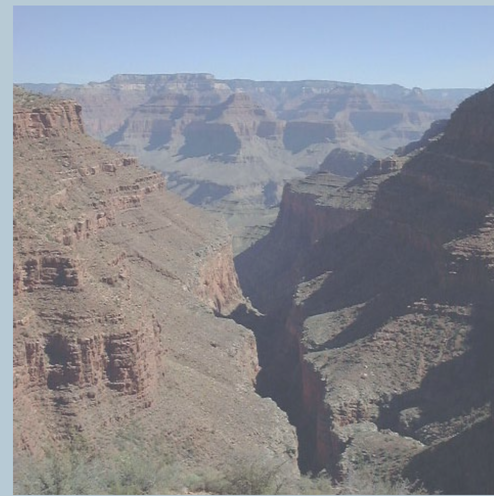
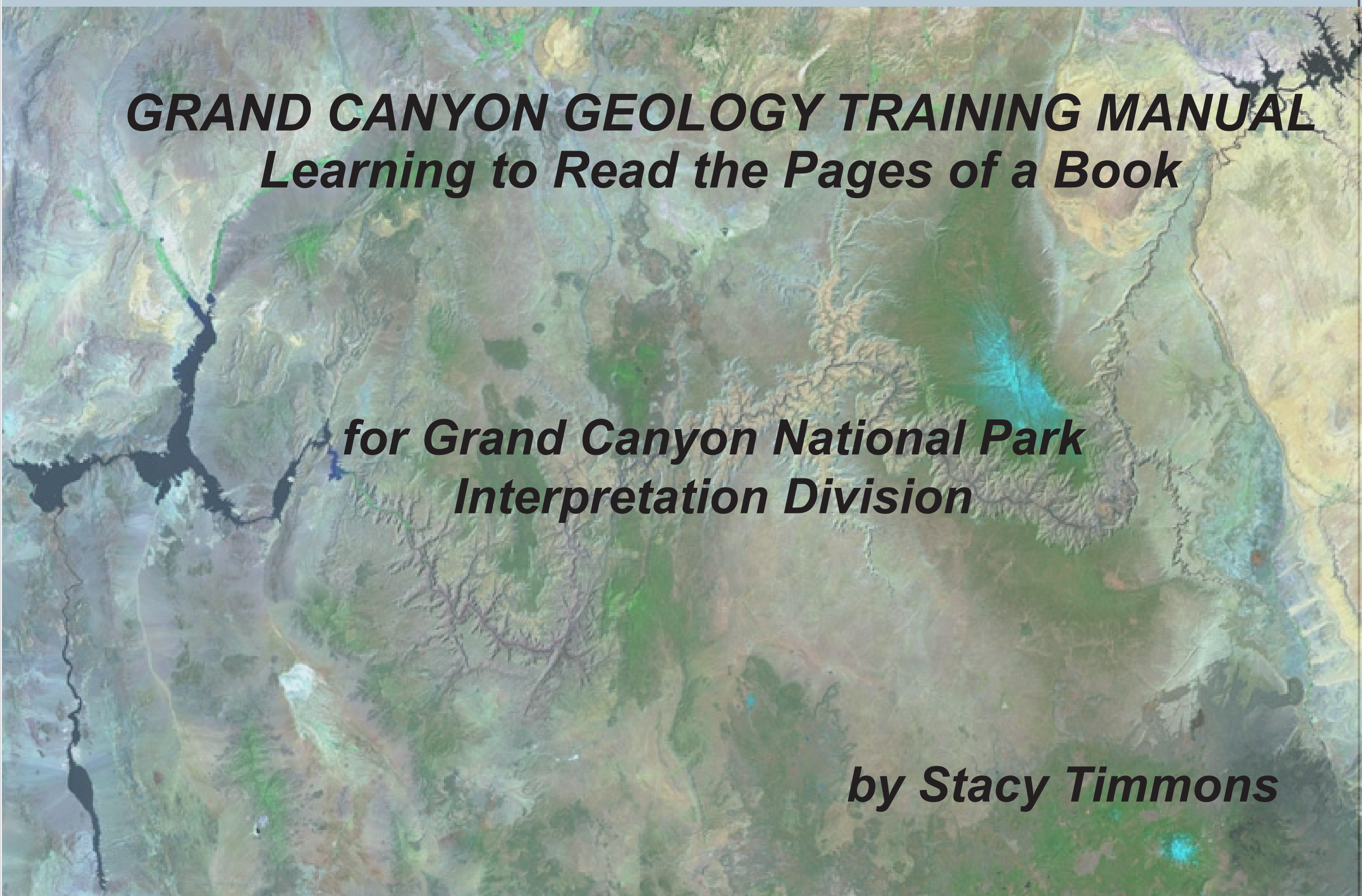
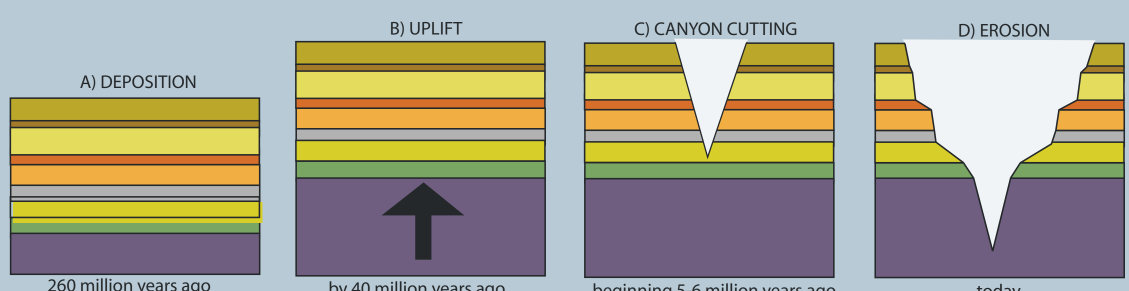


GRAND CANYON GEOLOGY TRAINING MANUAL
Learning to Read the Pages of a Book



for Grand Canyon National Park
Interpretation Division

by Stacy Timmons



Local Geology • Written for Interpreters • Introductory to Advanced

GRAND CANYON GEOLOGY TRAINING MANUAL
LEARNING TO READ THE PAGES OF A BOOK

Stacy Timmons

December 16, 2003

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Dedicated to the beautiful spirit of my mom, Jean Marie Wagner,
who taught me to love life and believe in my dreams.

Special thanks to:
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About the author:
Stacy Wagner created this geology training manual as part of her masters degree studies at Oregon State University. She worked for two summers as a seasonal interpretation ranger at Grand Canyon National Park. Working in the park was life changing for her, helping her develop deep appreciation for the Colorado Plateau geology and the southwestern US. She now lives in Socorro, NM, and works for the New Mexico Bureau of Geology and Mineral Resources.

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Learning to Read the Pages of a Book

PREFACE

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

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

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

Chapter 1: LEARNING THE LANGUAGE OF GEOLOGY

Introduction

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

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

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

GEOLOGY AT GRAND CANYON

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

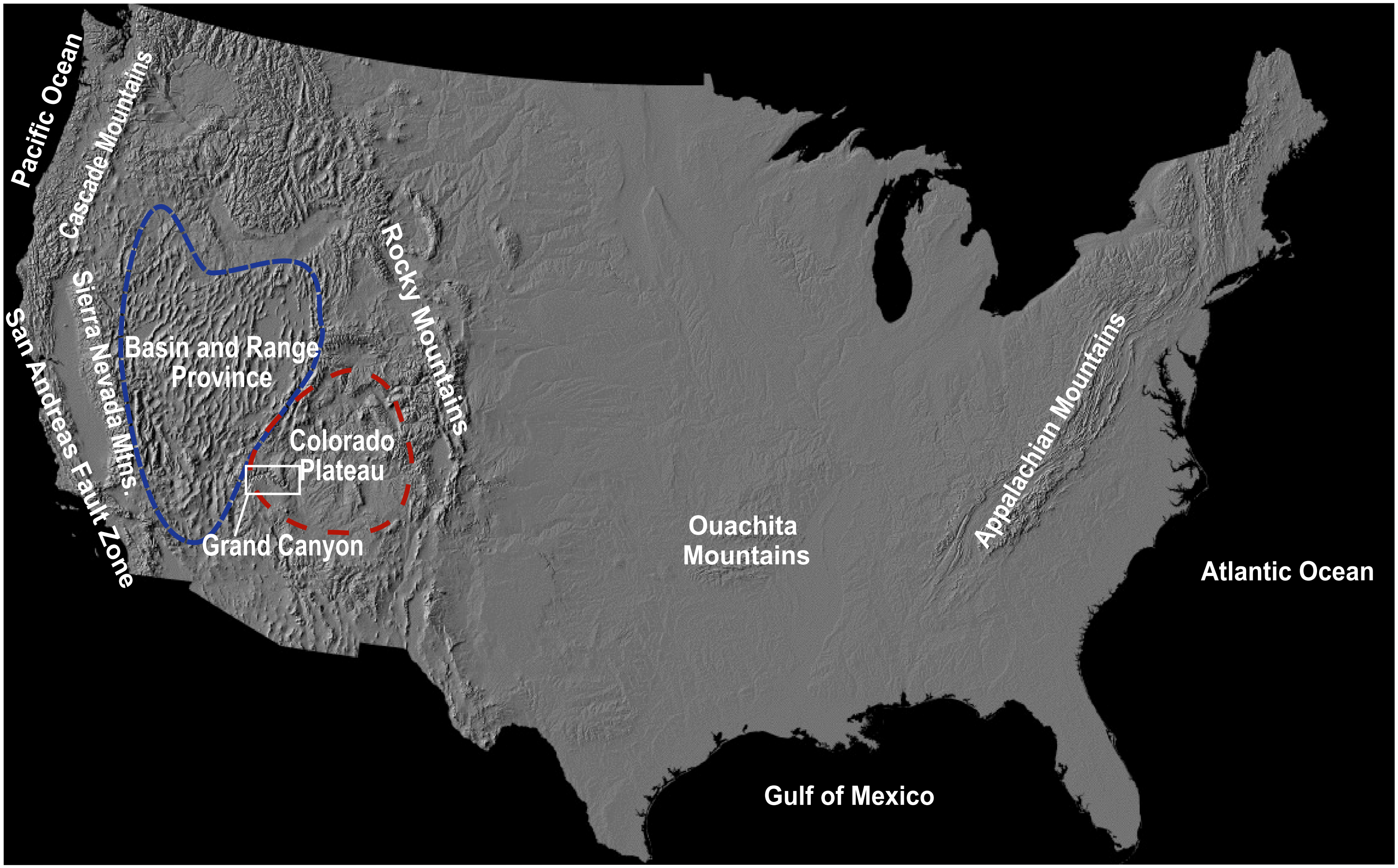


Figure 1.1 – Shaded relief map of United States. *Large landscape features, such as long mountain belts, broad flat plateaus, and rift zones, have formed as a result of millions of years of tectonic plate interactions. The Basin and Range Province is a large region that is presently being pulled apart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

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

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

PLATE TECTONICS

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

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

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

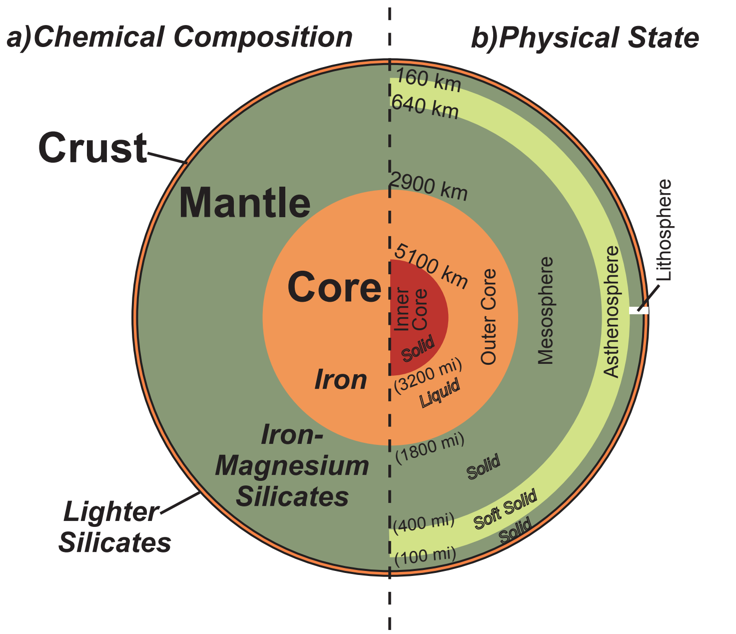


Figure 1.2 – The Earth's inner layers. *a) The left half shows the divisions of the Earth based on chemical composition (what the layers are made of). When the Earth was forming, the crust, composed of minerals rich in oxygen and silica called silicates, floated and formed the very thin crust. The mantle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

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

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

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

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

Tectonic Plate Movement

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

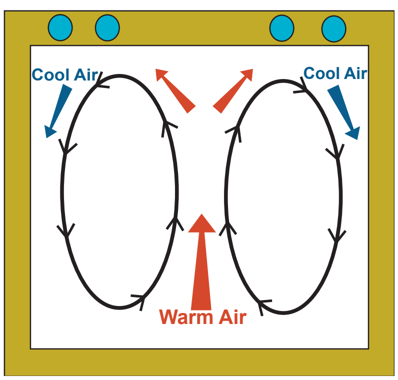


Figure 1.3 – Convection currents. *The Earth's asthenosphere circulates in a similar way as air in an oven. As heated air rises and then cools, it drives circulation by convection, which occurs because of differences in density. Cool air is denser than warm air, so it sinks while warm air rises. In this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

