EENS 1110	Physical Geology
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Geologic Time

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From the beginning of this course, we have stated that the Earth is about 4.6 billion years old. How do we know this and how do we know the ages of other events in Earth history?

Prior to the late 17th century, geologic time was thought to be the same as historical time.

Archbishop James Ussher of Armagh, Ireland, 1654, added up generations from the Old Testament and determined that Earth formed on October 23, 4004 BCE.

The goal of this lecture is come to come to a scientific understanding of geologic time and the age of the Earth. In order to do so we will have to understand the following:

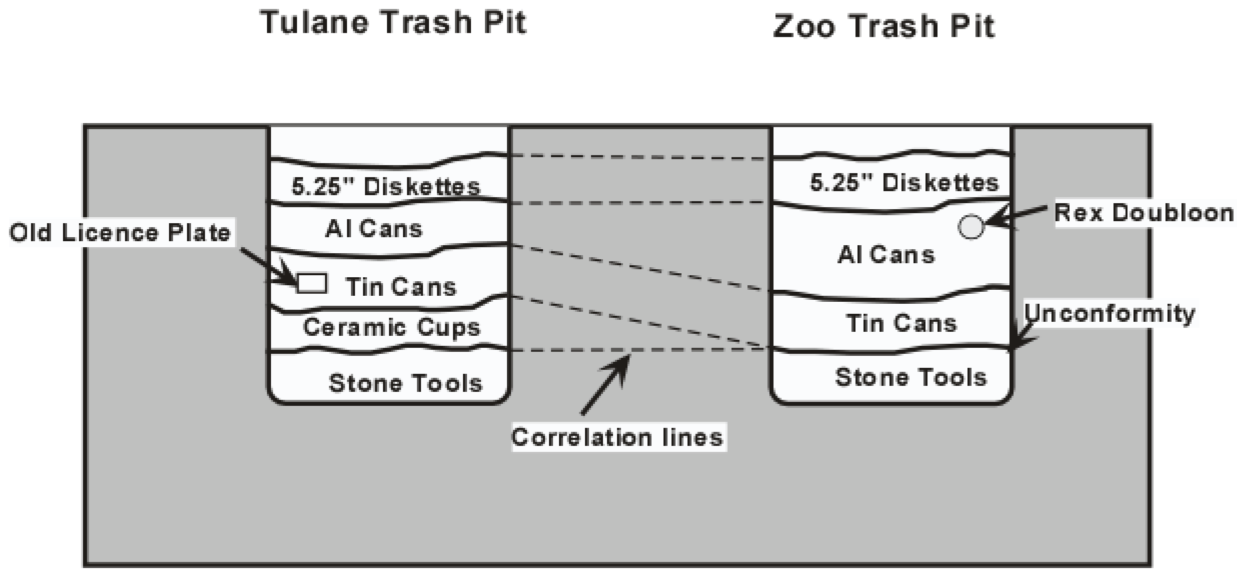
1. The difference between relative age and numeric age.
2. The principles that allow us to determine relative age (the principles of stratigraphy).
3. How we can use fossils and rocks to understand Earth History.
4. How rock units are named and correlated from one locality to another.
5. How the Geologic Column was developed so that relative age could be systematically described.
6. How we can determine the numeric age of the Earth and events in Earth History.

In order to understand how scientists deal with time we first need to understand the concepts of ***relative age*** and ***numeric age.***

- Relative age - Relative means that we can determine if something is younger than or older than something else. Relative age **does not** tell how old something is; all we know is the sequence of events. For example: The a volcano is younger than the rocks that occur underneath it.

- Numeric age- Numeric age means that we can more precisely assign a number (in years, minutes, seconds, or some other units of time) to the amount of time that has passed. Thus we can say how old something is. For Example this metamorphic rock is 3.96 billion years old.

To better understand these concepts, let's look at an archeological example: Imagine we are a group of archeologists studying two different trash pits recently discovered on the Tulane University campus and at the Audubon Zoo (where they all aksed for you). By carefully digging, we have found that each trash pit shows a sequence of layers. Although the types of trash in each pit is quite variable, each layer has a distinctive kind of trash that distinguishes it from other layers in the pits.



What can we say and learn from these excavations?

- Relative age of trash layers - Because of the shape of the pits the oldest layers of trash occur below younger layers i.e. the inhabitants of the area likely deposited the trash by throwing it in from the top, eventually filling the pits. Thus the ***relative age*** of the trash layers is, in order from youngest to oldest.:

    - 5.25" Disk Layer - Youngest
    - Al Cans Layer
    - Tin Cans Layer
    - Ceramic Cups Layer
    - Stone Tools Layer - Oldest

    Notice that at this point we do not know exactly how old any layer really is. Thus we do not know the ***numeric age*** of any given layer.

- The civilizations that deposited the trash had a culture and industrial capabilities that evolved through time. The oldest inhabitants used primitive stone tools, later inhabitants used cups made of ceramics, even later inhabitants eventually used tin cans and then changed to Aluminum cans, and then they developed a technology that used computers. This shows that society has evolved over the years.

- Similar cultures must have existed in both areas and lived at the same time. Thus we can make correlations between the layers found at the different sites by reasoning that layers containing similar distinctive discarded items (artifacts) were deposited during the same time period.

- Because the Ceramic Cups layer is found at the Tulane site, but not at the Zoo site, the civilization that produced the Ceramic cups probably did not live in the Zoo area. Thus, we can recognize a break in the depositional sequence at the Zoo site. The surface marking the break in deposition would be called an ***unconformity*** in geologic terms, and represents time missing from the depositional record.

- The trash pits contain some clues to ***numeric age***:
    - The Tulane trash pit has an old license plate in the Tin Cans layer. This plate shows a date of 1950, thus the Tin Cans layer is about 67 years old.
    - The Zoo trash pit has a Bacchus Doubloon in the Al Cans layer. The date on the doubloon is 1980. Thus the Al Cans layer is about 37 years old.

