Some Geology Basics

Geology (geo: 'earth', logos: 'knowledge or study of') is the study of planet Earth. Geology is in many ways the most complex of sciences, as a complete understanding of the workings of the earth requires training in mathematics, chemistry, physics, biology, and astronomy. The study of the Earth brings mathematics, chemistry and physics alive. It provides the opportunity to test many hypothetical and theoretical principles in the real world as we observe chemical reactions in rocks, minerals, water and atmosphere, and physical reactions in earthquakes, landslides and volcanic eruptions. The Earth is a product (a by-product, really) of star formation, and thus requires an understanding of the workings of the cosmos. And all life on evolved on and is intimately related to planet Earth, and our continued existence requires a complete understanding of how the earth works, and how we can continue to utilize the resources on the planet without destroying the ecosystem that we are part of.

The science of geology is generally divided into three subdisciplines: **physical** (the study of Earth materials and processes), **historical** (the study of the origin and development of the Earth), and **environmental** (the interrelationship of humans and the Earth). Our journey through the Colorado Plateau will most certainly touch on all of these areas. What follows is a brief introduction to this fascinating science.

What the Earth is made of

The solid Earth is composed of **rocks** and **minerals**. These two words are often lumped together, but they mean different things.

Minerals are naturally occurring crystalline compounds that can be defined by a specific chemical composition. In practice, the most common minerals are identified by looking at specific physical properties unique to each: the luster (the way the mineral reflects light), the hardness, the presence or absence of cleavage (the tendency to break into flat planes), and many others.

Rocks are solid aggregates or mixtures of one or more minerals. In other words, a mineral is a single compound, and analysis of any part will give the same composition. A rock consists of numerous mineral grains in a solid mass, and thus will provide different compositions as each different part is tested. Rocks are identified as **igneous, sedimentary,** or **metamorphic**, based on their origin.

The Rock Forming Minerals

There are thousands of different kinds of minerals, but over 95% of the earth's crust is igneous rock, and the igneous rocks usually contain no more than a few minerals and most of these are part of just four groups or families: these are called the **igneous rock-forming minerals**. The light-colored minerals are silica-rich and less dense. They are called the **felsic minerals**. The darker **mafic minerals** contain iron and magnesium, are denser, and only melt at high temperatures. The rock forming minerals are readily identified by observing certain basic physical properties.

Feldspar: The most common mineral family, the feldspars come in a variety of colors, including pink, white or gray. The most distinctive property is the tendency of the mineral to split or **cleave** in two directions. One variety, **plagioclase feldspar** may exhibit very fine lines, called **striations,** on some surfaces. These look like record grooves. The pink variety of feldspar is called **orthoclase** or **potassium feldspar**. All the feldspars can scratch glass. Chemically, the feldspars are aluminum silicates with varying amounts of calcium, sodium and potassium.

Quartz: Quartz is easily distinguished by great hardness (scratches glass), clear or light color (many shades are possible: milky, pinkish, purple, smoky, etc.), and unlike the feldspars, it **does not have cleavage**. Instead it fractures into smooth rounded surfaces much like glass does (**conchoidal fracture**). When crystals are present, they have a distinctive hexagonal shape. Quartz is a simple silicate composed only of silicon and oxygen.

Mica: A mineral familiar to most people, mica's most distinctive property is the tendency to **cleave** into very thin sheets. The dark variety is known as **biotite**, while the lighter clear variety is **muscovite**. The micas are softer than glass. Both micas are complex silicates with varying amounts of aluminum, potassium and iron.

Ferromagnesian Minerals: These minerals contain iron and magnesium in their chemical structure and are characterized by relative hardness, dark color (except for the bright green of olivine), and greater density. **Amphibole (hornblende)** is black and has a poorly developed cleavage. **Pyroxene (augite)** is usually greenish-black, also with cleavage. **Olivine** has no cleavage, occurs in granular masses, and has a bright apple-green glassy appearance. It is a main constituent of the Earth's mantle, the very thick layer underlying the thin continental or oceanic crust. It is also known to many as the gemstone peridot.

Sedimentary Rock Forming Minerals

Sedimentary rocks make up only a small percentage of the crust, but sediments and sedimentary rocks cover most of the planet’s surfaces and sea floor. Sedimentary rocks may contain some of the igneous rock-forming minerals (especially quartz), but the process of weathering tends to break the minerals down into new forms.

Clay: Around 70% of all sediments are composed of the clay minerals. The clays are the product of the weathering of feldspars and other igneous rock-forming minerals. They are generally characterized by an **even fracture**, an **earthy (or dull) luster**, and a distinctive **odor** (like moist soil) when wet. The clays are used in ceramics and building materials (adobe and bricks, for instance). Bentonite clay is a form that often develops from the weathering of volcanic ash, and is exposed widely in several formations on the Colorado Plateau, where it presents engineering problems because of the tendency of the clay to absorb water and swell.

Quartz is a very stable mineral at the earth's surface, but it will be much changed by sedimentary processes. Although it is often seen as small glassy grains of sand, in other cases, it occurs in a microcrystalline form called **chert** or **agate**. Microcrystalline quartz is found in many colors and forms, but can be distinguished by its extreme hardness (the only common sedimentary mineral that is harder than glass). Chert was often used by Native Americans to construct arrowheads and spear points.

