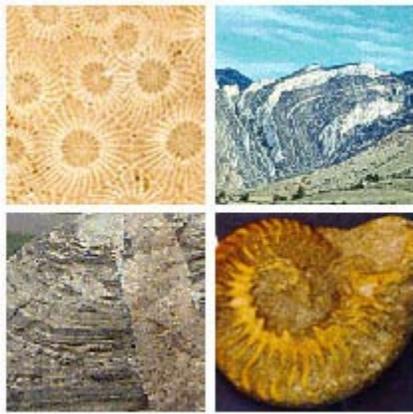


Geologic Time



Introduction

Relative Time

Geologic Time Scale

Numerical Time

Rates of Change

Summary

All things in nature work silently. They come into being and possess nothing. They fulfill their function and make no claim. All things alike do their work, and then we see them subside. When they have reached their bloom, each returns to its origin . . . This reversion is an eternal law. To know that law is wisdom.

Lao-tsu

The eye of the trilobite tells us that the sun shone on the old beach where he lived; for there is nothing in nature without a purpose, and when so complicated an organ was made to receive the light, there must have been light to enter it.

Louis Agassiz

Introduction

- The concept of time scales measured in billions of years is central to our understanding of geologic processes.
- Deep time corresponds to the bulk of the history of Earth, before fossils became abundant.
- The building blocks for life - water, heat, chemical elements - were all present nearly four billion years ago, soon after Earth had formed.
- Geologic time is measured in time intervals of millions of years and Earth is estimated to be 4.6 billion years old (4,600 million years).

One of the most important ideas in all of Earth science is the concept of **geologic time**. Advances in astronomy have shown us that the universe is a vast place, measured in incomprehensible distances far beyond the human experience. Time, the fourth dimension, is little different. We function in the here and now, a tiny fraction of Earth's history. Our commonly used dimensions of time, minutes-hours-days-weeks-months-years, are essentially indistinguishable in a geologic record that spans billions of years. We must train ourselves to think in units of time measured in millions or billions of years.

Standing at the rim of the **Grand Canyon** we can appreciate the immensity of the physical feature itself as we peer down over a thousand meters to the Colorado River below (Fig. 1). What is less obvious is the slow grinding of the river that has cut steadily downward through the rock pile. It has taken millions of years for the Colorado River to slice through the stack of sedimentary rock layers to expose the ancient igneous and metamorphic rocks at river level. This natural process has stripped away the physical representations of time. Each successive layer and the fossils it contains are like a page in Earth's history. As the river cut downward it carried us



Figure 1. The rock layers exposed in the Grand Canyon represent intervals of time stretching back hundreds of millions of years.

backward through time until it reached the billion-year-old rocks that make up the foundation of the canyon. Back in that distant time life on Earth was considerably different than it is today.

Geologic time is unevenly divided into the most recent 12% of Earth history that is represented by rocks with fossils and **deep time**, the much longer interval that occurred before the evolution of organisms with hard skeletons suitable for preservation. The **oldest known rock** that was deposited in water is nearly four billion years old and is found along the west coast of Greenland. These rocks contain the key chemical elements considered essential for life (carbon, nitrogen, sulfur). However, the state of Earth at this time would have been much different from the planet we call home today. About 3.9 billion years ago Earth would have been much hotter with surface temperatures around 50 to 70°C (compared with 15°C today), there would have been more extensive volcanism, the Sun was less bright, there was no oxygen in the atmosphere and no ozone layer to protect against incoming ultraviolet radiation. To make matters worse, Earth was being regularly bombarded by large asteroids and comets. Given the extreme conditions and the chemicals necessary for metabolic processes, scientists hypothesize that **primitive life** evolved from heat-loving bacteria in environments that might have been similar to those found today in the hot springs of Yellowstone National Park.

We begin by describing the observations used to place geologic events in sequential order. The earliest geologists were able to match rock units around the world and to place them in their relative order without the use of the sophisticated instruments available to us today. The section on **Relative Time** describes the evidence these scientists used to arrange rocks in their correct sequence of formation. Once described, even novice geologists can apply these rules to unravel the geologic history of the rocks below their feet.

The evolution of Earth's biosphere can be discerned from clues in the rocks. For much of our planet's past, life was dominated by primitive forms such as bacteria and later multicelled soft-bodied organisms not unlike jellyfish or worms. Such organisms were only preserved in ancient rocks on rare occasions under unusual conditions. It was not until 540 million years ago, when organisms developed hard skeletons with shells or bones, that fossils were commonly preserved (Fig. 2). Geologists use fossils in sedimentary rocks to



Figure 2. An example of a fossil: a fish from Tertiary rocks

subdivide the most recent segment of Earth history into time intervals known as **eras** and **periods**. We discuss how rocks can be matched between separate regions using their fossils in the section on Relative Time.

The **Geologic Time Scale** section provides a review the history of Earth including the major changes in the biosphere over the last half-billion years. We describe abrupt changes in the fossil record with special emphasis on a **mass extinction** event that wiped out most of life on Earth 250 million years ago. We consider the factors that may contribute to mass extinctions and why some species recover while others disappear.

The methods we use to measure time on a daily basis are useless for delving into the history of Earth. Rather than measuring time in minutes or years, we need techniques that enable us to measure rocks that are millions of years old. **Numerical Time** discusses how scientists attribute actual ages to igneous and metamorphic rocks by analyzing the spontaneous decay of radioactive isotopes.

Much of Earth appears fixed and unchanging when viewed through the lens of human experience. However, as we look more closely at the components of the Earth System we can recognize changes that occur on a variety of time scales. Geologic processes that occur over time intervals measured in minutes to decades typically operate on a local or regional scale and can often be observed directly. The patterns they create can be matched to those preserved in older rocks to help unravel some stories of the history of Earth. However, our planet is estimated to be **4.6 billion years old** and has been shaped by processes that operate on time scales measured in hundreds of millions of years. For example, the shape, size, and positions of the continents and ocean basins have changed dramatically throughout the geologic past. We must rely on our interpretation of the characteristics of the incomplete rock record to determine the temporal and spatial extent of such events. In **Rates of Change**, we examine how different

geologic processes operate on a range of time scales measured from seconds to hundreds of millions of years.

Relative Time

- Three simple rules, the principles of superposition, cross-cutting relationships, and original horizontality, can be applied to determine the sequence of formation of rock units in a specific area.
- Continental-scale interpretations require the correlation of sequences of rock units or fossils between different regions.