In geology, we use similar principles to determine relative ages, correlations, and numeric ages.

- Relative ages - Principles of Stratigraphy
- Correlations - Fossils, key beds, lithologic similarity
- Numeric ages - Radiometric dating.

Principles of Stratigraphy

Stratigraphy is the study of strata (sedimentary layers) in the Earth's crust. Geologist in the 1800s worked out 7 basic principles of stratigraphy that allowed them, and now us, to work out the relative ages of rocks. Once these age relations were worked out, another principle fell into place - the principle of fossil succession. We discuss the 7 principles of stratigraphy first and then see how these apply to fossils.

Principle of Uniformitarianism
The principle of Uniformitarianism was postulated by James Hutton (1726-1797) who examined rocks in Scotland and noted that features like mudcracks, ripple marks, graded bedding, etc. where the same features that could be seen forming in modern environments. He concluded that process that are currently operating on the Earth must be the same processes that operated in the past. This principle is often stated as "the present is the key to the past". A more modern way of stating the same principle is that the laws of nature (as outlined by the laws of chemistry and physics) have operated in the same way since the beginning of time, and thus if we understand the physical and chemical principles by which nature operates, we can assume that nature operated the same way in the past.

Principle of Superposition
Because of Earth's gravity, deposition of sediment will occur depositing older layers first followed by successively younger layers. Thus, in a sequence of layers that have not been overturned by a later deformational event, the oldest layer will be on the bottom and the youngest layer on top. This is the same principle used to determine relative age in the trash pits discussed previously. In fact, sedimentary rocks are, in a sense, trash from the Earth's surface deposited in basins.

Principle of Original Horizontality
Sedimentary strata are deposited in layers that are horizontal or nearly horizontal, parallel to or nearly parallel to the Earth's surface. Sediment deposited on steep slopes will be washed away before it is buried and lithified to become sedimentary rock, but sediment deposited in nearly horizontal layers can be buried and lithified. Thus rocks that we now see inclined or folded

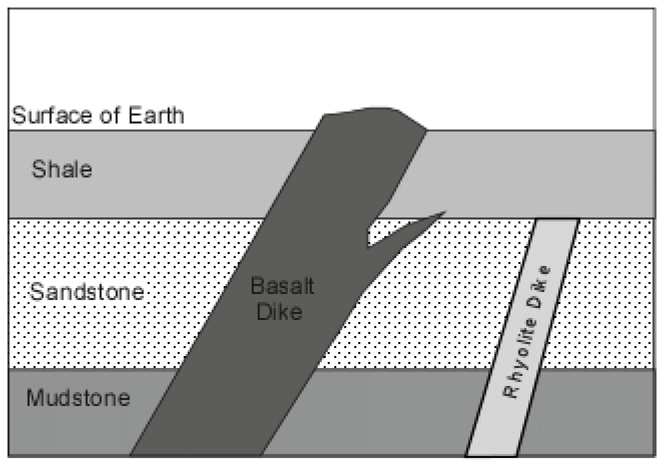
have been disturbed since their original deposition.

Principle of Original Continuity
If layers are deposited horizontally over the sea floor, then they would be expected to be laterally continuous over some distance. Thus, if the strata are later uplifted and then cut by a canyon, we know that the same strata would be expected to occur on both sides of the canyon.

Look at the many photographs of the Grand Canyon in your textbook. Note that you can follow the layers all along the walls of the canyon, and you can find the same layers on both sides of the canyon. The Grand Canyon is particularly good for this because different sedimentary rocks have different colors.

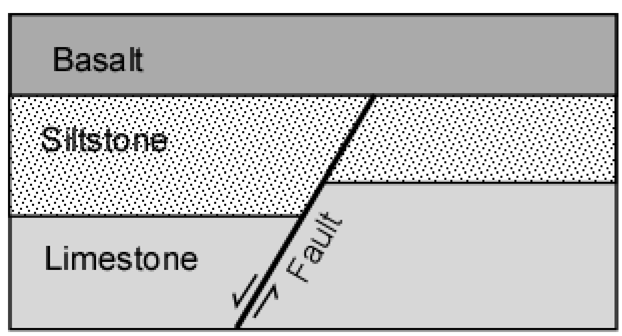
Principle of Cross-cutting Relations
Younger features truncate (cut across) older features. Faults, dikes, erosion, etc., must be younger than the material that is faulted, intruded, or eroded.

For example, the mudstone, sandstone and shale are cut by the basalt dike, so we know that the mudstone, sandstone, and shale had to be present before the intrusion of the basalt dike. Thus, we know that the dike is younger than the mudstone, sandstone, and shale.



Similarly, the rhyolite dike cuts only the mudstone and the sandstone, but does not cut across the shale. Thus, we can deduce that the mudstone and shale are older than the rhyolite dike. But, since the rhyolite dike does not cut across the shale, we know the shale is younger than the rhyolite dike.

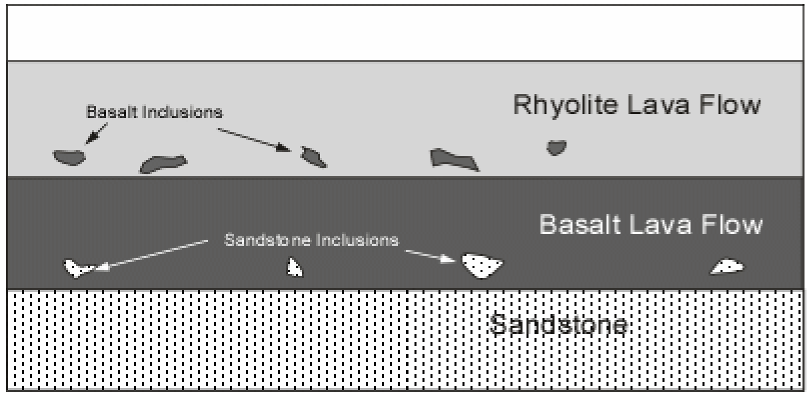
In the diagram to the right,the fault cuts the limestone and the sandstone, but does not cut the basalt. Thus we know that the fault is younger than the limestone and shale, but older than the basalt above.



