Chapter 5:

Geological Time: So Much, So Little

Forensic investigation is a currently popular theme for television shows. Much of astrobiology functions in this manner. We would like to know what happened during the Earth's history and the universe's history and how long it took to happen. Like TV detectives, we can only examine evidence that exists at present. Forensic geological methods date from antiquity. Their application came to the forefront of science in the 1800s. Modern geology is forensic, often high-tech, and by the way used to investigate crimes, for example, by tracing rock fragments on the suspect's shoes to the crime scene.

The sequence of local geological events

The modern study of geology traditionally begins in 1666, in Florence, Italy. A shark's head arrived at the office of a Danish physician. Fishermen had captured the large beast. The Duke of Tuscany wanted it dissected by a leading anatomist. The smelly carcass had already started to attract flies. Nicolas Steno (1638-1686) cut out formidable teeth. They looked familiar. They were the "tongue stones" found in rocks on

Malta (Figure 1). (The local belief was that the stones were serpents' tongues turned to rock.) Steno realized that the tongue stones are fossil teeth of long-dead sharks. The idea was not new. Fabio Colonna (1567-1650) had already reached the conclusion in 1616.

Figure 1: Assorted fossil shark's teeth from Maryland and California. Steno worked with similar teeth from Malta. These teeth are about 10 million years old. They look just like modern teeth to an untrained observer. You can find them weathering out of cliffs on some beaches. Photo by author. Teeth provided by Jim Ingle.

On the more general issue, Herodotus (ca. 484-425 BC) and Erastosthenes both recognized fossils as evidence of ancient marine life. However, most people in 1666 believed that fossils formed spontaneously within rocks. An enlightened minority regarded fossils to be evidence of marine organisms and giants that perished in Noah's Flood. A still tinier minority rejected the Flood for an old rational Earth. Leonardo da Vinci (1452-1519) kept his opinions private. He may have directly influenced Girolano Frascastoro (1483-1553), who ventured into print, as did the Frenchman Bernard Palissy (1510-1589).

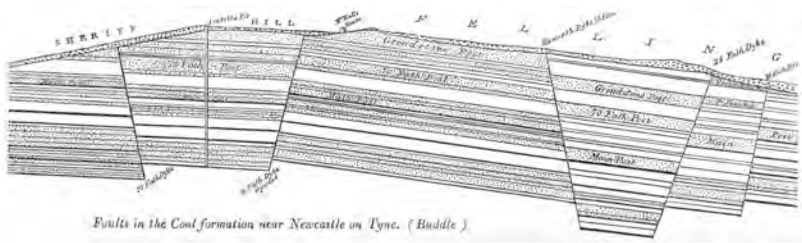


Figure 2: Geological cross section of coal fields near Newcastle, England, from 1836 edition of Buckland's geology book. (It is like bringing coals to Newcastle.) One can tell the sequence of events. The beds were originally deposited flat, one on top of the other. Then they were cut by faults. Then erosion occurred forming a rolling upland surface. The last event is deposition of a thin layer of surface deposits, now known to have been transported by glaciers. Geologists construct sections by interpolating between areas of good exposure and extrapolating into the subsurface. This section differs from modern ones in that it has no scale.

Steno became curious and started to study the local geology. He examined tongue stones still in the rocks. They were worn like used shark teeth. That is, they came from once living sharks. Some of them had turned into different minerals; he realized that this fossilization process occurred underground. That is, hard parts like teeth get fossilized much more often than soft parts like the purported serpents' tongues. He distinguished fossils that were once-living organisms from crystals and concretions that in fact grew within rocks.

There are excellent exposures of rocks near Florence. There are also young deposits of sediments near the coast and along rivers. Steno saw that sediments are originally deposited more or less flat and that the younger sediments cover older rocks. There are also veins (*tabular bodies*) containing useful mineral deposits that intrude through other rocks. He published the common-sense basic rules for determining the relative age of rocks (Figure 2). In modern terms,

(1) Sediments are initially flat lying and the younger beds of sediments form on the top of older ones. (Figure 3)

Figure 3: You can see bedding and geological contacts in many outcrops once you start to look for them. Here gravel and coarse sand beds overlie granite near Montara California. A trained geologist can tell that the contact is depositional, for example, because pieces of the granite occur in the gravel. The granite cooled from molten lava about 100 million years ago at a depth of several kilometers. It was exhumed by erosion. Gravel beds covered the granite. Recent beach erosion exposed the contact. We get information only about those events from this outcrop. Geologists must look far, deep, and wide to build up a coherent history of the Earth. Note that erosion destroys information about the granite while deposition records information in the gravel. Lens cap at contact gives scale. Photo by author.

(2) Faults, veins, and igneous (once molten) rocks are younger than the rock bodies that they cut across. (Figures 4 and 5)

Figure 4: Faults are fairly common in the Bay Area of California and often visible in outcrop. Here a minor fault places older granite on top of younger gravel and coarse sand beds near Montara California. The fault to the left of the man places older gravel on top of younger gravel. The faulting occurred after the deposition of the gravel. Photo by author.

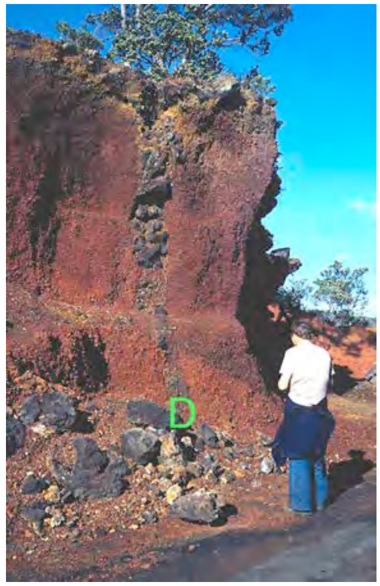


Figure 5: You can see dikes particularly when they cut different colored rock. Here a basalt dike cuts red rock in cinder cone in Hawaii. The dike ascends from “D” to the tree. It erupted to the surface at the top of the exposure. The dike is younger than the cinder cone. Both are less than a few hundred years old. The present exposure is from road building. Photo by the author.

He noted that the oldest rocks he saw are devoid of fossils. He considered that these were the primary rocks of the Earth that formed before life was created. The other rocks formed before, during, and after the Biblical Flood. There are river and beach deposits that obviously formed recently. His work was good enough that the terms Quaternary for the young deposits and Tertiary for somewhat older deposits are part of the geological time scale, until recently. They are still used informally

Steno had not looked much at rocks elsewhere even though he had traveled extensively. He incorrectly assumed that the sequence of rocks is the same everywhere in the world. He had already converted to Catholicism. He became a Bishop. He got into trouble for taking the vow of poverty seriously along with the plight of the poor. He died of his self-imposed lifestyle without returning to geology.

Steno’s simple relationships have the status of laws or axioms in geology, but they are little more than saying that you have to put something down before you put something on top of it. Yet they are extremely useful in any local geological study. Much of the training of field geologists involves recognizing contact relationships. This work includes studies that utilize the high-tech methods described later in this chapter.

However, the sequence of events is not the same everywhere. Field relationships are not useful when there is poor exposure and no drilling has been done. The relationships are useless for getting relative ages between rocks on different continents. They yield only modest information about detached rocks like cobbles or even meteorites.

Questions about the Flood. The idea of a biblical flood persisted among geologists until after 1800. The reasons for this did not all owe to religious fervor. The latest ice age ended with ice covering northern Europe and North America, melting mostly by 10,000 years ago. The landforms and glacial deposits in these regions in fact have (crudely) the biblical age of 6,000 years (Figure 6). Ice continued to melt causing the sea level to rise until it stabilized near its current level about 6,000 years ago. In most places, the coastal landforms have this age (Figure 7).

Figure 6: Road cut exposes glaciated rock surface in the Upper Peninsula of Michigan. The glaciers melted about 12,000 years ago, not grossly different from the Jewish age of the Earth. There is thin soil and the exposed hard rocks are virtually unweathered. Little erosion of nearby glacial deposits has occurred. Young glacial landforms occur throughout northern parts Europe and North America. The untrained eye tends to see the youngest major geological event, here glaciation. It also sees recent man-made events, here road building followed by graffiti. Photo by the author.

The climate also stabilized about 6,000 years ago. Large-scale agriculture became feasible and civilization took off. Coastal cities no longer had to move inland every century when they were flooded by the rising sea level. Irrigation became possible in the Nile Delta. Before 6,000 years ago, torrents flowed down canyons through the Delta to a Mediterranean with a lower sea level. Since then, the more placid streams in the Delta flooded gently over the land each year. The biblical age turns out to be a tolerable estimate with regard to folk memory of the rise of extensive civilization in the Middle East and thus not in obvious conflict with what was known about history in antiquity in the Middle Ages. The tendency to misassociate an age of an event with that of the Earth persisted until the discovery of radioactivity in the twentieth century.

