective, to be so obvious as to need no special mention, Steno is the first person who clearly stated this principle in writing, who proposed that it could be used to help determine the geologic history of an area, and who then applied it toward this goal. Using superposition, Steno formulated a rudimentary geologic history of Tuscany, Italy, and drew what may be the first geological cross-section, illuminating his findings.

Steno is also credited with the discovery of the Principle of Original Horizontality and the Principle of Lateral Continuity (see Appendix).

James Hutton (1726-1797), who is often called the "Father of Modern Geology," is credited with discovering several other important general geologic and relative age-dating principles. Based on detailed field studies that ranged throughout Great Britain, he was the first person to realize the logical consequence of the geologic history he saw "written" in the rocks. From the application of superposition and his own newly-discovered relative age-dating principles, he surmised that the Earth was not just a few thousand years old, the accepted wisdom of the time, but immeasurably ancient, and stated that he could see "no vestige of a beginning, no prospect of an end." The realization of the immensity of geologic time ("Deep time") is often considered to be the single greatest contribution of the geological sciences to human knowledge.

The two most important relative age-dating principles credited to Hutton are the Principle of Cross-cutting Relationships and the Principle of Unconformities. The Principle of Cross-cutting Relationships recognizes that geologic features that seem to cut or pass through outcrops of rocks, like faults and igneous intrusions, must be younger than the rocks through which they pass. (Our stack of pancakes cannot be sliced to eat until they are already on the plate, i.e., making a few cutting motions in the air above the plate just before placing your pancakes there, subsequently hoping to find them in ready-to-eat bites, simply won't work.) Some people credit Charles Lyell (1797-1875) with the discovery of this age-dating principle, but the idea was clearly Hutton's. Based on field

observations he made in Glen Tilt, Scotland in 1785, Hutton found "granite breaking and displacing the strata in every conceivable manner, including fragments of broken strata, and interjected in every possible direction among the strata." Lyell was a better writer, however, and popularized this and other geological principles with the publication of the first geology textbook in 1830.

Unlike Superposition and Cross-cutting Relationships, the Principle of Unconformities is not at all obvious. It is based on Hutton's recognition of the significance of unconformities, which are ancient erosional surfaces that are sometimes preserved within sequences of rocks. (The word 'unconformity' was coined a few years after Hutton's death by another geologist.) Unconformities are essentially ancient land surfaces, and indicate the passage of huge intervals of time, requiring multiple episodes of sediment deposition below sea level, transformation of sediments to sedimentary rocks during burial beneath younger strata, uplift of the former sea floor, erosion of the newly-formed land surface, followed by a rise in sea level and another period of sediment deposition in the sea. Of a discovery he made near Jedburgh, Scotland in 1787, Hutton wrote, "Here the vertical strata, similar to those that are in the bed of the Tweed appear, and above those vertical strata, are placed the horizontal beds, which extend along the whole country. From this it will appear, that the ...vertical strata... had been formed, and had been wasted and worn...before the horizontal strata were begun to be deposited. Those new or posterior strata had been indurated or cemented...and elevated from the bottom of the sea into the place of land, or considerably above the surface of the waters."

Hutton's friend, John Playfair, in a classic passage from the geologic literature, elegantly described his experience while visiting another unconformity with Hutton, which Hutton had discovered at Siccar Point, Scotland, in 1788. As he listened to Hutton's explanation of the series of events recorded in the rocks, Playfair claimed that "The mind seemed to grow giddy by looking so far into the abyss of time..."

In addition to the Principle of Superposition and the Principle of Unconformities, I also credit Hutton with the discovery of the Principle of Deformation and the Principle of Inclusions (see Appendix).

A plausible geologic history of a particular area can be constructed by using the relative age-dating principles of Steno and Hutton. Diligent field work could produce, for example, an accurate description of the geologic history of Bexar County, Texas, or even the history of the entire Texas Hill Country. A geologist in east Tennessee or the Wind River Mountains and adjacent basin of northwestern Wyoming could similarly determine the geological story of those locations, incorporating a reasonable chronologic sequence of rocks and geologic events, using these same principles of relative age-dating. A larger puzzle, however, can't be solved by these principles alone; with them we can create detailed geologic histories for relatively small areas, but how can we compare the geologic history of central Texas to that of east Tennessee or northwestern Wyoming? How can we do relative age-dating of rocks for widely separated

parts of the country or world? Without this capability, our efforts will be parochial at best, and we will not be able to determine the geological history of the entire Earth, or for all of North America, or even the whole state of Texas.

What is needed is something of intrinsic time significance, something within the rocks themselves that will enable geoscientists to compare the relative ages of rocks in widely separated areas. The key is fossils, and the Principle of Biologic (Fossil) Succession states that fossils can be used to do relative age-dating of rocks worldwide--rocks that have the same assemblage of fossils are the same relative age. William Smith (1769-1839) and Georges Cuvier (1769-1832) are credited with the nearly simultaneous but independent discovery of this principle, based on their respective work in England and France.

The preceding explanations track very closely to the approach used in a typical Historical Geology class or textbook. At the beginning of the class each semester, instructors and authors first briefly discuss the important early researchers in the geological sciences, and then give the name of the geologic principle, useful for relative age-dating of rocks and events, that these 17th and 18th century scientists are credited with discovering. After the instructor defines these principles, students are usually shown several examples so they can see how the principle can be applied.

