A Geology Training Manual for Grand Canyon National Park

by
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Abstract approved ______________________________
Robert J. Lillie

Grand Canyon National Park is a geologic experience like no other. Each year, many of the park's 5 million visitors attend ranger-led interpretive programs to learn how the spectacular scenery formed. It is crucial for interpretive park rangers at Grand Canyon to understand the geologic history of the region and be able to effectively communicate it to park visitors. Amazingly, Grand Canyon National Park, a park with world-renowned geology, presently has little formal geology training available for its interpretive park rangers.

Interpretive park rangers are often educated in fields other than geology and may not feel comfortable presenting geologic information to park visitors. But at Grand Canyon, discussion of geology is important and unavoidable. There is abundant technical literature regarding Grand Canyon geology, however this information is difficult for rangers to comprehend without prior geologic education. To alleviate this situation, this illustrated geology training manual has been developed for the interpretive park rangers at Grand Canyon.

The first section of this training manual introduces the reader to the "language" of geology by providing illustrated explanations of fundamental geology concepts that are important and applicable at Grand Canyon. These concepts are then applied to the geology found in the Grand Canyon region, as the "language" of geology is used to read the "book" of Grand Canyon geology in the second section. The third and final section is intended to help interpretive park rangers learn to effectively communicate the geologic history of Grand Canyon to park visitors.

ACKNOWLEDGMENTS

Most importantly, I would like to express my deep appreciation to Dr. Robert J. Lillie for his guidance and careful editting to help prepare this thesis. I would also like to thank several people who helped refine the text, as well as share their geologic expertise, including Dr. George Billingsley of the U.S.G.S., and Jim Heywood and Allyson Mathis of the Grand Canyon National Park Service. Special thanks also go to Judy Hellmich, Robin White, Tom Pittenger, and Ellen Seeley who supervised and supported my endeavors as a park ranger and geologist. I am also incredibly grateful for the numerous interpreters at Grand Canyon National Park, who generously volunteered their time for input and editing assistance, especially Marge Post, Ron and Pat Brown, and Carol Tepper. I would also like to express my appreciation to Kathy Daskal, Katie Sullivan, Phyllis Northrup, Russell Baker, Ralph Jones, Mike Weaver, Bob Audretch, and Rex Tilousi who all provided suggestions and support for the training manual.

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INTRODUCTION: LEARNING THE LANGUAGE OF GEOLOGY

PREFACE

Grand Canyon is like a tattered, old book. The pages of the book are the colorful, picturesque rock layers that make up the walls of the canyon, which have been opened by processes of erosion and weathering. As you look through this book you may notice that some of the pages have been ripped out, and others were never written. But before you can begin to read this geologic story, 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.

Grand Canyon is a geologic display like no other. In terms of geologic research and education, it has been 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 250 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 educational 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), incredibly long (277 miles/446 km) classroom! There is no place in the world with geology so simply, yet so dramatically displayed as Grand Canyon.

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 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 different specializations, some of which are applicable to Grand Canyon. One such study area is **plate tectonics**, which focuses on the movement of continental and oceanic 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 that were formed near sea level, are now at 7000 feet (2100 m) *above* sea level. **Stratigraphy** is especially useful at Grand Canyon. It is the study of the "strata," or layers of rock and the information they provide about environments that existed when the rock layers formed. Another aspect of geology is **structural geology**, which involves the study of deformation of the Earth's crust. Structural geology helps us explain why rocks are tilted, folded, and faulted at Grand Canyon, while other layers remain flat. **Hydrology**, the study of the movement of water, is useful in understanding the development and behavior of the Colorado River. **Geomorphology** investigates the geologic processes that create different landscapes and shape geologic landforms. It is 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 used to study Grand Canyon, but those mentioned above are the focus of this training manual.

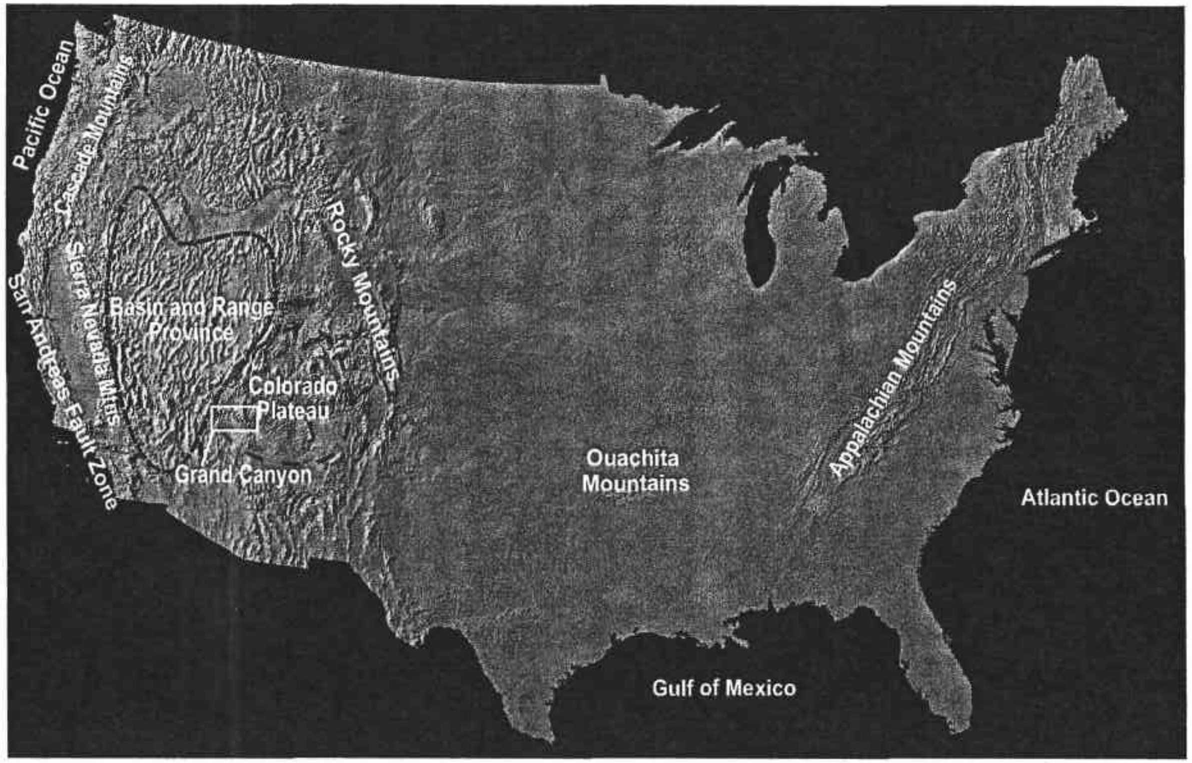


Figure 1.1 – Shaded relief map of United States. Large landscape features, such as mountain chains, plateaus, and coastlines, have formed as a result of millions of years of tectonic plate interactions. The **Basin and Range Province** is a large region that is presently being pulled apart by tectonic forces. The **Rocky Mountains** and **Colorado Plateau** were uplifted to their present elevation by relatively recent mountain building events (70 to 40 million years ago). **Grand Canyon** lies on the southwestern edge of the Colorado Plateau, adjacent to the Basin and Range Province.

> 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 seem unrelated because of the canyon's distance from 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 in warm, tropical waters more than 250 million years ago.

The Earth and other planets in our solar system formed from nuclear reactions within stars 4540 million years ago. After millions of years, the matter that makes up the Earth differentiated and formed the three fundamental layers of the Earth: the **crust**, **mantle**, and **core** (Fig. 1.2a). These layers are distinguished by their *chemical composition*, as each layer consists of different material. The crust is composed of minerals rich in oxygen and silica called **silicates.** The mantle consists of heavier silicates rich in iron and magnesium, and the core is composed of very heavy iron and some nickel.

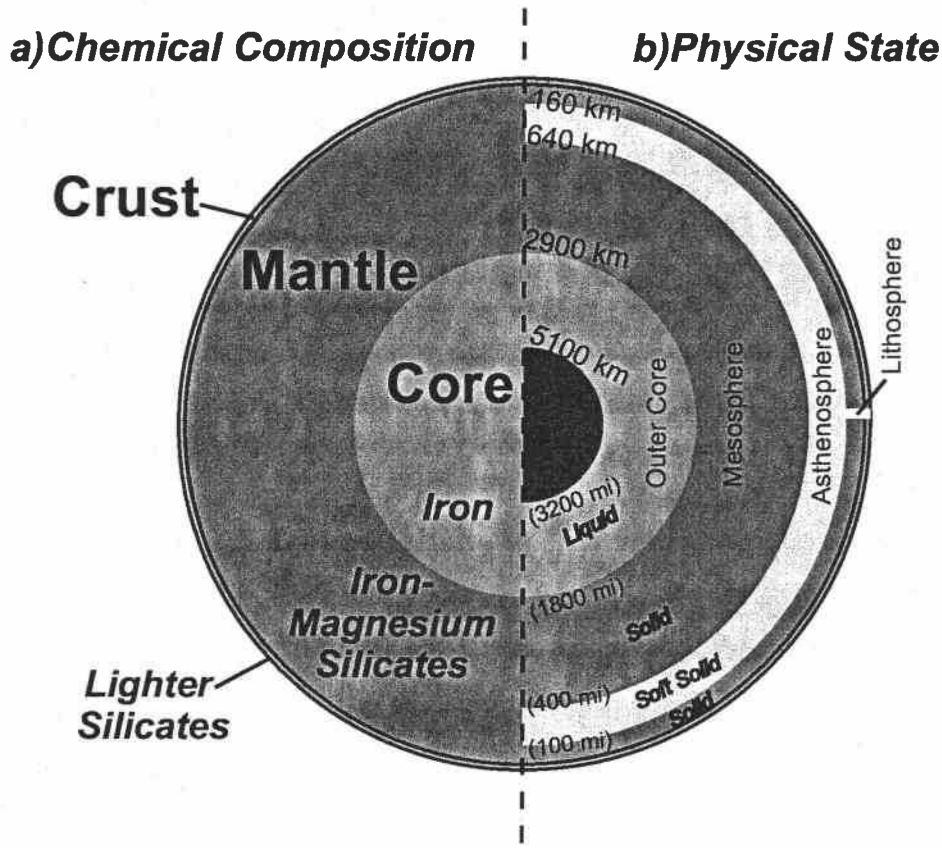


Figure 1.2 – The Earth's inner layers. a) The left half shows the divisions of the Earth based on *chemical composition* (what the layers are made up of). When the Earth was young and still very hot, the crust, composed of minerals rich in oxygen and silica called **silicates** floated to the top to form a very thin **crust**. The mantle formed below that, and made of heavier silicates rich in iron and magnesium. Very heavy iron and some nickel materials settled in the center of the Earth as 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 around on top of the softer asthenosphere. *(Diagram adapted from R.J. Lillie)*

Food analogies. Food is a universally understood item. Everyone eats and can relate to food, so it can be a useful and fun interpretive tool. For example, a peanut M&M is a great representation 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 M&M is made up of different material, just like the divisions of the Earth are chemically distinct.

In the early 1900's, geologists began studying seismic waves to gain 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 that 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 how the continents have shifted positions over time (continental drift) and how oceans widen 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.** Lithosphere is the Earth's hard outer layer, which is made up of both the crust and the uppermost part of the mantle. Notice the depth of the lithosphere in Fig. 1.2. Grand Canyon seems deep to us (about 1 mile/1.6 km), but it is just a scratch on the Earth's surface when 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 portion of the lithosphere. The lithosphere might be thought of as the roof of your house. The shingles are analogous to the thin crust, and the thicker boards below are like the hard upper mantle.

The physical division below the lithosphere, called the **asthenosphere**, is also part of the mantle but it is softer because it is so hot. 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. The asthenosphere is like 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 become solid. For example, the mesosphere is even hotter than the asthenosphere, but because it is under more pressure it is a solid layer.

Tectonic Plate Movement

Tectonic plates move on convection currents circulating in the soft, ductile asthenosphere. Asthenosphere material moves in much the same way that heat circulates in a convection oven or water boils in a pot (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!

As plates of lithosphere move, they have different interactions with each other (Fig. 1.4). **Divergent plate boundaries** occur where two plates rip apart, and move away from one another (Fig. 1.5a). Small, shallow earthquakes and volcanoes usually occur 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 this plate boundary forming new ocean crust.

A new divergent plate boundary is forming west of Grand Canyon in the **Basin and Range Province** (Fig. 1.1). 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. The Basin and Range Province is similar to the East African Rift Zone, where the Arabian Plate is pulling away from

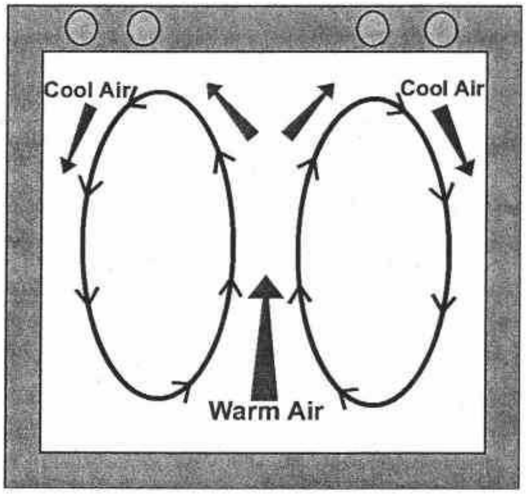


Figure 1.3 – Convection currents. The asthenosphere circulates in much the same way as air in an oven. As heated air rises and then cools it drives circulation by **convection**, which occurs because of differences in density. Cool air is denser than warm air, so it sinks while warm air rises. In this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

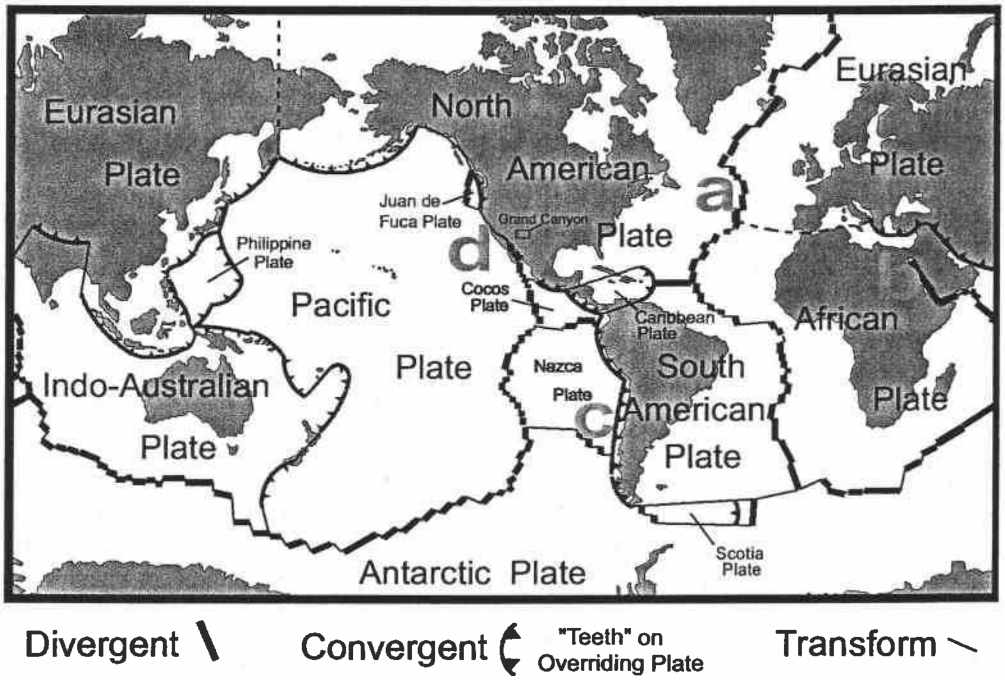


Figure 1.4 – Tectonic plates. Tectonic plates are constantly moving on the Earth's surface and interacting with each other in different ways. In some places, such as the Mid-Atlantic Ridge (a) or East African Rift (b), plates are moving away from each other at a **divergent plate boundary**. Where plates are moving towards each other at a **convergent plate boundary**, one plate is usually shoved beneath an overriding plate, like 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 located on a plate boundary, the geology has been affected by plate interactions similar to ones going on today. Note that western North America is an **active continental margin**. It is actively interacting with the Juan de Fuca, Pacific, and Cocos Plates. The eastern side of North America lies entirely within the North American Plate, and is therefore a **passive continental margin**. Most of the layers of rock exposed in Grand Canyon were formed when western North America was a passive continental margin in the past. *(Diagram by R.J. Lillie)*

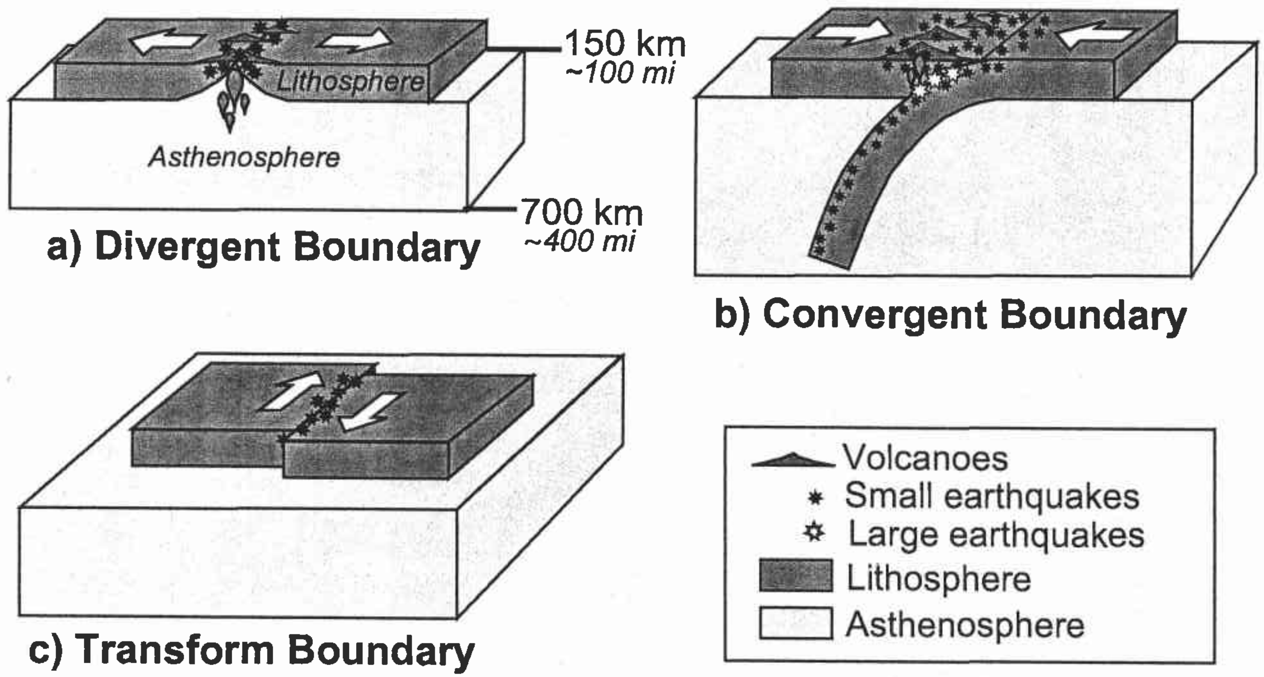


Figure 1.5 – Types of tectonic plate boundaries. If you sliced through the Earth at a plate boundary, it may look like these diagrams. White arrows show the direction of movement of the plates relative to each other. a) Where plates **diverge**, new lithosphere is created as hot molten material rises from the asthenosphere and cools, attaching to the moving 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 usually do not form at this type of plate boundary. *(Diagram adapted from R.J. Lillie)*

the African Plate (Fig. 1.4). The close proximity of the Grand Canyon region and the Basin and Range Province has had a significant effect on the development of the Colorado River and recent tectonic events.

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). 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 is part of the reason the Grand Canyon region is at such a high elevation (see page 126).

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

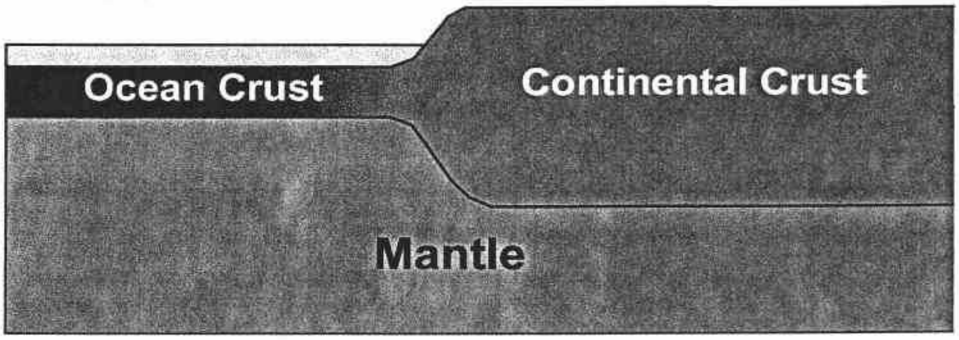
Have you ever wondered why our planet looks the way it does? From a distance, you can see green and brown land that seems to float above vast blue oceans. You can see that some places have tall, snow-capped mountains with nearby broad, flat lowlands. Plate tectonics helps us understand how these different landscapes develop.

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 below the water and the thicker it is, the higher it can float. Similarly, the thicker the Earth's crust is, the more mass it can support above it. Oceans cover parts of the Earth because the crust beneath the ocean is thin **ocean crust**, while 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 44 miles (20 to 70 km), and provides support from beneath to keep the crust afloat. Ocean crust is only 2 to 5 miles (3 to 8 km) thick so it floats much lower and is covered by the sea.

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). Thick crust can form near 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 are an example of an area with high elevation caused by thick crust. The Indian Plate is colliding with the Asian Plate to create these mountains and crust that is about 45 miles (70 km) thick.

Grand Canyon is located on a region with thick continental 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 approximately 22 miles (35 km). It is estimated that directly beneath Grand Canyon, on the southwestern edge of the Colorado Plateau, the crust is in the range of 19 to 25 miles (31 to 40 km) thick. The thickness of the Earth's crust in the Grand Canyon region is part of the reason for the elevation of approximately 7000 to 8000 feet (2100 to 2400 m) above sea level.

A)



B)

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 12-44 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 will be more buoyant and float higher above the water than a thin iceberg. *(Photo property of NPS)*

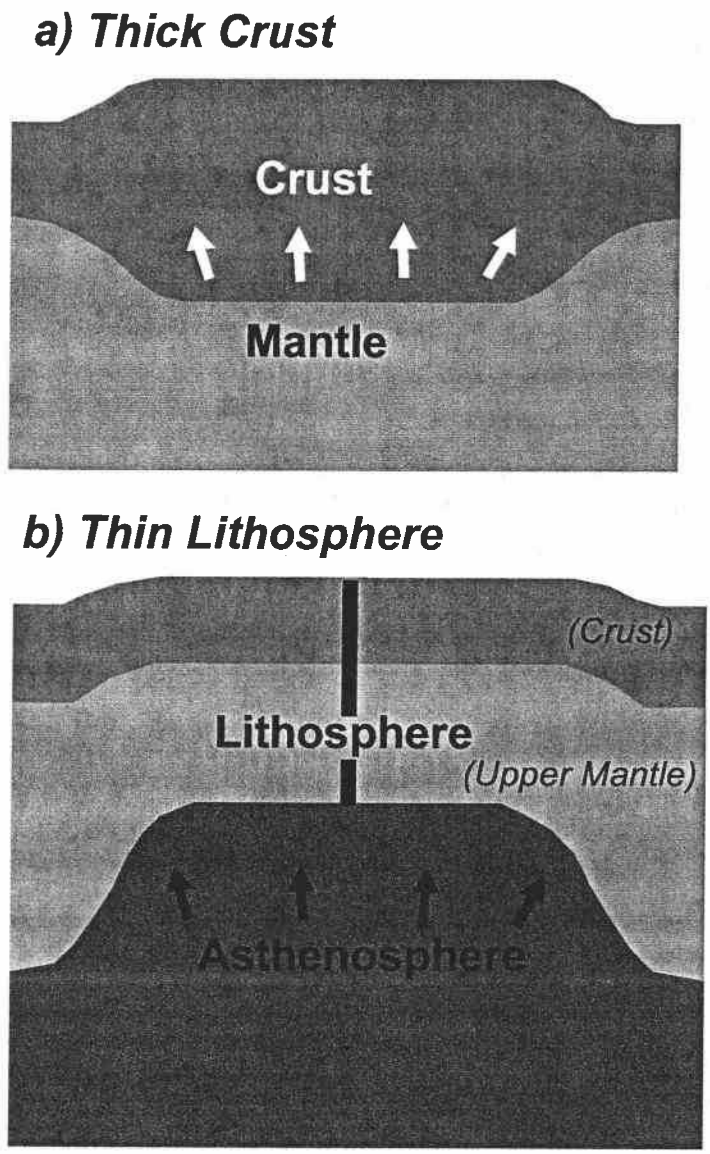


Figure 1.7 – The development of high elevation. There are two main ways that high elevation can develop. a) *Thick crust*. Thick crust is buoyant so it floats upward until it is counterbalanced by the weight of the overlying land. The high elevation of the Himalayan Mountains is supported by very thick crust beneath. b) *Thin lithosphere*. 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 start to develop until about 70 million years ago. Also, the North American continent has changed its shape over time due to plate tectonic processes. For the purposes of this manual, the general mass of continental rock that is now North America will be referred to as such.

Thin lithosphere can also cause high elevations to develop. In areas where the lithosphere is thin, the asthenosphere will rise and expand because there is less pressure from above. The asthenosphere can push upward and create a large bulge of high elevation on the surface of the Earth. Areas 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, where the North American Plate is stretching and ripping apart as a new divergent plate boundary forms (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 elevations of about 4000 to 5000 feet (1200 to 1500 m) above sea level.

Grand Canyon lies on the Colorado Plateau with thick crust, located next to the thin lithosphere of the Basin and Range Province. The effects of the thick crust *and* the nearby thin lithosphere allow the Grand Canyon region to have high elevation (Fig. 1.9).

TECHNICAL STUFF. The differences in crust and lithosphere thickness discussed here are for your edification. Discussing these details with park visitors in an interpretive program could end up seriously overwhelming them. The main point to convey is that the Colorado Plateau and Grand Canyon are at high elevation. 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 occasional technical questions.

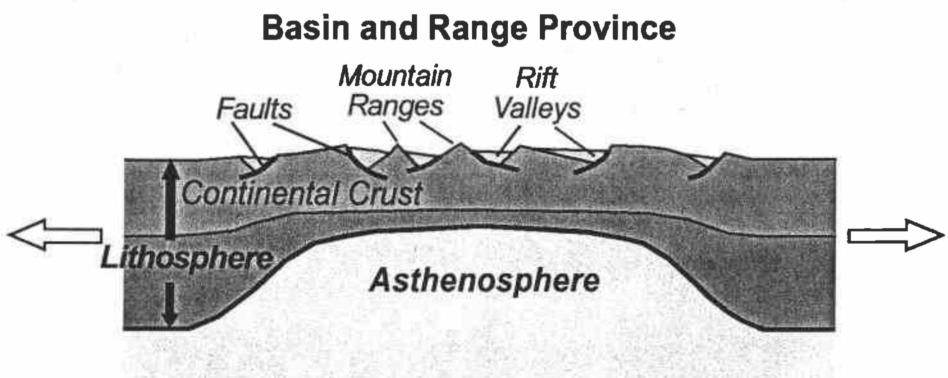


Figure 1.8 – High elevation in the Basin and Range Province. The Basin and Range Province is a divergent plate boundary in its beginning stages of development. This diagram shows what the Earth may look like beneath the Province. The asthenosphere beneath the Basin and Range Province rises upward beneath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

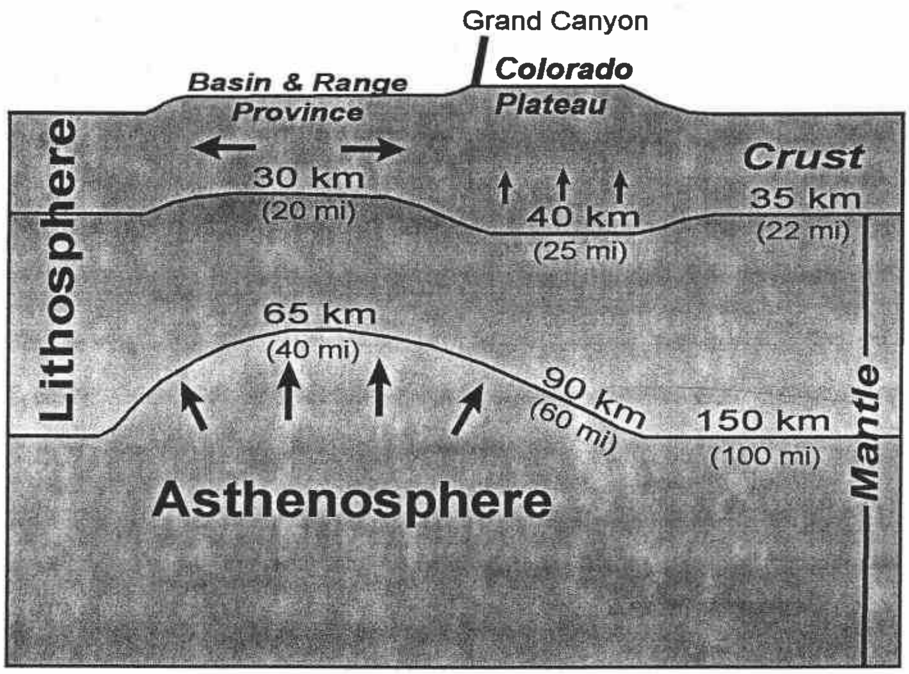


Figure 1.9 – Cross-section of the Grand Canyon region. The thick crust of the Colorado Plateau is part of the reason for the high elevation of the Grand Canyon region, because thick crust floats high on the mantle. The nearby thin lithosphere of the Basin and Range Province is another reason for the high elevation. It causes a broad bulge of high elevation in the region, also affecting the surrounding areas, including the Grand Canyon region.

TYPES OF ROCKS

Every rock has a story to tell, and at Grand Canyon there are a lot of rocks to provide stories. A **rock** is an aggregate of different minerals that have been chemically or physically cemented together. **Minerals** are substances that are naturally occurring, inorganic, and composed of different elements combined to make a crystalline solid (Fig. 1.10). The amounts of different minerals in a rock determine 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.

Sedimentary Rocks

In Grand Canyon, the sedimentary rocks are the abundant and beautiful layers commonly photographed and enjoyed by park visitors. **Sedimentary rocks** are 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 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 remains, traces, or remnants of once living organisms that are at least 10,000 years old. They can help geologists determine the age of a rock and the environment where it formed. By studying the fossils at Grand Canyon, geologists have determined that the sedimentary rocks formed between 550 and 250 million years ago.

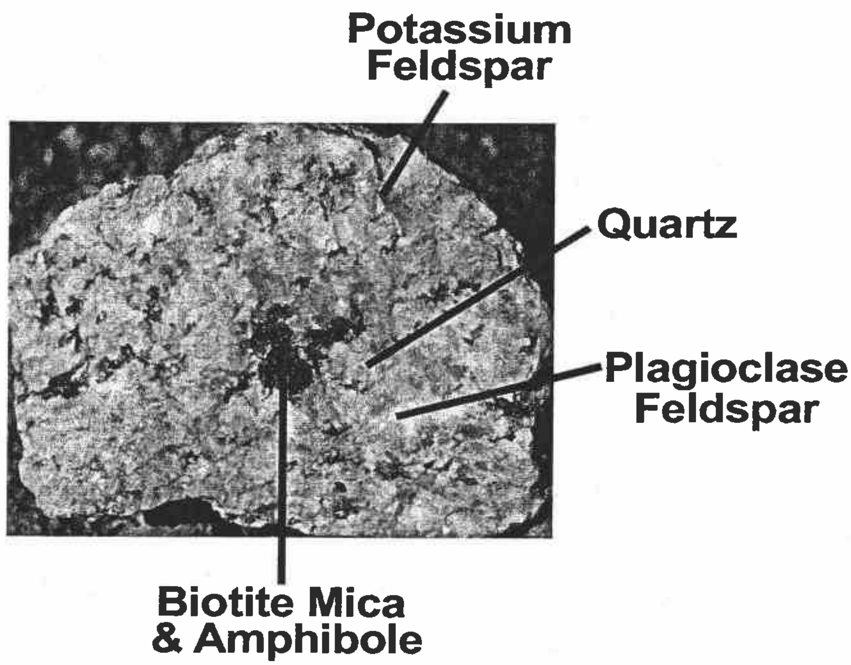


Figure 1.10 – Rocks and minerals. Granite is a rock composed of many different minerals. The pink mineral in granite is **potassium feldspar**, the white minerals are **plagioclase feldspar**, and the clear minerals are **quartz**. Granite also has small amounts of black minerals, which are **amphibole**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

Sedimentation in progress. You can see 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, or other fluids. In the corral, the ground is actually a little higher than the area surrounding it, as the "sedimentation" occurs within the corral at a higher rate.

At Grand Canyon, the three main types of sedimentary rocks are sandstone, shale, and limestone (Fig. 1.11). **Sandstone** commonly forms in environments that have strong water or wind activity. Agents responsible for sand deposition include fast-moving water in rivers, wave action along coastlines at beaches, and wind in sand dune areas. As the sand grains are deposited and buried, pressure from overlying sand helps bind the grains together. This process is aided by water carrying dissolved minerals that percolates through spaces between the sand grains. The dissolved minerals act as cement 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 fine sand (Fig. 1.13). Smaller particles of sediment can be easily carried in fast-moving water and therefore do not get deposited until water is calm and slow. Deposition of shale would likely occur in 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, rather than cliffs (Fig. 1.11b).

A rainbow of color in the rocks. The Bright Angel Shale is a very colorful shale 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. The predominant green color, as well as purple, yellow, and red in the Bright Angel Shale come from a mineral called **glauconite**. Other 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**.

A)

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

*Common sedimentary rocks at Grand Canyon

B)

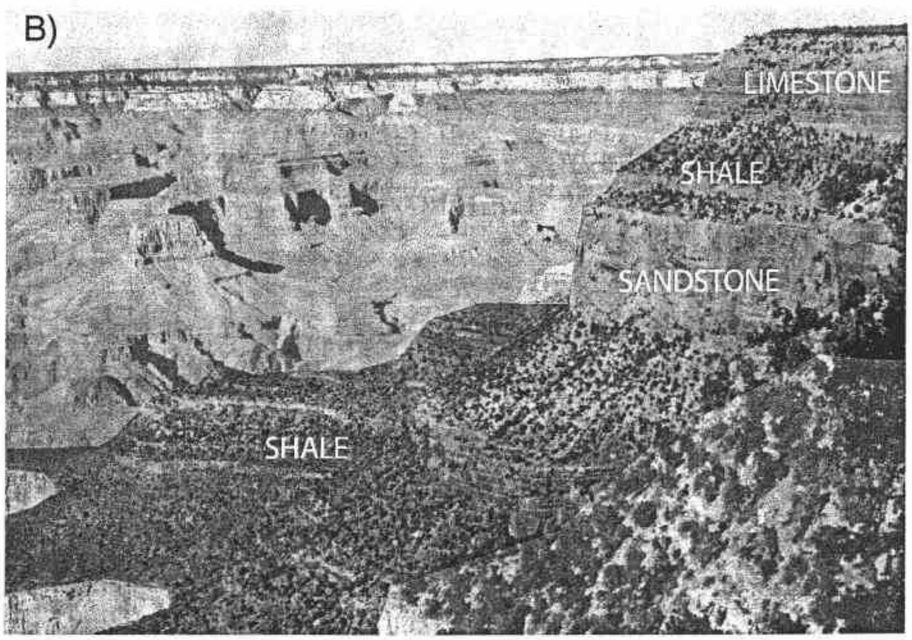


Figure 1.11 – Sedimentary rocks. A) Sedimentary rocks form anywhere that rocks have been weathered, transported, and eventually deposited in places such as lakes, oceans, and rivers. For example, shale and sandstone are composed of particles of rock that get deposited. Other sedimentary rocks, such as limestone or dolomite, form due to chemical reactions in seawater that produce solid matter (precipitates) that 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 limestone layer forming the canyon rim is the Kaibab Formation, and the purple sandstone layer is the Coconino Sandstone. These two rock types are noticeable cliff formers in the canyon. Shale layers are easily spotted because they form slopes and cover broad platforms. The shale (siltstone) layers identified here 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 different grains of sand. The rock formed as pressure and water carrying dissolved minerals through pores between sand grains cemented the grains together. The minerals chemically bonded the sand grains together, while the pressure physically bonded the grains.

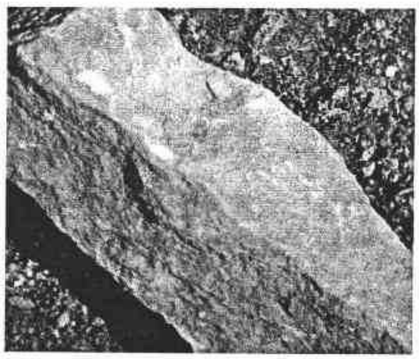


Figure 1.13 – Shale. The grains that make up shale are tiny pieces of mud, silt, and sand that were once soft mud. The water was squeezed out to make mud into rock. Shale is easily weathered because the particles are so fine and not easily cemented together.

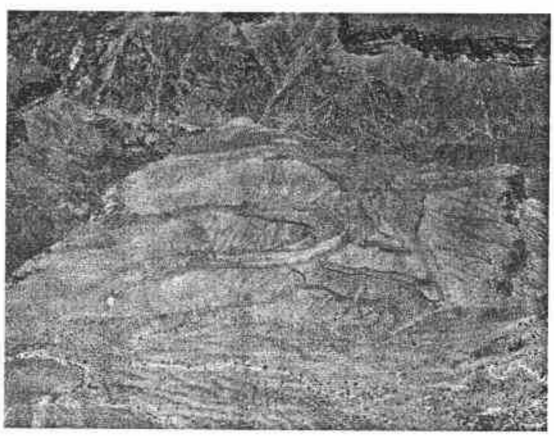


Figure 1.14 – Colorful Bright Angel Shale. Looking down from Pima Point towards the location of the old Hermit's Camp, you can see a variety of colors in the Bright Angel Shale. Most of these colors are due to minerals composed of iron oxide (rust). From other viewpoints along the canyon, this layer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

Limestone can form in a variety of depositional environments, including fresh water lakes and deep marine environments. The limestone in the Grand Canyon region has typically formed in deeper water than where sandstone or shale would form. Limestone is predominantly composed of calcium carbonate ($CaCO_3$), a mineral also known as calcite or lime. This mineral forms because of chemical reactions in seawater that cause the calcium carbonate to precipitate out of the water. This precipitation of lime is somewhat like 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 also come from organic material such as shells. Lime cements small particles of sediment and the remains of once living organisms together to form limestone (Fig. 1.15). The layers of limestone in Grand Canyon form cliffs because they are hard rocks that weather slowly in the dry, arid environment (Fig. 1.11b).

Hard rock or soft rock? If you are from a place with a humid climate, you may have observed that limestone is not always a hard, resistant rock. 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 cause the limestone to be hard and resistant to weathering, forming steep cliffs.

The rocks in the walls of Grand Canyon tell us about changes in depositional environments that occurred as seas came in and went out over the land and deposited different rocks. The progression of rock layers from sandstone to shale to limestone usually indicates that sea was coming in over the land as sea level rose, or the land was lowered. This type of change in depositional environment is called **transgression** (Fig. 1.16a). The changes in the rock types deposited are evidence of the sea coming in and covering the ancient continent. **Regression** occurs as the sea moves out from the land, when sea level gradually lowers, or the land is uplifted. The evidence of regression is found in the rock layers deposited and their change from limestone, to shale, and then sandstone (Fig. 1.16b).

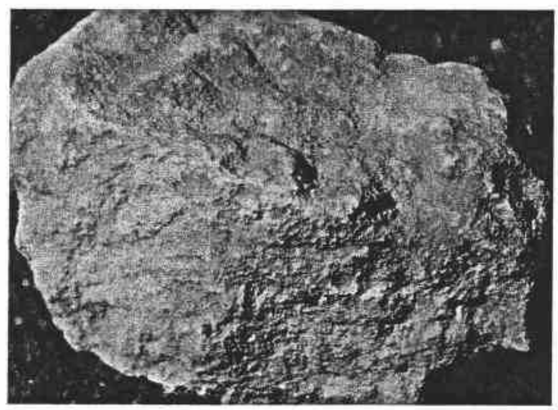


Figure 1.15 – Limestone. The calcite particles that make up limestone are tiny and difficult to see. This limestone is from the Kaibab Formation and forms the rim of the canyon. In eastern Grand Canyon, including the village area, the limestone of the Kaibab Formation has a great deal of sand in it.