Calcite and **dolomite** are both **carbonate** minerals. Calcite is often the cement that binds sedimentary rocks together and at times makes up the entire rock (**limestone**). The most interesting property of calcite is the reaction of calcite when hydrochloric acid is dropped on it. It fizzes in a reaction called **effervescence**. Dolomite is similar to calcite in many ways but is less reactive to acid and is slightly harder. The carbonate minerals often develop in warm shallow seas by both organic processes and by chemical precipitation. Dolomite is often secondary, developing when the already formed limestone reacts with magnesium rich groundwater.

Halite and **gypsum** are called **evaporite** minerals, because they precipitate as water evaporates in coastal bays or desert dry lakes. Halite is none other than common table salt, and has cubic cleavage. Gypsum has platy cleavage, and is softer than a fingernail. It is used in a variety of ways, most commonly as drywall and plaster of Paris.

Hematite (reddish brown) and **Limonite** (yellowish brown) are oxides of iron (in the most basic sense they are forms of rust). A small amount of either mineral is sufficient to stain other rocks bright red, brown or yellow. Many of the spectacularly colorful exposures of sedimentary rock in Grand Canyon, Zion and Bryce Canyon result from the presence of these iron oxide minerals.

The Rock Cycle

Essentially all rocks are made of the remains of some kind of pre-existing rock. Igneous rocks develop because some previous rock melted. Sedimentary rocks form because previously exposed rocks were weathered. Metamorphic rocks result when previous rocks are changed by heat and pressure. If they get hot enough, they melt and form magma. This recognition that the crust of the Earth is a vast recycling system was one of the fundamental discoveries that made geology a science two hundred years ago (figure 2).

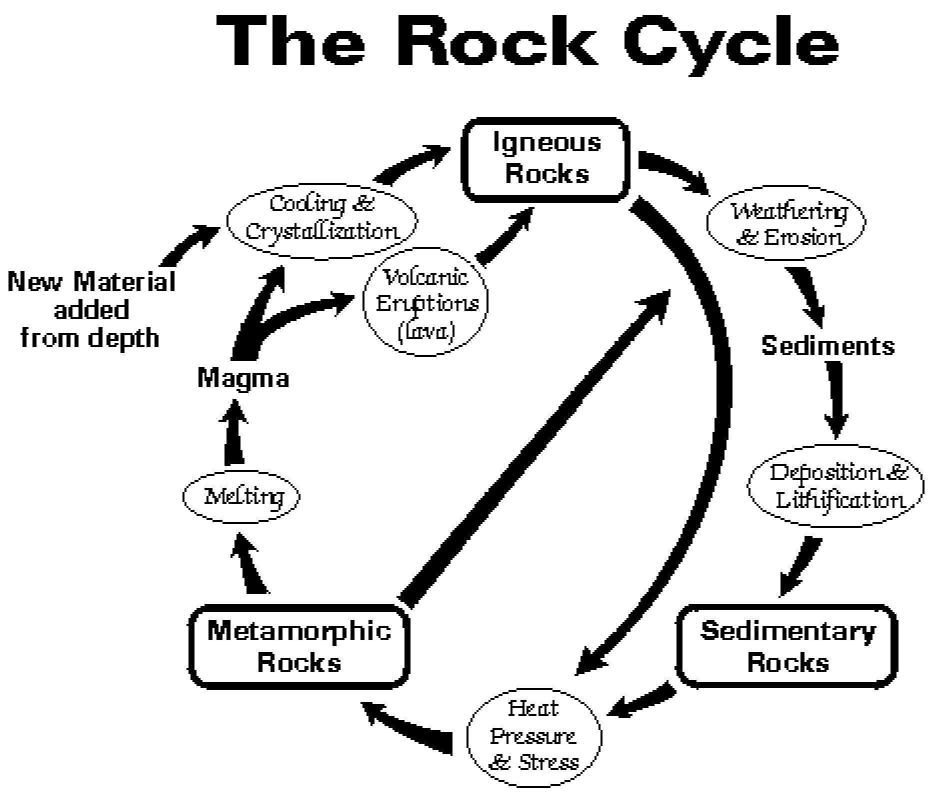

Figure 2: The rock cycle. Source: U.S. Geological Survey

One consequence of the rock cycle model is the recognition that truly ancient rocks are very rare. Once exposed the rocks are eroded and become incorporated into younger rocks. As a result, no rocks on the 4.6 billion year old Earth are older than 4 billion years, and in the western United States, the very oldest rocks date back to only 2.7 billion years. The oldest rocks on the Colorado Plateau are but 1.8 billion years old, less than half the age of the Earth.

Rock Identification

Igneous rocks develop as molten magma cools and crystallizes, either deep underground (plutonic or intrusive igneous) or at the Earth's surface (volcanic or extrusive). **Plutonic rocks** can be identified by their coarsely crystalline appearance, since crystals can grow large enough to see during the long cooling process deep in the crust. **Volcanic rocks** most often have a very fine crystalline structure because of rapid cooling, so that visible crystals are rare or absent (they are visible in a microscope however, with the exception of volcanic glass). The igneous rocks are categorized by the mineral content (felsic, mafic, or intermediate), which means overall color is a good guide to identifying them (Table 1). Obsidian and pumice are composed of volcanic glass and therefore do not have minerals.