Figure 7: Coastal landforms are young and date from when sealevel stabilized 6000 years ago. Civilization took off then. This seacliff is near Point Reyes, California. The hanging valley above “H” drains to the cliff face. It has not yet had time to cut down to the shore. Other unstable landforms including sea stacks and natural bridges are not present in the photo. Photo by the author.

Perhaps ironically, dates relative to the age of the Earth do not appear in either the Christian or Hebrew Bibles. The origins of this dating system are lost in time but are relatively recent. The Jewish practice of giving time relative to a fixed date rather than within the reign of each king came from the Greeks after Alexander's entry into the area in 312 B.C. The last reformation of the Jewish Calendar traditionally dates from 359 A.D. It is better than the Julian calendar but less accurate than the Gregorian calendar. The year of the world system did not become standard among Jews until well into the Middle Ages. A Christian Scholastic could not come up with exactly the Jewish age of the Earth without getting into big trouble.

Locally variable geology: Bon voyage! Bye-bye to an onion. Steno was fortunate to live in an area of good geological exposure. Like the blind men and the elephant, he generalized to the rest of the Earth. This stay-at-home tendency persisted until the late

1700s. A stay-at-home geologist with a little (but not too much) imagination could fit the Flood into his observations.

The matter came to a climax in Germany. Abraham Werner (1749-1817), a well-paid university professor and mining consultant, concluded that the layered rocks of his area settled out during the Flood. His other work in finding mineral deposits and developing a rational scheme for naming rocks and minerals was excellent. People paid attention. The Flood idea came from the Middle Ages, but he had layers of basalt in his region. This is the black volcanic rock that erupts on Hawaii (Figure 8). Sometimes basalt flows in thin layers far from its volcanic source. It then seems to be just another layer of sediments. Other times, basalt comes in as a molten (intrusive) rock between two layers of sedimentary rock. This feature, called a sill from the Whin Sill near Durham England, also looks like just another layer (Figure 9). (Whin is the local name for a basaltic rock that intrudes at a shallow level. For those with some geology, it is now called dolerite by the British and diabase by the Americans. Geologists really got into giving names before they understood a lot.) Modern geologists require careful observations to tell basalt flows from basalt sills. Werner concluded that basalt is a sedimentary rock that settled to the base of the ocean. He did not recognize subtle volcanic landforms in his homeland.

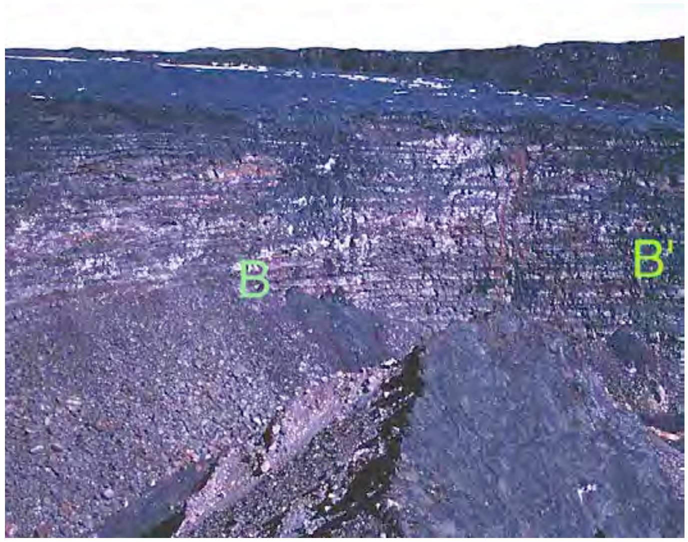


Figure 8: Layers of basalt exposed by the collapse of a lava pit on the top of Mauna Loa volcano, Hawaii. The lava beds formed by thin flows extend between "B" and B'". Werner considered beds of basalt within a sequence of sedimentary beds to be sediments deposited from water. Lava sometimes flows hundreds of kilometers over shallow slopes forming widespread flat-lying beds. Photo by author.

The hypothesis that basalt is a sedimentary rock immediately attracted attention. In the 1700s, a European could observe active lava flows by traveling to Iceland or to Mount Etna in Sicily (Figure 10). Well-preserved volcanic landforms were more accessible. Spectacular volcanoes exist near Puy du Dôme (Figure 11) in south central France. Nicolas Desmarest (1725-1815) made quick work showing that basalt actually comes from volcanoes. Geologists of the time (and historians to the present day) misleadingly concentrated on this quickly testable technical aspect of the controversy. They called Werner and his followers Neptunists after the god of the sea (where Werner thought basalt formed) and their opponents Plutonists after the god of the underworld.

Figure 9: Well-exposed sills are relatively uncommon, hence the remote locality. The basaltic sill (black) intruded granite (pink) about 183 million years ago in Antarctica. The granite at the top of the sill is barely visible on the left. Related intrusions and lava flows occur in South Africa. Australia, and New Zealand, which were nearer together at that time. Photo by Rob Dunbar.

A broader aspect of Werner's and Steno's thinking was that the Earth was like an onion with its initial rocks near the center surrounded by layers of sediment (Figure 12). They knew that this arrangement did not exist in detail, but thought it made a good analogy. This reasoning left time for only the creation of the Earth and the Flood. There were really two well-posed linked issues that do not involve the origin of basalt: young versus old Earth and catastrophic versus gradual geological change.

Figure 10: Active volcanism attracts tourists and geologists to Hawaii. This lava flow is near Kalapana, Hawaii in 1985. The flow extends several hundred meters to the trees in the background. It descends several kilometers from its source on the right to the sea on the left. Now cooled, the flow is a widespread bed several meters thick. It has been covered by more recent flows. The sequence will resemble bedded sediments if erosion or faulting exhumes it. Photo by the author.

Figure 11: Bleak landscapes occur where volcanism renews the surface faster than it can weather and erode. This drawing shows young volcanic landforms near Puy du Dôme, France. Geologists were able to trace lava flows from these obvious volcanic centers in the late 1700s to basalt beds over 100 kilometers away. This established that basalt is not a sedimentary rock. From Scrope's book, 1888.

Hutton and lengthy geological time. In 1788, a Scotsman wanted to check for himself. He saw that erosion was wearing down the craggy landscape. Given enough time, all of Scotland would be reduced to a plain near sealevel. Given further time, it might become even lower and therefore covered with sediments from higher ground. He searched far and wide. He finally found a locality where sedimentary rocks lay vertically. This could only mean that forces within the Earth tilted these rocks from their original horizontal position. The rocks then formed part of a mountain range like parts of the Alps. Erosion then beveled the surface. Flat lying sedimentary rocks covered the up-ended rocks.

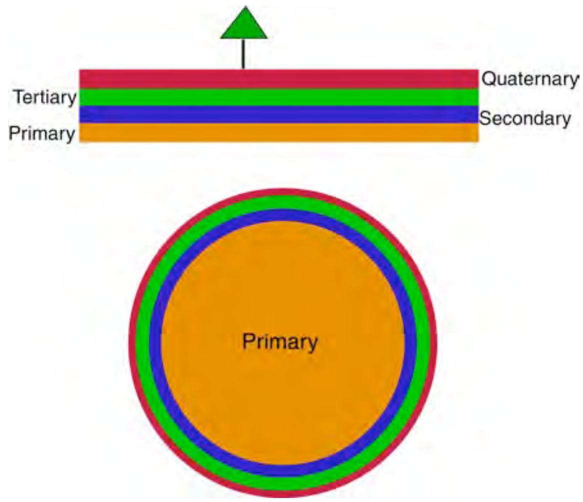


Figure 12: Early geologists viewed the Earth as an onion. Primary rocks in the Earth's interior formed at its start. Secondary rocks formed before the Flood. Tertiary rocks turning the Flood. Quaternary rocks are obviously young deposits. The same sequence of beds should occur everywhere. Proponents of this idea knew that local geology is more complicated, but regarded an onion-like young Earth as a reasonable generalization. Some geologists expected to find onion-like beds dating from the Earth's formation to the present in the deep ocean basins as late as 1970.

James Hutton (1726-1797) recognized the importance of the contact between the vertical older rocks and the younger sediments, now called an unconformity (Figure 13). A mountain range formed over a vast period of time, was eroded to sealevel, and then was slowly covered with sedimentary layers. Further work showed many ages of rock exist. In particular, granite, the purported primary rock at the creation of the Earth, intruded sediments in places and thus is in some cases younger than these supposed secondary rocks. He also found basalt intruding various rock types.

Hutton recognized that all this could not happen in 6,000 years. In fact, he did not find any primary rocks from the origin of the Earth. (No one ever has.) He surmised that the Earth is very (perhaps infinitely) old but could not give geological ages as numbers. Realizing that the geological history varied from place to place, he did not attempt to present a compete history of the Earth.