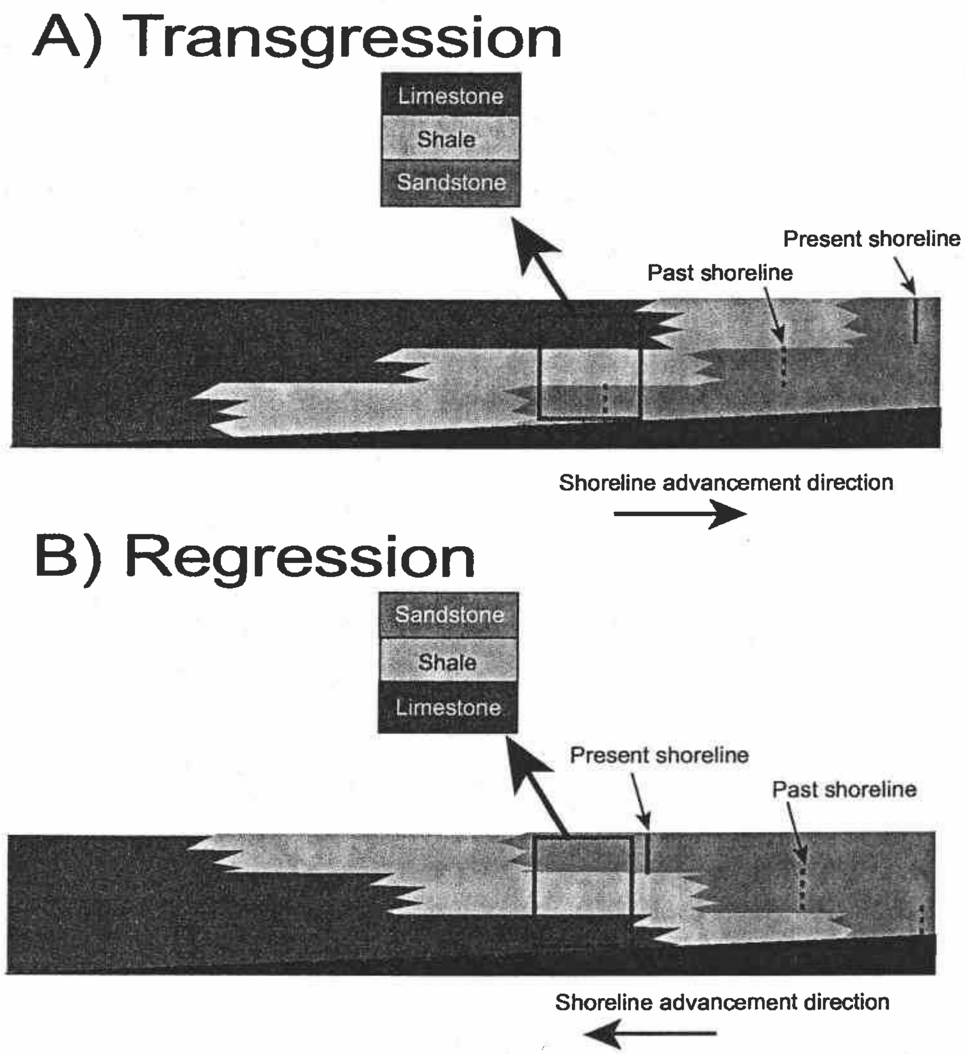


Figure 1.16 – Transgression and regression. Transgression and regression can occur as sea level rises or falls, or as the land surface uplifts or lowers. As these changes occur, the shoreline may encroach on the land or move further out towards sea. A) As the sea encroaches over land during **transgression**, deposition 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 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 sandstone, shale, and limestone. Technical papers usually use descriptive adjectives to help other geologists distinguish one rock layer from another. The three main sedimentary rocks discussed in this manual are the most basic types. Fortunately, they are all that is really needed for discussion of Grand Canyon sedimentary rocks with visitors.

The sedimentary rocks at Grand Canyon tell us stories of different depositional environments. Park visitors have experienced oceans, beaches, sand dunes, and rivers, so they can relate to environments where sedimentary rocks form. Most of the sedimentary rock layers of Grand Canyon were formed in a marine environment, which is in or along the edges of an ocean (Fig. 1.17). 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 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, heavy sediment, such as sand and gravel. Common beach deposits are sandstone and conglomerates.

Intertidal zones exist on gently sloped land that is covered by shallow water during high tides, and partially or completely exposed to the air during low tides. Intertidal zones that many visitors are familiar with include 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 features found in an intertidal zone (Fig. 1.18). **Ripples** are miniature, dune-like features that form as water transports and deposits fine

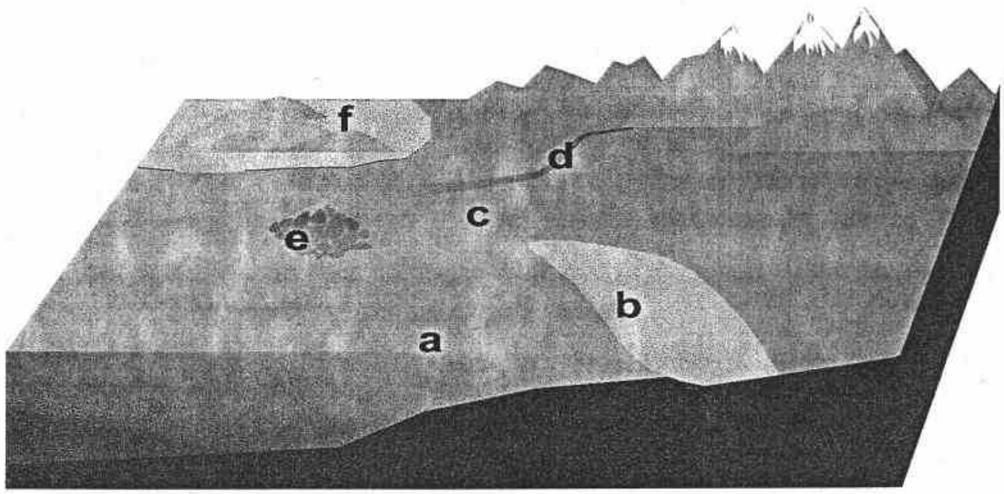


Figure 1.17 – Depositional environments. a) **Shallow marine** environments can form as an ocean inundates the land, forming inland seas. Water depth is usually less than 300 feet (90 m). b) Near the coastline, a **beach** environment is common. Rocks that form are made up of sediment transported to the sea by streams and rivers, that have 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 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.

A) B)

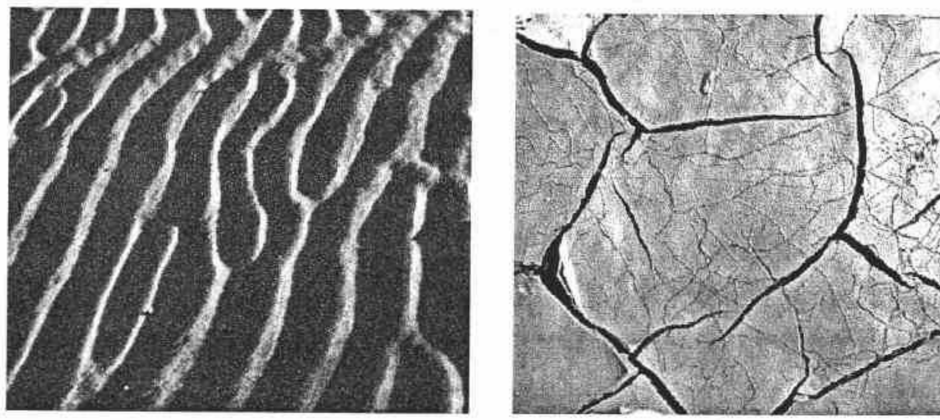


Figure 1.18 – Ripples and mud cracks. A) Ripples are depositional features formed by moving water. The water current forms miniature dunes as it moves sediment along a surface, such as a streambed. B) Mud cracks form as shallow water evaporates and the mud left behind dries and cracks. *(Photos property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

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 deposition occurs when the water velocity decreases. A **delta** forms where a river joins an ocean, lake, or other large water body. The sediment carried by the river is deposited in a triangular, fan-like pattern due to the decrease in velocity (Fig. 1.17).

Other sedimentary rocks at Grand Canyon formed in a coastal, desert environment with sand dunes. **Eolian** deposits are those that have been transported by wind. Sandstone is commonly formed as wind piles the sand into dunes (Fig. 1.19). With pressure and the aid of minerals dissolved in water, the grains of sand are cemented together to form sandstone.

The Earth: A giant rock recycling machine. Thanks to plate tectonics, we 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. This "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 has continued since the beginning of the Earth.

There are many more depositional environments in the world and the distinction between them can be fuzzy. For example, a beach environment may suddenly be submerged causing shallow marine deposits to form. Over geologic time, sea level has fluctuated often, 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.

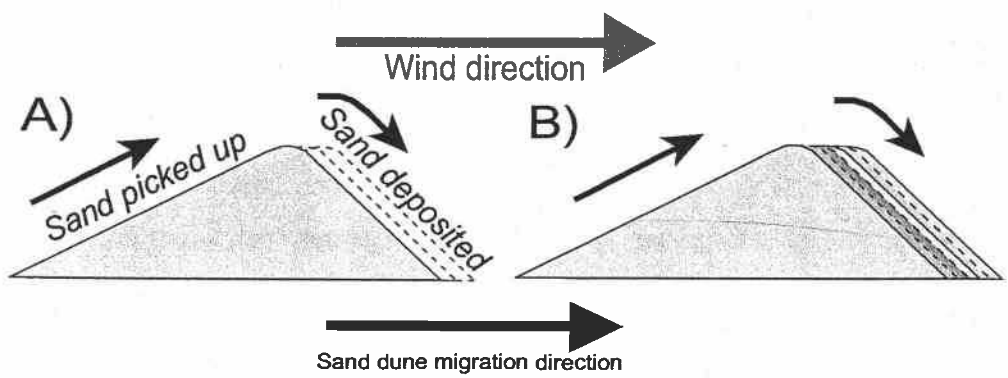


Figure 1.19 – Sand dunes. A) Wind picks up sand on one side of the dune and deposits it on the other side where the wind speed slows down. Sand dunes are not stationary. An entire dune will move (or migrate) in the direction the wind blows the sand. B) Sand is deposited at an angle, along the slope of the dune, and eventually more sand is piled on top. As the dune grows, pressure and water rich with minerals help to cement the grains together, preserving the sand layers at an angle.

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 develop. In contrast, **extrusive** (or volcanic) igneous rocks formed when magma pours out onto the surface of the Earth (Fig. 1.20). **Lava** is the term used to describe molten rock that has extruded onto the Earth's surface. When lava is exposed to the atmosphere or water, it cools very quickly forming very small mineral crystals.

Granite is a common intrusive igneous rock that can be seen in the inner canyon 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, white plagioclase minerals, clear quartz, and black biotite mica and amphibole. When Grand Canyon's granites were in their molten states 1840 to 1400 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**. All of this molten material cooled slowly, far beneath the Earth's surface, resulting in granite rocks with large mineral crystals.

Extrusive igneous rocks are found in western Grand Canyon area. On clear 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. Over 150 basalt flows came from these volcanoes over the last 700,000 years.

Grain Size		Composition: 70% Silica ⟵⟶ 40% Silica			
fine	**Extrusive**	Rhyolite	Andesite	**Basalt***	
↓ coarse	**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, high silica content, intrusive igneous rock. In the western reaches of Grand Canyon **basalt** is common. It is a dark colored, low silica content, extrusive igneous rock.

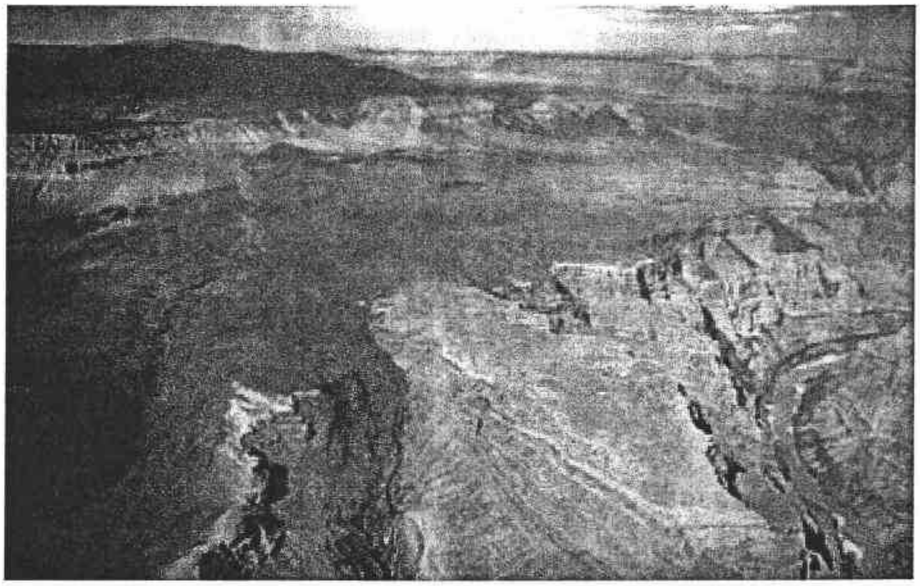
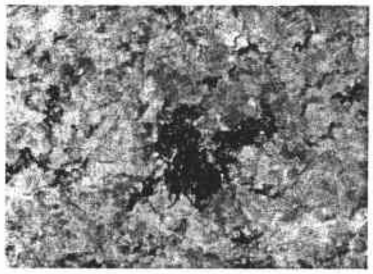


Figure 1.22 – Recent volcanism at Grand Canyon. Less than 1 million years ago, many small volcanoes were erupting and pouring lava into the western end of the canyon. The mountains in the distance (on left side of photo) are volcanoes known as the Uinkaret Mountains. They can be seen on clear days from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

A)



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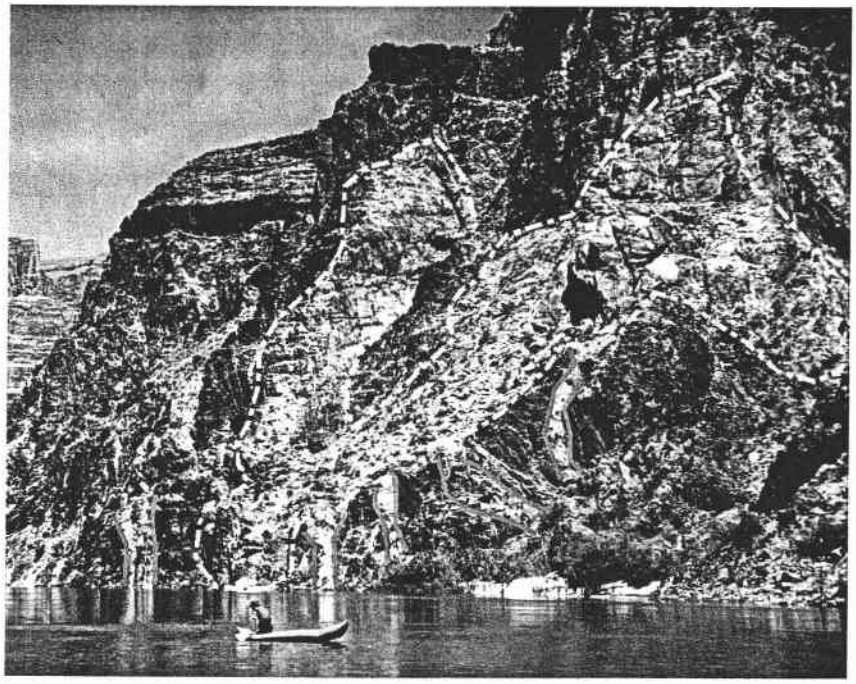


Figure 1.21 – Granite. A) Granite has large minerals because the rock cooled very slowly, deep beneath the Earth's surface. It is light colored rock because it has high silica content. B) In the inner canyon the light color of the granite stands out against the dark metamorphic rock surrounding it. It is often seen as bands called **dikes** (outlined in red), or as very large masses called **plutons** (outlined in yellow). 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 plutons and dikes have been metamorphosed during tectonic events that occurred after they were formed. *(Photo by Karl Karlstrom)*

Metamorphic Rocks

Metamorphic rocks are sedimentary, igneous, or other metamorphic rocks that have been changed by heat and/or pressure. The minerals in the original rock re-crystallize to different minerals, as the rocks are "geologically pressure cooked." By identifying the minerals that have formed and the alignment of the crystals, geologists can determine the temperature and pressure the metamorphic rock endured (Fig.1.23). Most of the metamorphic rocks at Grand Canyon began as sedimentary and igneous rocks that were metamorphosed between 1700 and 1660 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).

It's a different canyon down there. The rocks of the inner canyon do not have the classic stair-step appearance characteristic of the upper layers of Grand Canyon. The inner canyon is steep due to the metamorphic and igneous rocks, which are hard and very resistant to weathering. They do not have the alternating soft and hard layers characteristic of the upper canyon. It is difficult for water, even the raging Colorado River, to break down and smooth out the hard inner canyon.

The most common metamorphic rocks in the inner canyon are schist and gneiss. **Schist** is a metamorphic rock with platy minerals that are oriented parallel to each other. The parallel alignment of minerals in metamorphic rocks is called **foliation**. It can help geologists understand 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 foliation of alternating light and dark bands of minerals (Fig. 1.24c). The metamorphic rocks of the inner canyon indicate they 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 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 are very high.

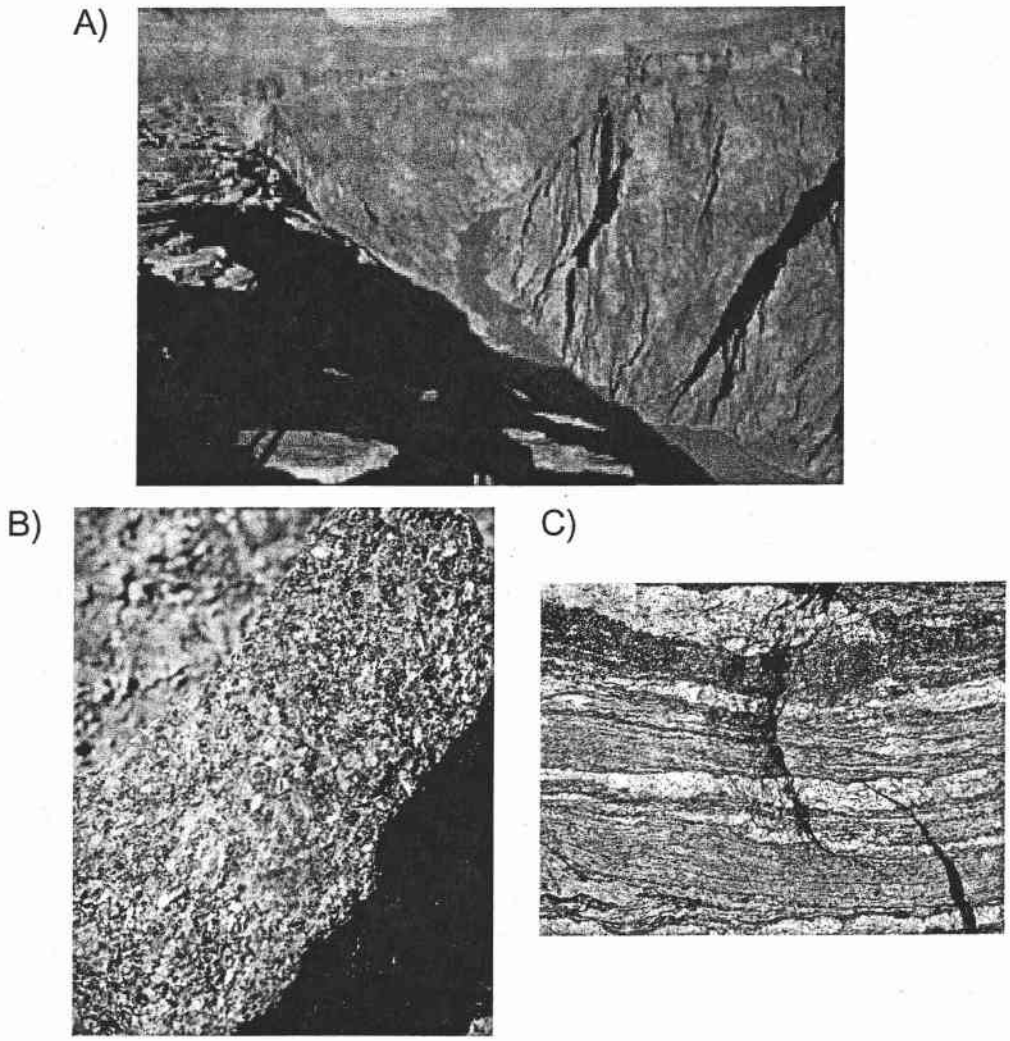


Figure 1.24 – Grand Canyon metamorphic rocks. A) The inner canyon is incredibly steep because of the hard, black metamorphic rocks that make up most of the inner canyon. More than 1700 million years ago, these rocks were sedimentary and igneous rocks. They have been put under extreme heat and pressure to metamorphose 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 due to great pressure. The platy minerals are biotite mica and amphibole minerals, which are usually dark black to dark green. C) Another variety of metamorphic rock that can be 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 form, with the snowflakes like sediment that 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 re-solidify it, this would be like 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.

STRATIGRAPHY

Stratigraphy is the description and classification of different sedimentary rock layers, or strata. It involves interpreting the clues in the rocks and developing hypotheses about the environment that existed when the rocks were deposited. Stratigraphers study the rocks closely to determine where one layer begins and another ends, indicating 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. 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. 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 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** (or cross-section) 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.

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 of time are represented in its rocks. The canyon's oldest rocks, which are 1840 million years old, are at the very bottom of Grand Canyon. 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 minute portion of geologic time. Our species, *Homo sapiens*, have probably been on the Earth for *less than* 0.01% of the Earth's life!

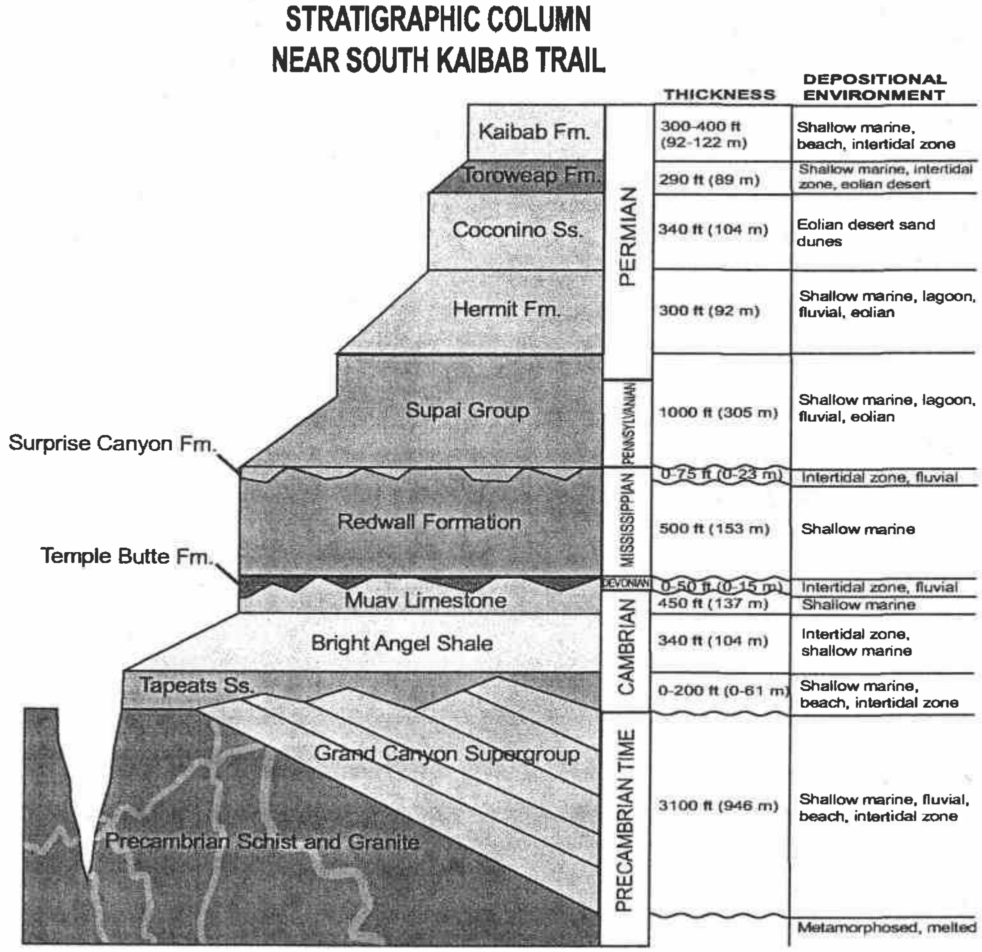


Figure 1.25 – Simplified stratigraphic column. This diagram is useful to have when roving or doing interpretive geology programs. Use it to help identify different layers in the canyon, how thick they are, environments they were deposited in, and when they formed. This particular stratigraphic column 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 erosion or no deposition.

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 middle fingertip on one arm represent the beginning of the Earth and the middle 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 essentially wipe out all of human civilization! (Other suggestions for discussing geologic time are found on pages 166 to 168.)

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 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 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 got easier as early

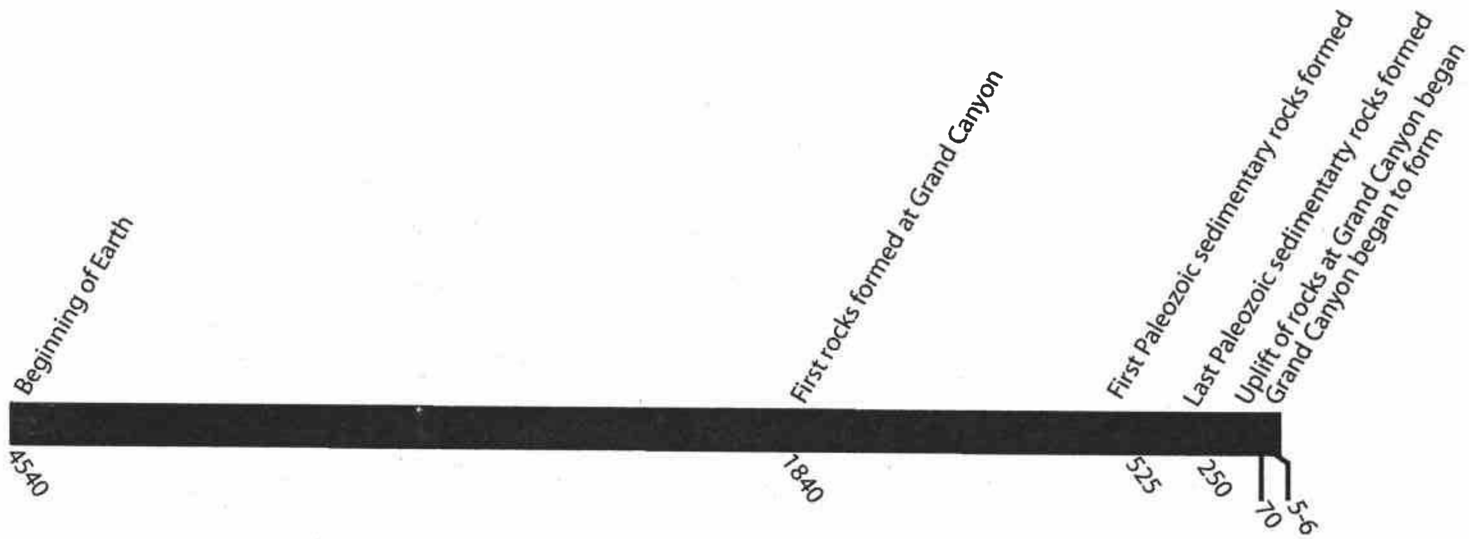


Figure 1.26 – Time line. Some of the major events in the geologic history of the Grand Canyon region are shown on this time line. When you lay the events out, you can see the broad range in ages of rocks, and that Grand Canyon is clearly a young geologic feature.

geologists compared the fossils in rocks. 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 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).

Absolute Dating

Absolute dating of rocks, called **radiometric dating**, was not possible until scientists began using radioactive isotopes as time indicators in the early 1900's. **Radioactive isotopes** 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 possibly forming 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 can be used to determine the absolute age of an igneous or metamorphic rock.

Eon	Era	Periods and Epochs
PHANEROZOIC EON 544 mya to Present	Cenozoic Era 65 mya to Present	Quaternary Period (1.8 mya to present) Holocene Epoch (8,000 years to present) Pleistocene (1.8 million to 8,000 years) Tertiary Period (65 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene Epoch (23.8 to 5.3 mya) Oligocene Epoch (33.7 to 23.8 mya) Eocene Epoch (55.5 to 33.7mya) Paleocene Epoch (65 to 55.5 mya)
	Mesozoic Era 248 to 65 mya	Cretaceous Period (145 to 65 mya) Jurassic Period (213 to 145 mya) Triassic Period (248 to 213 mya)
	Paleozoic Era 544 to 248 mya	Permian Period (286 to 248 mya) Carboniferous Period (360 to 286 mya) Pennsylvanian Period (325 to 286 mya) Mississippian Period (360 to 325 mya) Devonian Period (410 to 360 mya) Silurian Period (440 to 410 mya) Ordovician Period (505 to 440 mya) Cambrian Period (544 to 505 mya)
PRECAMBRIAN TIME 4,540 to 544 mya	Proterozoic Era 2,500 to 544 mya	Neoproterozoic (900 to 544 mya) Mesoproterozoic (1600 to 900 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"

Figure 1.27 – Geologic time scale. Using relative ages of rocks and fossils, geologists developed the geologic time scale, which initially was just the time periods without definite years. Geologic time is subdivided into eons, eras, periods, and epochs. 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.

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. The decay of the isotope is like a clock that starts ticking when the isotope formed, and keeps ticking at a regular, measurable rate.

As an igneous or metamorphic rock cools from high temperatures, certain minerals crystallize and hold the ^{40}K isotope within their crystal structure. The minerals begin with an 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 are like clocks. These "clocks" are rugged and reliable timers because they will not stop due to most chemical, pressure, or temperature changes 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).

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, nearly everything is in terms of millions of years. Remember that a ***billion*** (1,000,000,000) is ***one thousand million***.

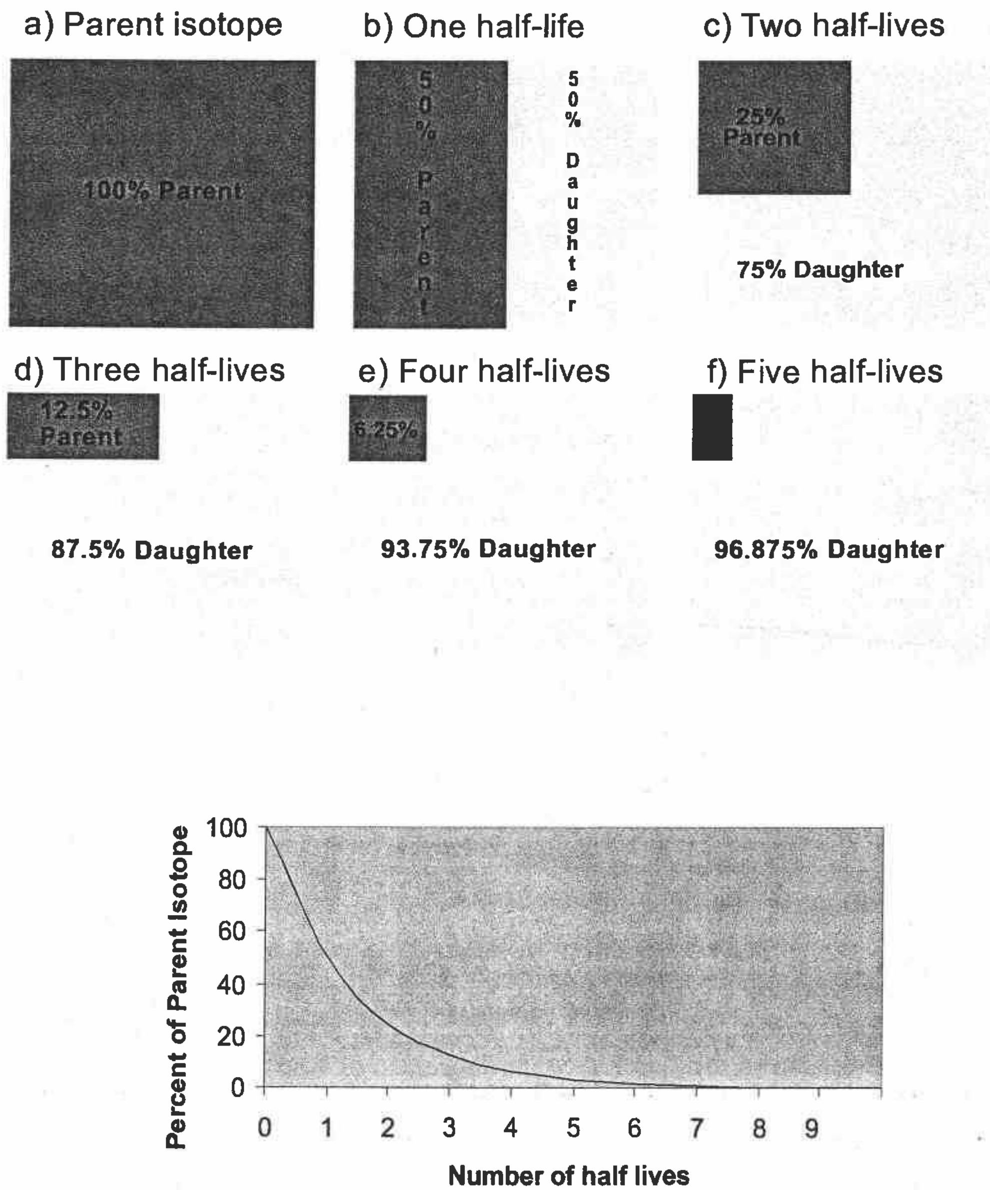


Figure 1.28 – Radioactive isotope decay. The boxes are simplified representations of an amount of parent isotope (green) which decays to form the daughter isotope (yellow). After one half-life of time passes, half of the parent isotope has decayed to form the daughter isotope. After another half-life, 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.

The rocks of Grand Canyon have been dated using various methods and principles. The igneous and metamorphic rocks in the inner canyon have been dated using 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 1.3 billion years. 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 older source rock material, not when the sedimentary rock 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 compared and correlated with fossils in other rock layers of known absolute age. Rocks with the same types of fossils in other places in the world provide an approximate age for Grand Canyon sedimentary rocks (Fig. 1.29).

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 (like meteorites), formed at approximately the same time. Using radioactive isotopes with long half-lives like lead (Pb) and uranium (U), 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 between 10,000 and 15,000 million years old, based on the rate of recession of distant galaxies.

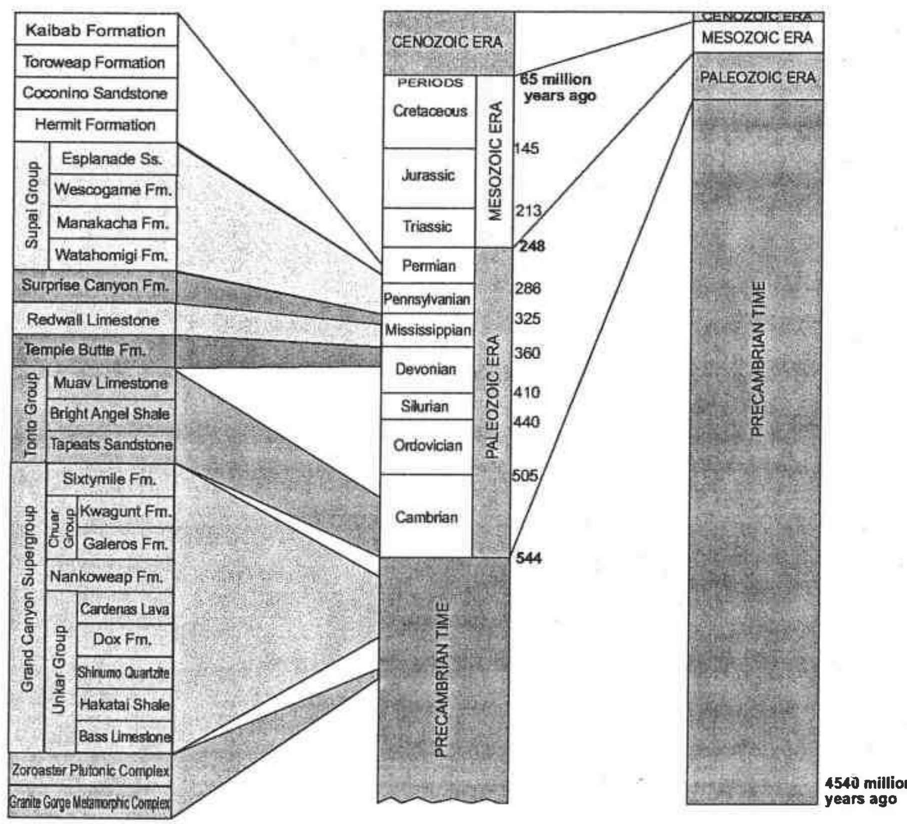


Figure 1.29 – Geologic time scale for Grand Canyon. The different rock layers of Grand Canyon are depicted to show their approximate ages on the geologic time scale. The geologic time representation in the middle is not drawn to scale. The time scale on the right side has the correct proportions of time.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

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 (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).

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. Joints, and 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 crack. If water freezes within a joint, expansion of the ice forces the joint to open further. After many winters pass, parts of the rock may eventually become unstable, break off, and fall into the canyon. Joints strongly influence the development of features like mesas, buttes, and temples in the canyon (see page 80).

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 substantial 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.

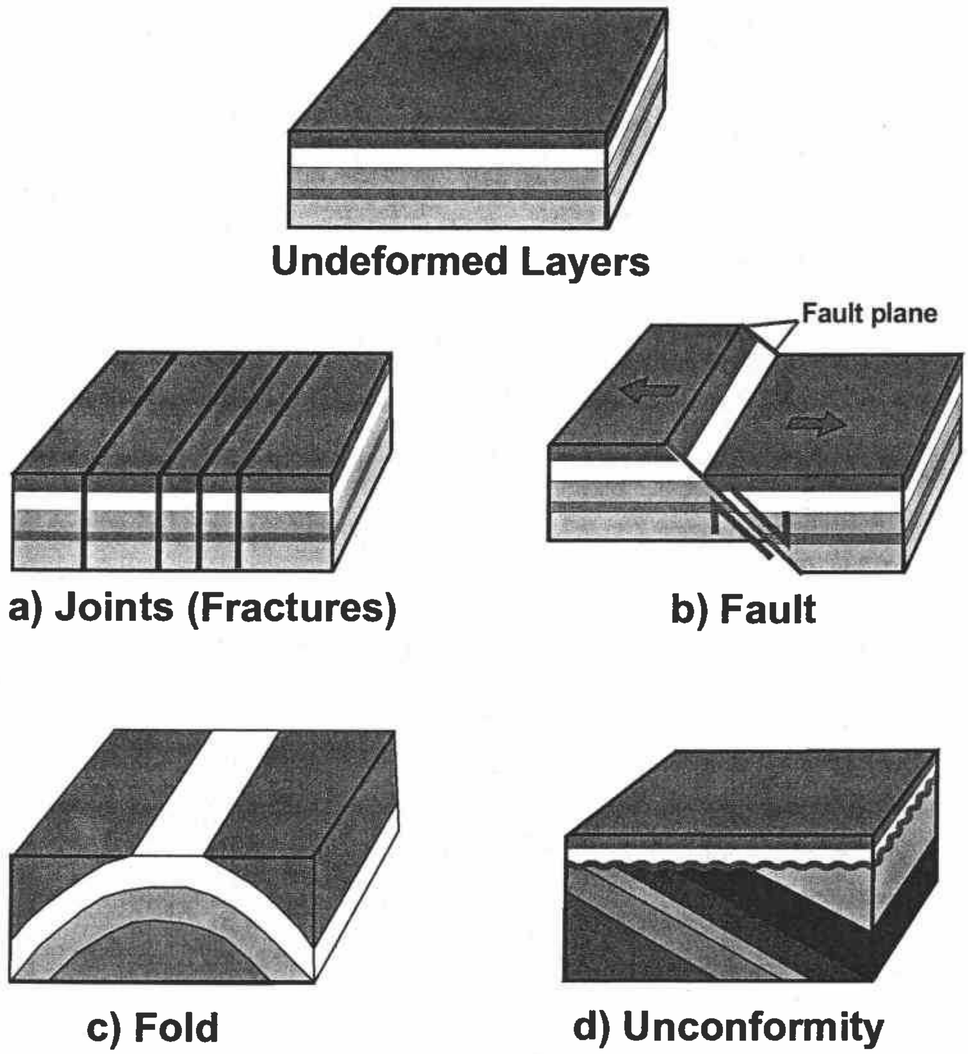


Figure 1.30 – Types of structures. a) **Joints** are cracks or fractures in the rock with movement *perpendicular* to the cracks. The rocks are cracked due to geologic forces of extension or compression. b) A **fault** is a break in the Earth's crust, where parts of the crust move relative to one another. 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 is usually the result of uplift and consequent erosion, followed by the deposition of younger rocks.

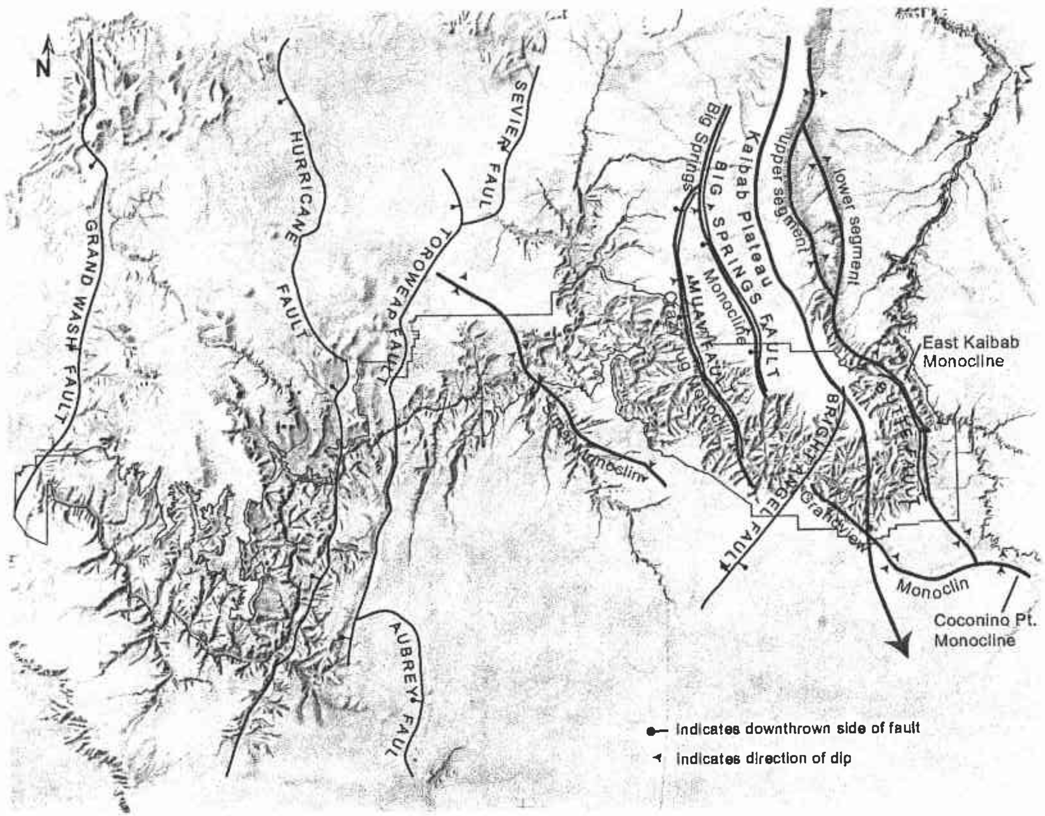


Figure 1.31 – Grand Canyon structures. This map shows the location of some of the major structural features (faults and folds) that are evidence of past geologic activity in the Grand Canyon region. Notice that many of the folds have faults associated with them. These faults are actually the reason the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

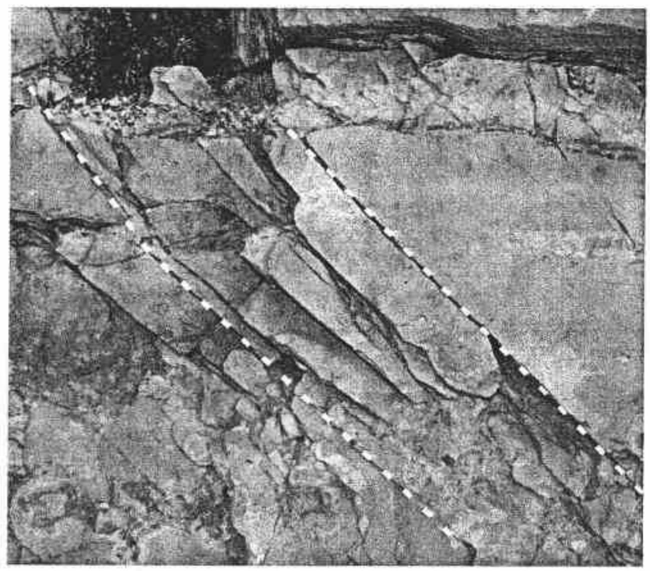


Figure 1.32 – Joints in Grand Canyon rocks. The rocks of Grand Canyon are riddled with joints. This example is in the Kaibab Formation along the South Kaibab Trail. A few of the joints have been dashed in white so you can see them.