Texture	Light (Felsic)	Medium (gray)	Dark (Mafic)	100% Olivine
Plutonic (coarse-grained)	Granite	Diorite	Gabbro	Peridotite
Volcanic (fine-grained)	Rhyolite	Andesite	Basalt	

Others: Obsidian - volcanic glass Pumice - frothy, light, glassy

Table 1: A basic igneous rock classification system

Sedimentary rocks form as a result of weathering and erosion at the surface of the Earth. Exposed rocks of all kinds are broken down by erosive processes into smaller bits and pieces, and many are changed chemically by way of interaction with water, acids, and gases in the atmosphere, especially carbon dioxide and oxygen. The eroded sediments are deposited in a variety of environments on land (**terrestrial**), at sea (**marine**), or at the complex boundary between the two, such as beaches or river deltas (**transitional**). **Clastic** (or **detrital**) sedimentary rocks are composed of fragments of previously existing rocks and are classified by the size of the grains (coarse, medium or fine). **Chemical** sedimentary rocks are the products of chemical reactions such as when seawater evaporates (rock salt is a common example) and are classified on the basis of mineral content. **Biogenic** sedimentary rocks form as the result of organic processes, such as the growth of a coral reef (forming limestone), or the accumulation of undecayed plant material in a swamp (forming coal and peat). They are also classified on the basis of composition (Table 2).

Clastic Sedimentary Rocks

Size of Grains	Shape of Grains or type of layering	Mineral Composition	Rock Name
Coarse, >2mm	Angular Grains	Any mixture of rocks and minerals	**Breccia**
	Rounded to subrounded	Any mixture of rocks and minerals	**Conglomerate**
Medium, 1/16mm - 2mm	Generally angular	quartz with clay and rock fragments	**Graywacke Sandstone**
	Subrounded to Angular	quartz and feldspar, plus micas & femromags	**Arkose Sandstone**
	Subrounded to rounded	Nearly 100% quartz	**Quartz Sandstone**
Fine, <1/16mm	Thin to massive layers	Quartz and clay minerals	**Siltstone**
	Fissile - very thin layers	Clay minerals	**Shale**

Biogenic Sedimentary Rocks

Mineral Composition	Size of fragments or crystals	Type of fragments	Rock Name
Calcite	Large fragments in finer matrix	Fossil shells in matrix of finer limestone	**Fossiliferous Limestone (specify fossil type)**
	Microscopic	Interlocking crystals of calcite	**Microcrystalline Limestone (Micrite)**
	Microscopic, powdery appearance	Microscopic fossils	**Chalk**
Quartz	Microscopic, powdery appearance	Microscopic fossils	**Diatomite**
Hydrocarbons	Massive	Black, 'dusty' surfaces	**Coal**

Chemical Sedimentary Rocks

Mineral Composition	Size of fragments or crystals	Type of fragments	Rock Name
Halite	Varies	Halite crystals	**Rock Salt**
Gypsum	Varies, microscopic to massive	Gypsum crystals	**Gypsum (Gyprock)**

Table 2: A basic sedimentary rock classification system

Metamorphic rocks form when previously existing rocks are buried deeper in the crust, subjecting them to extreme heat and pressure. The heat may be provided simply by deep burial, or by the presence of nearby igneous intrusions. By definition, melting doesn't take place (otherwise the rocks would be igneous), but minerals are changed by the reactions with hot chemical solutions into new and different minerals. Intense pressure results in layering or lineations in the rock referred to as **foliation**. Metamorphic rocks are subdivided on the basis of whether they are foliated or not (Table 3).

Class	Rock Type	Derived From	Characteristics
Foliated	**Slate**	Shale and Volcanic tuff	Splits into flat surfaces 'flagstone', usually darker colors
	Schist	Fine grained sedimentary rocks	Foliation caused by parallel alignment of micas and other platy minerals. Often contains quartz, feldspar or garnet
	Gneiss	Granite and sedimentary rocks	Alternating layers of light and dark colored minerals. Quartz, feldspar, mica and garnet are common minerals
Non-foliated (granular)	**Quartzite**	Sandstone	Hardest of common rocks. Sugary texture, glassy appearance on fresh surfaces
	Marble	Limestone	Similar to quartzite, but much softer. Individual grains show cleavage, effervesces in HCl acid
	Serpentinite	Peridotite	Green and black with polished surfaces.

Table 3: A basic metamorphic rock classification system

Earth Processes: Seeing the Big Picture

To understand what is happening on a small corner of the planet like the Colorado Plateau, it is helpful to know what is happening across the whole planet. A cursory look at a globe suggests that the fundamental features of the Earth are oceans and continents, but this is only partly true. The outer layer of the Earth, the **crust**, is in fact composed of thicker granitic **continental crust**, and thinner basaltic **oceanic crust** (covered by a thin layer of sediment). The crust is generally less than 20 miles (km) thick. Beneath the crust is the **mantle**, a layer composed of peridotite and related ultramafic rocks that extends half way to the core of the planet. The Earth's surface is covered with solid rock, and at first glance the continents and ocean basins seem immutable and unmoving.