Local-Scale Interpretations

Relative time deals with the order of events. When using relative time it is not important that we know when an event occurred, but only that we know if it occurred before or after another event. Sedimentary rocks lie uppermost in the crust. By interpreting the sequence of layers (beds) in sedimentary rocks, variations in the rocks themselves, and any associated igneous or metamorphic rocks, we can unravel the geologic history of a local area. When geologists examine a sequence of rocks they apply several rules (principles) to help them determine the relative order of events that occurred at that location.

Principle of Superposition

Sometimes papers pile up on my desk for several weeks before I have time to put them away. The oldest papers are at the bottom of the pile, the most recent additions near the top. The same principle holds for stacking plates, cards, books or any other flat objects. The lowermost objects must be placed first. Rocks are no different. This is simple idea behind the principle of superposition.

When we examine a series of undisturbed sedimentary rock layers we assume the rocks at the bottom of the stack are the oldest and the rocks at the top are the youngest (Fig. 3). The image below shows beds at Dead Horse Point, Utah. Using the principle of superposition we can assume that the beds at river level are older than the beds higher on the slopes. The same

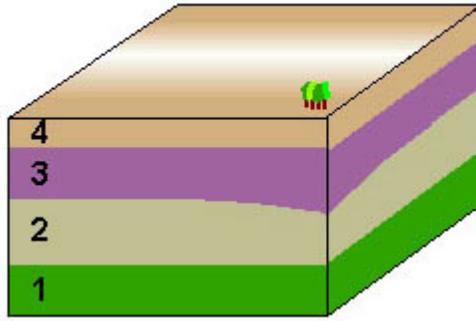
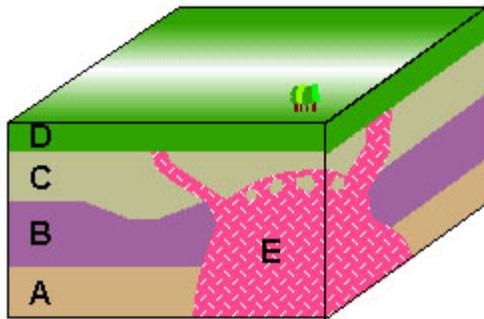


Figure 3. Left: The principle of superposition tells us that the beds near the river are older than the beds at the top of the slope. Right: the layers are numbered from oldest (1) to youngest (4) according to their sequence of formation.

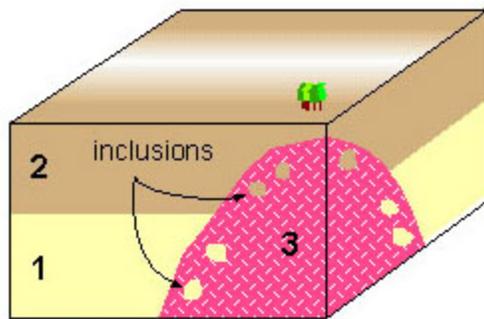
principle can be extended to apply to many forms of volcanic igneous rocks. Volcanic eruptions can produce layers from lava flows or ash and other debris falling back to Earth.

Principle of Cross-Cutting Relationships

Older rocks may be cut by younger rocks or other geologic features (Fig. 4). For example, an igneous intrusion must be younger than the rock it intrudes. The pink rock (an igneous intrusion) in the image below cuts across the layering in a boulder. The intrusion must have followed the formation of the surrounding rock. Similarly, a river channel is younger than the rocks it cuts through. The Colorado River's channel in the image above was the last thing to form as it cuts across the existing layering in the sedimentary rocks.



igneous pluton



igneous pluton

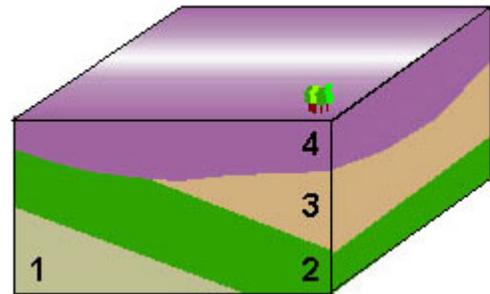
Figure 4. Top right: The broad diagonal band in the image is an igneous intrusion that cuts across the preexisting layering; therefore the intrusion must have followed formation of the layering. Top left: Place the lettered rock units in their correct chronological sequence from oldest to youngest. Left: Plutonic igneous rocks often incorporate chunks of surrounding "country" rock during their formation as inclusions, recognizable pieces of the original rock.

Figure 5. Left: Tilted and folded layers near Greybull, Wyoming, indicate that originally horizontal sedimentary beds were deformed after formation. Right: Layers 1, 2, and 3 were deposited in order as horizontal beds; these layers were then uplifted, tilted and eroded before layer 4 was deposited. Erosion requires that the rocks were uplifted above sea level and then re-submerged for layer 4 to be deposited.

Igneous plutons often incorporate pieces of surrounding rocks as magma forces its way upward through Earth's crust. These isolated pieces may be completely melted to become part of the magma or may be preserved in their original form as **inclusions** (Fig. 4). A rock preserved as an inclusion must be older than the pluton in which it is found. This is a variation of the principle of cross-cutting relationships.

Principle of Original Horizontality

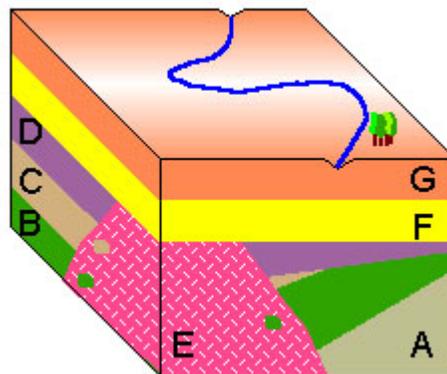
Sedimentary rocks are deposited in nearly horizontal layers (beds; Fig. 5). If layers are no longer horizontal they must have undergone deformation after formation. The majority of sedimentary rocks are deposited under water. They may be pushed above sea level and tilted during the formation of mountains. These processes expose rocks to weathering and erosion that serves to erase parts of the geologic record as rock units are worn away.