Three types of faults form in response to different geologic forces (Fig. 1.33). **Normal faults** form as a result of pulling or extensional geologic 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.

Most of the faults in Grand Canyon are very old and have been reactivated several times (Fig. 1.34). Many of them were initially faulted shortly after the oldest rocks in the canyon formed. One example is the Bright Angel Fault. It was a normal fault when it formed about 1700 million years ago. It was later reactivated about 70 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.

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. 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.

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

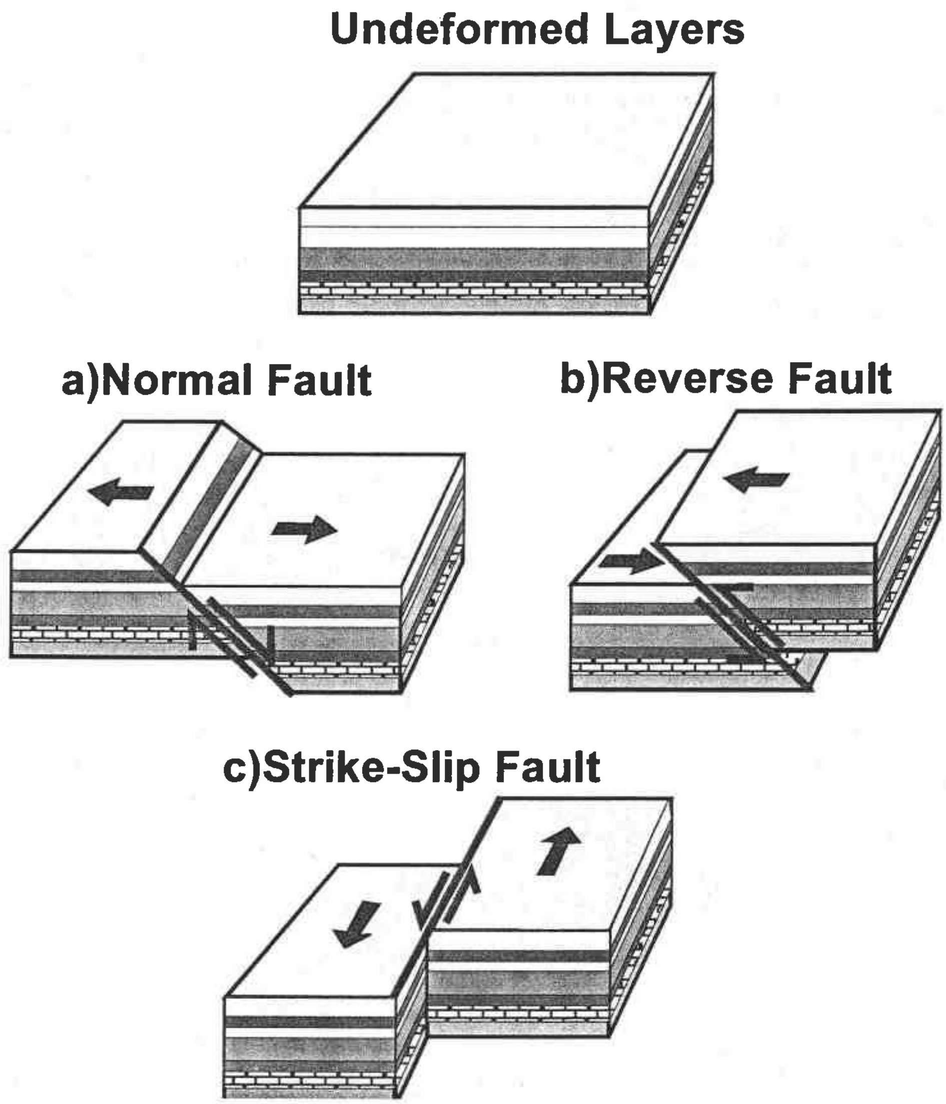


Figure 1.33 – Types of faults. The large, red arrows represent the main direction of the geologic forces that creates the fault. The black arrows show the direction of movement along the faults. a) **Normal faults** typically occur in an extensional tectonic setting, where the Earth's crust is being 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 a 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)*

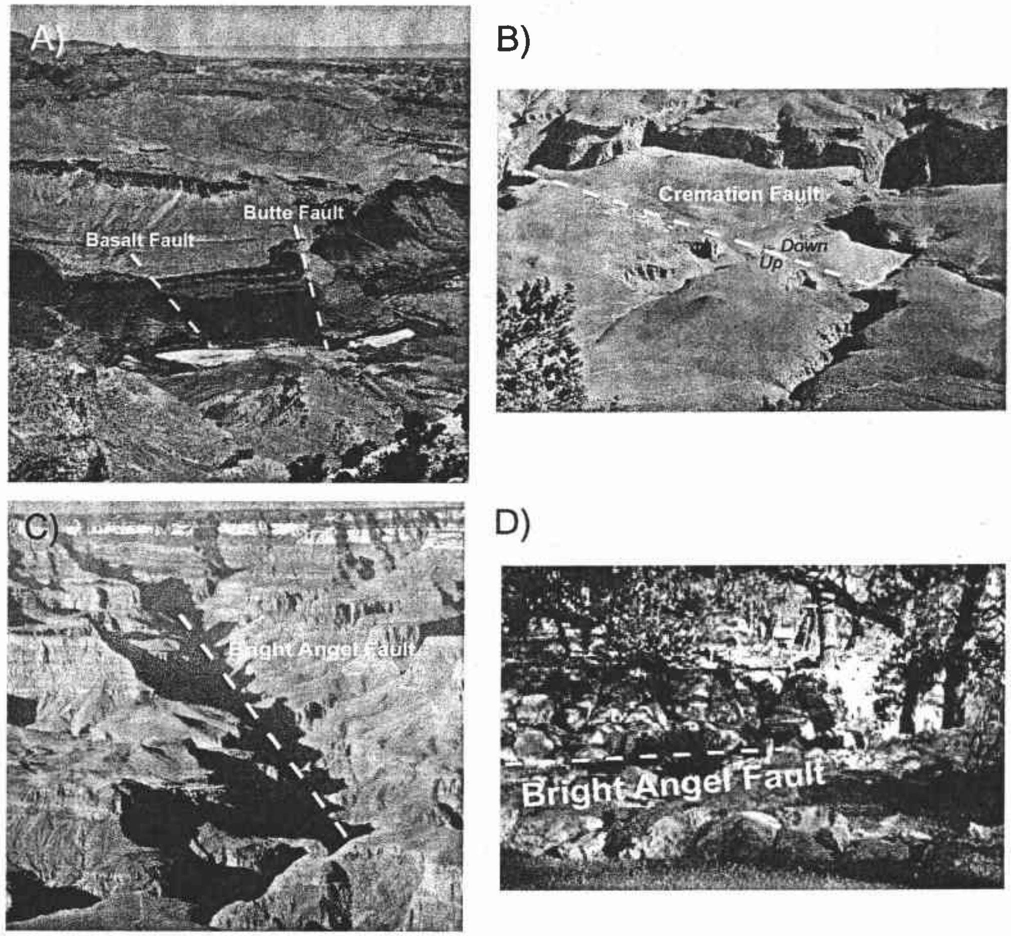


Figure 1.34 – Faults in Grand Canyon. Faults are seen along the dashed gray lines in these photos. As you observe the faults in the park, compare the pictures with the real-life scenery. A) **Butte Fault:** From Desert View, looking down towards the river, you can see Butte Fault and Basalt Fault. These 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 above the Bright Angel Shale. C) **Bright Angel Fault:** From the Village area, the Bright Angel Fault is very easily seen. It forms the straight side canyon on the north side of Grand Canyon named Bright Angel Canyon. The rocks within the Bright Angel Fault zone were weak 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 nearly impossible to ascend or descend in other locations. D) **Bright Angel Fault:** Along the Rim Trail, 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.

zones that will probably release strain energy again if geologic forces continue. Some earthquakes are very intense while others are barely noticeable.

Safe earthquakes. In the recorded history of Arizona, no earthquake has ever caused death or injury. The earthquakes that occur are usually small and not very intense. They are related to extension in 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 rounded letter "A." **Synclines** are downward folds, shaped similar to the letter "U." A fold that is neither an anticline nor a syncline, with only one folded side, is a **monocline**. It looks similar to a ramp connecting lower ground to higher ground.

Most of the folds in Grand Canyon are monoclines, and many 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, they faulted some of the deep layers close to the fault, and caused the uppermost layers to be folded into monoclines (Fig. 1.37).

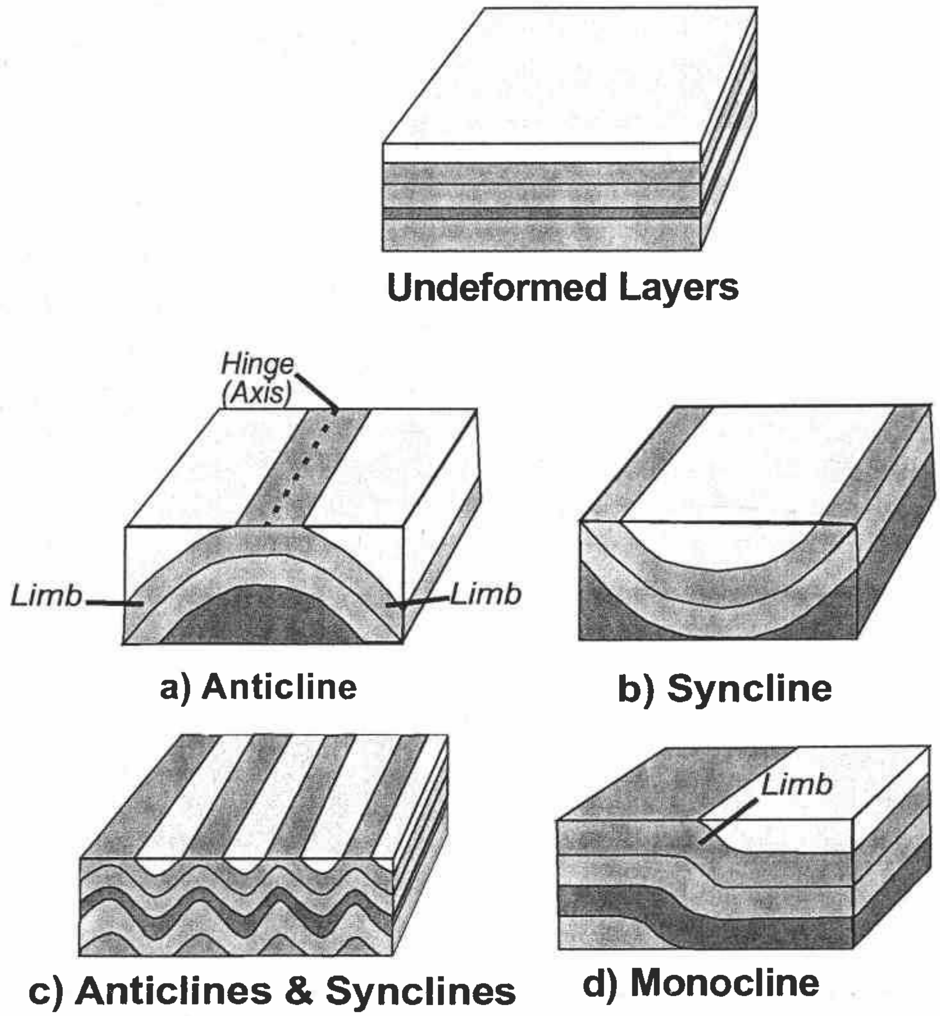


Figure 1.35 – Types of folds. Folds usually form because of slow geologic forces acting on the Earth's crust, like if you slowly pushed two ends of a rug together. The **hinge** or **axis** of the fold is where the curvature is greatest, and the **limbs** are the arms of the fold. a) An **anticline** is a fold that arches upward, forming a shape similar to a capital "A" (for Anticline!). b) A **synclines** 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)*

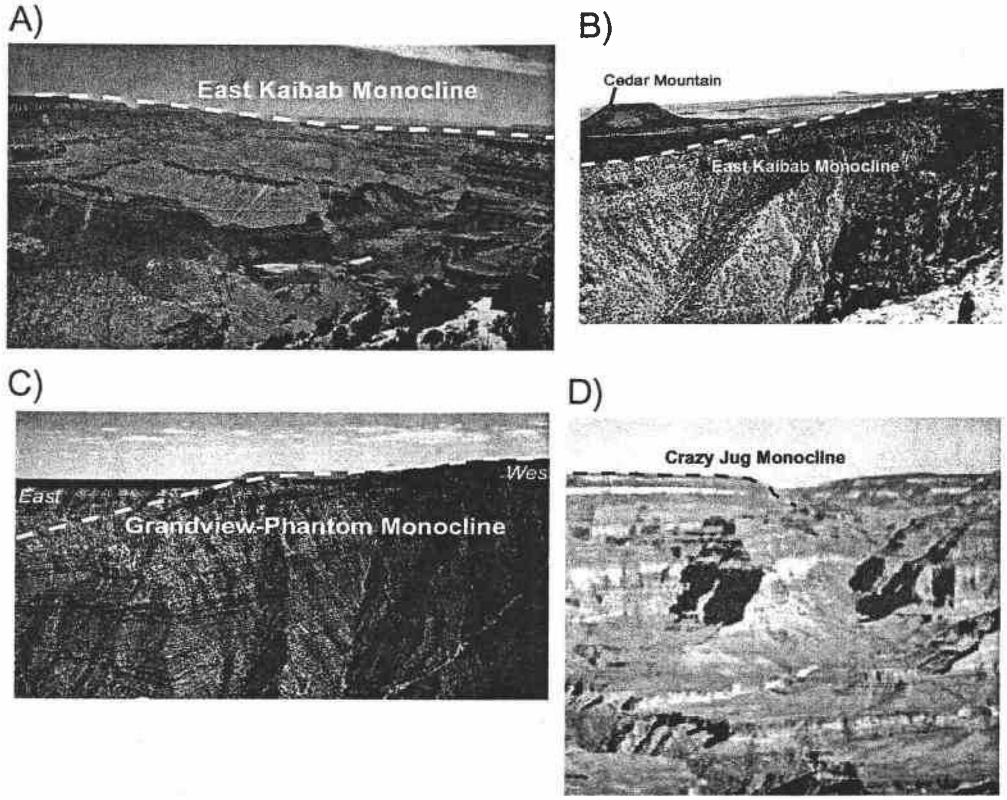


Figure 1.36 – Folds in Grand Canyon. When you see folds in the landscape, they may not look like the nice, straight folds in Figure 1.35. Try to imagine the general shape of the fold as you observe the following features in the canyon. A) **East Kaibab Monocline:** This photo of the East Kaibab Monocline was taken from the main lookout 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 rocks that were the limb of the monocline were broken up as they 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, 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 in the distance. It can be observed along Hermits Road and is especially visible from Pima Point, where this photo was taken.

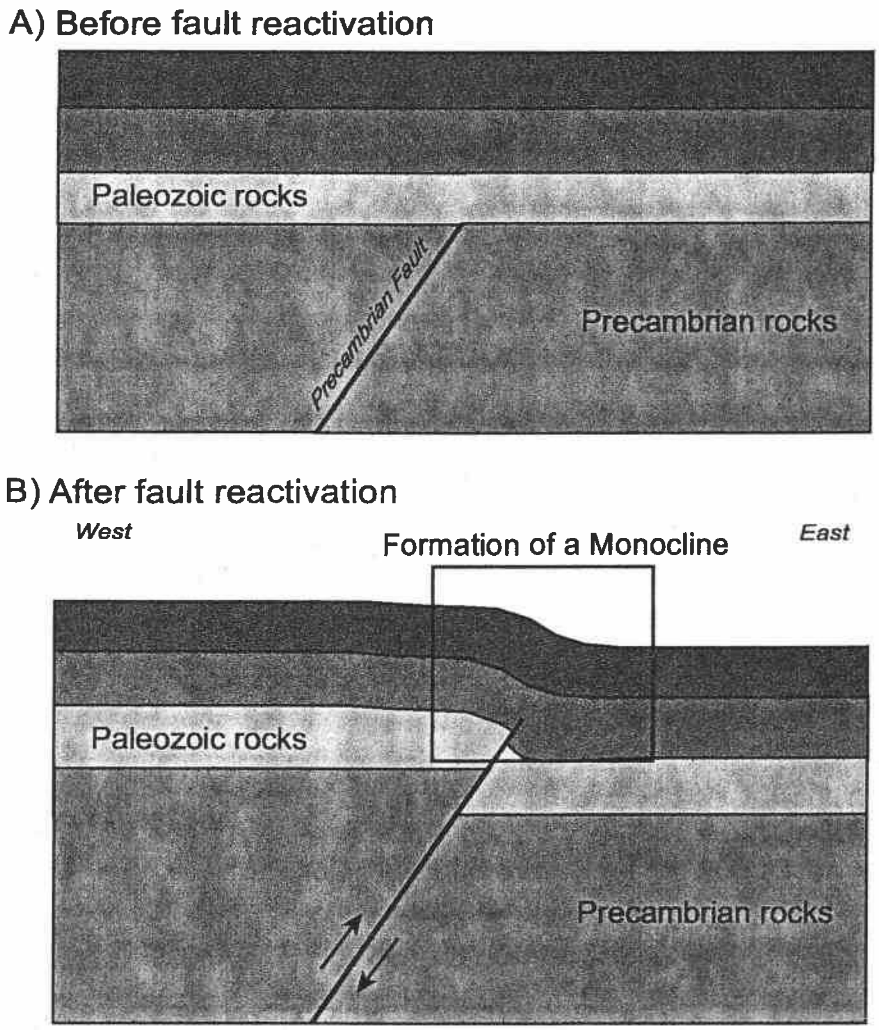


Figure 1.37 – Formation of monoclines at Grand Canyon. One way that folds form is because of faulting in rocks at depth. A) In the Grand Canyon region, faults that formed during Precambrian Time were buried beneath the Paleozoic sedimentary layers. B) When the faults were reactivated, the layers closest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

Folds 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, you are in the pigmy forest of mostly Pinion Pine and Juniper trees. 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 pigmy forest.

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 have removed pages, or no deposition occurred to write pages in the Grand Canyon book. There are many unconformities, some with large gaps in time and others missing just a few million years or less. Some of the 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 unconformity represents the period of time when no rocks are deposited or there is a period of erosion that removes rocks that were already deposited.

Several factors, including erosion, uplift of the land, drop in sea level, and structural deformation can contribute to the development of unconformities (Fig. 1.38).

There are three different kinds of unconformities, and Grand Canyon provides world-class examples of each type. An **angular unconformity** occurs where horizontal layers lie directly on top of layers that have been tilted (Fig. 1.39). To form an angular unconformity, rock layers are 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 **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, so that the layers are exposed to erosion. 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**, occurs 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 must have been a period of uplift and erosion, because metamorphism and melting usually occur very deep within the Earth.

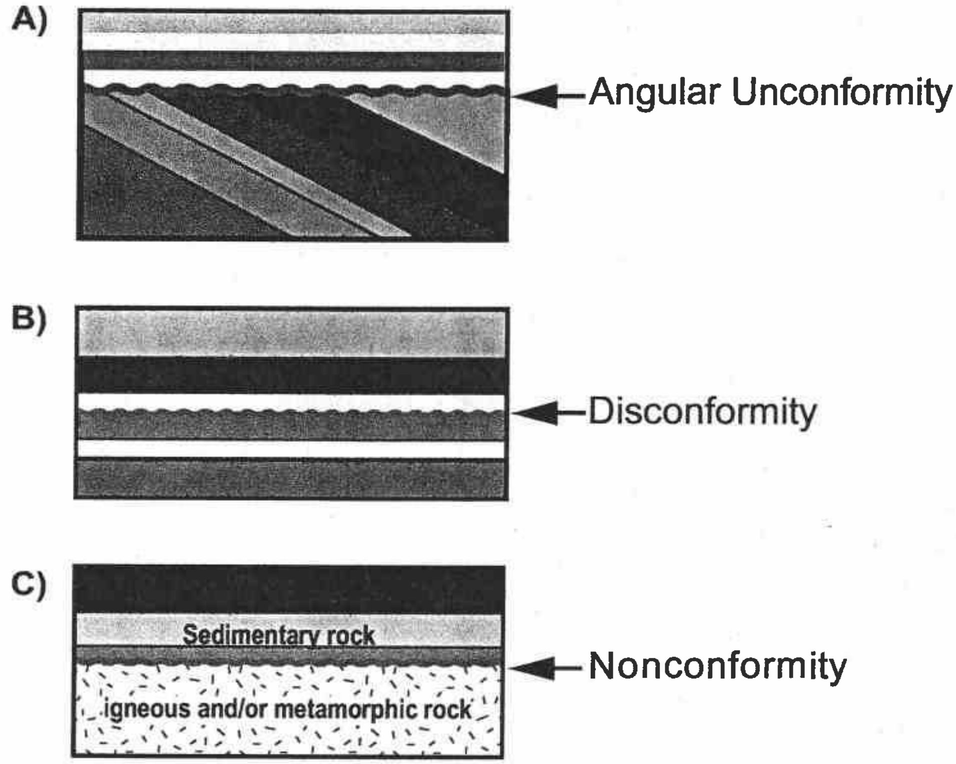
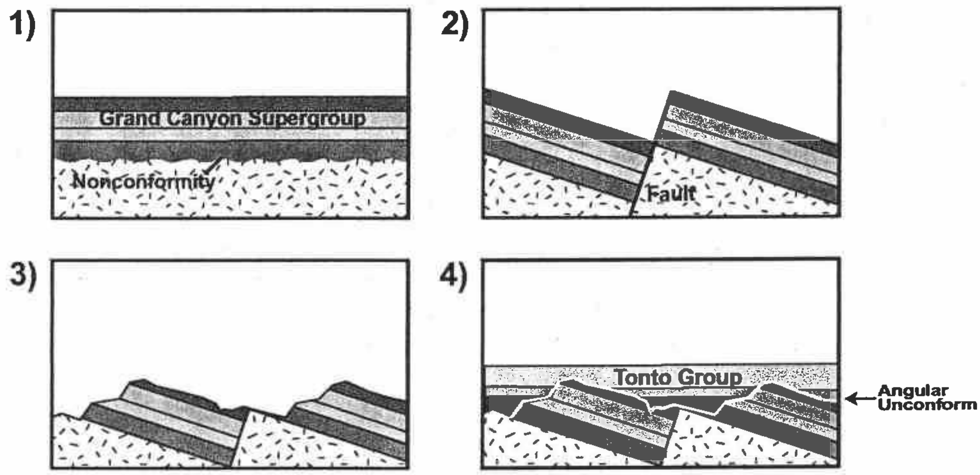


Figure 1.38 – Types of unconformities. Unconformities (shown as wavy red lines) are like pages missing from the geologic record. They commonly represent a period of uplift, erosion, no deposition, or a drop in sea level. A) **Angular unconformities** develop after horizontally-deposited layers are tilted, 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.

A)



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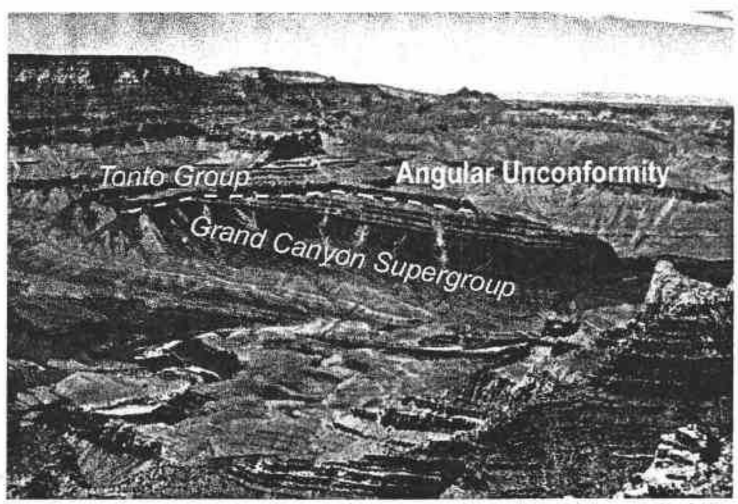
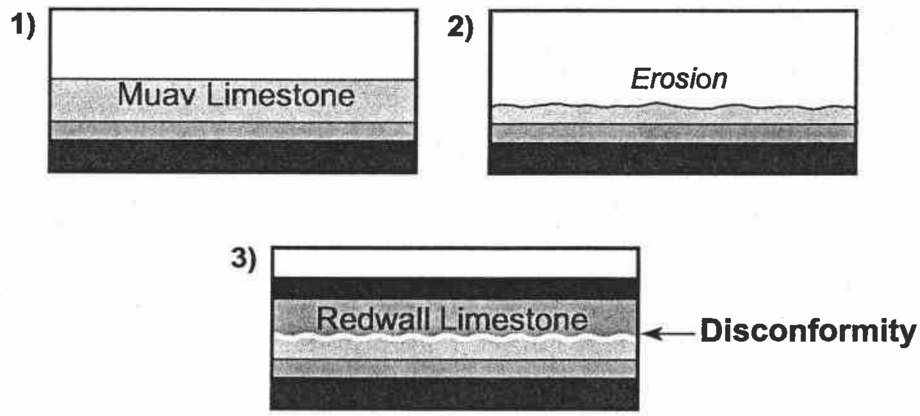


Figure 1.39 – Angular unconformity. A) A major angular unconformity at Grand Canyon occurs between the tilted layers of the Grand Canyon Supergroup and the overlying sedimentary layers known as the Tonto Group. 1) The Supergroup was first deposited on top of the crystalline rocks of the inner canyon (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 250 million years of time is missing from the geologic record at this unconformity.

A)



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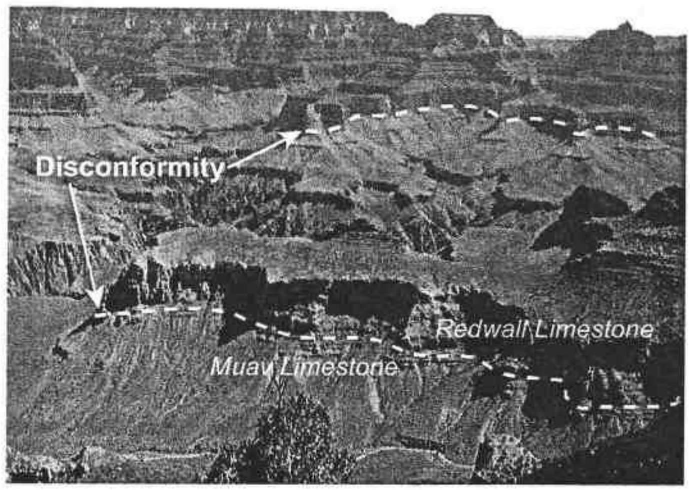


Figure 1.40 – Disconformity. A) The disconformity between the Muav Limestone (the uppermost layer of the Tonto Group) and the Redwall Limestone is the most significant (in terms of missing geologic time) disconformity within the sedimentary rock layers of Grand Canyon. This particular disconformity represents nearly 145 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.) 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.)

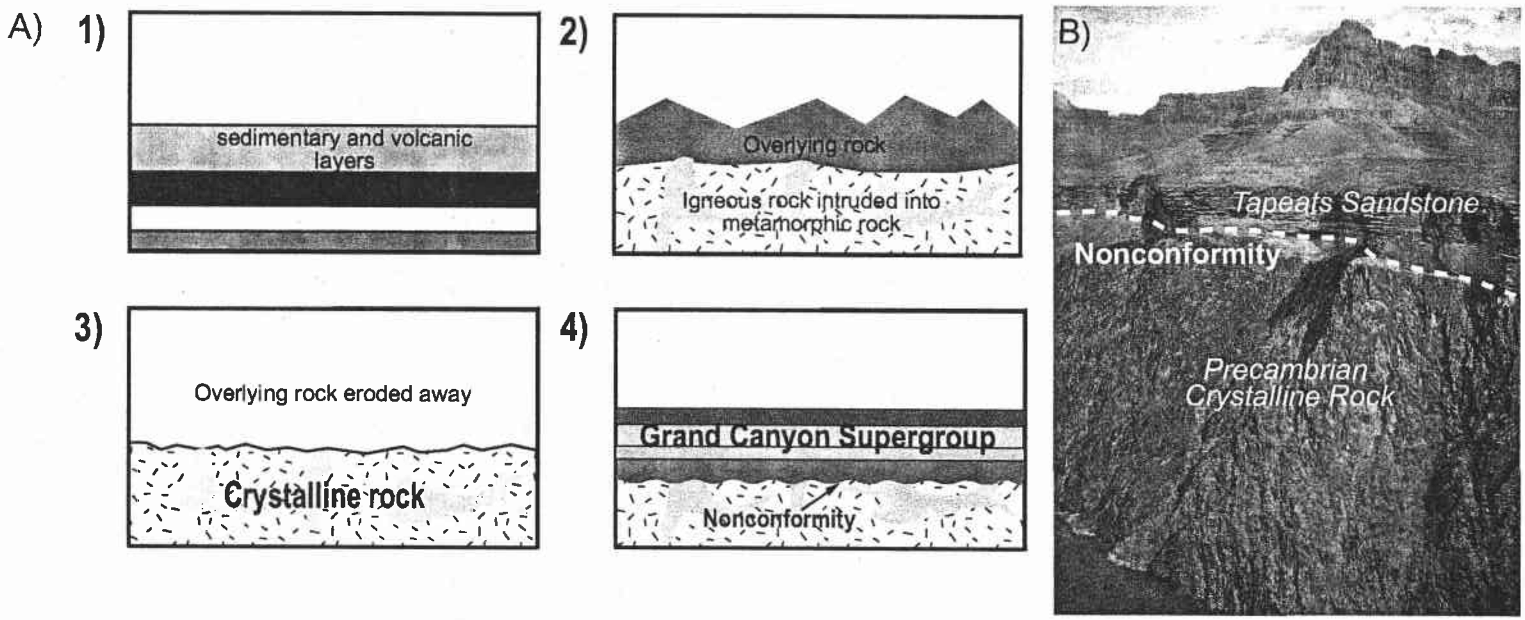


Figure 1.41 – Nonconformity. A) 1) The first step in the formation of one of the nonconformities at Grand Canyon was the deposition of sedimentary and volcanic layers. 2) These rocks were later metamorphosed and melted deep below the Earth's surface as a mountain building event occurred. This changed 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 and part of the Great Unconformity. Where the younger sedimentary rocks (550 million year old Tapeats Sandstone) are in contact with the crystalline rocks in the inner canyon, at least 850 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)*

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 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, or daily basis. Discharge depends 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 3,000 cfs. Glen Canyon Dam now regulates the discharge of the river, usually keeping it between 12,000 and 18,000 cfs.

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 discharge of a river affects how much sediment the river can carry, called the **sediment load**. Some fine sediment is completely suspended and transported by the current, while coarser sediment is bounced along the river channel. Other very fine material is dissolved in the water. During a flood in 1884, the discharge of the Colorado River reached 300,000 cfs. This tremendous volume of water carried at least 300 tons of sediment per day, as measured by a gauge near Phantom Ranch. With Glen Canyon Dam now in operation, the sediment load of the Colorado River through Grand Canyon is reduced to about 50 tons per day.

The sediment load of a river is also dependent on the water **velocity**, which is related to the discharge. 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 only *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.

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 1000 miles (1600 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 1,000 feet (305 m) over more than 2000 miles (3200 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 is then deposited in the stream channel because the velocity is not great enough to carry it.

River processes, like most 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).

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 ft/year (1 m/year). Over time, the waterfall at Niagara Falls progressively moves eastward 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)!

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.

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.

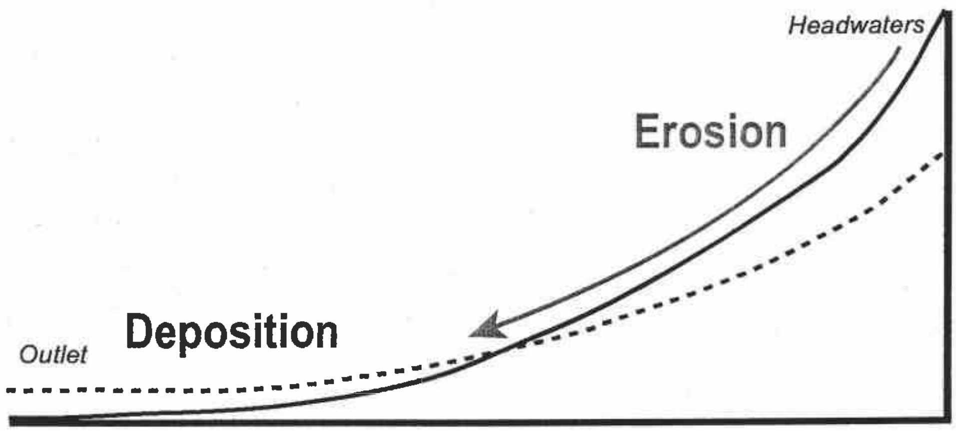


Figure 1.42 – Balance of erosion and deposition. This simplified diagram depicts how a river erodes sediment from the steeper part of the channel (red arrow), which is usually near the headwaters, and deposits it along the flatter part of the channel, near the mouth of the river. The solid line represents 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.

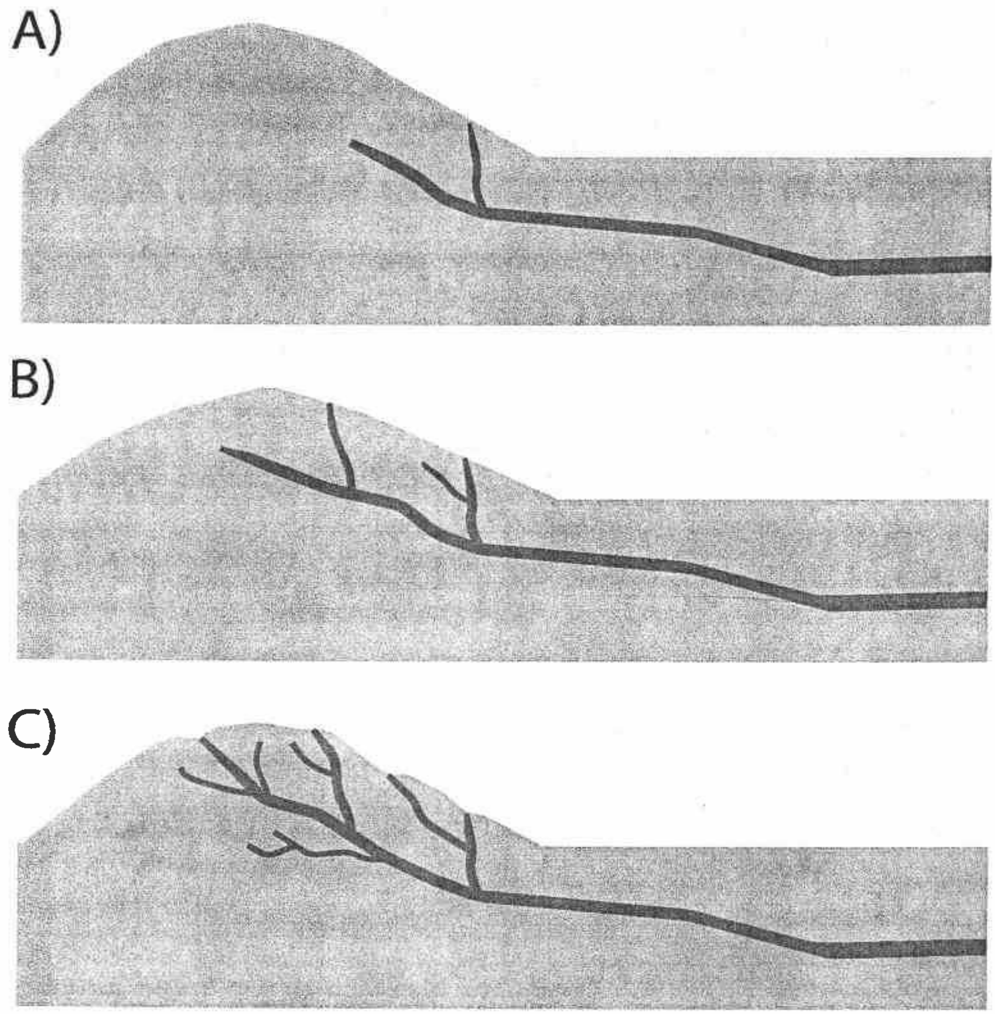


Figure 1.43 – Headward erosion. Headward erosion plays an important role in the development and lengthening of rivers. As a river travels down a steep slope it cuts into the river channel and removes sediment from the channel itself, as shown in Fig. 1.42. A river or stream will continue to grow progressively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

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 1000 feet (305 m) higher than the South Rim because the land slopes 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). Precipitation that falls on the North Rim flows south because of this, 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 toward the south, away from the canyon. The side canyons that develop on the South Rim are therefore much shorter and steeper compared to the side canyons on the North Rim.

Where does the drinking water come from? Drinking water is scarce on the South Rim because most of the 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 ground water from the North Rim enters the canyon. 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.

Whitewater rapids are commonly located at the ends of side canyons, where the tributaries join the Colorado River. The side canyons not only contribute water, but can also dump large-size sediment into the river. When the side canyons are flooded by rain or snow melt, they can transport large boulders into the river. The boulders and other sediment create rapids for river runners to enjoy (Fig. 1.46).

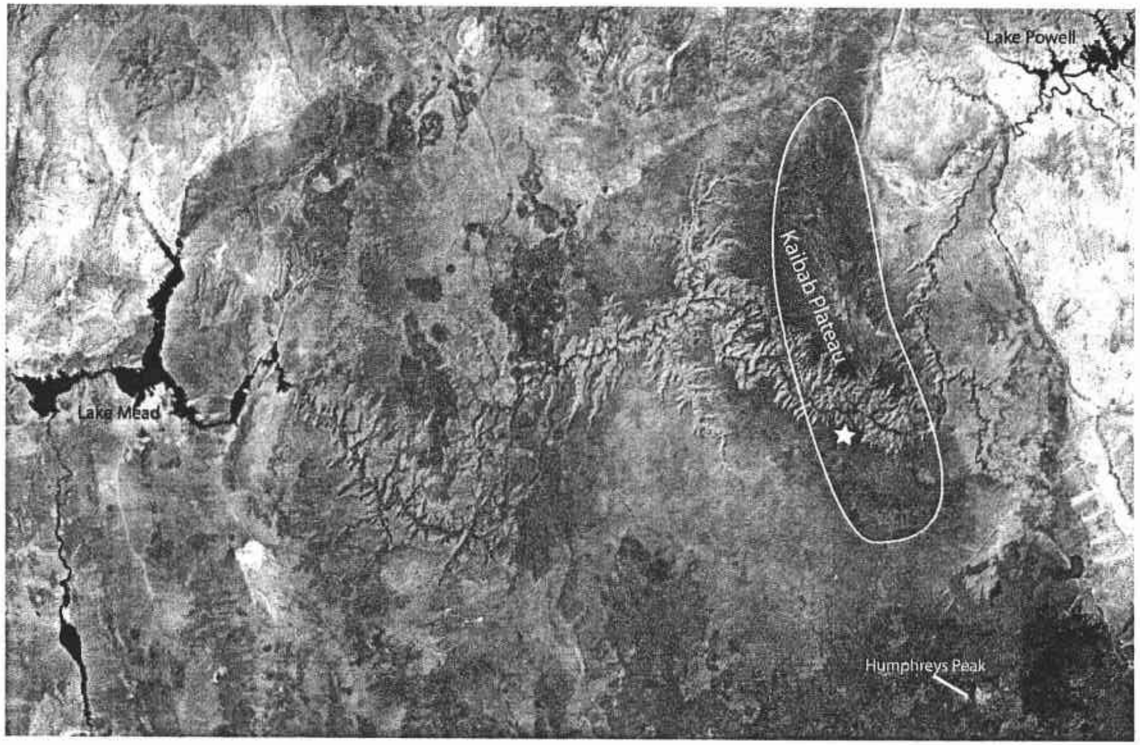


Figure 1.44 – Satellite image of Grand Canyon region. You can see that there are many side canyons along the Colorado River in Grand Canyon, which contribute to the naturally sculpted landscape. The large, oval-like shape circled along eastern Grand Canyon is the Kaibab Plateau. It is a lighter color than the surrounding area because of snow cover (bright blue color). The star on the image is the approximate location of the South Rim Village. *(Image property of NPS)*

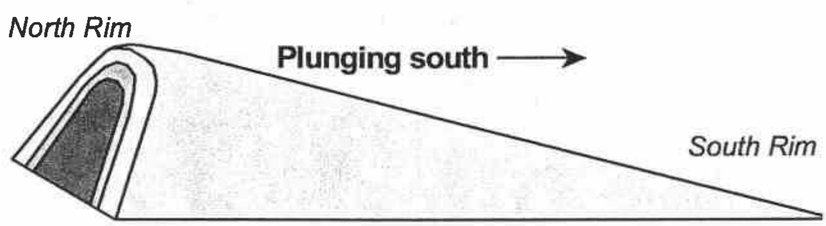


Figure 1.45 – The Kaibab Plateau. The region of upwarped land called the Kaibab Plateau seen in Figure 1.44 may have contributed to the development of the path of the Colorado River, as we know it today. The Kaibab Plateau is a broad **plunging anticline**. This means that the axis of the fold is not 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.

