Geological Time: Principles

Category:
Introductory

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Accepted for publication: February1999

Keywords: · stratigraphy · geochronology · geological timescale · biostratigraphy · radioactivity

Geologists determine the age of events in the geological past by relative dating (establishing which event comes first, usually by superposition and crosscutting relationships) and by numerical dating (obtaining a numerical age estimate on an event, usually by radioisotopic dating of interbedded or crosscutting igneous rocks). From these dating methods, geologists have determined that the earth is 4.5 billion years old, and that most events in the geological past took place millions to hundreds of millions of years ago.

Basic Stratigraphic Principles

The basic principles of understanding earth history and the rock record are known as stratigraphy, literally 'the study of layered rocks'. Although stratigraphy originally developed as a method of describing and interpreting layered sedimentary rocks, in recent years its meaning had broadened to include layered igneous rocks (lava flows, volcanic ash falls and flows) and even intrusive igneous rocks – any rocks that demonstrate a sequence of geological events. Based on stratigraphic principles, geologists have been able to reconstruct the past 4.5 billion years of earth history in surprising detail.

There are two primary means of determining the age of events in the geological past. A geologist can determine the relative sequence of events (event A is younger or older than event B), or determine the numerical age (i.e. this rock is so many millions of years old) of a rock unit, primarily by radioisotopic dating of igneous rocks. (Numerical dating is erroneously called 'absolute dating' in older books.) Over the past 200 years, the geological timescale was constructed by geologists who determined the relative sequence of events in earth history and have estimated the numerical ages of these events by interpolating radioisotopic dates wherever possible. However, numerical dating was not possible until about 1905, and was not widely applied to most geological problems until the 1950s and 1960s. In most situations, the geologist determines the age of rocks using relative dating and biostratigraphy; only rarely is it also possible to obtain a direct numerical date as well.

The basic principles of relative dating were first proposed by the Nicholaus Steno in 1669. In Steno's time, most scholars thought of the rocks of the earth's crust as created exactly as we now see them only 6000 years ago. They were puzzled by the occurrence of fossils in solid rocks, and thought that the fossils might have grown in the rocks by supernatural forces, or been stranded there by Noah's flood. Steno realized that the presence of fossils in sedimentary rocks showed that these rocks had not always been solid, but were once composed of loose sedimentary materials (sand, mud, lime) that consolidated around the fossils and later turned into stone. From this insight, Steno derived several principles of relative dating that are the foundation of all stratigraphy:

- Principle of superposition – if sedimentary rocks are deposited as layers of sand or mud, one on top of the other, then the layers on the top of the stack will be younger than those toward the bottom. It is analogous to a stack of papers on a desk which have accumulated for a long time without being shuffled. Those at the bottom of the stack were left there a while ago, while those at the top were placed there most recently.

- Principle of original horizontality – since sedimentary rocks are deposited as layers of sand or mud in bodies of water, they formed as horizontal sheets (assuming the laws of gravity applied in the past as they do today). If sedimentary rocks are found tilted or folded today, then they must have deformed at some time after they were deposited horizontally. The folding or tilting must be younger than the deposition of the sedimentary rock.
- Principle of original continuity – when we see sedimentary layers deposited today, they form broad sheets of sand, mud or lime that continue for long distances and only gradually thin out and disappear. Thus, when we find sedimentary rocks that end abruptly in a canyon wall or roadcut, we can assume that they were once continuous on either side, and the stream or road cut through the rocks long after they were deposited.
- Principle of crosscutting relationships – If a rock unit (such as an igneous dyke) or a fault cuts across another rock unit or fault, the unit that does the cutting must be younger than whatever it cuts through. If there are a series of crosscutting dykes or faults, it is possible to work out a sequence of their relative ages.