Principle of Inclusions
If we find a rock fragment enclosed within another rock, we say the fragment is an inclusion. If the enclosing rock is an igneous rock, the inclusions are called xenoliths. In either case, the inclusions had to be present before they could be included in the younger rock, therefore, the

inclusions represent fragments of an older rock.

In the example here, as the basalt flowed out on the surface it picked up inclusions of the underlying sandstone. So we know the sandstone is older than the basalt flow.



Similarly, the overlying rhyolite flow contains inclusions of the basalt, so we know that the basalt is older than the rhyolite.

This principle is often useful for distinguishing between a lava flow and a sill. (Recall that a sill is intruded between existing layers). In the case shown here, we know that the basalt is a sill because it contains inclusions of both the underlying rhyolite and the overlying sandstone.

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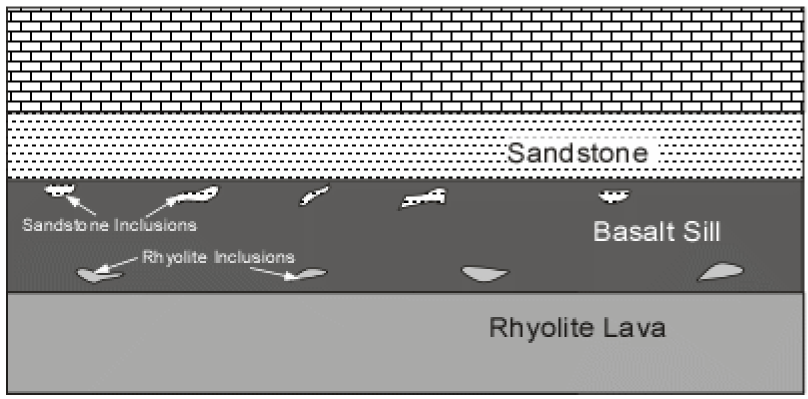
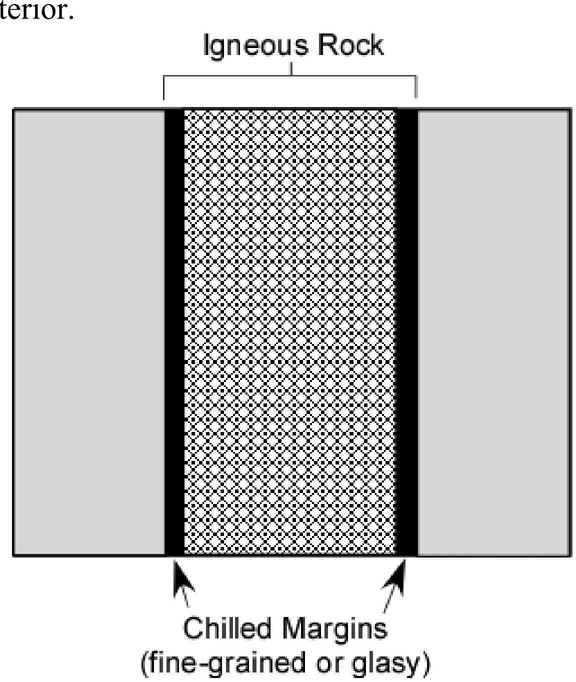


This also tells us that the sill is younger than the both the rhyolite and the sandstone.

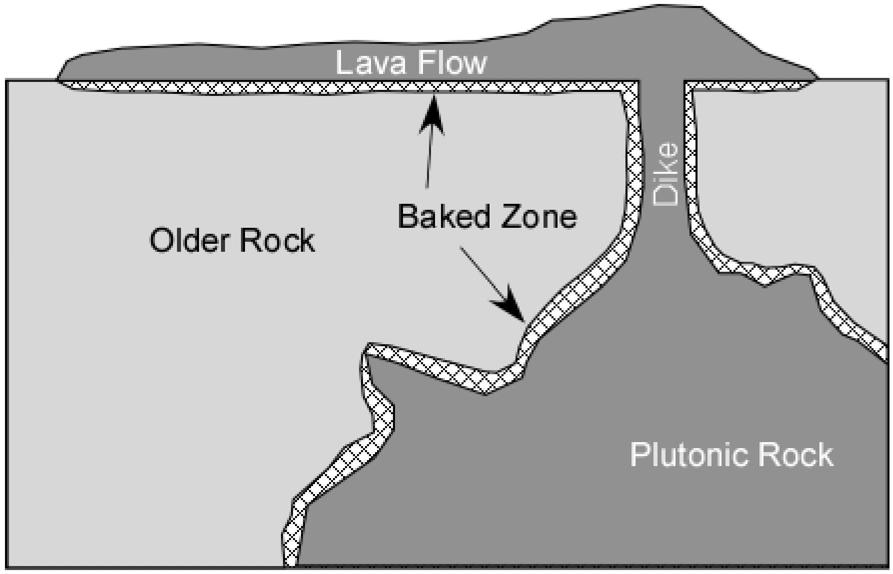
Principle of Chilled or Baked Margins

When a hot magma intrudes into cold country rock, the magma along the margins of the intrusion will cool more rapidly than the interior.

Rapid cooling of magma results in fine grained rock or glassy rock and if this occurs along the margins of the intrusion, we will see the effects of rapid cooling along the margins. Since slower cooling will occur farther away from the margin the rock farther away will be coarser grained. Thus, if we see chilled margins, we know that the intrusions must be younger that surrounding rock because the surrounding rock had to have been there first in order to cause the cooling effect.



When magma comes in contact with soil or cold rock, it may cause the soil or rock to heat up resulting in a baked zone in the surrounding rock near the contacts with the igneous rock. Such margins indicate that the igneous rock is younger that the soil or rock that was baked.