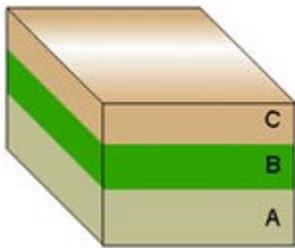
Applying the Rules

Identifying examples of these three principles in nature allows geologists to reconstruct the geologic history of a rock

Figure 6. This block diagram provides clues to the geologic history of an idealized region. Units A, B, C, D, F, and G are all sedimentary rocks. Unit E is an igneous pluton composed of a rock such as granite.

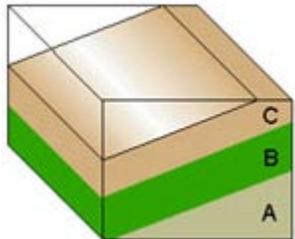


sequence. The geologic history of the figure below can be deconstructed using the three principles (Figs. 6, 7).

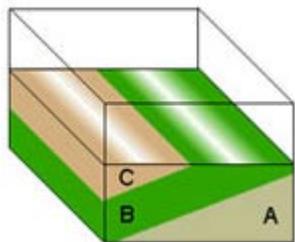


Superposition: A lies below B so A must be the oldest unit.

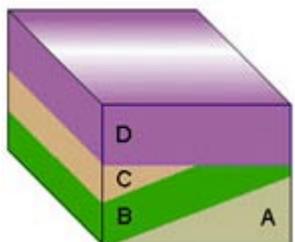
Original horizontality: A, B, and C must have been deposited as horizontal layers. Because they have the same orientation we can probably consider them a discrete group that experienced a similar geological history.



Original horizontality: Because A, B, and C are more steeply tilted than the overlying units they must have been uplifted and tilted early in the geologic history of the region.



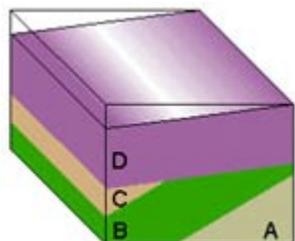
A, B, and C were subjected to weathering and erosion at Earth's surface. A relatively flat land surface was formed by erosion. A significant time interval may have passed while erosion occurred. This eroded surface is known as an **unconformity** and is the physical expression of a gap in time. An unconformity occurs when no beds are deposited or when part of the rock record is removed by erosion.



Superposition: D must have been deposited after C as it overlies B and C.

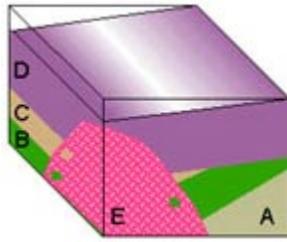
Original horizontality: D was deposited as a horizontal bed.

Cross-cutting: D must be younger than B and C because it cuts across the underlying layers.

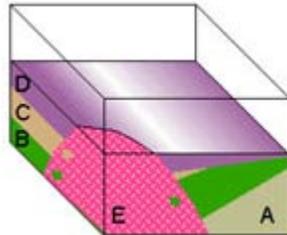


Original horizontality: D is no longer horizontal so it must have been slightly tilted after formation. This would also have increased the inclination of layers A, B, and C.

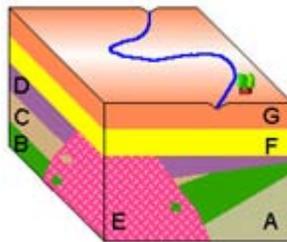
Figure 7. The sequence of events for the lowermost figure determined using the simple rules of superposition, cross-cutting relationships, and original horizontality.



Cross-cutting: All layers A through D are cut by the younger igneous pluton. The pluton contains inclusions of layers B and C, further indication that it must have formed subsequent to the deposition of those beds. We have no evidence to tell us whether E formed before or after D was tilted.



D and E were subjected to weathering and erosion at Earth's surface. A relatively flat land surface was formed by erosion. A second unconformity surface is formed.



Superposition: Layers F and G must have been deposited after E because they lie atop all other units.

Original horizontality: F and G were deposited as horizontal beds. Cross-cutting: F must be younger than D and E because it cuts across the underlying units. The river carved a valley through the upper part of G.

Think about it . . .

Examine the block diagram at the end of the chapter and place the lettered units in their sequence of formation from oldest to youngest. Can you also answer the questions related to the rocks that accompany the diagram?

Continental-Scale Interpretations

The principles outlined above work well in distinguishing the sequence of events for a specific region where the rocks remain consistent. However, when we try to match rocks from different areas of the U.S. and Canada we find that the rock types often are not consistent even within different parts of the same state or county. Consequently, if we are to determine the geologic history of a continent we must use other methods to **correlate** equivalent rock units separated by large distances.

How are we to determine if the thick layers of sandstone that form the upper cliffs of the Grand Canyon, Arizona, are the same sandstone beds that dominate the landscape of Dinosaur National Monument along the Utah/Colorado state line? There are two types of features that geologists use to correlate rock units separated by hundreds or thousands of kilometers: physical characteristics and fossil content.

Geologists long ago discovered that they could match similar **physical characteristics** between sequences of multiple rock units. For example, geologists may find two shale units with similar characteristics (color, grain size, bed thickness) in different parts of Utah (Fig. 8). Are these rocks the same age? We can first compare the sequences of beds above and below the shales to see if they match. The presence of relatively unusual rock types such as salt or lava flows in a section often aid correlation. If the physical characteristics of the beds are similar we can form the hypothesis that the shale layers were deposited at the same time.

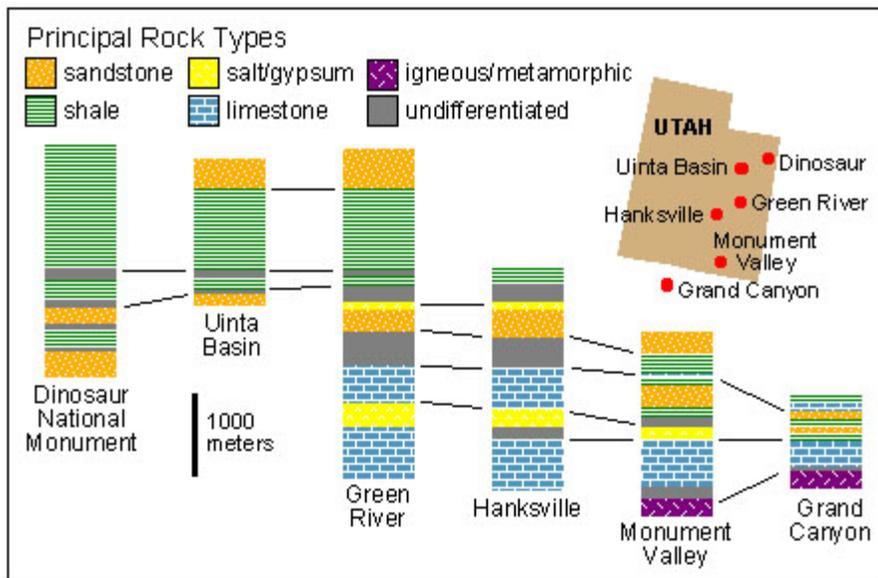


Figure 8. Rock units can be matched between several locations in northern Arizona and Utah by correlating specific groups of units such as the salt and limestone units toward the base of the section and the thick shale units near the upper parts of the sections.