But why not start with the examples, and let the students discover these principles for themselves?

Understanding Relative Age-Dating: The Discovery Method

Students don't have to be passively taught the important principles geologists use to do relative age-dating of rocks and geologic events—the first step in determining the geological history of an area. By careful analysis and critical thinking about accurate representations of rock outcrops, in one or two class periods they can discover these principles themselves!

Since there are only a few important relative age-dating principles, students are split into groups which each work to discover a different principle. The groups are given handouts with drawings and photos of rock outcrops illustrating the various principles. Students must put themselves into the shoes of the early researchers to discover the principle illustrated by their group's example. The early geoscientists did not have computers, libraries, or textbooks to consult in studying rocks. And students don't really need any of these either, as the principles can be derived by simply combining keen powers of observation of rocks in their natural setting with common sense—no elaborate equipment or experiments required!

Groups have worksheets for which they must answer a series of prompts that help to lead them to the discovery of their relative age-dating principle. Groups must also invent a name for the principle, and select a spokesperson. During the oral presentation, answers to the prompts for each example are provided to the rest of the class. After revealing the name of their principle, each spokesperson

discusses how the principle can be applied to relative age-dating of rocks and geologic events.

The Relative Age-dating exercise handout students are given is included. The different examples illustrate the various relative age-dating principles as follows:

Example 1: Principle of Superposition

Example 2: Principle of Superposition, Principle of Original Horizontality and Principle of Deformation

Example 3: Principle of Lateral Continuity

Example 4: Principle of Inclusions and Principle of Unconformities

Example 5: Principle of Cross-cutting Relationships

Benefits and Results of the Discovery Method

These exercises provide numerous benefits. Students enjoy the process, which provides a way for the students to interact and get to know each other early in the semester. Naming each principle they derive also offers students an opportunity for creativity. Students can invent some interesting and occasionally insightful names for their principle. For example, during a recent semester a group came up with the name "Pyramid Principle" for Example 1. This left most of the class rather puzzled, as they considered pyramid-shaped objects and the ancient Egyptian civilization, looking for connections which couldn't be found. I could almost literally see light bulbs igniting above the heads of students when the Example 1 spokesperson explained that to build the pyramids of Egypt, which are constructed from very large blocks of limestone, the stonemasons laid the bottom layer first, followed by the next, and so forth, with the last and youngest course of stones at the very top, completely analogous to the way sediments are deposited and sedimentary strata form.

Additionally, several students--the elected (or volunteer) spokespersons for each group--have an opportunity to practice their oral presentation skills.

Although I've been using and revising these exercises for several years, I haven't yet devised a statistically meaningful way to quantitatively measure the success of this discovery-driven exercise, but I believe it does increase student understanding and retention of the geologic principles used for relative age-dating of rocks and geologic events. These principles are extremely important, providing much of the scientific foundation for the rest of the Historical Geology course.

Future Work

I would like to develop a quantitative method of measuring student success when using my discovery method to teach the important relative age-dating principles versus a more traditional approach.

I also want to design an example that can be used to realistically illustrate the very important Principle of Biologic (Fossil) Succession for inclusion in my student handout and worksheets.

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Geologic Principles used in Relative Age-dating of Rocks and Geologic Events

1. Principle of Original Horizontality -- Sedimentary rocks form in relatively horizontal layers, more or less parallel to the Earth's surface, and remain in horizontal layers unless later deformed.

Why is this true?

Because sedimentary rocks are formed from sediments that settle out of water in layers or beds that are essentially horizontal and parallel to the Earth's surface.

2. Principle of Lateral Continuity -- Sedimentary strata (rock layers) are three-dimensional. Although typically not very thick, strata extend laterally in all directions and cover a relatively large geographic area.

(Note: The composition of the strata may change, for example, sandstone may gradually grade into shale in the direction of deeper water deposition.)

3. Principle of Superposition -- In a sequence of sedimentary or extrusive igneous rocks, the oldest rocks are on the bottom, and the strata become successively younger toward the top.

(Note: True unless deformation has caused the rocks to be flipped upside down. This is rare, and can usually be determined by careful study of the rocks.)

4. Principle of Unconformities -- An unconformity is a surface of erosion within a sedimentary sequence that represents a significant interruption in the continuous geologic record of that area. The missing rock record is younger than the strata below the unconformity, and older than rocks that form above the unconformity.

5. Principle of Deformation -- Deformation, such as folding and faulting, is younger than the rocks deformed and older than any overlying rocks that are not affected.

6. Principle of Cross-cutting Relationships -- Cross-cutting features, like igneous intrusions and faults, are younger than the rocks or other geologic features they cut across.

7. Principle of Inclusions -- Inclusions, and the rocks they came from, are older than other rocks that contain the inclusions.

8. Principle of Biologic (Fossil) Succession -- Fossils can be used to age-date rocks. Rocks with the same fossils can be correlated as the same age, even if the rocks occur in widely separated locations or are of a different rock type.

Why is this true?

a. Because the sequence of life forms on Earth has changed continuously through time as existing organisms became extinct and new organisms evolved in response to environmental changes.

b. Therefore, the fossils in the rock record, reflecting changes in the types of living organisms, have also changed in a definite, recognizable sequence.

c. So, rocks from each interval of Earth's history are characterized by groups of fossils that are recognizably different from the fossil assemblages in both older and younger rocks.