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

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

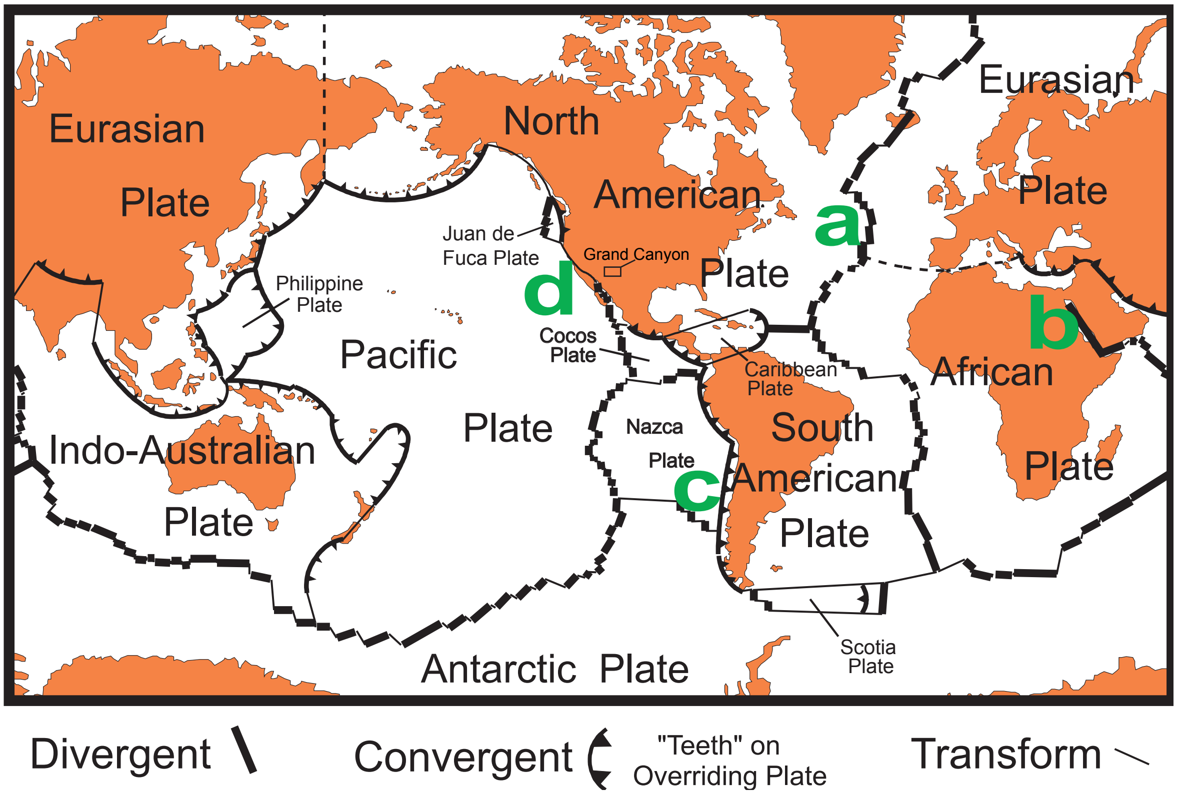


Figure 1.4 – Tectonic plates. *Tectonic plates are constantly moving and interacting with each other on the Earth's surface. In some places, such as the Mid-Atlantic Ridge (a) or East African Rift (b), plates are moving away from each other at a **divergent plate boundary.** Where plates are moving towards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

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

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

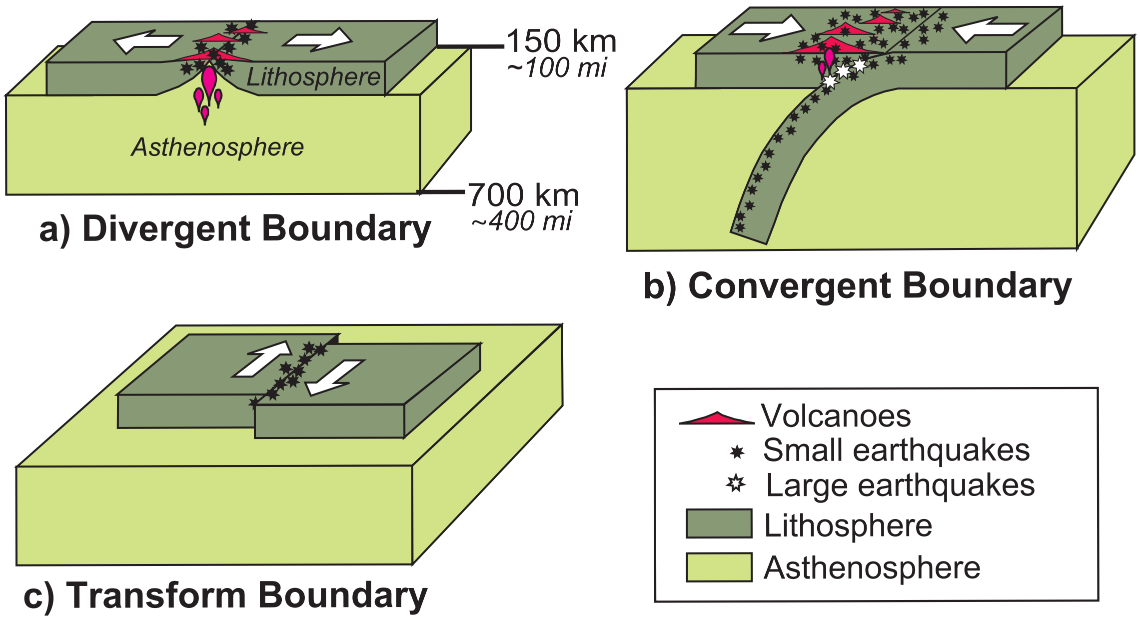


Figure 1.5 – Types of tectonic plate boundaries. *These schematic diagrams depict what the Earth might look like if you could slice through it at a plate boundary. White arrows show the direction of movement of the plates relative to each other. a) Where plates diverge, new lithosphere is created as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

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

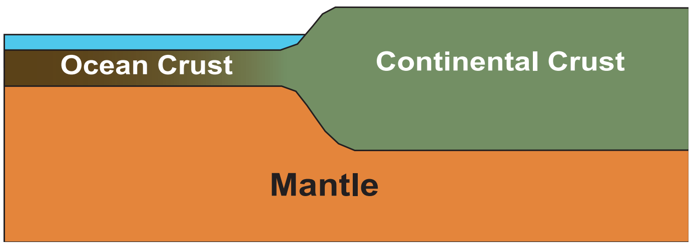
A **transform plate boundary** forms where two plates slide past one another (Fig. 1.5c). Along western California, the Pacific Plate is moving northward, sliding past the North American Plate, creating the San Andreas Fault Zone (Fig. 1.4). Large, shallow earthquakes are common along transform plate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

Development of High Elevation

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

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

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 12-45 miles (20-70 km) thick, so it floats higher on the mantle than ocean crust. B) You can think of the Earth's crust like an iceberg, where the iceberg is the crust and the mantle is the seawater. A thick iceberg is more buoyant and floats higher above the water than a thin iceberg. (Photo property of NPS)*

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

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

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

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

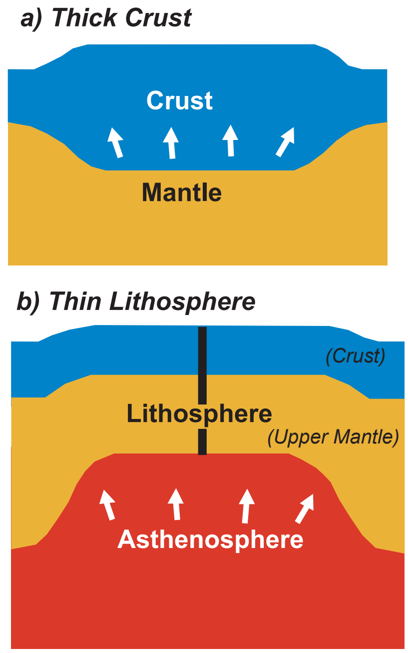


Figure 1.7 – The development of high elevation. *There are two main ways that high elevation can develop. a) <u>Thick crust</u>. Because thick crust is buoyant, it floats upward until it is counter-balanced by the downward weight of the overlying land. The high elevation of the Himalayan Mountains is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

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

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

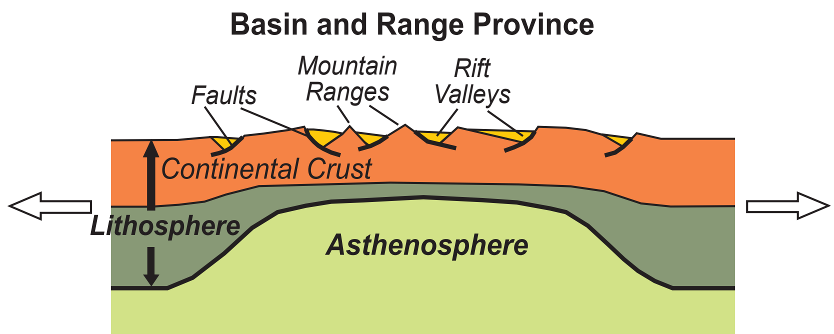


Figure 1.8 – High elevation in the Basin and Range Province. *The Basin and Range Province may be a divergent plate boundary in its beginning stages of development. This schematic diagram shows what the Earth may look like beneath the Province (a cross-section). The asthenosphere beneath the Basin and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

TYPES OF ROCKS

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

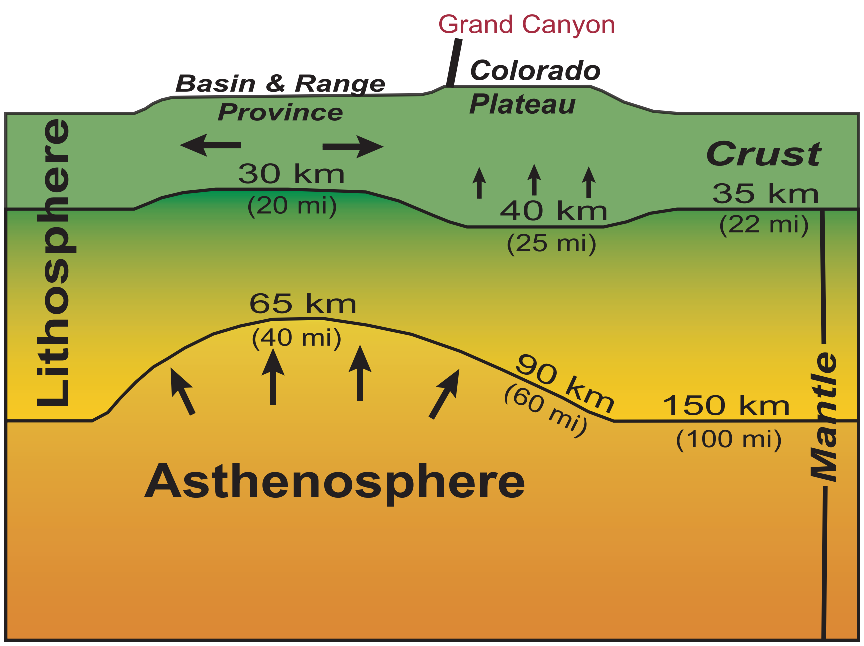


Figure 1.9 – Schematic cross-section of the Grand Canyon region. *The thicker crust of the Colorado Plateau may be part of the reason for the high elevation of the Grand Canyon region, because thick crust floats high on the mantle. The nearby thin lithosphere of the Basin and Range Province may also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

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

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

Sedimentary Rocks

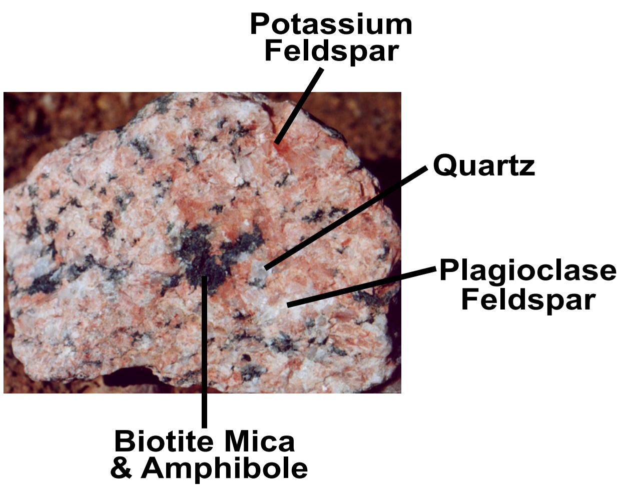


Figure 1.10 – Rocks and minerals. *Granite is a rock composed of several different minerals. The pink mineral in granite is potassium feldspar, the white minerals are plagioclase feldspar, and the clear minerals are quartz. Granite also has small amounts of black minerals, which are amphibole and biotite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