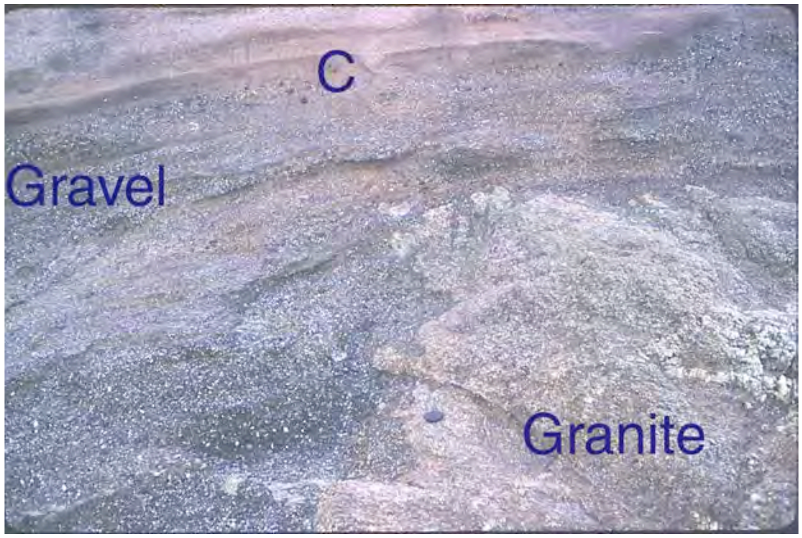


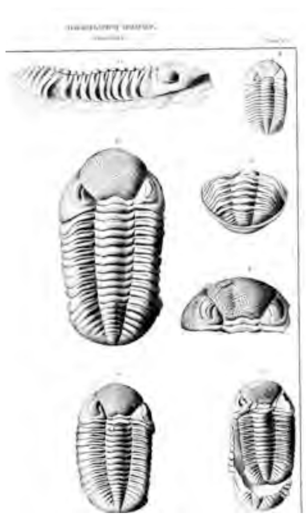
Figure 13: Unconformities indicate periods of exhumation and erosion in the geological record. The are quite common in the field. This unconformity is between granite and gravel at Montara, California. The granite was a hummocky surface at the time of deposition. Note the channel "C" within the gravel. This is a minor unconformity where a channel eroded in the gravel bed before deposition of a sand bend. Geologists use channel cuts to tell which beds are younger in areas of complicated folding. Photo by the author.

He concluded that processes now operating are responsible for the geology that he sees. This avoidance of magic is good in that the present is the key to the past and the past is the key to the present. However, later geologists elevated this principle of gradual present processes, *uniformitarianism*, to the status of a law. This impeded recognition of real catastrophic events (including the impact of asteroids, Chapter 11) in the twentieth century.

Hutton had scotched the influence of magical thinking on geology, but did not immediately kill it. The tendency to interpret the geological record as a series of catastrophes persisted. At first, the Flood was the last of the series. Gradually, it became relegated to a local event in the Middle East and then to myth. Recently geologists recognized that the Black Sea flooded rapidly about 8,400 years ago when a rising sealevel in the Mediterranean overtopped the Bosporus. The flood legends could derive from a folk memory of this regional event.

The onion myth died quickly for the rocks on land that one can actually see. However, it persisted with regard to the deep oceans, which many geologists regarded as basins that had been accumulating deposits since the dawn of the Earth. Geologists justified deep drilling in the oceans in the 1960s with the hope of obtaining a complete geological column. Instead, the drilling showed that ocean basins are far younger than most rocks on the continents. I return to this issue when I discuss plate tectonics in the Chapter 8.

Fossils and time



Steno correctly deduced past environments by carefully examining sedimentary rocks. In his case, a shark-invested sea once covered what is now Malta. He was not bothered by the abundance of fossil teeth. He noted that a single shark bears 600 teeth and grows and sheds many during its lifetime and that the carcasses of many dead sharks might drift onto one shore or that a school of sharks might meet its fate at one time.

Similar marine rocks crop out over much of Europe. It takes little effort to find fossil seashells and to recognize them as such. It was natural to consider shark's teeth and seashells vestiges of the Flood. Increased knowledge of modern life showed this simple idea to be inadequate. So did knowledge of geology. Leonardo da Vinci saw that the fossils and their beds accumulated gradually and that a brief 40-day flood could not sweep fossils upstream from the ocean. He kept his speculations very private, but by 1800 most geologists realized that sedimentary rocks did not form in the Biblical Flood. Practical considerations of the industrial age gave birth to the fossil time scale.

In 1666, Italian fishermen were certainly familiar with their usual catch. They knew that a large shark was notable enough to send to their duke. They had little idea what lay beneath their deepest nets and hooks or beyond the horizon. By 1800, any well-stocked European museum bulged with specimens from near and far. It was obvious that fossils from the youngest rocks resembled modern life and that fossils became progressively less familiar as one sampled older rocks. Most of the ancient organisms no longer existed on the Earth. That is, they were extinct.

Erasmus Darwin (1731-1802), the grandfather of Charles, and the French scientist Jean-Baptiste Lamarck (1744-1829) commented on this evolution of life forms. They contended that modern organisms descend from the ancient ones that are preserved in the fossil record. In contrast to this descent with modification, catastrophists maintained that God created batches of life and then exterminated them. This helped prepare the Earth for the Advent of Man. I will get back to evolution after I deal with a pressing need for coal.

Geological maps. The industrial revolution was in full sway in 1793 England.

Industrialists needed coal to free them from waterpower. The road system was often a quagmire, inadequate for large loads. Industrialists were digging canals everywhere. A canal engineer noted that he must cut through various rock types. They were typically nearly flat-lying sedimentary beds. He was an avid collector of the fossils that got dug up. (The word "fossil" originally meant something dug up. "Fosse" means trench in French.)

William Smith (1769-1839) recognized that the sedimentary beds in southern England always occur in the same order. The same fossils come with each bed. In 1815, Smith compiled his work into the first geological map of England. George Greenough (1778-1855) plagiarized Smith's map with a few minor changes. Greenough was rich and headed the Geological Society of London. He undercut the price of Smith's map. Smith was of lowly birth. He went broke and ended up in prison for debt. Eventually, other geologists recognized Smith's contributions. He was freed and ultimately awarded a pension. Both their maps hang in the Geological Society building.

This story is a typical example where selfish and pigheaded behavior by an elite individual crushed an individual innovative scientist. There, however, was little long-term damage to science itself, as Greenough had no secular power to suppress Smith's ideas in what was basically a free country. Smith's the valid scientific concepts survived with only modest delay in their acceptance. After Smith's map, geology had a democratizing influence on science in the British Isles. It took little equipment and to not a lot of training become a nineteenth century field geologist or paleontologist. Both the rich and those with some modest means flocked to rock outcrops.

Figure 14: Geological maps are an essential part of fieldwork. This 1822 map of England appeared Conybeare and Phillips book. It resembles modern maps in that each age of beds has its own color. Geologists interpolate between areas of good exposure on land to construct the map. The traditional convention is that they do not color the map when extrapolating across water, here the English Channel. Subsequent work has produced more detailed and accurate geological maps of England.

Geological maps based on fossils were helpful to canal construction since one can foretell which rock types need to be trenched (Figure 14). They were revolutionary for finding coal. In England, economical coal beds are about 350 million years old. Smith did not know this number, but one can tell whether a particular bed was above or below the "Coal Measures." (The name comes from the fact that the value of a coal bed is proportional to its thickness, which is immediately measured.) A skillful geologist needed only to know the typical local thickness of beds and to identify the surface bed from its fossils to tell whether it was economical to dig for coal. If the surface rocks are older than the Coal Measures, digging is fruitless. The local Coal Measures overlaid the present surface. They have been removed by erosion (Figure 15). If the surface rocks are much younger that the Coal Measures, there may be coal beneath your feet, but far below.

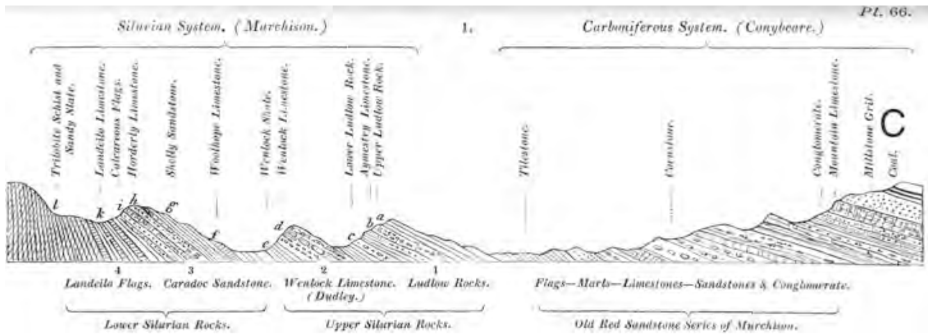


Figure 15: The industrial revolution in the 1800s depended on coal. This cross section through coal mining area in England from Buckland's 1836 edition demarcates fruitful areas to search for coal. All the erosed rocks to the left of "C" (my annotation) are older that the coal. Erosion has removed the coal-bearing beds. Digging for coal would be futile. Digging would be uneconomic if the surface beds were far younger than the coal beds that are hence deep underground.

