GRAND CANYON GEOLOGY TRAINING MANUAL
Learning to Read the Pages of a Book

PREFACE

Imagine you just opened a tattered, dusty, ancient book. As you look through the pages you realize that this very old book contains valuable and wonderful stories of events that took place long ago. Grand Canyon is like this just opened book, except instead of pages you see colorful, picturesque rock layers that hold tales of times long ago. A closer look at the book reveals that some of the pages have been ripped out, and others were never written. It is an incomplete book, yet it contains an overwhelming amount of information. Processes of erosion and weathering have opened the old Grand Canyon book relatively recently, as it is a young canyon carved into very old rocks.

Before you can start to read the geologic story written in the pages of Grand Canyon, you should first understand the words and the language the book is written in. The words are the geologic features observed in the rocks and the language is the science of geology. This training manual will help you to become proficient in the language of geology, especially what is applicable at Grand Canyon. Once you are comfortable reading the geologic story from the pages of Grand Canyon, you can then begin to tell the story to park visitors using your understanding of both the language of geology and techniques for interpreting geology provided in this manual.

The first section of this training manual will introduce the “language” of geology by providing illustrated explanations of fundamental geology concepts that are important at Grand Canyon. In the second section, the concepts are applied to the geology of the Grand Canyon region, as the “language” of geology is used to read the “book” of Grand Canyon geology. The final section is a small toolbox of interpretive tools intended to help you begin to effectively communicate the geologic history of Grand Canyon to park visitors.

Chapter 1: LEARNING THE LANGUAGE OF GEOLOGY

Introduction

Geology is undoubtedly the main reason Grand Canyon was set aside as a national park, therefore it is one of the most important aspects of the park for you and visitors to understand and appreciate. Grand Canyon is a geologic display like nothing else in the world. In terms of geologic research and education, it is a window into the past, revealing vast amounts of information about the Earth and the geologic history of southwestern North America. Looking down into the canyon gives you a glimpse nearly 2 billion years back in time. As you walk along the canyon rim, you step upon rocks that are a mere 270 million years old. And the huge, deep canyon (that you may fall into if you don't watch where you step!) is *only* 5 to 6 million years old. Not only are you at one of the most popular places in the world to visit, but also a place that is so informative that it is highlighted in almost *every* geology textbook. The canyon is a very deep (1 mile/1.6 km), very wide (5-18 miles/8-29 km), and incredibly long (277 miles/446 km) classroom. There is *no place* in the world with geology so simply, yet so dramatically displayed as at Grand Canyon!

However, what many people fail to see is the dynamic link between geology and all of the other natural resources in the park. Geology gives us insight into past ecosystems, which in turn, helps us to understand the present environment we live in and how the future may be shaped. For example, water has shaped the canyon, and without it there would be no Grand Canyon. Water also determines where life can exist in the desert. Often where water is found, you will find diverse ecosystems with a wide variety of plants and animals. Before we can improve the future of any endangered species in the park, we must understand the different effects geology has on a habitat, such as the availability of water. Studying the history of the Earth provided in the rock record gives us tremendous power to understand ecosystem dynamics and improve the future of our planet.

One of the goals of an interpretive park ranger at Grand Canyon National Park is to help visitors realize the importance of the park's resources and the need for preservation of the natural and scenic beauty. To achieve this goal, visitors must experience a connection with the park and develop an understanding of its value. At Grand Canyon, interpreters have an exciting and challenging opportunity to share with visitors some of the chapters in Grand Canyon's geologic story and help them see value in the pages of the book that have been exposed. Just as words on a page alone do not convey the author's intent, we need interpretation to convey the meaning and importance of the geologic story to park visitors.

GEOLOGY AT GRAND CANYON

Geology is a broad term describing the study of the Earth and the processes that shape it. The science of geology is divided into many different specialties, most of which

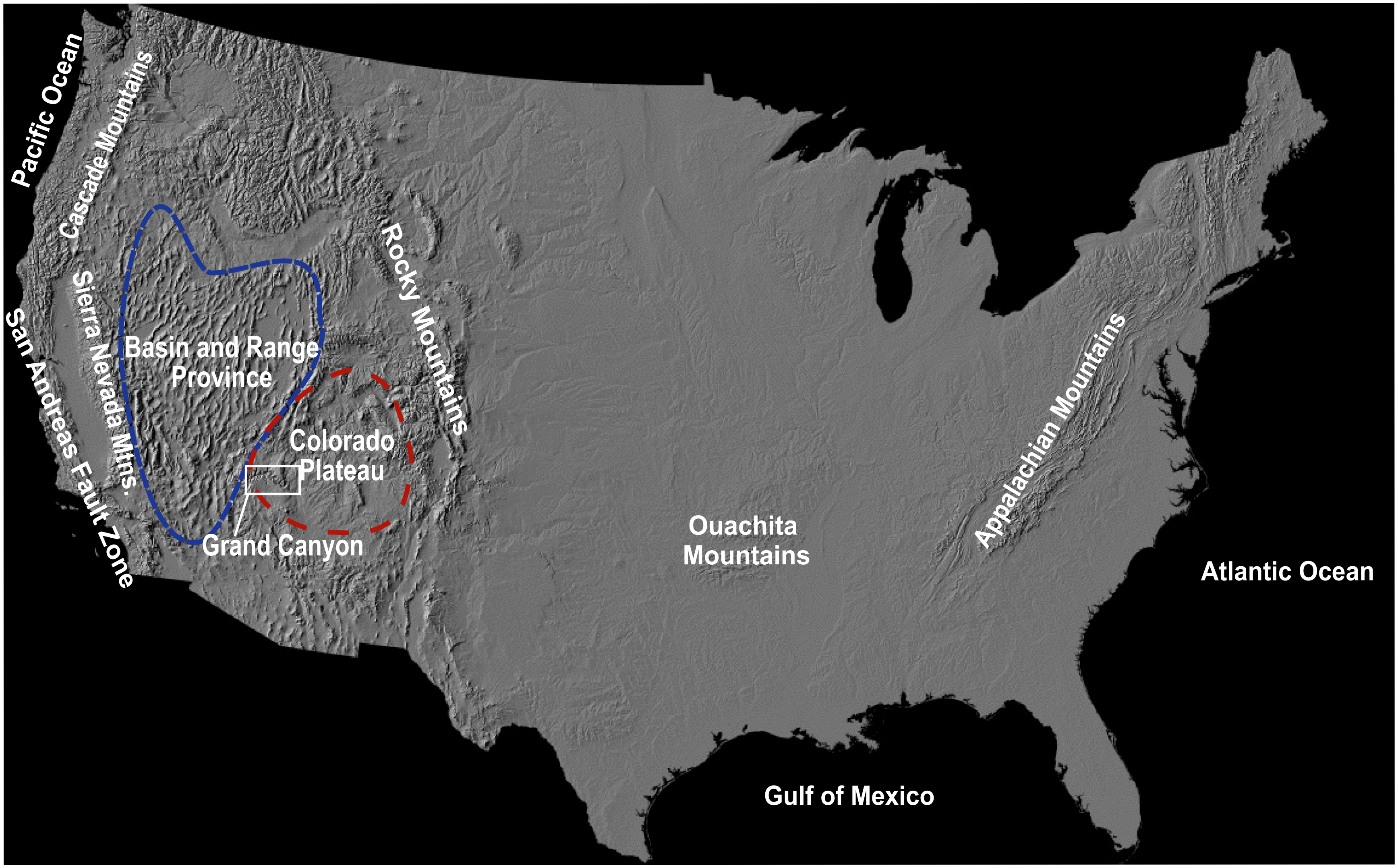


Figure 1.1 – Shaded relief map of United States. *Large landscape features, such as long mountain belts, broad flat plateaus, and rift zones, have formed as a result of millions of years of tectonic plate interactions. The Basin and Range Province is a large region that is presently being pulled apart by tectonic forces. The Rocky Mountains and Colorado Plateau were uplifted to their present elevation by relatively recent mountain building events (since 70 million years ago). Grand Canyon lies on the southwestern edge of the Colorado Plateau, adjacent to the Basin and Range Province.*

are applicable to Grand Canyon. One such study area is **plate tectonics**, which focuses on the movement of continental and ocean plates and the development of large-scale geologic features, like the ones seen in Fig. 1.1. Plate tectonics helps to explain why the layered rocks of Grand Canyon, which were formed near sea level, are now at 7000 feet (2100 m) *above* sea level. **Stratigraphy** is especially useful at Grand Canyon because it is the study of the “strata,” or the layers of rock. The stratigraphy holds a vast amount of information about past environments that existed when the rock layers formed. Another aspect of geology is **structural geology**, which involves the study of the deformation of the Earth’s crust. Structural geology explains why some of the rocks in the canyon are tilted, folded, and faulted, while other layers appear perfectly flat. **Hydrology**, the study of the movement of water, is useful in understanding the development and the behavior of the Colorado River and its tributaries. **Geomorphology** investigates the geologic and erosional processes that shape the Earth’s surface. It can be used to study the erosional forces that have carved Grand Canyon and created the picturesque canyon walls. There are many other facets of geology that are studied in Grand Canyon, but these are the focus of this training manual as they are the most fundamental to understanding of the essence of Grand Canyon geology.

> Have you listened to the Earth? Yes, the Earth speaks, but only to those who can hear with their hearts. It speaks in a thousand, thousand small ways, but like our lovers and families and friends, it often sends its messages without words. For you see, the Earth speaks in the language of love. Its voice is in the shape of a new leaf, the feel of a water worn stone, the color of evening sky, the smell of summer rain, the sound of night wind. The Earth’s whispers are everywhere… (Steve van Matre, *The Earth Speaks*, © 1983, The Institute for Earth Education)

PLATE TECTONICS

At first glance, Grand Canyon and plate tectonics may seem unrelated because the canyon is far from any plate boundaries. But when we begin to look at the rocks that make up the canyon, we see that they provide abundant information about past plate movements and the present geology of western North America. Plate tectonics helps explain why we have such intriguing geology at Grand Canyon – a relatively young canyon carved into old rocks that were deposited more than 270 million years ago.

Scientists believe the Earth and our Solar System began when a vast nebula of dust and gases coalesced to form the sun and the nine planets around 4540 million years ago. After millions of years, the matter that makes up the Earth had differentiated into the three fundamental layers of the Earth: the **crust**, **mantle**, and **core** (Fig. 1.2a). These layers are distinguished by their *chemical composition* because each layer consists of different materials. The crust is composed of minerals rich in oxygen and silica called **silicates**. The mantle is dominantly heavy silicates rich in iron and magnesium, and the core is composed of very heavy iron and nickel.

Food analogies. Food items are analogous to many geologic concepts and can be a useful and fun interpretive tool to use. For example, peanut M&M's® are great representations of the Earth's inner layers. The Earth's crust is like the thin candy coating on the M&M®, with the chocolate as the mantle, and the peanut as the core. Each layer of the peanut M&M's® are made up of different material, just like the divisions of the Earth are chemically distinct.

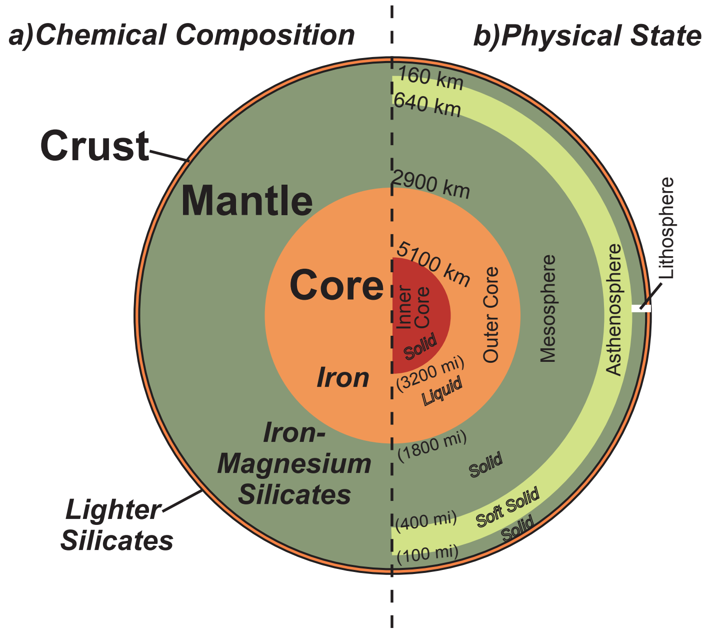


Figure 1.2 – The Earth's inner layers. *a) The left half shows the divisions of the Earth based on chemical composition (what the layers are made of). When the Earth was forming, the crust, composed of minerals rich in oxygen and silica called silicates, floated and formed the very thin crust. The mantle formed below, and is made of heavier silicates rich in iron and magnesium. Very heavy iron with some nickel-rich materials settled in the center to form the core. b) The right half shows the divisions of the Earth based on the physical state of the material. The basic chemical divisions of the Earth can be further subdivided according to whether they are solids, soft solids, or liquids. These layers are the solid lithosphere, soft solid asthenosphere, solid mesosphere, liquid outer core, and solid inner core. The lithosphere is the outer layer (which includes the crust and outermost mantle) that is broken up into tectonic plates that move on top of the softer asthenosphere. (Diagram adapted from R.J. Lillie)*

In the early 1900's, geologists began studying seismic waves to get a better understanding of the inside of the Earth. **Seismic waves** are vibrations of energy that travel through the Earth after a sudden movement of rock, such as an earthquake. By examining changes in the velocity of seismic waves, geologists found that some layers of the Earth are solid, and other layers are partially molten or liquid (Fig. 1.2b). The discovery of the different *physical states* of the material inside the Earth led to the development of the **Theory of Plate Tectonics**. This theory explains a lot about why the Earth looks the way it does, such as how the continents have shifted positions over time (continental drift) and how new ocean floor is created at mid-ocean ridges (sea-floor spreading).

Tectonic plates are large pieces of the Earth's hard outer shell that move slowly over the Earth's surface. These plates are pieces of **lithosphere**, which is the Earth's hard outer layer. The lithosphere is made up of both the crust and the uppermost part of the mantle. Notice the depth of the lithosphere in Fig. 1.2b. Grand Canyon seems deep to us (about 1 mile/ 1.6 km), but it is just a little scratch on the Earth's surface compared to the whole lithosphere thickness (about 100 miles/160 km).

Learning the lingo. The crust and the lithosphere are often confused and used interchangeably, but this is incorrect. They are not the same. The crust is actually the uppermost thin layer of the lithosphere. Beneath the crust, the upper solid portion of the mantle makes up the bottom part of the lithosphere. The lithosphere might be thought of as the roof on a house. The shingles are analogous to the thin crust, and the thicker boards below are like the hard upper mantle.

Below the lithosphere is the **asthenosphere**, which is also part of the mantle, but it is softer because it is hotter. The Earth's temperature increases with depth, so the asthenosphere is hotter than the lithosphere. The lithosphere is like butter that is cold and stiff after being in a refrigerator. Because it is warmer, the asthenosphere behaves similar to butter at room temperature, still a solid but softer than cold butter. Just as temperature increases with depth within the Earth, pressure also increases, causing some layers to actually behave as solids even at high temperatures. For example, the mesosphere is even hotter than the asthenosphere, but because it is under more pressure it is a solid layer (Fig. 1.2b).

Tectonic Plate Movement

Tectonic plates move on convection currents circulating in the soft, ductile asthenosphere. Asthenosphere material moves in much the same way as heat circulates in a convection oven (Fig. 1.3). Convection of heat has slowly moved plates in different directions through geologic time. As you read this page, notice your fingernails – the North American Plate is moving southwestward at a rate of about 2 inches (5 centimeters) per year, approximately the rate that your fingernails grow!

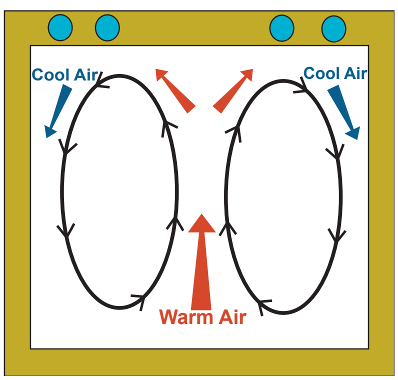


Figure 1.3 – Convection currents. *The Earth's asthenosphere circulates in a similar way as air in an oven. As heated air rises and then cools, it drives circulation by convection, which occurs because of differences in density. Cool air is denser than warm air, so it sinks while warm air rises. In this diagram the convection currents circulate the hot air upward in the center, which then cools and sinks as it reaches the top and sides. In a similar fashion, hot mantle material rises and is cooled as it nears the Earth's surface causing it to sink. This repeated circulation of soft mantle material in the asthenosphere drives the movement of the overlying lithosphere plates.*

As plates of lithosphere move, they have different interactions with each other (Fig. 1.4). **Divergent plate boundaries** exist where two plates rip apart, and move away from one another (Fig. 1.5a). Small, shallow earthquakes can occur and volcanoes usually form along these boundaries. Two plates are moving away from each other at the Mid-Atlantic Ridge, located beneath the Atlantic Ocean (Fig. 1.4). Hot molten material rises to the surface along the plate boundary forming new ocean crust.

A new divergent plate boundary may someday form west of Grand Canyon in the **Basin and Range Province** (Fig. 1.1). The

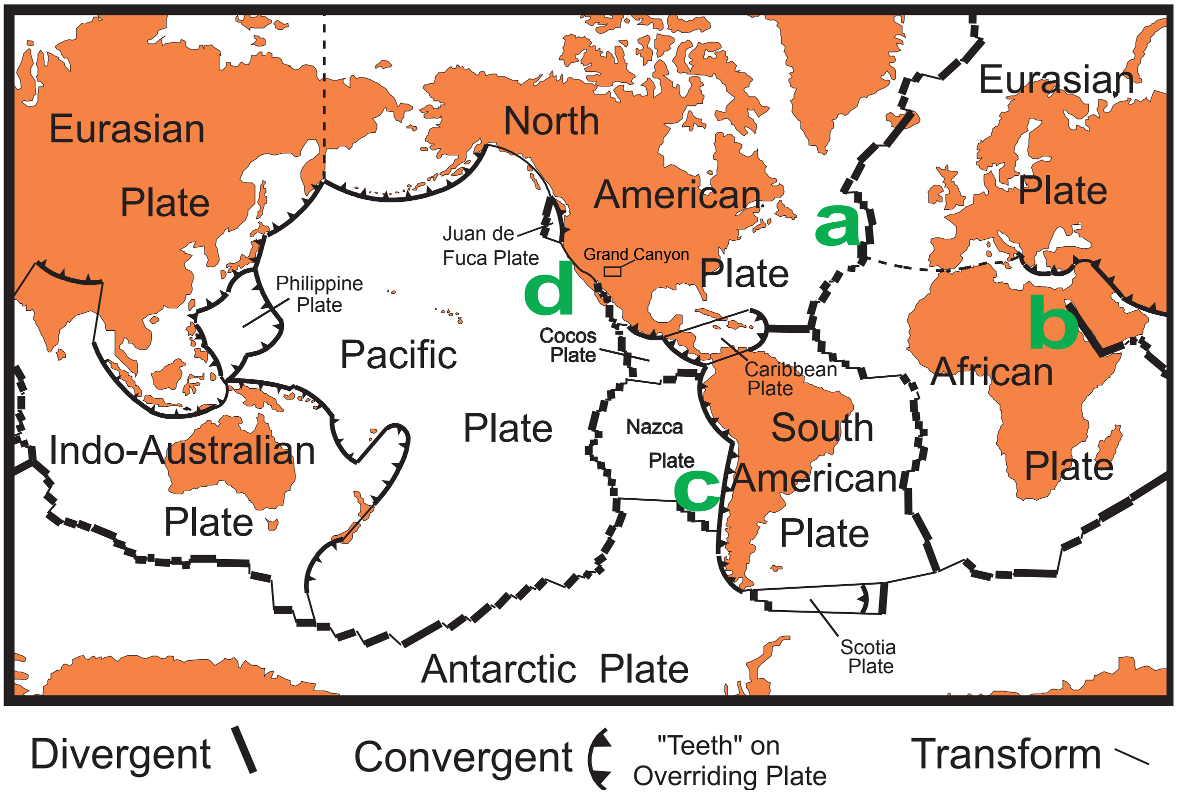


Figure 1.4 – Tectonic plates. *Tectonic plates are constantly moving and interacting with each other on the Earth's surface. In some places, such as the Mid-Atlantic Ridge (a) or East African Rift (b), plates are moving away from each other at a* ***divergent plate boundary.*** *Where plates are moving towards each other at a* ***convergent plate boundary****, one plate is usually shoved beneath an overriding plate, such as along the western coast of South America (c). Plates can also slide past each other, such as along part of western North America (d), forming a* ***transform plate boundary****. Although Grand Canyon is not presently on a plate boundary, the geology has been shaped by past plate interactions. Note that western North America is an active continental margin. It is actively interacting with the Juan de Fuca, Pacific, and Cocos Plates. In contrast, the eastern side of North America is a passive continental margin. This means that edge of the continent is not along a plate margin and it is passively moving westward behind the rest of North America. Most of the layers of rock exposed in Grand Canyon were formed when western North America was a passive continental margin. (Diagram by R.J. Lillie)*

Basin and Range Province seems to be an analog to the early phases of the East African Rift Zone, where the Arabian Plate is now pulling away from the African Plate (Fig. 1.4). As the North American Plate slowly rips apart in an east-west direction long valleys (basins) and mountains (ranges) have formed like stretch marks on the Earth's surface. Grand Canyon ends as the Colorado River enters the Basin and Range Province. The tectonic activity in the Basin and Range has had important effects on the development of the Colorado River and recent deformation of rocks in Grand Canyon (in the last 1 million years).