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

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

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

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

A)

Composition			Rock Name
ROCK PARTICLES	Grain Size fine ↓ coarse	mud, silt, fine grained sand	**shale***
		sand	**sandstone***
		rounded gravel	conglomerate
		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)

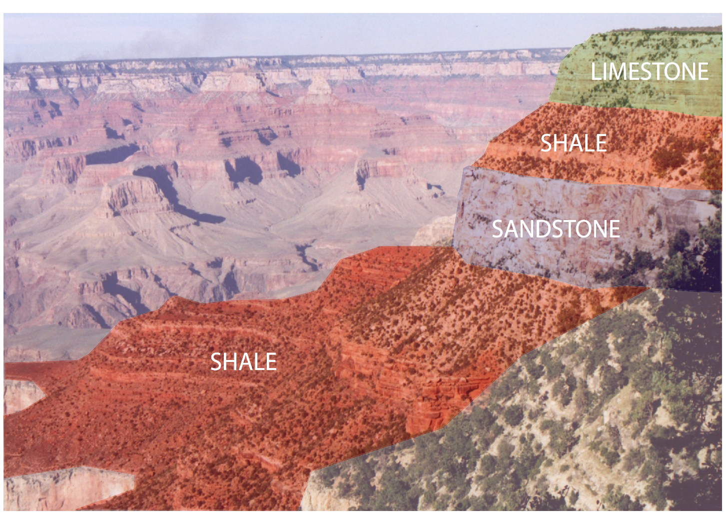


Figure 1.11 – Sedimentary rocks. *A) Sedimentary rocks form anywhere that rocks have been weathered, transported, and eventually deposited in places such as lakes, oceans, and rivers. For example, shale and sandstone are composed of particles of rock that get deposited. Other sedimentary rocks, such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

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

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

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

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

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

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

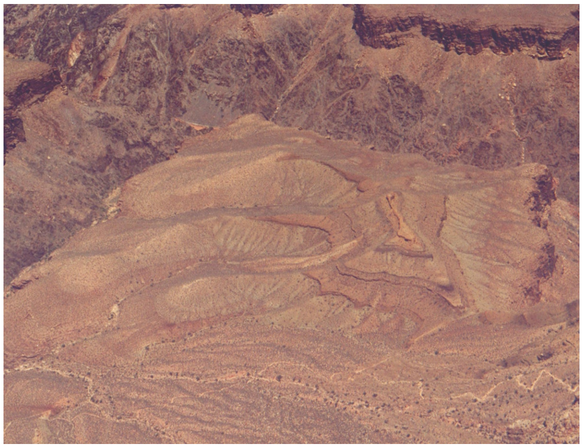


Figure 1.14 – Colorful Bright Angel Shale. *Looking down from Pima Point towards the location of the old Hermit's Camp, you can see a variety of colors in the Bright Angel Shale. Most of these colors are due to minerals composed of iron oxide (rust). From other viewpoints along the canyon, this layer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

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

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

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

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

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

Depositional Environments

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

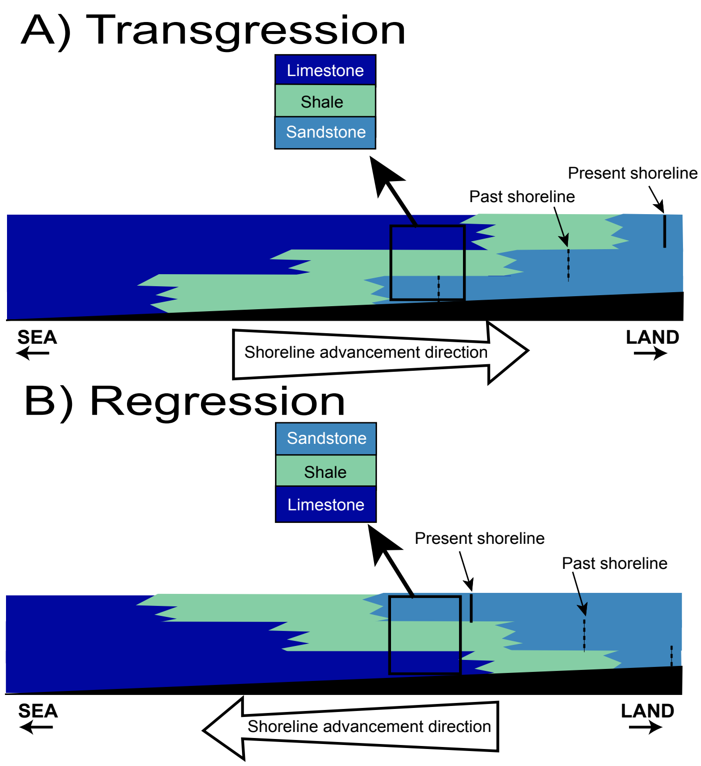


Figure 1.16 – Transgression and regression. *Transgression and regression can occur as sea level rises or falls, or as the land surface is uplifted or lowered. As these changes occur, the shoreline may move in over the land or move further out towards sea. A) As the sea encroaches over land during transgression,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

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

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

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

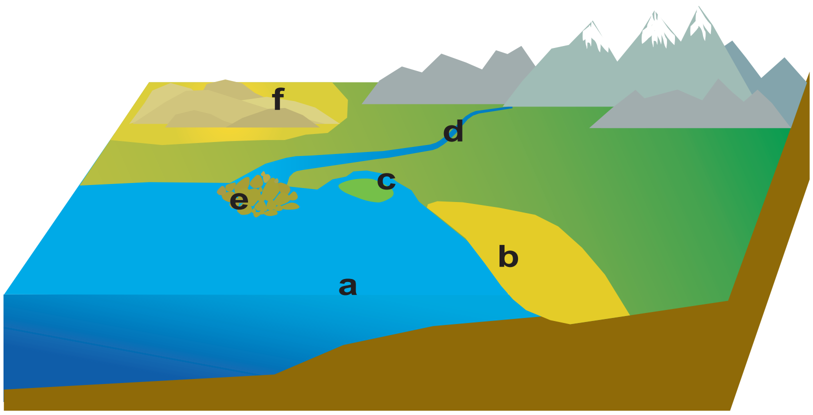


Figure 1.17 – Depositional environments. *a) Shallow marine environments can form as an ocean inundates the land, forming inland seas. Water depth is usually less than 300 feet (90 m). b) Near the coastline, a beach environment is common. Rocks that form are made up of sediment transported to the sea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

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

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

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

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

A)

B)

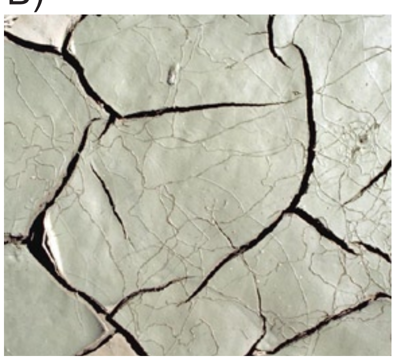


Figure 1.18 – Ripples and mud cracks. *A) Ripples are depositional features that can be formed by moving water. The water current forms miniature dunes as it moves sediment along a surface, such as a streambed. B) Mud cracks form as shallow water evaporates and the mud left behind dries and cracks. (Photos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

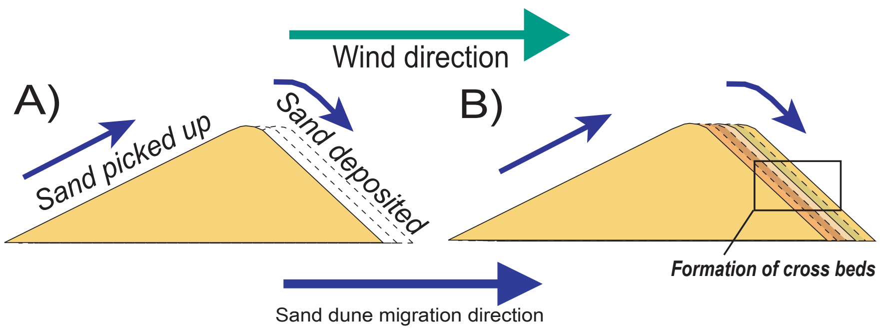


Figure 1.19 – Sand dunes. *Sand dunes are not stationary. An entire dune will move (or migrate) in the direction the wind blows the sand. A) Wind picks up sand on one side of the dune and deposits it on the other side where the wind speed slows down. B) Sand is deposited at an angle, along the slope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

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

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

Igneous Rocks

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

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

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

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

		Composition: 70% Silica ←→ 40% Silica			
Grain Size fine ↓ coarse	**Extrusive**	Rhyolite	Andesite	**Basalt***	
	Intrusive	**Granite***	Diorite	Gabbro	Peridotite

*Common igneous rocks at Grand Canyon

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

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

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

A)

B)

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

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

Metamorphic Rocks

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

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

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

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

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

*Common metamorphic rocks at Grand Canyon

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

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

STRATIGRAPHY

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

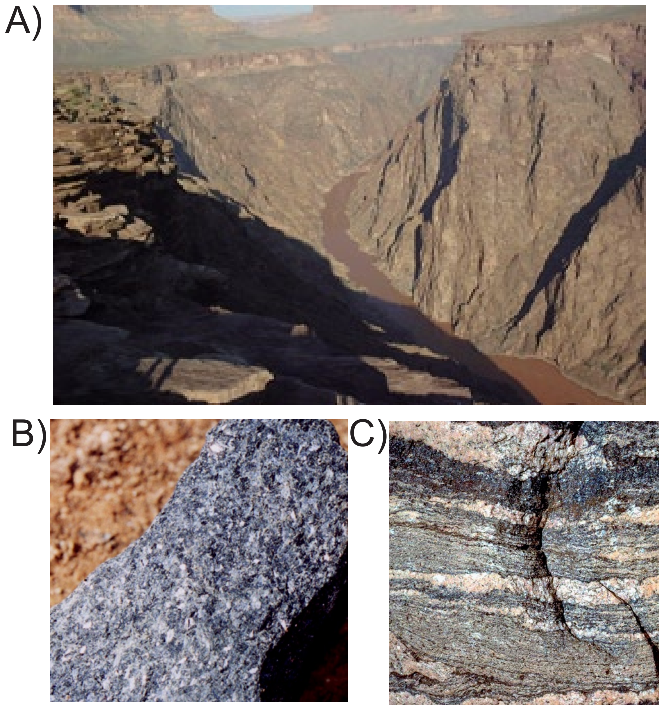


Figure 1.24 – Grand Canyon metamorphic rocks. *A) The inner canyon is incredibly steep because of the hard, dark metamorphic rocks that make up most of the inner canyon. Around 1750 million years ago, these rocks were sedimentary and igneous rocks. They were under extreme heat and pressure, which metamorphosed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

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

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

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

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

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

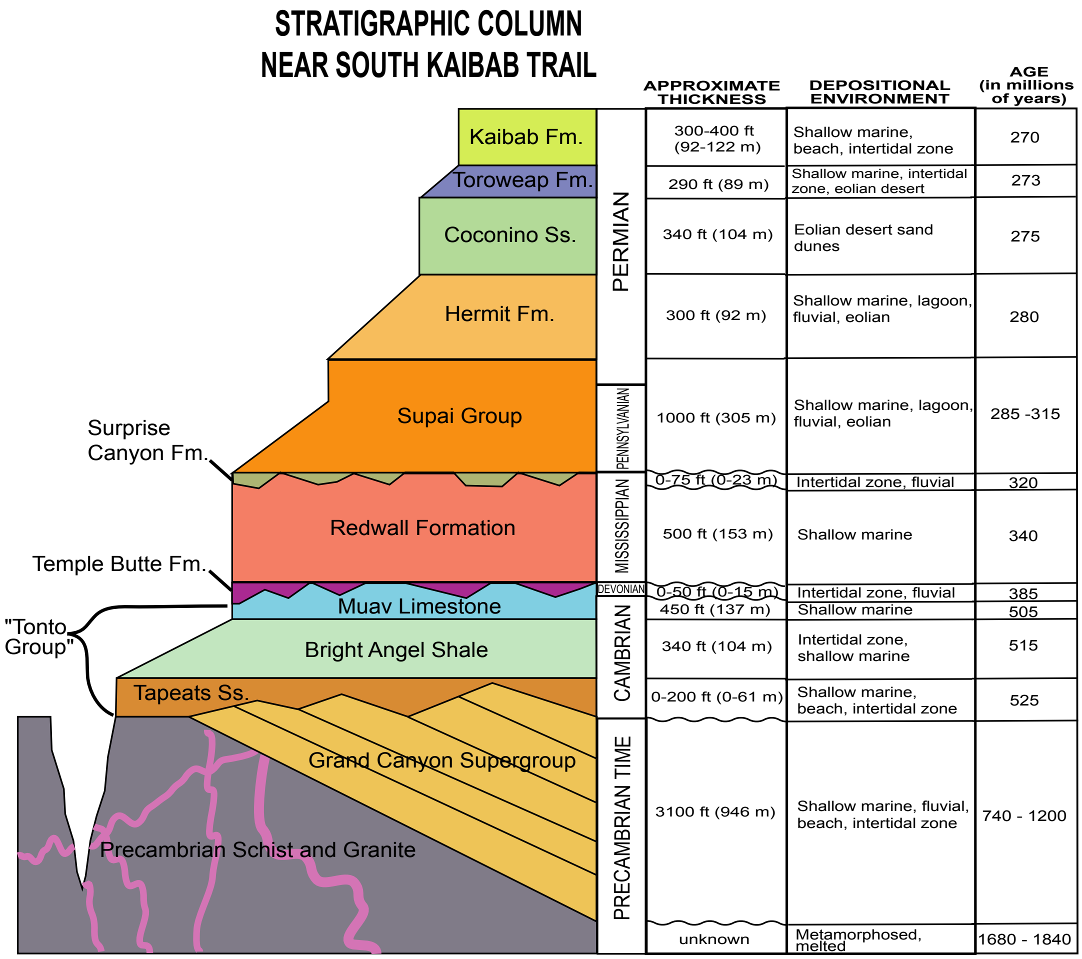


Figure 1.25 – Stratigraphic column. *This diagram is useful to have when roving or doing interpretive geology programs. Use it to help identify different layers in the canyon, how thick they are, environments where they were deposited, and when they formed. This particular stratigraphic column describes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