Geologists and geophysicists see the outer layers of the Earth differently. The crust and uppermost mantle are indeed seen as layers of solid rock, which they collectively call the **lithosphere**. But beneath the solid lithosphere at a depth of 100 and 200 km (~ 62 and 124 miles) is a layer that is hot nearly to the point of melting, but not quite. This layer, called the **asthenosphere**, is yielding and capable of flow (Figure 3).

The lithosphere is broken up into a series of what are called **plates** (somewhat like the pieces of shell on a broken boiled egg). A half dozen or so of the plates are thousands of miles or kilometers across, while others are considerably smaller (Figure 4). The lithospheric plates slide laterally across the asthenosphere, and it this motion that causes apparent continental drift, but the continents are best understood to be passively riding piggyback on the lithosphere. It is at the boundaries between these plates that many of the most important **tectonic** (Latin: *"to build"*) processes occur, including mountain-building, volcanism, and earthquake activity. In a few short decades, **plate tectonics** has become the prevailing theory in understanding the workings of planet Earth.

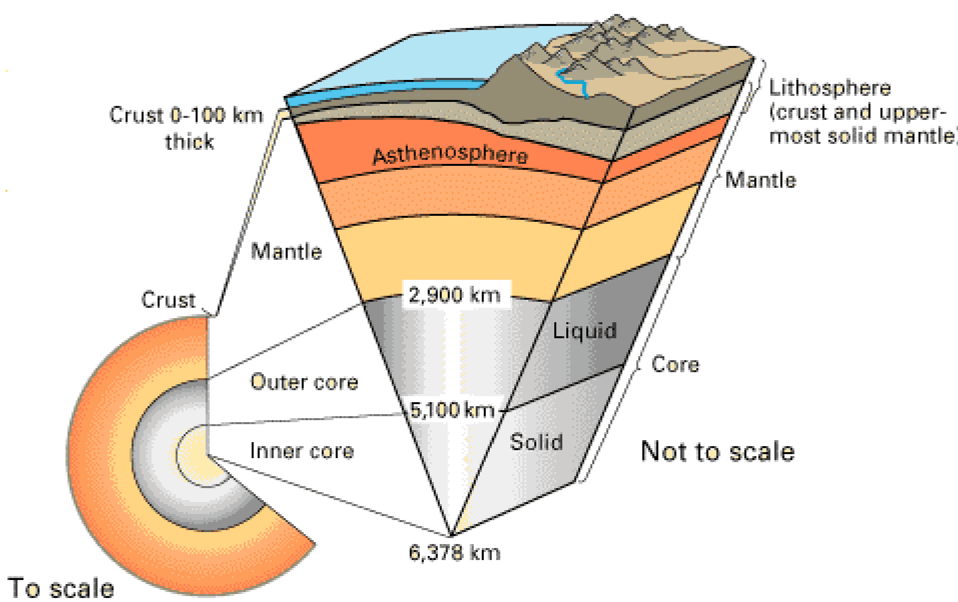

Figure 3: Interior layers of the Earth. Source: U.S. Geological Survey

Plate Boundaries

At boundaries, plates may either **diverge** (separate), **converge** (come together), or slide past each other (**transform** boundary). The plate edges may consist of oceanic crust, continental crust, or both (Figure 5).

At **divergent boundaries**, extensional forces cause the plate edges to move apart, fracturing the crust. The release of pressure in the underlying asthenosphere allows partial melting to take place, and basaltic magma will rise into the fractures as intrusive dikes. The basalt dikes may erupt on the seafloor, forming new oceanic crust. Divergent boundaries can be seen on maps of the ocean floor as **oceanic ridges** and **rift valleys**.

When divergent boundaries occur on continents, the uplift and spreading will result in rift valleys (the Rio Grande Valley in Colorado and New Mexico is an example) and sometimes basin and range topography, such as is found in Nevada and western Utah. Eventually a new ocean basin will form in between the newly separated continents. This is happening today in the Gulf of California, as Baja California separates from mainland Mexico, moving northwest along the San Andreas fault. Basalt flows on continents may form lava plateaus, like the Columbia Plateau in Washington and Oregon, or the Deccan Traps in India.