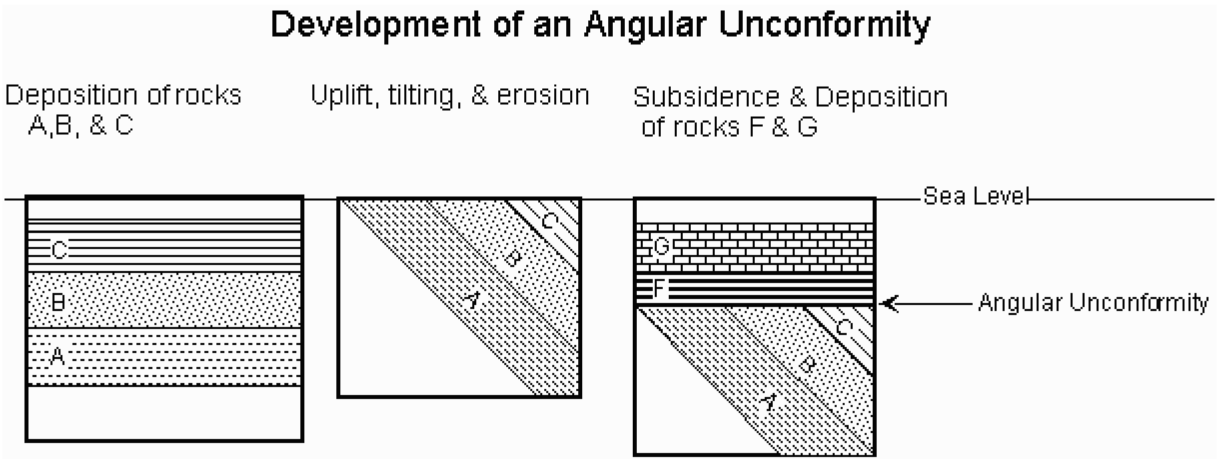
Application of the Principles of Stratigraphy
Figure 12.5 in your textbook shows a cross section of an imaginary sequence of rocks and shows how the geologic history of this sequence of rocks can be worked out by applying the principles of stratigraphy. Although we will go over this in lecture, you should study the methods and reasoning used so that you could determine the geologic history of any sequence of rocks.

Fossil Succession
Once geologists had worked the relative ages of rocks throughout the world, it became clear that fossils that were contained in the rock could also be used to determine relative age. It was soon recognized that some fossils of once living organisms only occurred in very old rocks and others only occurred in younger rocks. Furthermore, some fossils were only found within a limited range of strata and these fossils, because they were so characteristic of relative age were termed ***index fossils***. With this new information, in combination with the other principles of stratigraphy, geologists we able to recognize how life had changed or evolved throughout Earth history. This recognition led them to the principle of fossil succession, which basically says that there is a succession of fossils that relate to the age of the rock.

Unconformities - Breaks in the Stratigraphic Record

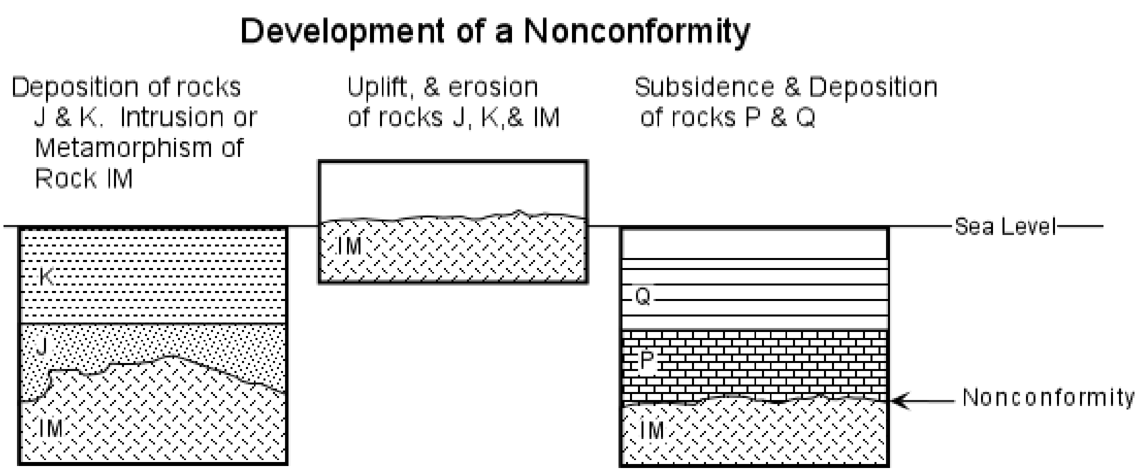
Because the Earth's crust is continually changing, i.e. due to uplift, subsidence, and deformation, erosion is acting in some places and deposition of sediment is occurring in other places. When sediment is not being deposited, or when erosion is removing previously deposited sediment, there will not be a continuous record of sedimentation preserved in the rocks. We call such a break in the stratigraphic record a ***hiatus*** (a hiatus was identified in our trash pit example by the non-occurrence of the Ceramic Cups layer at the Zoo site). When we find evidence of a hiatus in the stratigraphic record we call it an unconformity. An ***unconformity*** is a surface of erosion or non-deposition. Three types of unconformities are recognized.