At a **convergent plate boundary**, where two plates slowly collide, one plate often slides (subducts) beneath the other, creating a **subduction zone** (Fig. 1.5b). An ocean plate called the Juan de Fuca Plate is currently subducting beneath the edge of the North American Plate along northern California, Oregon, and Washington (Fig. 1.4).

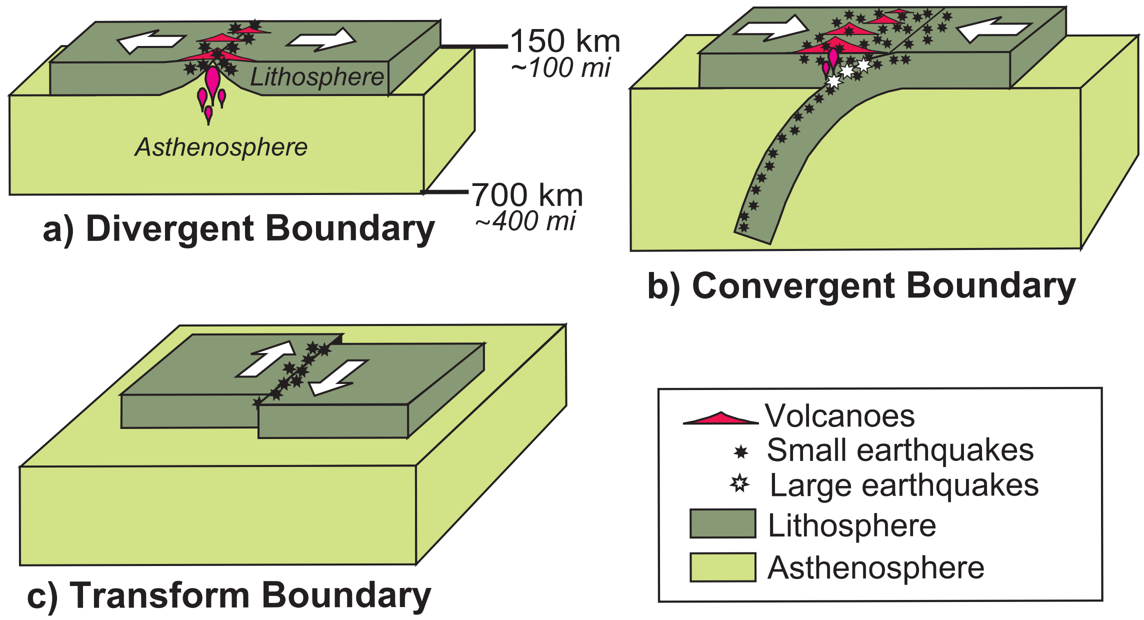


***Figure 1.5 – Types of tectonic plate boundaries.** These schematic diagrams depict what the Earth might look like if you could slice through it at a plate boundary. White arrows show the direction of movement of the plates relative to each other. a) Where plates diverge, new lithosphere is created as hot molten material rises from the asthenosphere and cools. As it cools, it attaches to the diverging plates. b) Where plates converge, one plate usually gets pushed down beneath the other. The heavier, denser plate is subducted, while the more buoyant plate rides over top. Volcanoes are created on the overriding plate, as the subducting plate "sweats" hot fluids that melt rock as they rise. c) At a transform plate boundary, earthquakes occur as the plates slide past each other. Volcanoes do not usually form at this type of plate boundary. (Diagram adapted from R.J. Lillie)*

As an ocean plate subducts into the hot asthenosphere, it "sweats" very hot fluids that melt rock as they rise up through the overriding plate. Where the molten rock material spews onto Earth's surface, it forms volcanoes, such as the Cascade Mountains in the Pacific Northwest (Fig. 1.1). Large earthquakes occur where the down-going ocean plate rubs against the overriding continental plate. The entire western margin of North America was a subduction zone from approximately 250 to 45 million years ago. This subduction zone has likely contributed to the uplift of the Grand Canyon region (see pages 68-69).

A **transform plate boundary** forms where two plates slide past one another (Fig. 1.5c). Along western California, the Pacific Plate is moving northward, sliding past the North American Plate, creating the San Andreas Fault Zone (Fig. 1.4). Large, shallow earthquakes are common along transform plate boundaries due to the plates slowly scraping past each other.

Development of High Elevation

Have you ever wondered why our planet looks the way it does? From outer space, the planet appears to have green and brown landmasses that float above vast blue oceans. Some places have tall, snow-capped mountains while other nearby regions are broad, flat lowlands. Plate tectonics helps us understand how these different landscapes developed.

Think about an iceberg. An iceberg floats on seawater like the Earth's crust floats on the mantle. An iceberg is less dense than seawater, so it floats, just like crust is less dense than mantle, causing it to float. Now consider that most of an iceberg is actually found below the water and the thicker it is, the higher it can float. Similarly, the thicker the Earth's crust is, the more overlying mass it can support. Oceans cover parts of the Earth because the crust beneath the ocean is thin **ocean crust**. The land stands above the water because it is made up of thick **continental crust** (Fig. 1.6). The thickness of continental crust ranges from 12 to 45 miles (20 to 70 km), and provides support beneath the Earth's surface to keep the continents above sea level. Ocean crust is only 2 to 5 miles (3 to 8 km) thick so it sits on the mantle at a much lower level than continents and is covered by the sea.

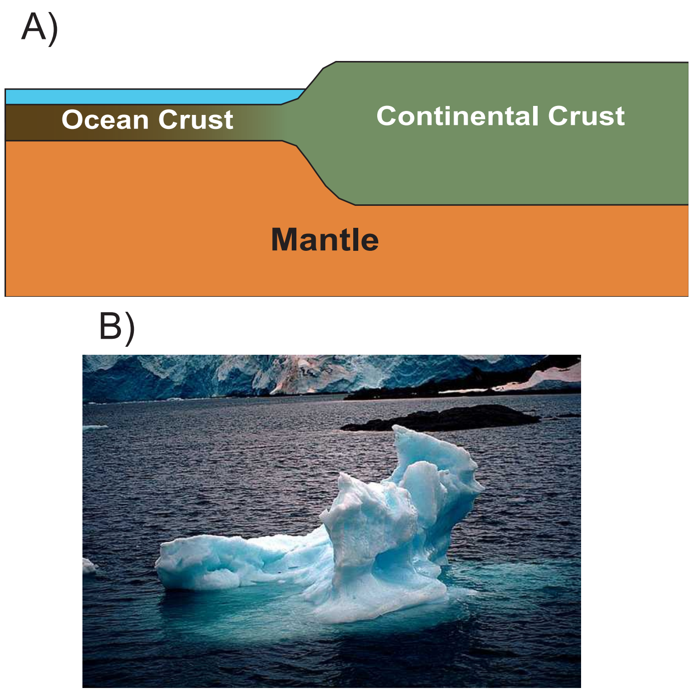


Figure 1.6 – Types of crust. *A) Ocean crust is only about 2-5 miles (3-8 km) thick, so it floats on the mantle at a lower level than continental crust. Continental crust is more buoyant because it is thicker, about 12-45 miles (20-70 km) thick, so it floats higher on the mantle than ocean crust. B) You can think of the Earth's crust like an iceberg, where the iceberg is the crust and the mantle is the seawater. A thick iceberg is more buoyant and floats higher above the water than a thin iceberg. (Photo property of NPS)*

The high elevation of a region is generally a consequence of two tectonic features: *thick crust* or *thin lithosphere*. In places where continental crust is thicker than surrounding regions, high elevations can develop (Fig. 1.7). Crust often gets thickened at convergent plate boundaries where masses of continental crust collide. Just as a collision of two cars creates a crunched up mass of metal, two plates colliding creates thickened, wrinkled-up crust. The Himalayan Mountains, which reach about 5.5 miles (8.8 km) above sea level on Mount Everest, are an example of high elevations caused by thick crust. The Indian Plate is colliding with the Asian Plate has formed these mountains with crust that is about 45 miles (70 km) thick.

Grand Canyon is located on the edge of a region with relatively thick crust known as the **Colorado Plateau** (Fig. 1.1). The Colorado Plateau has high elevations supported by continental crust that is about 30 miles (48 km) thick. The average thickness of continental crust is 22 miles (35 km). It is estimated that directly beneath Grand Canyon, on the southwestern edge of the Colorado Plateau, the crust is between 19 and 25 miles (31 to 40 km) thick. This is not unusually thick, but it seems to contribute to creating the high elevation of approximately 7000 to 8000 feet (2100 to 2400 m) above sea level.

Thin lithosphere can also explain why high elevations develop. In areas where the lithosphere is thin, the asthenosphere rises and expands because there is less pressure from above than where the lithosphere is thick. The asthenosphere pushes upward and creating a broad bulge of high elevation on the surface of the Earth. Regions with a thin lithosphere are essentially buoyed up as if they were on top of a rising hot air balloon.

The lithosphere is thin beneath the Basin and Range Province, because the North American Plate is stretching and ripping apart (Fig. 1.8). As hot mantle rises from below, it pushes upward on the thinning lithosphere and creates a broad region of high elevation. Evidence of this lies in the valleys of the Basin and Range Province, which are typically at high elevations of about 4000 to 5000 feet (1200 to 1500 m) above sea level.

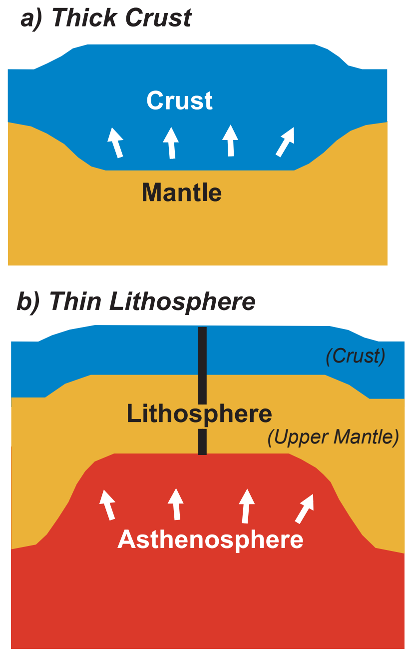


Figure 1.7 – The development of high elevation. *There are two main ways that high elevation can develop. a) <u>Thick crust</u>. Because thick crust is buoyant, it floats upward until it is counterbalanced by the downward weight of the overlying land. The high elevation of the Himalayan Mountains is supported by very thick crust beneath. b) <u>Thin lithosphere</u>. High elevation is also produced as asthenosphere rises like a hot-air balloon beneath a thin lithosphere. This effect is seen in the Basin and Range Province, west of Grand Canyon.*

Geographic locations. All of the rocks were deposited in the Grand Canyon region long before the canyon formed. This manual refers to the "Grand Canyon region" simply to define the geographic location, although the canyon did not begin to form until 5-6 million years ago. Similarly, the "Colorado Plateau region" refers to the general area of the Colorado Plateau, but the plateau did not begin to develop as a physiographic province until sometime after 70 million years ago. Also, the North American continent has changed its shape over time due movements and interactions of tectonic plates. For the purposes of this manual, the general mass of continental rock that is now North America will be referred to as such, even though its shape has changed through geologic time.

Most of the western United States is at high elevations compared to the central and eastern parts of the country. Geologists still work to understand why this is the case, but it seems to be related to a number of different factors. The western U.S. may be at high elevations due to thick crust in some places and thin lithosphere in other regions. It may also be caused by past and present tectonic events that have formed warmer regions in the mantle that buoy the land surface up. Grand Canyon is at an interesting location. It lies on the Colorado Plateau with its somewhat thicker crust, and right next to the thin lithosphere of the Basin and Range Province. The Grand Canyon region may be at high elevations due to both effects: the thick crust *and* the nearby thin lithosphere (Fig. 1.9).

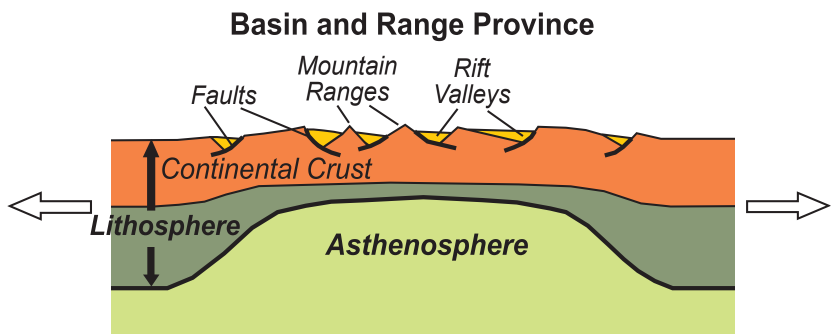


Figure 1.8 – High elevation in the Basin and Range Province. *The Basin and Range Province may be a divergent plate boundary in its beginning stages of development. This schematic diagram shows what the Earth may look like beneath the Province (a cross-section). The asthenosphere beneath the Basin and Range Province rises upward beneath the thin lithosphere, while pulling apart the North American Plate in an east-west direction. As this happens, north/south oriented mountain chains and valleys are formed (Fig. 1.1). The basins and ranges formed by the extension are seen all over Nevada, and in parts of Arizona, Idaho, Utah, Oregon, and California. The western portion of Grand Canyon is also undergoing extension related to Basin and Range extension. (Diagram by R.J. Lillie)*

TYPES OF ROCKS

Every rock has a story to tell, and at Grand Canyon there are certainly enough rocks to tell some good stories! A **rock** is an aggregate of different minerals that have been chemically or physically cemented together. **Minerals** are substances that are

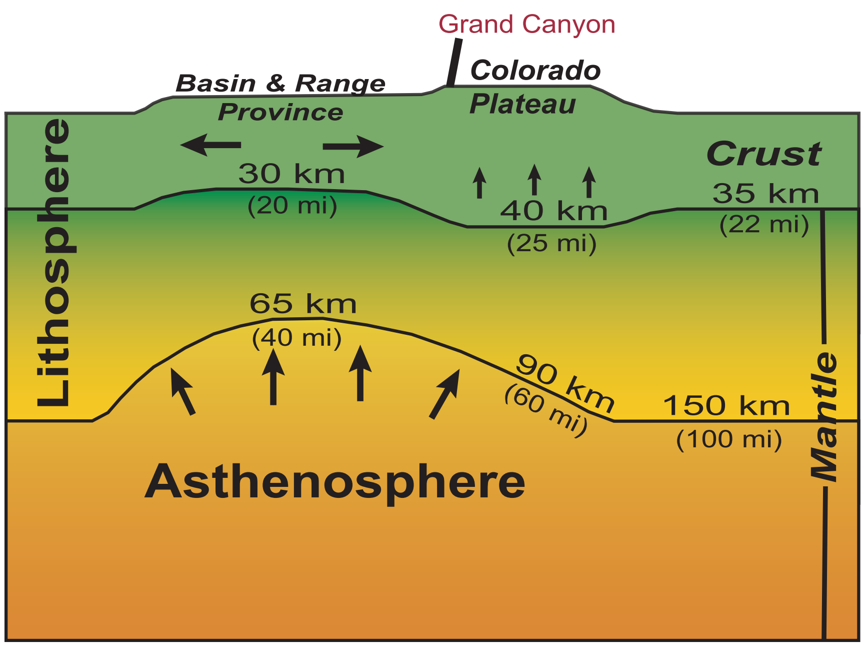


Figure 1.9 – Schematic cross-section of the Grand Canyon region. *The thicker crust of the Colorado Plateau may be part of the reason for the high elevation of the Grand Canyon region, because thick crust floats high on the mantle. The nearby thin lithosphere of the Basin and Range Province may also contribute to the high elevation. It creates a broad bulge of high elevation, which affects the surrounding region. Because Grand Canyon is on the edge of both the Colorado Plateau and the Basin and Range Province, it may be uplifted by the same forces that affect those regions.*

TECHNICAL STUFF. The differences in crust and lithosphere thickness discussed here are mostly just for your edification. Discussing these details with park visitors in an interpretive program could overwhelm them with too much information. The most important point to convey is that the Colorado Plateau and Grand Canyon have high elevations, which was crucial to the forming of Grand Canyon. It is to your benefit to have an understanding of the processes at work beneath Grand Canyon, as well as other geologic processes discussed in this training manual to prepare yourself for the occasional technical questions.

naturally occurring, inorganic, and composed of different elements to make a crystalline solid (Fig. 1.10). The amount of different minerals in a rock and how it formed determines what kind of rock it is. Grand Canyon is spectacular for many reasons, one of which is the exposure of all three major rock types – sedimentary, igneous, and metamorphic. These rock types are classified based on how the rocks were formed.