Smith did not know the reason for this. Coal forms from the remains of land plants in swamps. There were no land plants before about 400 million years ago and hence no coal. Younger coal deposits occur elsewhere in the world, but not in England.

Global fossil time scale. Practical industrialists and creationists/catastrophists developed the geological time scale based on fossils. As it turned out, the sequence of sedimentary beds over the last 600 million years is reasonably complete in Britain. There are no "gaps" between well-preserved rocks longer 50 million years for deposits over 100 million years old. There is no 10 million year gap younger than 100 million years.

The British geologists did not stay at home. They quickly showed that the time scale worked on the continent and in North America. The industrial age was booming in the

United States. The geological time scale ended random digging for coal in North America.

By 1850, it was evident that the geological time scale worked worldwide. One could estimate the age of any rock with descent fossils. It was imperfect, as the same fossilized organisms are not found in beds of the same age worldwide. For example, no one would expect to find the same creatures living on a tropical corral reef, in a mountain valley, at the bottom of the deep sea, in a freshwater lake, and in a shallow arctic sea. Geologists built up a coherent global time scale by taking advantage of places where marine and land deposits are interbedded, like an ancient river delta. They also took advantage of the fact the some species are widespread. Failing this, broader groups of fossils tended to be more widespread than species. For example, an arctic and a tropical assemblage might share similar though not identical fossils. The 1850 time scale was basically the pre-2000 one given here. I list only the major divisions.

Quaternary: Obviously young deposits, retained from Steno.

Tertiary: Young deposits with familiar looking fossils, retained from Steno.

Cretaceous: Meaning chalk, after the white cliffs of Dover and similar deposits in France and Britain.

Jurassic: After exposures in the Jura, part of the Alps between France and Switzerland.

Triassic: Three parts. Three beds in England were grouped into this period.

Permian: After exposures in Perm in the interior of Russia.

Carboniferous: The Coal Measures.

Devonian: After Devonshire in England. This is the oldest occurrence of land plants.

Silurian: After localities in Wales.

Ordovician: This period occurs in the modern time scale, but was not in use in 1850. The British geologists, Adam Sedgwick (1785-1873) and Roderick Murchison (1792-1871), could not agree on how to divide this part of the time scale. The pointless feud continued until after their deaths. Charles Lapworth (1842-1920) recognized that time is continuous and that the divisions of the time scale are for our convenience not our enslavement. He added this period as a compromise in 1879. It is based on localities in Wales. It did not become the global standard until 1960.

Cambrian: After localities in Wales. This is the first occurrence of macroscopic hard-shelled marine animals.

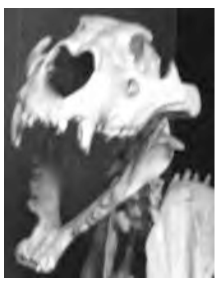
Precambrian: Anything older than Cambrian where there are no obvious large fossils.

The geologists recognized that Tertiary and Quaternary fossils resembled modern life. They grouped these periods into the Cenozoic or Cainozoic Era (Ceno = recent; zoic = animals.) They now divide the era into older Paleogene and younger Neogene periods that have approximately equal length, but the older terms are still in wide use. The Cretaceous, Jurassic, and Triassic rocks have an intermediate resemblance to modern life. They grouped these periods into Mesozoic Era (Meso = middle). They grouped the Permian through Cambrian Periods into the Paleozoic Era (Paleo = ancient). They further grouped the time with decent fossils (Cambrian and later) into the Phanerozoic Era (Phanero = obvious). This avoids having to say post-Precambrian. Modern geologists tweak the time scale as more is learned. They have greatly subdivided it. Fossils are still the best way to date most sedimentary rocks.

Three features of fossils preserved in the geological record were evident in 1850. Starting from the bottom up.

(1) The appearance of large fossils in the Cambrian was sudden. A high diversity of fossils occurred just above of beds devoid in large fossils. (Chapter 14)

(2) Mass extinctions of fossil organisms occurred. The most profound were at the ends of the Paleozoic and Mesozoic eras. The diversity of life increased toward its former levels after the extinctions. (Chapter 11)



(3) Bones of many large mammals exist in recent beds. These organisms are now extinct. The saber-toothed tiger in North America is a familiar example.

In 1850, geologists could still interpret these events in terms of gradual change or catastrophes. In fact, several architects of the time scale were catastrophists. These included the Frenchman Georges Cuvier (1769-1832), Sedgwick, and Murchinson. However, the later catastrophists were gradualists on many issues. William Buckland, for example, in his 1837 text recognized the great antiquity of the Earth. He argued quoting Galileo that the Bible should not be taken literally and that scientific knowledge is provisional. He provided strong arguments, basically those of da Vinci, against the

Flood. (da Vinci's work was rediscovered in the late 1800s after Buckland published.) Later Buckland showed that "drift" is a glacial deposit from the Ice Age, undermining the last rational pillar for the Flood. He relegated (but at great length) divine "design" to preparing the Earth for mankind and organisms for their ways of life.

Absolute Geological Time

The issue of the importance of natural catastrophes (as opposed to magical ones) has not been fully resolved. I get back to this later with asteroid impacts in Chapter 11. To make progress after 1850, geologists needed to assign numbers in years to their relative age scale.

The rate of sediment accumulation: The dust on antique time would lie unswept. (William Shakespeare (1564–1616), *The Oxford Shakespeare*, 1914. *Coriolanus*, Act II. Scene III.) Everyone knows that dust accumulates on surfaces. One might expect that there would be 4 times as much dust on a surface that was cleaned a month ago than one that was cleaned last week. The simple but key assumption is that the rate of dust accumulation is constant.

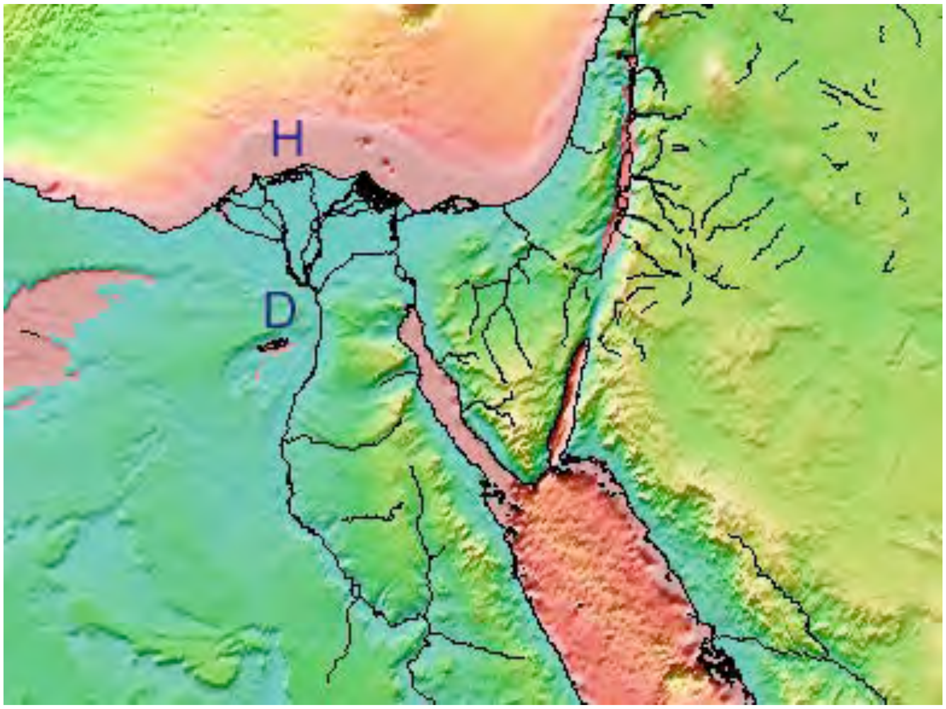


Figure 16: Topography and bathymetry map shows the Nile Delta. The Nile flows north and splits into several channels near "D". The river carries sediments into the sea. Over time 10-kilometer-thick deposits have accumulated where the river enters the sea. The coastline was more or less straight before deposition began, but now bows out toward "H." Herodotus did not know how deep the sea was but correctly deduced that river sediments cover the DELTA-shaped region between the channels.

Geological application of this method dates from antiquity. In about 460 B.C., a young Greek was determined to see the world. The prosperity of Athens and a period of relative peace made this possible. He arrived at the Nile coast. There were already ancient statues partly buried by river sediments. With local help, he read the inscriptions. The monuments were then over a thousand years old. Seeing that this ship was pushed by the river current in the channel, but not pushed when it was out to sea, Herodotus realized that sediments carried by the river drop to the bottom when the water enters the ocean. They then accumulate. The delta (his term from its shape like the Greek letter) built seaward as successive batches of sediment dropped at the end of the channel. (Figure 16) He correctly surmised that the surface of the delta that he could see had taken thousands of years to form.

In retrospect, Herodotus did quite well in dating the time since sealevel stabilized at the end of the ice age, 3,500 years before his time. He had no way of estimating the total thickness of sediments in the delta. He did not even know the depth of the deep Mediterranean filled by the delta. There are over 10 kilometers of sediment at the place where Herodotus stood. Their accumulation rate measured reasonably by Herodotus is around a meter per thousand years. So it took somewhere around 10 million years for the sediments to build up.