GEOLOGIC TIME

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

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

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

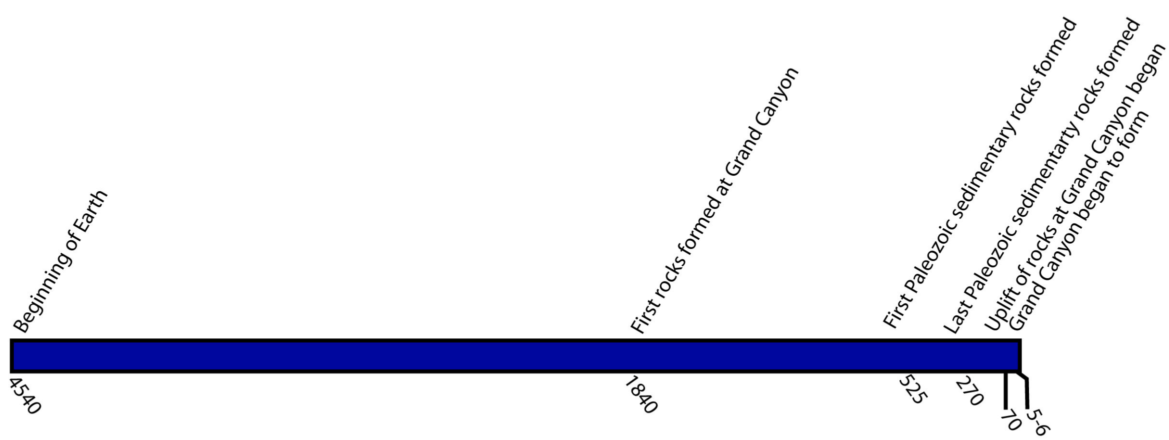


Figure 1.26 – Time line. *Some of the major events in the geologic history of the Grand Canyon region are shown on this time line. When you lay the events out, you can see the broad range in ages of rocks, and that Grand Canyon is clearly a young geologic feature.*

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

Relative Dating

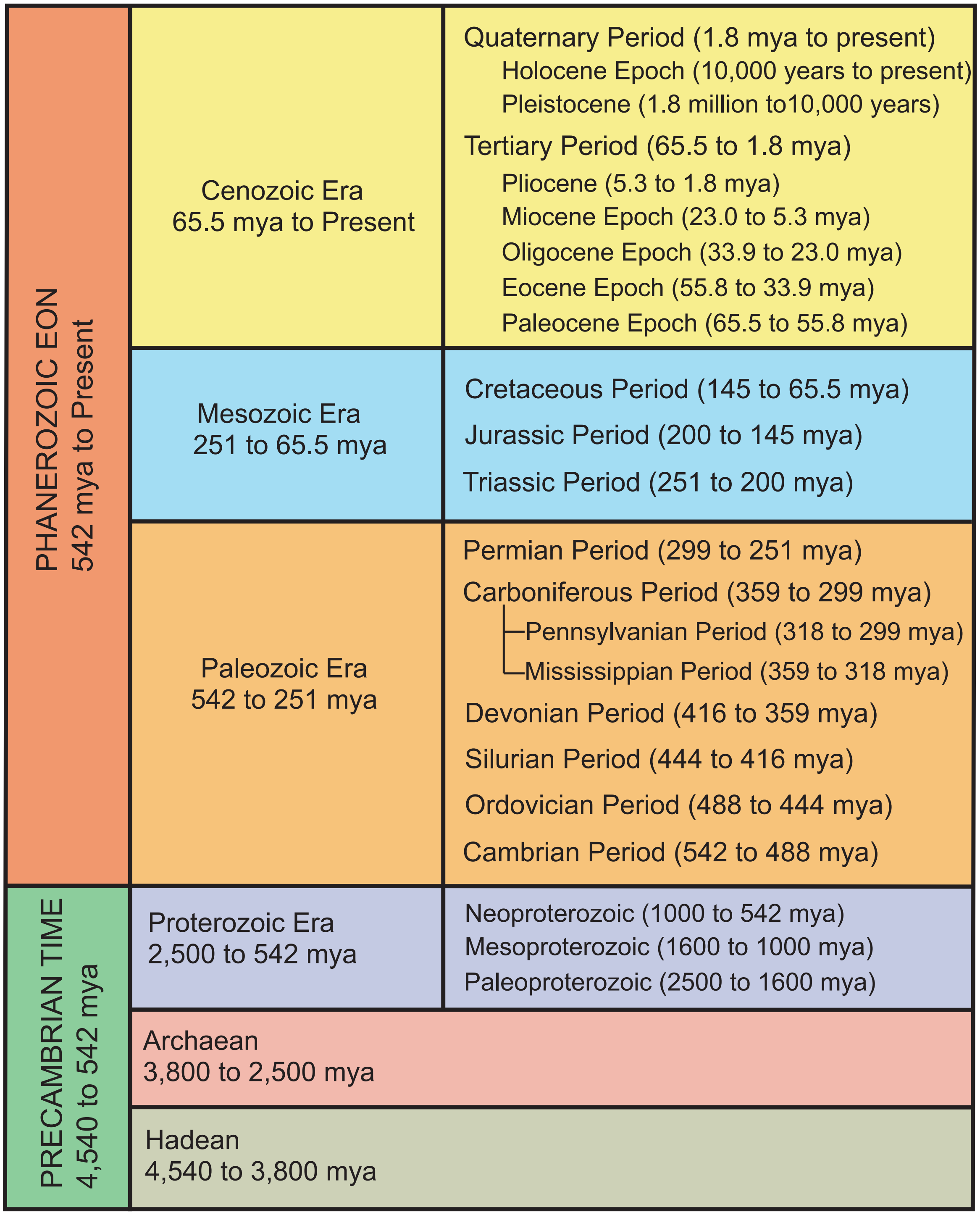
When early geologists studied rocks during the 1600's, they wanted to know how old the rocks were, but they did not have the means to determine absolute ages. They did, however, develop the **Principle of Superposition** to determine relative ages. This principle states that rock layers are deposited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

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

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

Absolute Dating

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



mya = million years ago

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

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

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

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

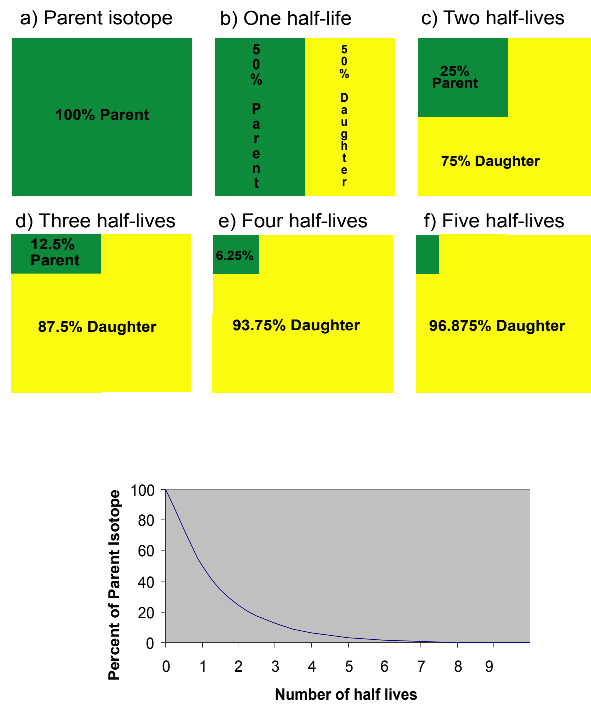


Figure 1.28 – Radioactive isotope decay. *The boxes are simplified representations of an amount of parent isotope (green) which decays to form the daughter isotope (yellow). After one half-life of time passes, half of the parent isotope has decayed to form the daughter isotope. After another half-life,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

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

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

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

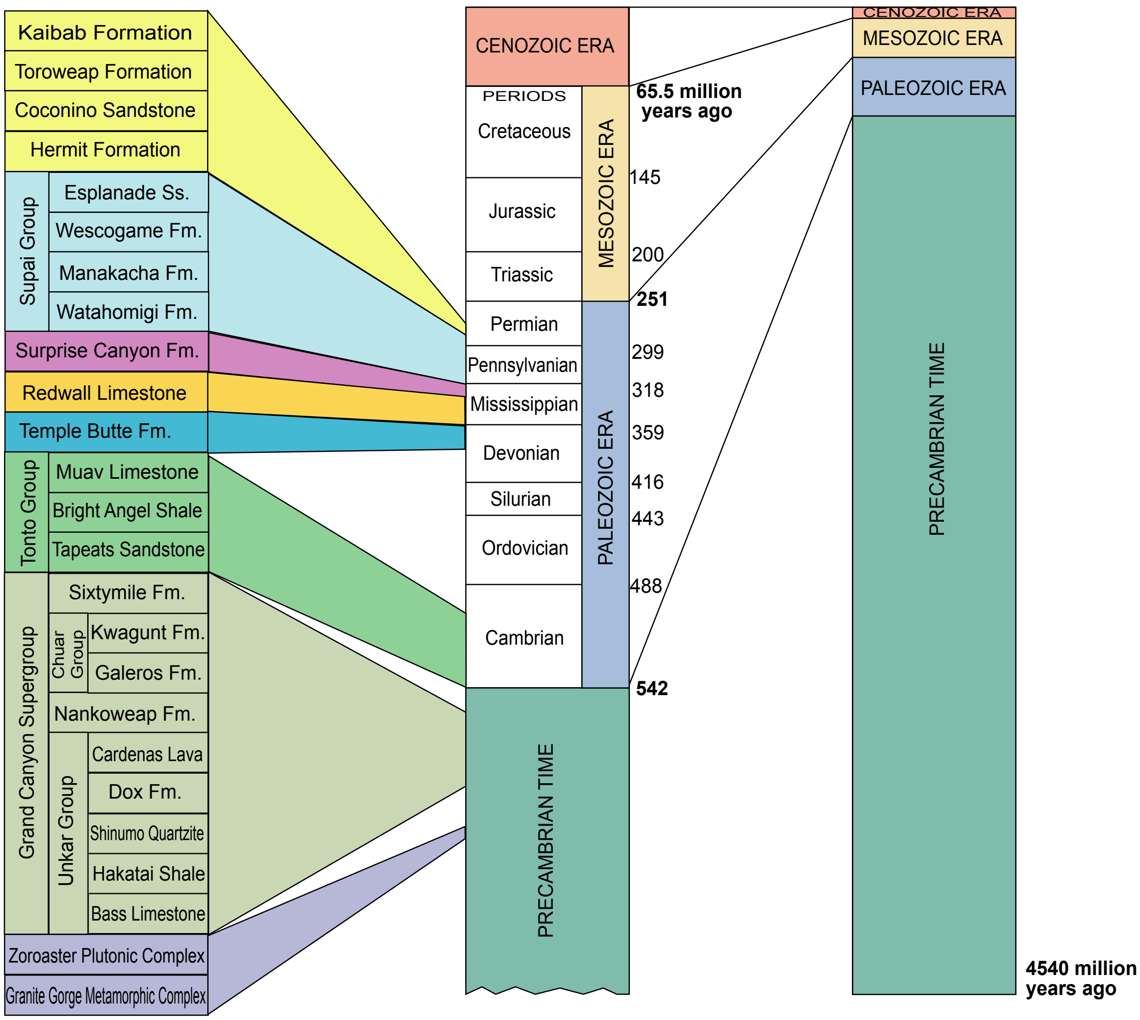


Figure 1.29 – Geologic time scale for Grand Canyon. *The different rock layers of Grand Canyon are depicted to show their approximate ages on the geologic time scale. The geologic time representation in the middle is not drawn to scale. The time scale on the right side has the correct proportions of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