Sedimentary Rocks

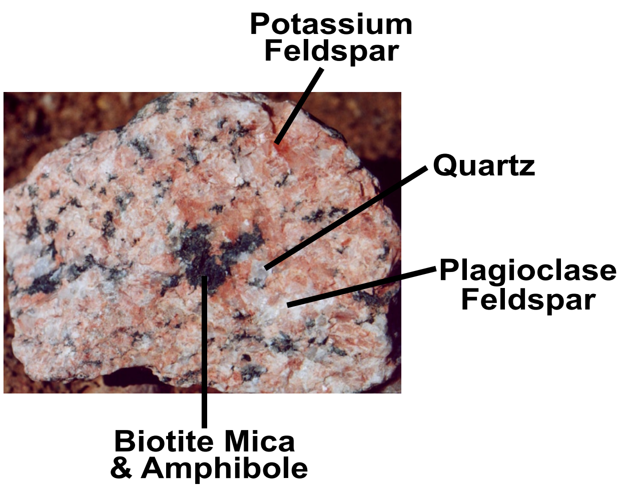


Figure 1.10 – Rocks and minerals. *Granite is a rock composed of several different minerals. The pink mineral in granite is potassium feldspar, the white minerals are plagioclase feldspar, and the clear minerals are quartz. Granite also has small amounts of black minerals, which are amphibole and biotite mica. Granite is identified by the specific amounts of each of these minerals. A different combination of minerals would make a different rock.*

In Grand Canyon, sedimentary rock is the rock type most often seen. They are the colorful rock layers that form most of the sculpted canyon walls. **Sedimentary rocks** can be composed of fragments of pre-existing rock, remains of deceased organisms, and/or chemical precipitates (such as salt or calcium carbonate) that have been compacted, cemented, and hardened. As particles of rock (**sediment**) accumulate layer upon layer, the weight of overlying material drives out water and compacts the sediment to create a solid rock. Chemicals dissolved in water (such as quartz, calcium carbonate, or iron oxide) may seep into tiny pores between particles of sediment and precipitate out of the water to cement the particles together. Fossils are often preserved in sedimentary rocks. **Fossils** are any mineralized remains, traces, or remnants of once living organisms. They can help geologists determine the age of a rock and what type of environment existed when the rock formed. By studying the fossils at Grand Canyon, geologists have determined that the horizontal layers of sedimentary rocks (those above the inner canyon) were formed between 525 and 270 million years ago.

At Grand Canyon, the three main types of sedimentary rocks are generally sandstone, shale, and limestone (Fig. 1.11). **Sandstone** can form along sandbars in rivers, in the wave-washed zone along beaches, and in sand dune fields, as well as other environments. It takes greater energy to move larger particles like pebbles and sand than it does fine mud particles. Sandstone will begin to form when the energy of the water or wind decreases so much that it can no longer carry the larger particles, but smaller particles can still be moved. Therefore, sandstone forms in higher energy environments,

> **Sedimentation in progress.** You can see a form of sedimentation in progress at the mule corral at the top of the Bright Angel Trail. The mules "deposit" their "organic remains" in this corral at least twice a day, on just about every day of the year. This "sediment" is compacted over time and cemented with water and other fluids. In the corral, the ground surface is actually higher than the area surrounding it because the "sedimentation" occurs at such a high rate in the corral.

when smaller particles would still be suspended in the water or wind. Once sand grains are deposited and buried, pressure from overlying sand physically binds the grains together. This process is aided by water carrying dissolved minerals that percolates into the spaces between the sand grains. The dissolved minerals can act as cement

A)

	Grain Size	Composition	Rock Name
ROCK PARTICLES	fine	mud, silt, fine grained sand	**shale***
ROCK PARTICLES	↓	sand	**sandstone***
ROCK PARTICLES	↓	rounded gravel	conglomerate
ROCK PARTICLES	coarse	angular gravel	breccia
CHEMICAL PARTICLES		precipitates of quartz (silica)	chert
CHEMICAL PARTICLES		precipitates of calcium carbonate (calcite) and organic remains	**limestone***
CHEMICAL PARTICLES		precipitates of calcium carbonate (calcite) that are chemically altered by adding magnesium after deposition	dolomite

*Common sedimentary rocks at Grand Canyon

B)

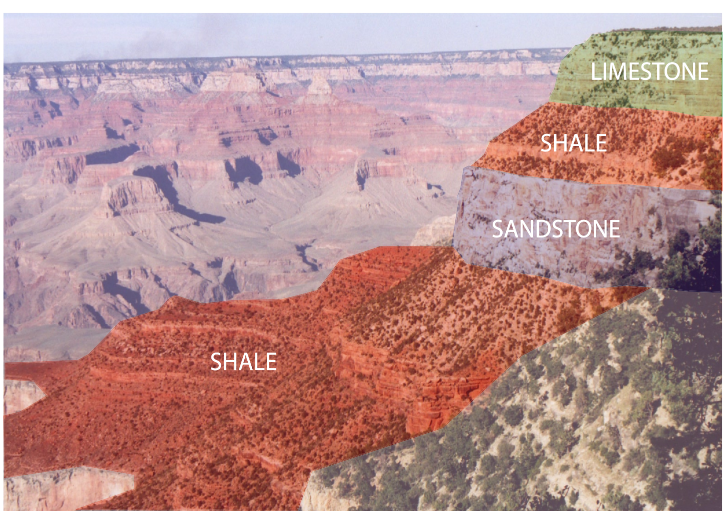


Figure 1.11 – Sedimentary rocks. *A) Sedimentary rocks form anywhere that rocks have been weathered, transported, and eventually deposited in places such as lakes, oceans, and rivers. For example, shale and sandstone are composed of particles of rock that get deposited. Other sedimentary rocks, such as limestone or dolomite, can form by chemical reactions in seawater that produce solid matter (precipitates), which are deposited in calm water. The most common rock types at Grand Canyon are shale (siltstone), sandstone, and limestone. B) Examples of the most common rock types are easily seen at the top of the canyon. In this diagram, the green-shaded limestone layer forming the canyon rim is the Kaibab Formation, and the purple-shaded sandstone layer is the Coconino Sandstone. These two rock types are predominant cliff formers in the canyon. Shale layers are easily spotted because they form slopes and cover broad platforms. The shale (siltstone) layers identified here by the red shading are the Toroweap Formation near the top, and the Supai Group below.*

Figure 1.12 – Sandstone. *Looking at sandstone up close, you can actually see the grains of sand. The rock formed as pressure caused the sand grains to become physically locked together, while minerals dissolved in fluids passed through spaces between sand grains and chemically cemented the grains together.*

between the grains (Fig. 1.12). In Grand Canyon, sandstone forms steep cliffs or ledges because it is relatively hard and resistant to weathering (Fig. 1.11b).

Shale (siltstone) is composed of smaller particles of mud, silt, and very fine sand (Fig. 1.13). Smaller particles of sediment are easily carried in fast-moving water and therefore are not deposited until water is calm and slow. Deposition of shale commonly occurs in environments such as lakes, lagoons or in deep, calm ocean waters. It is one of the easiest rock types to recognize in Grand Canyon because it is soft and erodes to form gentle slopes (Fig. 1.11b). [**Author's note**: The word "shale" is used loosely in this training manual, and in Grand Canyon in general. Technically speaking, shale is a sedimentary rock with a significant amount of clay in it. At Grand Canyon, there are actually very few *true* shale layers! The Bright Angel Shale is one of the only true shale layers because it contains glauconite (a clay mineral). Most of the other soft, easily eroded slopes in the canyon are technically siltstone or mudstone and contain no clay. In order to be consistent with the formal names of many of the layers and the information provided to visitors, the word "shale" will be used for all soft, easily eroded, fine grained rocks. However it is technically an oversimplification!]

Figure 1.13 – Shale. *The grains that make up shale are tiny pieces of mud, silt, and very fine sand that were once soft mud. The water was squeezed out to make mud into rock. Shale is easily weathered because the particles are so fine and may not be well cemented together.*

Limestone can form in many different depositional environments, including fresh water lakes and deep marine environments. Most of the limestones in the Grand Canyon region have formed in deeper water environments than where sandstone or shale would form. Limestone is predominantly composed of a mineral called calcium carbonate ($CaCO_3$), which is also known as calcite, or informally as lime. This mineral forms because chemical reactions in seawater cause the calcium carbonate to precipitate out of the water. Lime can also come from organic material such as shells. Pre-

A rainbow of color in the rocks. The Bright Angel Shale is a very colorful layer in Grand Canyon that forms a broad slope just above the inner canyon (Fig. 1.14). The colors throughout the canyon come from different minerals in the rock. **Glauconite** is a mineral that creates the green color in the Bright Angel Shale, but it can also form purple, yellow, and red colors in rocks. Some layers in the canyon have red, purple, pink, orange, and brown colors, which are from iron oxide, most notably the mineral **hematite**. Rocks with yellow colors usually contain an iron mineral called **limonite**. On cliffs in the canyon, you may see black streaks, which are from a substance called **manganese oxide**, also known as desert varnish.

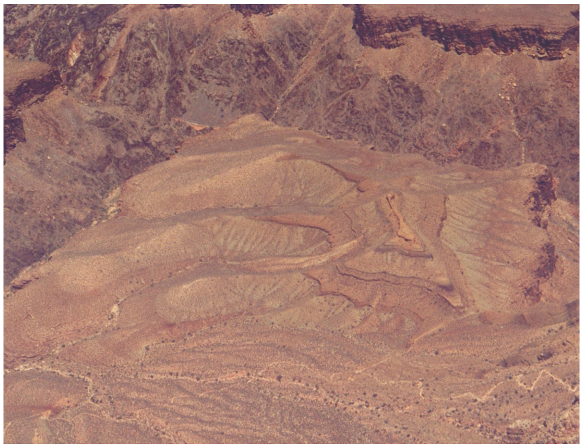


Figure 1.14 – Colorful Bright Angel Shale. *Looking down from Pima Point towards the location of the old Hermit's Camp, you can see a variety of colors in the Bright Angel Shale. Most of these colors are due to minerals composed of iron oxide (rust). From other viewpoints along the canyon, this layer has a distinct greenish tint due to the mineral glauconite.*

cipitation of lime is similar to making butter. When you shake a jar of cream, solid butter begins to form in the jar. This solid material settles to the bottom in the same way lime settles on the sea floor. Lime can act as cement for small sediment particles and the remains of dead organisms, and eventually harden the sea floor ooze to form limestone (Fig. 1.15). The layers of limestone in Grand Canyon form cliffs because they are hard and weather slowly in the dry, arid environment (Fig. 1.11b).

The rocks in the walls of Grand Canyon tell us about changes in depositional environments that happened as seas came and went, and deposited different materials. The vertical transition of rock layers from sandstone to shale to limestone usually indicates that a sea came in over the land as sea level rose, or the land was lowered, resulting in an increase of the water depth. This type of change in depositional environment is called **transgression** (Fig. 1.16a). **Regression**, the opposite, occurs as the sea moves out from the land when sea level gradually lowers, or when the land is uplifted.

Hard rock or soft rock? If you have spent time in a place with a humid climate, you may have noticed that limestone is not always the hard, resistant rock it appears to be in Grand Canyon. In fact, limestone dissolves when exposed to water. In humid environments, limestone is a soft, weak layer that is easily weathered by rain and moisture in the air. But at Grand Canyon, the dry air and infrequent rain prevent the limestone from weathering fast, making it a hard layer that can form steep cliffs.

Figure 1.15 – Limestone. *The calcite particles that make up limestone are tiny and hard to see with the naked eye. This limestone is from the Kaibab Formation but looks much like other limestone layers in the canyon. In eastern Grand Canyon, including the village area, the limestone of the Kaibab Formation has more sand in it than in western Grand Canyon. This indicates the depositional environment in the eastern Grand Canyon region was more turbulent, and closer to land than in the western region.*

A transition in a vertical rock sequence from limestone, to shale, to sandstone is evidence of regression (Fig. 1.16b).

Depositional Environments

The sedimentary rocks at Grand Canyon tell us about different depositional environments

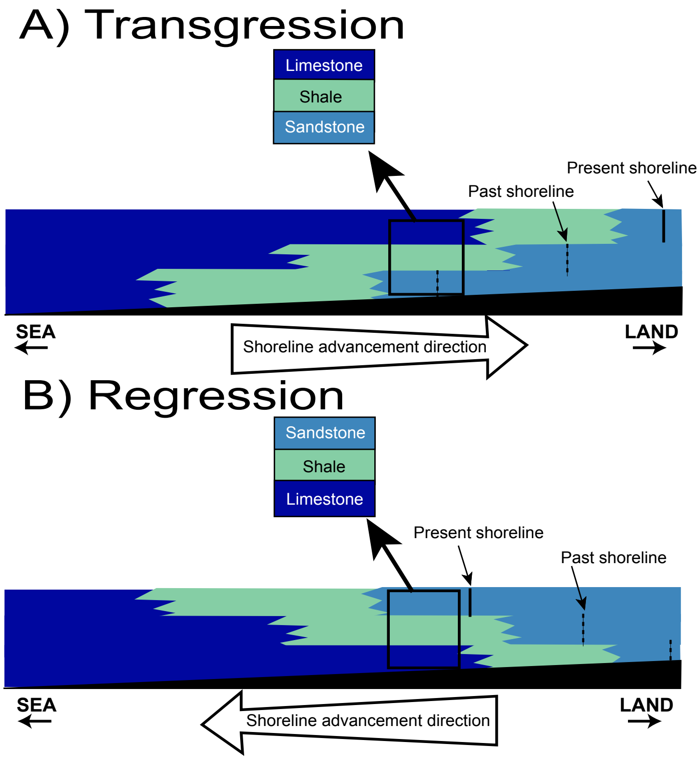


Figure 1.16 – Transgression and regression. *Transgression and regression can occur as sea level rises or falls, or as the land surface is uplifted or lowered. As these changes occur, the shoreline may move in over the land or move further out towards sea. A) As the sea encroaches over land during transgression, deposition of rock progresses from limestone in the deep water, shale in the shallower water and sandstone in the shallowest, beach-like environment. In one location (see box), the sequence of the rocks deposited would go from sandstone, to shale, to limestone. B) During regression, the sequence of rock types reverses as the shoreline moves away from land. The progression of rocks deposited would be limestone (deep water) to shale (shallower water) to sandstone (even shallower water).*

Layman's lingo. If you read more technical literature about the sedimentary rocks of Grand Canyon, you will find that there are more rock types than just sandstone, shale, and limestone. Technical papers usually use much greater detail to help other geologists distinguish one rock layer from another. The three main sedimentary rocks discussed in this manual have been selected because they are all that is necessary and appropriate for discussion of Grand Canyon sedimentary rocks with visitors. The bibliography at the back of this training manual provides other recommended publications where you can find more detailed information on these rocks.

that once existed in the region. Studying past depositional environments can sometimes help us better understand similar environments that exist today. Most of the sedimentary rock layers in Grand Canyon formed in or along the margins of an ocean in a marine environment (Fig. 1.17). Many park visitors have experienced oceans, beaches, sand dunes, and rivers so they can relate to environments where sedimentary rocks form. A **shallow marine** depositional environment describes the shallow part of an ocean near land, such as a continental shelf, or where a sea extends inland over a broad region (like Hudson Bay in Canada). Sandstone, shale, and limestone can all be formed in different areas of this depositional environment. The rocks formed in a shallow marine environment are typically composed of sediment that has been carried from land by rivers and ocean currents, as well as remains of organisms that lived in the shallow sea.

Most people are familiar with a **beach** environment that exists along the margin of a shallow marine environment. At a beach, strong waves can transport coarse, large,

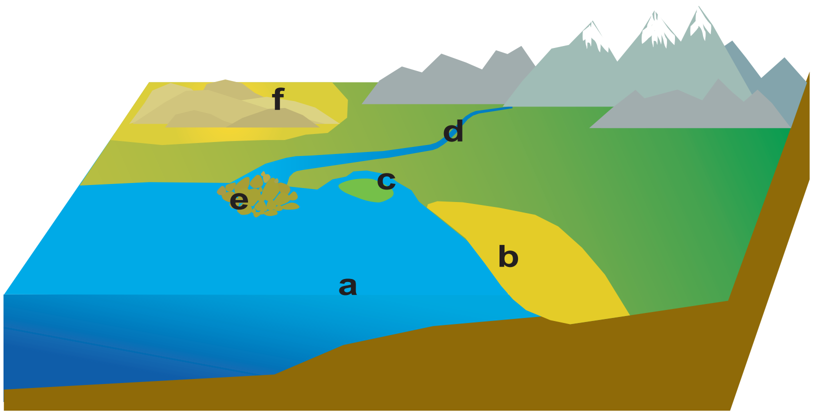


Figure 1.17 – Depositional environments. *a) Shallow marine environments can form as an ocean inundates the land, forming inland seas. Water depth is usually less than 300 feet (90 m). b) Near the coastline, a beach environment is common. Rocks that form are made up of sediment transported to the sea by streams and rivers and sediment that has been reworked by ocean currents and waves. c) Land areas intermittently covered by water during high tide would be classified as intertidal zone depositional environments. At times when the tide is low, these areas may be dry and exposed. d) Rivers not only move sediment, but also form fluvial deposits where the current slows and sediment can no longer be transported. e) As a river reaches the sea or some large body of water, the velocity of the water decreases. Most of the sediment carried by the river gets deposited, forming a delta. f) Eolian deposits form where wind transports sediment in areas such as sand dunes.*

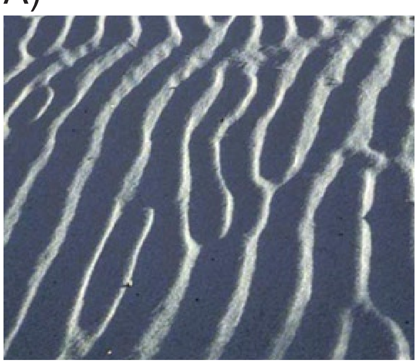
heavy sediment, such as sand and gravel. The sand and gravel over time becomes solidified to sandstone and conglomerates.

Intertidal zones exist on gently sloped land that gets covered by shallow water during high tides, and is partially or completely exposed during low tides. Many visitors are familiar with intertidal zones such as lagoons, estuaries and swamps. Deposition in intertidal zones fluctuates due to tides, so the resulting rocks vary, but shale and sandstone are common. Ripples and mud cracks are characteristic depositional features found in an intertidal zone (Fig. 1.18). **Ripples** are miniature, dune-like structures that form as water transports and deposits fine sediment. **Mud cracks** form when mud is exposed to air, dries out, and cracks as it shrinks.

Some sedimentary rocks form in a river or **fluvial** environment. Shale and sandstone can begin to form when the water velocity decreases. A **delta** will often form where a river joins an ocean, lake, or other large water body. Deltas get their name because the sediment that was carried by the river is deposited, and spreads out in a triangular, fan-like pattern (viewed from above) (Fig. 1.17). As a river begins mixing with the large body of water, the river current decreases rapidly, which then causes the sediment that was being carried to be deposited.

Other sedimentary rocks at Grand Canyon formed in a coastal, desert environ-

A)



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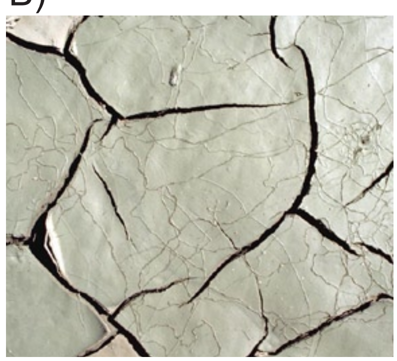


Figure 1.18 – Ripples and mud cracks. *A) Ripples are depositional features that can be formed by moving water. The water current forms miniature dunes as it moves sediment along a surface, such as a streambed. B) Mud cracks form as shallow water evaporates and the mud left behind dries and cracks. (Photos property of NPS)*

ment with sand dunes. **Eolian** deposits are those that have been transported by wind, and sandstone is a common rock type that is formed. With pressure and the aid of minerals dissolved in water, grains of sand are cemented together to form sandstone. **Cross-bedding** is a depositional feature that often preserved in eolian sandstone. As sand dunes are blown by strong winds, cross-bedding forms when layers of sand are deposited on the downwind slope of a dune, at an angle (Fig. 1.19). In sandstone, it can give the layer a tilted appearance when the layer itself is actually horizontal. Cross-bedding can be distinguished when it is compared to the upper and lower boundaries of the sandstone layer.