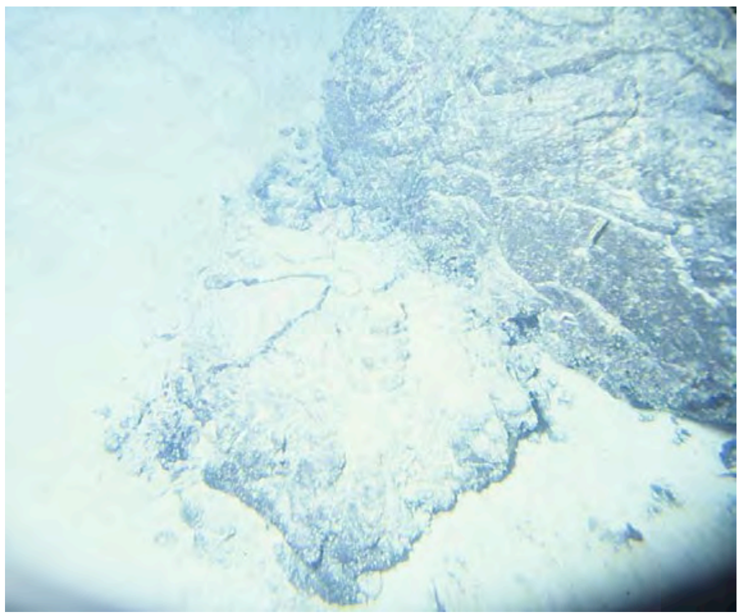


Figure 17: Sediments cover most of the seafloor. Here white sediment dusts dark basaltic outcrops on the seafloor. Sediment covers the low-lying areas, but currents keep dust from accumulating on the exposed basalt. The sedimentary particles are sand-sized fossils from one-celled planktonic (drifting) organisms called foraminifera. They make nice microfossils for dating rocks. Photo by the author.

It was easy for nineteenth century geologists to measure the thicknesses of exposed sedimentary beds and add them up. This method gave similar results to the one discussed above. It left a lot to be desired. It is obvious that erosion rather than deposition occurs in many localities. Vast intervals of time could be missing in a geological section. The sedimentation rate obviously differed from place to place. It was also evident to many that several intervals of deposition, mountain building, erosion followed by more deposition occurred.

Old as the hills: a good do it yourself project involves using the sediments behind a dam to estimate the rate of erosion. In turn, this lets you estimate the age that the landscape from the total amount of erosion. [see Do it Yourself Box with a Dam]

Rate of earth movements. In 1835, a young naturalist arrived on the west coast of South America. His father had reluctantly paid his way. The father did not want his son to become an idle country gentleman. The British expedition was supposed to survey the coast and study the region on the shore. There was an immediate problem. A large earthquake had heavily damaged the port of Concepción.

Charles Darwin (1809-1882) had felt the shaking far away a few days before. He got right to work. The earthquake had uplifted the seacoast exposing lots of shells for collection if one could stand the stench. Later, Darwin traveled over the Andes Mountains. He correctly surmised that the many earthquakes over a period of millions of years gradually uplifted the range. One of Darwin's other interests brought the number of years in geological time to the limelight.

Enough time for evolution? In 1859, Darwin published *Origin of Species*. He explained the evolution of fossil and modern life forms by descent with modification. This was not new. (The idea of the transformation of species was notorious by 1837. Buckland devoted much text to its refutation.) But Darwin demonstrated a viable mechanism, natural selection. Organisms with more fit inheritable characteristics tend (by definition) to be more successful in breeding. The beneficial modifications build up in the population over time and harmful ones die out. The process is similar to artificial breeding of domestic animals and plants. Over the vast length of geological time, all life descends from one (the modern answer) or at most a few common ancestors.

I get back to evolution in Chapter 9. In the 1860s, time was of the essence. Darwin had excellent observations of how fast animals could be modified by artificial selection. He had some idea on how little wild animals and plants have changed since antiquity. He offered a guess on how long evolution in the Phanerozic era (when there are decent fossils) had taken, several hundred million years.

Although Darwin was careful not to directly mention the evolution of humans from animals until a later book, the implication was obvious to all. At one end, animal breeders did not need to be convinced that traits are heritable. The British gentry were sure of their superior bloodlines. Social Darwinists muddied the water by considering the plight of the poor to be a beneficial form of natural selection. At the other, national selection was not for the squeamish. The gentry did not like having their ape ancestors pointed out anymore than they would ancestors hanged for horse theft. Churchmen did not like humans evolving by a natural process. Unlike the case of Galileo, the Hebrew Bible is explicit on the issue. The creation stories involve God and man, not monkeys and apes. However, Darwin and his supporters were never in physical danger. Neither did they have their activities restricted in any way. The debate proceeded, often civilly. Much of it stayed on scientific issues, not religion.

Part of the debate focused whether there has been enough time for evolution. Natural selection is slow, all agreed. Perhaps inheritance of acquired characteristics worked a lot faster. This “Lamarckian” form of evolution now seems silly to us, especially when presented as a caricature. Like one could breed tailless cats by cutting off the tail in each generation. Little was known about heredity in 1859. Darwin did not reject Lamarckian evolution altogether. It would have been premature for him to do it. Lamarckian inheritance is a testable scientific hypothesis that does not pan out; it is not an appeal to magic.

Of course, the often-explicit fallback was that if natural selection does not work, neither did evolution. This let in various forms of somewhat old-Earth divine intervention.

Heat flow from the Earth’s interior. It takes much longer to roast a thick turkey in an oven than it does to cook thin fish sticks. Late nineteenth century geologists viewed the Earth much like the cooling of a turkey after it left the oven. The principle of conservation of energy was a recent major accomplishment. Beginning with Jacques Fourier (1768-1830), it became possible to mathematically compute the variation of temperature within a body cooling by conduction. (For those who know French, Fourier’s name relates to his family’s involvement in the fur trade not the oven business.) Basically, the time for a body to cool depends on the square of its thickness. As in the case of the cooling turkey, the thickness of the outer cool region of the Earth increases with the square root of time.

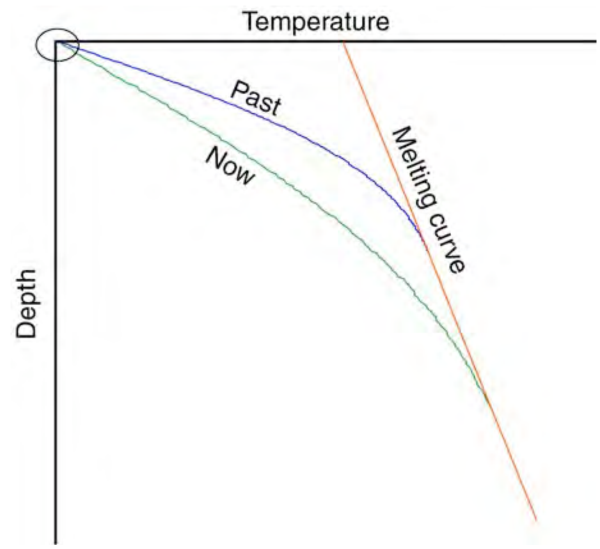


Figure 18: Lord Kelvin modeled cooling of the Earth after it formed. The Earth cooled quickly until it froze at the melting curve. It cooled after that by conduction. The geotherm at a past time is hotter than the modern one. Kelvin could only measure the geotherm at a shallow depth (ellipse). Kelvin's cooling depth is shallow enough, about 100 kilometers, that a flat model and drawing work OK. Kelvin used spherical geometry, which gives a more precise result, but the basic assumption of conduction is incorrect.

William Thomson (1824-1907), later Lord Kelvin, computed sophisticated models of the Earth cooling from its initially hot state ending around 1900. Unlike a turkey, spherical symmetry provided some simplification. His other assumptions were simple and logical. The Earth formed by the collapse or accretion of rocky material. He easily showed correctly that the gravitational energy of this material was more than enough to melt it. The molten Earth convected like soup on a stove until it froze to a solid. Afterwards, it cooled slowly by conduction.

Kelvin could guess the initial conditions after the Earth first froze (Figure 18). Scientists knew the melting temperature of rocks to some extent. They also knew from tides that the inside of the Earth is mostly solid. (Modern seismology confirms that the outer 2900 km of the Earth is solid rock.) Volcanoes are local features that tap small amounts of partial melt.