Angular Unconformity



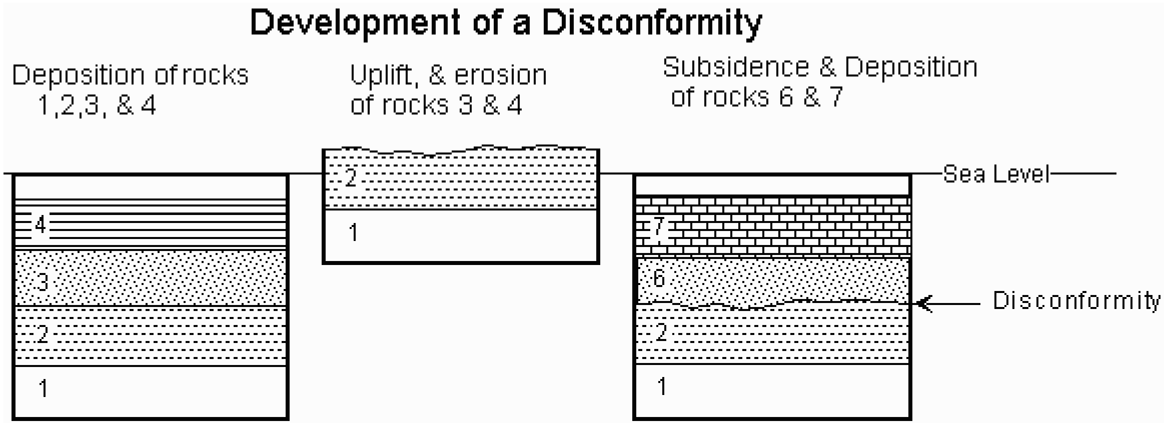
Because of the Principles of Stratigraphy, if we see a cross section like this in a road cut or canyon wall where we can recognize an angular unconformity, then we know the geologic sequence of events that must have occurred in the area to produce the angular unconformity. Angular unconformities are easy to recognize in the field because of the angular relationship of layers that were originally deposited horizontally.

Nonconformity



Nonconformities occur where rocks that formed deep in the Earth, such as intrusive igneous rocks or metamorphic rocks, are overlain by sedimentary rocks formed at the Earth's surface. The nonconformity can only occur if all of the rocks overlying the metamorphic or intrusive igneous rocks have been removed by erosion.

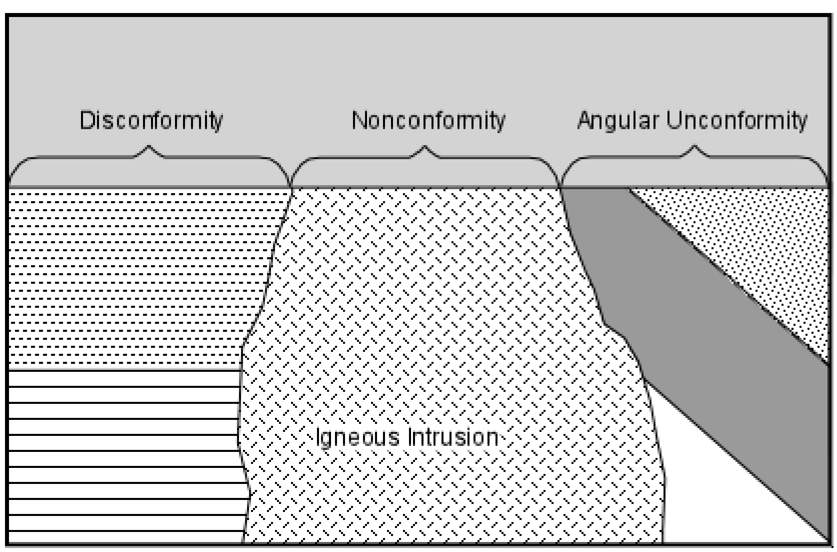
Disconformity



Disconformities are much harder to recognize in the field, because often there is no angular relationship between sets of layers. Disconformity are usually recognized by correlating from one area to another and finding that some strata is missing in one of the areas. The unconformity recognized in the Zoo trash pit is a disconformity.

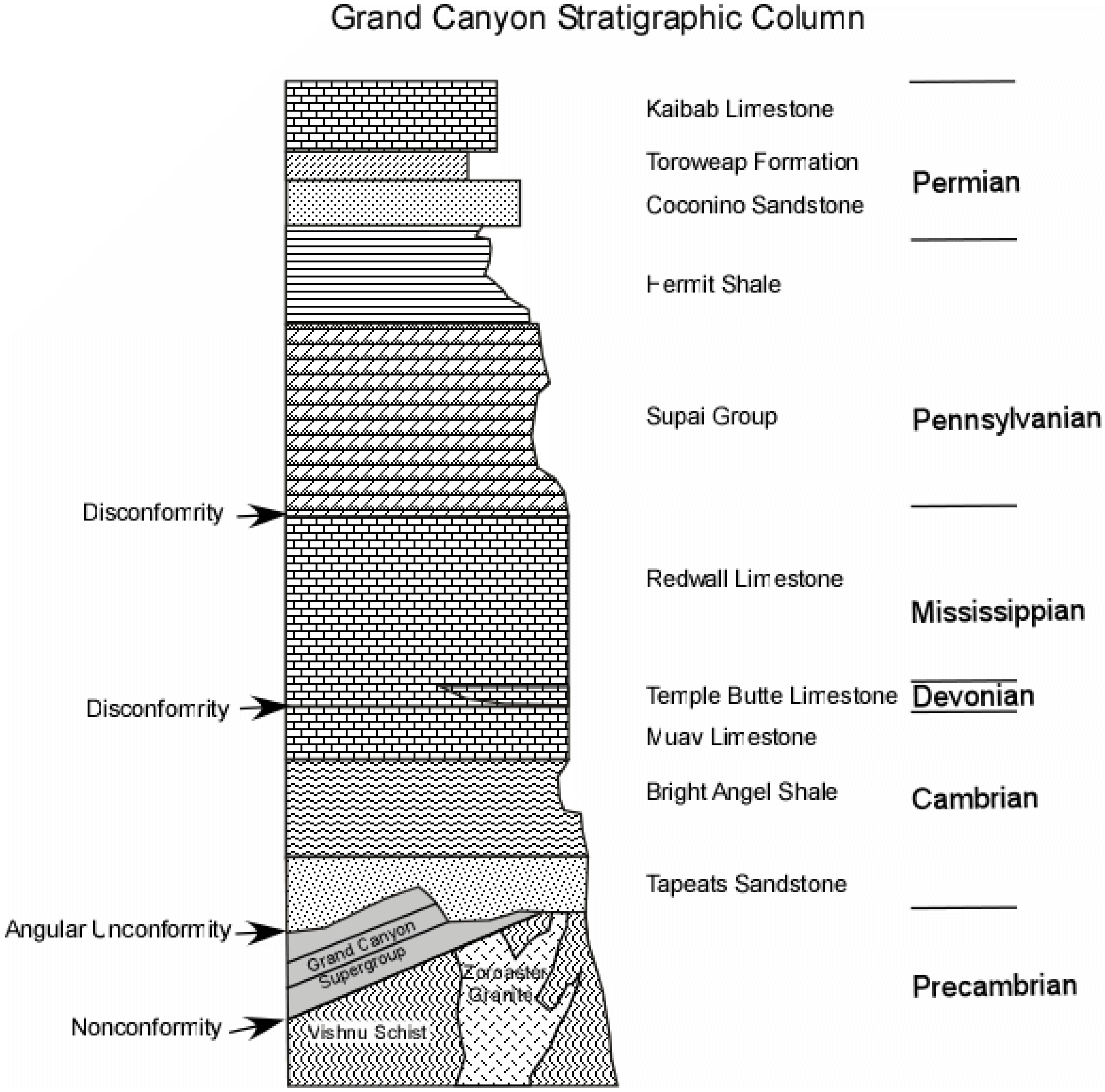
Disconformities can also be recognized if features that indicate a pause in deposition, like paleosols (ancient soil horizons), or erosion, like stream channels are present.