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

STRUCTURAL GEOLOGY

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

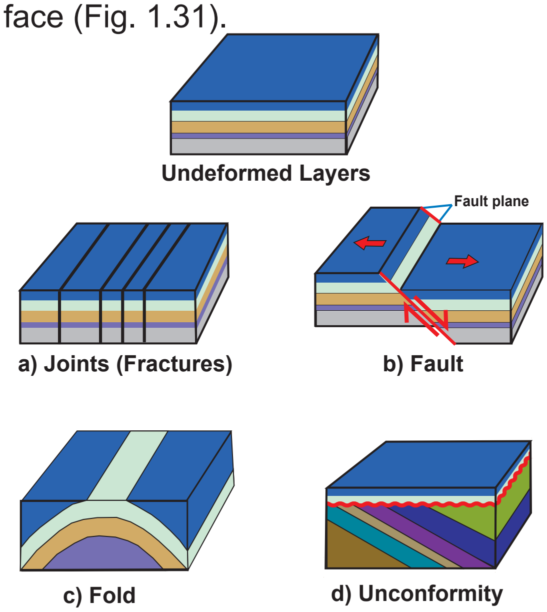


Figure 1.30 – Types of structures. *a)* ***Joints*** *are cracks or fractures in the rock with movement perpendicular to the cracks, but no vertical movement of the rocks. Joints can develop due to geologic forces of extension or compression. b) A* ***fault*** *is a break in the Earth's crust, where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

Joints

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

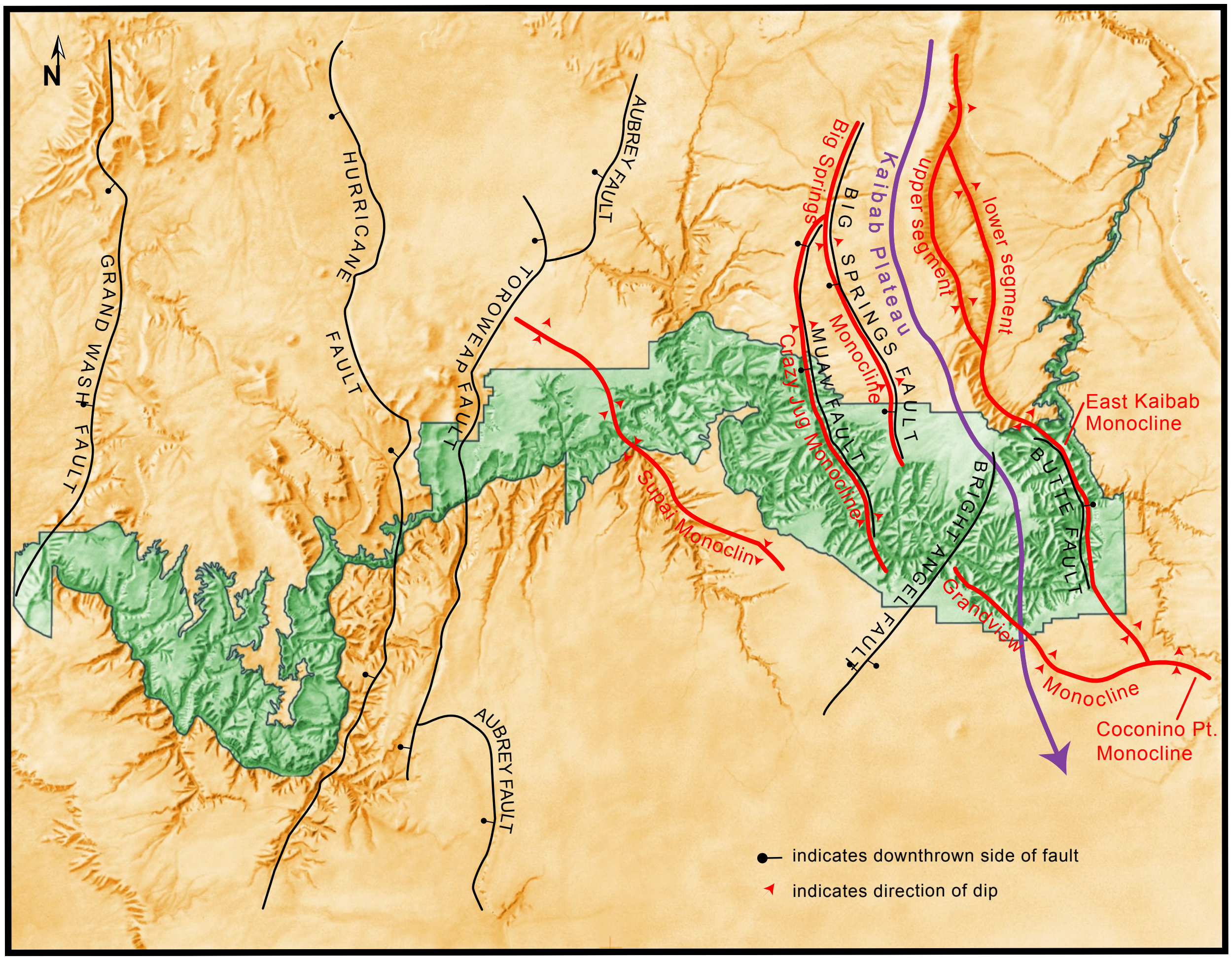


__Figure 1.31 – Grand Canyon structures.__ This map shows the location of some of the major structural features (faults and folds) that are evidence of past geologic activity in the Grand Canyon region. Notice that many of the monoclines (in red) have faults (in balck) associated with them. These faults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

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

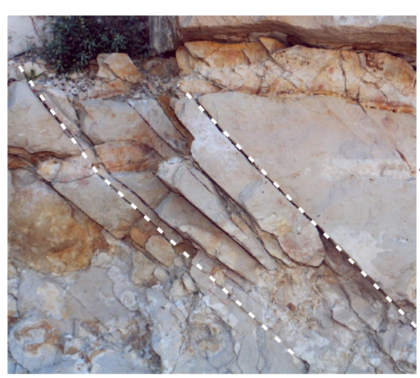


__Figure 1.32 – Joints in Grand Canyon rocks.__ The rocks of Grand Canyon are riddled with joints. This example is in the Kaibab Formation along the South Kaibab Trail. A few of the joints have been dashed in white to make them more visible.

Faults

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

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

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

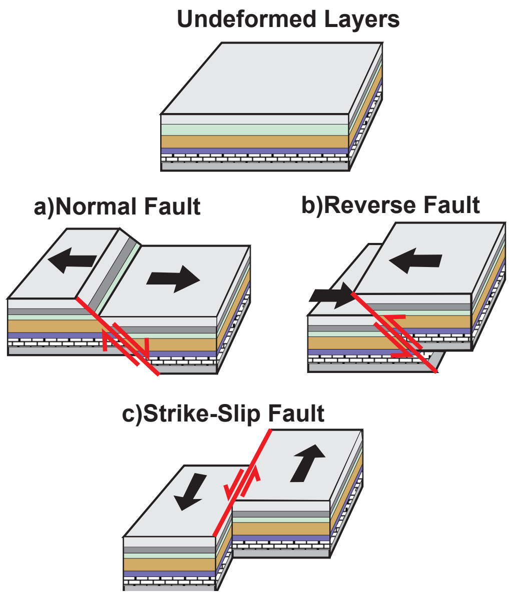


Figure 1.33 – Types of faults. *The larger black arrows represent the dominant direction of the geologic forces that creates the types of faults shown here. The red arrows show the direction of movement along the fault surface. a)* ***Normal faults*** *typically occur in an extensional tectonic setting,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

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

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

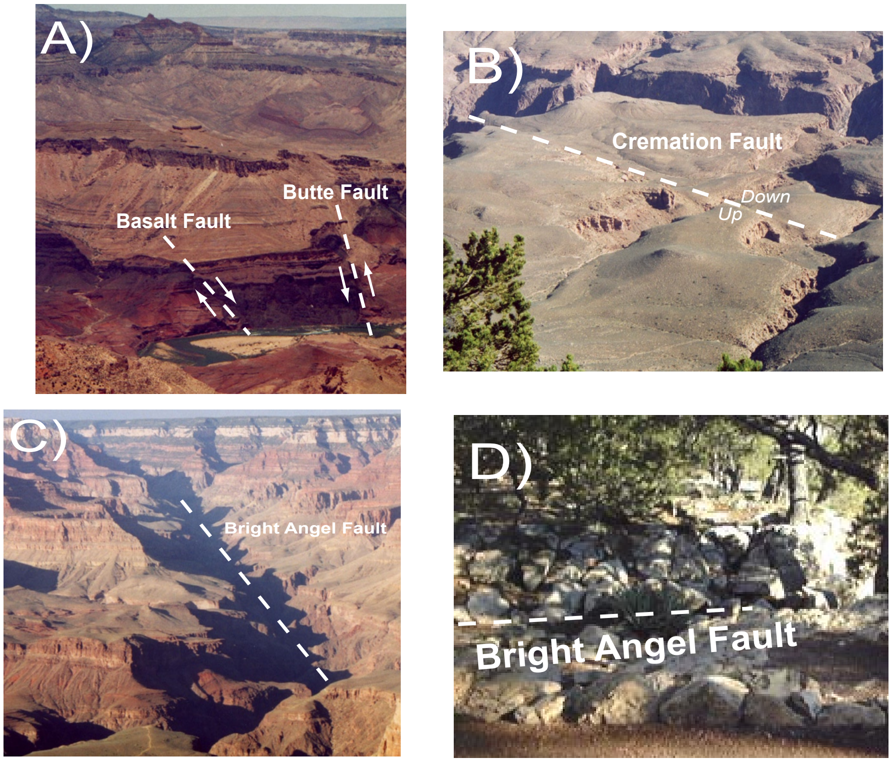


Figure 1.34 – Faults in Grand Canyon. *Faults are seen along the dashed gray lines in these photos. As you observe the faults in the park, compare these pictures with the real-life scenery. A)* ***Butte and Basalt Faults:*** *From Desert View, looking down towards the river, you can see Butte Fault and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

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

Folds

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

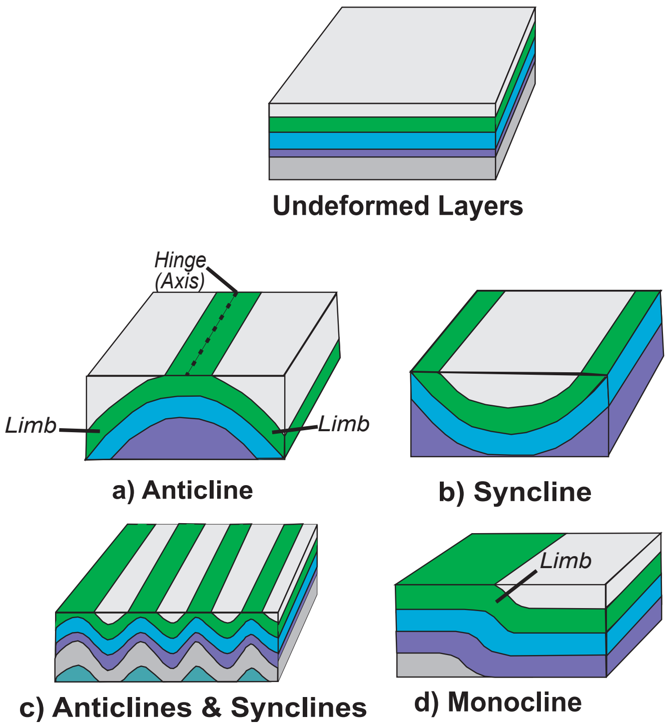


Figure 1.35 – Types of folds. *Folds usually form because of slow geologic forces acting on the Earth's crust, as if you slowly pushed two ends of a rug together. The* ***hinge*** *or* ***axis*** *of the fold is where the curvature is greatest, and the* ***limbs*** *are the arms of the fold. a) An* ***anticline***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

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

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

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

Unconformities

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

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

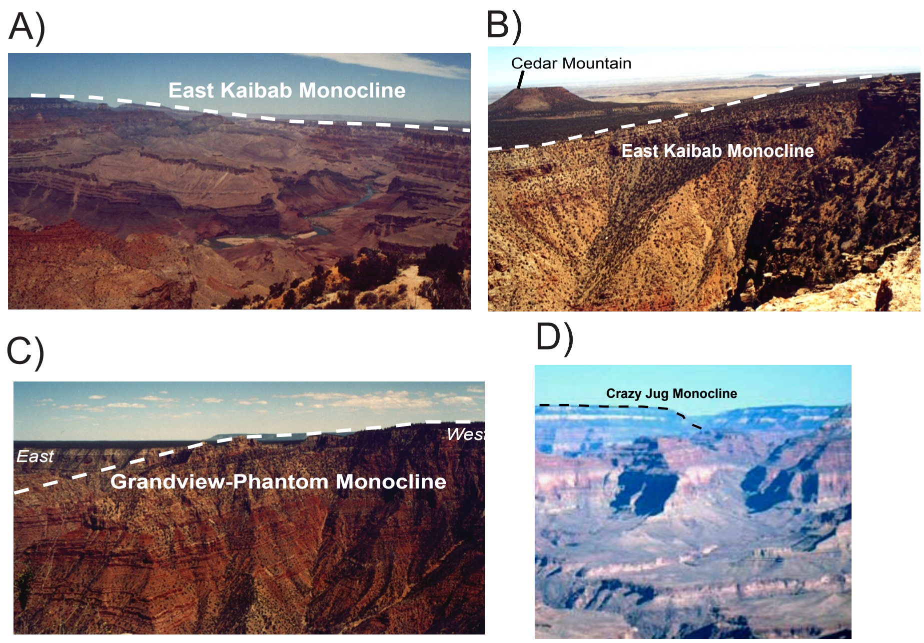


Figure 1.36 – Folds in Grand Canyon. *When you see folds in the landscape, they may not look like the nice, straight folds in Figure 1.35. Try to imagine the general shape of the fold as you observe the following features in the canyon. A)* ***East Kaibab Monocline:*** *This photo of the East Kaibab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