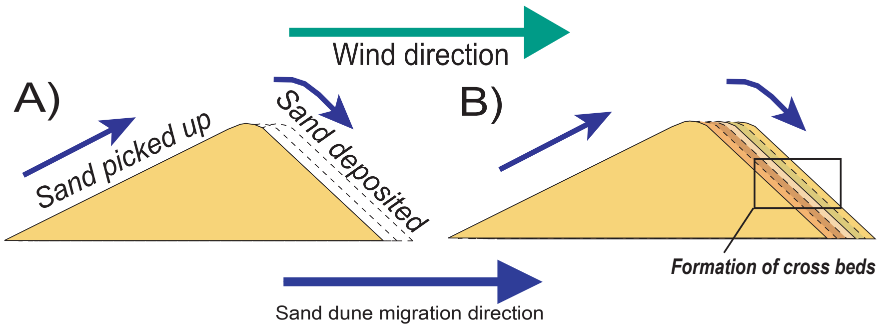


Figure 1.19 – Sand dunes. *Sand dunes are not stationary. An entire dune will move (or migrate) in the direction the wind blows the sand. A) Wind picks up sand on one side of the dune and deposits it on the other side where the wind speed slows down. B) Sand is deposited at an angle, along the slope of the dune, where the wind is not as strong. Eventually more sand is piled on top and the pressure builds. The pressure, along with water and minerals, cement the sand grains together, preserving the sand layers at an angle. This feature, often found in eolian sandstones, is called cross-bedding beause the individual sand layers are at an angle to the top and bottom surface of the overall sandstone layer.*

Sometimes the distinction between depositional environments can get fuzzy. For example, a beach environment may suddenly be submerged causing shallow marine deposits to form. It is still a beach environment, but for a short period of time non-beach sediment was deposited. This sort of fluctuation has occurred often over geologic time, so the sedimentary rocks left behind may not always represent the *overall* depositional environment. In this training manual, the focus will be on the overall depositional environment of the sedimentary layers. Keep in mind that some layers may have features that do not represent the overall setting.

Igneous Rocks

Igneous rocks form from melted rock material that has cooled and hardened. **Intrusive** (or plutonic) igneous rocks cool and solidify *within* the Earth. The term **magma** describes molten rock when it is beneath the Earth's surface. Because the Earth insulates the magma it cools slowly and large mineral crystals are able to develop. In contrast, **extrusive** (or volcanic) igneous rocks form when magma pours out onto the surface of the Earth (Fig. 1.20). **Lava** is the term used to describe molten rock that has been extruded onto the Earth's surface. When lava is exposed to the atmosphere, it cools very quickly, so only very small mineral crystals are able to form. If lava comes in contact with water, it is quenched so rapidly that the minerals are often microscopic giving the rock a glassy appearance.

Granite is a common intrusive igneous rock that can be seen in the inner canyon

The Earth: A giant rock recycling machine. Thanks to plate tectonics, weathering, and erosion, we can see a great variety of rocks exposed on the Earth's surface. For example, a sedimentary rock formed on an ocean floor may be shoved down to great depths in a subduction zone. There it would experience tremendous heat, pressure, and even melting, changing it to "recycled" igneous or metamorphic rock. After many, many millions of years, the "recycled" rock may be uplifted and returned to the Earth's surface, where weathering and erosion break it down and eventually return it to the ocean floor. Rock recycling is a slow but constant process that can take millions of years to renew the Earth's surface. As we use up our planet's resources, we should bear in mind the length of time it takes for geologic processes to recycle and renew.

as pink masses and vein-like bands (Fig. 1.21). It is colorful upon close inspection, as it is composed of pink potassium feldspar minerals, light plagioclase minerals, light or clear quartz, and black biotite mica and amphibole minerals. When most of Grand Canyon's various granite bodies were in their molten states 1840 to 1660 million years ago, some was pooled in large chambers. As the magma cooled, it formed a crystallized magma chamber called a **pluton**. Some of the magma squeezed into the surrounding rock forming the bands of granite called **dikes**. This molten material cooled slowly, far

		Composition (70% Silica ⟷ 40% Silica)			
Grain Size fine ↓ coarse		70% Silica			40% Silica
	Extrusive	Rhyolite	Andesite	**Basalt***	
	Intrusive	**Granite***	Diorite	Gabbro	Peridotite

*Common igneous rocks at Grand Canyon

Figure 1.20 – Igneous rocks. *Different varieties of extrusive (volcanic) igneous rocks are shown in this table along the upper row, with the intrusive (plutonic) varieties below. The chemical classification of igneous rocks is based on the amount of silica (silicate minerals) that it contains, like quartz and feldspar. Igneous rocks that have more silicates are usually lighter in color than igneous rocks with lower amounts of silicates. The most common igneous rock seen from the rim of Grand Canyon is granite, a light pink, intrusive igneous rock, with high silica content. In the western reaches of Grand Canyon basalt is rather common. It is a dark colored, extrusive igneous rock with low silica content.*

beneath the Earth's surface, resulting in granite rocks with large mineral crystals, and tectonic processes have brought them to the surface for us to see today.

Extrusive igneous rocks are found in the western Grand Canyon area. On clear

A)

B)

Figure 1.21 – Granite. *A) Granite has large minerals because the rock cooled very slowly, deep beneath the Earth's surface. It is light colored rock because it has high silica content. B) In the inner canyon the light color of the granite stands out against the dark metamorphic rock surrounding it. It is often seen as bands called dikes (outlined in pink), or as very large masses called plutons (outlined in white). The plutons were chambers that held large quantities of magma, and dikes were the cracks where the magma squeezed into the surrounding rock. In Grand Canyon, some of the plutons and dikes have been metamorphosed during later tectonic events. (Photo by Karl Karlstrom)*

days, a group of small volcanoes known as the Uinkaret Mountains can be seen west of the village area (Fig. 1.22). These volcanoes produced **basalt**, which is usually dark in color (black, gray, and dark red). Basalt is composed of tiny, low silica, iron-rich minerals. More than 150 basalt flows came from the region around these volcanoes just in the last 700,000 years.

Metamorphic Rocks

Metamorphic rocks form from pre-existing rocks (sedimentary, igneous, or other metamorphic rocks) that have been changed by heat and/or pressure. The minerals in the original rock re-crystallize forming different minerals, as the rocks are "geologically pressure cooked." By identifying the minerals that have formed and the alignment of the crystals in the rock, geologists can determine the temperature and pressure the

Figure 1.22 – Recent volcanism at Grand Canyon. *Less than 1 million years ago, many small volcanoes were erupting and pouring lava into the western end of the canyon. The small mountains in the distance (on left side of photo) are volcanoes known as the Uinkaret Mountains. They can be seen on clear days from most viewpoints along the rim, especially along Hermits Road. The volcanoes can be considered active, the most recent eruptions are less than 1,000 years ago. (Photo property of NPS)*

metamorphic rock endured (Fig.1.23). Most of the metamorphic rocks at Grand Canyon began as sedimentary and igneous rocks that were metamorphosed during different tectonic events between 1750 and 1680 million years ago. They are the dark, angular, sharp-looking rocks that surround the pink bands of granite in the inner canyon (Fig. 1.24a).

The most common metamorphic rocks in the inner canyon are called schist and gneiss. **Schist** is a metamorphic rock with platy minerals (like micas) that are oriented parallel to each other. The parallel alignment of minerals in metamorphic rocks is called **foliation**. It can help geologists determine the amount of pressure the rocks were exposed to, as well as the direction the pressure was coming from. Foliation gives the rocks a layered or banded appearance, like "foliage," or leafy layers. The schist from the inner canyon is black with flat, platy minerals in alignment (Fig. 1.24b). **Gneiss** is a metamorphic rock that has endured more heat and pressure than schist. It has the appearance of alternating light and dark bands of minerals (Fig. 1.24c). The metamorphic rocks of the inner canyon indicate they were metamorphosed as much as 13 miles (21 km) below the Earth's surface. That means a 13-mile thickness of rock was eroded away as these rocks were uplifted, only to be covered by younger sedimentary rocks. That is about *13 times* the depth of Grand Canyon!

	Increasing Temperature and Pressure →		
Parent Rock	**Metamorphosed Rock**		
Shale	Slate	**Schist***	**Gneiss***
Sandstone	Quartzite		
Limestone	Marble		

*Common metamorphic rocks at Grand Canyon

Figure 1.23 – Metamorphic rocks. *Shown here are some examples of different metamorphic rocks and their associated parent rocks. The parent rock is the original rock that existed before metamorphism. Like igneous rocks, metamorphic rocks can be identified by their mineral composition. The minerals are a result of the chemistry of the parent rock, as well as the temperature and pressure that the rock endured. The common metamorphic rocks of the inner canyon are schist and gneiss. They were formed at considerable depth within the Earth, where temperature and pressure were very high.*

It's a different canyon down there. The rocks of the inner canyon do not have the classic stair-step appearance that is characteristic of the upper layers of Grand Canyon. The inner canyon is steep and narrow because of the metamorphic and igneous rocks. They are not composed of alternating soft and hard layers as are the sedimentary rocks of the upper canyon. The igneous and metamorphic rocks are hard and very resistant to weathering so they do not easily erode to form gentle slopes. It is difficult (but not impossible) for water to break down and smooth out the hard inner canyon walls, even for the raging Colorado River.

STRATIGRAPHY

Stratigraphy is the description and classification of different sedimentary rock layers, or strata. It involves interpreting the clues and features in the rocks and developing hypotheses about the environment that existed when the rocks were deposited.

A) B) C)

Figure 1.24 – Grand Canyon metamorphic rocks. *A) The inner canyon is incredibly steep because of the hard, dark metamorphic rocks that make up most of the inner canyon. Around 1750 million years ago, these rocks were sedimentary and igneous rocks. They were under extreme heat and pressure, which metamorphosed the rocks into schist and gneiss. (Photo by Marge Post) B) Upon close inspection of the schist, you can see the foliation of the platy, sparkly minerals. These minerals were aligned because of great pressure. The platy minerals are biotite mica, which are mix with dark black to dark green amphibole minerals. C) Another variety of metamorphic rock commonly found in the inner canyon is gneiss. The foliation of light and dark minerals indicates this rock has endured tremendous heat and pressure. The intensity of the metamorphism created the bands of dark minerals (biotite mica and amphibole) separated from bands of lighter colored minerals (feldspar and quartz). (Photo property of NPS)*

Let it snow, let it snow, let it snow. A useful analogy you may use to describe the three different rock types is snow. As snow falls, the snowflakes settle on the ground day after day, and layers are formed. This is how sedimentary rock forms. The snowflakes, like sediment, builds layer upon layer over time. If you took a large scoop of the snow and melted it on the stove, and then put it into the freezer to resolidify it, this would be analogous to an igneous rock. You can demonstrate metamorphism by making a snowball. The heat from your hands, and the pressure you apply re-crystallizes the snowflakes just like heat and pressure inside the Earth metamorphoses rocks.

Stratigraphers study the rocks closely to determine where one layer begins and another ends, which indicates a change in the depositional environment.

Layers of rock are like the pages of a book. These pages have been subdivided and grouped, based on similarities in rock type, just like a book is divided into chapters. The most basic division is a **member**, which is analogous to a page in a book. Each page has slightly different information, but is closely related to the pages nearby. Members make up formations. **Formations** are mappable rock layers of distinct and recognizable rocks that can be distinguished from the rocks above and below. Formations are like the chapters of a book. They group different members, or pages, together and describe events that happened around the same time and in similar environments. As an example, the *Kaibab Formation* is a formation that has two members, the *Fossil Mountain Member* and the *Harrisburg Member*.

A **group** is made up of several different formations. Groups are analogous to books, composed of different chapters that are all related and tell a story. One example of a group at Grand Canyon is the *Supai Group*, which is made up of several different red-colored formations. Continuing with this analogy, a series of related books, or groups, is called a **supergroup**. These different books are related, tell similar stories, and when put together make up a series or volume set. The *Grand Canyon Supergroup* is one example of this large type of assemblage. It includes the orange, red, and black tilted layers that can be seen in parts of the inner canyon, particularly in eastern Grand Canyon below Desert View.

A **stratigraphic column** is a reference used to identify rock layers, similar to the "table of contents" of a book. It displays a basic description of the rock type and simplified drawing of features of the rock layer (Fig. 1.25). The stratigraphic column is like a "cheat sheet" to the stories in the rock layers.

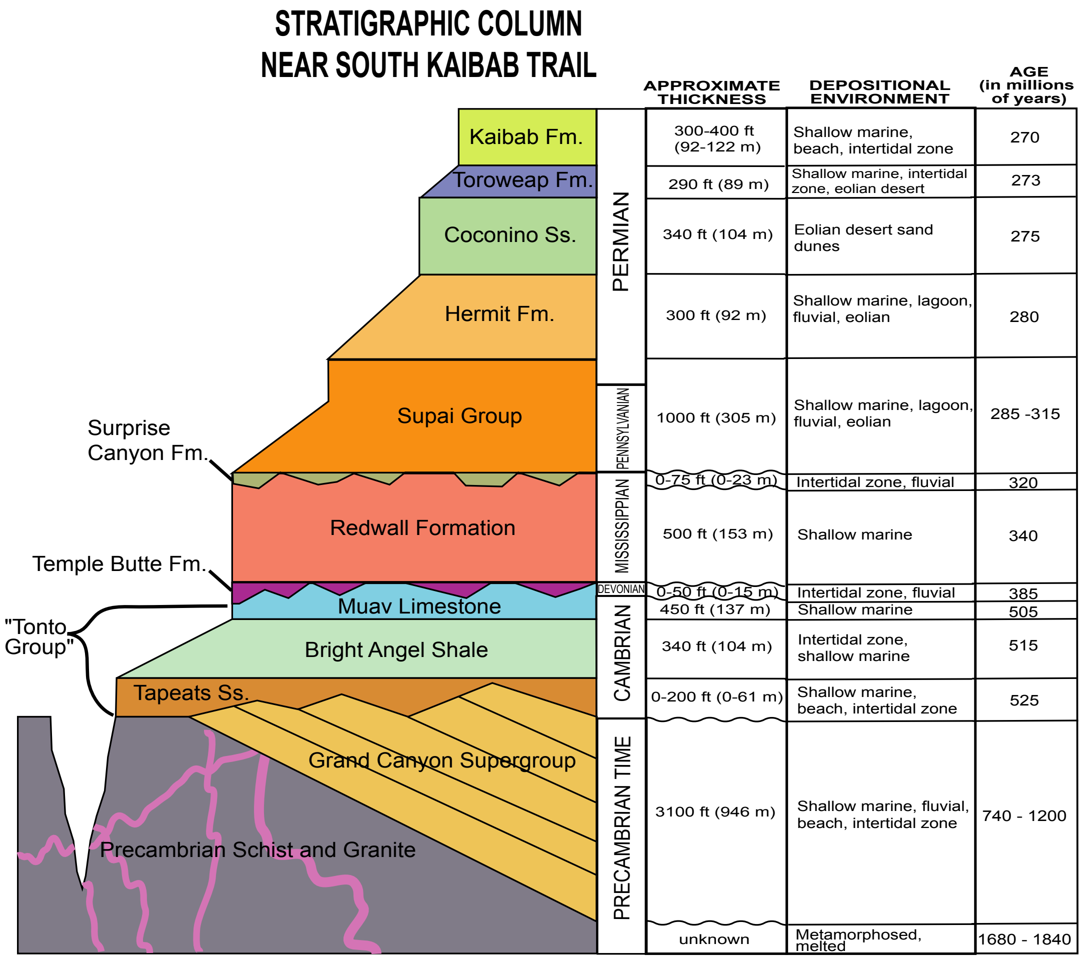


Figure 1.25 – Stratigraphic column. *This diagram is useful to have when roving or doing interpretive geology programs. Use it to help identify different layers in the canyon, how thick they are, environments where they were deposited, and when they formed. This particular stratigraphic column describes the rocks along the South Kaibab Trail, but it is applicable to most of the canyon visible from the village area. A wavy line rather than a straight line indicates an unconformity exists between layers. Unconformities occur where there was a period of erosion or no deposition.*

GEOLOGIC TIME

The amount of time represented in Grand Canyon is one of the most impressive features of the park's geology. Grand Canyon does not have the oldest rocks in the world, but hundreds of millions of years are represented in its rocks. The canyon's oldest rocks, which are 1840 million years old, are at the very bottom of Grand Canyon in Elves Chasm. They formed when the Earth was just over half the age it is now – 4540 million years old. Geologic time can be hard for people to grasp, in part because the human life span is only a tiny fraction of geologic time. Our species, *Homo sapiens*, has been on the Earth for *less than* 1/10,000 (or 0.01%) of the Earth's life!

Two ways of looking at geologic time are relative time and absolute time. When two or more rocks are compared and it is determined that one rock is older than the

A picture (or visual aid!) is worth a million years. Visual aids like the time line in Figure 1.26 are especially useful when discussing geologic time with visitors. You can also use your arm span to represent timing of geologic events. If you hold your arms straight out from your sides, let your fingertip (of your longest finger) on one arm represent the beginning of the Earth and the fingertip on your other arm represent today. At the fingertip that represents today, where your fingernail separates from your fingernail bed, is about when the canyon formed. The canyon is very young, geologically speaking, at only about 5-6 million years old. Humans have only been around for less than a millimeter of your fingernail length. If you clipped that fingernail off you would wipe out all of human civilization! (Other suggestions for discussing geologic time are found on pages 90 to 93)

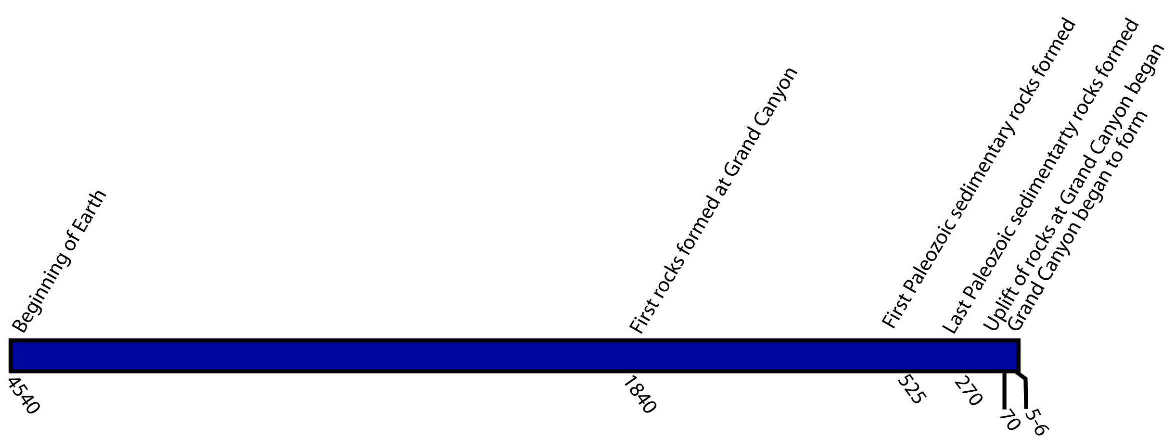


Figure 1.26 – Time line. *Some of the major events in the geologic history of the Grand Canyon region are shown on this time line. When you lay the events out, you can see the broad range in ages of rocks, and that Grand Canyon is clearly a young geologic feature.*

other, but the exact ages of the rocks are unknown, the rocks have been assigned **relative ages**. One rock is older, *relative* to the other. Similarly, when you compare a child and an adult, you know the adult is older than the child even if you do not know the exact age of each. On the other hand, **absolute ages** assign an exact numerical age.

Using absolute ages, you can then say that the adult is 34 years old, and the child is 9 years old.