The most straightforward method of correlating units is to compare their fossil content. Some fossils extend over long intervals of geologic time and are therefore found in many rock units spanning millions of years. These units allow broad correlations but make it difficult to match individual layers between different regions. Geologists can make more precise correlations using index fossils. Fossils that lived for relatively

short periods are known as **index fossils** because they are found in only a few units. This makes them useful because their appearance in the rock record represents a specific time interval that can readily be identified and correlated between different regions.

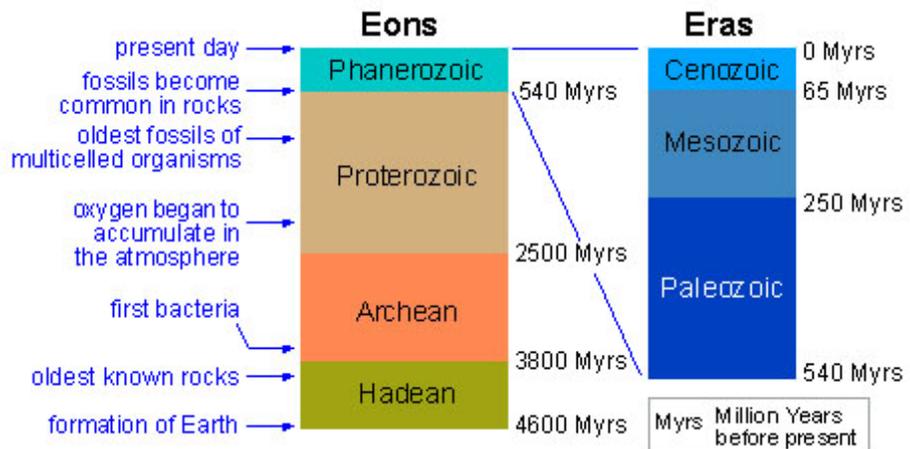
Paleontologists, geologists who study fossils, have applied these methods not only to correlate the rocks of individual continents but also to match rocks from around the world. Consequently, they have been able to make interpretations about Earth history based upon the characteristics of the rocks themselves and the fossils they contain. The most recent 540 million years of Earth history is summarized in the section on the Geologic Time Scale.

Geologic Time Scale

- Earth history is divided into four eons, the most recent of which (Phanerozoic) is characterized by abundant fossils.
- The Phanerozoic is further divided into three eras separated by mass extinction events.
- The fossil record has been interpreted to reveal the changes in the biosphere over the most recent 600 million years of Earth history.

Figure 9. Geologic time is divided into four long eons. The Hadean, Archean, and Proterozoic eons have not been separated into shorter time intervals because of the relative absence of fossils. The Phanerozoic, the most recent eon, is characterized by abundant fossils that allow it to be further subdivided into three eras that are in turn broken down into shorter time intervals known as periods.

Time can be considered in relative or absolute terms. Geologists used relative time for a couple of centuries to arrange geologic events in the correct sequence (see Relative Time). Early in this century, scientists realized they could use



the radioactive decay of isotopes to determine the actual age of some kinds of rocks and put dates on the sequence of events (see Numerical Time).

The presence or absence of fossils has been used to compare the relative ages of rocks around the world and to arrange sedimentary rocks into a geologic time scale. **Eons** are the largest intervals of the time scale and range from 540 to 2,050 million years in length (Fig. 9). The Earth was a hostile and inhospitable place for most of its early history spanning much of the first three eons. Life did not evolve beyond primitive bacteria until the latter half of the **Proterozoic eon** and few fossils were preserved until the Phanerozoic eon. Geologists use the informal term Precambrian to refer to all geologic time prior to the **Phanerozoic**.

Mass Extinctions

Rock units of the **Phanerozoic eon** have been assigned to three **eras** of varying lengths based upon their fossils (Fig. 9). The eras were further subdivided into shorter time intervals known as **periods**; we recognize 12 periods (see Geologic Time Scale). Rocks of the same age typically contain similar fossils. The beginning of the oldest period, the Cambrian, signaled an explosion of diversity within the biosphere. The number of species represented by the fossil record increased progressively from the Cambrian onward and evolving organisms left behind more complex fossil forms moving forward in time.

Occasionally the diversity of life was threatened by **mass extinction** events (Fig. 10) that resulted in the death of large numbers of species. So dramatic were these events that the assemblages of fossils formed prior to an extinction are

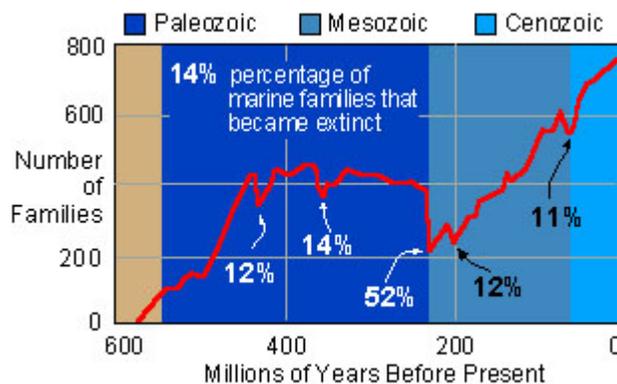


Figure 10. Biodiversity as measured by the number of families of organisms over the last 600 million years. Decreasing biodiversity signals extinction events. Five events are highlighted with the Permian-Triassic extinction representing the greatest drop in biodiversity.

substantially different from those found in rocks deposited following the extinction event. These differences characterize the three eras of the Phanerozoic eon. The mass extinction that ended the reign of the dinosaurs occurred 65 million years ago at the close of the Mesozoic era. This event is known as the Cretaceous-Tertiary extinction or K-T event after the two periods that lie on either side of the time boundary. No dinosaurs survived the event and their places in nature were taken over by mammals that had been a relatively minor group until that point. This extinction is attributed to a large asteroid or comet colliding with Earth.