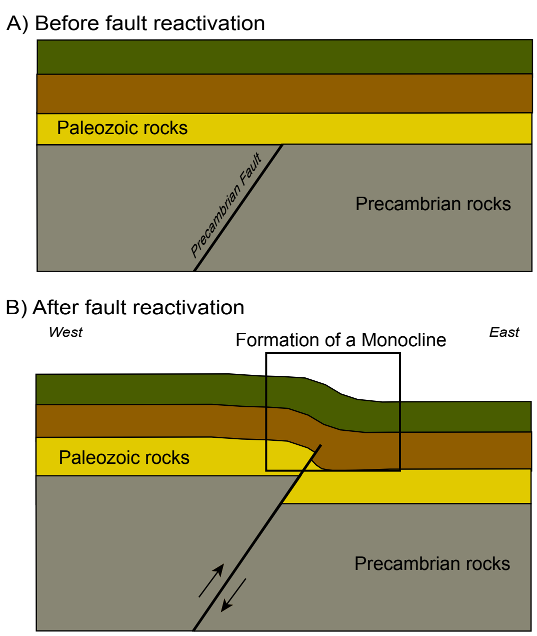


Figure 1.37 – Formation of monoclines at Grand Canyon. *One way that folds form is because of faulting in rocks at depth. A) In the Grand Canyon region, faults that formed during the Precambrian were buried beneath the Paleozoic sedimentary layers. B) When the faults were reactivated, the layers closest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

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

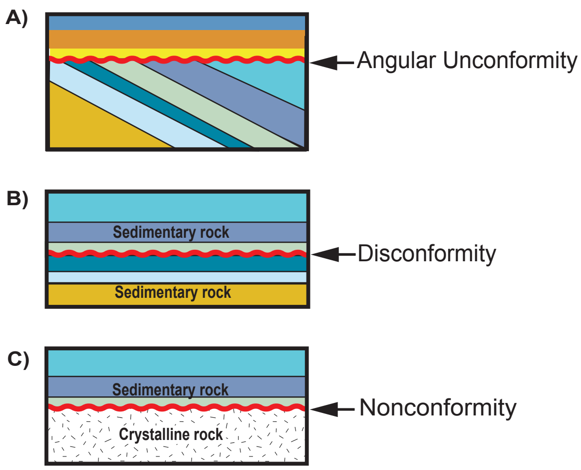


Figure 1.38 – Types of unconformities. *Unconformities (shown as wavy red lines) are like pages missing from the geologic record. They commonly represent a period of uplift, erosion, no deposition, and/or a drop in sea level. A)* ***Angular unconformities*** *develop after horizontally deposited layers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

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

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

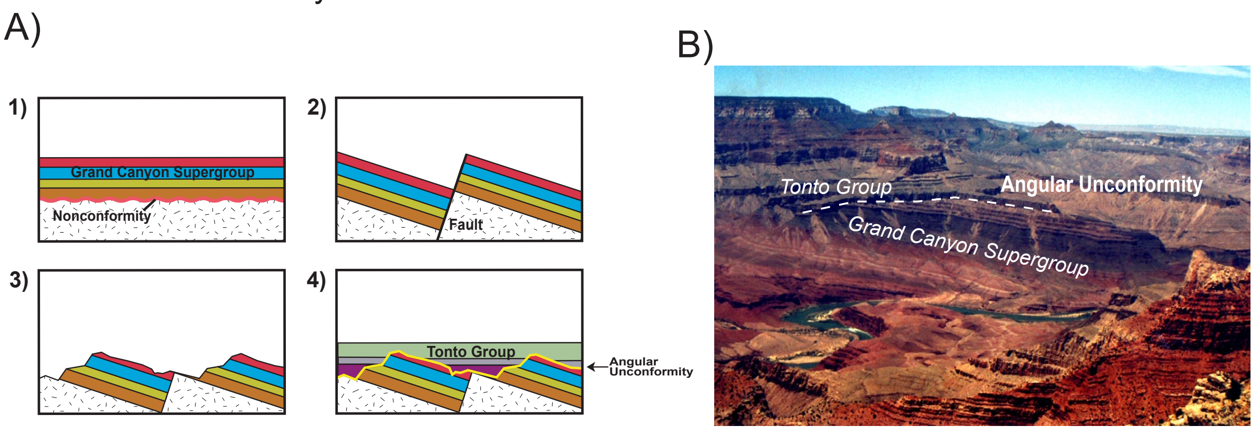


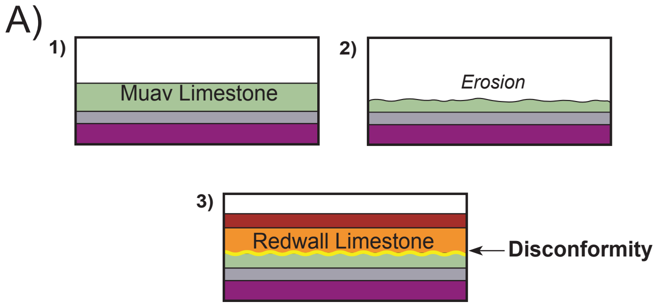
Figure 1.39 – Angular unconformity. *A) A major angular unconformity at Grand Canyon occurs between the tilted layers of the Grand Canyon Supergroup and the overlying sedimentary layers known as the Tonto Group (includes the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone). 1) The Supergroup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

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

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

HYDROLOGY

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



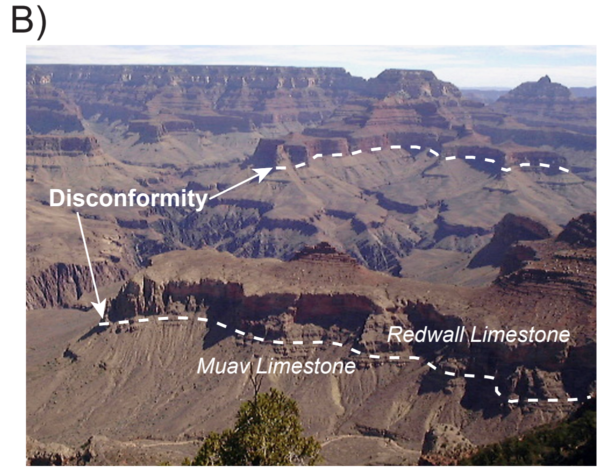
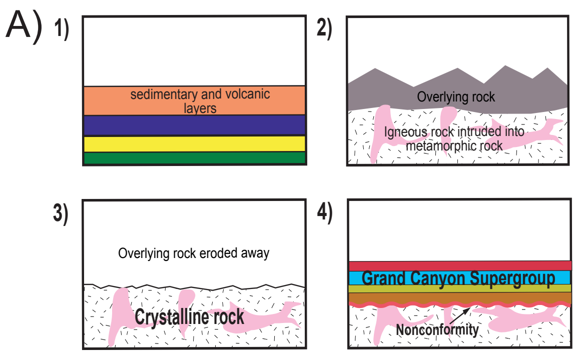


Figure 1.40 – Disconformity. *A) The disconformity between the Muav Limestone and the Redwall Limestone is one of the most significant disconformities (in terms of missing geologic time) within the sedimentary rock layers of Grand Canyon. This particular disconformity represents nearly 165 million years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



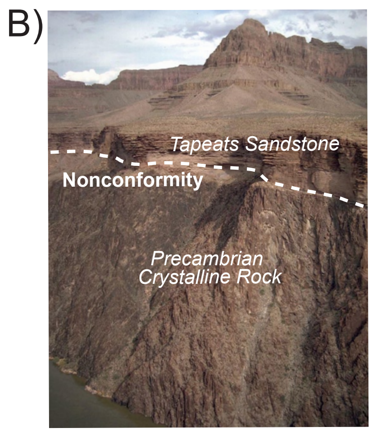


Figure 1.41 – Nonconformity. *A) 1) The first step in the formation of one of the nonconformities at Grand Canyon was the deposition of sedimentary and volcanic layers. 2) These rocks were later metamorphosed and melted deep below the Earth's surface as a mountain building event occurred. This changed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

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

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

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

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

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

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

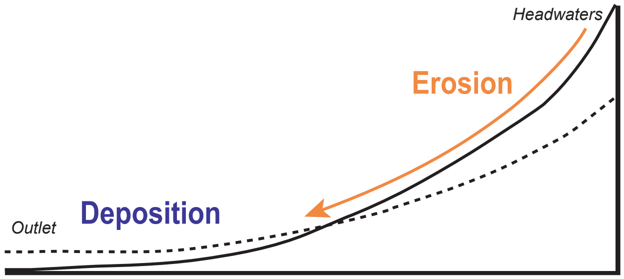


Figure 1.42 – Balance of erosion and deposition. This simplified diagram depicts how a river erodes sediment from the steeper part of the channel (red arrow), which is usually near the headwaters, and deposits it along the flatter part of the channel, near the mouth of the river. The solid line represents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

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

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

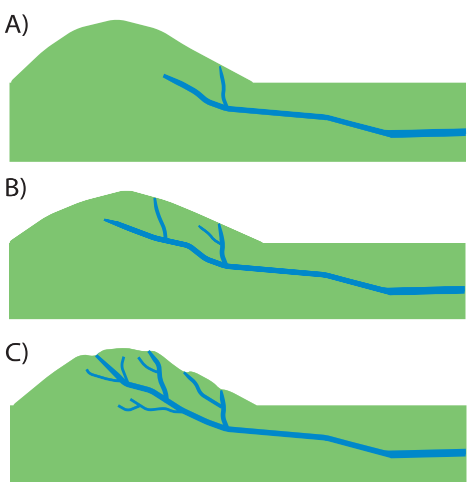


Figure 1.43 – Headward erosion. Headward erosion plays an important role in the evolution and lengthening of a river or stream. As a stream travels down a steep slope it cuts down into the channel and removes sediment from the channel itself, as shown in Fig. 1.42. A river or stream will also grow in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

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

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

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

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

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

Side Canyons

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

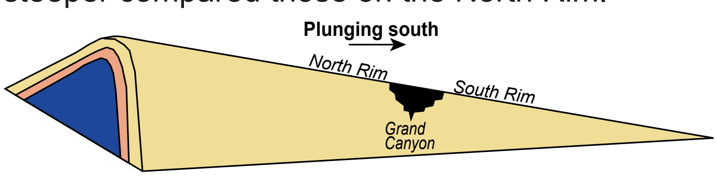


Figure 1.45 – The Kaibab Plateau. *The region of upwarped land called the Kaibab Plateau seen in* Figure 1.44 *may have contributed to the development of the path of the Colorado River, as we know it today. The Kaibab Plateau is a broad plunging anticline schematically shown here. This means that the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

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

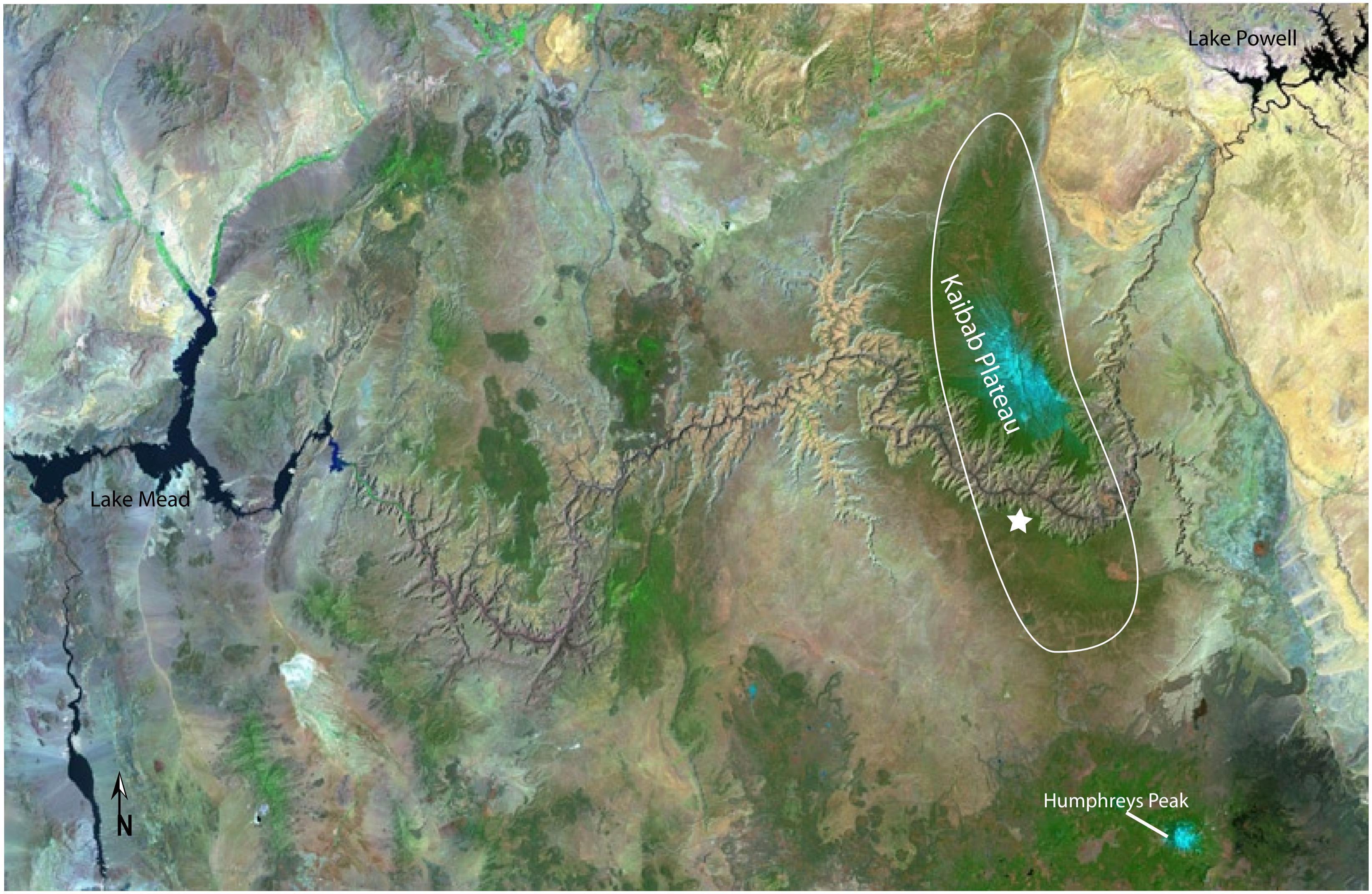


Figure 1.44 – Satellite image of Grand Canyon region. *You can see that there are many side canyons along the Colorado River that contribute to the great width of Grand Canyon. The large, oval-shape area circled in eastern Grand Canyon is the Kaibab Plateau. It has a spot of lighter color (bright blue)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