Relative Dating

When early geologists studied rocks during the 1600's, they wanted to know how old the rocks were, but they did not have the means to determine absolute ages. They did, however, develop the **Principle of Superposition** to determine relative ages. This principle states that rock layers are deposited one on top of another from oldest to youngest, like a stack of pancakes. As you make pancakes, the first one (the oldest) ends up on the bottom of the stack, with the youngest and freshest one on the top. Similarly, the oldest rock layers are at the bottom of Grand Canyon, and the youngest at the top. Determining relative ages became easier as early geologists compared the fossils in rocks around the world. Rocks with similar fossils were assumed to have the same age, while other rocks with different fossils were apparently older or younger.

Along with the Principle of Superposition, the **Principle of Original Horizontality** was also defined. It states that sedimentary rock layers are normally formed in flat, horizontal layers. Therefore, if layers are tilted or bent, they were probably deformed by a geologic event that occurred *after* the rock layers formed. Determining the relative ages of rocks based on their position and fossils, as well as the timing of geologic events, led to the development of a relative geologic time scale that is still used today (Fig. 1.27).

Chemistry refresher. An **element** is the most basic form of matter, with distinct physical and chemical properties. Elements are composed of **atoms**, which have a nucleus of protons and neutrons with electrons that orbit the nucleus. The number of protons in an atom determines what kind of element it is. One element must always have the same number of protons, but it can have different numbers of neutrons. Elements with varying numbers of neutrons are called **isotopes**. Some isotopes are stable, while others are **radioactive**. Radioactive isotopes decay to eventually become stable isotopes of the same or a different element. Every radioactive isotope has its own distinct decay rate (called a half-life, see below). The decay of the isotope is like a clock that starts ticking when the isotope formed, and keeps on ticking at a regular, measurable rate.

Absolute Dating

Absolute dating of rocks was not possible until scientists began using radioactive isotopes as time indicators in the early 1900's. One type of absolute dating used on rocks is called **radiometric dating**. It uses **radioactive isotopes**, which are isotopes that are unstable and naturally decay to form stable isotopes. When a radioactive isotope decays, the nucleus of the atom changes, releasing radioactive energy in the process, and commonly forming an isotope of a different element. One of the potassium isotopes, ^{40}K, is radioactive and decays to form an argon isotope, ^{40}Ar, which is a stable gas. The rate of decay of potassium to argon has been used to determine the absolute ages of igneous and metamorphic rocks.

Eon	Era	Periods / Epochs
PHANEROZOIC EON 542 mya to Present	Cenozoic Era 65.5 mya to Present	Quaternary Period (1.8 mya to present) Holocene Epoch (10,000 years to present) Pleistocene (1.8 million to10,000 years) Tertiary Period (65.5 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene Epoch (23.0 to 5.3 mya) Oligocene Epoch (33.9 to 23.0 mya) Eocene Epoch (55.8 to 33.9 mya) Paleocene Epoch (65.5 to 55.8 mya)
	Mesozoic Era 251 to 65.5 mya	Cretaceous Period (145 to 65.5 mya) Jurassic Period (200 to 145 mya) Triassic Period (251 to 200 mya)
	Paleozoic Era 542 to 251 mya	Permian Period (299 to 251 mya) Carboniferous Period (359 to 299 mya) Pennsylvanian Period (318 to 299 mya) Mississippian Period (359 to 318 mya) Devonian Period (416 to 359 mya) Silurian Period (444 to 416 mya) Ordovician Period (488 to 444 mya) Cambrian Period (542 to 488 mya)
PRECAMBRIAN TIME 4,540 to 542 mya	Proterozoic Era 2,500 to 542 mya	Neoproterozoic (1000 to 542 mya) Mesoproterozoic (1600 to 1000 mya) Paleoproterozoic (2500 to 1600 mya)
	Archaean 3,800 to 2,500 mya	
	Hadean 4,540 to 3,800 mya	

mya = million years ago

Diagram adapted from "http://www.ucmp.berkeley.edu/help/timeform.html" and the International Stratigraphic Chart.

Figure 1.27 – Geologic time scale. *Geologic time is subdivided into eons, eras, periods, and epochs. Using relative ages of rocks and fossils, geologists developed the geologic time scale, which initially was just the time periods without absolute ages in years. Once absolute dating methods were developed, the time scale was calibrated with absolute ages, and has been refined over time to the ages you see here.*

As an igneous or metamorphic rock cools from high temperatures, some minerals crystallize and hold ^{40}K isotope within their crystal structure. The minerals begin with a certain amount of **parent isotope** (^{40}K), which will decay at a distinctive, regular rate (called a half-life) to form the **daughter isotope** (^{40}Ar). The **half-life** of a radioactive isotope is the length of time it takes for half of the parent isotope to decay to the daughter isotope (Fig. 1.28). It takes 1250 million years for half the original amount of ^{40}K to decay to ^{40}Ar. The argon gas gets trapped in the crystalline structure of the mineral as the potassium decays. Geologists can carefully compare the amount of parent isotope (^{40}K) remaining and the amount of daughter isotope (^{40}Ar) trapped in the mineral to measure how much time has passed since the rock formed.

Some radioactive isotopes, like ^{40}K and ^{40}Ar, are geologic clocks. These “clocks” are rugged and reliable timers because they cannot be stopped by normal chemical, pressure, or temperature changes that occur within the Earth. Using various isotopes, geologists have been able to calibrate the relative geologic time scale, providing absolute ages for the different divisions of geologic time (Fig. 1.27).

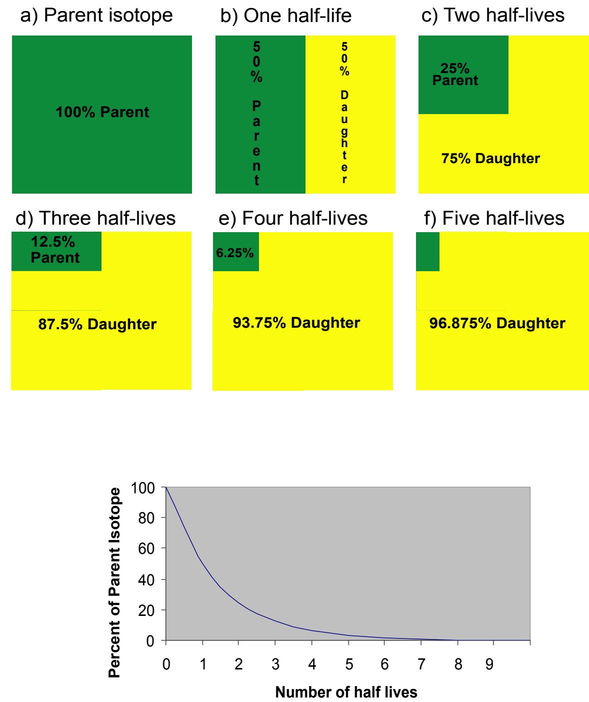


Figure 1.28 – Radioactive isotope decay. *The boxes are simplified representations of an amount of parent isotope (green) which decays to form the daughter isotope (yellow). After one half-life of time passes, half of the parent isotope has decayed to form the daughter isotope. After another half-life, half of the remaining amount of parent material decays to the daughter isotope, and so on. The graph shows this process, as the percent of parent isotope decreases by half with each half-life that passes.*

BIG time. Because geologic time is so large, using words like billions and millions of years interchangeably can confuse you and park visitors. It is important to keep your units of time consistent when discussing geologic time. In this manual, instead of using billions of years, almost everything is written in terms of millions of years. Remember that a ***billion*** (1,000,000,000) is ***one thousand million***.

The rocks of Grand Canyon have been dated using various methods and principles. One methods that has been used to date the igneous and metamorphic rocks in the inner canyon is the decay of uranium to lead (^{238}U to ^{206}Pb), which has a half-life of 4500 million years. Igneous rocks in western Grand Canyon (basalts) have been dated using the decay potassium to argon (^{40}K to ^{40}Ar), with a half-life of 1250 million years. This method for dating rocks has more recently been replaced by ^{40}Ar/ ^{39}Ar, which has improved the precision of the ages of the rocks. The process of decay of ^{40}Ar to ^{39}Ar is similar to ^{40}K to ^{40}Ar decay and the dating technique described here.

The sedimentary rock layers of Grand Canyon cannot be accurately dated radiometrically because they are composed of minerals eroded from other rocks. A radiometric age for a sedimentary rock would give the age of the source rock material, not when the sedimentary rock itself was formed. Most of the sedimentary rocks have been dated using the fossils preserved in them. Some fossils only existed during specific periods in the Earth's geologic history, which narrows down the timing of when the rock formed. The fossils at Grand Canyon have been correlated with fossils in rock layers outside of Grand Canyon with known absolute ages. Rocks with the same types of fossils in other places in the world can provide an approximate age for Grand Canyon sedimentary rocks (Fig. 1.29).

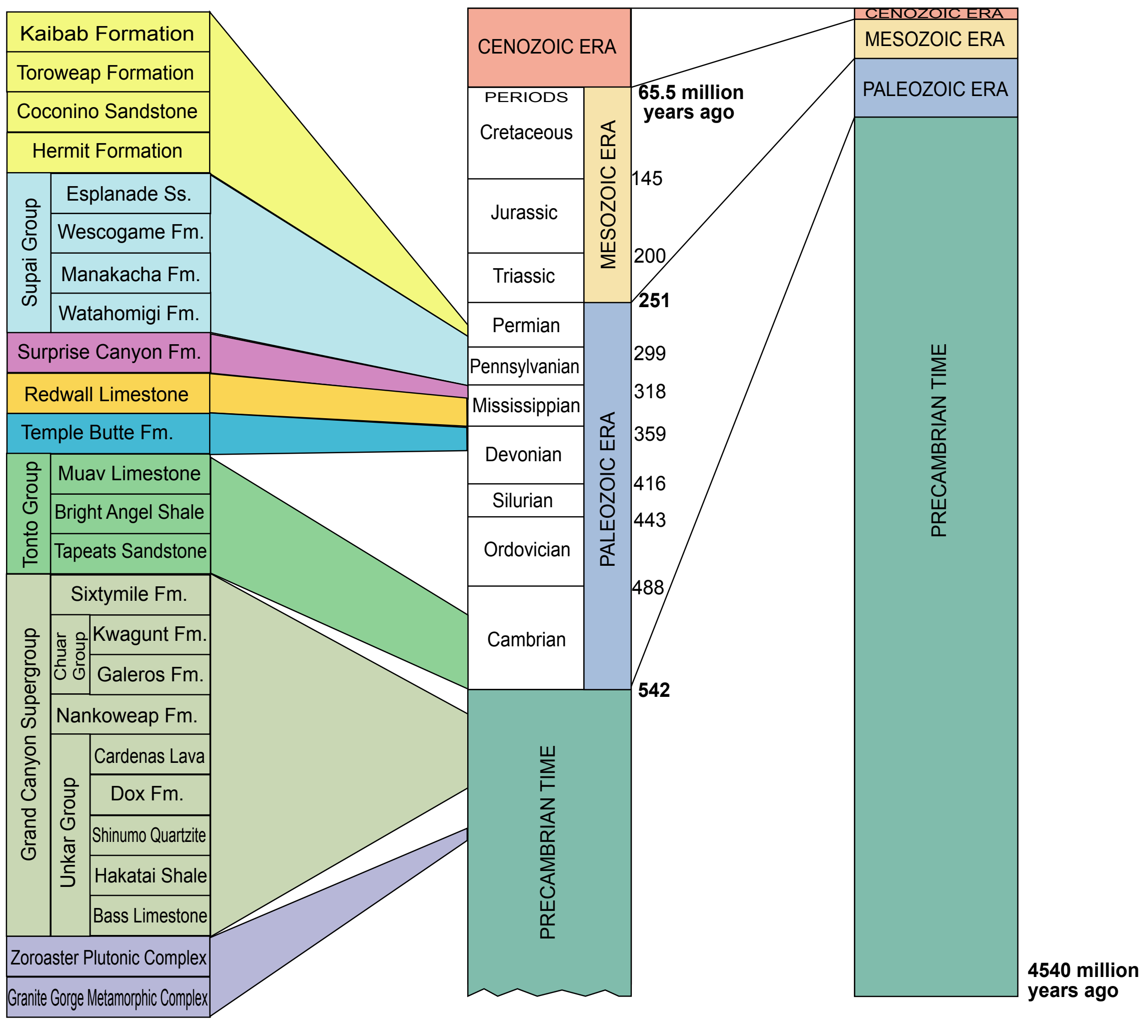


Figure 1.29 – Geologic time scale for Grand Canyon. *The different rock layers of Grand Canyon are depicted to show their approximate ages on the geologic time scale. The geologic time representation in the middle is not drawn to scale. The time scale on the right side has the correct proportions of time. Notice that Precambrian Time covers 87% of the Earth's existence! (Diagram adapted from L. Greer Price, An Introduction to Grand Canyon Geology, 1999)*

The age of Earth. Scientists have not been able to determine the exact age of the Earth from Earth rocks *directly* because the oldest rocks have been recycled and destroyed by processes of plate tectonics. It is assumed that the entire Solar System, which includes the other planets and solar bodies (such as meteorites), formed at approximately the same time. Using radioactive isotopes with long half-lives, scientists have measured the age of meteorites, which provide the best measurements for the age of the Solar System. The meteorites, and therefore the Solar System and the Earth, are about 4540 million years old. Although that seems incredibly old to us, our Solar System is a relatively young member of our Universe. Just for comparison, the Milky Way Galaxy is estimated to be about 11,000 to 13,000 million years old, based on the evolution of globular cluster stars. And the Universe is somewhere between 10,000 and 15,000 million years old, based on the rate of recession of distant galaxies.

STRUCTURAL GEOLOGY

Structural geology is the study of deformation of the Earth's crust, such as folding or faulting that occurs as rocks are compressed or stretched. Structural features, expressed as the cracking and bending of rocks, give us clues about the geologic events that have taken place in the past (Fig. 1.30). Many geologic forces have acted on the Grand Canyon region since the rocks formed, leaving scars on the Earth's surface (Fig. 1.31).

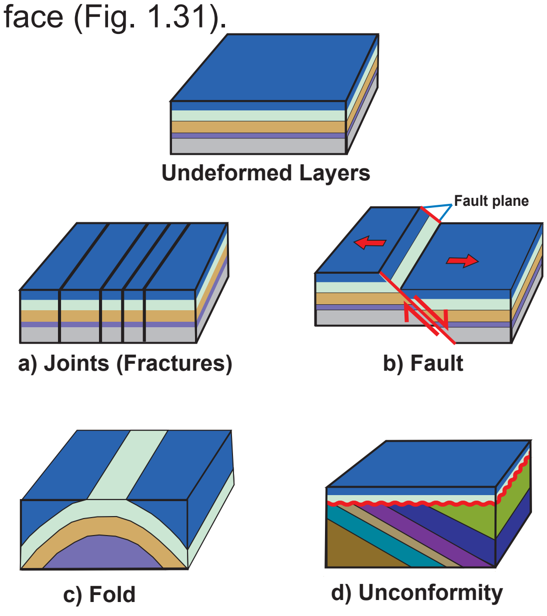


Figure 1.30 – Types of structures. *a)* ***Joints*** *are cracks or fractures in the rock with movement perpendicular to the cracks, but no vertical movement of the rocks. Joints can develop due to geologic forces of extension or compression. b) A* ***fault*** *is a break in the Earth's crust, where parts of the crust move up or down relative to one another. The movement that occurs is parallel to the broken surface, or fault plane. Faults can form where the Earth's crust is being extended, compressed, or sheared. c) A* ***fold*** *is formed when rock layers are bent due to geologic forces of compression or extension. d) The wavy red line indicates an unconformity. An* ***unconformity*** *represents a gap in the geologic record, as if some of the pages of the story have been ripped out. This can be the result of uplift and consequent erosion, followed by the deposition of younger rocks.*

Joints

Joints are cracks that form in response to geologic forces that break rocks apart. There is little or no upward or downward movement in directions parallel to the crack, the rocks simply move apart *perpendicular* to the cracked surface. Joints, and

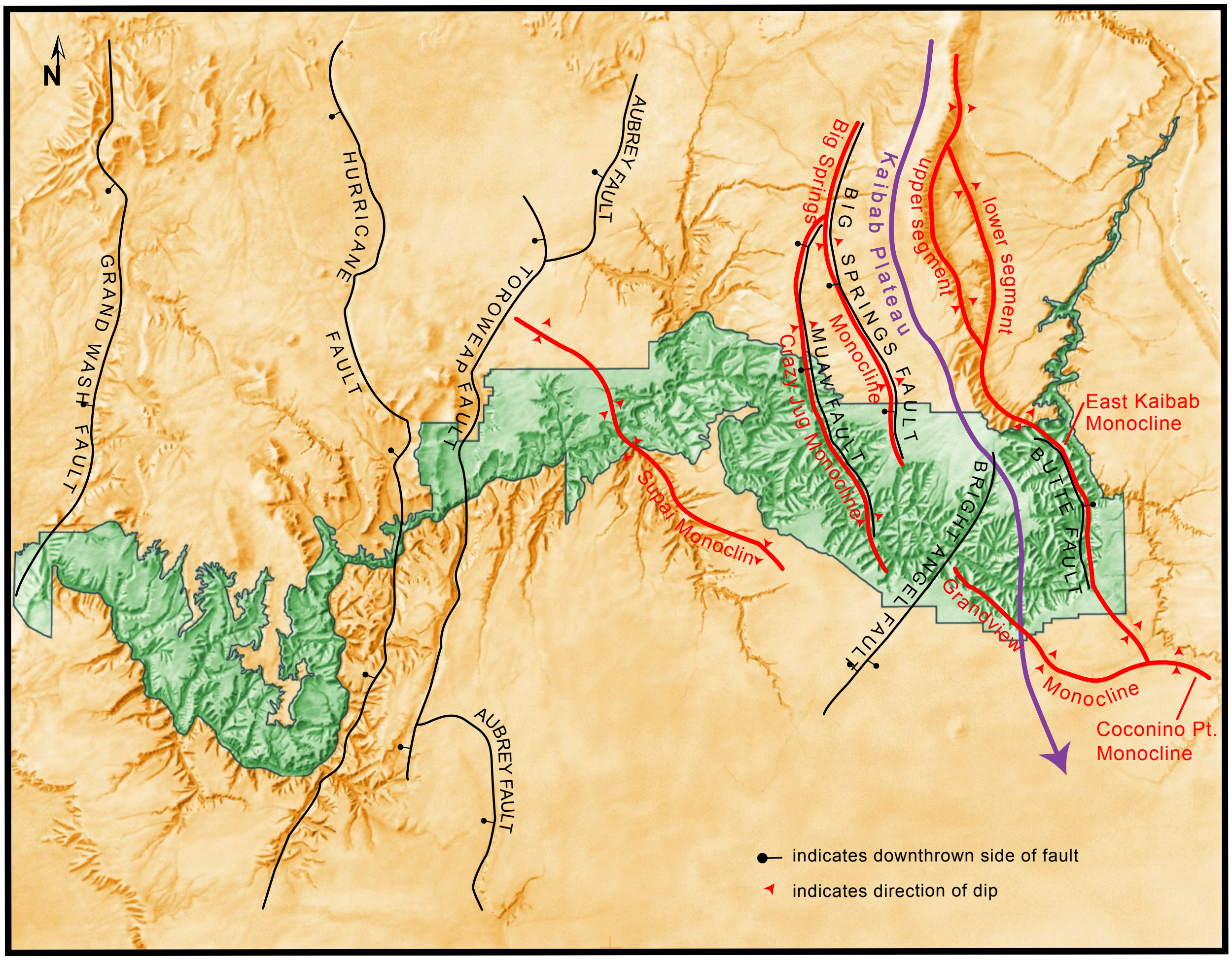


Figure 1.31 – Grand Canyon structures. *This map shows the location of some of the major structural features (faults and folds) that are evidence of past geologic activity in the Grand Canyon region. Notice that many of the monoclines (in red) have faults (in balck) associated with them. These faults are actually the reason the folds formed where they did. (Diagram adapted from Greer Price, An Introduction to Grand Canyon Geology, 1999)*

their effects on the landscape, are seen all around Grand Canyon (Fig. 1.32). Rocks tend to weather quickly along joints, especially when water seeps into the openings. If water freezes within a joint, expansion of the ice forces the joint open further. After many winters pass, parts of the rock may eventually become unstable, break off, and fall into the canyon. Joints have a strong influence on the development of features like mesas, buttes, and temples in the canyon (see page 46).