Although Steno laid the groundwork for modern geology over 300 years ago, the scholars of his time and for the next century still clung to the Noah's flood story and biblical literalism to explain the rock record. The implications and widespread application of Steno's principles did not occur until the birth of modern geology in 1788, which culminated in the early 1800s. Within years after the publication of James Hutton's ideas in 1788, geologists no longer viewed the rock record as created instantaneously as we see it, or laid down by Noah's flood, but instead as the product of slow, steady processes of deposition of sediment, uplift of mountains, and other phenomena that operate under natural law, rather than under the control of supernatural processes as described in the Bible. This approach is known as uniformitarianism, and simply says that geologists must assume that natural laws (such as gravity) have applied in the past as they do now. In Archibald Geikie's words, 'The present is the key to the past.' Geologists, like all other scientists, must exclude supernatural processes because they are not testable by scientific methods.

Once the principle of superposition was widely applied and used to describe events in the geological past, it became apparent that interpreting the rock record in most places could be complicated. Some rock units could be traced over long distances, but others thinned out until they vanished, or changed lithology over long distances (for example, a coarse sand can become finer grained until it is a shale). This is because sedimentary rocks formed originally as sediments, which are products of specific sedimentary environments. For example, in the modern world, one can see the sands of beach and nearshore region become finer grained as one travels further offshore until they become offshore muds. Based on this insight, geologists should expect rock units to change in lithology or appearance (facies) if they are traced laterally over enough distance. Specific lithologies (such as sandstone) are products of a specific sedimentary environment (such as a beach, or a river channel), and should not persist laterally before they transform into a sedimentary facies produced by a different but adjacent sedimentary environment (such as the offshore muds of the ocean, or the mudstones of the floodplain around the river channel).

At any given time on the earth's surface, a wide variety of sedimentary rocks are being formed in different environments. Conversely, sedimentary environments that produce a specific lithology (for example, a beach sand) can persist for millions of years and produce a long record of sandstone that spans considerable amounts of time. Sedimentary rocks are not the product of a single geological event representing a short instant in time, but instead span long increments of time, and cannot be thought of as time units. It seems natural and intuitive to see a persistent layer of sandstone and limestone as a single event and think of it as representing a specific time, but our understanding of facies change tells us that most rock units are inherently time-transgressive, and typically get older or younger if you follow them over considerable distances.

The Timescale: Origins

The geological timescale (Figure 1) developed in Europe mostly between 1795 and 1840, as a new breed of geologists applied superposition and a uniformitarian view of the world. It was not organized in a logical or systematic fashion from first principles, but grew in a haphazard fashion with different parts of the timescale named at different times by different people. The geological periods follow no logical pattern, but reflect historical accidents of naming. However, the timescale is such a fundamental tool that all geologists find it the most useful way to communicate the age of geological events. The relative age term is much more practical than referring to geological events by numerical dates (which are often poorly known and subject to change). This is analogous to describing historical events by such landmarks as the monarchs of England. Although we can often refer to historical events by the precise year, terms like 'Elizabethan' and 'Victorian' are often more useful to the historian, and only require a knowledge of the sequence of kings and queens of England and the approximate years of their reign.

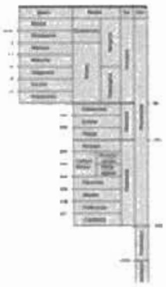

Figure 1
The geological timescale.

Before 1800, geologists viewed the rock record as a product of Noah's Flood, with 'Primary' or 'primitive' granites and metamorphic rocks (typically found in the cores of mountains) representing the rocks of the original created earth, tilted layered 'Secondary' sedimentary rocks representing deposits of the Flood itself, and horizontal, less consolidated sediments 'Tertiary' sediments above them as post-Flood deposits. Today, only the term 'Tertiary' survives from this Flood geology concept of the rock record, now dated between 65 and 2 million years ago.

Although scholars attempted to force the rock record into a biblical straitjacket, miners were more concerned with practical matters like naming and describing distinct rock layers that were important to them. All over Europe, the Industrial Revolution and its demand for coal had led to widespread mapping and mining of the beds known as the 'Coal Measures'. In 1822, Conybeare and Phillips (following J. J. d'Omalius d'Halloy) formally renamed these rocks the 'Carboniferous' (meaning 'coal-bearing' in Latin). Likewise, the chalks of the White Cliffs of Dover inspired their name for the Cretaceous Period (from the Latin for 'chalk'). Even earlier (1795), the famous explorer Alexandre von Humboldt had coined the name 'Jurassic' for the rocks exposed in the Jura Mountains of the southwestern Alps. In 1815, Friedrich von Alberti used the term 'Triassic' for the three-fold succession of rocks found over Germany and elsewhere in Europe.