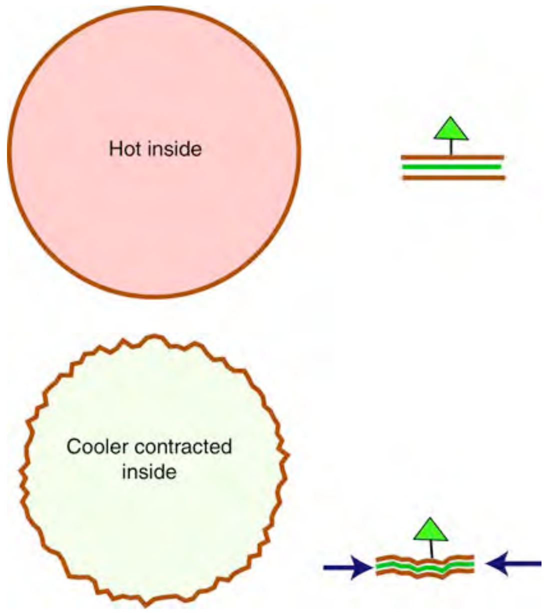


Figure 19: A dried up apple provides a model for mountain building. Soon after its formation, the outside of the Earth is a cool rigid spherical shell (red). The inside is still hot. Over time the inside cools and contracts. This wrinkles the surface producing folds. The net contraction of the Earth's circumference is several tens of kilometers. It was not evident in the 1800s that this amount is insufficient to produce the observed mountains. The process does deform the surfaces of Mars and the Moon so it is just the wrong hypothesis for our planet.

He had reasonable constraints on the present thermal state of the Earth. The invention of reliable explosives allowed miners to dig deeply. Deep mines are hot and become hotter as one goes down. The need to keep the miners cool is one limit on the practical depth of mines. (Note that shallow caves and mines equilibrate to about the mean annual temperature. They feel cool if you go in on a hot day.) Kelvin extrapolated the thermal gradient in mines downward to great depths. The thermal gradient could not continue down forever. Otherwise, the temperature would exceed the melting point of rocks. Kelvin used the intersection of the extrapolated temperature with the melting points of rocks to get the thickness of the cool rind that had formed since the Earth became solid. He got less than 100 kilometers. (This is a modest underestimate for England.) It takes tens of million years for the Earth to cool to this depth. To boot, Kelvin calculated the time for the Sun to cool. He got a similar number. This was far less than Darwin wanted. It seemed that natural selection was in deep trouble from basic physics.

Kelvin's hypothesis provided a testable prediction (Figure 19). The outermost rind of the Earth cooled quickly to the surface temperature, like the skin of a roast turkey on the platter. Later the shell inside of the surface cooled. Rocks contract when they cool. (Bridges and roads have expansion joints so that daily heating and cooling does not produce cracks.) Contraction of the inside of the Earth caused the weak outside layer to crumple, much like the wrinkles in a dried apple. This provided an attractive mechanism for mountain building. Too little was known at the time to apply this test. This mechanism is not applicable to the Earth where there are plate tectonics. See Chapter 8. It is applicable to the Moon and much of the history of Mars.

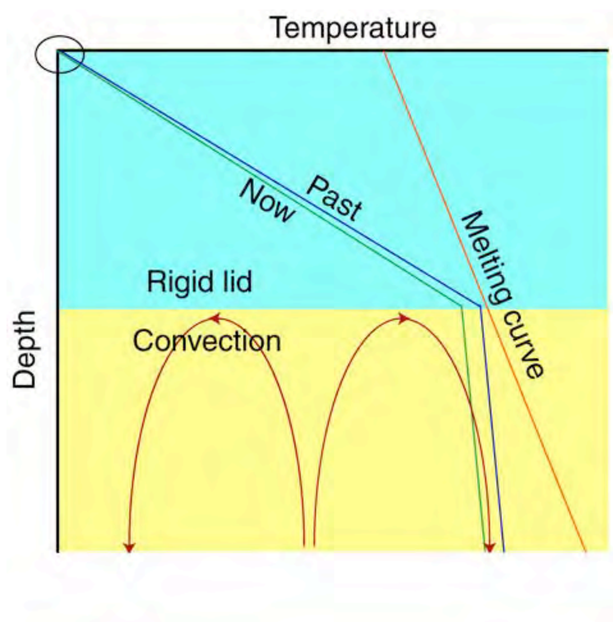


Figure 20: Osmond Fisher modeled the cooling of the Earth by convection. The Earth consists of a thin rigid shell and an underlying convecting region. The entire deep interior of the Earth cools as a well-mixed fluid. It contains a lot more heat than does the shallow shell. The past geotherm is not much different from the present one. One cannot get the age of the Earth from the geotherm because the thickness of the lid may change with time in addition to the interior temperature. The entire Earth is cooler than the melting curve. Most geophysics did not think that solid rock could flow as a fluid until the late 1960s.

Kelvin's reasoning came under scientific attack from Osmond Fisher (1817-1914) and later from John Perry (1850-1920) (Figure 20). Both scientists concentrated on Kelvin's assumption that the Earth behaves as a conducting solid. If the inside of the Earth convected (like in Kelvin's models of the inside of the Sun), the thickness of the outer cool rind had no simple relationship to the Earth age. In Kelvin's model, heat could come only from the thin rind as the deep interior of the Earth stayed at its original temperature. In Fischer's and Perry's, it came from the entire interior of the Earth. They deduced correctly that is plenty of heat to maintain the surface heat flow for a few billion years.

The idea of a solid that could convect slowly like a fluid was too strange in the late eighteen hundreds. It received some support from physicists, but it seemed absurd to most geophysicists until geologists amassed overwhelming evidence of plate tectonics in the 1960s. In the meantime, science discovered radioactivity. Convection in the Earth's interior seemed unnecessary. Perry, who began troubled by Kelvin's inconsistency of adhering to physics to obtain the age of the Earth while imposing the supernatural on biology, no longer had reason to press this worldview issue; he did not. Fisher's works are quite difficult to read and obscure the point made simply by Perry. They got little further attention; Fisher died a forgotten man.

Radioactivity: A gentlemen's wager. In the late 1800s, physics seemed to be close to becoming a solved field. James Clerk Maxwell (1831-1879) unified the previously mysterious effects of magnetism and electricity with 4 simple equations. He showed that light is a form of electromagnetic radiation. His equations became the basis of radio communication through another form of electromagnetic radiation. Gravity and mechanics seemed well in hand. Thermodynamics provided the platform for understanding chemistry and heat flow.

Problems remained but seemed obscure, like astronomers not being able to predict the orbit of Mercury. All this changed when Henri Becquerel decided to investigate phosphorescence. You have probably seen glow-in-the-dark plastic. To glow, it needs to be exposed to light. The material absorbs energy from the light and later readmits it as light. Eventually, the glow material runs down. This process involves transformation of light energy into chemical energy in the material and then back to light energy. It is interesting and in full accord with conservation of energy.

Becquerel studied a uranium salt using photographic film to detect its feeble amounts of phosphorescence. One day it was dark and cloudy. He could not expose his samples to sunlight so he tried to detect light from samples that had been in the dark as a control. Scientists frequently run controls, like sugar pills in medical trials. The uranium samples exposed the film. This should not have happened as it violates conservation of energy.

Scientists crave situations were a key concept appears to fail. Becquerel and Marie and Pierre Curie went right to work to repeat the experiment to confirm the result and to see what was happening. Natural uranium minerals emit three classes of rays. The first type, called alpha, is easily stopped by paper. It is deflected by magnetic fields and hence electrically charged. Further work, showed that alpha particles have two positively charged particles, called protons, and two neutrally charged particles called neutrons. They are the same as the nucleus of a helium atom. The second class of particles, called beta, turned out to be electrons. The third class, called gamma rays, is high-energy electromagnetic radiation. A uranium atom decays to a lead atom over a series of steps and produces several helium atoms in the process. The decay produces lots of energy. The element radium discovered by the Curies glows in the dark. It was used to make luminous watch dials, which are now banned as dangerous. You may be able to find one if you or a relative is over 60 and a packrat.

It was painstaking but straightforward to determine the rate at which uranium atoms decay to lead and produce helium. The most common form of uranium has an atomic mass number of 238 (that is, it is about a factor of 238 heavier than a proton). It contains 92 protons and 146 neutrons. It decays in a series of steps into lead-206 (82 protons and 124 neutrons) and 8 helium atoms (each with 2 neutrons and 2 protons). The uranium-238 decays with a half-life of 4.51 billion years. That is, if we had a sample of uranium-238, half the uranium would turn to lead in that time. In another 4.51 billion years, 3/4 of the uranium would have turned to lead.

Uranium decay provided an immediate method of dating rocks. Uranium minerals that initially had very little lead or helium are most easily studied. One gets an age merely by measuring the amount of helium or lead and the amount of uranium in a crystal and making a simple calculation on the number (actually a fraction less than 1 for Earth samples) of half-lives that had occurred. This method worked in the early 1900s on Precambrian rocks.

In 1904, a young scientist presented his results on the dating of some rocks with helium produced by uranium decay at the Royal Institution in England. He had samples over a billion years old. Ernest Rutherford (1871-1937) realized that Lord Kelvin was in the audience and was wide-awake at the key point of his talk. His ages were far older than the acceptable range given by Kelvin's calculations on the cooling of the Earth. Rutherford was prepared for this and stated that Kelvin's calculations assumed that there was no unknown heat source in the Earth. Radioactivity is that that heat source and Kelvin's calculations, though mathematically correct, are inapplicable to the Earth.