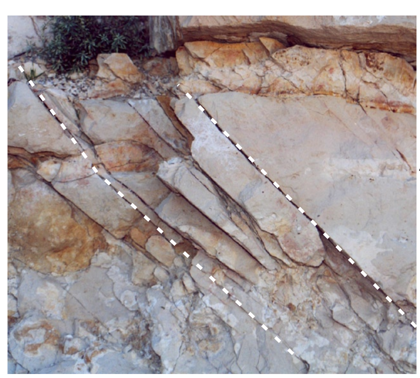


Figure 1.32 – Joints in Grand Canyon rocks. *The rocks of Grand Canyon are riddled with joints. This example is in the Kaibab Formation along the South Kaibab Trail. A few of the joints have been dashed in white to make them more visible.*

Faults

Another type of deformation is a **fault**, which is a crack with movement parallel to the cracked surface. The difference between a fault and a joint is that a fault has significant slippage or movement along the cracked surface, while a joint does not. Faults form as parts of the Earth's crust are pulled apart and extended, squeezed together and compressed, or sheared.

Three types of faults form in response to different geologic forces (Fig. 1.33). **Normal faults** form as a result of pulling or extensional forces, such as occurs at divergent plate boundaries. Where the Earth's crust is squeezed in compressional tectonic settings **reverse faults** will form. They are common near convergent plate boundaries. **Strike-slip faults** form where parts of the Earth's crust slide past one another, such as along transform plate boundaries. Little or no vertical movement occurs along strike-slip faults, rather, the crust on one side of the fault slides laterally past the other.

Faults are like scars or zones of weakness in the Earth's crust. If you break a vase and glue it back together, you know that if it breaks again, it will probably break where it was glued because it is weak there. Likewise, **fault reactivation** happens when an old fault is "re-broken" in response to renewed geologic forces.

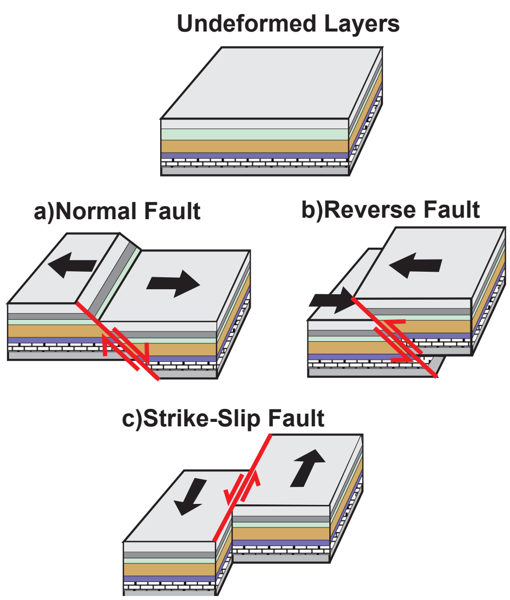


Figure 1.33 – Types of faults. *The larger black arrows represent the dominant direction of the geologic forces that creates the types of faults shown here. The red arrows show the direction of movement along the fault surface. a)* ***Normal faults*** *typically occur in an extensional tectonic setting, where the Earth's crust is being pulled apart, such as at divergent plate boundaries. As a result of being pulled, the crust on one side of the normal fault drops down relative to the other. b)* ***Reverse faults*** *occur in a compressional tectonic setting, such as at convergent plate boundaries where crust is smashed together. Along a reverse fault, the crust on one side of the fault is shoved up over the other. c)* ***Strike-slip faults*** *occur where parts of the Earth's crust slide past one another, such as at transform plate boundaries. Little or no vertical movement occurs on this type of fault. (Diagram adapted from R.J. Lillie)*

Most of the faults in Grand Canyon are very old and have been reactivated several times, behaving sometimes as normal faults, and other times as reverse faults (Fig. 1.34). Many of them were initially faulted shortly after the oldest rocks in the canyon formed. One such example is the Bright Angel Fault. It was a normal fault when it formed about 1700 million years ago. It was later reactivated between 70 and 40 million years ago, but this time with reverse fault movement. In the last 15 million years it has been reactivated again as a normal fault. It has been a very busy fault, responding to the variety of geologic forces that have acted on the region.

As geologic forces push or pull on the Earth's crust, strain energy builds up until the rocks cannot take anymore. The result is an **earthquake**, which is the sudden release of built up strain energy along a fault. An earthquake occurs almost every time a fault moves. One can occur when a new fault forms or when an old fault is reactivated. If the rocks have already been faulted, they are weak zones that will probably release strain energy again if geologic forces continue. Some earthquakes are very intense while others are barely noticeable.

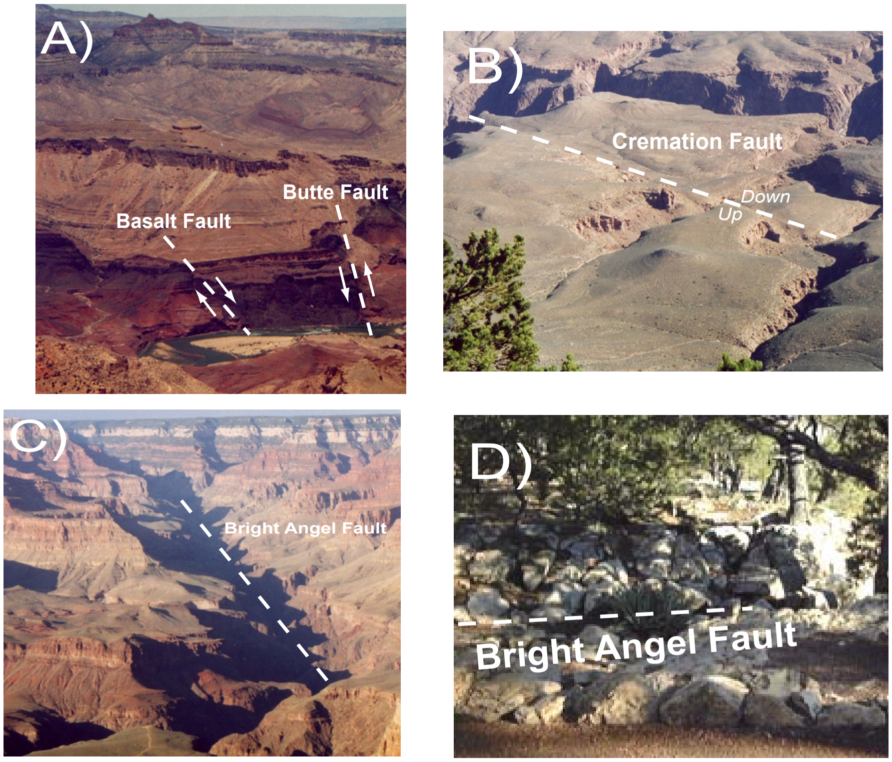


Figure 1.34 – Faults in Grand Canyon. *Faults are seen along the dashed gray lines in these photos. As you observe the faults in the park, compare these pictures with the real-life scenery. A)* ***Butte and Basalt Faults:*** *From Desert View, looking down towards the river, you can see Butte Fault and Basalt Fault. These two faults caused the dark gray basalt layer, known as the Cardenas Lava, to drop down at this location. B)* ***Cremation Fault:*** *If you look down into the canyon from Yaki Point you can see the Cremation Fault. This fault cut through the rock layers, and shoved the Tapeats Sandstone up so that it is now above the Bright Angel Shale. C)* ***Bright Angel Fault:*** *From the Village area, the Bright Angel Fault is very easily seen.The straight side canyon (named Bright Angel Canyon) formed along this fault, on the north side of Grand Canyon. The rocks within the Bright Angel Fault zone were weaker and easily eroded, allowing Bright Angel Creek to gradually carve the side canyon. The fault also created a place for the Bright Angel Trail because it broke up the steep cliffs that are otherwise impossible to ascend or descend. D)* ***Bright Angel Fault:*** *Along the Rim Trail, west of the Village, the Bright Angel Fault crosses the South Rim near the fossil site. Part of the fault can be seen as a small gully along the trail.*

Safe earthquakes. In the recorded history of Arizona, no earthquake has ever caused death or injury to humans. The earthquakes that occur are usually small and not very intense. They are commonly caused by the extension of the Basin and Range Province. As the crust of the North American continent is pulled apart, it breaks along normal faults creating small earthquakes. Most of the normal faulting in the Grand Canyon region occurs along pre-existing faults that formed long ago, during Precambrian time. Faults in western Grand Canyon, such as the Hurricane and Toroweap Faults, have been active in the last 3 million years (Fig. 1.31). These faults are considered to be the most active faults in Arizona.

Folds

A **fold** is another type of structural feature that forms as the Earth's crust is strained. Folds occur in rocks in the same way that a rug wrinkles when it is pushed from the edges. There are three simple types of folds: anticlines, synclines, and monoclines (Fig. 1.35). **Anticlines** are folds that bulge upwards, similar to the shape of a capital letter "A." **Synclines** are downward folds, shaped similar to the letter "U." A fold that

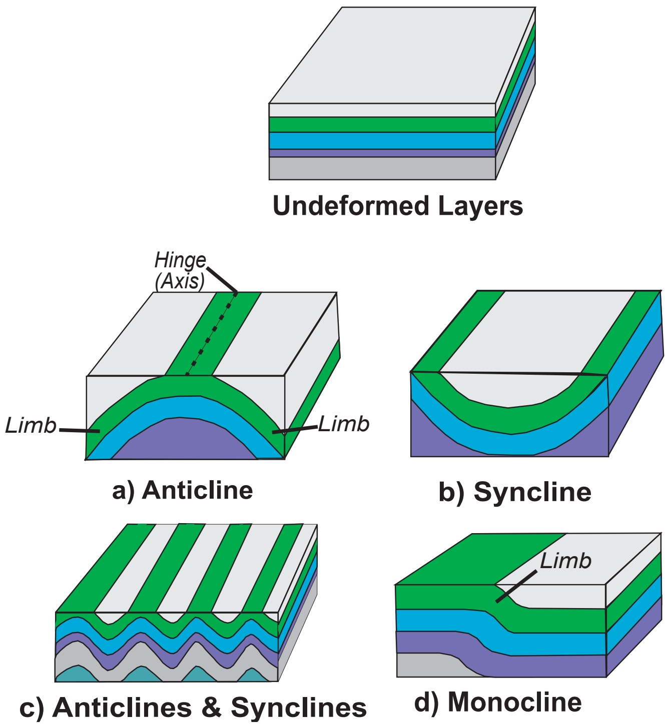


Figure 1.35 – Types of folds. *Folds usually form because of slow geologic forces acting on the Earth's crust, as if you slowly pushed two ends of a rug together. The* ***hinge*** *or* ***axis*** *of the fold is where the curvature is greatest, and the* ***limbs*** *are the arms of the fold. a) An* ***anticline*** *is a fold that arches upward, forming a shape similar to a capital "A" (for Anticline!). b) A* ***syncline*** *is the opposite, and arches downward, to form a shape similar to the letter "U." c) Anticlines and synclines often form in series, like wrinkles in a rug. d)* ***Monoclines****, folds with only one limb rather than two, are common at Grand Canyon and on the Colorado Plateau. (Diagram adapted from R.J. Lillie)*

is neither an anticline nor a syncline, with only one folded side, is a **monocline**. It looks like a ramp that connects lower ground to higher ground.

Most of the folds in Grand Canyon are monoclines, and several can be seen from the rim (Fig. 1.36). These monoclines formed because old faults exist deep below the layers of sedimentary rocks that were deposited as flat-lying, horizontal layers. When the faults underneath were reactivated after the deposition of the sedimentary rocks, they faulted some of the deep layers close to the fault, and also caused the uppermost layers to be folded into monoclines (Fig. 1.37).

Geology toys. A good tool for understanding how the Earth deforms is silly putty. When you deform the putty slowly, bending and stretching occurs. The putty behaves in a ductile fashion, like taffy. But if you pull the silly putty quickly, it snaps and behaves brittlely, like peanut brittle. Likewise, if the strain on a rock is gentle and slow, the rock might bend to form folds. But the same rock might snap, behaving in a brittle fashion when the stress is quick and forceful.

Unconformities

If the layers of rock are like pages in a book, **unconformities** are places where pages were never written, or they were written but later ripped out. Unconformities represent the missing pages from the book of geologic time at Grand Canyon. Episodes of uplift and/or erosion may have removed pages, or no deposition occurred to write some of the pages in the Grand Canyon book. There are many unconformities, some with hundreds of millions of years missing and others missing just a few million years or less. Some of the big unconformities are depicted on the stratigraphic column in Figure 1.25.

When rocks are deposited one layer on top of another, with no lapses in deposition or periods of erosion, the geologic record is complete, or "conformable." But exposures of complete rock sequences, with no geologic time missing, are rare. An unconfor-

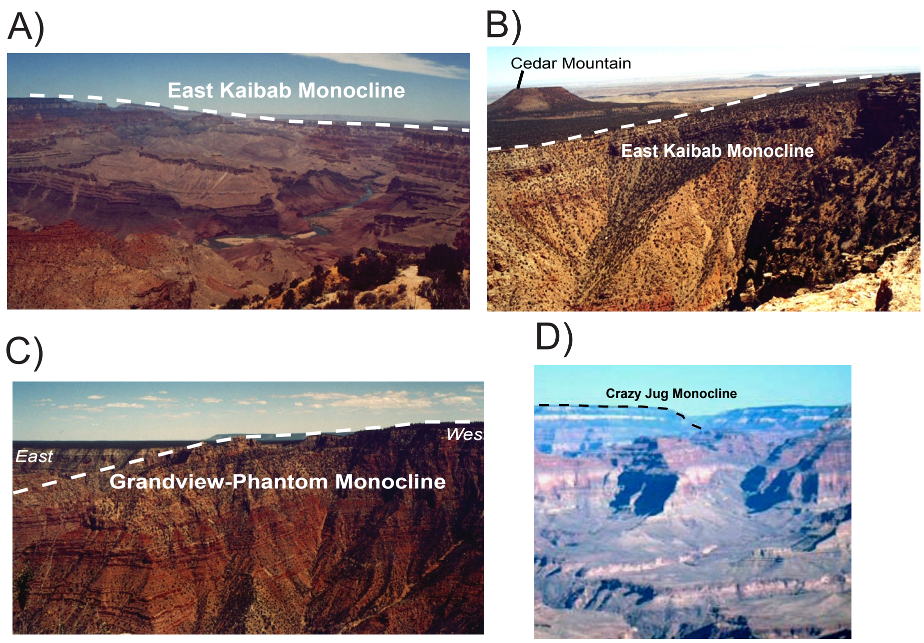


Figure 1.36 – Folds in Grand Canyon. *When you see folds in the landscape, they may not look like the nice, straight folds in Figure 1.35. Try to imagine the general shape of the fold as you observe the following features in the canyon. A)* ***East Kaibab Monocline:*** *This photo of the East Kaibab Monocline was taken from the main look-out at Desert View. It may first appear that the photo is crooked, but it is not. This illusion is because the rock layers on the western side of the monocline are at a slightly higher elevation than on the eastern side. The axis of the monocline was broken up as it was folded. This caused the rocks to be eroded faster than the surrounding flat-lying rocks, so now the entire monocline cannot be seen. B)* ***East Kaibab Monocline:*** *The East Kaibab Monocline bends southeastward. Walk east along the rim from the overlook at Desert View, and find the trail leading to a small overlook. From this point, you have a clear view of the folded rocks. C)* ***Phantom-Grandview Monocline:*** *Grandview Point is known for the geologic feature called the Sinking Ship, on the east side of the main overlook. The Sinking Ship is made up of the tilted layers in the limb of the Grandview-Phantom Monocline. The monocline makes the rim higher toward the west (nearest to Grandview Point), and lower toward the east (closer to Moran Point). D)* ***Crazy Jug Monocline:*** *This monocline can be seen to the northwest from Hermits Road, but it is in the distance. It is especially visible from Pima Point, where this photo was taken.*

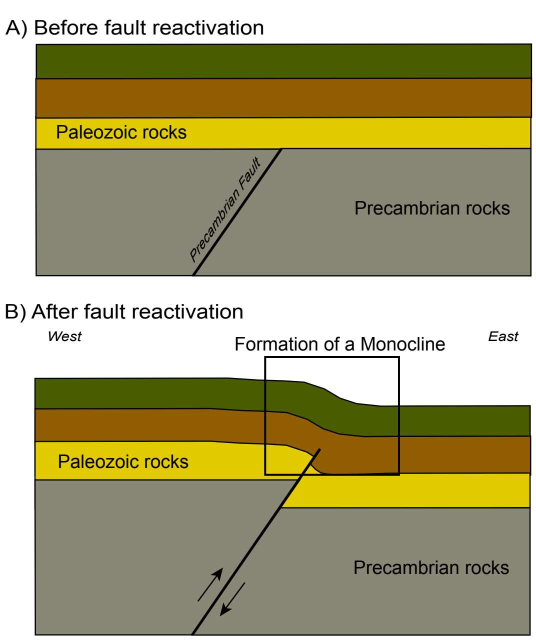


Figure 1.37 – Formation of monoclines at Grand Canyon. *One way that folds form is because of faulting in rocks at depth. A) In the Grand Canyon region, faults that formed during the Precambrian were buried beneath the Paleozoic sedimentary layers. B) When the faults were reactivated, the layers closest to the fault were faulted as well. But overlying layers were gently folded rather than faulted because they lay further from the fault.*

Geology and life zones. Driving along Desert View Drive, particularly along the section known as Buggelin Hill, provides an opportunity to see the effects of geology on the vegetation. This hill is actually part of the Grandview-Phantom Monocline. Check out the tilted rocks along the northern side of the road as you drive up or down the hill. These rocks are the folded layers in the limb of the monocline. Also take notice of the vegetation around you. On the lower portion of the fold, mostly Piñon Pine and Juniper trees surround you. Once you are up on the higher part of the fold, between mile markers 249 and 253, you are in a Ponderosa Pine and Gambel Oak forest. This change in vegetation is due to the small change in elevation caused by the monocline. Pigmy forests exist between about 4000 – 7500 feet (1220 – 2290 m) elevation, while the Ponderosas and oaks thrive at about 7000 – 8000 feet (2100 – 2400 m) elevation. Buggelin Hill's highest point is about 7500 feet (2290 m). Where it drops back down to 7000 feet (2290 m) the vegetation changes back to the Piñon and Juniper forest.