In the 1830s, Adam Sedgwick (first professor of geology at Cambridge) and the gentleman geologist Roderick Impey Murchison started field work in western England and Wales to decipher the base of the 'Secondary' sequence. In 1834, Sedgwick named the lowest rocks the 'Cambrian' (after the Roman name for Wales), and Murchison called the upper rocks the 'Silurian' (after the Roman name for an ancient Welsh tribe, the Silures). However, they used different criteria for recognizing their systems. Murchison based the Silurian on distinctive fossils, so it could be recognized around the world, while Sedgwick did not. Eventually, they argued about the boundary between their two systems, and soon Murchison's

Silurian had swallowed up Sedgwick's Cambrian. The dispute was not settled until after they died, when Charles Lapworth recognized a distinctive interval between the Cambrian and Silurian in Scotland, which he called the 'Ordovician' (after the Roman name for another Welsh tribe, the Ordovices) in 1879.

Before the Cambrian–Silurian feud destroyed their friendship, however, Murchison and Sedgwick collaborated on the naming of the rocks just beneath the Carboniferous. In most of the British Isles, they are river deposits known as the 'Old Red Sandstone', but in southwestern England (Devon and Cornwall), they change facies into marine beds that were long confused with the Carboniferous or Silurian. In 1840, Sedgwick and Murchison coined the term 'Devonian' for rocks of this age, whether they were marine or non-marine. In 1841, Murchison went to Russia at the invitation of the Czar, where he studied the geology, and confirmed much of what he had already discovered about European geology. In the Ural Mountains, he recognized a sequence of rocks above the Carboniferous which he called the 'Permian' (after the town of Perm in the Urals).

By the late 1830s, the character of these time divisions was becoming apparent, and large-scale units could be proposed. In 1838, Sedgwick proposed the Palaeozoic Era for the early part of the timescale, and in 1840 John Phillips used the term Mesozoic Era for the Triassic–Jurassic–Cretaceous, and Cenozoic Era for the post-Mesozoic. These divisions were based on the recognition that many of the characteristic organisms of the Palaeozoic became extinct during the great extinction at the end of the Permian, and that a second mass extinction, which wiped out dinosaurs, ammonites, and many other forms, separated the Mesozoic from the Cenozoic. In 1833, Charles Lyell named the subdivisions (or epochs) of the Cenozoic and Tertiary as the Eocene, Miocene and Pliocene; the Palaeocene Epoch was named by the palaeobotanist W.P. Schimper in 1874, and the Oligocene Epoch by H.E. von Beyrich in 1854.

Since these terms were proposed, the timescale has undergone over a century of finer and finer subdivision and refinement. Thus, we now recognize three eras, each subdivided into periods, which are in turn subdivided into epochs. All of the epochs are further subdivided into smaller units called ages, which are based on biostratigraphic stages and ultimately on the zones of individual fossils. Current versions of the timescale can be found in the references listed in Further Reading at the end of the article.

Modes of Dating in Outline

As discussed above, the fundamental method of determining the age of geological events is relative dating, worked out by using the principle of superposition. This was the way that geologists worked out the sequence of strata in Europe that were the basis for our modern timescale. However, at the same time, they found that many rock units were similar in appearance, and hard to distinguish from similar rock units; others change facies over distance. In the late 1700s, the English canal engineer William Smith realized that each rock unit in his English succession contained its own distinctive assemblage of fossils, and that each rock unit could also be recognized by its fossil content. The fact that fossils change continuously through time is known as faunal succession, and is the basis for biostratigraphy, the scientific study of the distribution of fossils in rock sequences. As the Murchison–Sedgwick battle over the Cambrian and Silurian demonstrates, biostratigraphy is the only practical means of dating most sedimentary rocks. Rock types may change over distance, or become difficult to distinguish, but distinctive assemblages of fossils are unique to certain segments of geological time, and can be used around the world to recognize that time interval. Most palaeontologists who work for oil companies are biostratigraphers, using their fossils to date and correlate rocks as precisely as possible. Without them, the search for oil that powers our modern civilization would be impossible. As long as geologists want to know the age of rocks, there will always be a need for palaeontologists who do biostratigraphy.