Spectacular as the K-T extinction event was, it pales in comparison to an even more widespread disruption of the biosphere that occurred at the end of the Paleozoic era, 250 million years ago. This event is known as the **Permian-Triassic extinction** or P-T event after the two periods that lie on either side of the time boundary. The P-T mass extinction, often called "**The Great Dying**," killed off up to 90% of all marine species and 70% of land species. There are two basic questions scientists hope to answer by studying such events: What causes mass extinctions? and Why do some species survive the event while others perish? In the case of the P-T extinction scientists are closing in on a potential explanation of the event that may help answer these questions.

The P-T event was global in scale and impacted both land and marine species. Extinction was not instantaneous but occurred over approximately 500,000 to 5 million years. Some groups of organisms died off more rapidly in response to regional environmental changes and others may have already been in decline prior to the event. Geologists have identified several phenomena that appear to have contributed to the global P-T extinction.

- **Sea-level dropped by nearly 100 meters** as the size of the world's ocean basins increased. Sea-level began to decline a few million years before the culmination of the P-T extinction. The drop in sea-level exposed much of the shallow ocean floor around the continents that was home to a majority of marine species. Organisms that lived directly on the sea floor were more likely to be wiped out than those that were more active swimmers.
- 251 million years ago there was a **massive eruption of lava** in Siberia, northeastern Russia. Over 1.6 million square kilometers (1 million square miles) was covered with lava, an area equivalent to the western half of the

conterminous U.S. Volcanic dust blocked incoming solar radiation resulting in a short-term cooling and sulfur dioxide and other gases would have contributed to widespread acid rain. Carbon dioxide emissions from the eruptions exaggerated the global greenhouse effect, increasing long-term global temperatures following the eruption.

- A **large asteroid** is suspected of colliding with Earth approximately 250 million years ago. The impact site has not been found but scientists have discovered chemical substances in P-T rocks that are considered indicative of an impact event.

Although none of these events would have caused a mass extinction on the scale of the P-T event on their own, together their combined effects resulted in a massive change in Earth's physical and chemical environments. Those species that were able to adapt to the changes survived to thrive in the Mesozoic era that followed whereas others breathed for the last time and their remains became part of the fossil record.

The Geologic Time Scale

The table below divides the **Phanerozoic eon** into its constituent eras and periods and describes the evolution of the biosphere through the most recent interval of Earth history.

Think about it . . .

Develop a metaphor for geologic time. Select some of the most significant geologic events from the geologic time scale and convert them into your own metaphor. Go [here](#) to view an example of a time metaphor and learn how to construct your own.

The Geologic Time Scale

ERA	PERIOD	REMARKS	TIME (Myrs)
Cenozoic	Quaternary	Ice Age over North America – large mammals abundant (e.g., mastodons, mammoths)	1.6 - 0
	Tertiary	Age of Mammals began – first elephants, horses, deer, bears – earliest human ancestors appeared at the end of the period	66 - 1.6
Mesozoic	Cretaceous	Dinosaurs dominated the earth (tyrannosaurus) – first grasses and flowering plants appeared – dinosaurs wiped out by an extinction event at the end of the period	144 - 66
	Jurassic	Atlantic ocean began to form – first birds appeared – dinosaurs and flying reptiles (pterosaurs) common	208 - 144
	Triassic	Pangaea began to split apart – reptiles dominated the earth – some early dinosaurs – earliest mammals appeared – first conifers	250 - 208
Paleozoic	Permian	Much marine life was wiped out in a massive extinction at the end of the Permian	288 - 250
	Pennsylvanian	Appalachian Mountains formed when North America collided with Africa – insects and early reptiles on land – first evergreen trees appeared	320 - 288
	Mississippian	Shallow tropical oceans covered much of the interior of North America - marine fossils in limestone common	360 - 320
	Devonian	Age of Fishes – first land animals (tetrapods: amphibians and insects) – first seed plants, trees, and forests	408 - 360
	Silurian	First life on land represented by primitive plants (ferns, mosses) – first fish with jaws appeared - much of North America was under a shallow tropical sea with abundant reefs	438 - 408
	Ordovician	North America was near the equator – abundant marine life	505 - 438
	Cambrian	Explosion of organisms with hard skeletons (that can be preserved as fossils) occurred at beginning of Cambrian	540 - 505
Precambrian	Fossils rare in Precambrian rocks – soft-bodied organisms present in the youngest Precambrian rocks	540 – 4,600	

Numerical Time

- Radioactive decay of unstable isotopes can be used to determine the age of igneous and metamorphic rocks.
- Radioactive decay occurs when a parent isotope gains or loses protons, neutrons, and/or electrons as it is converted to a daughter atom.
- The half-life is the length of time taken for half of the radioactive material to decay.

The geologic time scale was established before scientists discovered a method for accurately determining the age of rocks. Early attempts to determine the age of Earth were based on an incomplete understanding of the rates of geologic processes and yielded ages that were much younger than the actual age of formation (4.6 billion years). Scientists estimated Earth to be at least several million years old but it was not until the discovery of the **radioactive decay** of uranium that science was able to provide a potential method for accurately determining the age of certain rocks.

Radioactive Decay

Each chemical element has a specific number of protons and neutrons in its nucleus. The number of protons is the **atomic number**, the number of protons and neutrons combined is the **mass number**. Atoms with different numbers of neutrons in their nucleus are **isotopes**. For example, the element potassium has three isotopes. Potassium's atomic number is always 19 but its mass number may be 39, 40, or 41 depending on the number of neutrons (20, 21, 22). These isotopes are identified as ^{39}K , ^{40}K , and ^{41}K .

Some isotopes are unstable and will spontaneously decay to a more stable form. The unstable original isotope is termed the **parent isotope**, the stable product of the decay is the **daughter atom**. For example, ^{40}K decays to ^{40}Ar (argon) and ^{40}Ca (calcium). Decay begins when the element is originally formed such as during the cooling of magma or when elements recombine to form new minerals under changing physical conditions as a result of metamorphism.