Variation in Unconformities
The nature of an unconformity can change with distance. Notice how if we are only examining a small area in the figure above, we would determine a different type of unconformity at each location, yet the unconformity itself was caused by the same erosional event.



Stratigraphic Formations and Their Correlation

A Formation is a a rock or group of rocks that differ from rocks that occur above or below and have distinctive characteristics and fossils such that the rocks can be recognized over wide areas. Formations are given a formal name, normally a geographic locality. If it is a group of rocks, for example, interbedded sandstones and shales, then it might be called something like the Toroweap Formation. If it is a single rock type, then only the rock name is specified in the formation name, for example the Kaibab Limestone. If several formations can be grouped together as a distinctive set of formations, this called a Group. For example the Supai Group.



Geologist often make a graphic to display stratigraphic information in an understandable way. Such a graphic, as shown above is a called a ***stratigraphic column***. The column shows the relative thicknesses of each Formation or Group, the Formation Name, and gives an approximate idea of whether the rocks are hard- cliff forming units or softer more easily erodable units.

People often say that rocks exposed in the Grand Canyon offer a complete record of geologic history, however this is incorrect. Note that there are several unconformities in the Grand Canyon Stratigraphic Column that represent gaps in the record. For example the Nonconformity near the bottom represent a gap of about 1.5 to 2 billion years. Nowhere on Earth is there a complete section that shows strata deposited over the entire history of the Earth. In the past, some areas were above sea level and being eroded and other areas were below sea level where deposition was occurring. Thus, in order to develop a complete record, correlations must be undertaken in order to see how everything fits together.

Stratigraphic Correlation

In order for rock units to be correlated over wide areas, they must be determined to be equivalent. Determination of equivalence is based first on lithologic similarity. If the rock units have the same type of rocks and look similar then they may correlate. Sometime very distinctive rocks that don't change over large distances can be identified. These are referred to as ***key beds***. Relative age must also be taken into account. If rocks are equivalent they must have the same relative age relationships to surrounding rocks in all areas. Finally, fossils, since they are key indicators of relative age as well as depositional environment, can be used to determine equivalence.

The Geologic Column

Over the past 150 years detailed studies of rocks throughout the world based on stratigraphic correlation have allowed geologists to correlate rock units and break them into time units. The result is the geologic column (on next page), which breaks relative geologic time into units of known relative age.

Note that the geologic column was established and fairly well known before geologists had a means of determining numeric ages. Thus, in the geologic column shown below, the numeric ages in the far right-hand column were not known until recently.

Large divisions are Eons - Oldest to Youngest are

- Hadean (very few rocks of this age are known, thus they are deeply buried if still present at all.
- Archean (Ancient Rocks)
- Proterozoic (Proto means early, zoic is life - so this means early life)

These three units above are often referred to as the Precambrian.

- Phanerozoic (means visible life)

The Eons are divided into Eras (only Phanerozoic Eras are shown in the chart). These include, from oldest to youngest:

- Paleozoic (means ancient life)
- Mesozoic (means middle life, also called the age of dinosaurs)
- Cenozoic (means recent life, also called the age of mammals).

Geologic Time Scale

Eon	Era	Period	Epoch	Age(my)
Phanerozoic (Visible Life)	Cenozoic (Recent Life) (Age of Mammals)	Quaternary	Holocene	0.01
			Pleistocene	1.8
		Tertiary	Pliocene	5.3
			Miocene	23.0
			Oligocene	33.9
			Eocene	55.8
			Paleocene	65.5
	Mesozoic (Middle Life) (Age of Reptiles)	Cretaceous		145
		Jurassic		200
		Triassiac		251
	Paleozoic (Ancient Life)	Permian		299
		Pennsylvanian		318
		Mississippian		359
		Devonian		416
		Silurian		444
		Ordovician		488
		Cambrian		542
Proter-ozoic (Early Life)		Oldest Known Life		2500
Archean		Oldest Known Rocks		3800
Hadean		Age of the Earth		4600

The Eras are divided into Periods. The Periods are often named after specific localities.

The Paleozoic Era has the following Periods:

- Cambrian
- Ordovician (first vertebrate organisms - fish)
- Silurian (first land plants)

- Devonian (first amphibians)
- Carboniferous (in the U.S. this is further divided into: Mississippian and Pennsylvanian (first reptiles)
- Permian

The Mesozoic Era has the following Periods:

- Triassic (first dinosaurs)
- Jurassic
- Cretaceous (first mammals. ended with extinction of dinosaurs).

The Cenozoic Era has the following Periods:

- Tertiary
- Quaternary

Further subdivisions of Periods are called Epochs. Only Epochs of the Cenozoic Era are shown in the Chart.