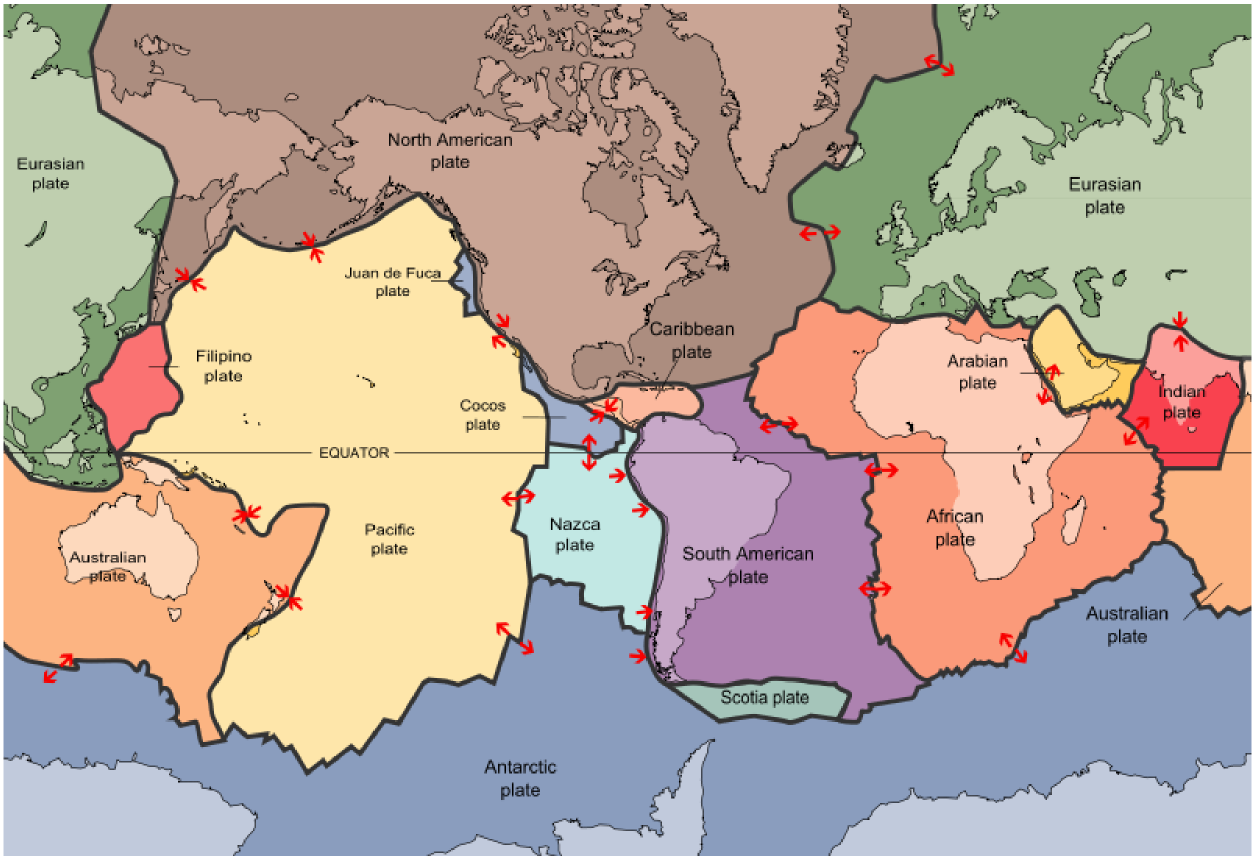

Figure 4: The major plate boundaries. Source: U.S. Geological Survey

Convergent boundaries occur when plates come together, either from compressional forces, or because cold dense oceanic crust is sinking into the mantle. When both plate margins are composed of oceanic lithosphere, one will slide beneath the other, forming a trench and a subduction zone. As the plate sinks into the mantle, it heats up, and water liberated in the subduction process lowers the melting point of the rocks above. Plutons of basaltic and andesitic magma will rise through the crust and erupt onto the seafloor. A system of volcanic islands will develop above the descending plate. Because they have a curving aspect, the system of volcanoes is called an **island arc.** The Aleutian Islands of Alaska are an excellent example.

Continental crust is less dense than oceanic crust, so if one margin of a convergent boundary is continental, the oceanic plate will sink beneath it. A trench will form, but the volcanic arc will be found on land as a chain of andesitic stratovolcanoes called a **magmatic arc**. Deep in the crust, plutons of granite and diorite will intrude and cool off slowly over time. The Cascades Range of Washington and Oregon is an example of a magmatic arc. The Sierra Nevada of California is an example of an ancient magmatic arc that has been uplifted and exposed by erosion.

If two continents converge, neither will be subducted. Instead, the margins of the plate will be pushed upwards into a major mountain range. The Himalayan Range is forming today as the Indian subcontinent is pushing into southern Asia.

A **tectonostratigraphic terrane** (or simply a terrane) is a fault-bound section of crust that has been moved from its point of origin by divergence or transform fault motions. The islands of New Zealand and the Baja Peninsula are present-day examples. Terranes may also collide with the edge of another continent, forming large mountain ranges, although not on the scale of Himalayan convergence. The mountain ranges of southern Alaska formed in this way. The oldest rocks of the Colorado Plateau formed in large part as a result of terrane collisions.