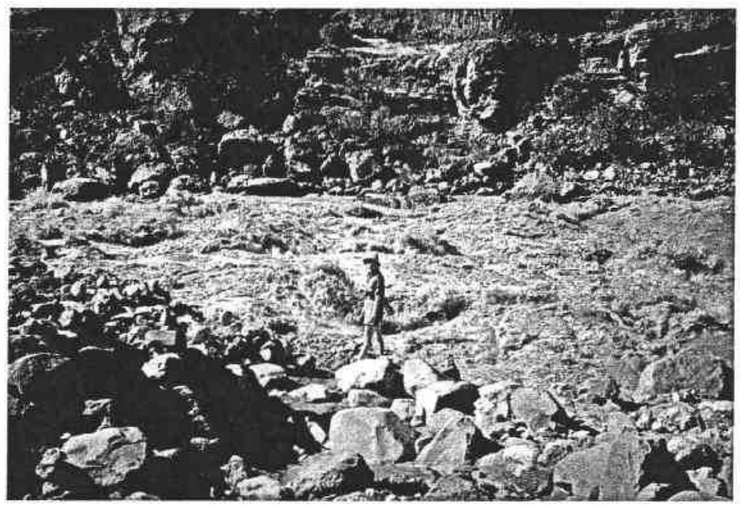


Figure 1.46 – Rapids on the river. Tributaries flowing from side canyons contribute water and sediment to the Colorado River. When flooding occurs in the side channels, large-size sediment, like boulders and cobbles, are deposited in the river, which make large rapids. These rapids are in western Grand Canyon. Note the size of the rapids in comparison to the person! *(Photo property of NPS)*

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 Colorado River no longer flows through Grand Canyon with the same vigor it once did. Glen Canyon Dam, in Page, Arizona, began controlling the water released into Grand Canyon in 1963. Since then, the dam and reservoir (Lake Powell) have provided water and electricity for many desert cities, as well as a place for water recreation. As the Colorado River passes through Glen Canyon Dam, it typically has a blue-green color rather than the muddy-brown color it once had. This is because most of the river's sediment has been deposited in Lake Powell. When thunderstorm season arrives at the end of each summer, the muddy-brown color returns as red and brown sediment is washed from side canyons and tributaries down-river from the dam.

Hundreds of thousands of tons of sediment that was once transported 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. 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 must retain it. But with each year that passes, the volume of water that the lake can hold decreases as sediment builds up. As the capacity of the lake decreases with time, the chances of the dam overflowing increases. Downstream, Hoover Dam would not likely be able to contain the enormous volume of water that it would receive if Glen Canyon Dam overflowed.

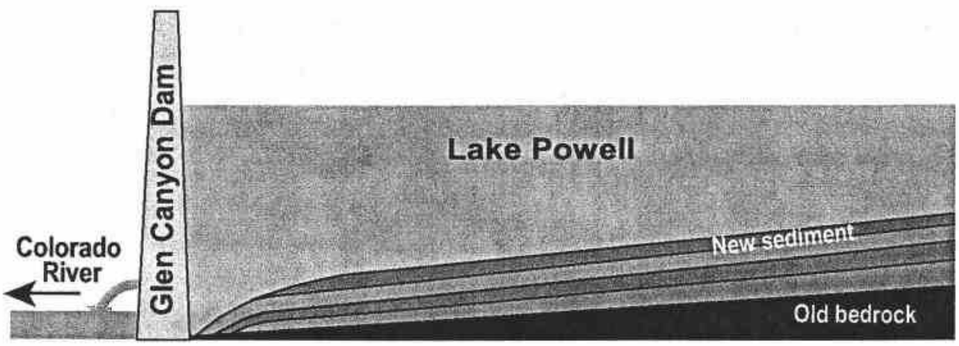


Figure 1.47 – Lake Powell. Glen Canyon Dam has stopped the flow of the Colorado River through Glen Canyon. As the river enters Lake Powell, the water velocity decreases, causing the sediment carried by the Colorado River to be deposited on the bottom of the lake. Someday the back up of sediments may cause the demise of Glen Canyon Dam.

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. Dams are the blink of an eye in terms of geologic time. In fact, the Colorado River has been dammed in the past by lava flows. But most of the lava dams and the effects they may have had on the environment are now 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.

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 break down 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 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 occurs, for example, when limestone is dissolved upon exposure to water, or when iron-rich sediment is oxidized in the atmosphere, producing red and other colors in rocks. Chemical weathering is a predominant weathering process in humid climates, where water in the air slowly dissolves the rock. But that type of weathering does not have much effect on rocks in the arid climate of the Grand Canyon region.

At Grand Canyon, physical weathering plays an important role in weathering rocks and widening of 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 as 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 thunderstorm season in late summer, water can wash away large amounts of sediment. **Rockslides** occur when a large portion of rock breaks off along a weak zone (like a joint) and slides down slope, usually because of excess water. A **rock fall** can also occur when any small or large rock breaks off and free falls (Fig. 1.48). Over time, these weathering processes have sculpted the rocky cliffs and slopes of the canyon walls and the side canyons, creating the spectacular landscape at Grand Canyon.

Weathering forecast. Weathering of the rocks of Grand Canyon by physical processes has helped make the canyon wide. This has been happening sporadically 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 thunderstorm season. Other times, little erosion may occur during a dry year. Accurately estimating the *average widening* of the canyon is rather 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 a difficult thing to do without knowing what climate or tectonic changes may occur in the future.

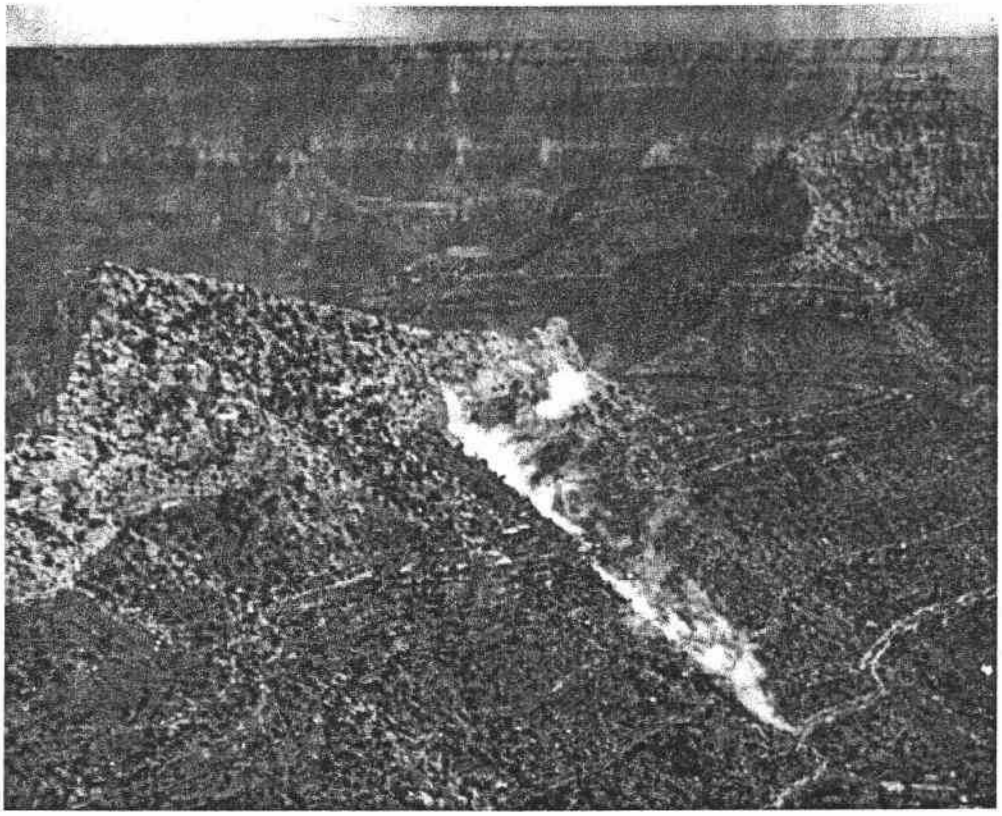


Figure 1.48 – Rock falls in Grand Canyon. Rocks can fall from the canyon walls at any time. This photo captures a rock fall in action. Eventually these rocks may get carried away by the Colorado River as erosional processes carry them away. *(Photo property of NPS)*

The stair-step landscape characteristic of Grand Canyon's walls is partly due to the variation of rock types in the canyon. Different rock types weather differently. Soft layers in the canyon are 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.

Super sunsets. The landscape of Grand Canyon, with its many tall rock peaks, curves, 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. 1.50). 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 are slender features and much taller than they are wide.

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 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. 1.51). 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 in the past, when small streams flowed

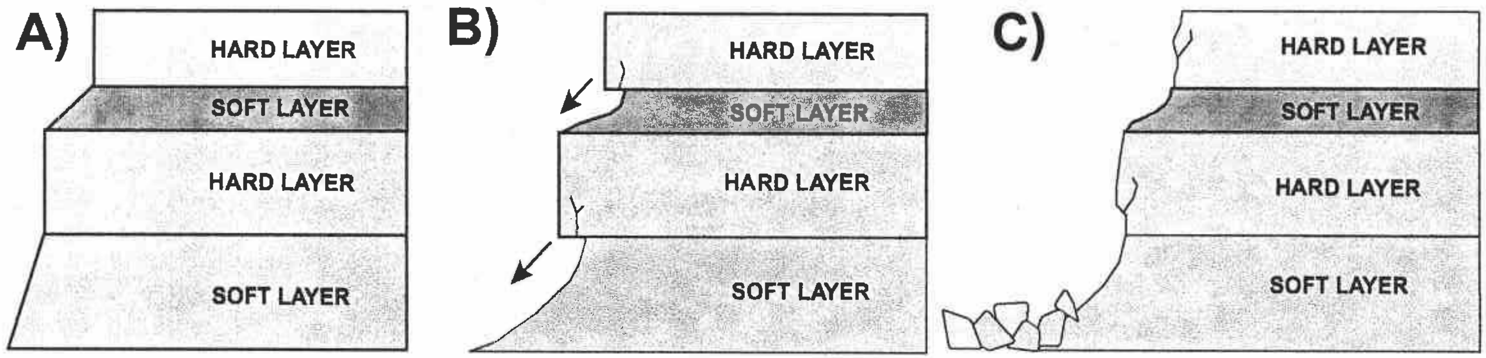


Figure 1.49 – Widening the canyon walls. Mass movements help to widen the canyon, especially where the slope is overly steep and cannot support the overlying rock. After weathering processes weaken the rocks, these rocks submit to the force of gravity and eventually fall into the canyon. A) The alternate 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, possibly causing mass movement of rocks. This begins the process over, exposing the soft layer to erosional processes again and gradually widening the canyon.

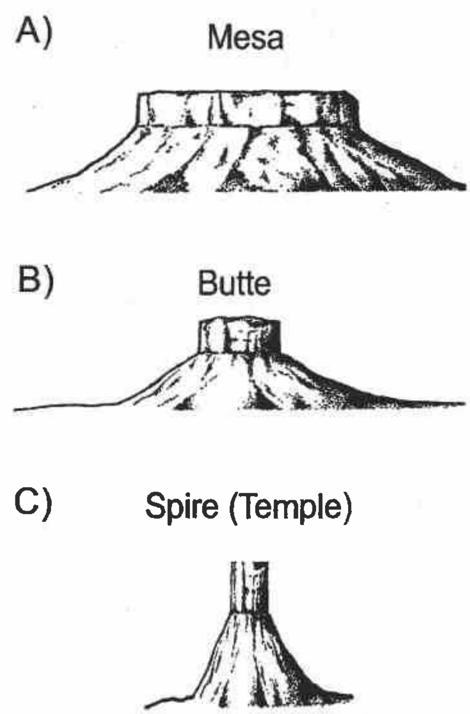


Figure 1.50 – Landscape features. A) A **mesa** is a broad, flat feature that is wider than it is high. B) **Buttes** are approximately as tall as the width of the feature. C) **Spires** or **temples** are narrow features, as they are taller than their width. *(Diagram adapted from Greer Price, An Introduction to Grand Canyon Geology, 1999)*

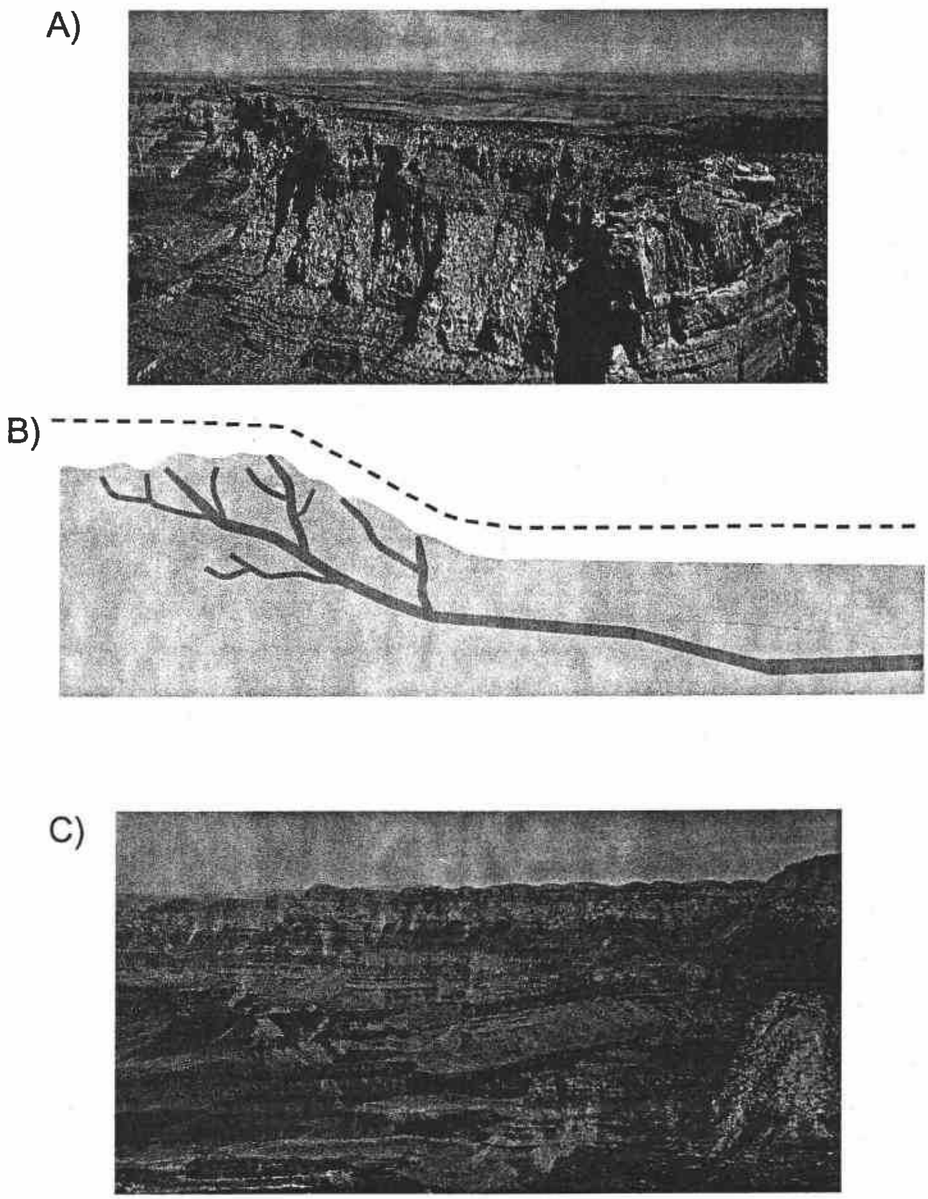


Figure 1.51 – The Palisades of the Desert. A) This photo shows the hills that give the Palisades of the Desert its distinct appearance. The rocks are part of the East Kaibab Monocline. The middle, steeply-sloped portion of the monocline was located where Grand Canyon is now. B) Small streams once flowed east, down the East Kaibab Monocline, downslope along the layers tilted by the monocline. This formed small channels that are preserved as evidence of the streams existence. Remnants of the channels are 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 shape.

eastward in channels over the sloping East Kaibab Monocline. The stream channels incised small valleys with the rolling hills around them.

APPLICATION: READING THE PAGES OF GRAND CANYON GEOLOGY

> One might imagine that this was intended for the library of the gods; and it was. The shelves are not for books, but form the stony leaves of one great book. He who would read the language of the universe may dig out letters here and there, and with them spell the words, and read, in a slow and imperfect way, but still so as to understand a little, the story of creation. (J.W. Powell, *The Exploration of the Colorado River and its Canyons*, ©1961, Dover Publications, Inc.)

The rock layers in Grand Canyon are the pages of an ancient history book, written in the language of geology, with chapters of information about places and environments that existed long ago. This vast book of geologic information can be overwhelming, as it would be to read an entire encyclopedia. Many of the pages of the book are missing because they were removed as rocks were eroded and washed away during various periods in geologic time.

Now that you've been introduced to the fundamentals of the "Language of Geology," we can begin to read the pages of Grand Canyon, and think about how to convey the geology to park visitors in a meaningful way. Just as the rocks in the canyon were deposited, this manual will discuss important events in the geologic history of Grand Canyon chronologically from the bottom of the canyon to the top.

Interpreting the rocks. It is not as important to memorize the names or the ages of all the rock layers, as it is to recognize the rock types and the environments of deposition they represent. Although you may "wow" visitors by naming off each layer, they will probably not find a program enjoyable or meaningful if you go into excruciating detail about each of the layers. An overload of details would bore visitors, as it would bore you to hear a detailed description of the internal workings of a frog intestine! Have a few carefully selected and intriguing topics to discuss about some of the layers. The layers you choose should be easy to recognize from the rim, have geologic stories relevant to your program theme, and represent a depositional environment that visitors can relate to. Consider carrying a stratigraphic column (Fig 1.25) as a "cheat sheet" to help you answer more specific questions about layers.

THE PRECAMBRIAN TIME (4540 TO 544 MILLION YEARS AGO)

Even though Precambrian Time comprises about 87% the Earth's history, we know relatively little about it. Since the Earth formed 4540 million years ago, it has been cooling and releasing heat and gases that formed the planet's atmosphere and water. The Earth must have looked very different during Precambrian Time. The continents were gradually forming in locations different than today, and the oceans held the only life on the planet. The first life forms were unicellular, simple microorganisms that developed about 3500 million years ago. Their fossilized remains have been found in western Australia.

The "oldies" of Earth rock. Grand Canyon has old rocks (the oldest are 1840 million years old), but they are certainly not the oldest rocks on the Earth. In fact, rocks at least 3500 million years old are found on every continent. The oldest rock, called the Acasta Gneiss, is about 4030 million years old, and is found in northwestern Canada near the Great Slave Lake. Even older are tiny zircon crystals from western Australia, which are about 4300 million years old.

Precambrian Metamorphic Rocks

In the ancient history book of Grand Canyon, the first pages date back to the early Proterozoic Eon of Precambrian Time (Fig. 2.1). During this time, the continent that is now North America had a very different shape and was located south of the equator. A shallow ocean existed along the margin of the continent around 1750 to 1740 million years ago, where sedimentary and volcanic rocks were forming (Fig. 2.2). Some of these rocks were deposited on top of the oldest rocks now found in Grand Canyon, the Elves Chasm Gneiss, which is 1840 million years old. On the margin of the shallow ocean, a volcanic island chain was converging with the North American continent. The ocean basin gradually closed as the volcanic islands collided with the continent between about 1750 and 1660 million years ago.

Eon	Era	Periods and Epochs
PHANEROZOIC EON 544 mya to Present	Cenozoic Era 65 mya to Present	Quaternary Period (1.8 mya to present) Holocene Epoch (8,000 years to present) Pleistocene (1.8 million to 8,000 years) Tertiary Period (65 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene Epoch (23.8 to 5.3 mya) Oligocene Epoch (33.7 to 23.8 mya) Eocene Epoch (55.5 to 33.7mya) Paleocene Epoch (65 to 55.5 mya)
	Mesozoic Era 248 to 65 mya	Cretaceous Period (145 to 65 mya) Jurassic Period (213 to 145 mya) Triassic Period (248 to 213 mya)
	Paleozoic Era 544 to 248 mya	Permian Period (286 to 248 mya) Carboniferous Period (360 to 286 mya) Pennsylvanian Period (325 to 286 mya) Mississippian Period (360 to 325 mya) Devonian Period (410 to 360 mya) Silurian Period (440 to 410 mya) Ordovician Period (505 to 440 mya) Cambrian Period (544 to 505 mya)
PRECAMBRIAN TIME 4,540 to 544 mya	Proterozoic Era 2,500 to 544 mya	Neoproterozoic (900 to 544 mya) Mesoproterozoic (1600 to 900 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"

Figure 2.1 – Geologic time scale.

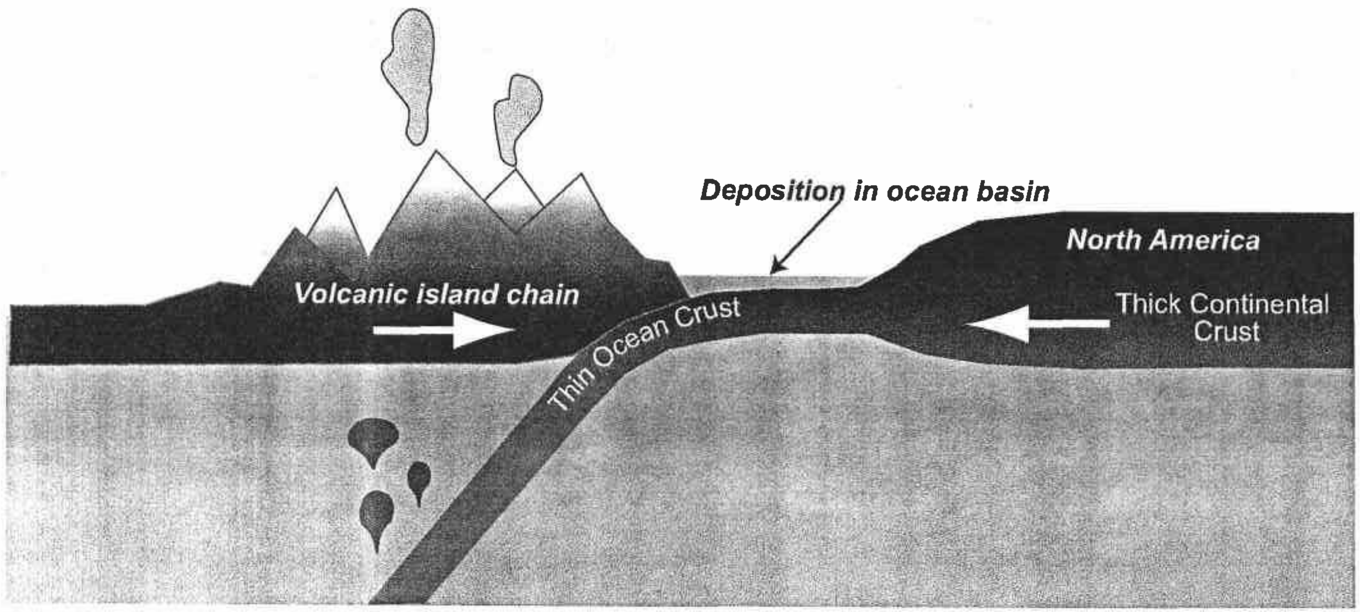


Figure 2.2 – Volcanic island collision during Precambrian Time. Precambrian sedimentary and volcanic rocks were depositing in an ocean basin, situated between a volcanic island chain and the North American continent. A subduction zone may have existed that created the volcanic islands on the overriding plate. As the landmasses moved toward each other and collided, the ocean basin rocks were shoved down to great depth (up to 13 miles below the surface) and exposed to intense heat and pressure that metamorphosed and melted the rocks.

During this collision, the rocks were pushed down to depths of up to 13 miles (21 km) below the Earth's surface. Intense heat and pressure at those depths metamorphosed the sedimentary and volcanic rocks, changing them into schist and gneiss. These metamorphic rocks are the dark, angular rocks found in the inner canyon near the river today (Fig. 2.3a). All of the Grand Canyon metamorphic rocks can be grouped into the **Granite Gorge Metamorphic Complex**, which includes the **Brahma**, **Rama**, and **Vishnu Schists**.

> I saw, when I looked up from the rim, that the uppermost layers of rock were bright and bold and youthful. Their unseamed faces shone pink or white or suntan-brown, untouched by the upheavals that time brings to all of us. But below the Redwall they began to show their age. There, in staid maturity, they wore dark greens and subdued browns. And their faces had begun to wrinkle. Then, as my eye reached the lip of the Inner Gorge, the rocks plunged into old age. Now they wore gray and sober black. The wrinkles had deepened. And their features had twisted beneath the terrible weight of the years. Old age had come to them, just as it does in the end to all of us who live long enough. (Colin Fletcher, *The Man who Walked Through Time,* © 1967, Random House, Inc.)

Precambrian Igneous Rocks

Rock was melting deep below the Earth's surface at the time of the volcanic island collision and intense metamorphism, about 1740 to 1400 million years ago. Magma was squeezed into fractures and weak areas in the Granite Gorge Metamorphic Complex. It then cooled slowly within the Earth, forming intrusive (or plutonic) igneous rocks, including several varieties of granite collectively called the **Zoroaster Plutonic Complex**. These rocks are the light-colored bands and masses of granite within the dark Granite Gorge Metamorphic Complex in the inner canyon today (Fig. 2.3b).

A)

B)

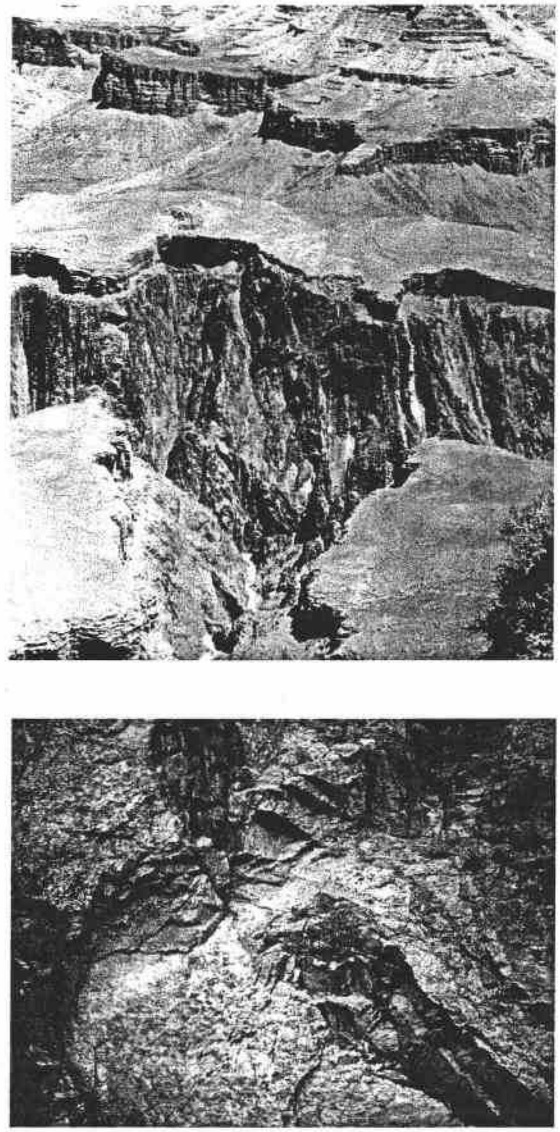


Figure 2.3 – The inner canyon. A) The metamorphic rocks are the dark, craggy rocks that contribute to the steepness of the inner canyon. They are very resistant to weathering and erosion, making it hard for the river to through them. B) The igneous rocks are within the dark metamorphic rocks in the inner canyon. Most of this rock is granite, although other varieties of intrusive igneous rocks have been identified in the canyon. Large masses of granite (**plutons**), like the one seen here, were once chambers of magma. Bands (or **dikes**) of granite also formed as the molten rock squeezed into cracks and weak areas in the surrounding metamorphic rock.

Interpreters tip. When discussing the Granite Gorge Metamorphic Complex or Zoroaster Plutonic Complex, the long names and big words may confuse or distract visitors. Many publications available to visitors informally and incorrectly refer to all metamorphic rocks as the Vishnu Schist. But in the area of Phantom Ranch for example, the Brahma, Rama and Vishnu Schists are complexly inter-layered. Rather than incorrectly referring to all of them as Vishnu Schist, it is more accurate to refer to the metamorphic rock as "***Precambrian schist***." Similarly, the Zoroaster Granite, another informal name used for the igneous rocks, is just one among many of the igneous rocks of the Zoroaster Plutonic Complex. To simplify things, consider referring to the igneous intrusions as the "***Precambrian granite***," rather than incorrectly naming the rock. When talking with visitors, it is better to simplify and generalize geology, rather than using too much detail or providing incorrect information.

The metamorphic and igneous rocks of Grand Canyon, and similar rocks from the same time period in other places, are commonly referred to as **Precambrian crystalline basement**. They are "crystalline" because they are made up of metamorphosed rock and/or intrusive igneous rocks with large, visible mineral crystals. Precambrian rocks underlie most continents, hence the term "basement." They are seen at the surface only after a significant amount of uplift and erosion has removed the overlying layers. Precambrian crystalline rocks similar to those in Grand Canyon are also found at Black Canyon of the Gunnison and Rocky Mountain National Parks.

Grand Canyon Supergroup

It took at least 200 million years of uplift and erosion to remove 13 miles (21 km) of rock and expose the Precambrian crystalline basement in the Grand Canyon region. But their return to the surface was short lived. Between 1200 and 700 million years ago, shallow seas intermittently covered the area. The **Grand Canyon Supergroup** is made up of layers of sedimentary and volcanic rocks that were deposited in the shallow seas. They were deposited on top of the Precambrian crystalline basement rocks, creating a nonconformity (Fig. 1.41a). The depositional environments of the Grand Canyon Supergroup were predominantly shallow marine and fluvial (river) environments. These red, gray, and orange-colored layers are visible at the eastern end of the canyon, where they are as much as 12,000 feet (3600 m) thick (Fig. 2.4).

The Grand Canyon Supergroup is extraordinary because it is one of the most complete rock exposures from its time period in all of North America. It is subdivided into two smaller groups, comprised of several different formations. The **Unkar Group** is 1200 to 1100 million years old and includes the *Bass Formation*, *Hakatai Shale*, *Shinumo Quartzite*, *Dox Sandstone*, and *Cardenas Basalt*. The **Chuar Group** is 800 to 742 million years old, and includes the *Galeros* and *Kwagunt Formations*. The *Nankoweap Formation* is sandwiched between the Unkar and Chuar Groups, and the *Sixtymile Formation* lies on top of the Chuar Group.

The oldest fossils in Grand Canyon geologic record are found in the limestone of the Bass Formation, in the Unkar Group. These fossils are **stromatolites**, which are made up of alternating mats of algae and layers of fine sediment (Fig. 2.5). Stromatolites were very abundant during the Proterozoic Eon. The photosynthetic processes performed by the algae used the carbon dioxide in the atmosphere and changed it to oxygen. These algae caused an increase in the oxygen content of the atmosphere. Without the abundance of stromatolites, oxygen-breathing life as we know it may not have developed!

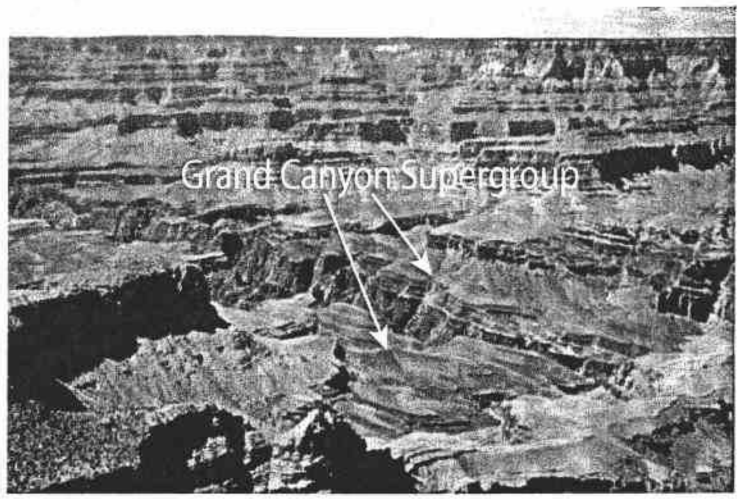


Figure 2.4 – Grand Canyon Supergroup. The colorful, tilted layers of the Grand Canyon Supergroup can be seen in the eastern reaches of Grand Canyon. Notice that the inner canyon to the east is not as steep compared to the inner canyon west of the Grand Canyon Village. The Supergroup layers are comparatively softer and more easily eroded than the underlying igneous and metamorphic rocks. Some of these same bright red/orange layers can be seen in the inner canyon near Bright Angel Canyon, just north of the Village area. Because this particular section of the Supergroup has been deformed intensely, the tilt of the layers is not very distinguishable.

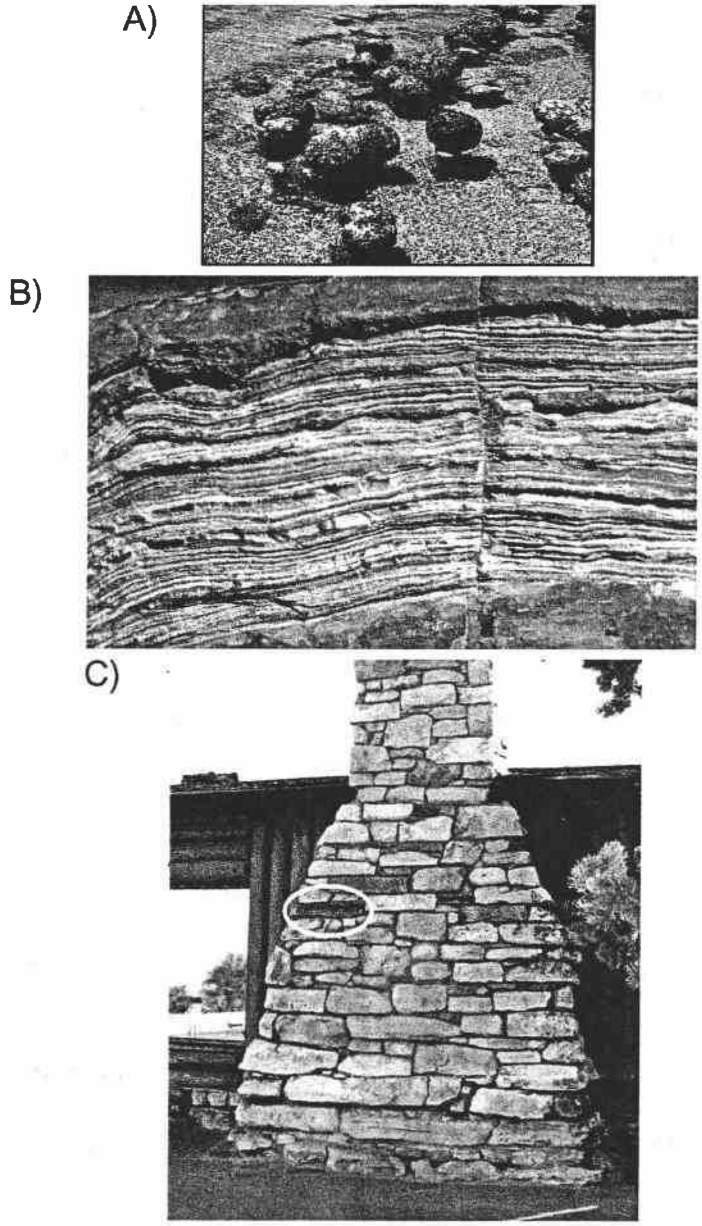


Figure 2.5 – Stromatolites. A) These are present-day examples of stromatolites. The organisms are made of algae and look similar to a stack of very thin crepes. B) This is a fossilized stromatolite. Stromatolites grew as a new algal mat formed and was covered by a layer of fine sediment. The process continued in this way, creating thin layers in the stromatolite. C) The outside of the chimney at the Bright Angel Lodge can be useful for fossil programs. The dark red block of rock circled is an example of a stromatolite. Look for a similar rock on the chimney on the inside of the building.

Ages of sedimentary rocks. The ages of the sedimentary rock layers given in this manual are *approximate*, not exact. Unlike igneous and metamorphic rocks, sedimentary rocks usually cannot be dated using radiometric methods. Because sedimentary rocks are often composed of minerals from other rocks, radiometric dating provides the ages of the rocks the minerals came from, not when the sedimentary rock formed. Sedimentary rocks are often dated using fossils preserved within them. The fossils in a sedimentary rock layer can be compared and correlated with other rock layers that have been dated and have known absolute ages. The age of a sedimentary rock correlates to a specific time unit on the geologic time scale (Fig. 2.1). Geologists refer to portions of the time units early, middle, and late, providing more detail to the approximate time when the rock formed. "Early" indicates the beginning of the time period, while "late" indicates the end of the time period.

As the Grand Canyon Supergroup was deposited, the region experienced two periods of intense deformation that created many faults. Huge blocks of Grand Canyon Supergroup and the crystalline basement were tilted about 10° eastward by these faults forming small mountains (Fig. 2.6). After about 250 million years of exposure to weathering and erosion, the small mountains were eroded down to rugged hills and valleys. Some parts of the Supergroup and crystalline basement rocks were beveled down to sea level. This long period of erosion leads us to the next chapter in the ancient history book of Grand Canyon.

Scars in the rocks. Deformation that took place during Precambrian Time had a dramatic effect on the rocks of Grand Canyon. Most of the faults in the Grand Canyon region formed initially during this time. Faults are commonly zones of weakness. These Precambrian faults have since been reactivated several times during subsequent tectonic events, and some are still active today.

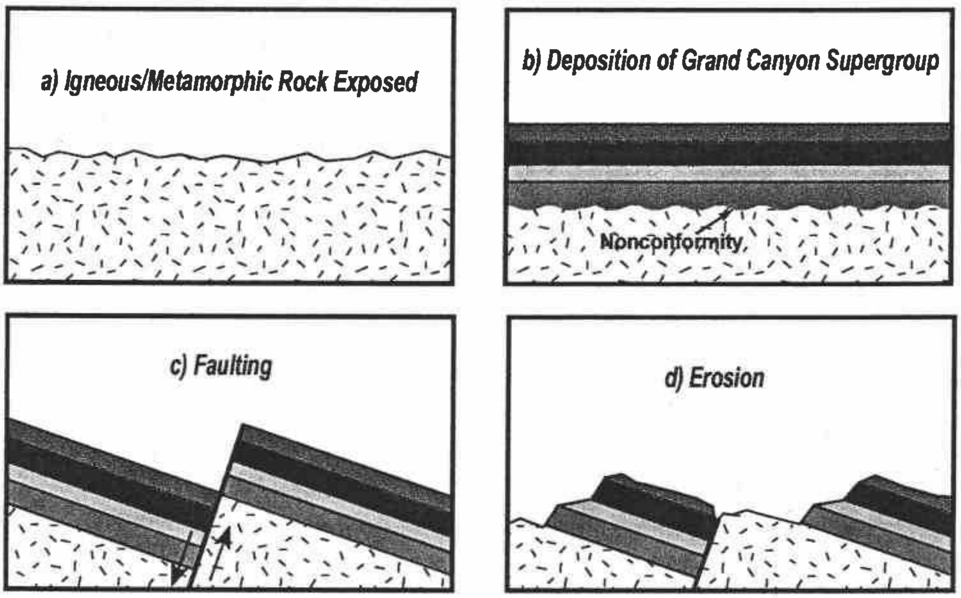


Figure 2.6 – Grand Canyon Supergroup faulting. This may have been what the area looked like after the faulting of the Grand Canyon Supergroup and crystalline basement in the Precambrian Time, from approximately 1200 to 700 million years ago. The huge blocks of rock between the faults were tilted down to the east about 10°, leaving small mountains that were eventually eroded down

THE PALEOZOIC ERA (544 TO 248 MILLION YEARS AGO)

Life became extremely abundant and diverse during the Paleozoic Era, the era of "early life." Fossils preserved in Paleozoic rocks reveal a dramatic change from Precambrian Time, when there were no complex life forms, to an era when thousands of new species evolved. Some organisms that developed are very different from anything we know today.

When the Paleozoic Era began, the North American continent was near the equator and its climate was warm and tropical (Fig. 2.7). During the early periods of the Paleozoic, the only living organisms were those that lived in the sea.

The "firsts" of the Paleozoic Era. The Paleozoic Era was a time when many organisms first appeared on the Earth, as seen by the fossils preserved in the sedimentary rock record. Take a look at the geologic time scale (Fig. 2.1) and note the period when some important "firsts" occurred.

- First shelled marine organisms – Cambrian Period
- First fish – Ordovician Period
- First land plants – Silurian Period
- First amphibians and insects – Devonian Period
- First reptiles – Pennsylvanian Period

The first dinosaurs, birds and flowering plants didn't appear until the next era, the Mesozoic Era. Dinosaurs appeared during the Triassic Period, the first birds developed during the Jurassic Period, and the first flowering plants during the Cretaceous Period.

The pages that were written during the Paleozoic Era in the Grand Canyon region indicate that shallow seas covered the land numerous times while many different sedimentary layers were deposited (Fig. 2.8). Some of the pages of this ancient history book are missing due to erosion or periods without deposition. These periods of erosion or no deposition left unconformities between the sedimentary layers as clues for us to interpret.