Later the scientists retired for dinner at an estate. Kelvin was intrigued with radioactivity but did not yet know much about it. It was not clear to him that there is enough radioactivity in the Earth to matter. He was still skeptical that radioactivity really exists. He made a bet of several pounds with Robert John Strutt (later the 4th Lord Rayleigh) on whether radioactivity exists and heats the interior of the Earth. Kelvin paid off within a year.

Modern geochronology. Today, scientists no longer need uranium minerals to study uranium decay. They have precise equipment that can measure minute amounts of uranium and lead. The mineral zircon (zirconium silicate) is particularly useful (Figure 21). So is natural cubic zirconia, zirconium oxide. Uranium atoms substitute for zirconium atoms in minor amounts. Very little lead enters the crystal when it forms. Once formed zircon crystals retain their uranium and the lead produced by its decay. They even sometimes survive partial melting of a rock in the Earth's crust. The oldest dated samples on the Earth are 4.4 billion-year-old zircon grains within beds that were originally (over 3 billion years ago) sedimentary sandstones.

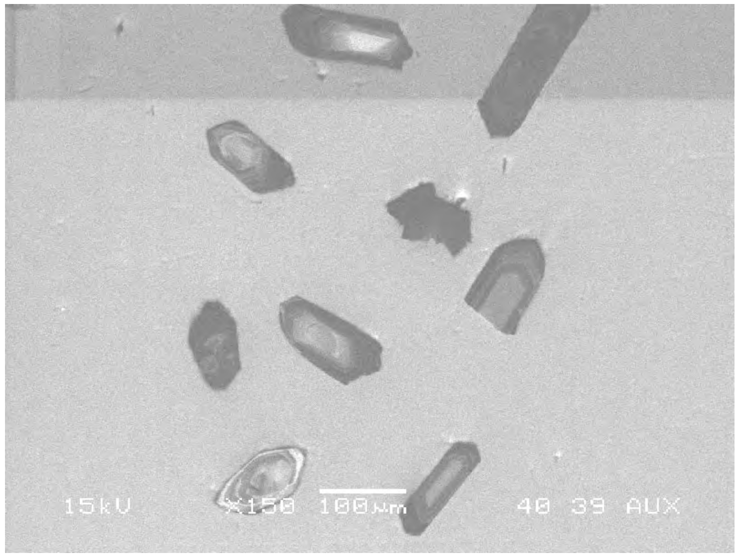


Figure 21: Geochronologists date rocks using trace amounts of uranium and lead in zircon crystals. The crystals grew like tree rings (called zoning). This makes it possible to date several events in the history of the rock. Image by Chris Mattinson.

Geochronologists routinely use several radioactive parent-stable daughter pairs to date rocks. Radioactive dating works well to determine when igneous rocks froze. It can be used to tell when rocks cooled beneath a given temperature. It works poorly with sand in that each grain retains the properties of its source rock, like with the 4.4-billion-year-old zircons. Geologists use contact relationships, like interbedded volcanic rocks, to link the fossil time scale with the radioactive one. This is still being done, but the ages of the ends of geological periods are known to at worst a few percent.

As Darwin suspected, geological time is vast. Humans, depending on how one defines that term, have been around for a few million years. Modern man evolved about 100,000 years ago. The end of the Cretaceous period occurred 66 million years ago. The Cambrian period began 543 million years ago. The oldest preserved sediments on the Earth are around 3.9 billion years old. The Earth itself is about 4.5 billion years old. The oldest meteorites and the solar system are about 4.567 billion years old.

Recent geological activity on the Earth. Vestiges of Steno's and Werner's thinking persisted even after the advent of radioactive dating. You can guess the age of a car by how beat up it looks. On average, a banged up car is older than a shiny one. However, a new car can get lots of dents if one drives it off road. With respect to geology, it is obvious that fresh looking sediments on the beach are young. However, the Earth is quite geologically active. Sedimentary rocks get buried to great depths, heated to high temperatures, and then sometimes get exhumed to the surface. The deformation and heating of sedimentary rocks, called *metamorphism*, tends to destroy sedimentary structures and fossils originally in the rock.

Geologists believed that all highly metamorphosed rocks were quite old. Even in the 1960s, the official policy of the United States Geological Survey was that all highly metamorphosed rocks were Precambrian unless conclusively demonstrated otherwise. This resulted in absurdities. For example, a bed with Devonian fossils in Maine was mapped Devonian at the fossil locality but Precambrian elsewhere. The official philosophy was that radioactive dating was to help mapping in areas of poor exposure. This assured that field relations could not be used to extrapolate the results. Eventually, dating became routine, the idea that the intensity of metamorphism was a reliable indictor of age died out.

Cosmic time

Bruno angered the Church both by pointing out the insignificance of the Earth and even the solar system as well as stating that time is infinite and that we live at no special time. He had little evidence on how old the universe is and no one did until the 1920s. Yet some problems with an infinite universe were evident in the 1600s.

Why is it dark at night? The dark night sky was a serious problem. If there were infinite numbers of (statistically) equally spaced stars, the sky would appear as bright as the surface of the Sun. This can be seen into two ways. First, a line of sight drawn in any direction eventually hits the surface of a star. The second more mathematical one involves imaginary spherical shells (of say 1 light year thickness) at distances R from the Earth. Each shell contains a number of stars proportional to R squared. The brightness of each star is proportional the inverse of R squared (Figure 22). Thus the total light from each shell is proportional to R squared stars divided by the inverse square of distance or a constant. We can add up a very large number of shells to get a bright sky.

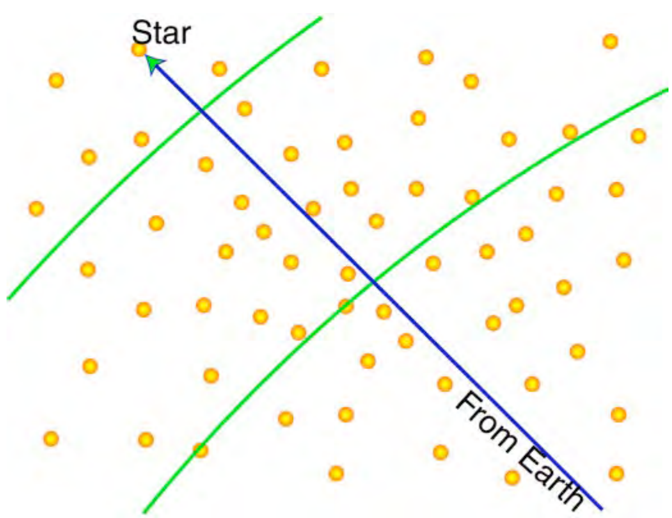


Figure 22: The sky should be bright at night if there are an infinite number of stationary stars (here shown close together to get a workable drawing). Then a line of sight from the Earth will eventually intersect the surface of a star. Alternatively, the light coming from the shell-shaped region between the green circles is independent of its distance (radius) from the Earth because the number of stars in the region increases with the radius squared while the light from each star decreases with the radius squared.

Halley faced this problem. He realized that a finite universe would gravitationally collapse towards its center. He preferred an infinite universe where no center exists. Halley contended that light from the more distant stars gets absorbed by passing through space. Light does get absorbed when passing through ordinary materials, including air. This concept looked good at the time, but the absorbed light would heat up space and reradiate the energy. Astronomers observe only feeble light sources from reradiated light. The existence of galaxies provides no solution. Stars are irregularly clumped into galaxies, but the problem remains if galaxies themselves are infinite in number.

The Big Bang. The answer came from scientists' penchant for measuring, here mundane studies to resolve the motions of stars and galaxies. Stars preferentially emit light radiation at given wavelengths where the energy matches that to change an atom (or molecule) from one energy state to another (see discussion of spectra in next chapter). I used this quantum mechanical result to discuss chemistry in the last chapter. Conversely cool gases surrounding a star absorb specific wavelengths. A prism produces a spectrum where these bright emission bands and dark absorption bands are evident. The wavelength (position of a band in the spectrum) is known from laboratory measurements. It depends on the physics of the energy states.

The wavelength of light from a star moving away from us is longer (redder) than it would be if the star were stationary with respect to us. Conversely, the light has shorter (bluer) wavelength if the star is approaching us. This Doppler effect is the basis for radar in speed traps. A simple calculation gives the velocity of the car or the star. A similar effect occurs with sound. An approaching train is higher pitched than a receding one.

In the 1920s, telescopes were good enough to resolve stars in nearby galaxies, showing that they (as standard candles in Chapter 2) were vastly farther away than the stars in our own Milky Way galaxy. Astronomers inferred the distance of other galaxies using a variety of standard candles and took spectra. Nearby galaxies do not show any systematic motion, but all distant galaxies flee away from the Earth, the farther the faster. It was tempting to place the Earth stationary at the center of this motion. However, astronomers saw nothing special about our Sun or even our galaxy. Their solution would have pleased Bruno. All space is expanding on the scale of moderately distant galaxies. An observer on a distant galaxy would see everything fleeing her. A two-dimensional analogy is the surface of a rubber sheet. Spots on the sheet move away from each other as the sheet expands (Fig 23).