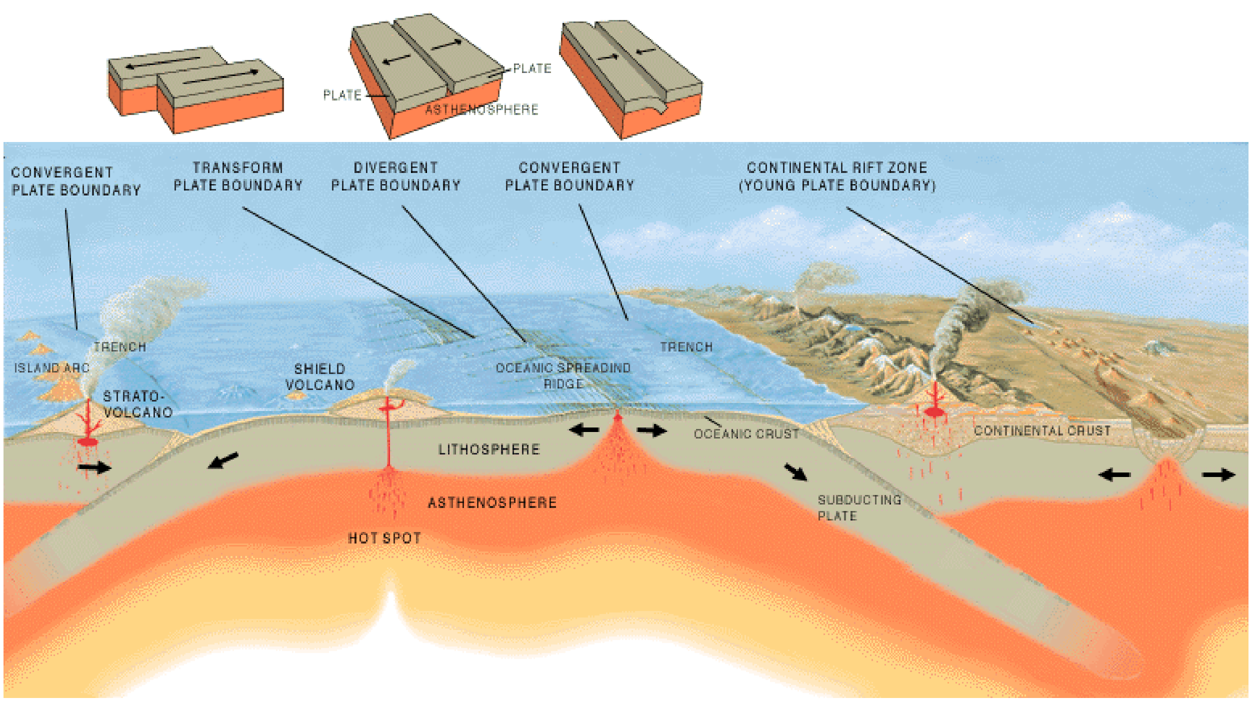

Figure 5: Examples of plate boundaries. Source: U.S. Geological Survey

At **transform boundaries**, plates slide past each other. The San Andreas fault of California is one of the most familiar examples. Transforms are common features of the ocean floor, forming fault zones between the offset edges of mid-ocean ridges.

Geologic Structures

Rocks respond in different ways to stress. They may fracture and shift, forming **faults**, or they may bend, forming **folds**. The types of faults and folds found in an area are clues to the forces that have acted on a landscape, whether compression, extension, or shearing. Erosion of structures can produce an additional feature called an **unconformity**. All of these structures are well-displayed in the Colorado Plateau.

Faults

Everyone should be aware of their faults, and this is especially true in field geology. Faults are defined as breaks in the crust of the earth along which movement has occurred. They can range from minor breaks with offsets of a few inches or feet, to major systems that can have hundreds of miles of offsets, like California's San Andreas fault.

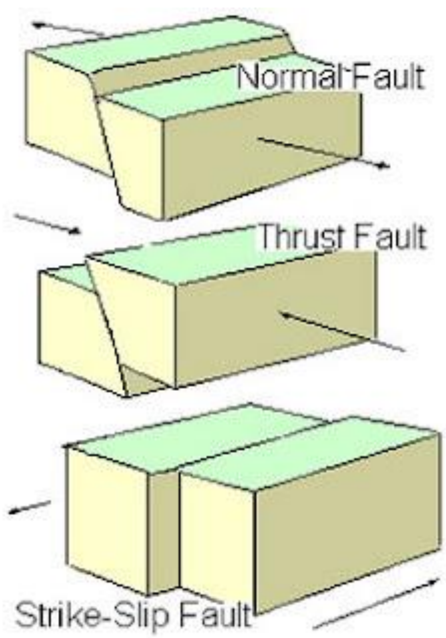

Figure 6: Types of faults. Source: [National Park Service]

As can be seen in Figure 6, there are four basic fault types: ***normal*** (caused by extensional force), ***reverse*** or ***thrust*** (compressional forces), and ***strike-slip*** (the fault above is a ***left-lateral strike-slip***; the blocks would move the opposite direction if they were along a ***right lateral*** fault). Strike slip faults are caused by shearing motion.

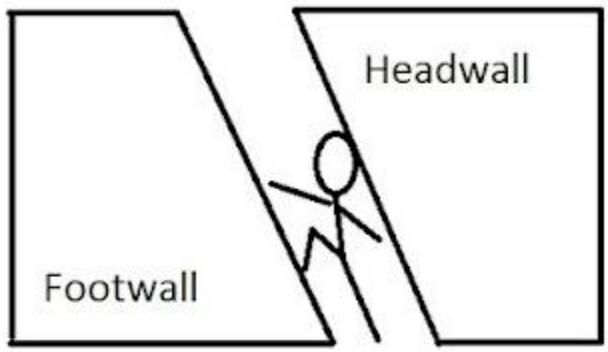

Figure 7: Examples of headwall and footwall

Normal and reverse faults can be distinguished by observing the relative motion of the ***headwall*** and ***footwall*** (Figure 7). Extension causes the headwall move down relative to the footwall, making a normal fault. Compression forces the headwall upward relative to the footwall, forming a reverse fault.

The Colorado Plateau has had a complex history that included periods of extension and compression, so both kinds of dip-slip faults can be seen. A strike-slip fault crosses the Las Vegas Valley.

Folds

Rock layers that have been subjected to stress under conditions of high hydrostatic pressure may bend rather than fracture. A fold in which the center (axis) is pushed upward is called an **anticline** (Figure 8). When the axis is pushed downward, the fold is a **syncline**. Folds may be further defined as symmetrical, asymmetrical, or plunging.