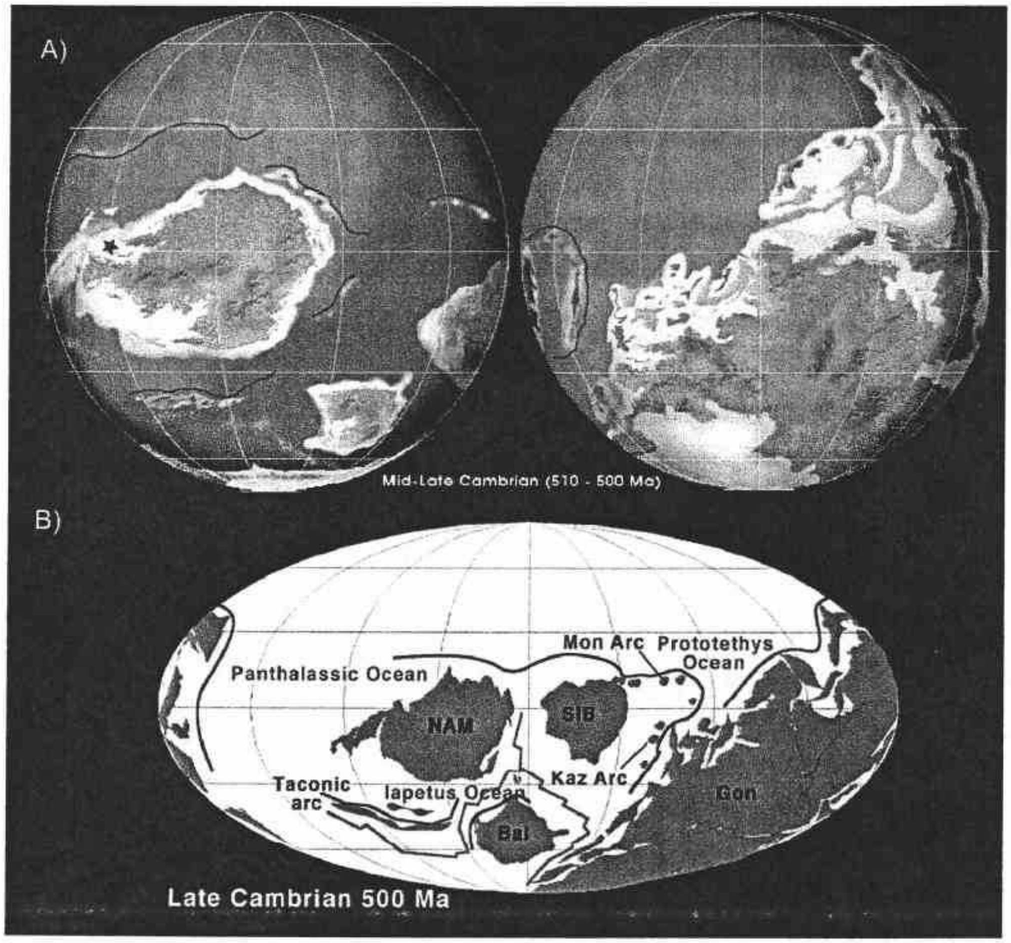


Figure 2.7 – The Earth during the early Paleozoic Era. A) Physiographic depiction shows the topography of the land, and extent of the shallow continental shelves. B) The outlines of the plates and the plate interactions are shown. "NAM" represents North America. In both, the red stars mark the approximate location of the Grand Canyon region about 500 million years ago. The North American continent as we know it did not exist yet, and during this time the land was largely bare and lifeless. It was not until about 440 million years ago, during the Silurian Period, that life developed on land. *(Diagram from Ronald Blakey, Northern Arizona University)*

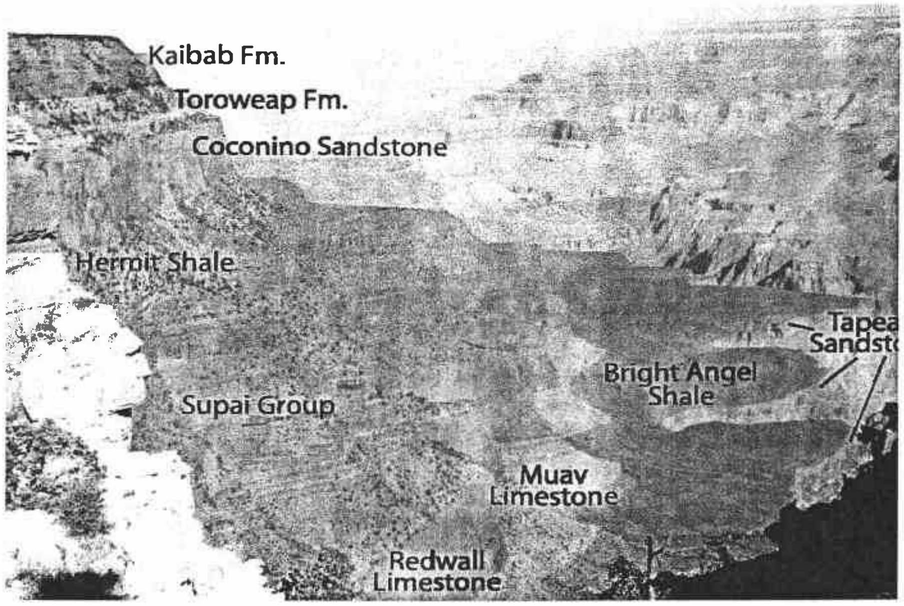


Figure 2.8 – The Paleozoic layers. The different sedimentary layers that were deposited are highlighted. In order of deposition, from the bottom up, the layers you can easily see from the rim are the Tapeats Sandstone, Bright Angel Shale, Muav Limestone, Redwall Limestone, Supai Group, Hermit Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Formation. The table below describes each of these Paleozoic sedimentary layers, including the approximate thickness in the Village area, whether it is mainly a cliff or slope former, the depositional environment, and identifying characteristics. *Note: The Temple Butte and Surprise Canyon Formations are not included in these diagrams because they are difficult to view from the rim.*

Rock layer	Thickness	Shape	Depositional Environment	How to identify from the canyon rim
Kaibab Formation	300 to 400 feet (92 to 122 m)	cliff	Shallow marine, beach-like, and intertidal zone	At top of canyon, not much vegetation
Toroweap Formation	200 to 300 feet (61 to 92 m)	slope	Shallow marine, intertidal zone, and eolian desert	Small, vegetated slope between cliffs of Coconino and Kaibab
Coconino Sandstone	400 feet (122 m)	cliff	Eolian sand dunes	Bath tub ring of canyon, distinct beige color with cross-bedding
Hermit Formation	300 feet (92 m)	slope	Shallow marine, lagoon, fluvial, and eolian	Dark red-orange slope
Supai Group	1000 feet (305 m)	slope; small cliffs	Shallow marine, lagoon, fluvial, and eolian	Thin, red-orange step-like layers
Redwall Limestone	500 feet (153 m)	cliff	Shallow marine	Thick red to beige colored layer; many caves
Muav Limestone	up to 450 feet (137 m)	cliff	Shallow marine, occasional intertidal zone	A thick limestone, at base of Redwall Limestone
Bright Angel Shale	up to 340 feet (104 m)	slope	Intertidal zone and shallow marine	Very gentle slope, often has greenish tint
Tapeats Sandstone	0 to 200 feet (0 to 61 m)	cliff	Fluvial, beach-like and shallow marine	Looks like a stack of pancakes or graham cracker with bites in it

The Tonto Group

The first sedimentary layers of the Paleozoic Era are the **Tonto Group**, made up of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone. They formed during the middle Cambrian Period, from about 525 to 515 million years ago (Fig. 2.9). The Tonto Group was deposited directly overlying the Precambrian rocks forming the **Great Unconformity** (Fig. 1.41b). The **Tapeats Sandstone** was deposited in a transitional environment, where sea level was rising and slowly encroaching on the rugged Precambrian hills and valleys. Rivers flowing to the sea deposited some parts of the Tapeats Sandstone, while other portions were formed in a very shallow marine, beach-like environment. The **Bright Angel Shale** was deposited as sea level continued to rise and the shoreline moved eastward. It formed in deeper transitional environments, which include an intertidal zone and shallow marine environment deep enough to be unaffected by waves. As the sea encroached further over the continent the **Muav Limestone** was deposited. It formed in a deeper marine depositional environment, with intermittent periods of shallow marine or intertidal zone deposition (Fig. 2.10).

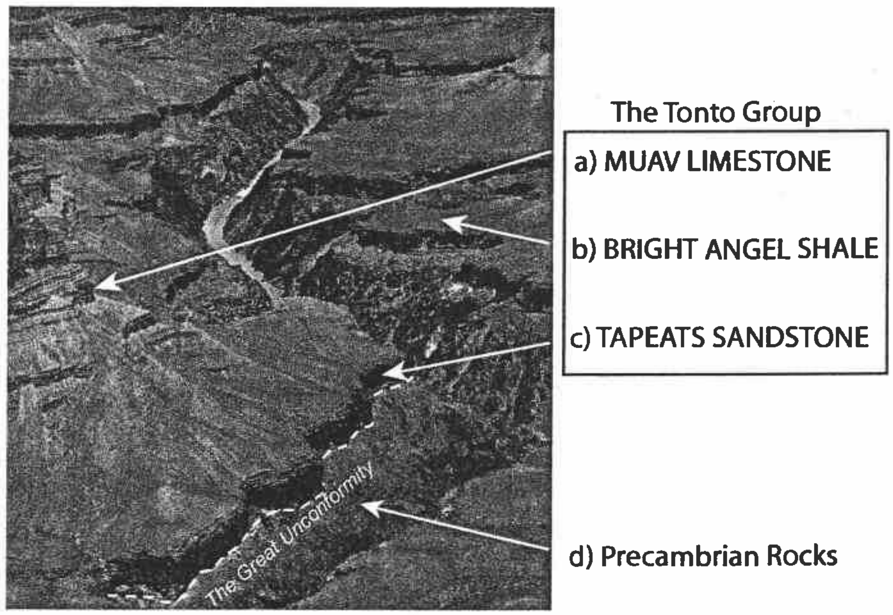


Figure 2.9 – The Tonto Group. a) The Muav Limestone is a large cliff that is below a younger layer of limestone called the Redwall Limestone. Viewed from the canyon rim, those two layers can be difficult to tell apart. b) The Bright Angel Shale forms a broad, gently sloped, colorful shale layer. c) The Tapeats Sandstone is the cliff layer that looks similar to a stack of pancakes or a graham cracker with a bite taken from it. d) The Great Unconformity is the surface where the Tonto Group overlies the Precambrian rocks of much greater age. This is a visually stunning unconformity, with the very old, dark crystalline rocks overlain by the contrasting Tapeats Sandstone.

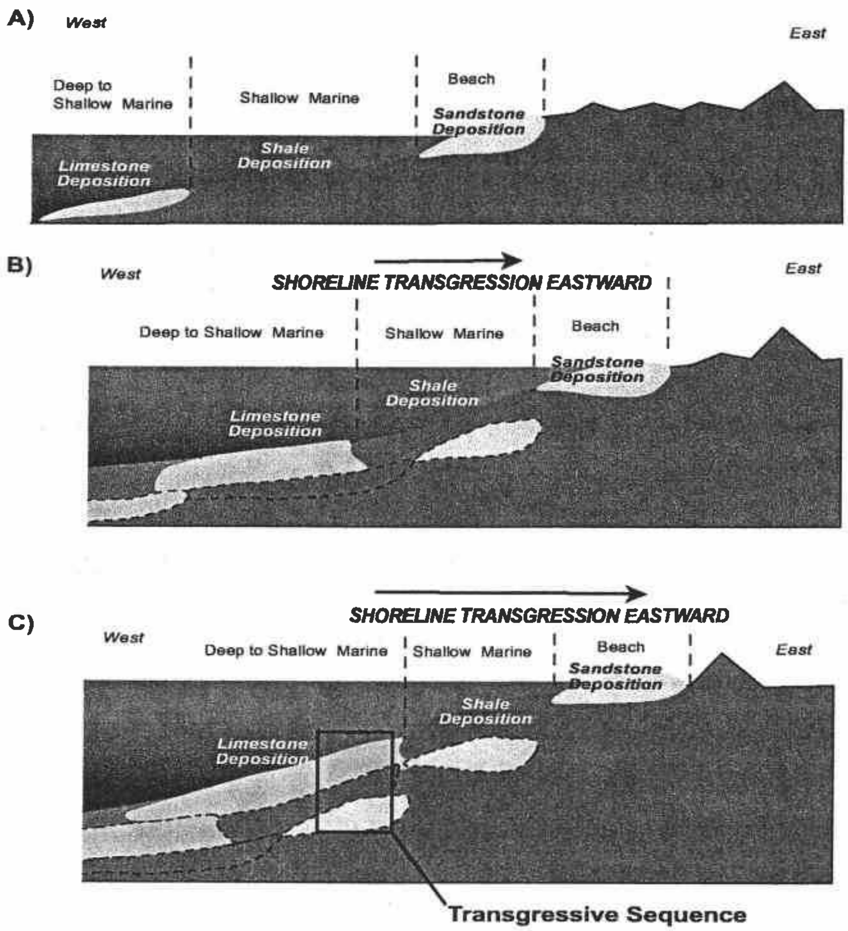
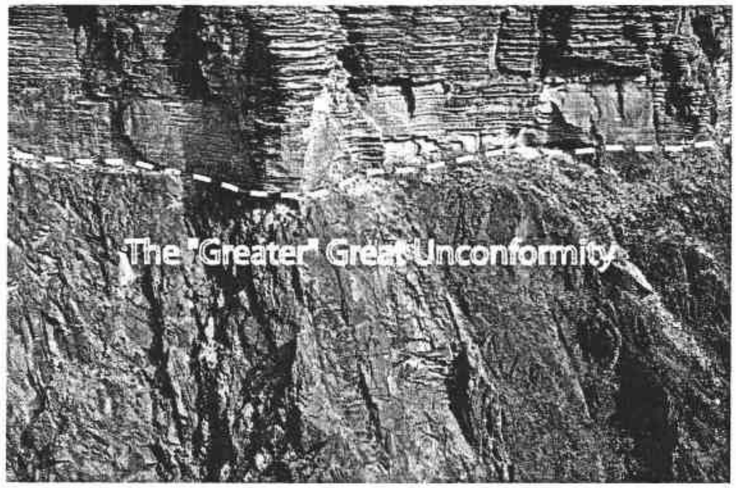


Figure 2.10 – Transgression in the Grand Canyon region. As sea level rises or the land elevation decreases, the shoreline moves inland depositing various sediments along the way, as shown here in the progression from A to C. The deposition of sandstone, shale, then limestone is called a **transgressive sequence**. The Tonto Group is one example, as the layers change from the Tapeats Sandstone, to Bright Angel Shale, to Muav Limestone. The Tonto transgression occurred from about 525 to 515 million years ago, as the shoreline moved progressively eastward over the Grand Canyon region. In these diagrams, the yellow represents sandstone, green represents shale, and grey represents limestone. The dashed lines indicate old deposits that are buried by younger ones.

The Great Unconformity of Grand Canyon. John Wesley Powell, a self-taught geologist that led the first expedition to explore the entire Grand Canyon by boat, was one of the very first to observe unconformity between the old Precambrian crystalline rocks and the younger Paleozoic sedimentary rocks. He named it the Great Unconformity for the incredible and striking contrast he saw in the rocks. In some parts of the canyon different layers are in contact, but the same erosional surface makes the Great Unconformity throughout the canyon. Where the Tonto Group overlies the Precambrian crystalline basement rocks, the Great Unconformity is a *nonconformity*. At least 850 million years are missing along this surface. It is especially distinct from the western end of the canyon, along Hermits Road, but it can be seen from many places (Fig. 2.11a). Where the Tonto Group rocks directly overly the Grand Canyon Supergroup it forms an *angular unconformity*. This 250 million year gap can be seen best from the eastern end of the canyon, at Lipan Point and Desert View (Fig. 2.11b). The Great Unconformity is not the *greatest* unconformity in the world in terms of the length of time it represents, but it is one of the most impressive to see. Unconformities that represent more missing time exist; such as at Death Valley and Colorado National Monument, where Precambrian rocks are overlain by rocks of the Triassic Period (208 to 245 million years ago). That is a gap in time of nearly 1200 million years!

The Cambrian Sea deposited the Tonto Group over the rugged Precambrian hills. Initially, as sea level rose, there were taller hills that remained above the sea level as islands, while valleys were submerged. Because of this, some of the tall Precambrian hills were not covered by all of the Tonto Group. Most of the valleys have the entire group from Tapeats Sandstone, to Bright Angel Shale to Muav Limestone. But some tall islands were not completely covered with sediment until the Muav Limestone was deposited, when the sea level had risen high enough to cover them (Fig. 2.12).

A)



B)

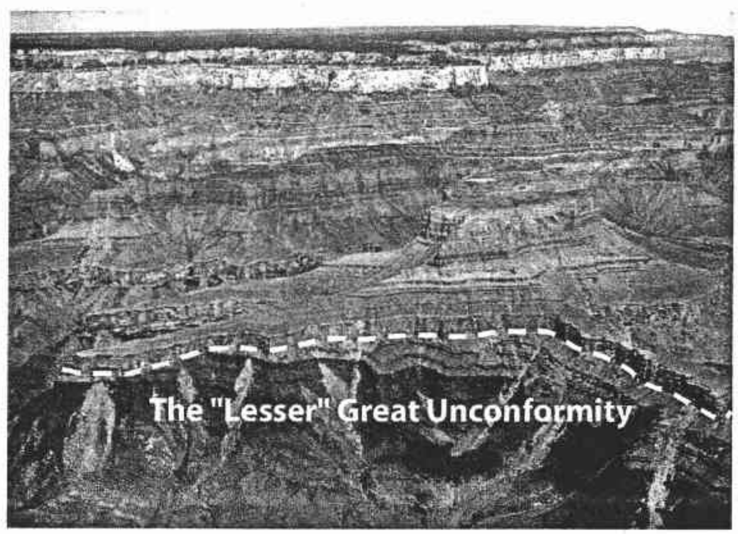


Figure 2.11 – The Great Unconformity. A) This photo shows the distinct contrast between the dark, old rocks of the inner canyon and the overlying, layered Tapeats Sandstone. At least 850 million years are missing between these layers. This **nonconformity** has a large length of time missing and is therefore the "greater" part of the Great Unconformity. (*Photo property of NPS*) B) The **angular unconformity** seen in this photo from Desert View Point is also part of the Great Unconformity. The 250 million year gap at this part of the unconformity is less than the "greater" part, thus the term "lesser" Great Unconformity.

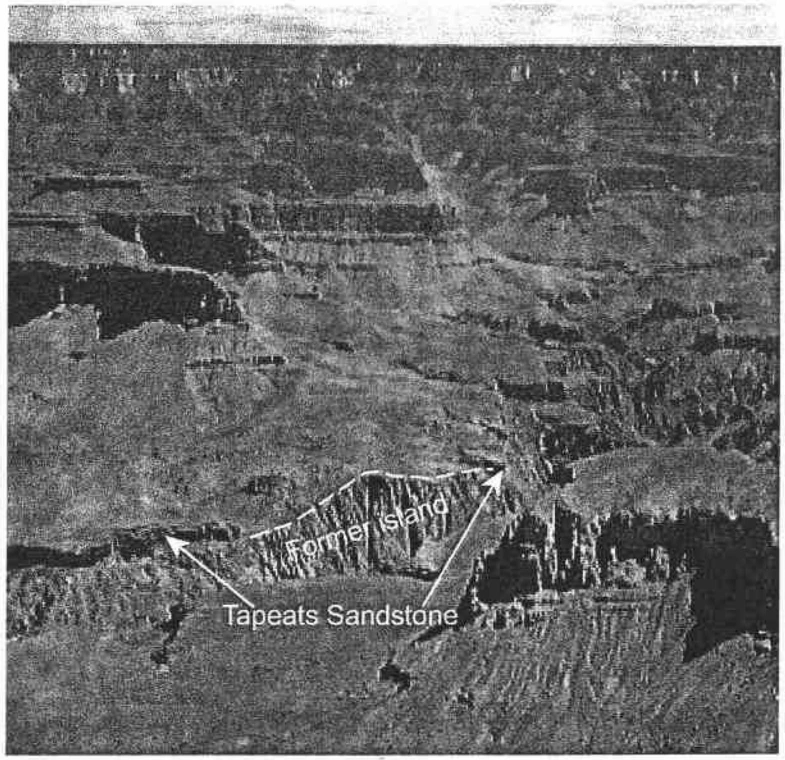


Figure 2.12 – Islands during the Cambrian Period. As the Tonto Group was deposited on the rugged, hilly Precambrian landscape, some of the taller areas were islands above the sea. In this photo, the dashed white line outlines one of these ancient islands. If you look closely you can see that it has almost no Tapeats Sandstone or Bright Angel Shale overlying it. This view of the inner canyon is seen from Yaki Point, looking northeastward down into the canyon.

The Temple Butte Formation

Following deposition of the Muav Limestone and about 100 million years of erosion, river channels and valleys were cut into the Muav Limestone. A new sedimentary layer called the **Temple Butte Formation** was deposited as the sea transgressed over the Grand Canyon region again. It formed during the middle of the Devonian Period, approximately 390 to 405 million years ago. It is composed of a variety of shallow marine and fluvial deposits, including limestone and dolomite with some sandstone and siltstone. In the western reaches of Grand Canyon the Temple Butte Formation is a thick gray cliff, while in the eastern canyon it is thinner. A former river channel that has been filled with the Temple Butte Formation is exposed along the South Kaibab Trail (Fig. 2.13).

A disconformity exists between the Muav Limestone and Temple Butte Formation, where at least 100 million years of erosion took place. Another disconformity formed after the Temple Butte Formation was deposited, where 40 million years of the geologic record is missing. It's hard to tell if rocks other than the Temple Butte Formation were deposited during that time. If there were other layers that formed, they were eroded away and no evidence has been found. These disconformities are just a few of many that exist in the Paleozoic record. Together they represent at least 140 million years (nearly half!) of the 300 million years of the Paleozoic Era.

The Redwall Limestone

During the Mississippian Period, the seas transgressed over the Grand Canyon region forming a shallow inland sea. The Redwall Limestone was deposited in this sea between 360 and 320 million years ago. The thick red cliff is named "Redwall" because its surface is stained red, not because the rock is actually red (Fig. 2.14). The soft rock layers that lie above it, the Supai Group and the Hermit Formation, have a distinct red color. As these overlying layers erode, the red sediment runs down-slope and stains the face of the limestone cliff. If you

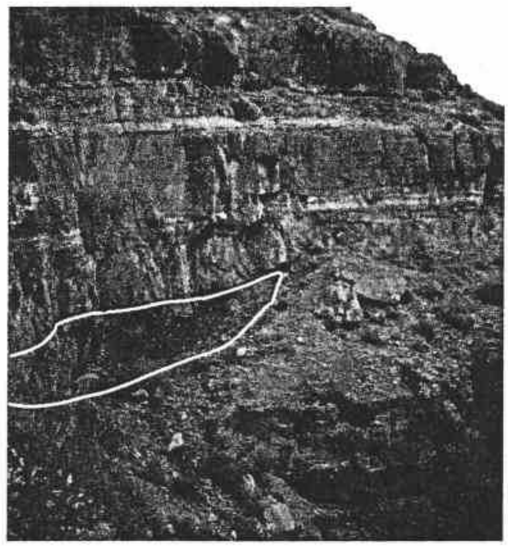


Figure 2.13 – Temple Butte Formation. This example of the Temple Butte Formation is found along the South Kaibab Trail at the base of the Redwall Limestone, just above the portion of the trail called the "Red and Whites" (Fig. 2.15). You can see these same rocks with binoculars from the rim at Yaki Point. In the eastern Grand Canyon region, the Temple Butte Formation was deposited in river channels that existed on the Muav Limestone. This outlined area was a river channel that was filled in by Temple Butte sediment.

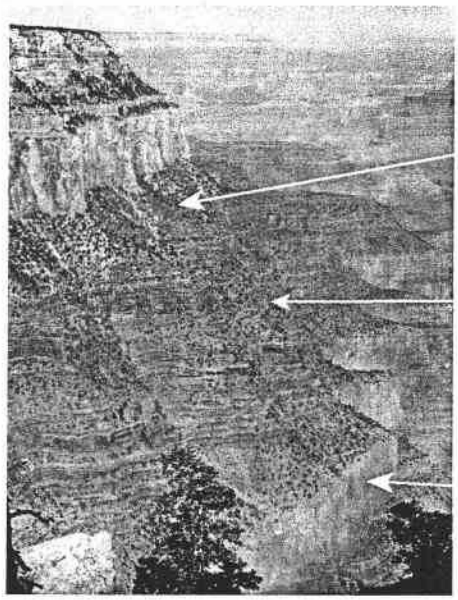


Figure 2.14 – The red rock layers. The red color in these layers is due to iron oxide (rust) that is in the minerals that make up the rocks. The Redwall Limestone forms a steep cliff, but is not truly red, only stained red by the sediment washed down from the layers above it. The Supai Group is a red slope with small cliffs within it and the Hermit Formation is a red, slope-forming layer.

were to break away from the exposed, red surface, you would find that the true color of the Redwall Limestone is bluish-gray to beige (Fig. 2.15).

The Redwall Limestone is a layer with thousands of caves. Some of the caves formed shortly after the rock itself formed. Limestone is dissolved by water, so caves can form as ground water percolates though cracks or pores the rock. At one time, the Redwall Limestone may have been a major ground water system, channeling water underground through the caves.

Related rocks. If you've been to Mammoth Cave National Park in Kentucky or Wind Cave National Park in South Dakota, you've seen limestone layers that are closely related to the Redwall Limestone. During the Mississippian Period, much of North America was covered by a broad inland sea that deposited vast, thick layers of limestone. Mammoth Cave, Wind Cave, and the caves in the Redwall have formed in limestone deposited during this period. The caves themselves began forming shortly after this extensive layer of "related" limestone was deposited.

The Surprise Canyon Formation

The Surprise Canyon Formation was deposited on top of the Redwall Limestone 320 to 305 million years ago. It formed in fluvial and intertidal zone depositional environments, along the edge of a shallow sea that existed west of the Grand Canyon region. The Surprise Canyon Formation filled in channels and caves that had formed in the Redwall Limestone. Red-brown conglomerate, limestone, and siltstone are the main rock types found in this formation. This layer forms small slopes in a few places in eastern Grand Canyon, such as along the New Hance Trail. The Surprise Canyon Formation has the most abundant and diverse fossils of all the Paleozoic layers.

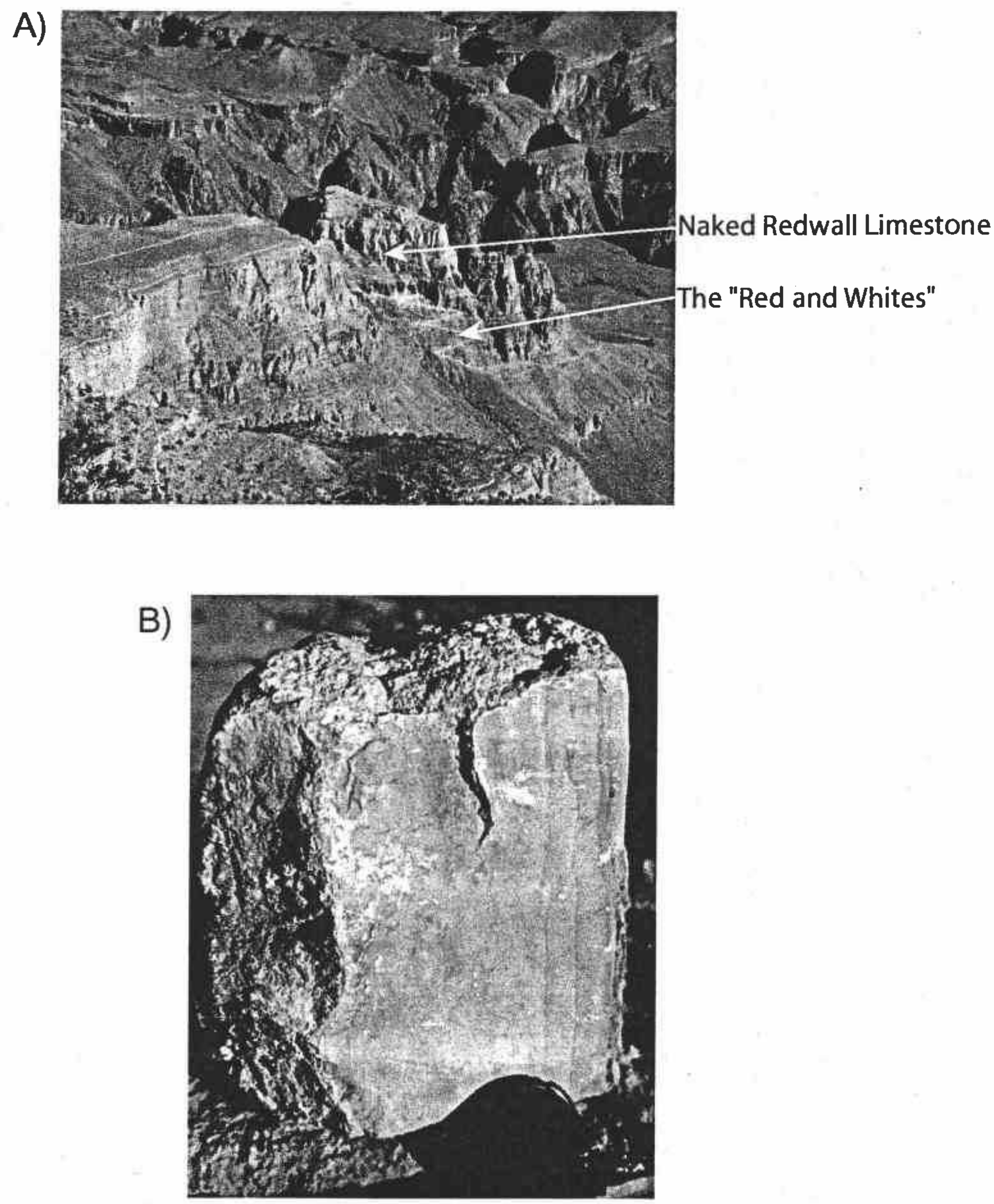


Figure 2.15 – Naked Redwall Limestone! A) From Yaki Point you can see the tight switchbacks of the South Kaibab Trail called the "Red and Whites." Just north of the trial you can see a part of the Redwall Limestone that is not red. The red rock layers that used to overlie the Redwall Limestone were removed by erosion at this location. Without the red sediment to wash down and stain the limestone, it is left exposed in its natural, "naked" color. B) This photo shows the true color of the Redwall Limestone. This rock has broken off the main layer, and you can see it is a bluish-gray color, not red.

The Supai Group and Hermit Formation

The layers of slopes and thin cliffs above the Redwall Limestone are mostly red siltstone and sandstone known as the **Supai Group**, which are overlain by red layers of shale and sandstone called the **Hermit Formation** (Fig. 2.14). These layers were deposited during the early Pennsylvanian Period through the early Permian Period, approximately 300 to 275 million years ago. Sea level fluctuated greatly during this time, as indicated by the diverse depositional environments, which include shallow marine, lagoon, and fluvial environments. They also include the first layers deposited in an eolian (wind) environment in the Grand Canyon region. These layers mark the onset of the coastal sand dune environment that was dominant in the region through the late Jurassic Period.

Red layers in the canyon. Part of Grand Canyon's picturesque value lies in the colorful red layers that make up parts of the canyon walls. The minerals that make up the red rock came from rocks that were rich in iron. One possible source is granite, which is composed of iron-rich minerals. As the source rock was eroded, the iron was oxidized, changing from Fe^{2+} to Fe^{3+} to make rust (iron oxide). The red iron oxide was then deposited along with other sediment to make the red rock layer and now provides colorful scenery throughout Grand Canyon.

The Coconino Sandstone and Toroweap Formation

Above the red layers of the Supai Group, the contrasting beige layer is the **Coconino Sandstone**. The Coconino Sandstone is the lower member of the Toroweap Formation, which includes the reddish sloping layer above the sandstone. Because the Coconino Sandstone is such a large, easily recognized layer, it is often referred to by itself.

The beige cliff formed by the Coconino Sandstone is sometimes called the "bathtub ring" of Grand Canyon because it is an obvious "ring around the rim" of the canyon (Fig. 2.16). Upon close inspection, the sand of the Coconino Sandstone is sparkly, quartz-rich sandstone. At the beginning of the Permian

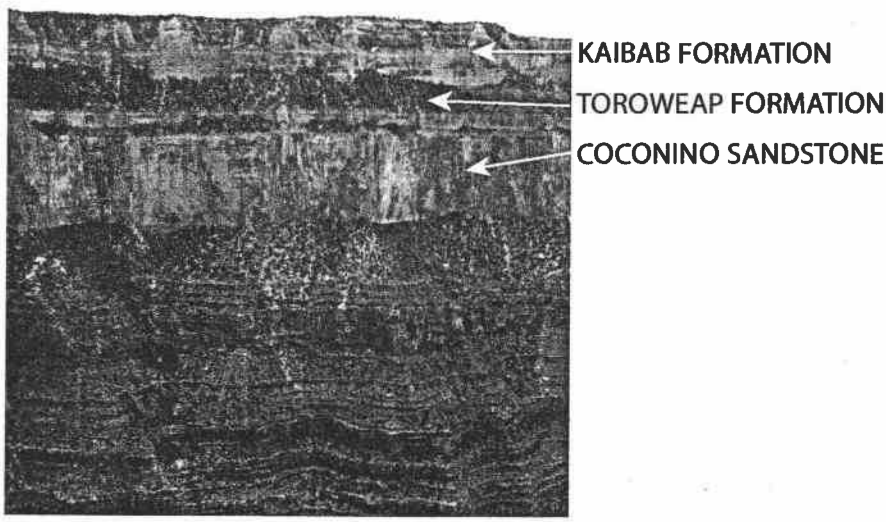


Figure 2.16 – The Permian layers. The three uppermost layers of Grand Canyon were all deposited during the Permian Period. The Coconino Sandstone forms a massive cliff that is light in color compared to the red layers below it. The Toroweap Formation is a small slope that appears to have more vegetation on it than the layers above and below it. The Kaibab Formation is the cliff at the top of the canyon.

Period, about 275 to 270 million years ago when the Coconino formed, the Grand Canyon region was covered with coastal sand dunes. As sand dunes blew across the land, **cross-bedding** features developed. Cross-bedding occurs when layers of sand are deposited on the slope of a dune. Because deposition occurs at an angle, the preserved cross-bedding has a tilted appearance (Fig. 2.17). The cross-bedding can be clearly distinguished when it is compared to the upper and lower boundaries of the sandstone layer.

The sloping layer above the Coconino Sandstone is called the **Toroweap Formation**. This layer was deposited in fluctuating depositional environments that existed during the middle of the Permian Period, roughly 270 to 265 million years ago. The Toroweap Formation formed in shallow marine, intertidal zone, and eolian coastal dune environments. It includes several different rock types, but is predominantly sandstone and limestone. Because this layer is not as hard as the Kaibab Formation or the Coconino Sandstone, it forms a slope between the two cliffs (Fig. 2.16).

Natural blending. The sedimentary layers at Grand Canyon are often inter-layered and mixed, with no distinct lines marking the change from one layer to the next. Keep in mind that in nature, changes in a depositional environment usually occur slowly and the environment may not always be constant. So except where there are unconformities, layers usually fade one into the next.

The Kaibab Formation

The Paleozoic layer most available for you and visitors to observe is the **Kaibab Formation.** The Kaibab Formation forms the cap rock of Grand Canyon because it is a hard, resistant rock layer (Fig. 2.16). It was deposited near the end of the Paleozoic Era, in the middle of the Permian Period, about 265 to 250 million years ago. Although it is the youngest layer of the canyon, it is too old to have any remains of dinosaurs. The dinosaurs actually roamed the Earth after the Kaibab Formation was formed.

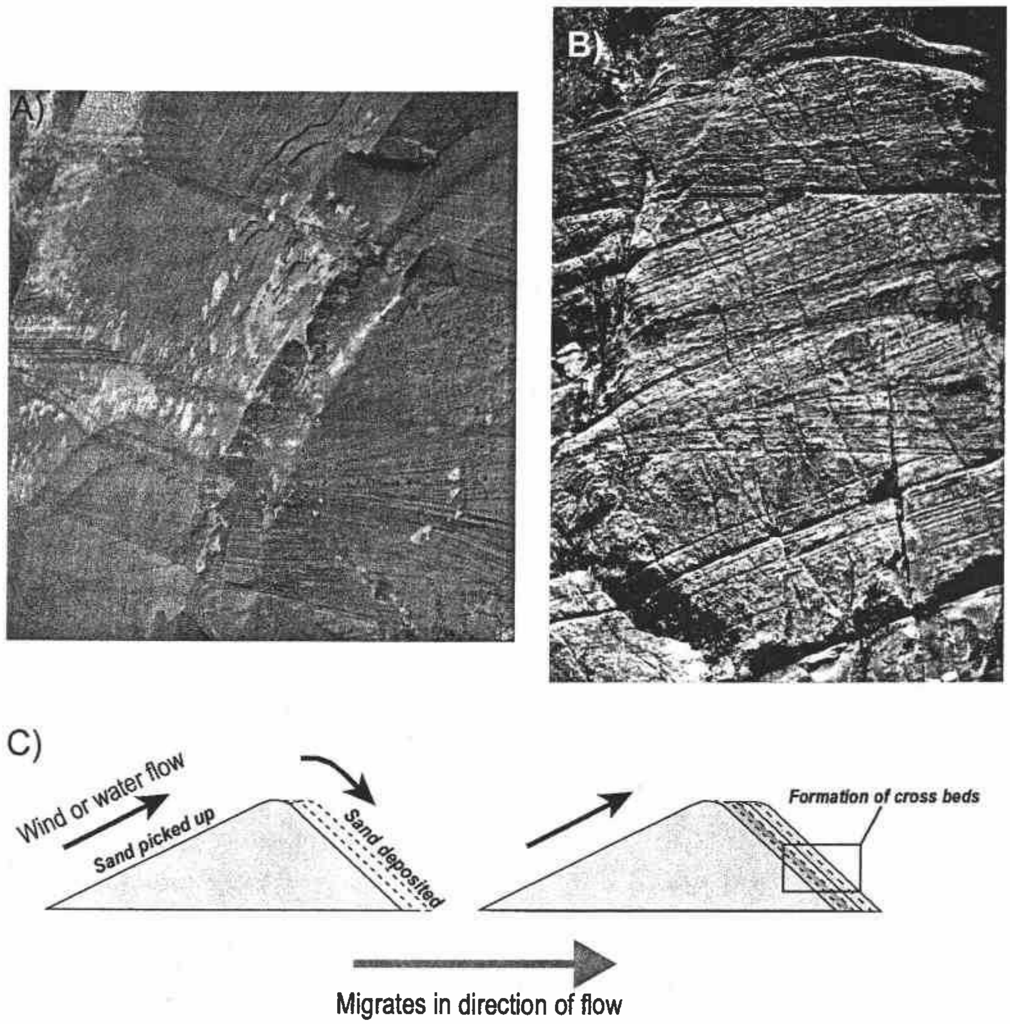


Figure 2.17 – Sand dunes preserved. Cross-bedding in the Coconino Sandstone seen along the South Kaibab Trail (A) and along the Bright Angel Trail (B). It may appear that these layers have been tilted, but the sand was actually deposited at this angle, while the overall sandstone layer is horizontal. This is **cross-bedding**, where thin layers are deposited at an angle to the upper and lower surface of the overall layer. The cross-bedding in the Coconino Sandstone indicates that coastal sand dunes were blowing across the land as it formed. C) Cross beds form as wind moves sand up and over a sand dune. The sand is deposited on the down-wind side of the dune, where the wind is not as strong, at an angle on the slope. As more sand is piled on top, the pressure builds. The pressure, along with water and minerals, cement the sand grains together and preserve the cross-bedding features.

What is that white crust? In many locations along the canyon rim, the surface of the Kaibab Formation is coated with a thick, crusty, white substance (Fig. 2.18). It is not bird droppings, as some might speculate! This white coating is called **caliche** or **calcrete**, which is made up of calcium carbonate, the main constituent of limestone. It is common in arid and semi-arid climates where precipitation is often followed by periods of sun and heat. As water seeps into limestone after it rains, the water dissolves some of the calcium carbonate in the rock. When the rock is exposed to warm temperatures caused by sunlight and heat, the heat forces the water to come out of the rock. As the water leaves the rock, it carries dissolved calcium carbonate with it. After the water evaporates, the calcium carbonate is left behind, leaving a crust on the rock's surface and in cracks. As this process goes on year after year, the crust on the rock gets thicker and thicker. It is similar to the crust of salt that develops on your skin or clothing when you sweat in a dry, arid climate.

The Kaibab Formation has an abundance of **chert**, which forms in irregular blobs and nodules in the limestone (Fig. 2.19). Chert is composed of very tiny quartz crystals, made of pure silica (SiO_2). Dark gray chert, called **flint**, gets its color from impurities and other minerals. Red chert is another variety called **jasper**. In the Kaibab Formation, the chert nodules are commonly light in color, which indicate it is relatively pure silica with few other minerals. Chert is more resistant to weathering and often sticks out where the limestone has weathered away around it.

The Kaibab Formation is subdivided into two members, the Fossil Mountain Member (older) and the Harrisburg Member (younger). In western Grand Canyon, far beyond the area usually seen by visitors, the Fossil Mountain Member is pure limestone. At places to the east like Pima Point, the limestone is mixed with some sand. Even farther east, toward Desert View, the limestone has a great deal of sand. This composition change tells us that as the Fossil Mountain Member was deposited, the sea was relatively deep and calm to the west. But in the east the sea was shallower, and the nearby beach and fluvial environments contributed the sand. Many fossils are found in this member of the Kaibab Formation, including

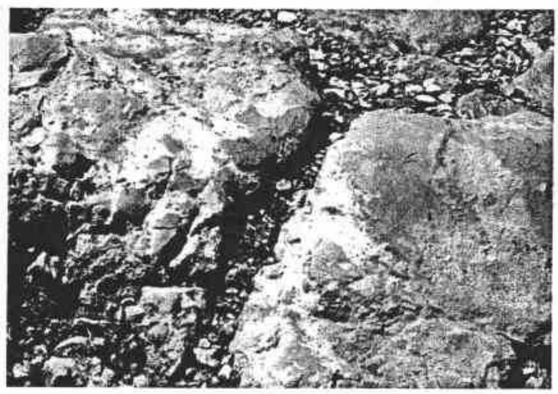


Figure 2.18 – Crust on Kaibab Formation. This white crust on the surface and in cracks of the Kaibab Formation is composed of calcium carbonate, which is the same mineral that makes up limestone. In this form it is called **caliche** or **calcrete**, and is very common in arid climates.