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

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

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

Glen Canyon Dam

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

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

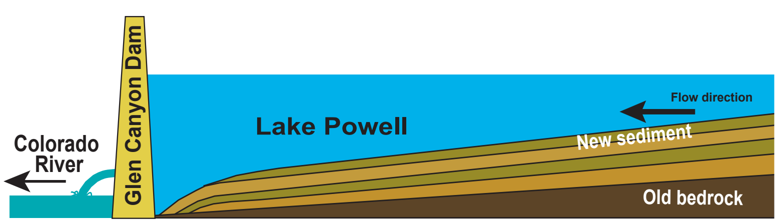


Figure 1.47 – Lake Powell. *(not to scale) In this simplified diagram of Lake Powell, you can see how Glen Canyon Dam has stopped most of the flow of the Colorado River through Glen Canyon. As the river enters Lake Powell, the water velocity decreases, causing the sediment carried by the Colorado River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

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

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

GEOMORPHOLOGY

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

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

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

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

quick.

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

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

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

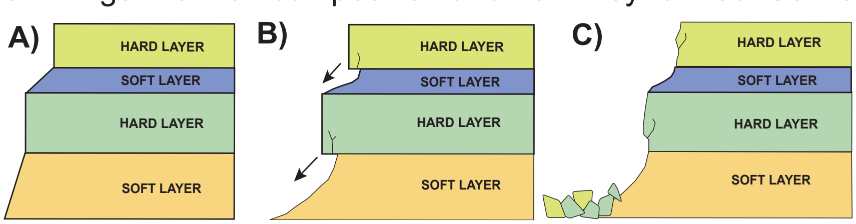


Figure 1.49 – Widening the canyon walls. *Mass movements help to widen the canyon, especially where the slope is overly steep and cannot support the overlying rock. After weathering processes weaken the rocks, these rocks submit to the force of gravity and eventually fall into the canyon. A) The alternate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

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

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

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

A) B) C)

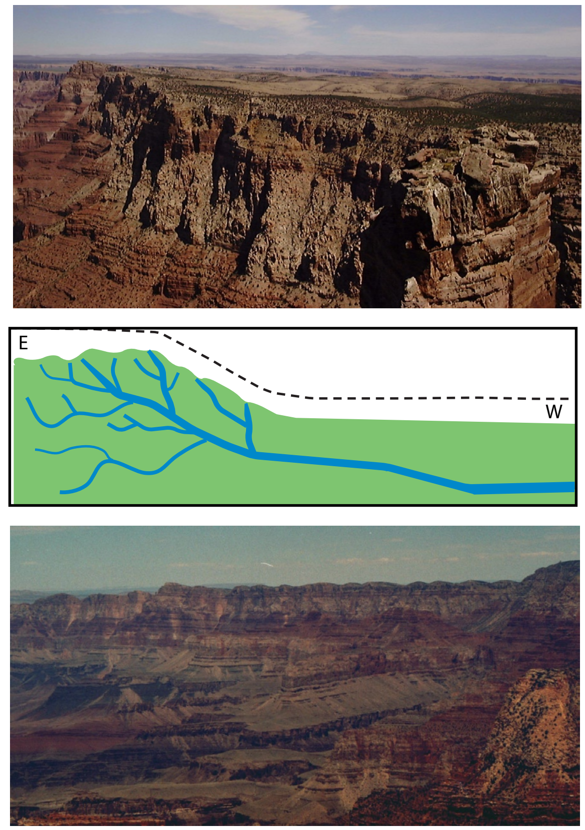


Figure 1.50 – The Palisades of the Desert. *A) This photo shows the hills and small valleys that give the Palisades of the Desert its distinct profile. The rocks are part of the East Kaibab Monocline. The middle, steeply-sloped portion of the monocline was located where Grand Canyon is now. B) Small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

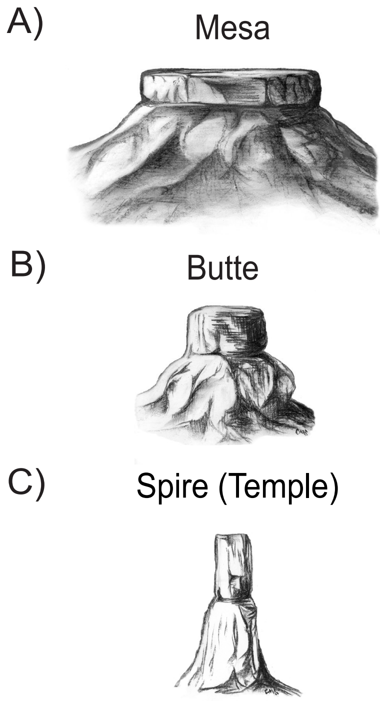


Figure 1.51 – Landscape features. *A) A mesa is a broad, flat feature that is wider than it is high. B) Buttes are approximately as tall as the width of the feature. C) Spires or temples are narrow features, as they are taller than their width. These eventually are broken down until nothing remains but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

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

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

Chapter 2: 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 initially impress 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 the rocks.

THE PRECAMBRIAN TIME (4540 TO 544 MILLION YEARS AGO)

Even though the Precambrian time comprises about 87% of the Earth's history, we know little about it compared to more recent geologic periods. Since the Earth formed 4540 million years ago, it has been cooling and releasing heat and gases. The planet's atmosphere and water were formed by the gases released, and the continents gradually formed (in locations different than today) after millions of years of volcanic and tectonic events. Undoubtedly, the Earth looked very different during the Precambrian, especially because the oceans held the only life on the planet. The first life forms were simple, unicellular 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 or even in North America. In fact, rocks at least 3500 million years old can be 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 the Precambrian (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 1700 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, metamorphosing the rocks between about 1700 and 1680 million years ago.

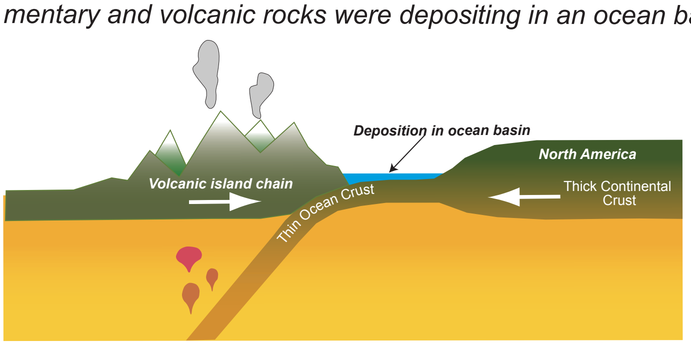
PHANEROZOIC EON 542 mya to Present	Cenozoic Era 65.5 mya to Present	Quaternary Period (1.8 mya to present) Holocene Epoch (10,000 years to present) Pleistocene (1.8 million to10,000 years) Tertiary Period (65.5 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene Epoch (23.0 to 5.3 mya) Oligocene Epoch (33.9 to 23.0 mya) Eocene Epoch (55.8 to 33.9 mya) Paleocene Epoch (65.5 to 55.8 mya)
	Mesozoic Era 251 to 65.5 mya	Cretaceous Period (145 to 65.5 mya) Jurassic Period (200 to 145 mya) Triassic Period (251 to 200 mya)
	Paleozoic Era 542 to 251 mya	Permian Period (299 to 251 mya) Carboniferous Period (359 to 299 mya) Pennsylvanian Period (318 to 299 mya) Mississippian Period (359 to 318 mya) Devonian Period (416 to 359 mya) Silurian Period (444 to 416 mya) Ordovician Period (488 to 444 mya) Cambrian Period (542 to 488 mya)
PRECAMBRIAN TIME 4,540 to 542 mya	Proterozoic Era 2,500 to 542 mya	Neoproterozoic (1000 to 542 mya) Mesoproterozoic (1600 to1000 mya) Paleoproterozoic (2500 to 1600 mya)
	Archaean 3,800 to 2,500 mya	
	Hadean 4,540 to 3,800 mya	

mya = million years ago

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

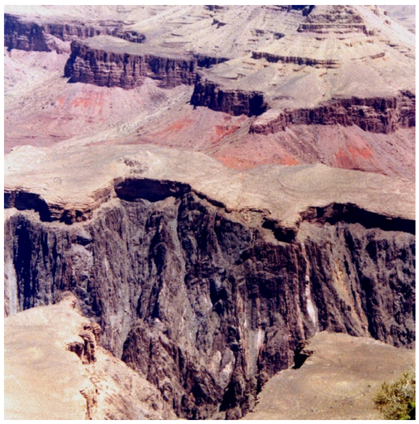
Figure 2.1 – Geologic timescale.

Figure 2.2 – Volcanic island collision during the Precambrian. *It is thought that Precambrian sedimentary and volcanic rocks were depositing in an ocean basin, situated between a volcanic island chain and the North American continent around 1750 to 1700 million years ago. A subduction zone may have existed that created 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 between 1700 and 1680 million years ago.*



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 Suite**, which includes the **Brahma**, **Rama**, and **Vishnu Schists**.

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 cut through them. B) The igneous rocks are found within the dark metamorphic rocks in the inner canyon. Most of this rock is granite, although other varieties of intrusive igneous rocks occur in the canyon. Large masses of granite (plutons), like the one seen here, were once chambers of magma. Bands (called dikes or sills) of granite also formed as the molten rock squeezed into cracks and weak areas in the surrounding metamorphic rock.*

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 1660 million years ago. Magma was squeezed into fractures and weak areas in the Granite Gorge Metamorphic Suite. It then cooled slowly within the Earth, forming intrusive (or plutonic) igneous rocks, including several varieties of granite, such as the **Zoroaster Granite.** These rocks are the light-colored bands and masses of granite within the dark Granite Gorge Metamorphic Suite in the inner canyon today (Fig. 2.3b).

A very complex suite. The intermingled igneous and metamorphic suite of rocks of Grand Canyon formed during complex sequence of events in the region. The oldest rocks, called the Elves Chasm Gneiss, formed from a pluton of magma about 1840 million years ago. There are separate igneous and metamorphic events that took place between 1750 and 1680 million years ago that caused the formation of the Granite Gorge Metamorphic Suite and the granitic igneous intrusions. These events were both related to the volcanic island magmatism and continental collision. Completely separate from these events was a Precambrian igneous event, which took place approximately 1400 million years ago. The rocks that were formed are found in western Grand Canyon in Quartermaster Canyon. Strictly speaking, the Precambrian rocks of Grand Canyon range in age from 1840 to 1400 million years of age. However, this is also simplified for the purposes of this training manual because most of the rocks in the region that you and visitors will encounter are in the 1750 to 1680 million-year range.

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 all 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.

Vishnu basement rocks. Because there is no formal geologic name for all the Precambrian crystalline basement rocks exposed in Grand Canyon, the National Park Service uses the informal term "Vishnu basement rocks." "Vishnu" is used because many visitors are familar with the Vishnu Schist and to differentiate these rocks from basement rocks exposed elsewhere on the continent. The Granite Gorge Metamophic Suite includes the Vishnu, Brahma, and Rama Schists, but each granitic pluton is named separately. The Zoroaster Granite is one of many igneous intrusions in the Vishnu basement rocks, each with its own specific crystallizatoin history. Referring to all the igneous rocks in Grand Canyon the incorrectly oversimplifies this complex assemblege of igneous rocks. Using the informal term "***Vishnu basement rocks***" is a straightforward way to refer to all these rocks when talking with visitors.