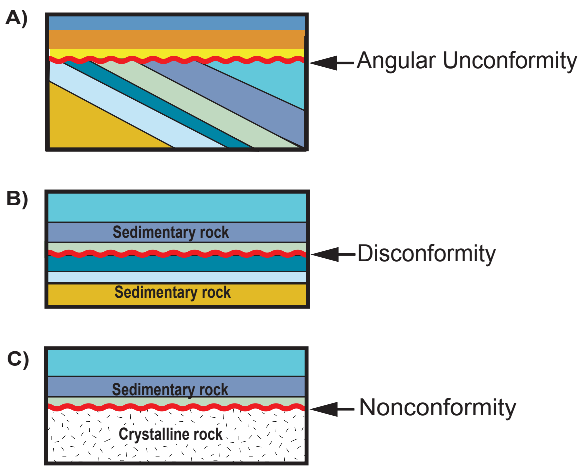


Figure 1.38 – Types of unconformities. *Unconformities (shown as wavy red lines) are like pages missing from the geologic record. They commonly represent a period of uplift, erosion, no deposition, and/or a drop in sea level. A)* ***Angular unconformities*** *develop after horizontally deposited layers are tilted, and then partially eroded. New rock layers are eventually deposited horizontally over them. The surface where the tilted rocks and horizontal rocks touch is the angular unconformity. B) A* ***disconformity*** *is similar to an angular unconformity, but the layers above and below the unconformity are parallel. They can be difficult to see when the rocks on either side of the unconformity are similar. They form as rocks are deposited, followed by a period of erosion and/or no deposition. More deposition occurs later, without tilting or deformation of the layers, forming the disconformity. C) A* ***nonconformity*** *is where sedimentary rocks overly intrusive igneous or metamorphic rocks (referred to as crystalline rocks). First, metamorphism or rock melting creates the crystalline rocks deep within the Earth. Those rocks are later uplifted, as the overlying rocks are eroded away. When sedimentary rocks cover the exposed crystalline rocks, it creates a nonconformity where the two different rock types are in contact.*

mity represents the period of time when no rocks were deposited or a period of erosion that has removed rocks that were deposited. Several factors, including erosion, uplift of the land, drop in sea level, and/or structural deformation can contribute to the development of unconformities (Fig. 1.38). Each of these events can leave evidence that time has passed between the deposition of two adjacent layers. For example, the two layers may have greatly different fossil assemblages or they are very different types of rock, suggesting that time had to pass in order for the environment to dramatically change. Unfortunately, it is hard to tell what may have been deposited or what may have caused the unconformity because there is nothing left of it in the record.

There are three different kinds of unconformities, and Grand Canyon provides world-class examples of each type. An **angular unconformity** is where horizontal layers lie directly on top of layers that have been tilted (Fig. 1.39). For an angular unconformity to form, rock layers are first deposited horizontally, and then titled during an episode of deformation. Usually some of the tilted layers are eroded away and new layers are eventually deposited on top. The angular unconformity is the surface between the tilted and horizontal layers.

A)

B)

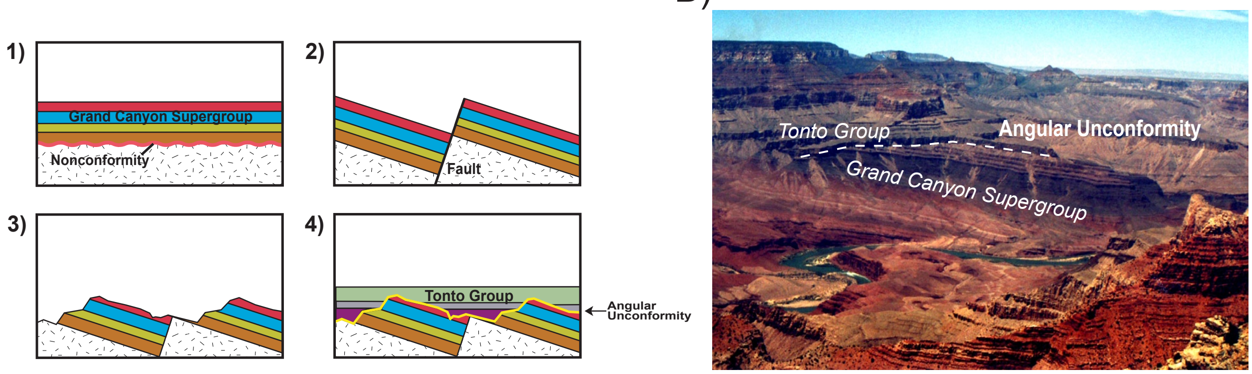


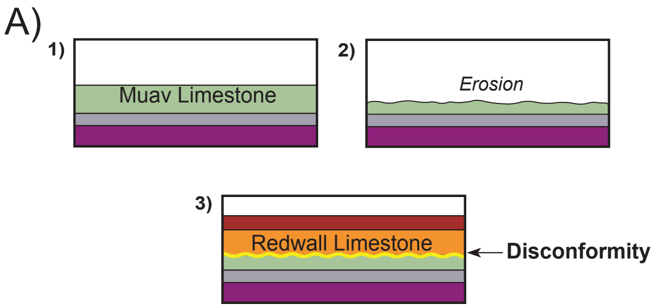
Figure 1.39 – Angular unconformity. *A) A major angular unconformity at Grand Canyon occurs between the tilted layers of the Grand Canyon Supergroup and the overlying sedimentary layers known as the Tonto Group (includes the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone). 1) The Supergroup was first deposited on top of the crystalline rocks of the inner canyon (creating a nonconformity). 2) The Supergroup and the crystalline rocks were then faulted, which tilted the layers of the Supergroup. 3) Intense erosion wore down the small mountains that had formed as a result of the faulting. 4) The Tonto Group was deposited as the sea inundated the region and covered the tilted Supergroup layers. B) The angular unconformity can be seen from the eastern end of Grand Canyon, especially at Lipan Point, where this photo was taken. About 215 million years of time is missing from the geologic record at this unconformity.*

A **disconformity** can form between sedimentary layers when there is a period of erosion or no deposition, but there is no tilting of the layers (Fig. 1.40). This typically happens because a region has been uplifted above sea level or sea level has dropped, causing the rocks to be exposed to erosion. Later, land subsidence (lowering) and/or sea level rise leads to the deposition of more layers above the eroded surface. Disconformities can be difficult to see because the eroded surface is parallel to the rock layers.

The third type of unconformity, a **nonconformity**, is where sedimentary layers lie directly on top of intrusive igneous or metamorphic rock (referred to as crystalline rock) (Fig. 1.41). For a nonconformity to form, rocks must first be metamorphosed or melted, then cooled and hardened deep beneath the surface. Uplift and erosion eventually exposes the crystalline rock at the Earth's surface. A nonconformity forms where sedimentary layers are deposited on top of the crystalline rock. Nonconformities indicate that there has been a period of uplift and erosion, because metamorphism and melting usually occur very deep within the Earth.

HYDROLOGY

Despite all other geologic forces that have contributed to the forming of Grand Canyon and its layers, the single most powerful force acting on the canyon today is water. Without water, neither the canyon nor the people would be here. **Hydrology** is



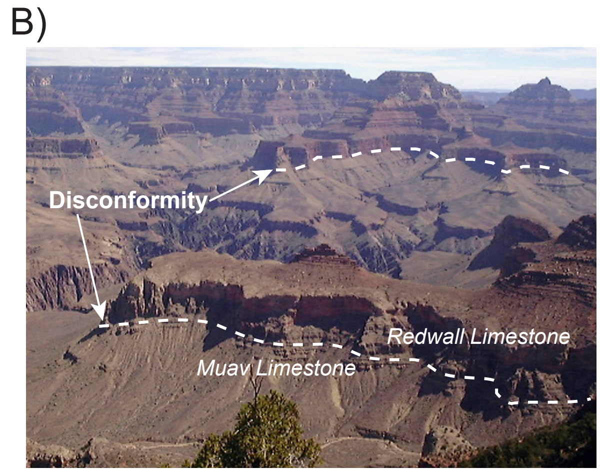
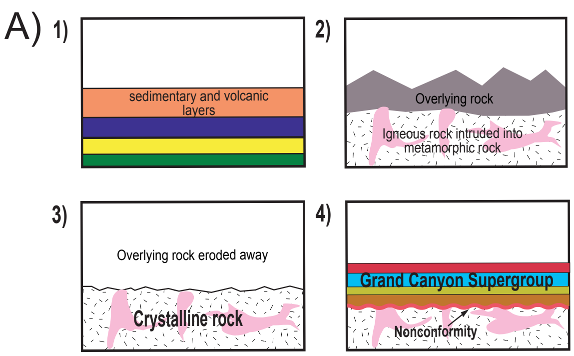


Figure 1.40 – Disconformity. *A) The disconformity between the Muav Limestone and the Redwall Limestone is one of the most significant disconformities (in terms of missing geologic time) within the sedimentary rock layers of Grand Canyon. This particular disconformity represents nearly 165 million years of missing time. 1) It formed as the Muav Limestone was deposited; 2) followed by a long period of uplift, erosion and/or no deposition. 3) The sea returned, covering the Muav Limestone with the Redwall Limestone. (In some places a layer called the Temple Butte Limestone was deposited in between the Muav and Redwall Limestones, but this is not easily seen from the canyon rim in the Village.) B) Disconformities can be hard to see in the sedimentary layers because the rocks on either side of the disconformity are parallel. This photo was taken at Yaki Point. (Both dashed lines that mark the disconformity highlight the same disconformity at different locations in the canyon.)*



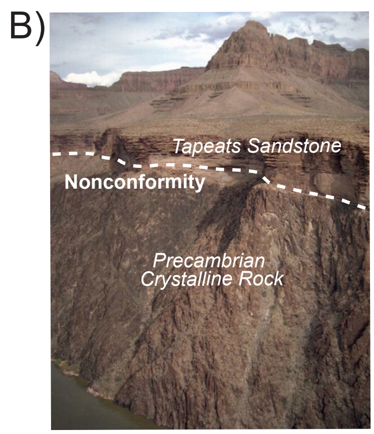


Figure 1.41 – Nonconformity. *A) 1) The first step in the formation of one of the nonconformities at Grand Canyon was the deposition of sedimentary and volcanic layers. 2) These rocks were later metamorphosed and melted deep below the Earth's surface as a mountain building event occurred. This changed the parent rocks to metamorphic and igneous rocks (crystalline rocks). 3) After many millions of years of uplift and erosion, the crystalline rocks were exposed at the surface. 4) Later sea level rose and covered the region, depositing the Grand Canyon Supergroup. A nonconformity has developed where these two different rock types are in contact. B) This is a different nonconformity than the one depicted in (A), but it is also very important. It is the most dramatic unconformity in Grand Canyon, also known as the Great Unconformity. Where the younger sedimentary rocks (525 million year old Tapeats Sandstone) are in contact with the crystalline rocks in the inner canyon, as much as 1200 million years of time is missing from the geologic record. At least 13 miles (21 km) of rock was removed by erosion before this nonconformity formed. This photo was taken near Plateau Point, but the same nonconformity can be seen from almost anywhere along the canyon rim. (Photo property of NPS)*

the study of the movement of water. River systems are dynamic and constantly changing, affected by many different hydrologic factors. The powerful movement of the water of the Colorado River has unveiled the impressive, colorful rock layers and geologic features in Grand Canyon that would otherwise lie buried deep beneath the Earth's surface.

The volume of water carried by a river or stream is its **discharge**, which can fluctuate on a yearly, seasonal, and daily basis. Discharge can depend on factors such as climate change, snowmelt, local weather conditions, and human involvement. Prior to Glen Canyon Dam, the Colorado River's discharge fluctuated greatly. When snow melted in the Rocky Mountains in the spring, the flow of the river could reach 100,000 cubic feet per second (cfs). During late summer, fall, and winter, flows typically dropped to less than 5,000 cfs. Glen Canyon Dam now regulates the discharge of the river, usually keeping it between 8,000 and 18,000 cfs throughout the year.

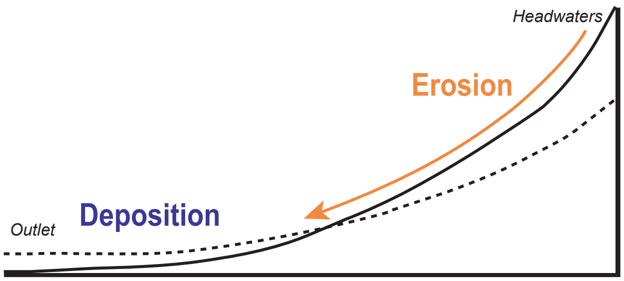
Factors such as discharge and water velocity determine how much sediment the river can carry. The **sediment load** is the material of various sizes that is transported by the river. This includes sediment that is bounced along the channel bottom, or completely suspended and carried by the water. Finer sediment is often suspended in the current, while coarser sediment is bounced along the river channel and only suspended briefly. Other very fine sediment can also be dissolved in the water. During a flood in 1884, the discharge of the Colorado River reached 300,000 cfs and the river was carrying at least 300 tons of sediment per day, as measured by a gage near Phantom Ranch. With Glen Canyon Dam now in operation, the sediment load of the Colorado River through Grand Canyon is reduced to less than 50 tons per day.

The sediment load of a river is also dependent on the water **velocity**. When the water velocity is high, a river can carry a large volume of sediment, including coarse sand, gravel, and boulders. The more sediment carried by the water, the more erosive power it has. A river with a large sediment load and high water velocity is like a sandblaster, intensely eroding as sediment rubs against the river's channel. Although the discharge of the Colorado River is less than *one-tenth* of the Mississippi River's, the erosive power of the Colorado is far greater because of the high water velocity *and* sediment load. Thus, the Mississippi River is sluggish, and creates a wide, shallow river valley while the Colorado River has cut through tons of rock to form deep canyons.

Semi-trailer analogy. The discharge of a river is traditionally measured in cubic feet per second (cfs), but this is a volume that visitors may have difficulty visualizing. To help visitors understand the volume of water that flows in the Colorado River, have them imagine a trailer of a semi-truck that they probably passed on I-40 as they traveled to Grand Canyon. The average volume of a semi-trailer is about 5900 cubic feet. That means that two to three trailers full of water pass through Glen Canyon Dam *every second*! That's about 100-200 semi-trailers *every minute*!

The **gradient**, or slope, of a river is the change in elevation of the channel. This can affect a river's velocity and sediment load. When you ride a bicycle downhill, gravity and momentum help you go much faster than on flat land. In the same way, water travels faster down a steep gradient. The Colorado River loses a great deal of elevation over a relatively short distance, and has a steep gradient compared to the Mississippi River. The Colorado River travels just over 1400 miles (2240 km) from its headwaters in the Rocky Mountains nearly 12,000 feet (3600 m) above sea level, to its outlet at sea level in the Gulf of California (the Sea of Cortez). In Grand Canyon alone the Colorado River drops 2,200 feet (670 m), with a gradient of about 8 feet/mile (1.5 m/km). In comparison, the Mississippi River loses only about 1400 feet (420 m) over more than 2300

__Figure 1.42 – Balance of erosion and deposition.__ This simplified diagram depicts how a river erodes sediment from the steeper part of the channel (red arrow), which is usually near the headwaters, and deposits it along the flatter part of the channel, near the mouth of the river. The solid line represents the channel before erosion and deposition, and the dashed line is how the same channel would look after some erosion and deposition has taken place. The increase in velocity that occurs as water travels down a steep slope enables it to erode and pick up large amounts of sediment. As the water velocity decreases along flatter parts of the channel, it can no longer carry the sediment and some of it is deposited.



miles (3680 km) as it reaches its outlet in the Gulf of Mexico. Its average gradient is only about 0.5 foot/mile (0.09 m or 9 cm/km).

Another important factor in the hydrology of a river is its **base level**, which is the elevation of the river's outlet. The base level of most large rivers is sea level, but it may also be a lake or reservoir. It is the lowest elevation a river can cut down into its channel. If there is a change in base level, the gradient, water velocity, and sediment load of a river will usually change. For example, when a river is dammed or sea level rises, the base level of the upstream river rises accordingly. This decreases the gradient of the channel, which decreases the water velocity. Some of the sediment load transported by the river can be deposited in the stream channel because the velocity is not great enough to carry it. This has happened in western Grand Canyon due to the effect of Hoover Dam and Lake Mead. There the river behaves more like a lake, and some of the rapids once existed are now submerged by deep water and sediment.

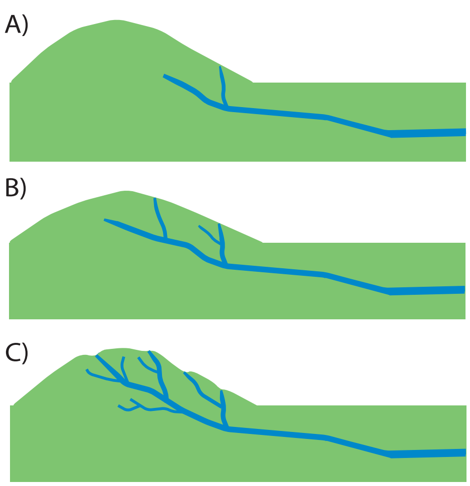


__Figure 1.43 – Headward erosion.__ Headward erosion plays an important role in the evolution and lengthening of a river or stream. As a stream travels down a steep slope it cuts down into the channel and removes sediment from the channel itself, as shown in Fig. 1.42. A river or stream will also grow in length by cutting back into the steep parts of its channel, as shown here in the transition from A to B to C. This often occurs at the headwaters of a stream where the channel is steepest.

River processes, like many other processes in nature, eventually achieve a balance or equilibrium. River equilibrium is a balance between erosion and deposition. Erosion smoothes the steep parts of the channel and then the eroded sediment is deposited on the gently sloping parts. Rivers with initially steep gradients eventually develop gentle, low gradients as they carry away the rock material eroded from their headwaters and deposit it downstream (Fig. 1.42). Someday, millions of years from now, the Colorado River may be more like the Mississippi River, when all of the channel has been smoothed by erosion and deposition processes.

The process of erosion in the steepest parts of a river channel is known as **headward erosion**. It occurs as a river or stream erodes and cuts back towards its headwaters as it tries to create a smooth, gradual gradient. Headward erosion is a process that eventually lengthens river channels (Fig. 1.43).

As headward erosion of a stream or river extends the channel, it may intersect with another stream. **Stream capture** occurs when one stream takes the water from another stream, diverting the stolen water along a new, more vigorous stream channel. Rivers change course and take new paths, leaving old, abandoned channels as evidence that stream capture has taken place.

> **Niagara Falls.** If you've ever visited Niagara Falls near Buffalo, NY, you've seen processes similar to headward erosion in action. As the Niagara River flows over the waterfalls, it erodes and slowly cuts back into the rock at a rate of about 3.3 feet/year (1 meter/year). Over time, the waterfall at Niagara Falls progressively moves eastward, upstream as the river tries to develop a smooth channel. In the last 12,000 years, the falls have eroded more than 7 miles (12 km) of the river channel!

The processes of headward erosion and stream capture have been important in the development of the landscape of the Colorado Plateau and the Grand Canyon region. Many ancient rivers may have existed on the Colorado Plateau that may have been pieced together to form the rivers and streams we see today.

Side Canyons

Tributaries to the Colorado River create side canyons along the main Colorado River channel (Fig. 1.44). More side canyons are found along the North Rim than the South Rim in eastern Grand Canyon. In eastern Grand Canyon, the North Rim is about 1000 feet (305 m) higher than the South Rim because the land slopes down gently to the south. The southward slope is due to a broad bulge of the rocks called the **Kaibab Plateau**, which is a large anticline that dives down into the Earth at its southern end (Fig. 1.45). Because of this structure, any precipitation that falls on the North Rim flows south, down-slope toward the canyon. Over time the water has formed tributaries that have eroded long side canyons along the North Rim. But when precipitation falls on the South Rim it also runs down-slope towards the south, away from the canyon. Because there is less water coming into the canyon from the south, there is also less erosion. Therefore, the side canyons that develop on the South Rim are much shorter and steeper compared those on the North Rim.