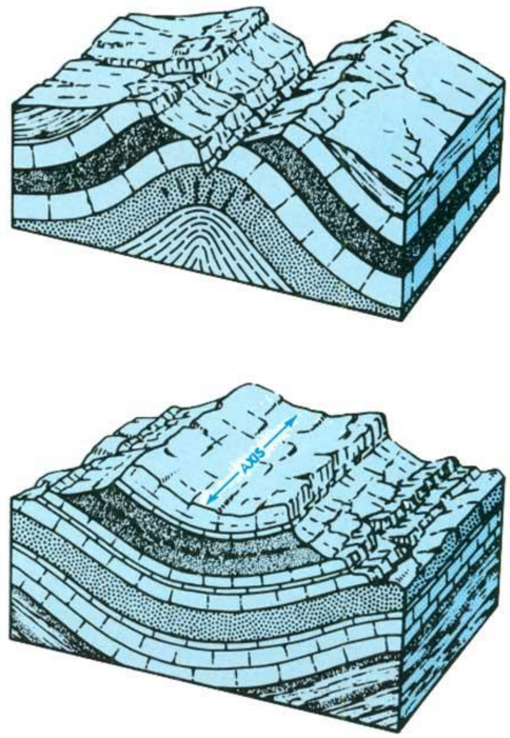

Figure 8: Block diagrams of an anticline and a syncline. Source: National Park Service

A **structural dome** may develop when a pluton of magma or salt pushes upwards in such a way that layers slope away from a center. A **structural basin** has formed if the layers slope towards the center. A step-like fold called a **monocline** may form when a fault breaks rocks at depth but simply bends the overlying layers (Figure 9). Such folds are prominent on the Colorado Plateau, especially at the eastern end of Grand Canyon National Park.

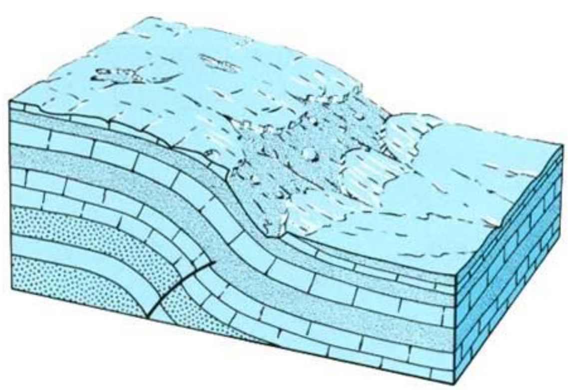

Figure 9: A monocline is a step-like fold which may form over deep faults. Source:NPS.

Unconformities:

No single spot in the world exposes a continuous record of the Earth's history. Erosion has stripped away vast quantities of sediments, and in a series of layers, gaps of many years may be present between those layers. Such buried erosion surfaces are called **unconformities**.

A **nonconformity** is an erosion surface on igneous or metamorphic rocks that has been covered by sedimentary layers (Figure 10). Since these kinds of rocks form deep in the crust, the fact that they have been exposed suggests that a vast amount of uplift and erosion has taken place. A profound nonconformity is found in the depths of the Grand Canyon where Proterozoic metamorphic rocks are capped by the Cambrian Tapeats Sandstone.

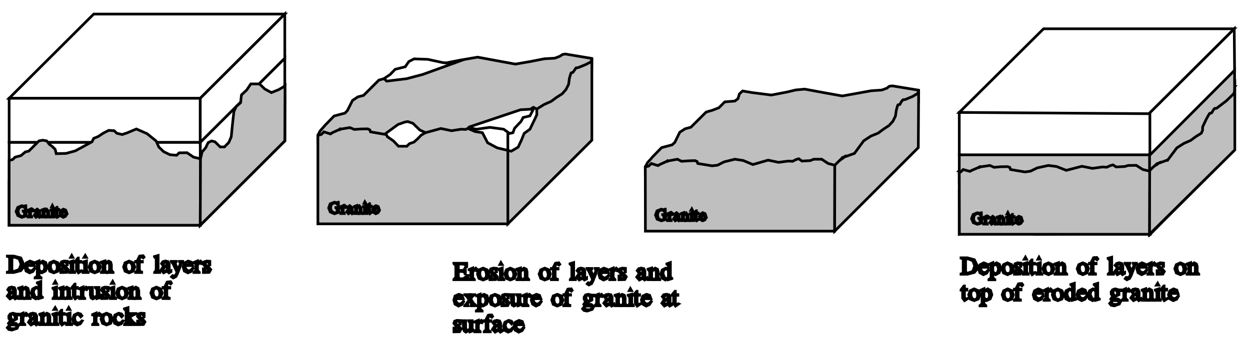

Figure 10: Steps in the development of a nonconformity

An **angular unconformity** occurs when sedimentary layers form and then are tilted and eroded. The tilted layers are then covered by horizontal sediments (Figure 11). Again, the Grand Canyon provides an outstanding example of an angular unconformity where Late Proterozoic sediments of the Grand Canyon Supergroup are covered by Cambrian rocks.