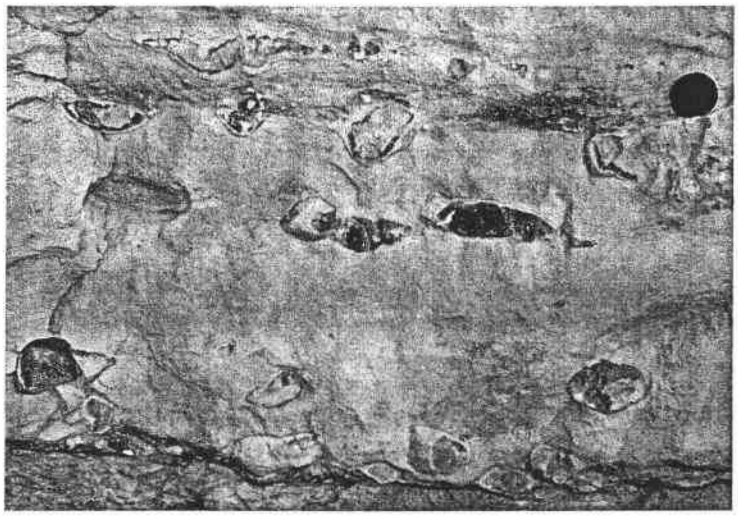


Figure 2.19 – Chert. These oddly shaped blobs in the Kaibab Formation are commonly mistaken for fossils or bones. They are made of **chert**, which is composed of very fine-grained quartz (silica). It may form where there is a void or empty space that silica-rich water percolates through, and the silica slowly accumulates. Voids may form because of plant roots, burrowing organisms (such as worms), or where part of the rock was dissolved. Chert can also form where an organism that is made up of silica, such as a sponge, is deposited, creating a concentration of silica. (Lens cap for scale).

the fossils along the Rim Trail near the Bright Angel Fault (Fig. 2.20). Another good location for finding fossils is near the top of the Hermit Trail.

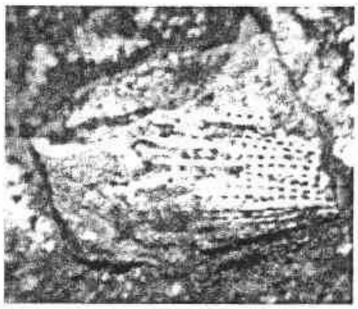
The change from the Fossil Mountain Member to the Harrisburg Member is gradual, sometimes making it hard to see. The base of the Harrisburg Member has a layer of white, butterscotch, or red colored chert that marks the change from one member to the next. The Harrisburg Member was deposited as the sea gradually retreated to the west, leaving restricted areas of shallow water. Oxidized iron-rich, rust colored sediment was deposited in this shallow water. The reddish color of the soil in the village area, and along Village Loop Road near the turnoff for Desert View Drive, is a remnant of the Harrisburg Member (Fig. 2.21). **Evaporites** are also found in the Harrisburg Member. They are minerals that were once dissolved in water, but as the water evaporated they were leached out. Gypsum is the most common evaporite mineral in the Harrisburg Member.

The Close of the Paleozoic Era

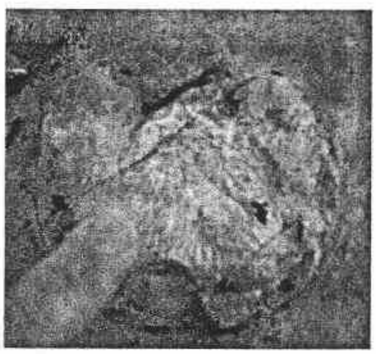
Although life grew and flourished with diversity, it all came to a screeching halt as a mass extinction event occurred at the end of the Paleozoic Era. Fewer than 5 percent of sea life and 33 percent of land animals survived, as a total of about 90 percent of all of the planet's species died off. This event was bigger than the extinction of the dinosaurs that occurred at the end of the following era. The exact reason for the Paleozoic extinction is still unknown, but it was likely a combination of catastrophic events. The possibilities include massive volcanic eruptions, cooling of the seas, and dramatic climate changes due to development of large ice caps.

At the closing of the Paleozoic Era, all of the continents had smashed together to form the super-continent known as Pangea (Fig. 2.22). Prior to the Permian Period (286 to 248 million years ago), the western edge of North America had been a passive continental plate margin, much like the eastern coast of North America today. After millions of years of the sea repeatedly coming and going over southwestern North America, depositing layer upon layer of sedimentary rock, the

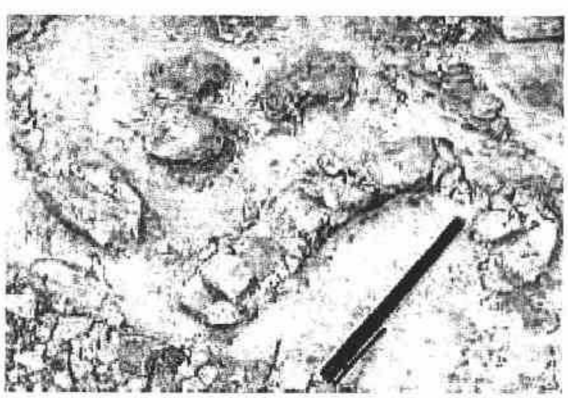
Stick Bryozoan. These were once small, tree-like, marine plant organisms. These fossils, as well as most of the fossils at the fossil site, fed by a process called filter feeding. Water with microscopic organisms would pass through the pores of the organism, providing the nutrients to sustain the plant.



Windowed Bryozoan. This bryozoan is closely related to the stick bryozoan. They both filter fed through the pores that are visible on the fossil. The Windowed Bryozoan was a marine plant organisms that was like a thin sheet or sea fan that waved through the water capturing the tiny food particles it needed. *(Photo property of NPS)*

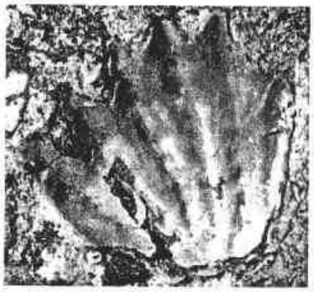


Sponge. The sponges of the Kaibab Formation were much like the natural sponges we know today, with holes and a soft texture. Sponges are preserved because they are composed of silica. As the sponge dies and is deposited, tiny particles of silica from the sea water bond to it, essentially preserving the organism. These fossils are often protruding from the limestone because the silica is more resistant to weathering than the calcium carbonate that makes up the rock.



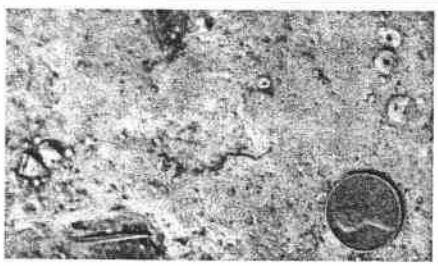
Chert nodules. These irregularly shaped blobs made up of chert are common at the fossil site. Visitors often guess they are bones. They usually form after deposition of the rock layer, where a void was created and left open for silica to fill in. The voids may have been formed by burrowing creatures (worms), or plant roots.

Figure 2.20 – Fossils of Grand Canyon. B) (continued)

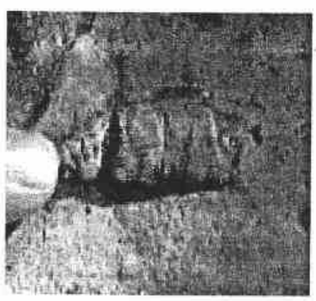


Meekella Brachiopod. This type of brachiopod resembles a wavy potato chip, with its large ridges. Brachiopods are far more common at the fossil site than other clam-like fossils. They can be distinguished because the top shell is often convex, while the accompanying bottom shell is concave, fitting into the other shell. When you see shells that have been preserved vertically in the rock you can see this. *(Left photo property of NPS)*

Productid Brachiopod. This type of brachiopod is usually large, sometimes as large as an adult fist. They are quickly identified by the ridge down the middle of the convex, upper shell. *(Right photo property of NPS)*



Crinoid. These are fossils that are remains of the stem of a sea lily-like organism that lived at the bottom of the Kaibab Sea. The fossils look like small, Cheerios or beads. They would have been stacked to form the stem of the plant, but when the plant began to decay the individual pieces of the stem broke up.



Horn Coral. (Rugose) There are only a few of these horn shaped fossils to find at the fossil site. They existed at the base of the Kaibab Sea, attached at the pointed end of the organism.

Figure 2.20 (continued) – Fossils of the Kaibab Formation. B) Characteristics that will help you identify some of the common fossils found at the fossil site are noted here. The fossils are made up of minerals that have replaced the hard parts of original organism. These minerals are mainly calcite (calcium carbonate) or silica.

A)

Figure 2.20 – Fossils of Grand Canyon. A) The fossil site along the Rim Trail, west of the Hermits Shuttle Transfer, is adjacent to the Bright Angel Fault. The fault formed during Precambrian Time, about 1700 million years ago, and was reactivated about 70 million years ago. It was reactivated again in the last 15 million years. The result of all of the fault movement is that fossils in the Fossil Mountain Member (Kaibab Formation) have been exposed west of the fault. Without movement along the Bright Angel Fault and subsequent weathering and erosion, these fossils would still be 100 to 200 feet (30 to 60 m) down in the canyon and covered by the Harrisburg Member.

Figure 2.21 – The Harrisburg Member of the Kaibab Formation. These deep red rocks are part of the Harrisburg Member, seen here along Village Loop Road, just north of the turn off for Desert View Drive. The red color, caused by iron oxide (rust) in the rock, is common of the soil throughout the Village and in the residential area.

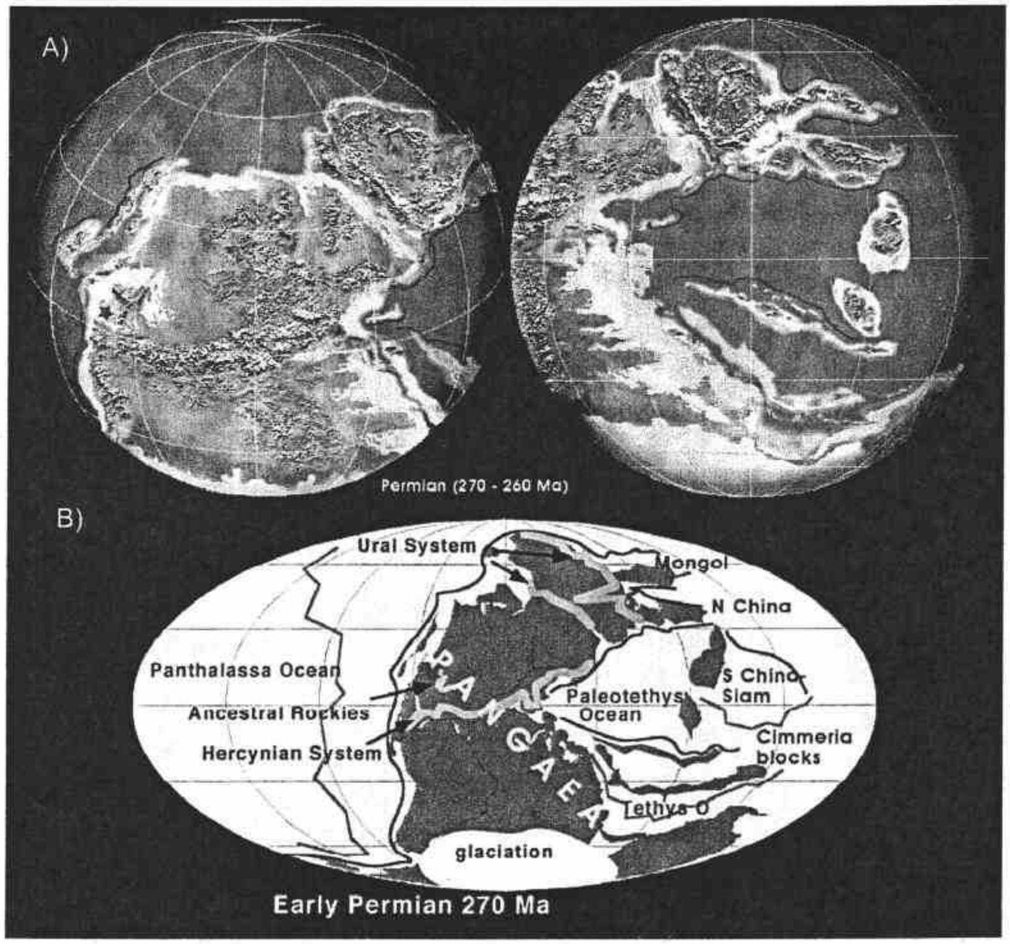


Figure 2.22 – The Earth at the end of the Paleozoic Era. A) Physiographic depiction shows the topography of the land, and extent of the shallow continental shelves. B) The outlines of the plates and the plate interactions are shown. On both, the red stars indicate the approximate location of the Grand Canyon region 544 million years ago. At this time, the continents were smashed together to form Pangea. Until the closing of the Paleozoic Era, the western margin of the North American continent had been a passive continental margin, far removed from the tectonic activity that occurs at plate boundaries. But by the Permian Period (about 280 million years ago), a subduction zone had formed along the western margin, which had a very important effect on the Grand Canyon and Colorado Plateau development. *(Diagram from Ronald Blakey, Northern Arizona University)*

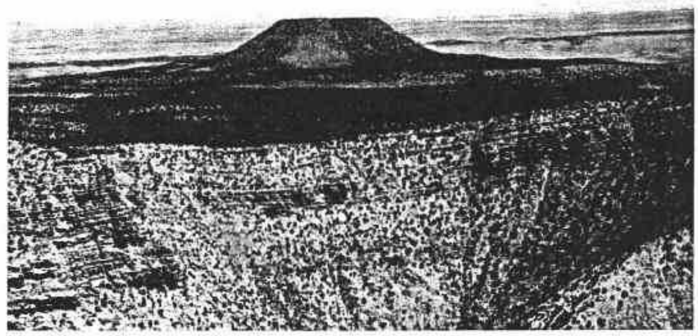
tectonic environment changed dramatically. Since the Permian Period, the western continental margin of North America has been a site of active plate boundary processes.

THE MESOZOIC ERA (248 TO 65 MILLION YEARS AGO)

During the Mesozoic Era, the era of "middle life," living creatures recovered and proliferated after the extinction at the end of the Paleozoic Era. It was a window of opportunity for the development of mammals, birds, and dinosaurs. Pangea was breaking apart and the continental plate fragments began to drift toward their present locations.

During the Mesozoic Era, marine and land sediments were deposited over the entire southwestern Colorado Plateau region. However, the Mesozoic Era in the Grand Canyon region is a mystery to geologists because there are few of those Mesozoic rocks remaining. Uplift of the Grand Canyon region that began during the Mesozoic Era initiated intense erosion, which led to the removal of most of the Mesozoic rocks. Dinosaurs may have roamed over the region, but no remains have been found at Grand Canyon. There may have been *one mile* (1.6 km) of Mesozoic rocks that once covered the Kaibab Formation. Some remnants of the Mesozoic Era exist near Grand Canyon, including Cedar Mountain and Red Butte (Fig. 2.23 and Appendix 1). As you travel east toward Cameron and Lake Powell, you can also see Mesozoic layers, which were formed during the Triassic Period, approximately 248 to 213 million years ago.

A)



B)

Figure 2.23 – Mesozoic remains. A) Cedar Mountain is a mesa located near Desert View Point, just east of Grand Canyon. It is composed of the Mesozoic Moenkopi (early to middle Triassic Period) and Chinle Formations (late Triassic Period), which formed between 248 and 213 million years ago. B) Red Butte is south of Grand Canyon and Tusayan along Highway 64. It is also composed of the Moenkopi and Chinle Formations, but it is capped with a basalt layer that is only about 9 million years old. This hard basalt layer helps to prevent the underlying Mesozoic layers from being eroded.

Hypotheses under construction! As you read on about the Colorado Plateau and the development of Grand Canyon, it's important to know that their development is not well understood. Much of the recent geologic history of is still being unraveled and pieced together by geologist. This provides an opportunity to share with visitors the thought and research process that geologists use, called the **scientific method**. This systematic process can lead to the development of a theory to explain scientific observations. The scientific method begins with detailed observations of a phenomenon. The next stage is developing a reasonable, testable **hypothesis** that takes into account all of the observations, and explains how the phenomenon may have occurred. The hypothesis then must be repeatedly tested, and not proven wrong in order to become a **theory**. Many of the ideas of how the Colorado Plateau and Grand Canyon developed are still in the hypothesis stage. Unfortunately, much of the evidence necessary to thoroughly evaluate the hypotheses has been eroded from the region during the past 40 million years. Be sure that you convey to visitors that science and geology are continuing to develop, and we don't have all the answers.

The removal of Mesozoic rocks from the Grand Canyon region was initiated because of uplift that began during the **Laramide Orogeny.** An **orogeny** is a large-scale episode of mountain building that is commonly accompanied by volcanism, metamorphism, and deformation of rocks. The Laramide Orogeny began about 70 million years ago and continued into the Cenozoic Era, until about 40 million years ago. Uplift of the Grand Canyon region, Colorado Plateau and mountains surrounding the Plateau began during this orogeny.

The onset of the Laramide Orogeny was caused by a change in the subduction zone that existed along the western margin of North America. Prior to the orogeny, a plate called the Farallon Plate had been subducting beneath western North America, causing deformation and volcanoes to form near the convergent plate boundary (Fig. 2.24a). For some reason, about 70 million years ago the plate began to subduct faster and at a shallower angle (Fig. 2.24b). This change in subduction left the volcanoes dormant because the plate did not extend deep enough to cause melting to occur deep beneath the continent. It also caused

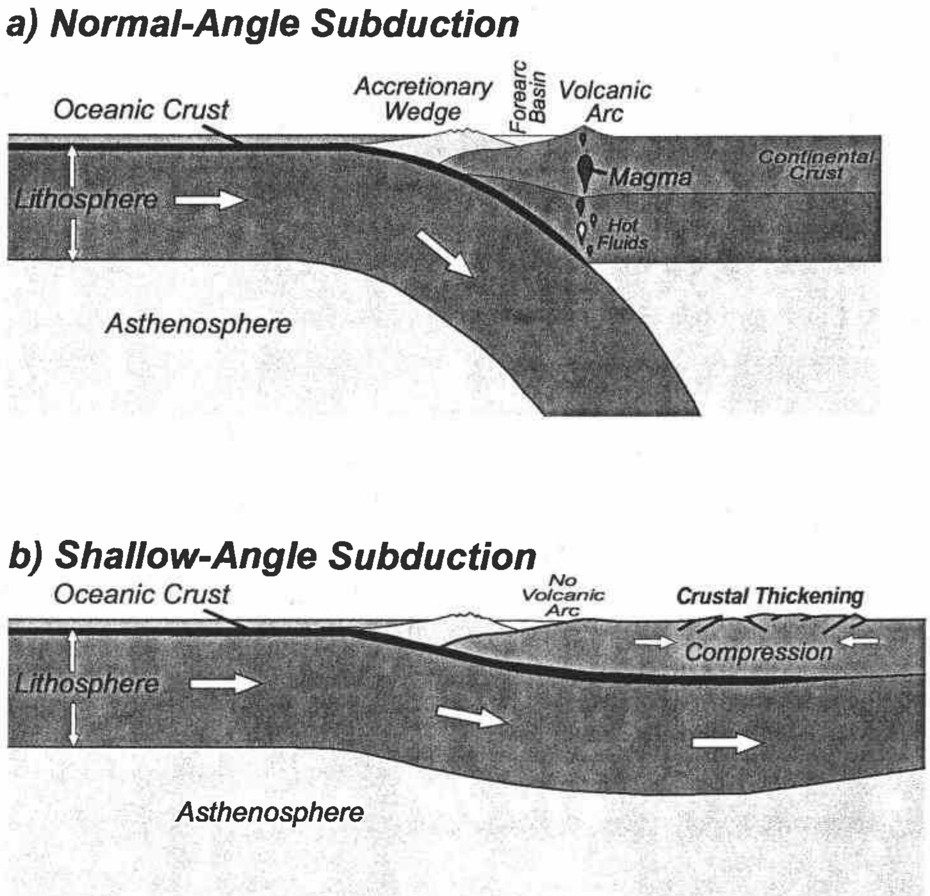


Figure 2.24 – Subduction during the Laramide Orogeny. a) In a "normal" subduction zone, the down-going plate subducts at a steep angle, causing deformation and volcanism on the overriding plate. As the Farallon Plate subducted beneath the North American Plate it created volcanoes where California is today. The remnants of these volcanoes are the Sierra Nevada Mountains. These mountains are made of the intrusive igneous rocks that were in the magma chambers of the volcanoes. b) During the Laramide Orogeny the angle of plate subduction became very shallow, possibly because the speed of subduction increased. As the shallowly subducting plate scraped along the bottom of the overriding North American Plate, it caused deformation (faults and folds) far inland from the actual subduction zone. That deformation also thickened the crust, further uplifting the region. The volcanoes became dormant because the plate was not subducting deep enough to melt. *(Diagram from R.J. Lillie)*

deformation to move inland on the North American continent as far as 625 miles (1000 km) from the plate boundary. Geologists suspect the Farallon Plate began to scrape along the bottom of the North American Plate, causing intense east-west compression over much of western North America. The compression led to the Laramide Orogeny as huge blocks of crust were shoved upward to form mountain ranges surrounding the Colorado Plateau.

The deformation continued for least 30 million years, as the compression deformed and uplifted much of western North America, including the Colorado Plateau and the Rocky Mountains (Fig. 2.25). The Colorado Plateau is unusual because it rose at least 7,000 feet (2100 m) yet somehow escaped serious deformation. If more deformation had occurred, the flat-lying sedimentary rocks in the Grand Canyon region would probably have been faulted, folded, and tilted, and the region would look more like the Rocky Mountains. Instead, the Colorado Plateau was gradually uplifted, allowing the rocks to remain relatively flat. It is not clearly understood exactly why this happened.

Why the Colorado Plateau stands tall. One reason for the high elevation of the Colorado Plateau may be that it has 30 mile (48 km) thick crust, which is thicker than normal continental crust (about 22 miles; 35 km). Because thick crust floats higher on the mantle than thin crust (due to its buoyancy), the land rose upward (Fig. 1.7a and 2.26). Another reason for the high elevation of the Grand Canyon region may be its proximity to the Basin and Range Province, which could cause the region to be buoyed up by the effect of the thin lithosphere (Fig. 1.7b). The boundary between the Colorado Plateau and Basin and Range Province is located in western Grand Canyon at the Grand Wash Fault (Fig. 2.27). Uplift of the Grand Canyon region began during the Laramide Orogeny as the crust thickened and the entire Colorado Plateau uplifted. The high elevation may then be sustained by the thinning lithosphere of the Basin and Range Province. Thus, the high elevation at Grand Canyon may be the result of two factors: **thick crust** and **thin lithosphere**.

Even though most of the sedimentary layers on the Colorado Plateau are flat-lying, they have not escaped deformation completely. Compressional forces during the Laramide Orogeny reactivated old Precambrian faults that were weak zones in the rocks. As faults ruptured in the deep Precambrian rocks, folds were

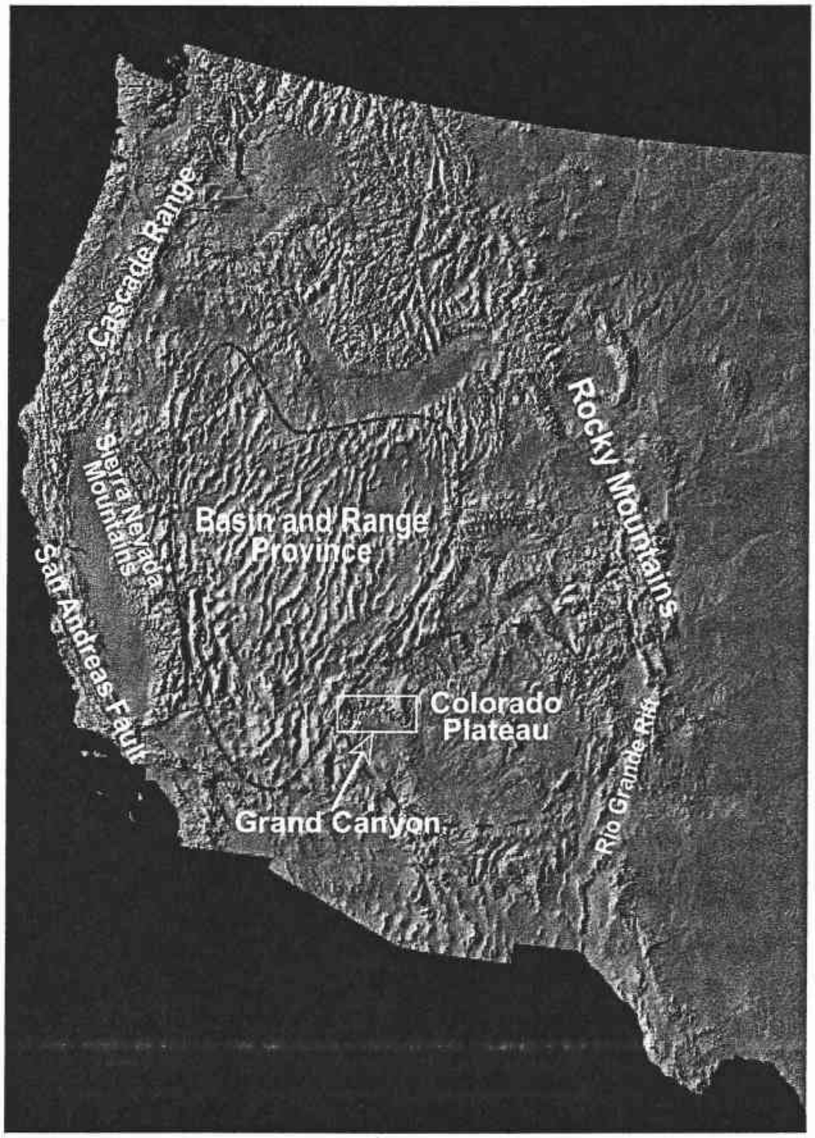


Figure 2.25 – Recent tectonic development of the western US. The Laramide Orogeny may have initiated the development of many of the geologic provinces identified in this diagram, like the Colorado Plateau and Rocky Mountains. The Colorado Plateau was gradually uplifted and somehow escaped serious deformation, while the Rocky Mountains were highly deformed. The Rockies and other mountainous areas formed along the margins of the Colorado Plateau. The Basin and Range Province began to form after the Laramide Orogeny, about 20 million years ago. Prior to the Basin and Range rifting, the region all around the Colorado Plateau was probably very mountainous, much like the Rocky Mountains.

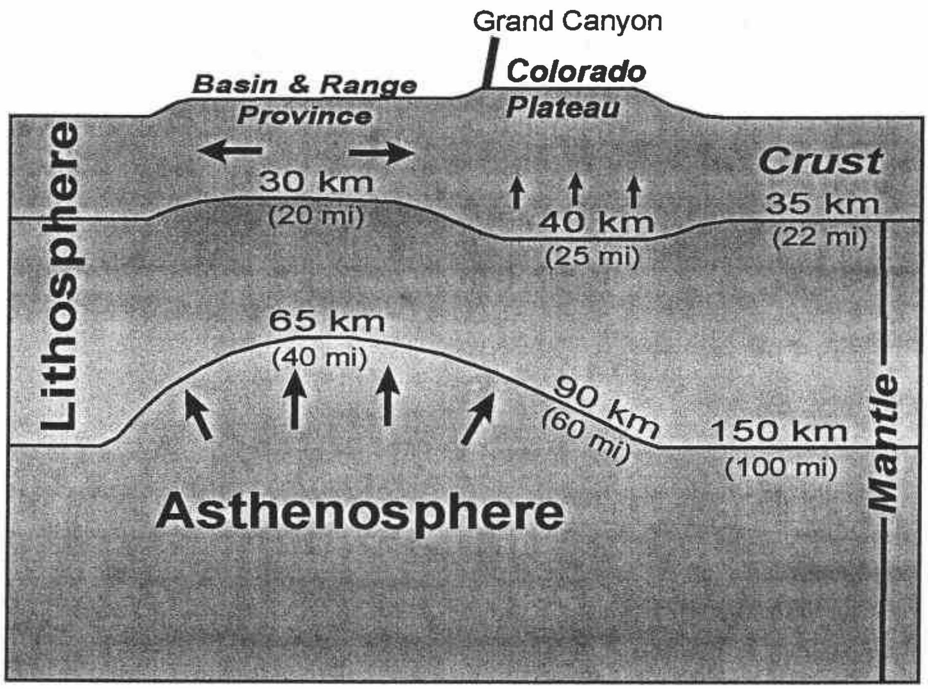


Figure 2.26 – High elevation of the Colorado Plateau. The Colorado Plateau remains at a relatively high elevation due to both the thick crust beneath the Plateau, and the thin lithosphere of the Basin and Range Province. It is suspected that the thick crust may have developed during the Laramide Orogeny, 70 to 40 million years ago. As the Farallon Plate subducted at a shallow angle, it scraped along the bottom of the North American Plate (Fig. 2.24b). This caused intense compression and created faults and folds that eventually thickened the Earth's crust beneath the Colorado Plateau region. After the Laramide Orogeny, thinning of the lithosphere began in the Basin and Range Province about 20 to 15 million years ago. The Basin and Range Province is the beginning of a divergent plate boundary, where the North American Plate is being ripped apart (Fig. 1.8). As the continent is pulled apart, the lithosphere is stretched and thinned, allowing the asthenosphere to rise like a hot-air balloon. The broad bulge of high elevation in the Basin and Range Province also affects surrounding areas, including the Grand Canyon region.

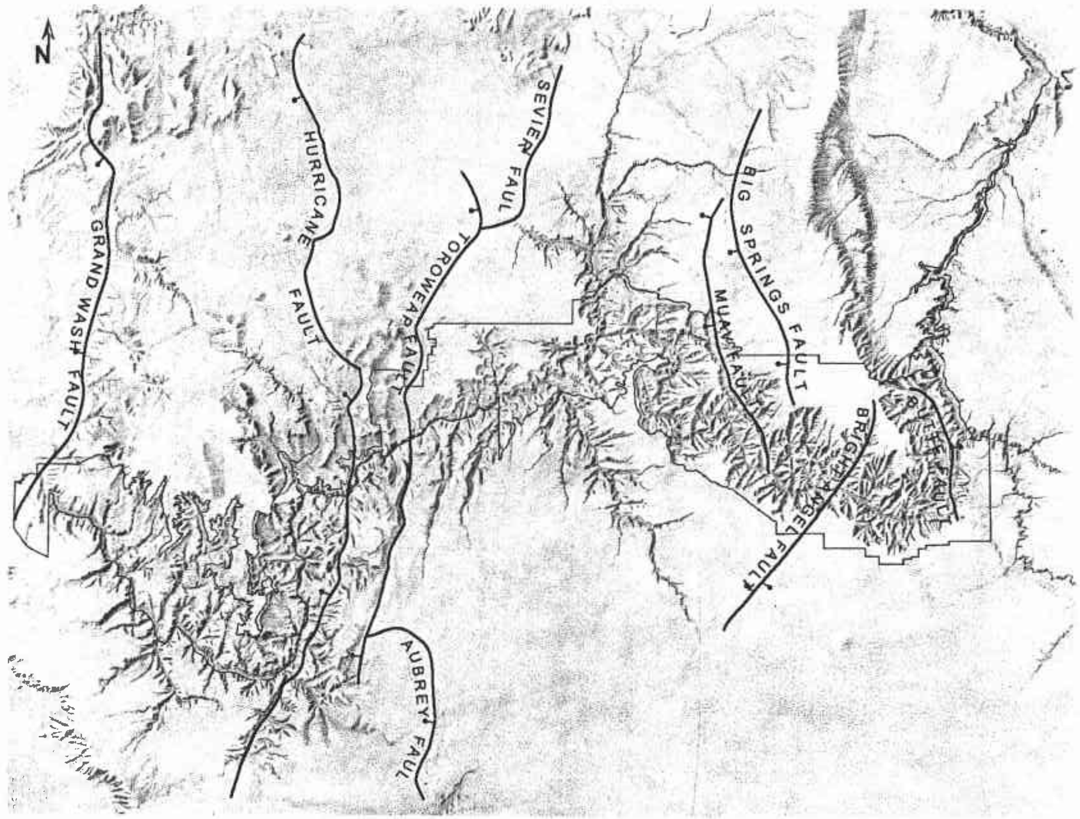


Figure 2.27 – Map of faults in Grand Canyon. A few of the prominent faults in Grand Canyon are shown on this diagram. Most of these faults formed during Precambrian Time and were reactivated during the Laramide Orogeny. Some of them, such as the Toroweap and Hurricane Faults, were reactivated as recently as 3 million years ago due to extension in the Basin and Range Province.

created in the overlying layers of Paleozoic and Mesozoic rocks (Fig. 2.28). The folds that formed, and the faults that were reactivated during the Laramide Orogeny can be seen from various locations along the rim (Fig. 2.29). The overlying Mesozoic rocks were like the crust on hard Italian bread. When the bread folded, the crust got broken up and began to crumble away. After the folding during the Laramide Orogeny, the uppermost cracked and broken Mesozoic rocks were eventually eroded away.

Interpreters tip. Describing the Laramide Orogeny to visitors at Grand Canyon can be a challenge. It is helpful to have analogies, diagrams, or props. The main idea to convey is that a major mountain building event uplifted the Colorado Plateau and the Grand Canyon region, which was essential for Grand Canyon to form. The convergence of the Farallon Plate and North American Plate can be related to a car crash, where the front end of one car goes beneath the other. The Colorado Plateau was like a safety cage in the crashed car. The mountains around the plateau are like the mangled and deformed metal of the wrecked car. While much of western North America was deformed during the "crash," the plateau stood strong.

The end of the Mesozoic Era is marked by another mass extinction event. Approximately 65 million years ago, a large asteroid struck the Earth in the area of the Yucatan Peninsula (Mexico) creating a 180-mile (290 km) wide crater. Scientists estimate the asteroid was about 6 miles (10 km) in diameter! The impact caused incredible destruction to the area surrounding the impact and dumped huge amounts of ash, carbon dioxide, and water vapor into the atmosphere. This resulted in a dramatic climate change. The sum of these events was the demise of two-thirds of the planet's sea and land organisms, including the dinosaurs.

THE CENOZOIC ERA (65 MILLION YEARS AGO TO PRESENT)

The Cenozoic Era, the era of "recent life," began as life recovered from the mass extinction at the end of the Mesozoic Era. The continents continued to move toward their present locations and mammals began to diversify and spread over

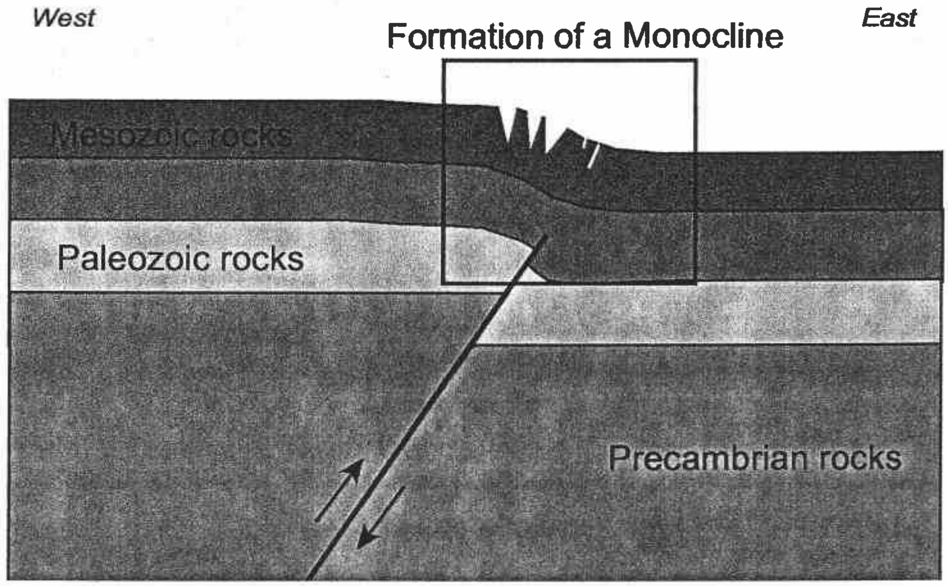


Figure 2.28 – Formation of monoclines at Grand Canyon. The Precambrian faults deep beneath the Paleozoic and Mesozoic sedimentary layers were zones of weakness reactivated during the Laramide Orogeny. As the reactivated faults ruptured in the Precambrian rocks, they broke through some of the older, deeper Paleozoic layers, while the young Paleozoic and Mesozoic layers on top were folded. The folding of the uppermost Mesozoic layers caused them to crack as they were extended on the top of the fold, making the rocks less resistant to erosion.

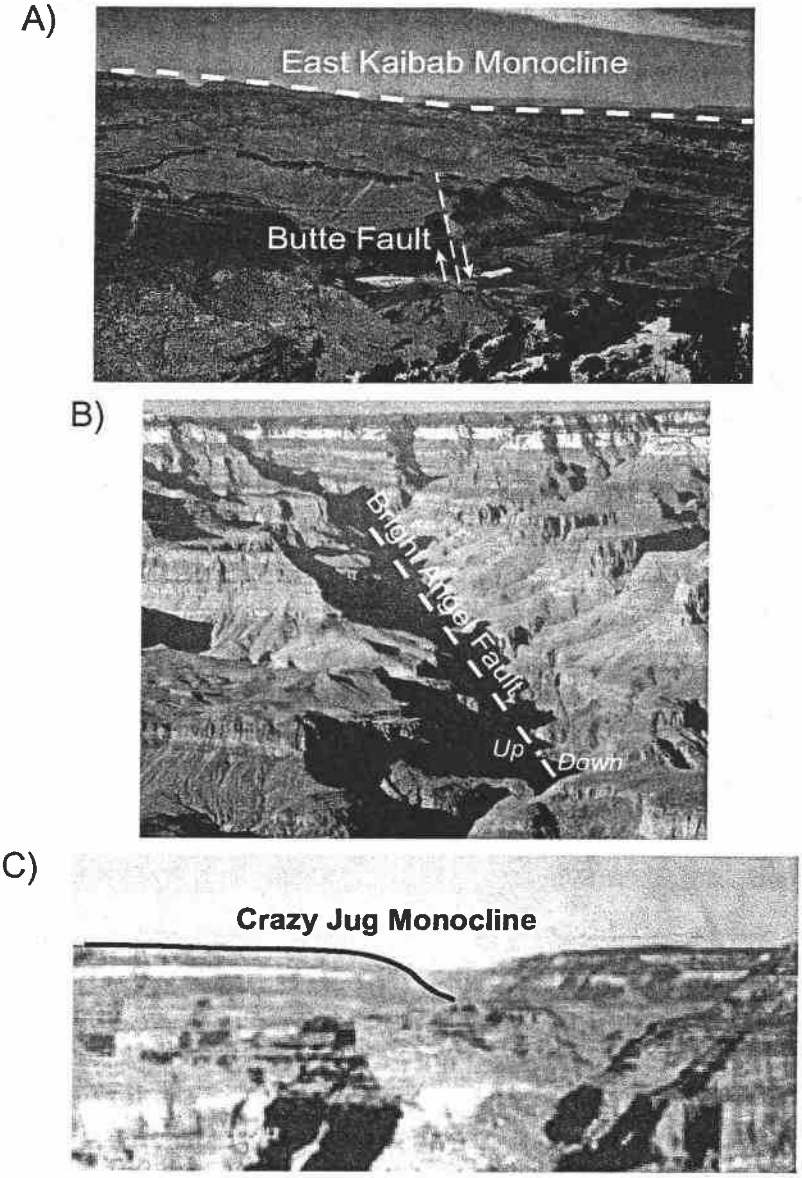


Figure 2.29 – Faults and folds of the Laramide Orogeny. A) At Desert View the Butte Fault folded overlying sedimentary layers, creating the East Kaibab Monocline. The arrows show the direction of movement along the fault during the Laramide Orogeny. This photo was taken from Desert View. B) The Bright Angel Fault was reactivated during the Laramide Orogeny, leaving an area of weakness that was eroded to form Bright Angel Canyon. The west side of the fault moved up relative to the eastern side during this event. This photo was taken at the village area. C) From Pima Point, the Crazy Jug Monocline can be seen to the northwest. It was created as the Muav Fault ruptured beneath the sedimentary layers. This photo was taken from Pima Point.

the Earth. Many new types of plants and animals like the ones we know today developed. Because the Cenozoic is the shortest and most recent era, it is the one geologists usually know the most about… except maybe in the case of Grand Canyon!

The geologic events that occurred during the Cenozoic Era have greatly influenced the development of the landscape in the Grand Canyon region. During this era, erosion intensified as the area was uplifted during the Laramide Orogeny. Therefore, many of the Mesozoic and Cenozoic rocks in the region have been eroded away. West of the Grand Canyon region, the Basin and Range Province began to rip apart approximately 20 to 15 million years ago. A period of volcanism began about 9 million years ago along the southwestern boundary of the Colorado Plateau, which created the San Francisco Peaks near Flagstaff (Appendix 1). Of course, one of the most important events of the Cenozoic Era was the development of the Colorado River and Grand Canyon.

Uplift at Grand Canyon. Some geologists speculate that uplift is still occurring on the Colorado Plateau in the Grand Canyon region. But others think it may be an illusion because of faults in western Grand Canyon. These faults are responding to the Earth's crust being pulled in an east-west direction by the rifting of the Basin and Range Province. As that region extends, the crust is broken along normal faults. In western Grand Canyon, the rock on the west side of the faults drops down, causing the west end of the canyon to essentially lower in elevation (Fig. 2.30). As western Grand Canyon lowers, it may cause an illusion of uplift in the east. An explanation for the apparent uplift may be that the land in the west is simply dropping down.

Once the Colorado Plateau and Grand Canyon region were uplifted, the stage was set for Grand Canyon to form. The big question is – WHY DID GRAND CANYON FORM HERE? The answer to that question is complex, because it relates many different but interconnected factors. One of the factors is the Laramide Orogeny that ***uplifted*** the rocks. To form a canyon as deep as Grand Canyon, the rocks had to be well above the base level of the river, which is sea level in this case. With the rocks in the Grand Canyon region more than 7000 feet (2100 m) above sea level, the Colorado River had its work cut out!