Radioactive decay occurs when the parent isotope gains or loses particles. Protons in the nucleus may become neutral with

the addition of an electron or neutrons may gain a positive charge and become protons with the loss of an electron.

Particles	Changes	Change in Atomic Number	Change in Mass Number
Alpha decay	Two protons and two neutrons lost from nucleus	- 2	- 4
Beta decay	Neutron loses an electron, and is converted to a proton	+ 1	0
Electron capture	Proton captures an electron and is converted to a neutron	- 1	0

The mass number (40) stays the same when ^{40}K decays to ^{40}Ar but the atomic number decreases by one. In contrast, when ^{40}K decays to ^{40}Ca , the atomic number increases by 1. The first process is an example of electron capture, the second is the result of beta decay.

Alpha decay occurs when there are large changes in the mass number between the parent and daughter isotopes. For example, eight alpha particles and six beta particles are released when ^{238}U (uranium) decays to ^{206}Pb (lead). The mass number decreases by 32 and the atomic number decreases from 92 to 82 (-16 from alpha decay and +6 from beta decay).

Think about it . . .

1. What type of decay converts radium ^{226}Ra (radium) to ^{222}Rn (radon)?
2. ^{14}C has six protons and eight neutrons and converts to ^{14}N which has seven protons and seven neutrons. What type of decay converts ^{14}C and ^{14}N ?

Half-lives

Radioactive decay is measured in half-lives. The **half-life** of an isotope is the time taken for half of the parent isotopes to decrease to daughter atoms. The relative proportions of parent and daughter are used to determine the number of half-lives (Fig. 11).

Prior to decay, 100% of the parent exists and no daughter products have been formed. After one half-life 50% of the parent remains and the other 50% of the atoms are converted to daughter atoms. After two half-lives the number of parent



Figure 11. Plot of the variation of parent and daughter isotopes for an idealized example of radioactive decay.

isotopes is again halved (25%) and the number of daughter atoms increases by an equivalent amount (to 75%).

Number of Half-lives	Parent Isotopes (% total isotopes)	Daughter Isotopes (% total isotopes)
0	100	0
1	50	50
2	25	75
3	12.5	87.5

The **relative proportion** of parent and daughter atoms can be used to determine how many half-lives have passed since the formation of the mineral that contained the radioactive isotopes. With the exception of ^{14}C (carbon-14), the half-life lengths for the most common radioactive isotopes are measured in millions or billions of years. ^{14}C can be used to date items up to approximately 50,000 years of age. It has been used to date cloth fragments from Egyptian pyramids and charcoal found in a rock shelter at one of the oldest sites of habitation in North America. Isotopes with half-lives measured in billions of years can be used to measure the ages of the oldest rocks in the world. The oldest recorded date is approximately 4 billion years for some rocks in northern Canada.

Parent Isotope	Daughter Product	Length of Half-life
Uranium 238 (^{238}U)	Lead 206 (^{206}Pb)	4.5 billion years
Uranium 235 (^{235}U)	Lead 207 (^{207}Pb)	704 million years
Rubidium 87 (^{87}Rb)	Strontium 87 (^{87}Sr)	48.8 billion years
Potassium 40 (^{40}K)	Argon 40 (^{40}Ar)	1.25 billion years
Carbon 14 (^{14}C)	Nitrogen (^{14}N)	5,730 years

Radioactive decay begins when an igneous or metamorphic rock cools below a specific setting temperature. Sedimentary rocks may be formed from minerals weathered from other rocks. Minerals found in sedimentary rocks cannot be used to date the formation of the rock itself but instead give the age of the igneous or metamorphic rock in which the mineral was first formed.

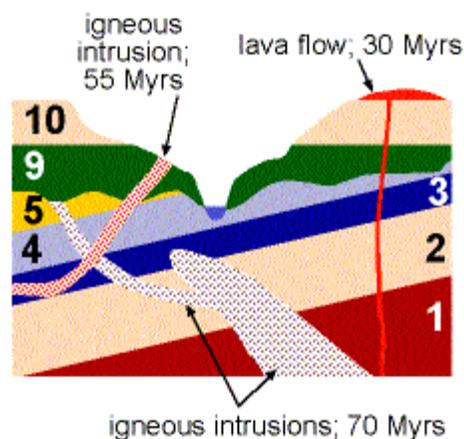
Think about it . . .

1. Isotope X has a half-life of 10 days. If you began an experiment with a 400-gram sample of the isotope, how much would be left after 40 days?
a) 100 b) 50 c) 40 d) 25 e) 20
2. The world's oldest known rock is approximately 4 billion (4,000 million) years old (actually 3.96 Byrs). What are the approximate relative percentages of parent and daughter isotopes for uranium-238 and lead-206?
a) 75% parent and 25% daughter
b) 55% parent and 45% daughter
c) 45% parent and 55% daughter
d) 25% parent and 75% daughter

Using Relative and Absolute Time

Sedimentary rocks are arranged in relative chronological order using relative dating methods discussed above. The absolute age of these rocks can be determined using the cross-cutting relationships for igneous intrusions and the principle of superposition for layers of volcanic ash or lava flows (Fig. 12). Dates can be obtained for the igneous rocks that will act to bracket the formation of the adjoining sedimentary layers. Although highly effective, such techniques are limited to

Figure 12. Relative time and absolute time elements can be used together to determine the ages of sedimentary rocks. For example, bed 9 must be older than the 55 Myr old pluton (intrusion) but younger than the 70 Myr intrusion.



regions where there are enough igneous rocks to provide a sufficient range of ages to constrain the associated sedimentary rocks.

The igneous rocks in Figure 12 have been dated by radioactive decay techniques and have yielded the dates shown on the diagram. Based on this information we can bracket the age ranges of the sedimentary units labeled 1 to 5 and 9 and 10.

- Beds 1 to 5 are greater than 70 million years old because they are cut by all the intrusions and must be older than the oldest intrusion.
- Bed 9 truncates the oldest intrusion but is cut by the younger intrusion, therefore it must be between 55-70 million years old.
- Bed 10 is younger than bed 9 (superposition) but the relationship between the 55 Myr intrusion and bed 10 is unresolved because we can't tell from the information available if the bed truncates the intrusion or the intrusion cuts the bed. However, the bed is overlain by a lava flow dated as 30 Myrs old so we can estimate the age range for bed 10 as between 30-70 million years old.