Note that for this course, you need to know the Eons, Eras, and Periods in age order. You will not be asked about the Epochs (at least for now). Also, you will not be asked to give the numeric ages for the above (at least for now).

Numeric Ages

Although geologists can easily establish relative ages of rocks based on the principles of stratigraphy, knowing how much time a geologic Eon, Era, Period, or Epoch represents is a more difficult problem without having knowledge of numeric ages of rocks. In the early years of geology, many attempts were made to establish some measure of numeric time.

- Age of Earth was estimated on the basis of how long it would take the oceans to obtain their present salt content. This assumes that we know the rate at which the salts (Na, Cl, Ca, and CO_3 ions) are input into the oceans by rivers, and assumes that we know the rate at which these salts are removed by chemical precipitation. Calculations in 1889 gave estimate for the age of the Earth of 90 million years.

- Age of Earth was estimated from time required to cool from an initially molten state. Assumptions included, the initial temperature of the Earth when it formed, the present temperature throughout the interior of the Earth, and that there are no internal sources of heat. Calculations gave estimate of 100 million years for the age of the Earth.

In 1896 radioactivity was discovered, and it was soon learned that radioactive decay occurs at a constant rate throughout time. With this discovery, Radiometric dating techniques became possible, and gave us a means of measuring numeric age.

Radiometric Dating

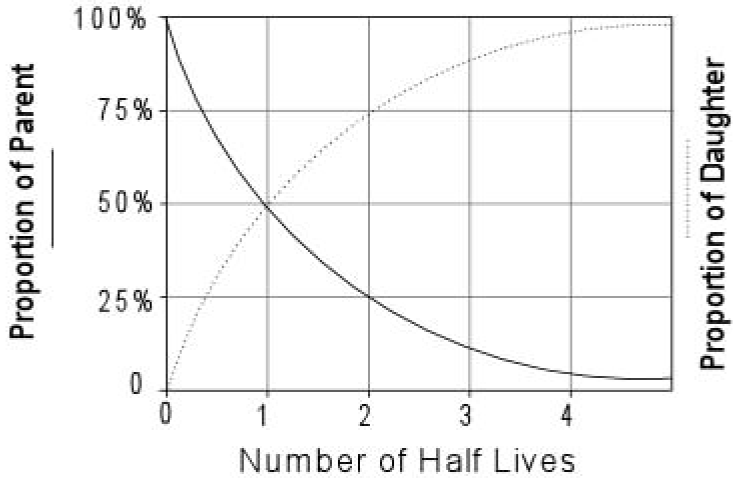
Radiometric dating relies on the fact that there are different types of isotopes.

- Radioactive Isotopes - isotopes (***parent isotopes***) that spontaneously decay at a constant rate to another isotope.

- Radiogenic Isotopes - isotopes that are formed by radioactive decay (***daughter isotopes***).

The rate at which radioactive isotopes decay is often stated as the half-life of the isotope ($t_{1/2}$).

The ***half-life*** is the amount of time it takes for one half of the initial amount of the parent, radioactive isotope, to decay to the daughter isotope. Thus, if we start out with 1 gram of the parent isotope, after the passage of 1 half-life there will be 0.5 gram of the parent isotope left.



After the passage of two half-lives only 0.25 gram will remain, and after 3 half lives only 0.125 will remain etc.

Some examples of isotope systems used to date geologic materials. Note that with the exception of 14C, all techniques can only be used to date igneous rocks. Some elements occur in such small concentration or have such long half lives, that they cannot be used to date young rocks, so any given isotope system can only be used if the material available is suitable for that method.

Parent	Daughter	$t_{1/2}$	Useful Range	Type of Material
^{238}U	^{206}Pb	4.5 b.y	>10 million years	Igneous Rocks and Minerals
^{235}U	^{207}Pb	710 m.y		
^{232}Th	^{208}Pb	14 b.y		
^{40}K	^{40}Ar & ^{40}Ca	1.3 b.y	>10,000 years	
^{87}Rb	^{87}Sr	47 b.y	>10 million years	
^{14}C	^{14}N	5,730 y	100 - 70,000 years	Organic Material

Example: Potassium - Argon (K-Ar) Dating

In nature there are three isotopes of potassium:

- ^{39}K - non-radioactive (stable)
- ^{40}K - radioactive with a half life of 1.3 billion years, ^{40}K decays to ^{40}Ar and ^{40}Ca, only the K-Ar branch is used in dating.
- ^{41}K - non-radioactive (stable)

- K is an element that goes into many minerals, like feldspars and biotite. Ar, which is a noble gas, does not go into minerals when they first crystallize from a magma because Ar does not bond with any other atom.
- When a K-bearing mineral crystallizes from a magma it will contain K, but will not contain Ar. With passage of time, the ^{40}K decays to ^{40}Ar, but the ^{40}Ar is now trapped in the crystal structure where the ^{40}K once was.
- Thus, by measuring the amount of ^{40}K and ^{40}Ar now present in the mineral, we can determine how many half lives have passed since the igneous rock crystallized, and thus know the absolute age of the rock.

Example - Radiocarbon (^{14}C) Dating

Radiocarbon dating is different than the other methods of dating because it cannot be used to directly date rocks, but can only be used to date organic material produced by once living organisms.

- ^{14}C is continually being produced in the Earth's upper atmosphere by bombardment of ^{14}N by cosmic rays. Thus the ratio of ^{14}C to ^{14}N in the Earth's atmosphere is constant.
- Living organisms continually exchange Carbon and Nitrogen with the atmosphere by breathing, feeding, and photosynthesis. Thus, so long as the organism is alive, it will have the same ratio of ^{14}C to ^{14}N as the atmosphere.
- When an organism dies, the ^{14}C decays back to ^{14}N, with a half-life of 5,730 years. Measuring the amount of ^{14}C in this dead material thus enables the determination of the time elapsed since the organism died.
- Radiocarbon dates are obtained from such things as bones, teeth, charcoal, fossilized wood, and shells.
- Because of the short half-life of ^{14}C, it is only used to date materials younger than about 70,000 years.