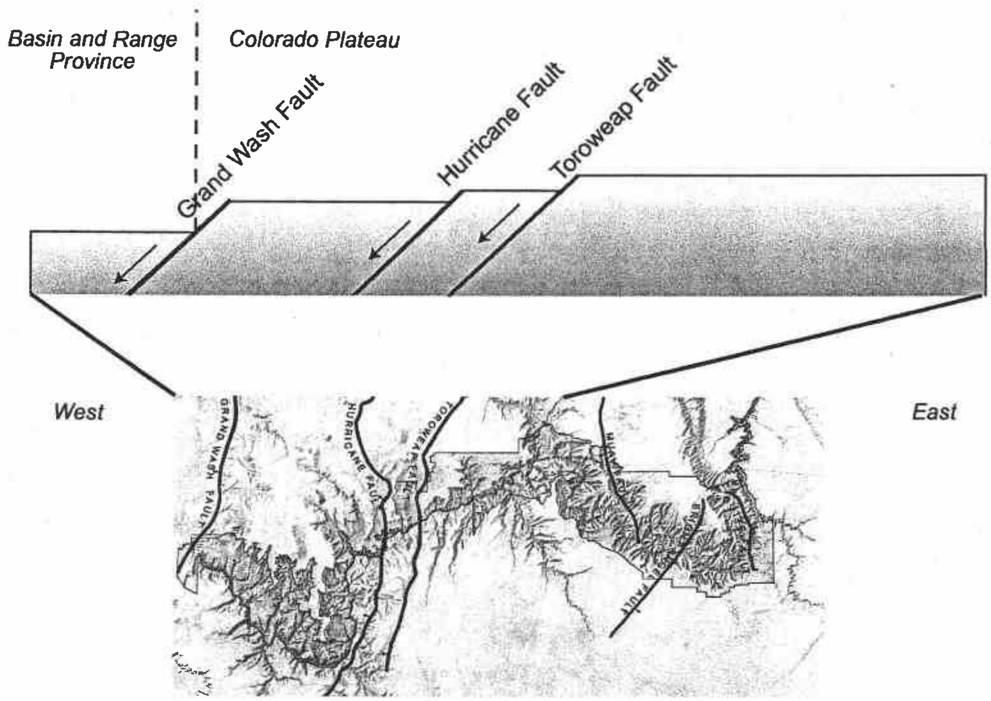


Figure 2.30 – Down-dropping along normal faults. The upper diagram is a cross-section of what the Earth may look like in western Grand Canyon. The rocks on the west side of the faults drops down in response to the extension and rifting of the nearby Basin and Range Province. The boundary of the Colorado Plateau and Basin and Range Province is at the Grand Wash Fault. This down-dropping in the west may be producing the illusion that the Grand Canyon region and Colorado Plateau have been uplifted.

The Colorado River had to be a ***very powerful river*** to carve Grand Canyon. With its steep gradient, the Colorado River has a high water velocity and can carry a large sediment load. The sediment enabled the river to slice down through the rocks and carve the canyon. Also, because most of the canyon layers are comparatively soft ***sedimentary rocks***, rather than very hard metamorphic or igneous rocks, it was easier for the river to cut through them.

The Laramide Orogeny did not seriously deform the sedimentary rock layers, so they remained mostly ***flat-lying***. It would have been more difficult for the river to flow over seriously tilted and deformed rocks or carve such a deep canyon. Also if the rocks were not flat-lying, the canyon would not have such continuous, visible layers of alternating cliffs and slopes that it does today.

Grand Canyon exists in this location also because of the ***semi-arid desert climate***. Weathering and erosion in this dry climate, such as ice wedging and mass movement, have widened and sculpted the canyon. These processes have helped create the landscape features like buttes, mesas, and temples. Also, if Grand Canyon were in a more humid climate, the canyon would be covered by vegetation, disguising the colorful, picturesque layers.

Glaciers, faults, earthquakes, meteorite impacts, and wind... are some of the common incorrect ideas of how Grand Canyon formed. We know glaciers did not directly carve Grand Canyon. During the most recent ice ages (1.8 million to 8,000 years ago) glaciers did not reach as far south as northern Arizona. However, melting of glaciers in regions far upstream may have contributed to the carving of the canyon by increasing the discharge of the Colorado River with their melt water. Major faulting did not form Grand Canyon either. If a large fault had broken open the canyon, there should be evidence of the fault in the inner canyon, but there is none. An earthquake could not have created the canyon because there would have to be a fault for the earthquake to occur along throughout the length of Grand Canyon, and there is not one. A meteorite also did not form Grand Canyon. A meteorite would have probably formed a crater, rather than a linear canyon, because impact sites are usually circular (like Meteor Crater, near Winslow, AZ). Additionally, no remains of meteorites have been found at the canyon. Wind has had a *very small* role in the development of Grand Canyon. It may have helped a little to widen the canyon by transporting small sediment particles, but it certainly has not cut down through one mile (1.6 km) of rock.

The Giant Puzzle: The Colorado River and Grand Canyon

It is certain that the Colorado River carved Grand Canyon, but exactly how the river came to be is a big puzzle that geologists are still piecing together. Many critical pieces of the puzzle are missing. Large gaps occur in the geologic record between the formation of the rocks, uplift and erosion, and the carving of the canyon. Somewhere in these gaps lie the pieces geologists need to complete the puzzle.

One of the biggest problems that geologists face when trying to understand the history of a river is that the river itself tends to wash away much of the crucial evidence. In the case of Grand Canyon, the Colorado River has removed most of the rocks and river deposits that would help geologists clearly understand the development of the canyon. Sometimes when evidence is found it is inconclusive and only creates more questions. An additional problem is that the study area within the Grand Canyon and Colorado River Basin is enormous (Fig. 2.31). The rugged terrain of Grand Canyon alone is 277 river miles (446 km) long, 5 to 18 miles (8-29 km) wide, and about one mile (1.6 km) deep.

Another obstacle geologists face is the vast length of time that has passed and intense erosion that has occurred since the uplift of the Colorado Plateau and the formation of the canyon. The Colorado River could be as old as the Colorado Plateau (70 million years) as suggested by early geologists like John Wesley Powell and G.K. Gilbert. It is possible that the river flowed through other places before entering the Grand Canyon region. The past 70 million years worth of erosion and other geologic processes has severely hindered the establishment of a solid hypothesis of the river's formation and later canyon carving.

Enlighten the visitors. Visitors often assume that the river was at one time as wide as the canyon is today. Not so! The river has always been about the same width (300 to 400 feet; 90 to 120 m), give or take a few feet during floods or dry spells. The canyon has been widened by erosion and weathering processes, such as ice wedging and mass movements. As you look out today at the massive cliffs of rock, like the Coconino Sandstone and Redwall Limestone, be aware that the Colorado River has never actually touched the rocks that are now exposed. The rock that was at the top of the canyon when the river first carved down through the layers are now long gone.

Pieces of the Puzzle

Piecing together the Grand Canyon puzzle begins with understanding the development of the Colorado River. Using the scientific method, geologists have developed several different hypotheses for how Grand Canyon and the Colorado River came to be, and they are researching and collecting evidence that can help prove or disprove the hypotheses. An initial hypothesis was that the Colorado River has always followed the same path it does today. It is now clear that river

Figure 2.31 – The Colorado River Basin. The Colorado River begins in the Rocky Mountains of Colorado more than 10,000 feet (3000 m) above sea level. It drains an area of about 242,000 square miles (627,300 square km) of North America, the area highlighted on the map.

systems are much more complicated and dynamic. The Colorado River as we know it seems to have formed from at least two segments that eventually connected.

The initial hypothesis about the Colorado River was disproved as evidence was gathered that indicates that the northeastern part of the Colorado River (upper part) is older, while the southwestern region (lower part) is younger. The upper part of the river is sometimes referred to as the "old Colorado River" or "ancestral Colorado River." The younger, southwestern part of the river that flowed to the Gulf of California is the "young Colorado River". Some time in the past, the older and the younger parts may have combined to form the Colorado River that flows though Grand Canyon, as we know it today.

The shape of the land at the time when the Colorado River formed is an important factor in its development. One obstacle that seems impossible for a river to cross is the **Kaibab Plateau**. The Kaibab Plateau is a broad, elevated area that was uplifted along the East Kaibab Monocline (Fig. 2.32). Where the Colorado River makes a sharp turn to the west, it has somehow managed cut right through this large area of upwarped land. Water normally follows gravity and travels down slope, away from or along hills, rather than through them. It is possible that 10 to 30 million years ago the Kaibab Plateau may not have been as large as it is today. The land may have been relatively flat and easy for the river to cross, and then the plateau may have developed after the river had established its course (Fig. 2.33a). Alternatively, relatively flat-lying Mesozoic rock layers may have covered the Kaibab Plateau. As these Mesozoic rocks were eroded away by the river, the Kaibab Plateau was exposed, and the Colorado River had established its channel right through the Plateau (Fig. 2.33b).

Looking at clues in western Grand Canyon, geologists suspect that mountains once existed on the south and southwest flanks of the region. These mountains would have formed during the Laramide Orogeny and remained until rifting of the Basin and Range Province began. Streams flowed northward from the mountains, over the Grand Canyon region, and onto the Colorado Plateau region. The sediment that was carried by the north flowing streams is referred to as **rim gravels**. This sediment is composed of rock that was eroded from the mountains

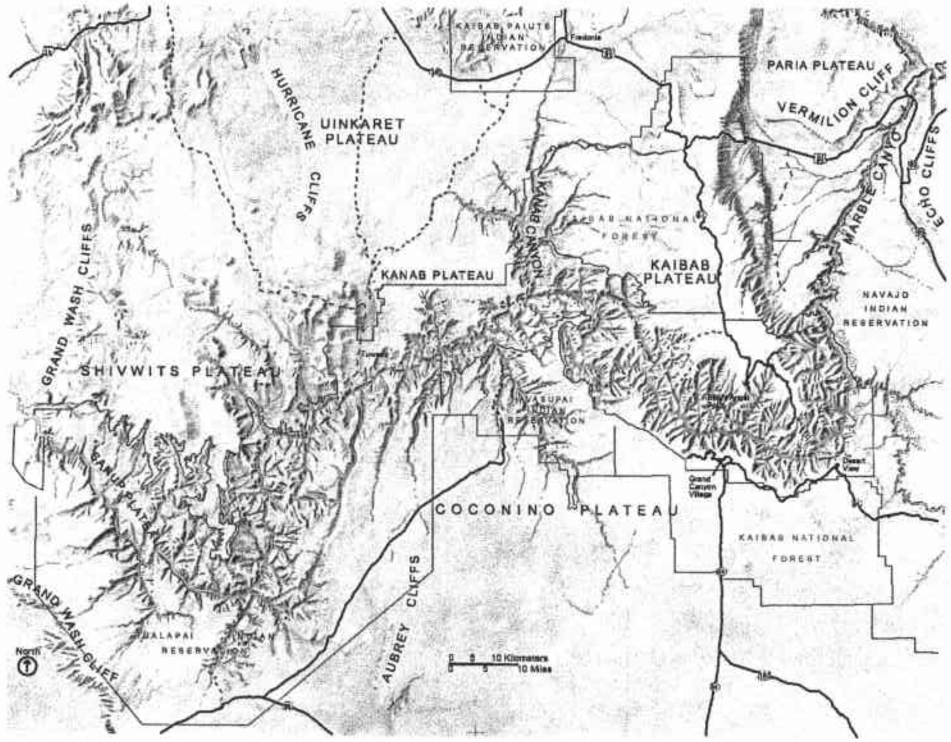


Figure 2.32 – Colorado River and Grand Canyon. Evidence shows that the northeastern reaches of the Colorado River are older than the southwestern part of canyon, which is about 5-6 million years old. These findings suggest that the entire Colorado River through Grand Canyon did not form as one connected river, but rather it was formed from at least two segments. Some of the important features that may have had a role in the development of the Colorado River and Grand Canyon are depicted on the map.

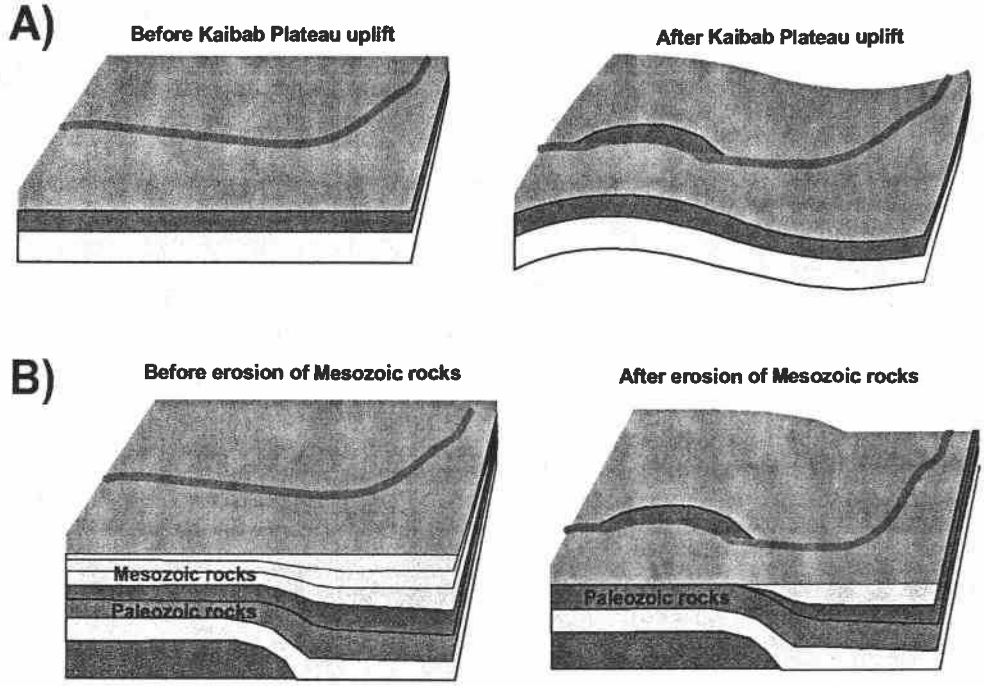


Figure 2.33 – The Kaibab Plateau. The Kaibab Plateau may not have been an obstacle for the early Colorado River, as it seems to be today. A) One hypothesis is that the Colorado River may have flowed over a relatively flat region prior to the Kaibab Plateau uplift and development of the East Kaibab Monocline. After the Colorado River established its channel, the Kaibab Plateau developed . The river would have cut down through the slowly-rising sedimentary layers of the Kaibab Plateau, like a layered cake being uplifted beneath a knife. B) Another hypothesis, and a more likely one, is that the river developed when the Kaibab Plateau was covered by relatively flat Mesozoic layers. After intense erosion, the Mesozoic rocks were mostly eroded away, exposing the upwarped layers in the Kaibab Plateau. The Colorado RIver would have established its course without noticing the effect of the upwarped land below.

that existed on the rim of the Colorado Plateau. In western Grand Canyon, rim gravels have been found on *both* the north and south sides of the canyon. If Grand Canyon or the Colorado River had existed when the rim gravels were deposited, the north-flowing stream would not have been able to cross to the north side (Fig. 2.34). The rim gravels were then covered by basalt that has been radiometrically dated and was measured to be 6 million years old. According to geologist Ivo Lucchitta, this reveals that the western Grand Canyon could not have existed prior to 6 million years ago.

The real world. Geology is a developing science that is constantly changing. Geologists are learning more about the Earth as research techniques are refined and technology develops. Old ideas about geologic processes are changed and updated as new insights are gleaned from research. Geologists are currently studying topics related to the development of the Colorado Plateau region, evolution of the Colorado River, and forming of Grand Canyon. As an interpreter, you should be aware that ideas and hypotheses are changing and developing. Search the Internet for new publications or read articles in recent geology journals to keep up to date on geologic research. Don't get too bogged down by the details, as very technical information is of little interest to most park visitors.

The Bouse Formation is a sedimentary deposit that is evidence of the Colorado River reaching the sea. It was deposited approximately 4.8 million years ago where the Colorado River joined the Gulf of California. Interestingly, the Bouse Formation is found near Needles, California (Appendix 1). This indicates that the Gulf of California was much farther north than it is today. The Colorado River has deposited so much sediment in the Gulf of California that it has essentially filled it in, moving the river's outlet southward to where it is today.

Lava that flowed from the Vulcan's Throne area provides another clue to the rate and timing of the canyon carving (Fig. 2.35). The lava (basalt) flowed into the canyon, and down to present river level. The radiometric age of the basalt is about 1.2 million years. This shows that the canyon was at its current depth by 1.2 million years ago.

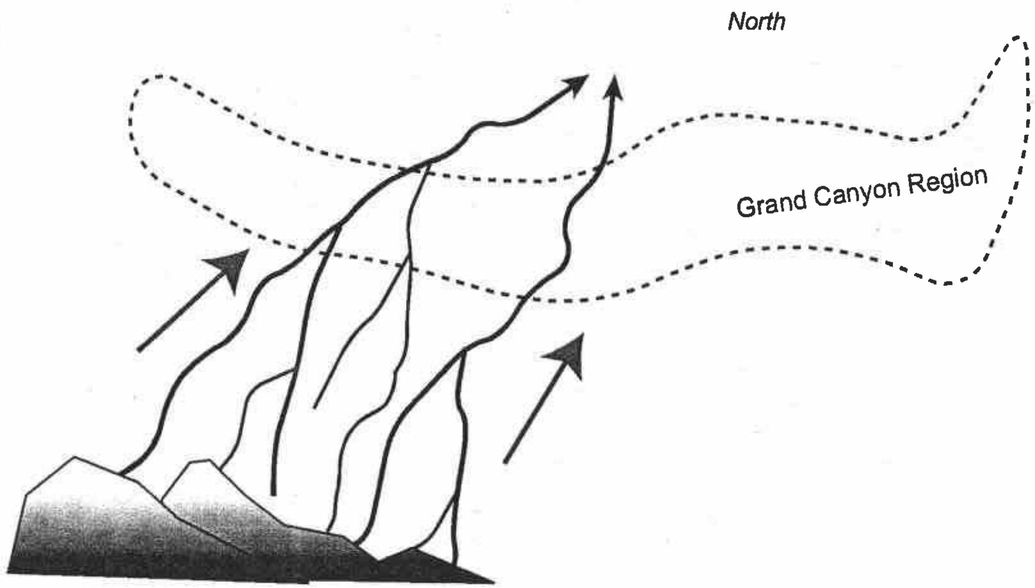


Figure 2.34 – Former highlands near Grand Canyon region. a) A mountainous region likely existed south/southwest of the Grand Canyon region, prior to Grand Canyon forming. North flowing streams ran off the mountains over the Grand Canyon region, and deposited sediment known as rim gravel. As the Basin and Range Province began rifting 20 to 15 million years ago, the mountains were gradually broken down and the elevation of the region was reduced to where it is today. The northward flowing streams are thought to have changed direction approximately 15 to 16 million years ago. They began to flow south/southwest after the initiation of the Basin and Range Province rifting. However, evidence shows that these streams were not following the path of the Colorado River today, and did not initiate the carving of Grand Canyon.

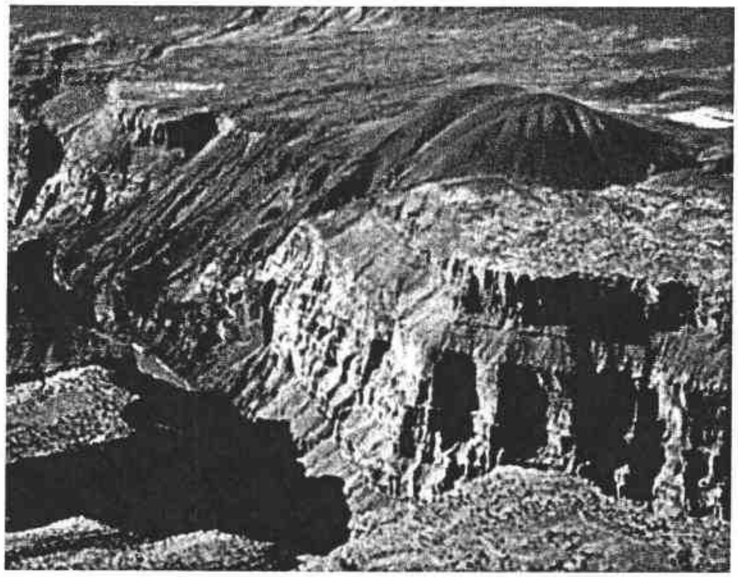


Figure 2.35 – Vulcan's Throne. This **cinder cone** is one of many that produced massive volcanic eruptions less than one million years ago in western Grand Canyon. Near Vulcan's Thone some of the basalt flowed into the canyon to the current river level. This basalt has been radiometrically dated and is approximately 1.2 million years old, indicating that the Colorado River had cut down to the approximate depth it is today in western Grand Canyon by that time.

The puzzle pieces that have been pieced together so far indicate Grand Canyon (in its entirety) did not exist before 6 million years ago. By 4.8 million years ago the Colorado River had reached the sea at the Gulf of California. And it had cut the rocks of Grand Canyon down to the present depth by 1.2 million years ago. All of the pieces may seem discombobulated and scattered, just as when you open a jigsaw puzzle box the pieces inside are jumbled and confusing. As you pull hundreds of puzzle pieces out of the box one by one, you eventually find one piece that matches to another. With great time and patience, more pieces begin to fit together, giving you a glimpse of what the complete puzzle will one day look like.

The Grand Canyon puzzle is a huge, million-piece puzzle, involving not only the Grand Canyon but also the entire Colorado Plateau and other nearby regions. Geologists are diligently piecing together the geologic story of Grand Canyon and the Colorado River, putting together small parts of the puzzle. Unfortunately, many of the puzzle pieces are lost forever – eroded and washed away. As geologists work together, sharing information and developing hypotheses, the chances of solving the Grand Canyon puzzle get better.

Hypotheses for the Puzzle

There are an incredible number of hypothesis and variations of those hypotheses about how Grand Canyon came to be. It is important to bear in mind that the development of the Colorado River and Grand Canyon has not been decisively concluded. Only a few of the different hypotheses are discussed here.

Many of the hypotheses about the Colorado River and Grand Canyon development address the difference in age of the upper and lower canyon. Edwin McKee and others (1967) were the first to consider that the Colorado River in Grand Canyon formed as a combination of two different rivers. They suggested that the "old Colorado River," prior to 5.5 million years ago, flowed in its present channel from the northeast toward the Kaibab Plateau. In their hypothesis, the river then followed the path of the Little Colorado River to join the Rio Grande River, and finally to the Gulf of Mexico (Fig. 2.36a). As the "young Colorado River"

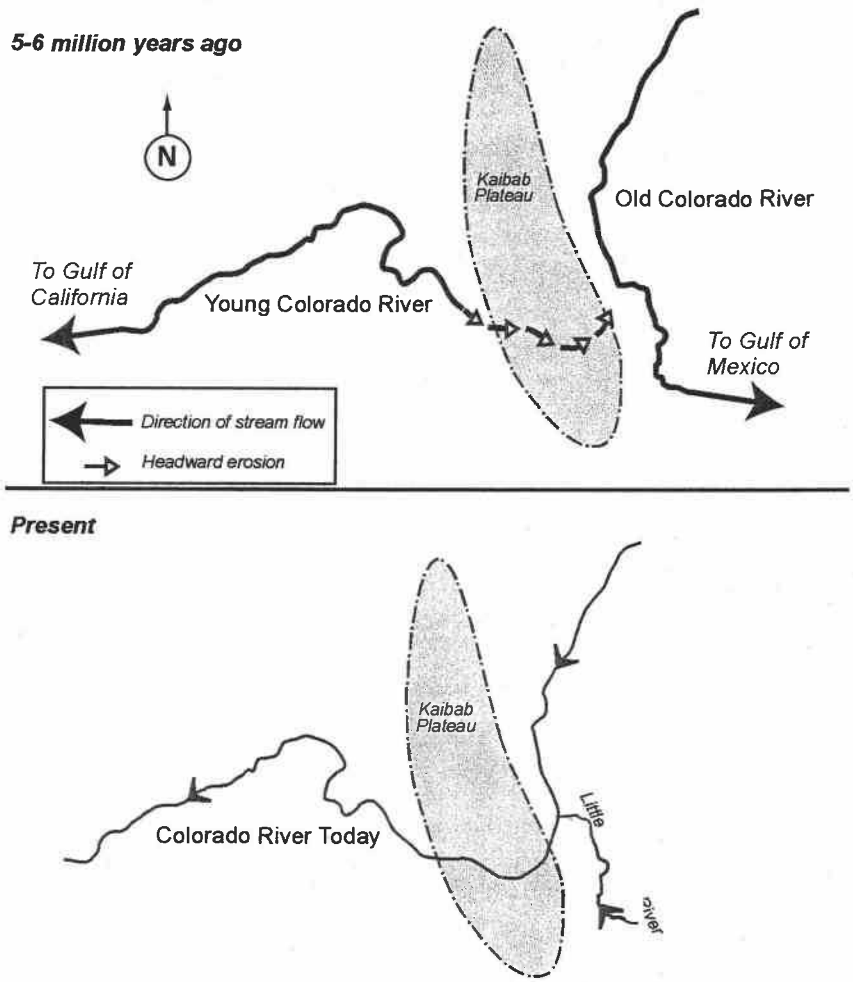


Figure 2.36 – The Little Colorado River hypothesis. McKee and others (1967) suggested this model for the development of the Colorado River through Grand Canyon. In the top diagram, the "old Colorado River" (blue) flowed to the Kaibab Plateau, then turned to the southeast, and flowed down the channel of what is now the Little Colorado River. The "young Colorado River"(red) eventually captured the "old Colorado River," as it eroded headwardly from the west, shown by the red and white arrows, as it cut through the Kaibab Plateau. In this hypothesis, the two rivers were joined to form what is now the Colorado River. The Little Colorado River was abandoned as the outlet and now flows into the Colorado River.

worked its way toward the Kaibab Plateau by headward erosion, it intersected the "old Colorado River" about 5.5 million years ago and captured its waters (Fig. 2.36b). The problem with this hypothesis is that there is no evidence to show that the "old Colorado River" flowed out to the Gulf of Mexico through the Little Colorado River channel.

A hypothesis by Ivo Lucchitta (1975, 1984) suggests that the "old Colorado River" flowed past the Kaibab Plateau, but did not change course at the Plateau as suggested by McKee. Lucchitta's hypothesis suggests that the Kaibab Plateau did not exist or it was not as big as it is today when the Colorado River first came through. This hypothesis suggests that the "old Colorado River" crossed the Kaibab Plateau, then flowed northwest along the Kanab, Uinkaret, or Shivwits Plateaus (Fig. 2.32). Lucchitta's hypothesis is similar to McKee and others, as he suggests that the "old Colorado River" later joined the "young Colorado River" (Fig. 2.37). There has not yet been enough solid evidence found to prove or disprove this hypothesis.

Geologists don't have all the answers... From June 7 to 9, 2000, about 80 geologists involved in studies of the Grand Canyon region gathered at Grand Canyon National Park. For three days, they presented and discussed new findings related to the development of Grand Canyon. They reviewed various hypotheses for how the canyon formed and the timing of events leading up to its formation. Of all the hypotheses discussed, none was completely accepted. And it may be quite some time before a consensus is reached. The only thing that is certain is that ***the river did it***! One way or another, about 5 to 6 million years ago, the Colorado River began to carve this spectacular landscape we know today as Grand Canyon.

A few geologists believe that the "old Colorado River" flowed approximately within its present channel to the Kaibab Plateau, where it was temporarily dammed. With no outlet to the sea, the water was pooled behind the Kaibab Plateau, forming a lake that extended to the north and east. Eventually the lake disappeared, possibly because an outlet to the sea developed, approximately 5.5 to 6 million years ago. One possibility is that the lake was drained when the "young Colorado River" cut through the Kaibab Plateau by headward erosion (Fig. 2.38a). It would have essentially pulled the plug on the lake and drained the water from it.

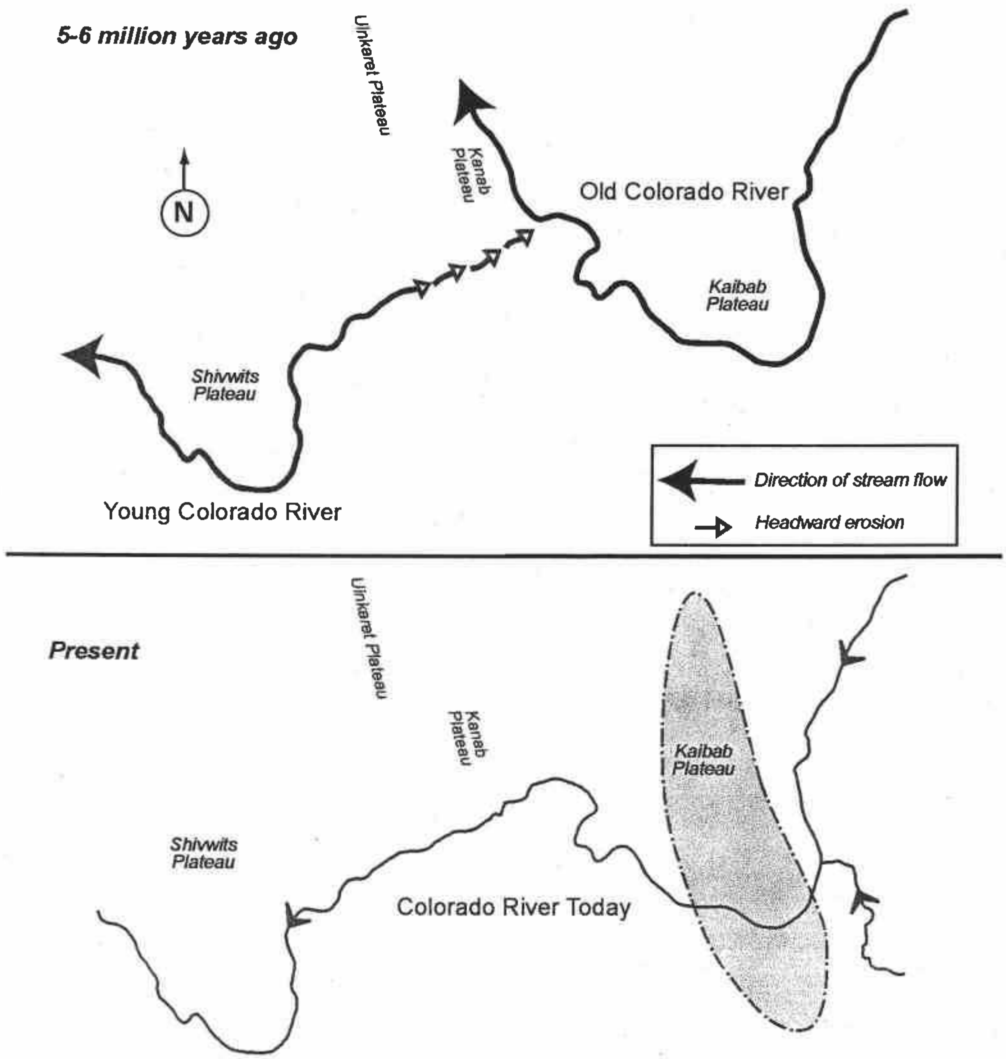


Figure 2.37 – The northwest flowing river hypothesis. Ivo Lucchita's hypothesis is that the "old Colorado River" flowed northward along a ridge after it crossed the the region where the Kaibab Plateau is today. The diagram at top shows one such possibility, but it may have flowed along the Kanab, Uinkaret, or Shivwits Plateaus. In his hypothesis, the Kaibab Plateau was not as big as it is today, or was not there at all when the river formed 5 to 6 million years ago. The "young Colorado River" later captured the "old Colorado River" by headward erosion.

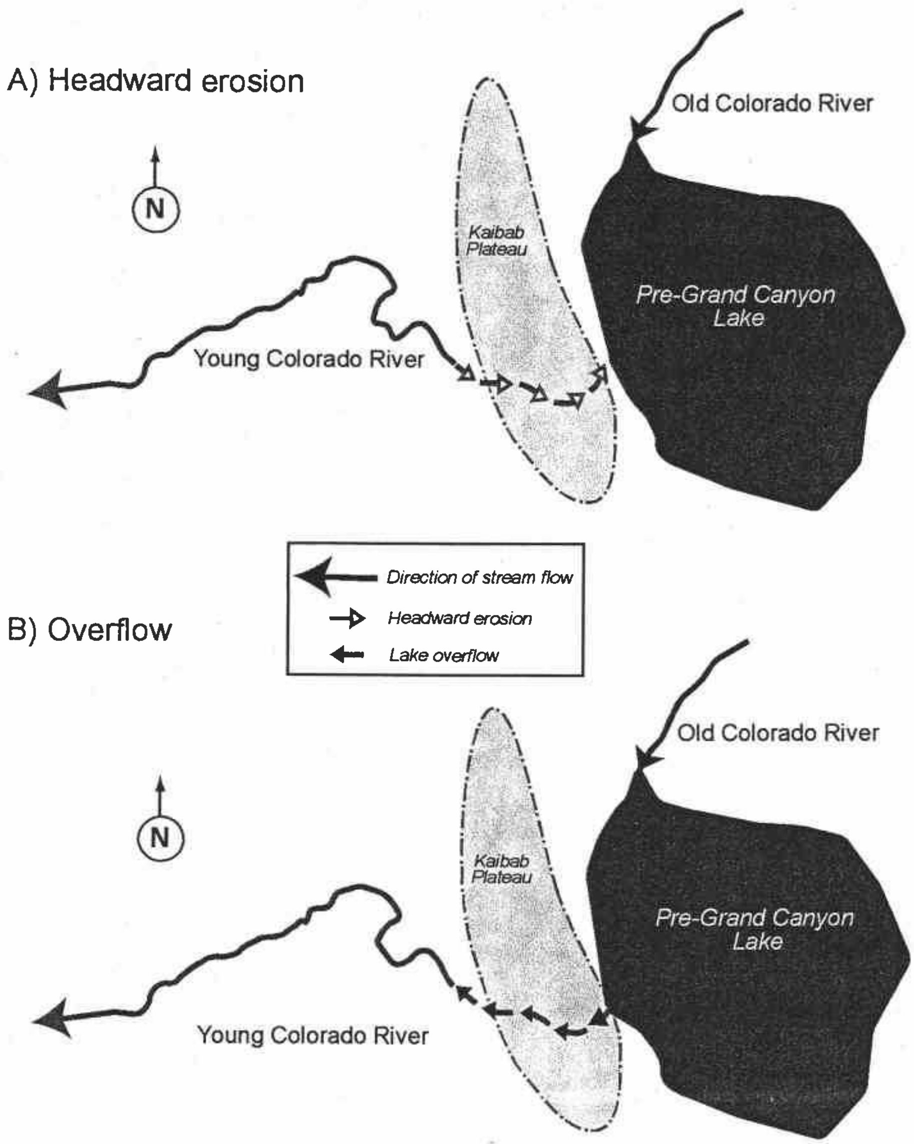


Figure 2.38 – The lake hypothesis. Some geologists believe that the "old Colorado River" was dammed behind the Kaibab Plateau to form a lake until the lake either: A) was drained as the "young Colorado River" eroded headwardly through the Kaibab Plateau, essentially capturing the water from the lake; or B) overflowed the Plateau and headed westward where it rapidly carved the younger portion of the canyon.

Another twist to the hypothesis is that the lake overflowed the Kaibab Plateau, eroding through it to form the "young Colorado River" and Grand Canyon. As the lake drained, the Colorado River became a through-flowing river that eventually reached the Gulf of California (Fig. 2.38b). There is evidence that a lake existed southeast of Grand Canyon about 16 million years ago. The Bidahochi Formation, comprised mainly of non-marine sedimentary and volcanic ash deposits, is evidence that that a lake existed 16 million years ago, but it may or may not have any direct relationship to the development of Grand Canyon.

There are other hypotheses about how the Grand Canyon may have formed, but there is no viable evidence to decisively prove any of them. It is important to also consider that the canyon may have formed due to a combination of different factors and models. It may not be a simple joining of two rivers, but possibly four or five! There are many ways of looking at the clues, but so far none of them have been piece together in just the right way – yet!

Interpreters tip. Park rangers and volunteers occasionally encounter visitors with religious views that differ from interpretations based on scientific observations. Rest assured that most visitors come to geology programs to hear what you have to say, not to argue the facts. As an interpreter for representing the National Park Service, your job is to present the *scientific view* of how the canyon *may* have formed based on evidence found in the rocks. According to the NPS 2001 Management Policies the "Constitution prohibits the National Park Service from endorsing or promoting any religious position in explaining natural processes. However, alternative theories of processes and events may be acknowledged." Talk to your seasoned colleagues for suggestions on how to handle argumentative, opinionated visitors. There is no *one right way* to handle visitors who don't acknowledge scientific evidence. Not everyone accepts scientific views and that's okay! Keep in mind that religion is a belief system and beliefs don't necessarily change. Scientific explanations are based on testing and observation and may change as new information becomes available.

The 2001 Management Policies for Grand Canyon National Park states: The content of interpretive and educational programs must be accurate, represent multiple points of view and be free of cultural, ethnic, and personal biases. However, in accordance with section 7.5.5 of *Management Policies* (2001), "acknowledging multiple points of view does not require interpretive and educational programs to provide equal time, or to disregard the weight of scientific or historical evidence." Section 8.4.3 on scientific research states, "Questions often arise around the presentation of geologic, biological and evolutionary processes. The interpretive treatment used to explain the natural processes and history of the Earth must be based upon the best scientific evidence available, as found in scholarly sources that have stood the test of scientific peer review and criticism. The facts, theories, and interpretations to be used will be those that reflect the thinking of the scientific community in such fields as biology, geology, physics, astronomy, chemistry, and paleontology."

For the past 5 to 6 million years, Grand Canyon has been gradually getting wider and deeper. But it hasn't been happening in a regular or systematic way. Periods of intense erosion during the Cenozoic Era have whittled away the canyon walls, creating side canyons and tributaries along the river. Referencing averages for how fast the canyon is getting wider or deeper can be misleading to park visitors who do not know that the erosion of the canyon appears to happen episodically. For example, as glaciers melted 8,000 years ago at the end of the last ice age, an enormous amount of water may have been added to the Colorado River, which could have intensified erosion and deepening of the canyon.

The very basics. When it comes to discussing with visitors how the canyon formed, one of the most important concepts to convey is that all of the rocks formed long before the canyon formed – more than 250 million years before. After the rocks formed, the next major event was the uplift of Colorado Plateau, which occurred from about 70 to 40 million years ago. The canyon itself did not begin to form until about 5 to 6 million years ago, as the Colorado River cut down through the uplifted rock layers. The widening of the canyon has taken place since then, gradually sculpting the canyon into its present panorama. To sum it all up in one sentence: *The rocks were laid down, uplifted, carved by the river, and then the sides of the canyon fell in – all with major gaps of time between these events.*

The Cenozoic Era brings us to today, when both geologic and human forces are at work on Grand Canyon. Glen Canyon Dam maintains the flow of the Colorado River through the canyon. In geologic time the dam will be a short moment in the Colorado River's life (Fig. 2.39). The Colorado River has overcome many natural dams during its life. Over the past 3 million years episodes of volcanic eruptions in the western Grand Canyon created massive lava dams. The lava was extruded from weak areas in the canyon walls and volcanoes near the rim, and then flowed into the canyon, damming the river. Some of the dams were over 2000 feet (610 m) high. One may have been more than 84 miles (135 km) long! Huge lakes were formed as the Colorado River backed up, filling side canyons and depositing sediment. The river overcame those dams after only a few hundred years. As a dam broke, the water would have rushed out, carrying away much of the evidence of the lake and lava dam. Eventually the same fate will come of the current dams on the Colorado River as their lakes fill with sediment, and the powerful Colorado River overcomes its man-made barriers.

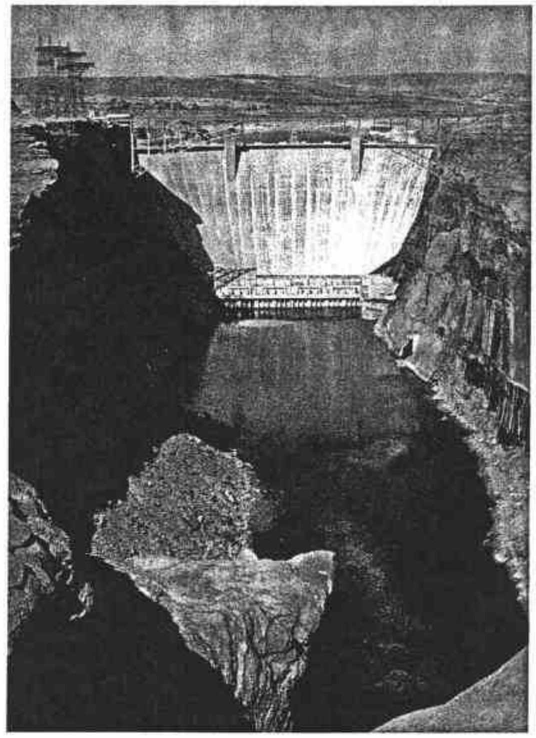


Figure 2.39 – Glen Canyon Dam. Glen Canyon Dam near Page, Arizona, now controls the Colorado River. This dam not only creates a recreational resource (Lake Powell), it also provides water and power for much of Arizona. One day it too will succumb to nature and geologic forces, as it slowly fills with sediment from the muddy Colorado River.

INTERPRETATION: OTHER TIPS FOR INTERPRETERS

FREQUENTLY ASKED GRAND CANYON GEOLOGY QUESTIONS

As an interpreter, you will encounter certain geology questions quite frequently. The following section is designed to help you answer some of the questions that you may get after a geology program or as you are roving (besides 'where is the bathroom?').

What is the oldest rock in Grand Canyon? The youngest rock? The oldest rock in the canyon is the 1840 million year old Elves Chasm Gneiss. It is found in the inner canyon, while the youngest rock is the top layer of the canyon, known as the Kaibab Formation. It is approximately 250 million years old. (Technically, the *very youngest* rocks at the canyon are the recently paved parking lots, roads and paths. One might call that kind of rock "urbanite!")