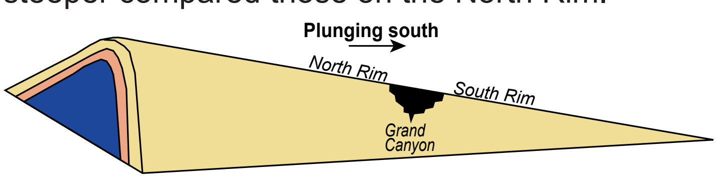


Figure 1.45 – The Kaibab Plateau. *The region of upwarped land called the Kaibab Plateau seen in Figure 1.44 may have contributed to the development of the path of the Colorado River, as we know it today. The Kaibab Plateau is a broad plunging anticline schematically shown here. This means that the axis of the fold is not parallel to the Earth's surface, but rather it is inclined. One end of the fold appears to be diving into the Earth. In the case of the Kaibab Plateau, the fold is plunging into the Earth on its southern end, causing the South Rim to be 1000 feet (300 m) lower in elevation than the North Rim. Interestingly, the anticline is actually compsed of several small monoclines (not shown here), which together give the general shape of an anticline.*

Whitewater rapids are often found at the ends of side canyons, where the tributaries join the Colorado River. The side canyons not only contribute water, but can also dump sediment into the river. When the side canyons are flooded by rain or snow melt,

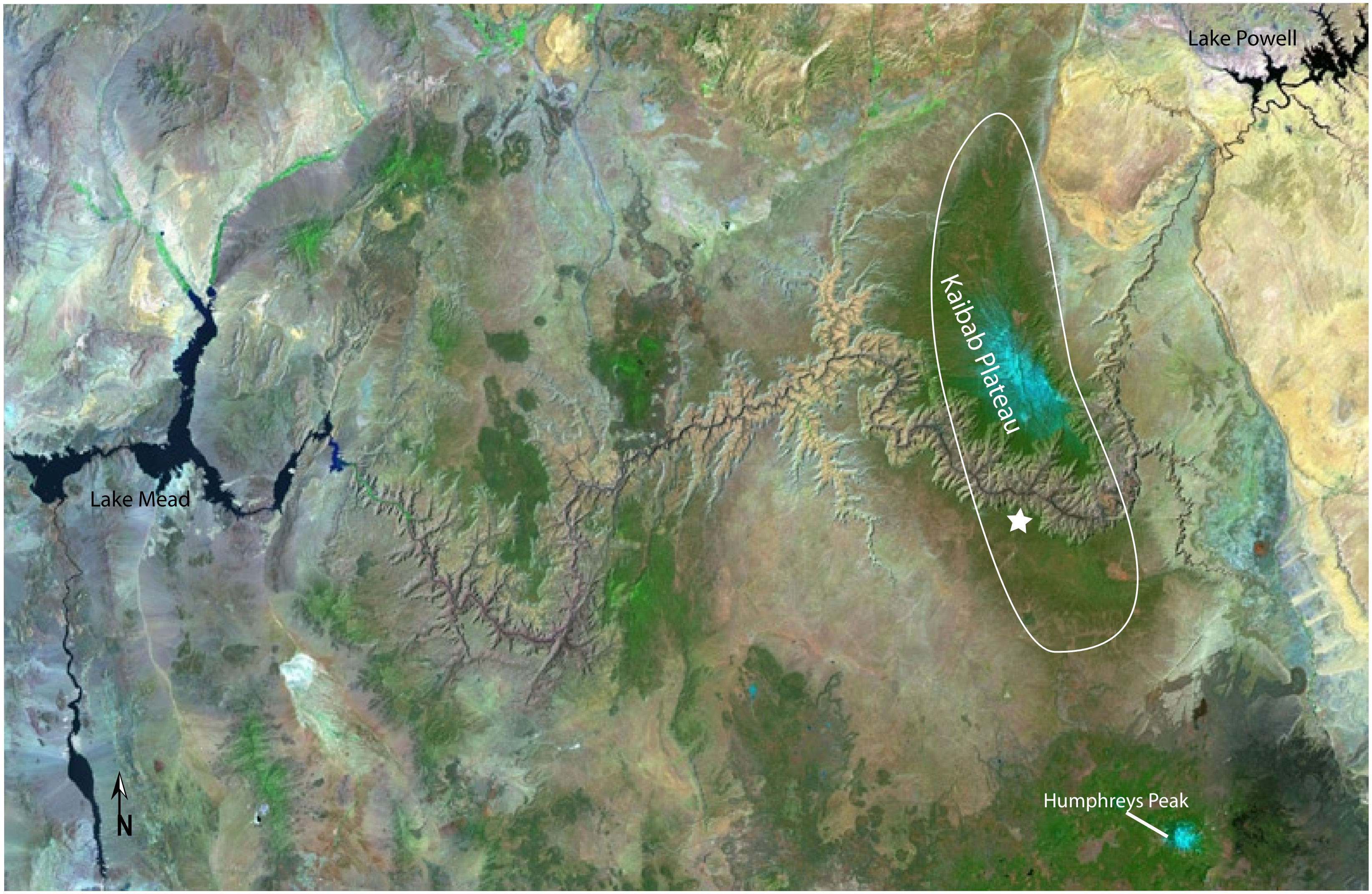


Figure 1.44 – Satellite image of Grand Canyon region. *You can see that there are many side canyons along the Colorado River that contribute to the great width of Grand Canyon. The large, oval-shape area circled in eastern Grand Canyon is the Kaibab Plateau. It has a spot of lighter color (bright blue) on the North Rim because there was snow cover on the high elevations when the image was acquired. The star on the image is the approximate location of the South Rim Village. (Image property of NPS)*

__Figure 1.46 – Rapids on the river.__ Tributaries flowing from side canyons contribute water and sediment to the Colorado River. When flooding occurs in the side channels, large, boulder-size sediment gets deposited in the river, which make large rapids. The rapid shown here is Lava Falls, in western Grand Canyon. Note the size of the rapids in comparison to the person! (Photo property of NPS)

they can transport large boulders into the river. The boulders create rapids for river runners to enjoy (Fig. 1.46).

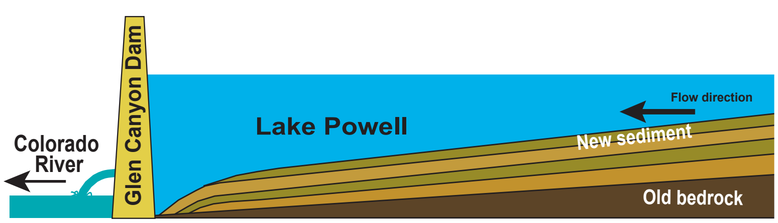
Where does the drinking water come from? Drinking water is scarce on the South Rim because most of the water flows southward, away from the Rim. Thankfully, a terrific feat of engineering has solved the problem. Roaring Springs, along the North Kaibab Trail in Bright Angel Canyon, is a large spring where groundwater enters the canyon from the North Rim. The spring is located about 1000 feet (305 m) higher than Indian Garden on the South Rim. Water from Roaring Springs is piped down to Phantom Ranch, across the river to Indian Garden. The water flows naturally downhill to that point. From Indian Garden, it is pumped up to the South Rim and stored in tanks for later usage.

Glen Canyon Dam

The Colorado River was described as “too thick to drink, and too thin to plow” because of the large amount of sediment it once carried. But now the river no longer flows through Grand Canyon with the same vigor it once did. Glen Canyon Dam, near Page, Arizona, began controlling the water released into Grand Canyon in 1963. Since then, the dam and reservoir (Lake Powell) have provided water for agriculture and electricity for many desert cities, as well as a place for water recreation. As the Colorado River passes through Glen Canyon Dam, it is typically a blue-green color rather than the muddy-brown color it once was. This is because most of the river’s sediment gets deposited in Lake Powell. When monsoon season arrives at the end of each summer, the muddy-brown color returns, as red and brown sediment is washed in from side canyons and tributaries downstream from the dam.

Hundreds of thousands of tons of sediment that was once carried through Grand Canyon now settle at the bottom of Lake Powell (Fig. 1.47). As the sediment builds up, it gradually decreases the capacity of the lake and the volume of water it can hold.

__Figure 1.47 – Lake Powell.__ (not to scale) In this simplified diagram of Lake Powell, you can see how Glen Canyon Dam has stopped most of the flow of the Colorado River through Glen Canyon. As the river enters Lake Powell, the water velocity decreases, causing the sediment carried by the Colorado River to be deposited on the bottom of the lake. Someday, unless humans intervene, the amount of sediments will decrease the capacity of the lake so much that the water may overtop the dam.



When snow melts from the mountains each spring, the Colorado River is at its peak discharge. When the water reaches Lake Powell, Glen Canyon Dam somehow must retain it. But with each year that passes, the volume of water that the lake can hold decreases as sediment builds up. Without human intervention the lake may eventually fill up and overflow the dam. The downstream effects of the dam overflowing on Grand Canyon's human, plant, and animal inhabitants, as well as the impact on Hoover Dam and all life dependent on its existence, will be absolutely tremendous.

> **It's about dam time!** In the perspective of humans, Glen Canyon Dam has profoundly changed the habitat of the Colorado River for the plants and animals in Grand Canyon. But in the perspective of geologic time, these effects are minimal. If the entire life of the Earth were viewed as one year, the life span of a dam (300-600 years) is about 4.2 seconds – just the blink of an eye in terms of geologic time. In fact, the Colorado River has been dammed in the past by lava flows in western Grand Canyon. But most of the lava dams and their effects on the environment are now almost completely gone. The effects of Glen Canyon Dam will someday soon (geologically speaking!) be washed away. Millions of years from now, there may be no evidence that dams ever existed along the Colorado River. However reassuring as this may be, it does not negate the importance of the park's role in protecting and preserving its resources.

GEOMORPHOLOGY

Geomorphology is the study of the processes that control the development and shape of landscape features. Changes of the Earth's surface due to erosion and weathering are considered in geomorphology. **Weathering** is the physical or chemical breakdown of rocks. **Erosion** is the transport of rock material by forces such as water and wind that takes place subsequent to weathering. The water and sediment carried by the Colorado River has eroded tons of rock to deepen the canyon, and in other ways, water and gravity has gradually widened and shaped the canyon walls.

Chemical weathering occurs when rocks are chemically broken down and minerals that make up the rock are altered. Chemical weathering happens, for example, when limestone is dissolved upon exposure to water, or when iron-rich sediment is oxidized in the atmosphere to produce colors in the rocks. Chemical weathering is a predominant weathering process in humid climates, where water in the air slowly alters the rock. In the arid climate at Grand Canyon, the impact of this type of weathering is not significant.

At Grand Canyon, physical weathering plays an important role in weathering rocks and widening the canyon. **Physical weathering** (mechanical weathering) is the simple breakdown of rocks by physical processes, without any chemical changes. For example, when rocks are cracked or smashed they are physically weathered. Also, when water freezes in cracks in rocks, and the ice expands, it widens the cracks. Over time, ice gradually wedges the cracks wider in a physical weathering process called **ice wedging**. Ice wedging takes many years, but on a geologic time scale, the effect is quick.

Other physical weathering processes that take place at Grand Canyon include **mass movements**, which occur when parts of the canyon walls are loosened and eventually washed away. Water often contributes to the movement and gravity pulls the rocks down slope. The steep walls of Grand Canyon, with thin soil, sparse vegetation and accompanying plant roots, are ideal places for mass movements of rock to occur. Water is not absorbed well by the canyon walls, which means that during monsoon season in late summer, large amounts of sediment can be washed away. **Rockslides** occur when a large portion of rock breaks off along a weak zone (like a joint) and slides down slope lubricated by excess water. Also, a **rock fall** can take place when any small or large rock breaks off and free falls (Fig. 1.48). Over time, these weathering processes have sculpted the stair-stepped cliffs and slopes of the canyon walls and side canyons, creating the spectacular landscape at Grand Canyon.

Figure 1.48 – Rock falls in Grand Canyon. *Rocks can fall from the canyon walls at any time. This photo captures a rock fall in action. These rocks may one day end up deep in the canyon and get carried away by the Colorado River. (Photo property of NPS)*

Weathering forecast. Weathering of the rocks of Grand Canyon by physical processes has helped make the canyon wide. This has been happening episodically since the Colorado River began to carve Grand Canyon 5-6 million years ago. Intense erosion has happened occasionally and quickly, such as mass movements during monsoon season. Other times, little erosion may occur during a dry year. Accurately estimating the *average widening* of the canyon is difficult because it sometimes happens all at once and at other times not at all. Forecasting what the canyon will look like in the next few million years is difficult to do without knowing what climate or tectonic changes may occur.

The stair-step landscape characteristic of Grand Canyon's walls is partly due to the variation of rock types in the canyon. Rocks all weather differently, depending on things like their composition and how they formed. Soft layers in the canyon are

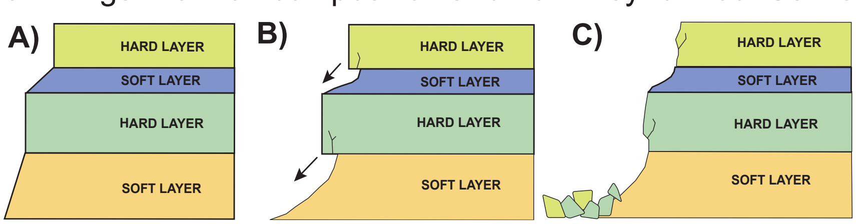


Figure 1.49 – Widening the canyon walls. *Mass movements help to widen the canyon, especially where the slope is overly steep and cannot support the overlying rock. After weathering processes weaken the rocks, these rocks submit to the force of gravity and eventually fall into the canyon. A) The alternate layering of hard and soft rock causes the stair-step shape of the walls of Grand Canyon to develop. B) Because soft layers erode easier and faster, the hard layers are undercut, leaving them with no support from below. C) The harder rocks eventually break off in large chunks and may cause a mass movement of rocks. This begins the process over again, exposing the soft layer to weathering and erosion. This process has gradually widened the canyon.*

weathered easily, but hard layers are more resistant. Hard layers occasionally break off in large chunks (Fig. 1.49). The canyon gets its classic stair-step landscape from the large cliffs made up of harder sandstone and limestone layers, alternating with the broad slopes of soft shale layers.

Visitors often wonder why some rock features in the canyon remain tall, while the other rocks around them have been eroded away. More than 6 million years ago, the layers at Grand Canyon were continuous layers. Faults, cracks, joints, and other weaknesses existed in the rocks that made some more susceptible to weathering and erosion. Once the canyon began forming 6 million years ago, the weakened rocks were eroded leaving mesas, buttes, and spires as evidence that the layer was once continuous. Commonly, the tall features are topped with one of the hard rock types, like limestone or sandstone. But the rocks on the top of the feature are no different than the rocks that have been eroded away around them - just the last to go.

A unique landscape feature at Grand Canyon is the Palisades of the Desert at the eastern end of the canyon (Fig. 1.50). From Desert View as you look to the northeast, you can see the large mesa known as Cedar Mountain, and the land surrounding it that is somewhat hilly. These hills give the Palisades their picturesque scalloped appearance seen from many viewpoints along the rim, such as Grandview Point. The Palisades formed when small streams flowed eastward in channels over the sloping East Kaibab Monocline. The stream channels incised small valleys with the rolling hills around them.

A)
B)
C)

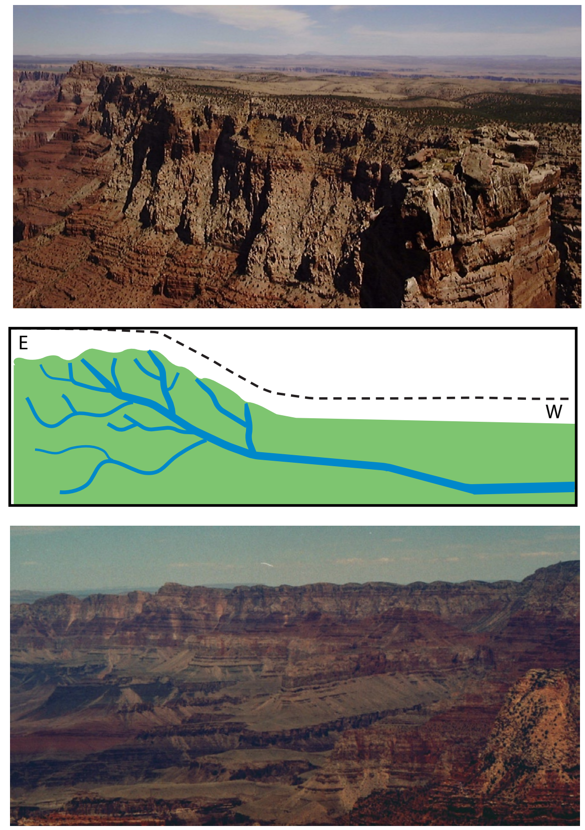
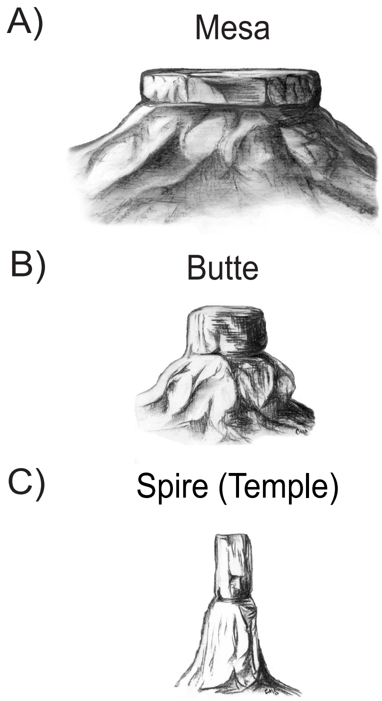


Figure 1.50 – The Palisades of the Desert. *A) This photo shows the hills and small valleys that give the Palisades of the Desert its distinct profile. The rocks are part of the East Kaibab Monocline. The middle, steeply-sloped portion of the monocline was located where Grand Canyon is now. B) Small streams once flowed east, over the East Kaibab Monocline, downslope along the layers tilted by the monocline. This formed small channels that remain today as the valleys between the hills. The dashed line shows the outline of the monocline. C) Grandview Point provides an excellent view of the Palisades with their scalloped, or fence-like profile that is created by the hills and valleys that developed on the monocline.*



Super sunsets. The landscape of Grand Canyon, with its many tall rock pinnacles, cliffs, and slopes, create beautiful shadows that seem most spectacular at sunset. Some of the tall features are referred to as mesas, buttes, or temples (Fig. 1.51). The word “mesa” means table in Spanish, so mesas are large hills with flat tops that look like tables. Technically, a **mesa** is wider than it is tall. After a period of erosion, the mesa is worn down and becomes a **butte**, which is at least as tall as it is wide. As weathering continues breaking away rocks, the feature becomes even smaller. The result is a **spire** or **temple**, which is a slender feature that is much taller than its width.

Figure 1.51 – Landscape features. *A) A mesa is a broad, flat feature that is wider than it is high. B) Buttes are approximately as tall as the width of the feature. C) Spires or temples are narrow features, as they are taller than their width. These eventually are broken down until nothing remains but a flat surface. (Illustrations by Christi Sorrell.)*

Geology on a human time scale. The effects of erosion and weathering can be seen in real time, on a human time scale, as the rates of geomorphic processes are directly affected by the development of humans. For example, in a natural setting, rainwater is dispersed and used in many different ways – it soaks into the soil, some evaporates into the atmosphere, and plants absorb and use it. As humans move into the picture, pavement replaces areas that were once open land and covered by vegetation. Rainwater then has no where to go but run off the pavement, possibly carrying a variety of automotive and human waste. This can cause erosion and weathering to be greatly intensified surrounding areas impacted by humans. It could lead to effects such as increased runoff, removal of vegetation, groundwater contamination, and mass movements as the land becomes saturated by the influx of water. Understanding of geomorphic processes plays an increasingly important role in resource management and urban planning, especially in sensitive and preserved areas such as national parks.