When the timescale developed in the early 1800s, no one could tell how many years each of their time terms represented. Some thought the age of the earth was nearly infinite (Hutton noted that there was 'no vestige of a beginning'), but other scientists gave the earth only 20 million years or less for its entire history. The discovery of radioactivity in 1896, however, gave us the first method of obtaining a numerical age for geological events. When a radioactive atom, such as uranium or rubidium, spontaneously decays by nuclear reactions, it gives off heat, radioactive particles, and leaves a nonradioactive daughter atom. The rate of this nuclear reaction is well known, and half of the original parent atoms decay to their daughter atoms in a fixed interval of time, known as a half-life. If we can measure the ratio of parent to daughter atoms, we can determine when this atomic decay reaction began, and date the material which contains these atoms. However, this system only works for minerals which have cooled down from a very hot state (igneous or high-grade metamorphic minerals), locking in the parent atoms at the time of their crystallization. Thus, it is inapplicable to normal sedimentary rocks, which are formed from pre-existing grains eroded from other rocks, and not from a molten state. To determine the age of sedimentary rocks, the geologist needs interbedded igneous rocks (such as ash falls or lava flows) which give numerical ages in certain parts of the sedimentary sequence, or crosscutting igneous dykes, which bracket the age of the rocks through which they cut, and which cut across them.

There are other constraints on radioisotopic dating as well. The method only works on crystals which have locked in all their parent and daughter material, and preserved their ratio faithfully. Anything that disturbs the crystal and changes the ratio will lead to erroneous dates. If the crystal has been weathered, so that either parent or daughter atoms can leak out, then the ratio has been altered. In other cases, atoms of parent or daughter material can percolate through the groundwater and seep into the crystal, contaminating it and altering the ratio. Thus, geochronologists only use the freshest samples, and often examine each crystal under the microscope before analysis to detect any sign of alteration (although such an alteration may be undetectable, and still give erroneous dates). In some cases, an igneous rock (such as an ash flow) may have picked up ancient sedimentary mineral grains as it settled and cooled, and these detrital contaminants will give an artificially old age for the volcanic event. Geochronologists control for these problems by running the analysis several times, often using different decay systems. If each independent system gives a consistent age, and they are also consistent with the biostratigraphic and other age estimates, then they are considered acceptable.

Another constraint is the analytical error inherent in the system. The ratios of different atoms are measured with a mass spectrometer (which sorts isotopes by their masses), which has a certain minimum level of sensitivity. The date can only be estimated to a certain level of precision, given by the 'plus or minus' error bars that are attached to every date. For example, if the date is 100 ± 2 million years, then there is a 95% chance that the true age lies between 98 and 102 million years. Even the best laboratories still have errors of ±1–2%; this analytical precision gets progressively worse with increasing age, since it is a percentage of that age. For example, the error on typical Cenozoic dates is 500 000 years, but for billion-year-old Precambrian rocks, it is typically on the order of ±10–20 million years.

There are many different radioactive elements in the earth, but only a few are sufficiently abundant in crustal rocks and have a long enough half-life to allow them to be used for measuring geological events. Their use for dating is described below.

- Potassium–argon dating – this is the most widely used technique, since potassium is one of the more abundant elements in the earth's crust, found in potassium feldspars, micas, and many other common minerals. Even though it has a long half-life of 1250 million years, many minerals contain enough potassium for there to be a measurable daughter product even at this slow rate of decay.