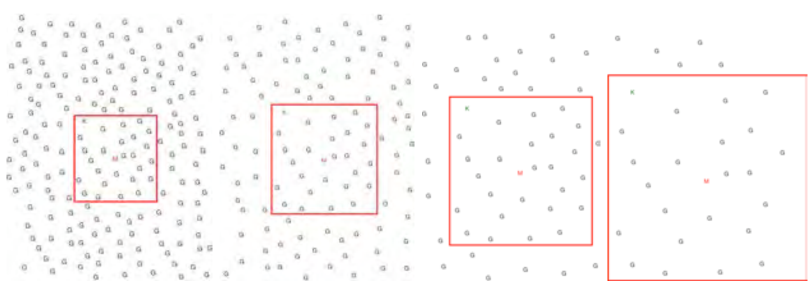


Figure 23: The expanding universe is shown at 4 times in 2-D. Red open square indicates region around the Milky Way "M" and another galaxy "K" in upper left of box. An observer on any galaxy "G" sees other galaxies moving away, the farther the faster. The galaxies themselves (indicated by the constant letter size) and the solar system are gravitationally bound and do not expand. One obtains the age of the Big Bang by working back to where everything was at a point.

It was a simple matter to take the velocities and the distances (distance equal rate times time) and to see when the universe began to inflate from a point. The early results were only a few billion years; that is less than the age of the Earth. This did not please anyone, particularly geologists who held older rocks in their hands. The velocities were good because only the Doppler effect is involved. It turned out that the distances were systematically underestimated, as standard candles were not well calibrated. The current result is 13.7 billion years. Expansion quenched the worry from Halley's time about the universe immediately collapsing under its own gravitation.

This Big Bang hypothesis yielded a testable prediction that resolved the dark sky problem. Matter was closely packed early in the Big Bang with temperatures and energies (after a slight amount of time) crudely like those in an atomic accelerator or a nuclear explosion. Physicists are familiar with these conditions. Early on, space was optically thick. It was filled with high-energy light, which was absorbed as soon as it was emitted. About 300,000 years after the big bang, space became transparent. Almost all of the light that existed at that time has continued on unimpeded.

A minute fraction of this light is now arriving at the Earth. Its sources are the age of the universe minus 300,000 light years away. They are fleeing us at almost the speed of light. The light is red-shifted by the Doppler effect into feeble radio waves. The sky is bright at night but its temperature is only 3 degrees above absolute zero. Astronomers study subtle variations in this background to infer the existence of heterogeneities that led to the formation of galaxies and clusters of galaxies.

The universe became transparent to neutrinos (small uncharged nearly massless particles) earlier. These particles would give information on its state about 200,000 years after its formation if we could reliably detect them.

Bottom line: Old Earth and Young Universe

The Big Bang and astrophysics in general are still poorly enough understood that philosophy enters discussions. For example, undetectable dark matter seems to keep galaxies gravitationally bound. Unseen forces accelerate distant galaxies when it seems that gravity should slow the rate of expansion down. This would have pleased René Descartes who filled the universe with vortices of unseen matter. The age of the universe in some sense gives an absolute time, yet from general relativity this time plays no part in the physics.

The Big Bang has an aura of creation, which delights some traditionally religious individuals. The hypothesis disquiets some others. The comparable lengths of geological and cosmic time are part of the queasiness. Our insignificant planet has been around for a third of eternity. The lack of time for life to form and evolve intelligence becomes more striking when we consider astrophysics in the next chapter. Our Sun has already used up half of its useful life.

The Big Bang, like any major hypothesis in science, undergoes continual scrutiny, often by those who find it philosophically troubling. Astrophysicists including Fred Hoyle (1915-2001) of England made serious attempts to formulate a steady state, infinitely old universe where the observed expansion does not involve inflation from a small volume. To date, none have proved viable.

Science welcomes attempts to explain the appearance of the universe from "nothing" in the Big Bang. Physicists attempt to look back beyond the start of the Big Bang. Have other universes formed so that things are really infinitely old? Why does our universe have its physics? These efforts have yet to yield anything that is observable and testable. They certainly have not yielded anything with respect to planetary habitability beyond that the universe needs to be habitable to be observable.

Notes

Unlike astronomy, ancient paleontology had a negligible influence on Renaissance thought. The ancients collected fossils especially the bones of large animals. They typically viewed them as the remains of heroes, dragons, and giants. Nineteenth century archeologists treated these bones with distain when they found them in temples. Paleontologists did not rediscover that certain mythical creatures (like Griffins and Cyclops) were based on actual common fossils until late in the twentieth century. Herodotus did conclude that fossils are the remains of long dead organisms.

It is easy to come up with issues in modern cosmology that might trigger philosophical qualms. Here is an example. The Big Bang provides an absolute time in some sense. In addition, the background radiation provides an absolute coordinate system where there is no net Doppler effect. However in general relativity, this time and this coordinate system have no special roles.

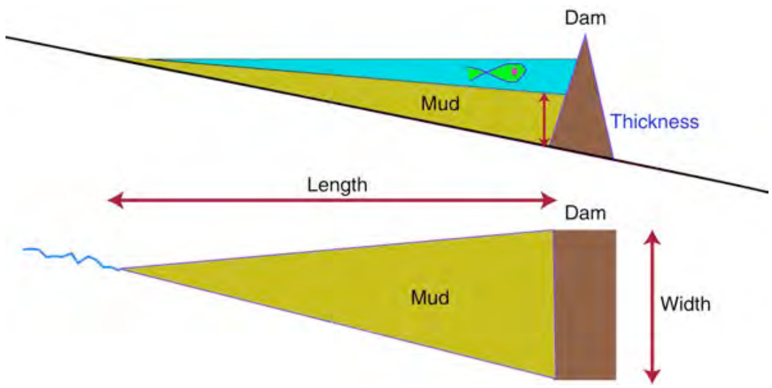
Georges Lemaître (1884-1966) was a Jesuit physicist and astronomer. His work provides an excellent example that religion can aid the progress of science by supplying a diversity of worldviews. When Einstein published the general theory of relativity, Lemaître sought and found a mathematical solution that had the universe expand from a point. Einstein confirmed that Lemaître's mathematics is correct, but was highly skeptical that his physics is correct. His worldview (like Bruno's and Halley's) expected an infinitely old and steady universe. (The term "Big Bang" was initially a pejorative used by its opponents.) Lemaître acted as a scientist cooperating with astronomers to find testable aspects of his theory. By the middle 1930s, it was evident that the universe is in fact expanding. Einstein nominated Lemaître for a high scientific award.

Astronomers are well aware that our place in time and space biases their observations. We can only expect to find ourselves living at a time in the universe's and our Sun's history that habitable planets exist.

For those interested in crime solving I recommend: "Evidence from the Earth; Forensic Geology and Criminal Investigation" by Raymond C. Murray, Mountain Press Publishing Company, Missoula, Montana, 2004.

Exercise

You can estimate the rate that erosion removes landscape. You will need a dam pond where you have access to the top of the dam. You will also need to know the age of the pond.



Walk out on dam to the center of the stream channel. You will use the difference between the upstream and downstream sides to measure the accumulated sediments. You may need a long fishing pole with a weight tied to the end.

Hold the rod at a comfort height and lower weight into pond until it hits the bottom. Hand pull the line in and record line length from rod tip to sinker.

A _______________

Repeat on downstream side to bottom of stream channel. Hand pull line in and measure line length.

B _____________

Sediment accumulation is approximately B – A _______ - ________ = C________

Measure surface area of pond by counting squares. Use same unit that you used for line length. __________________ D

The sediment volume in the pond is approximately C × D ÷ 3 = sed vol

___________ × ___________ ÷ 3 = _________________________

(The factor of 3 approximately accounts for the fact that the sediment thickness varying from the maximum you measured to zero at the edges of the pond.)

Now refer to a topographic map of the area upstream from the pond. Determine the watershed area that drains into the pond and count squares. Continue to use same unit of length. If you want to be precise record the difference (the average elevation in each square minus the dam elevation) and multiply it by the area of the square to get the volume eroded from the square and then add up all the squares. It is quicker simply to count the total area of the watershed and record

W ____________________

The record maximum elevation in watershed M ______ and dam elevation E __________

Eroded volume is approximately

W × (M-E) ÷ 3 = eroded vol

___________× (__________-_________) ÷ 3 = ________________________

The time taken for the erosion to occur is

(Age of dam) × (eroded vol) ÷ (sed vol) = ____________× ____________ ÷ ___________=

____

Geologists used such methods with the ocean basins to estimate the age of the Earth in the 1800s. They use these methods locally today.

We have assumed that the present rate the sediment enters the pond is the long-term rate. Do you think this is a good assumption and why?