How did the canyon form? The short answer is that water formed the canyon! Without water the rocks would not have been deposited and the canyon would never have been carved. The rocks of Grand Canyon formed from about 1840 million years ago until 250 million years ago. Subsequently, about 70 to 40 million years ago, these rocks were uplifted to their present elevation of 7000 feet (2100 m) above sea level. The stage was set for the canyon to form. The Colorado River began to carve Grand Canyon about 5-6 million years ago, very recently, geologically speaking. As the Colorado River cut down about one mile (1.6 km), the canyon gradually widened by processes aided by water. Weathering processes like ice wedging and mass movement of rock have widened the canyon to its present width of 5 to 18 miles (8 to 29 km) over the past 5-6 million years (Fig. 3.1).

Why is Grand Canyon here? Part of the reason the canyon is here is because of the type of rocks in the region. The picturesque layered rocks are ***sedimentary rocks***, and they are easier to erode than igneous or metamorphic rocks. Grand Canyon formed here also due to the fact that these rocks are at a

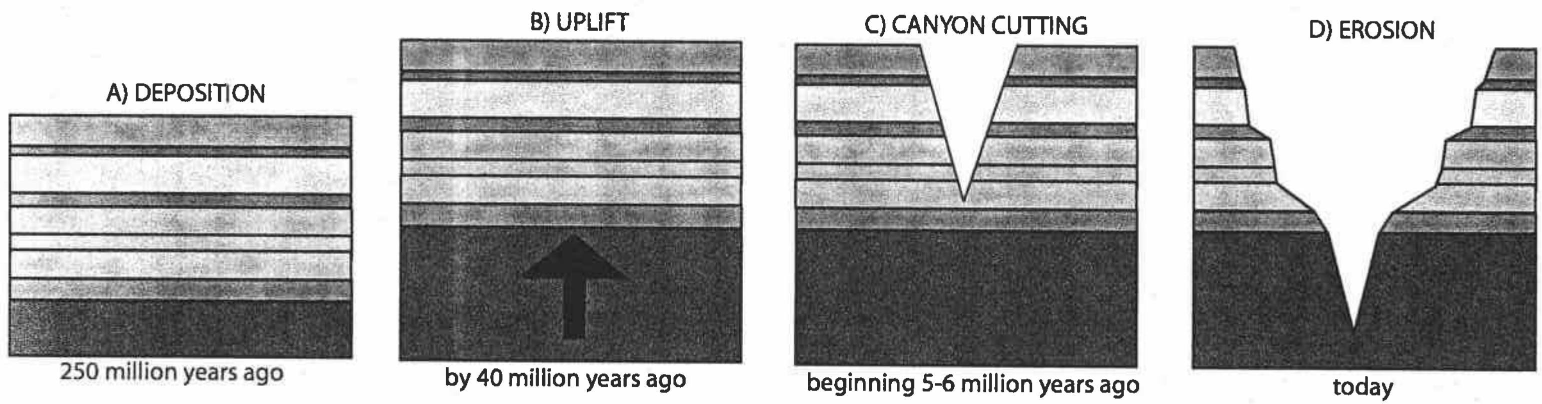


Figure 3.1 – Simplified story of how Grand Canyon formed. a) The rocks that make up the walls of Grand Canyon were first deposited by water or wind. b) Then the rocks were uplifted. c) Much later, the Colorado River began to carve Grand Canyon. d) Over time the canyon walls have fallen in and eroded away, widening the canyon.

high elevation. The rocks were uplifted more than 7000 feet (2100 m) above sea level during a mountain building event that took place 70 to 40 million years ago called the Laramide Orogeny. The high elevation is important because the rock had to be up high enough for the Colorado River to cut *down* through it. During the Laramide Orogeny, the sedimentary rocks were not seriously deformed so they remained mostly ***flat-lying***. If the rocks were not flat-lying, horizontal layers, the canyon would not look the way it does with its alternating cliff and slope layers. It's not just any river that can form a Grand Canyon. The Colorado River is a ***very powerful river***. It was capable of carrying a large volume of sediment, which was like a sand-blaster cutting down through the rock. Grand Canyon exists in this location also because of the ***semi-arid desert climate***. Erosion in a dry climate can be rather sporadic and dramatic, such as when thunderstorm season arrives. Most other times though, the erosion is a gradual process. The rocks are also preserved better in a dry climate than they would be in a humid climate, which tends to dissolve limestone. In a desert climate, there is usually no dense vegetation. So plants do not disguise Grand Canyon, as would be the case if it had formed in a location with a humid climate. **It would not be such a *GRAND* Canyon if the rocks were not uplifted, flat-lying sedimentary rocks, carved by a very powerful river in a dry desert climate!**

Is the canyon getting bigger? As long as Grand Canyon is exposed to the atmosphere and erosional processes it will continue to get bigger. This rate has changed over time and is affected by factors such as climatic changes, sea level changes, ice ages, and even human involvement. The canyon continues to get slightly wider due to physical weathering processes like ice wedging and mass movement, as well as erosion by tributary streams. In the past, great floods with high discharges and sediment loads carved out the depth of the canyon. Now that Glen Canyon Dam controls the Colorado River, these floods are infrequent so the depth of the canyon is probably not changing much. Another contributing factor is that the river had reached the hardest rocks of the canyon, the Precambrian igneous and metamorphic rocks. They are much more resistant to weathering than the overlying sedimentary layers, making it difficult for the river to cut down through them.

Where did the all the rocks that once filled the canyon go? Over the last 5-6 million years, since the Colorado River first began to carve the canyon, sediment has been carried down river toward the Gulf of California. However, in the past the Gulf of California was much further north than it is now, near Needles, California (Appendix 1). Sediment and rock that was once in Grand Canyon have deposited in the Lake Mead area, down to Needles, and southward. Now with Hoover Dam just beyond western Grand Canyon, any sediment that comes out of Grand Canyon is deposited in Lake Mead.

What lies beneath Grand Canyon? Beneath Grand Canyon there is more metamorphic and igneous rock similar to the rock in the inner canyon. This type of rock and rocks of similar mineral composition continue at least 19 to 25 miles (31 to 40 km) below the canyon (Fig. 3.2). Below that is the mantle layer of the Earth, which is composed of mainly the igneous rock called peridotite (Fig. 1.20).

How are the rock layers and fossils dated? The igneous and metamorphic rocks of Grand Canyon have been dated using radioactive isotopes. Minerals in the crystalline igneous and metamorphic rocks in the inner canyon have been dated using isotopes of uranium, which decays to lead (^{238}Ur-^{206}Pb) with a half-life of 4500 million years. Because sedimentary rocks are often composed of minerals from other rocks, radiometric dating would give the age of the rock the minerals came from, not when the sedimentary rock formed. Sedimentary rocks at Grand Canyon have been dated using their fossils, and correlating them to the same kinds of fossils in other layers in the world with known ages. These various techniques of dating the layers of rock at Grand Canyon have helped geologists see when the rocks formed over geologic history of the Earth (Fig. 3.3).

How do we know the age of the canyon? The length of time that it took to form the canyon has been estimated using basalt flows that erupted in western Grand Canyon, and gravels and sediment that were deposited by the Colorado River once it had established its course through Grand Canyon. In western Grand Canyon, basalt flows overly rim gravels that were deposited by older streams

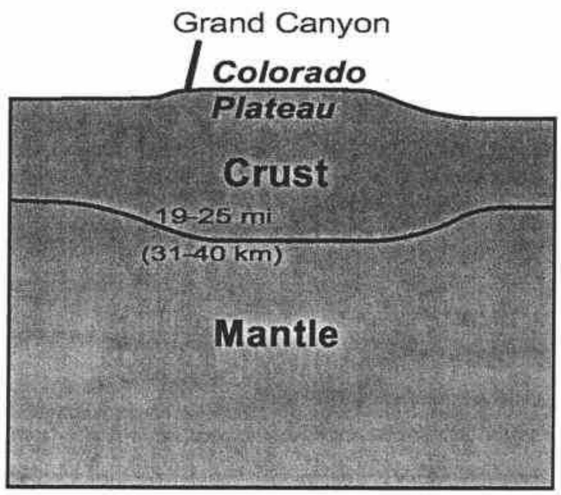


Figure 3.2 – Below Grand Canyon. This cross-section of the Earth below Grand Canyon shows that the crust is about 19 to 25 miles (31 to 40 km) thick. Most of the crust is solid rock material composed of silica-rich minerals similar to the metamorphic and igneous rocks found in the inner canyon. The mantle below is composed primarily of the igneous rock called peridotite.

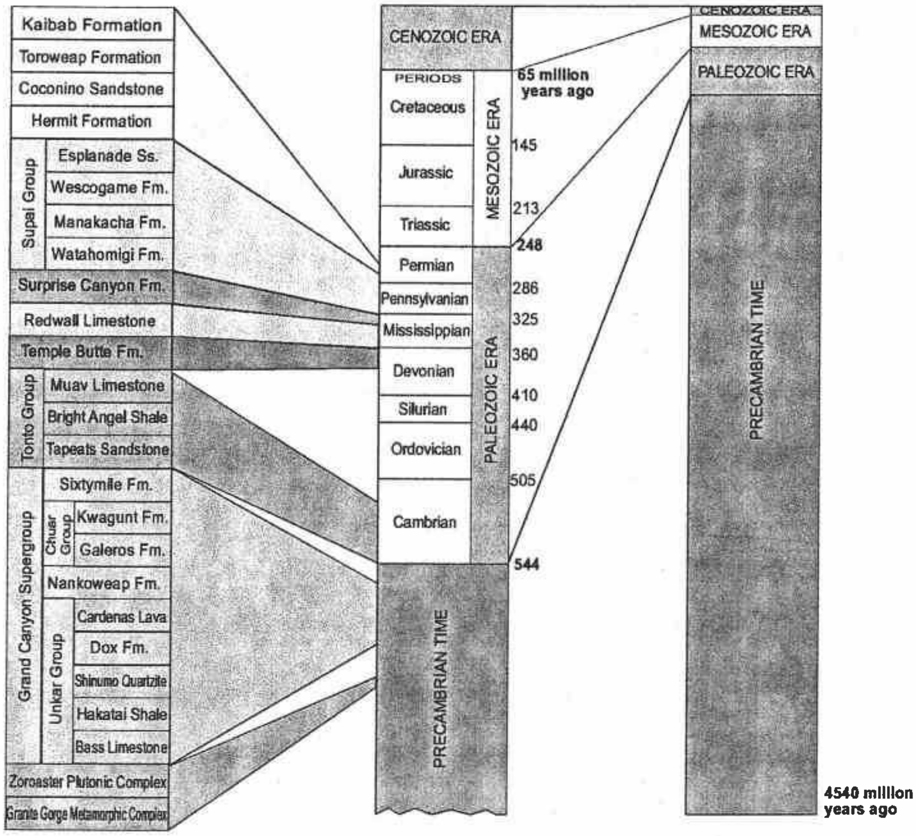


Figure 3.3 – Geologic time scale for Grand Canyon. The different rock layers of Grand Canyon are depicted to show their approximate ages. The geologic time scale in the middle is not drawn to scale, but the time scale on the right side has the correct proportions. Notice that Precambrian Time covers about 87% of the Earth's history. *(Diagram adapted from L. Greer Price, An Introduction to Grand Canyon Geology, 1999)*

before the Canyon existed. The age of this basalt is approximately 6 million years old, which tells us the canyon *did not* exist before 6 million years ago. Other younger basalt flows have flowed into the canyon to the present river level, and they have been measured to be 1.2 million years old. This tells us that the canyon was always as deep as it is now (about one-mile) by 1.2 million years ago. Also, sediment that originated in Grand Canyon was deposited by the Colorado River in the Lake Mead area 4.8 million years ago, which implies that the Grand Canyon was beginning to form by that time.

Why are features like mesas, buttes, and temples still standing? Tall features have remained while the rocks around them were eroded away due to several factors. At Grand Canyon the rocks were all continuous layers prior to the canyon forming. The rock on the top of the tall features is usually one of the hard rock types, like limestone or sandstone, but they are just the same as the rock that was eroded away around them. The rock that once surrounded the mesa, butte, or temple may have had fractures, joints, or some other weaknesses in it, making it more susceptible to weathering. Tall features in the canyon are the remnants of the layer that was once continuous. They are just the last to be eroded away.

Why do the canyon walls have a stair-step shape? Different rock types erode at different rates. Hard rock types, like sandstone and limestone, have the ability to withstand intense weathering; while softer rock types, like shale, do not endure as well. The canyon walls have a variety of these three rock types. Where a soft layer erodes, the canyon wall develops a gentle slope because the rock is so easily removed. On the other hand, harder rock layers that are more resistant to weathering form steep cliffs and break off sporadically in large chunks (Fig. 3.4).

Is the Colorado Plateau and Grand Canyon region currently being uplifted? Maybe – this is an issue that is still debated amongst geologists. Some geologists speculate that uplift is still occurring on the Colorado Plateau, but a good reason for the uplift has not been conclusively identified. Other geologists agree that most of the uplift of the Colorado Plateau took place during the Laramide Orogeny, from about 70 to 40 million years ago, and there is only an *illusion* of uplift today. Sometime between 20 and 15 million years ago, the Basin and Range Province began to form adjacent to the Colorado Plateau and Grand

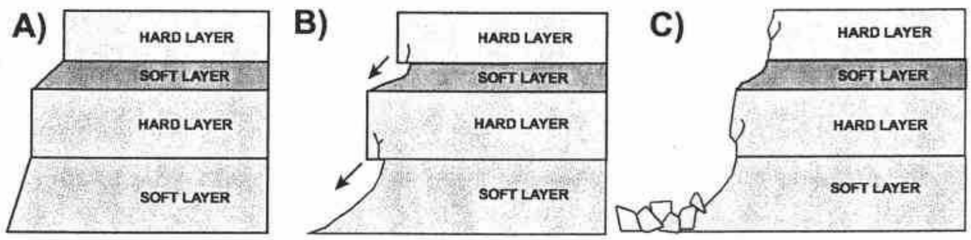


Figure 3.4 – Erosion of canyon walls. a) The alternation of hard and soft rock cause the stair-step shape of the walls of Grand Canyon. b) Because soft layers erode easier and faster, they undercut the hard layers above, leaving them no support from below. c) The harder rocks eventually break off in large chunks, which could cause a mass movement. This begins the process over, exposing the soft layer to erosional processes and gradually widening the canyon.

Canyon region, activating normal faults as the region was extended and stretched. As extension continues, the southwestern edge of the Colorado Plateau and the Grand Canyon region is affected by the extension of the Basin and Range causing normal faulting to occur. Along the normal faults, the western side of the faults drops down, causing the western end of the canyon to gradually lower in elevation (Fig. 3.5). As the westernmost edge of the Colorado Plateau and Grand Canyon drops down, it gives the illusion of uplift of the Plateau.

Are the faults in Grand Canyon active? Faults in western Grand Canyon, such as the Toroweap Fault and Hurricane Fault, have been active as recently as 3 million years ago (Fig. 3.6). Most other faults have not been active since the Laramide Orogeny (70 to 40 million years ago).

ANALOGIES FOR INTERPRETING GEOLOGY

Analogies are some of the most useful tools that interpreters have, especially when it comes to geology. The following section provides just a few of the analogies that have been successfully used by other interpreters at Grand Canyon.

- **How Grand Canyon formed.** Forming Grand Canyon is somewhat like making a cake according to Grand Canyon Interpretive Park Ranger Katie Sullivan. Her recipe goes like this:
  1. *Deposition.* Deposition of the rocks is like gathering the ingredients for the cake. At Grand Canyon the ingredients are the main rock types. This could be sedimentary, igneous, and metamorphic, or the three common sedimentary types (limestone, sandstone, and shale). So gather your ingredients (the rocks) but do not mix, just arrange them in nice layers in the pan.
  2. *Uplift.* Put the ingredients into the oven. The “cake” rises due to plate tectonic processes (the Laramide Orogeny) and uplifts the Colorado Plateau.

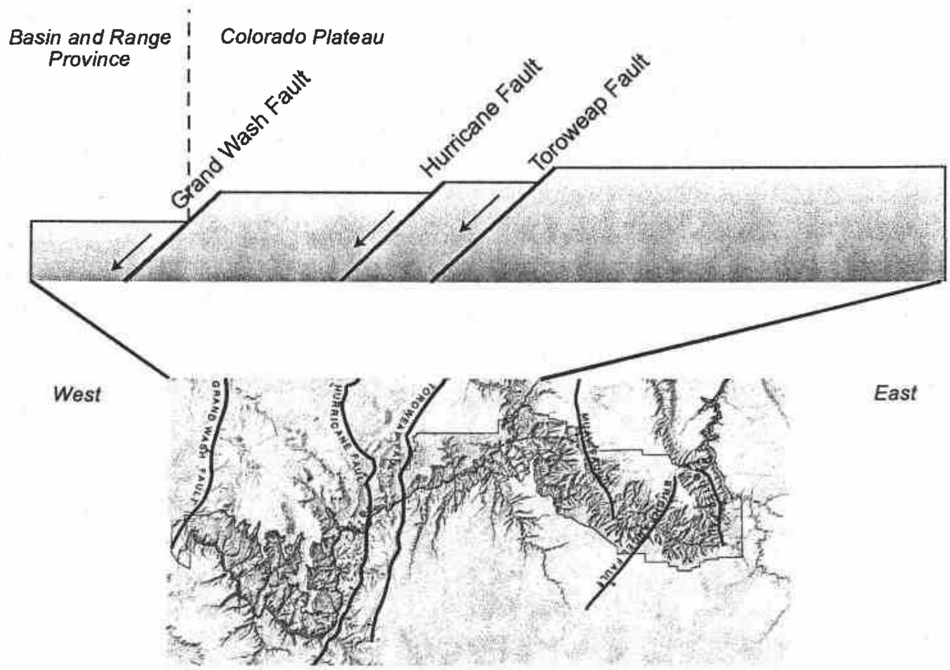


Figure 3.5 – Down-dropping along normal faults. The upper diagram is a cross-section of what the Earth may look like in western Grand Canyon. The western block of the faults drops down in response to the extension and rifting of the nearby Basin and Range Province. The boundary of the Colorado Plateau and Basin and Range Province is at the Grand Wash Fault. This down-dropping in the west may be producing the illusion that the Grand Canyon region and Colorado Plateau have been uplifted.

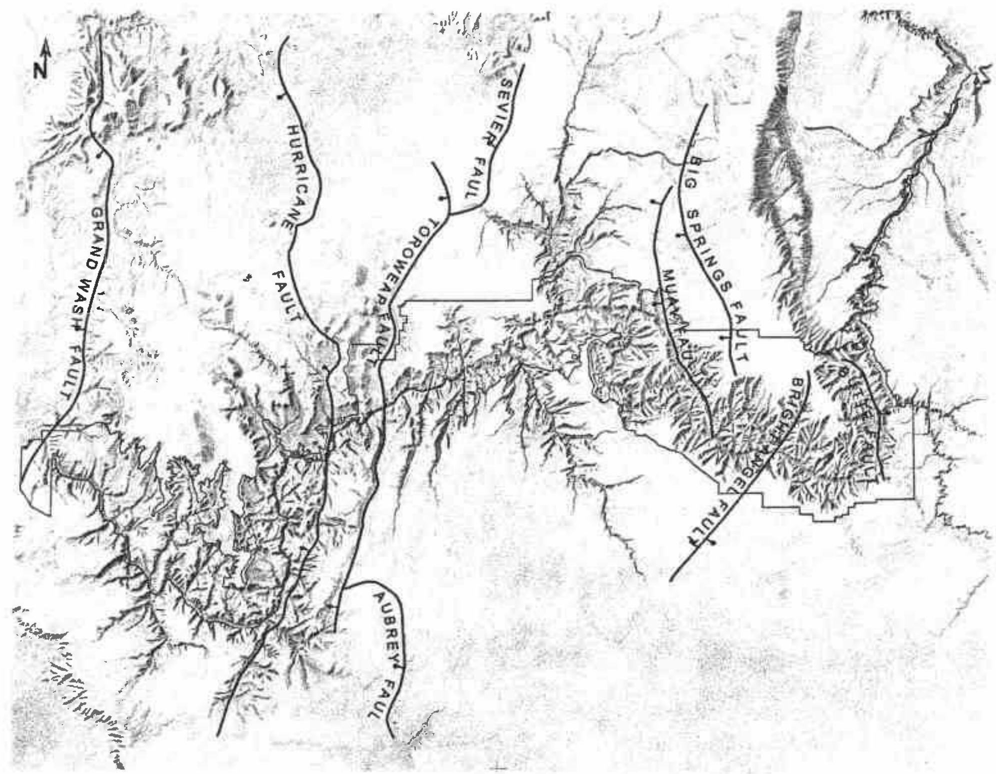


Figure 3.6 – Map of faults in Grand Canyon. Some of the prominent faults in Grand Canyon are shown on this diagram. Most of these faults formed during Precambrian Time and were reactivated during the Laramide Orogeny (70 to 40 million years ago). Some of these faults have been reactivated as recently as 3 million years ago, such as the Toroweap and Hurricane Faults, because of extension in the Basin and Range Province.

3. *Erosion.* The cake is cut by a knife (the Colorado River) and the "crumbs" fall to the center of the cut (canyon widening). Weathering and erosional processes are like someone eating/nibbling away the sides of the "cake" and widening the canyon.

- **Laramide Orogeny.** The event that caused the uplift of the Colorado Plateau and formation of many western mountains was like two cars crashing into each other. As the Farallon Plate collided with and subducted beneath the North American Plate, it created a mess of uplifted, folded, crinkled, broken, faulted rocks. Just like when two cars crash, the metal of the cars gets bent and mangled.
- **Colorado Plateau and the Laramide Orogeny.** Grand Canyon Interpretive Park Ranger Allyson Mathis continued with the above analogy of the car crash and the Laramide Orogeny. The Colorado Plateau was like a "safety cage" during the collision. The Earth around the Colorado Plateau was much more crumpled and mangled, while the Plateau withstood serious deformation.
- **Earth's layers.** Grand Canyon Interpretive Park Ranger Keith Green likes to use peanut M&M's to represent the Earth and its compositional layers. The thin candy coating is like the crust of the Earth. The chocolate is the mantle, and the peanut is the core of the Earth.
- **Significance of geology at Grand Canyon.** Volunteer Naturalist Anna Licameli (Summer, 2000) used a watermelon to help visitors understand the geologic significance of Grand Canyon. If you had never seen the inside of a watermelon and just saw the green and white rind, you may never guess that a watermelon was pink with black seed inside unless it was cut it open. Similarly, the Earth is like a watermelon. Grand Canyon is like a slice into the watermelon (the Earth), which allows us to see some of the rock that lies beneath our feet. The Colorado River has acted as a knife, cutting it open so we can get a peek at what's inside.
- **Depositional environments.** Grand Canyon Interpretive Park Ranger Jim Heywood likes to help visitors understand the depositional environments by relating them to other vacation spots. Many of the sedimentary layers at Grand

Canyon were deposited in environments that are similar to locations on Earth today. For example the Tonto Group (Tapeats Sandstone, Bright Angel Shale, and Muav Limestone) were deposited in a warm, tropical environment south of the equator. It may have been similar to the climate of the Caribbean, but with one major difference – NO PLANTS! The Supai Group and the Coconino Sandstone were formed in a semi-arid coastal environment that may have been like southern, coastal Texas, such as Galveston and Padre Islands. The Kaibab Formation was deposited in a warm, equatorial inland sea, which may have looked like the Hudson Bay, but the climate would have felt more like Hawaii or the Caribbean.

- **Geologic time.** If the age of the Earth could be viewed as one year, the Earth formed on January 1. "During January and part of early February, the Earth became organized into core, mantle, and crust. On about February 21 life evolved. During all of spring, summer and early fall the Earth evolved to continents, and ocean basins something like those of today and plate tectonics became active. On October 25, at the beginning of the Cambrian Period, complex organisms, including those with shells arrived. On December 7 reptiles evolved, and on Christmas Day the dinosaurs became extinct. Modern humans, *homo sapiens*, appeared on the scene at 11 pm on New Year's Eve, and the last glacial age ended at 11:58:45 pm. Three-hundredths of a second before midnight, Columbus landed on a West Indian island. And about a few thousandths of a second ago, you were born." (Press, Frank and Raymond Siever, *Understanding Earth,* ©1994, W.H. Freeman and Company)
- **Layers of rocks at Grand Canyon.** The layers of rock in the canyon can be related to pancakes. When you make pancakes, you stack the pancakes on a plate, with the oldest one on the bottom of the stack and the freshest pancake on top. The rocks in the canyon are laid down in the same way with the oldest at the bottom of the canyon and the youngest at the top. If an inexperienced chef (like myself) were making the pancakes, the first ones may burn and be overcooked, similar too the "well-done" metamorphic and igneous rocks at the bottom of Grand Canyon. And the freshest, evenly cooked pancakes are at the top.

- **Geologic time.** Former Grand Canyon Interpretive Park Ranger Kathy Daskal found this one. If you view formation of Grand Canyon and its rocks on a 24-hour timeline, its 2 billion year history would begin at midnight. At midnight the Precambrian metamorphic and igneous rocks of the inner canyon are formed. At noon (12 hours later), the first ocean moves in from the west and retreats back to the west a few minutes later, leaving the first sedimentary layers behind. From noon till 9pm, six more oceans come and go leaving behind the layers seen today at Grand Canyon. At 11:00pm on this very long day, uplift of the Colorado Plateau begins. At 11:45pm the Colorado River begins carving through the rock layers (about 5 million years ago). And then at 11:59:59pm humans arrive at Grand Canyon.

VISUAL AIDS FOR INTERPRETING GEOLOGY

Visual aids are especially useful tools to help convey difficult concepts such as geologic time, and the help get visitors (especially children) involved and interested. Here are a few suggestions that may help you.

- **Geologic time.** Use your arm span as a time line. Hold your arms out to your side. Designate the tip of your right hand as the beginning of the Earth 4600 million years ago, and the tip of your left hand as today.
  a) The Precambrian schist and granite formed at your left shoulder
  b) The first Paleozoic sedimentary rock (Tapeats Sandstone) formed at the middle of your left forearm
  c) The deposition of the last Paleozoic layer (Kaibab Formation) and the beginning of the time of the dinosaurs occurred at your left at wrist, getting closer to today
  d) The extinction of the dinosaurs and the uplift of the Colorado Plateau (Laramide Orogeny) began at last joint of your longest finger on your left hand
  e) The beginning of the cutting of Grand Canyon is at the end of your fingernail bed (pink stuff) of your longest finger closest to you fingertip!

f) Humans did not come along until the very end of your fingernail! You could erase all of human civilization with just a nail clipper!

- Former Grand Canyon Interpretive Park Ranger Phyllis Northup had visitors trace a profile of a canyon wall with their fingertip and one eye closed. It can help them develops a keen awareness of the landscape of cliffs and slopes due to the different rock types.
- Phyllis Northup also liked to have signs or posters with names of rock layers and their ages. Kids can hold the signs and make a visual time line.
- Folks at Dinosaur National Monument like to use a geologic yardstick. Here's how some of Earth history events would measure up on a yardstick (total 36 inches):
  - ❖ At 36 inches, the Earth was born.
  - ❖ The oldest known rocks on Earth were formed at 31 inches.
  - ❖ The first fossils of single celled organisms formed at 28 inches.
  - ❖ At about 4¾ inch multi-cellular life began to evolve.
  - ❖ At 4½ inch life diversified tremendously in the Cambrian Period.
  - ❖ The massive extinction at the end of the Paleozoic Era occurred at about 2 inches.
  - ❖ From 1¾ to about ½ inch the dinosaurs lived.
  - ❖ And finally at less than ½ inch the first members of the human family of primates appeared.
- Also coming soon to Grand Canyon will be the Trail of Time! The Trail of Time will be the most hands-on visual aid yet mentioned, and will be constructed right along the Rim Trail. The Trail will be marked so that one-meter represents one million years of Earth history. Visitors will have an opportunity to learn about fundamentals of geology, important events in the Earth's history, and the geology of the Grand Canyon region as they walk along and enjoy the spectacular scenery and classroom of Grand Canyon! It is still in its early planning stages, but will hopefully be opening along with the newly renovated Yavapai Geology Museum.

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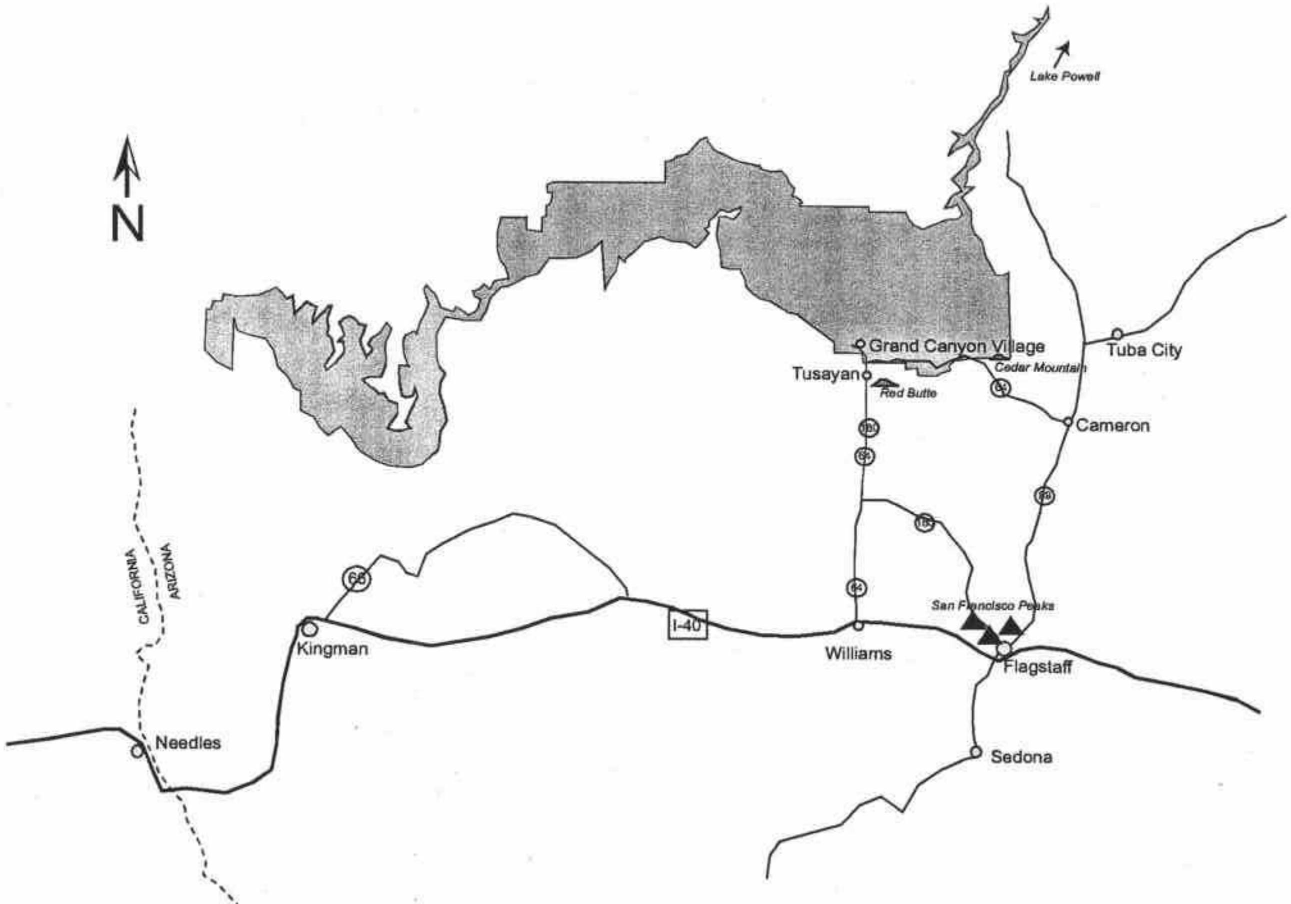

Appendix 1 - Regional Map. The green area is the approximate area of Grand Canyon National Park.

APPENDIX 2: GLOSSARY

absolute age – a number or age unit that is assigned to signify the age of something

angular unconformity – a gap in the geologic record formed where horizontal layers lie directly on top of layers that have been tilted

anticline – an upward fold in rock layers (in the shape of an "A"), where the youngest layers are usually on the top of the fold, and the oldest layers are in the middle of the fold

asthenosphere – the soft solid layer of mantle that lies below the lithosphere and drives the movement of tectonic plates

atom – the smallest particle of an element, composed of protons, neutrons and electrons

atomic number – the total number of protons in an atom

atomic weight – the total of the masses of the protons and neutrons in an element

basalt – a dark, extrusive igneous rock composed of small, low silica, iron-rich minerals

base level – the elevation of a stream's mouth or outlet; the lowest elevation that the stream can cut down to

butte – a landscape feature with a flat top that is at least as tall as it is wide

calcrete – (see *caliche*)

caliche – a hard, white substance composed of primarily calcium carbonate that forms on the surface of limestone

chemical weathering – the process by which the chemical make-up of a rock is broken down and minerals that make up the rock are altered

chert – a hard substance composed of very fine quartz crystals, made of pure silica (SiO_2), which can form irregularly shaped nodules and blobs

continental crust – the thick, buoyant crustal material that underlies continents, which causes the land to float higher on the mantle and sit above sea level

convergent plate boundary – where two plates slowly collide and one plate usually subducts beneath the other, which causes volcanoes to form on the over-riding plate and earthquakes to occur

convection – the transport and circulation of energy due to differences in density caused by the circulation of less dense hot material as it rises while cold, denser material sinks

core – the center portion of the Earth, which is composed of heavy nickel and iron material

cross bedding – the angled layered appearance in a sedimentary rock, formed as wind or water deposits particles in ripples or sand dunes

crust – the Earth's outermost layer, which is mainly composed of compounds of oxygen and silica (silicates)

crystalline – a description of metamorphosed rock and/or intrusive igneous rock with large, visible mineral crystals

daughter isotope – the product of radioactive decay of an unstable, radioactive parent isotope

delta – the triangular sedimentary feature formed where a river meets the ocean or some large body of water, and the sediment carried by the river begins to settle out and deposit

dike – a vertical intrusive igneous feature formed when magma cuts across or squeezed into rock **discharge** – the volume of water that a river or stream carries

disconformity – a gap in the geologic record between sedimentary layers, formed when there is a period of erosion or no deposition, but there is no tilting of the layers

divergent plate boundary – where two plates rip apart, and move in opposite directions, usually accompanied by volcanoes and small, shallow earthquakes

earthquake – the energy released due to built up strain energy along a fault

element – the most basic form of matter, with distinct physical and chemical properties

eolian – sediment transported and deposited by wind, such as sand dunes

erosion – the transport of rock material by forces such as water and wind that takes place subsequent to weathering

estuary - a body of water near a shoreline that is joined with the ocean where fresh and saline water mix

extrusive – igneous rocks that form as lava pours out onto the Earth's surface and quickly cools (volcanic)

evaporite – a mineral that was once dissolved in water, but as the water evaporated the mineral was leached out

fault – a crack in rocks with movement parallel to the surface of the crack

flint – dark grey chert colored by impurities

fluvial – river or stream depositional environment

fold – a bend in rocks that were once horizontal and flat

foliation – the parallel alignment of minerals in metamorphic rocks

formation – a mappable rock layer of a distinct and recognizable rock type that can be distinguished from the rocks above and below it

fossil – any remains, traces, or remnants of once living organisms that are at least 10,000 years old

fracture – (see *joint*)

geology – the study of the Earth and the processes above and below its surface that shape it

geomorphology – the study of the geologic processes that create landscapes on the Earth's surface and shape geologic landforms

glauconite – a common mineral in clay or shale that often has a greenish color

gneiss – a highly metamorphosed rock with foliation of light and dark bands of minerals

gradient – the slope of a stream or change in elevation of the channel over some distance

granite – a light, usually pink colored, intrusive igneous rock composed of large, high-silica minerals

groundwater – water that flows through channels and pores spaces within rocks beneath the Earth's surface

group – several formations, in stratigraphy, that represent similar depositional environments in a time period

gypsum – a soft evaporite mineral usually colorless, yellow, white, grey, or pink

half-life – the amount of time it takes for half of a parent isotope to decay to form a daughter isotope

headward erosion – the process of erosion from the steepest parts of river channels as a river cuts back towards its headwaters

hydrology – the study of the movement of water

ice wedging – the physical weathering process that occurs when water freezes in cracks and the ice expands, gradually widening the cracks in the rock

igneous rock – cooled and hardened Earth material that was once partly or completely molten

inner core – the center-most, solid portion of the Earth, composed of the densest and heaviest materials

intertidal zone – a low-lying area near sea level that is sometimes submerged and other times exposed due to tidal or sea level changes

intrusive – igneous rocks that cool and harden slowly beneath the Earth's surface (plutonic)

isotope –one of many forms of an element that has the same number of protons, but a different number of neutrons, giving it a different atomic weight; one element can have several isotopes and all may not be radioactive

jasper – red chert colored by impurities

joint – a crack in a rock with no up or down movement of the rock parallel to the crack

lava – igneous, molten rock that comes out of the Earth onto the surface

limestone – a sedimentary rock composed mainly of calcium carbonate ($CaCO_3$), or lime, that has chemically precipitated from seawater and settled on the sea floor, eventually forming a hardened rock

lithosphere – the Earth's solid outer layer made up of both the crust and the uppermost part of the mantle; it is divided into tectonic plates

mantle – the layer between the core and the crust of the Earth made up of compounds of oxygen and silica (silicates) rich in iron and magnesium

magma – igneous, molten rock that exists below the Earth's surface

mass movement – the physical weathering process that occurs when huge portions of rock are washed away

mechanical weathering – (see *physical weathering*)

member – the most basic division of layers of rock used in stratigraphy

mesa – a large, flat-topped hill that is wider than its height

mesosphere – the lower, solid layer of the mantle that lies between the asthenosphere and the outer core

metamorphic rock – sedimentary, igneous, or other metamorphic rocks that have been changed by heat and/or pressure

mineral – a substance that occurs naturally, is inorganic, and is composed of different elements combined to make a crystalline solid

monocline – a fold that is neither an anticline nor a syncline, with only one folded side, which looks similar to a ramp

mud crack – a sedimentary feature formed when mud is expose to air, dries and cracks into pieces

nonconformity – a gap in the geologic record formed where sedimentary layers lie directly on top of intrusive igneous or metamorphic rock

normal fault – a fault that forms as the upper block drops down relative to the lower block, usually as a result of pulling or extensional geologic forces, such as occurs at divergent plate boundaries

ocean crust – the thin, heavy crustal material that exists beneath the oceans

outer core – the liquid, outer portion of the core of the Earth

parent isotope – the initial unstable, radioactive isotope that decays to form a daughter isotope

physical weathering – the simple breakdown of the rocks by physical processes, without any chemical changes (mechanical weathering)

plate tectonics – the theory that states that Earth's outer shell is composed of plates that move and interact with each other

pluton – a large chamber that holds magma beneath the Earth's surface

plutonic – (see *intrusive*)

precipitate – the process that forms solids from liquid as chemicals interact; or the solids that form due to liquid chemical reactions

Principle of Original Horizontality – the concept that rock layers are deposited as flat, horizontal layers, therefore if the layers are tilted or bent, they must have been deformed by some later geologic event

Principle of Superposition – the concept that layers are deposited one on top of another over time, therefore the oldest layer is on the bottom, and layers above are progressively younger

radioactive isotopes – isotopes that are unstable and naturally decay to form stable isotopes

radiometric dating – the absolute dating of materials performed by comparing the amount of parent and daughter isotopes within the material

reactivation - when a fault is "re-broken" in response to geologic forces that occur after those that formed it

regression – when the shoreline moves away from land, possibly because of a lowering of sea level or uplift of the land

relative age – a comparative age without a number value assigned

reservoir – a lake or body of water that forms as water backs up behind a dam or other obstruction

reverse fault – a fault that forms as the upper block is shoved up relative to the lower block, usually as a result of compressional geologic forces, such as occurs at convergent plate boundaries

rim gravel – gravel deposited by an ancient river or stream that flowed northward over the Grand Canyon region before the canyon existed

ripple – miniature dune-like features that form as water transports and deposits fine particles

rock – an aggregate of different minerals that have been chemically or physically cemented together

rock fall – the physical weathering process that occurs when any small or large rock breaks off and free falls

rockslide – the physical weathering process that occurs when a large portion of rock breaks off along a weak zone and slides down slope, usually because of excess water

sandstone – a sedimentary rock composed of particles of sand that are cemented together by chemical processes and pressure

schist – a metamorphic rock with platy minerals, such as biotite mica, that have a parallel orientation

shale – a sedimentary rock composed of very tiny particles of mud, silt, and sand that are compressed together (siltstone)

silicate – a mineral rich in compounds of oxygen and silica

sill – a horizontal layer of igneous rock that forms as magma pools between horizontal layers of rock

sediment – particles of rock of any size

sediment load – the amount of sediment carried by a river

sedimentary rock – a rock 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

seismic wave – a vibration of energy that travels through the Earth after a sudden movement of rock during an earthquake

spire – a landscape feature that is tall and slender, and usually much taller than they are wide (temple)

stratigraphic column – a cross-sectional drawing that describes rock types and features in rock layers

stratigraphy – the study, description, and classification of different sedimentary rock layers, or strata

stream capture – when one stream intersects with another stream and diverts the water into its channel, leaving the other channel abandoned

strike-slip fault – a fault that forms where parts of the Earth's crust slide past one another, such as along transform plate boundaries, with little to no vertical movement of the rocks on either side of the fault

stromatolite – a finely layered fossil formed of alternating layers of mats of algae and very fine sediment layers

structure – a feature created as the Earth's crust is deformed, such as a fault, fold, or fracture

structural geology – the study of deformation of the Earth's crust, such as folding and faulting of rocks

subduction zone – where two plates collide and one plate is shoved beneath the other (subducts)

supergroup – a large group of formations in stratigraphy

syncline – a downward fold in rock layers (in the shape of an "U"), where the oldest layers are on outside of the fold, and the youngest layers are in the middle of the fold

tectonic plates – large pieces of the Earth's hard outer shell (the lithosphere) that move slowly over the asthenosphere

topography – the difference in elevation between high points and the surrounding region on the Earth's surface

trace fossil – a fossilized remain of a once living organism, such as a track, mold, or footprint, that does not include actual parts of the organism

transform plate boundary – where two plates slide past one another, often accompanied by earthquakes, but not volcanoes

transgression – when the shoreline moves inland over a region, possibly because of a rise of sea level or lowering of the land

unconformity – a gap in the geologic record formed as rocks are deposited followed by a period of erosion or a period when no rocks are deposited

volcanic – (see *extrusive*)

weathering – the process of rocks being physically or chemically broken down