Thus, it can be used for measuring ages as old as the oldest rocks, although rocks younger than a million years old rarely have measurable daughter products. The major limitation of this method is that the parent atom (potassium-40, a solid) decays to argon-40 (a gas), which has a tendency to leak out of the crystal and give ages which are too old. To circumvent this problem, laboratories have now begun to use a variant called argon-40/argon-39 dating, which uses argon-39 as a proxy for potassium-40. This method measures two similar gases, so there is less problem with leakage or contamination. It has become the method of choice for obtaining ages with very small error estimates, and also for screening out problems with leakage or contamination that might give an unreliable date.

- Rubidium–strontium dating – this method uses the decay of rubidium-87 to strontium-87 as the basis for its analysis. The main limitation of this method is that rubidium is a relatively rare element in the earth's crust, so most minerals have no measurable rubidium-87. Rubidium ions have a +1 charge and a large ionic radius, so they can substitute for potassium or sodium in some minerals, but only in trace amounts. Another problem is that the daughter product, strontium-87, has a +2 charge, so it tends to migrate out of the crystal lattice to sites where it is electrically stable. Rubidium–strontium also has a very long half-life (48 800 million years), so very little material has decayed except in the very oldest rocks. For this reason, the method is used primarily in dating potassium- or sodium-rich granitic rocks that are at least 500 million years old (Precambrian), or occasionally early Palaeozoic rocks.
- Uranium–lead dating – there are two different radioactive isotopes of uranium, uranium-235 and uranium-238, which decay to lead-207 and lead-206, respectively. These elements are also relatively rare in crustal rocks, and have long half-lives (703 million years and 4468 million years, respectively), so they are primarily used for Precambrian rocks, and for meteorites and moon rocks. Uranium is most often found in minerals such as zircon, sphene and apatite, which form in the final stages of crystallization of a granitic magma, and have large enough lattice spaces that they can accommodate huge cations like those of uranium.
- Fission-track dating is a related method. The crystal lattices in crystals of zircon may become damaged as the uranium decays and emits radiation, leaving a pathway of destruction in the crystal. These fission tracks can be seen under the microscope if the crystal has been etched in hydrofluoric acid. The geochronologist will count the fission tracks in the etched crystal and then irradiate it in a nuclear reactor to stimulate new fission tracks. It is then possible to determine how much parent material was originally present. The main limitation of the method is that the tracks close up and disappear, giving a false track count in crystals which have been reheated. In addition, fission-track dating tends to give relatively large error estimates (typically ±1–2 million years, even for relatively recent Cenozoic dates), and zircons are very stable as sedimentary minerals, so there is a good chance of detrital contamination.
- Carbon-14 dating – all of the methods mentioned so far only work on crystals that have cooled down from a molten state, such as in igneous or metamorphic rocks, and thus cannot be used directly on fossils or sedimentary rocks. Although living things are made largely of the stable isotope of carbon, carbon-12, they also contain carbon-14. This isotope is produced in the atmosphere when nitrogen-14 is bombarded by cosmic radiation, and is taken up by plants during photosynthesis, so that animals and plants all contain trace amounts. When an organism dies, it no longer takes up carbon-14, and that material begins its radioactive decay. Thus, a geologist or archaeologist can take any carbon-bearing material – wood and other vegetable matter, coal, baskets, bones, pottery, shells – and determine the amount of carbon-14 present and thus its age since death. The main limitation of the system is that the half-life is only 5730 years, so the decay is very rapid, and there is no measurable parent material after about 60 000 years. Thus, this method is of practical use for archaeologists and geologists who study the last Ice Age, but of no use to geologists who study anything older than about 60 000–80 000 years old.

Synopsis

These are the main methods by which geologists determine the age of ancient events. Most deposits must be dated by superposition and recognition of distinctive rock units and their contained fossils, so biostratigraphy is the method of choice. Wherever igneous flows, ashfalls, or intrusions are present, it is also possible to obtain a numerical date. By finding many places around the world where igneous rocks are interbedded or crosscutting with fossiliferous sedimentary rocks, it is possible to place numbers on the relative timescale. When geologists want to know the numerical age of a given rock, they use its fossils to determine where it is on the standard timescale, and then read off the latest numerical age estimate for that time interval.

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