Think about it . . .

Examine the block diagram found at the end of the chapter and identify the age range for bed G given the following data: pluton I is 180 million years old; pluton A is 145 million years old; and lava flow C is 60 million years old.

Rates of Change

- Uniformitarianism is the theory that the geologic processes operating today operated in the geologic past in much the same manner.
- Catastrophism assumes that features on Earth's surface formed by geologic processes that are no longer active

Prior to the acceptance of the scientific method people recognized the grandeur of the landscape but could not identify how it developed. Features such as mountains and oceans were

Figure 13. The mud cracks in the image on the left formed on the floor of a quarry in West Virginia. The features on the right are ancient mud cracks preserved in rocks of the quarry wall that are over 400 million years old.



assumed to have formed by catastrophic events beyond comprehension. This perspective is known as catastrophism.

Today we know that most of the features on Earth's surface are formed by steady, gradual processes operating over very long time periods of thousands or millions of years.

Uniformitarianism is the theory that the geologic processes that operate today also operated in the geological past in much the same manner, that Earth processes are uniform over time (Fig. 13).

The principle of uniformitarianism was proposed by Scottish scientist **James Hutton** over 200 years ago and represented an early geologic example of the use of the scientific method. One discovery that followed from Hutton's observations was that Earth was much older than had previously been thought. It was realized that the slow pace of most geologic processes required millions of years to erode mountains and form oceans. What was not realized was just how many million years were required. Not all processes work so slowly. High-energy processes such as wave action or flood events may erode less resistant earth materials over short time intervals measured in days or decades (Fig. 14).

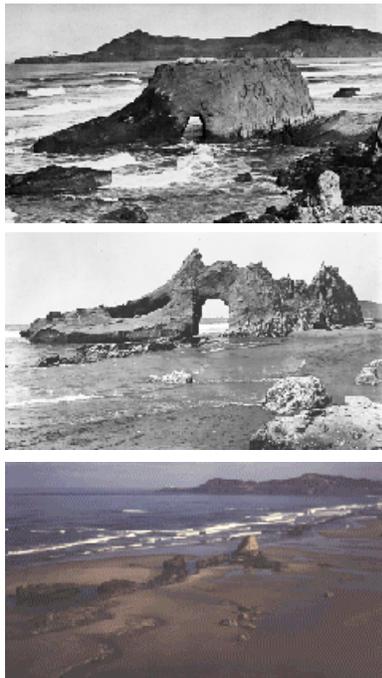


Figure 14. Erosion of Jump-Off Joe sea stack along the Oregon coast from 1890 (top), 1920 (middle), and 1970 (bottom). Erosion of the relatively weak rocks of the sea stack is an example of a geologic process that has occurred on human time scales. Image from USGS.

Although uniformitarianism is widely accepted it does not account for every feature on Earth. Some processes, such as an asteroid or comet impact, have occurred infrequently during the geologic past. Consequently, it is necessary that we recognize that some events are catastrophic in nature and although they are not unique in the history of Earth, they are relatively rare.

Events that take millions of years:

- Opening/closure of ocean basins;
- Uplift of mountain ranges;
- Evolutionary changes in plants, animals;

- An ice age;
- Mass extinctions;
- Carving the Grand Canyon.

Events that take thousands of years:

- Formation of fertile soils;
- Lifetime of giant redwoods;
- Circulation of deep ocean waters;
- Migration of peoples through North America.

Events that take hundreds of years:

- Growth of major U.S. cities;
- Erosion of sea stacks;
- Build up to earthquakes or volcanic eruptions;
- Doubling of atmospheric carbon dioxide.

Events that take years:

- Circulation of surface currents in oceans;
- Advance/retreat of glaciers;
- Cooling resulting from large volcanic eruptions or asteroid impact events.

Events that take weeks or months:

- Floods;
- Hurricanes;
- Large volcanic eruptions;
- Seasonal climate changes.

Events that take hours or days:

- Earthquakes and their aftershocks;
- Small volcanic eruptions;
- Most landslides.

Summary

1. What are the dimensions of geologic time?

The Earth is 4.6 billion years old. Many geologic processes operate on time scales measured in millions of years whereas human time scales are obviously much shorter. We must rely on a combination of the use of fossils and the radioactive decay of certain isotopes to assign ages to rocks.

2. What are the oldest life forms on Earth?

The oldest evidence for life is represented by fossilized bacteria that are about 3.5 billion years old. The early Earth was a much more hostile and changeable environment than our planet today, making it difficult for life to establish a foothold. It is likely that the first bacteria were heat-loving, living in hot springs. Primitive life may actually have evolved earlier and been wiped out several times as the oldest known rocks are nearly four billion years old and contain the basic elements necessary for metabolic processes in organisms.

3. What is the difference between relative and numerical time?

Relative time places events in order; numerical time determines the ages of rocks (in millions of years).

4. How do we determine the order of geologic events?

Geologists apply three simple rules to determine the order in which rocks formed. These principles are: superposition - younger rocks on top of older rocks; cross-cutting relations - younger rocks cut across older rocks; and original horizontality - sedimentary rocks are initially formed as horizontal layers. We can couple these rules with a knowledge of how rocks form to unravel the geologic history of a rock sequence.

5. How do geologists compare the ages of rocks from different regions?

The rules described above work well in relatively small areas where rocks are well exposed but how do we know if two limestone layers from different parts of the country are the same age? In this case we must use other methods because the layers are not in contact with each other. The sequence of rocks above and below the limestone bed may be consistent, indicating the rocks were formed under similar conditions. The better the match of units, the greater the likelihood that the layers can be correlated. The fossil content of the beds can provide evidence on their relative ages. More diverse, complex fossils are present in younger rocks (more time for evolution). If the fossils are the same the ages of the rocks are probably similar.

6. How is geologic time divided?

Just as we divide a year up into four parts termed the seasons, we can divide the history of Earth into four long time intervals known as eons. Unlike the seasons, eons are of different lengths. From oldest to youngest they are the Hadean, Archean,

Proterozoic, and Phanerozoic. Only the latter eon is further subdivided because it is the only one to contain abundant fossils that can be used to arrange rocks in their relative order of formation. The Phanerozoic represents 540 million years, but just 12% of all Earth history. It is subdivided into three eras (Paleozoic, Mesozoic, Cenozoic), each characterized by changing fossil assemblages. Each era can be further divided into shorter time intervals tens of millions of years in length called periods.