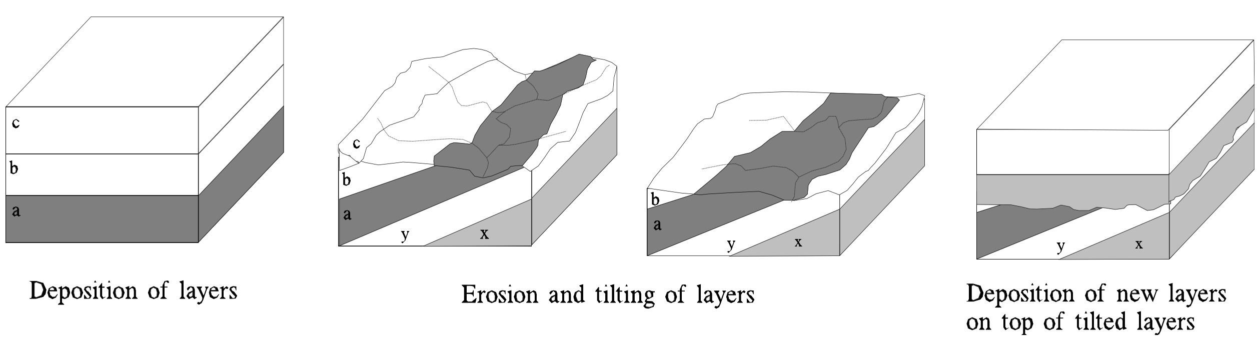

Figure 11: Steps in the development of an angular unconformity.

A **disconformity** happens when horizontal sediments are eroded without tilting. They are covered by other horizontal sediments (Figure 12). Since all the layers are horizontal, it is sometimes difficult to discern a disconformity. River or tidal channels, soil horizons, and the fossil record will often help to identify an erosion surface. Disconformities are common across the Colorado Plateau country, although they are rarely obvious. There are at least 14 in the Grand Canyon Paleozoic sequence alone.

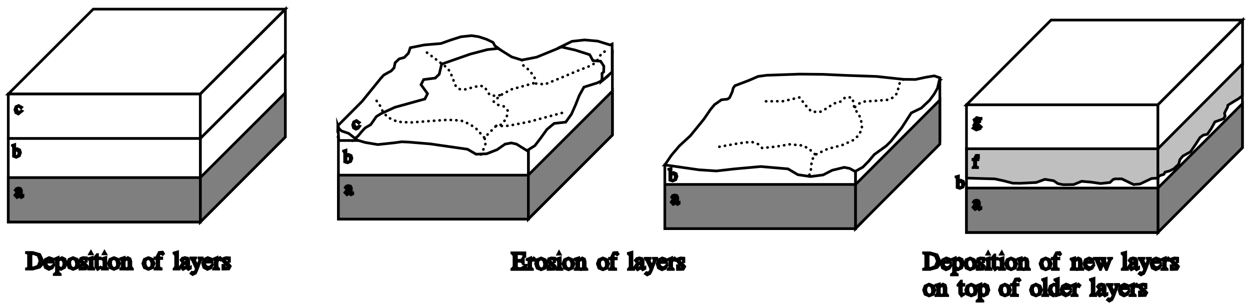

Figure 12: Steps in the development of a disconformity

Geologic History and the Geologic Time Scale

One of the hardest concepts for many to comprehend is that of geological time. Humans live for decades, but geological processes are measured in thousands, millions, and billions of years. A canyon will change little in a human lifetime, a rockfall here and there, but in 10 million years the Grand Canyon can become a reality. It was the acceptance of the overwhelming evidence for the great age of the Earth that made geology a quantitative science in the early 1800s.

It often helps to perceive the immensity of geologic time by using symbols. Grand Canyon National Park has constructed a Trail of Time along the South Rim that does a marvelous job of placing human lives in context with geologic time. The trail begins with markers that allow walkers to see their own age on a scale of one meter per year. The next section places a human lifetime into the context of a million year period. The remainder of the trail compresses one million years into one meter, and displays with rock samples set along the trail describe important geologic events in the history of the canyon. The trail is 2.1 kilometers (1.3 miles) long! The entire history of human civilization (10,000 years or so) encompasses no more than a centimeter (0.4 inch) of that 2.1 kilometer trail!

As geologists and paleontologists worked at understanding the rocks exposed in Europe and North America in the 1800s, they came to realize that major discontinuities existed in the fossil record where major extinctions had taken place. They began to identify eons, eras, periods and epochs based on places where the discontinuities were best exposed. Decades later, radiometric age dating made it possible to pinpoint the age of the rocks in years, resulting in the geological time scale that is used today. It is constantly being refined as more information is gathered about the precise dating of geologic events. The most recent iteration is shown in Figure 13.

Eon	Era	Period		Epoch	Time Began (Million Years)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	1.8
		Tertiary	Neogene	Pliocene	5.3
				Miocene	23.0
			Paleogene	Oligocene	33.9
				Eocene	55.8
				Paleocene	65.5
	Mesozoic	Cretaceous			146
		Jurassic			200
		Triassic			251
	Paleozoic	Permian			299
		Carboniferous	Pennsylvanian		318
			Mississippian		359
		Devonian			416
		Silurian			444
		Ordovician			488
		Cambrian			542
Proterozoic					2500
Archean					4000
Hadean					4560

Figure 13: Geologic time scale (source: U.S. Geological Survey)