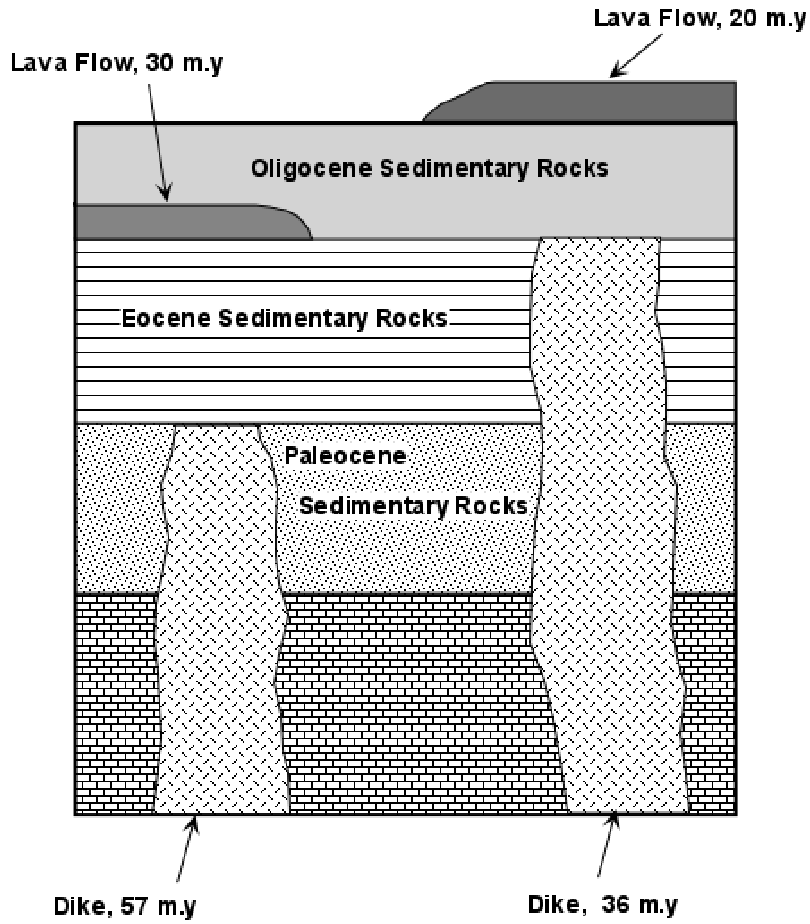
Other Numeric Age Methods

There are other means by which we can determine numeric age, although most of these methods are not capable of dating very old materials. Among the methods are:

- Tree Ring Dating- based on annual growth rings produced by trees.
- Fission Track Dating - based on counting scars left by nuclear decay products in minerals
- The Magnetic time scale, based on reversals of the Earth's magnetic field.

Absolute Dating and the Geologic Column

Using the methods of absolute dating, and cross-cutting relationships of igneous rocks, geologists have been able to establish the numeric ages for the geologic column. For example, imagine some cross section such as that shown below.



From the cross-cutting relationships and stratigraphy we can determine that:

- The Oligocene rocks are younger than the 30 m.y old lava flow and older than the 20 m.y. old lava flow.
- The Eocene rocks are younger than the 57 m.y. old dike and older than the 36 m.y. old dike that cuts through them.
- The Paleocene rocks are older than both the 36 m.y. old dike and the 57 m.y. old dike (thus the Paleocene is older than 57 m.y.

By examining relationships like these all over the world, numeric age has been very precisely correlated with the Geologic Column. But, because the geologic column was established before radiometric dating techniques were available, note that the lengths of the different Periods and Epochs are variable.

The Age of the Earth

Theoretically we should be able to determine the age of the Earth by finding and dating the oldest rock that occurs. So far, the oldest rock found and dated has an age of 3.96 billion years. Individual zircon grains in sandstones have been dated to 4.1 to 4.0 billion years old. But, is this the age of the Earth? Probably not, because rocks exposed at the Earth's surface are continually being eroded, and thus, it is unlikely that the oldest rock will ever be found. But, we do have clues about the age of the Earth from other sources:

- Meteorites - These are pieces of planetary material that fall from outer space to the surface of the Earth. Most of these meteorites appear to have come from within our solar system and either represent material that never condensed to form a planet or was once in a planet that has since disintegrated. The ages of the most primitive meteorites all cluster around 4.6 billion years.
- Moon Rocks - The only other planetary body in our solar system from which we have collected samples of are moon rocks (samples of Mars rocks have never been returned to Earth). The ages obtained on Moon rocks are all within the range between 4.0 and 4.6 billion years. Thus the solar system and the Earth must be at least 4.6 billion years old.

Summary

We have now presented most of the tools necessary to interpret Earth history. These tools include knowledge of different kinds of rocks and the conditions under which they form and the laws of stratigraphy. To make sure you have acquired the knowledge necessary to use these tools, make sure you understand how the interpretations were made in the production of the artwork on pages 454-455 in your textbook and figure 12.5.

Questions on this material that might be asked on an exam

1. Define the following: (a) relative age, (b) numeric age, (c) index fossil, (d) baked zone, (e) chilled margin, (f) key bed, (g) fission track dating.
2. What are the principles of stratigraphy and what is the importance of these principles?
3. What are the three different kinds of unconformities, and what does each tell us about the geologic history when we find one?
4. Be able to interpret the geologic history in terms of relative age if you were to be given any geologic cross section, such as the one shown in figure 12.5 in your textbook.
5. Know the relative ages and names of all of the Geologic Eons, Eras, and Periods in the Geologic Column. Make sure you understand what the prefixes Protero, Phanero, Paleo, Meso, and Ceno mean as well as the suffix -zoic.
6. What is the radioactive half-life, and how is it used to determine numeric age?
7. What is the main difference between Radiocarbon age dating and other methods of radiometric age dating?

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