7. Why did the biosphere change during the Phanerozoic eon?

Life evolved from simple to more complex forms throughout the Phanerozoic. Both the number of species and the complexity of life show an gradual increase but there were several occasions when conditions changed causing many species to become extinct at the same time. These events are known as mass extinctions. Two of the greatest mass extinctions mark the boundaries between the eras. These changes were typically global in scale and geologically sudden occurring in less than a million years. When some species were wiped out, others took their places. For example, the extinction of the dinosaurs made possible the expansion of the mammals.

8. What were the major changes in the biosphere in the Phanerozoic?

The Paleozoic era was characterized by organisms with the first hard skeletons. Early life was exclusively marine and the first land plants and animals did not appear until about half-way through the era. The most diverse life forms were in oceans with the Devonian period christened the "Age of Fishes." Early reptiles and insects only appeared toward the close of the Paleozoic era that ended with the most extensive extinction event in geologic history, wiping out the majority of life on Earth. Life was considerably different in the following Mesozoic era. Dinosaurs dominated the land and we see the first birds, grasses, and flowering plants. This era also ended with the infamous extinction of the dinosaurs resulting in the Cenozoic era being subtitled the "Age of Mammals." The diversity of life forms increased through the Cenozoic to give us the organisms we see today.

9. What is uniformitarianism?

Uniformitarianism is the theory that the geological processes that operate today also operated in the geological past in much the same manner (i.e., that earth processes are uniform over time).

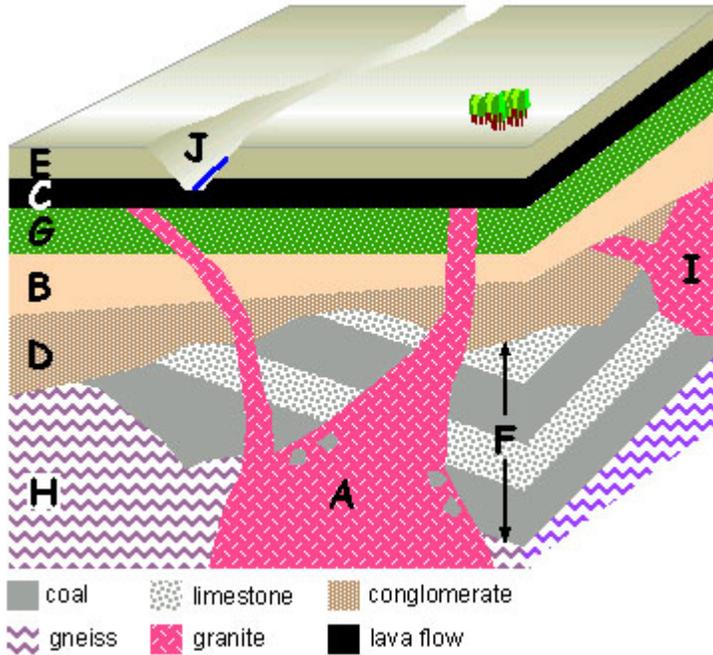
10. Do all geologic processes take millions of years?

No. Some earth processes such as earthquakes may take just seconds to occur whereas others such as the formation of a mountain range typically take millions of years. Short-term events often leave little evidence of their passing in the geologic record or may be overprinted by later larger-scale phenomena. Geologists can recognize where ancient mountains were located and when they formed but could not identify when and where a single earthquake or flood occurred millions of years ago. Consequently, when we pick apart the history of Earth we tend to emphasize large-scale and/or long-term events.

Relative Order of Geologic Events

Use the laws of superposition, cross-cutting relationships, and original horizontality to unravel the sequence of formation of the diagrams illustrated below.

Determine the order of events for the idealized location shown in the figure below.



Identify which rock units best match the descriptions below

- _____ Interbedded layers of rocks that indicate alternating shallow marine environments and freshwater swamps in tropical conditions.
- _____ An erosional surface (unconformity surface) overlain by coarse (large) grained clastic sedimentary rocks.
- _____ An example of a plutonic igneous rock.
- _____ Rock containing a foliation.
- _____ Most recently deposited sedimentary rock.
- _____ Sedimentary bed that has undergone contact metamorphism on its uppermost surface.
- _____ Basalt.

Geologic Time Metaphor

If all of geologic time were proportional to the length of a football field (100 yards), the Earth would have formed at the opposing team's goal line (100 yards) and present day would represent the home team's goal line (0 yards).

The general equation that can be used to calculate the dimensions of any geologic time metaphor is:

$$(Y/A) \times MM = UV$$

where Y = years before present; A = age of Earth; MM = metaphor maximum; and UV = metaphor unknown value.

Example using a metaphor of a 100-yard football field:

Oldest fossil bacteria = 3500 million years old

Age of Earth = 4,600 million years

Metaphor maximum = 100 yards

Metaphor value = $(3,500,000,000/4,600,000,000) \times 100$
= 76 yds

In other words, we would have traveled about a quarter of the length of the football field from the opposing team's goal line before the most primitive life forms first appeared in the geologic record

Key football field metaphor dimensions:

- 100 yards = 4,600 million years
- 1 foot = 15.3 million years
- 10 yards = 460 million years
- 1 inch = 1.3 million years
- 1 yard = 46 million years
- inches = 130,000 years
- 0.0000008 inches = 1 year

Distance from Home Team's Goal Line	Time (million years)	Event
100 yards	4,600	Earth formed
76 yards	3,500	Oldest fossil bacteria
43 yards	2,000	First oxygen in the atmosphere
12 yards	540	Hard skeletons become common (fossils)
5.4 yards	250	Widespread extinction ends Paleozoic Era
1.4 yards	65	Dinosaurs become extinct
2.3 inches	3	Early human ancestors
0.00036 inches	0.00051	Columbus landed, 1492

Develop your own metaphor for geologic time and describe it in the space below. Choose some of the most significant geologic events from the geologic time scale and convert them into your own metaphor using the equation above.

Don't try to be too detailed in your analysis. The intention here is to recognize the length of the geologic time scale and the relative position of key events. Approximate lengths, distances, heights, widths, depths, sizes, time periods, etc. are OK as long as you recognize the relative proportions of the time intervals.