Grand Canyon Supergroup

It took as much as 400 million years, and a great deal 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 740 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

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 that particular section of the Supergroup is deformed by several faults, the tilt of the layers is not very distinguishable.*

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 only 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 770 to 740 million years old, and includes the Galeros and Kwagunt Formations. The Nankoweap Formation is sandwiched between the Unkar and Chuar Groups (with unconformities above and below it), and the Sixtymile Formation lies on top of the Chuar Group. It should be noted that the Supergroup is an incomplete rock record with many gaps in time. For example, millions of years of time are missing in the Unkar Group between the Hakatai Shale and Shinumo Quartzite.

The oldest fossils in the Grand Canyon geologic record are found in the limestone of the Bass Formation of 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

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, unless, for example, the sedimentary layer has volcanic ash associated with it that can be dated. Because sedimentary rocks are often composed of minerals from other rocks, radiometric dating will usually provide the ages of the rocks the minerals came from, not when the sedimentary rock formed. Most times, sedimentary rocks are dated using the 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 as early, middle, and late, providing a tighter time constraint for when the rock formed. “Early” indicates the beginning of the time period, while “late” indicates the end of the time period.

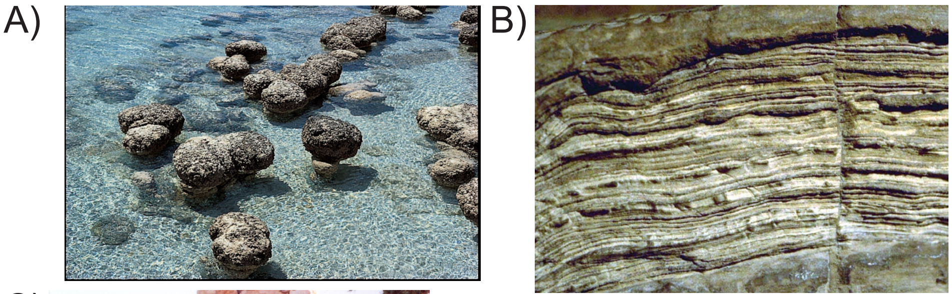



Figure 2.5 – Stromatolites. *A) These are present-day examples of stromatolites, whichare several feet wide. The organisms are made of layered algae and look similar to a stack of very thin crepes. B) This is a fossilized stromatolite. Stromatolites grew as a new algal mat formed and was covered by a 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. A similar rock is also found in the chimney on the inside of the building.*

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 actually 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!

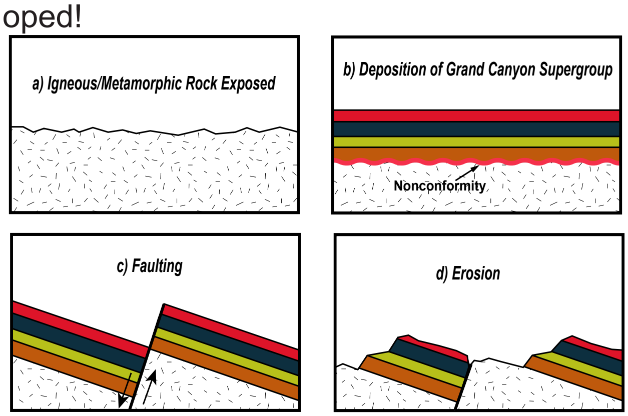


Figure 2.6 – Grand Canyon Supergroup faulting. *This cartoon schematically depicts the Grand Canyon region after the faulting of the Grand Canyon Supergroup and crystalline basement during Precambrian time. Several periods of deposition and faulting took place between about 1200 and 740 million years ago. Huge blocks of rock in between faults were tilted down to the east about 10°, leaving small mountains that were eventually eroded down to rugged hills.*

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 200 million years of exposure to weathering and erosion, the small mountains were eroded down to rugged hills and valleys (100's of feet of relief). 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 the Precambrian 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.

THE PALEOZOIC ERA (542 TO 251 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.

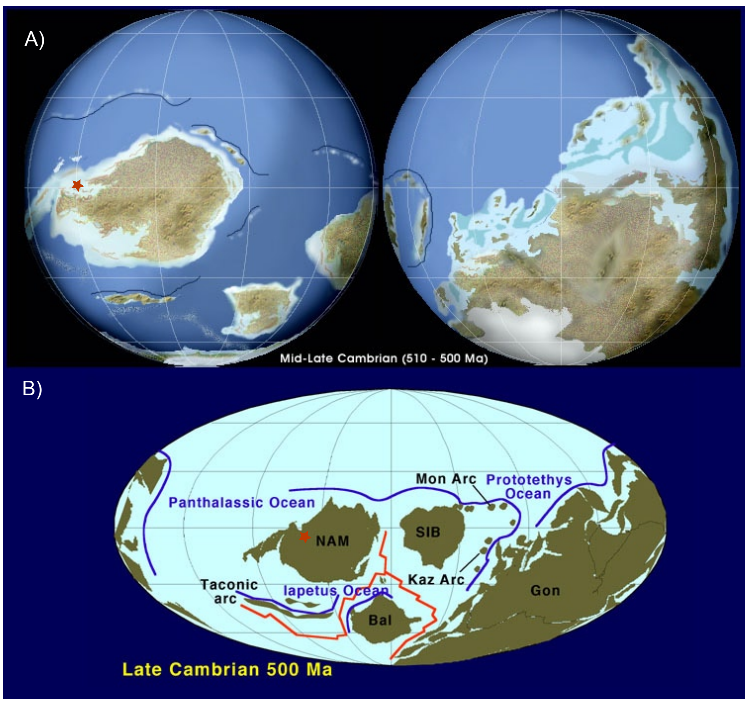


Figure 2.7 – The Earth during the early Paleozoic Era. *A) The physiographic depiction shows the topography of the land (grey and brown), and extent of the shallow continental shelves (light blue). B) The outlines of the plates and the plate interactions are shown (blue lines indicate convergence, red lines indicate divergence). "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)*

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.

The Tonto Group

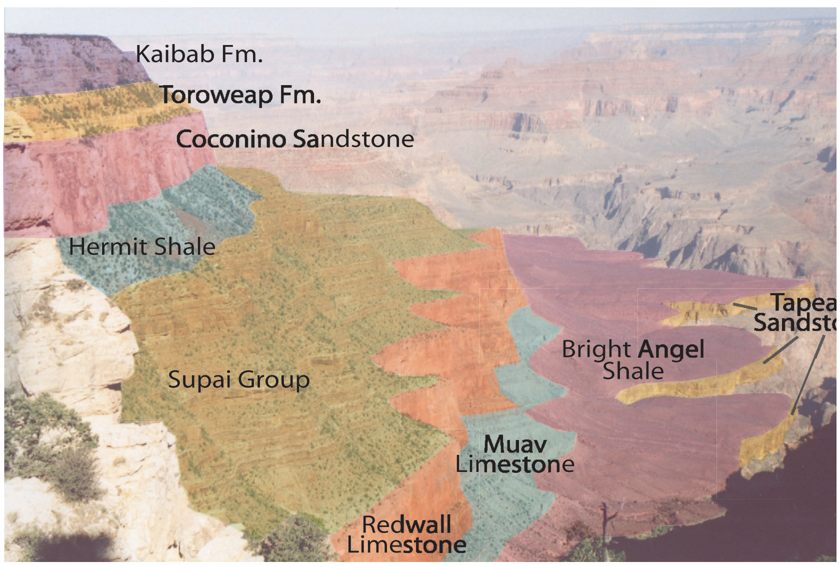
The first sedimentary layers of the Paleozoic Era in Grand Canyon are the **Tonto Group**, made up of the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone. They formed during the Cambrian Period,

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.

A)



B)

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

Figure 2.8 – The Paleozoic layers. *A) 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 (these first three are together known as the Tonto Group), Redwall Limestone, Supai Group, Hermit Formation, Coconino Sandstone, Toroweap Formation, and Kaibab Formation. B) The table breifly describes identifying characteristics of each of these Paleozoic sedimentary layers.* Note: The Temple Butte and Surprise Canyon Formations are not included in these diagrams because they are difficult to view from the rim.

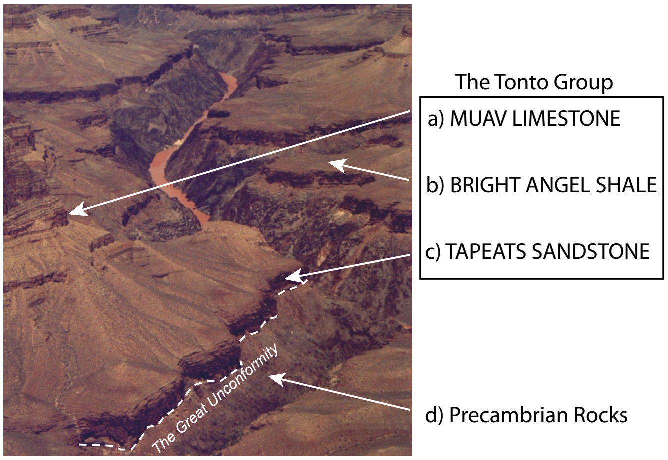


Figure 2.9 – The Tonto Group. *From younger to older: a) The Muav Limestone is a large cliff that is below a younger layer of limestone called the Redwall Limestone. Viewed from the canyon rim, those two layers can be difficult to tell apart. b) The Bright Angel Shale forms a broad, gently sloped, greenish shale layer. c) The Tapeats Sandstone is the cliff layer that looks similar to a stack of pancakes or a graham cracker bites 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.*

between about 525 and 505 million years ago (Fig. 2.9). The Tonto Group was deposited directly overlying the Precambrian rocks forming the **Great Unconformity** (Fig. 1.41b). The first layer, 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 of the Tapeats Sandstone, while other parts of the unit 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).

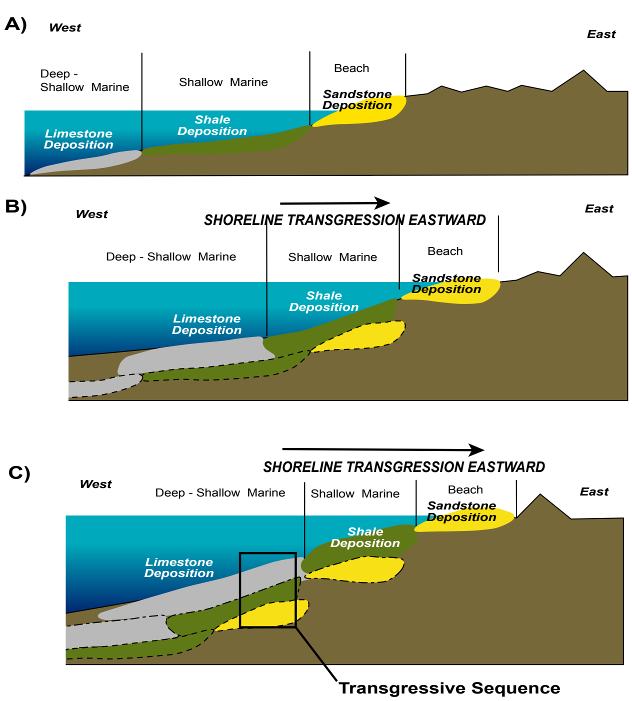


Figure 2.10 – Transgression in the Grand Canyon region. *As sea level rises or the land elevation decreases, the shoreline can move inland and deposit various sediments along the way, as shown in the progression from A to C. The deposition of sandstone, shale, then limestone is called a **transgressive 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 505 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 outlines indicate old deposits that are buried by younger ones.*

The Great Unconformity of Grand Canyon. John Wesley Powell, the self-taught geologist who 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 there are different layers in contact with each other, 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*. Around 1200 million years (see caption for range) 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 unconformity of at least 200 million years 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.

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. Up to 1200 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 approximately 215 million year gap at this part of the unconformity is less than the "greater" part, thus the term "lesser" Great Unconformity.*

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

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 Devonian Period, approximately 385 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 a smaller, thin cliff. 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 time is gone. Another disconformity formed after the Temple Butte Formation was deposited, where 45 million years of the geologic record is missing. Together they represent at least 140 million years (nearly half!) of the 300 million years of the entire Paleozoic Era. 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. But these disconformities are just a few of the many that exist in the Paleozoic record.

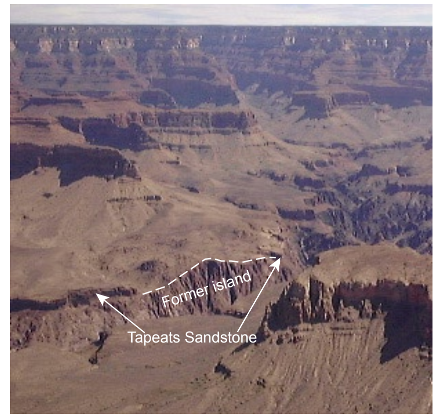


Figure 2.12 – Islands during the Cambrian Period. *As the Tonto Group was deposited on the rugged, hilly Precambrian landscape, some of the taller areas were islands above the sea. In this photo, the dashed white line outlines one of these ancient islands. If you look closely you can see that it has 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 Redwall Limestone

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.*

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 about 340 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 downslope and stains the face of the limestone cliff. If you were to break off 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 form as groundwater percolates though cracks and pores in the rock. At one time, the

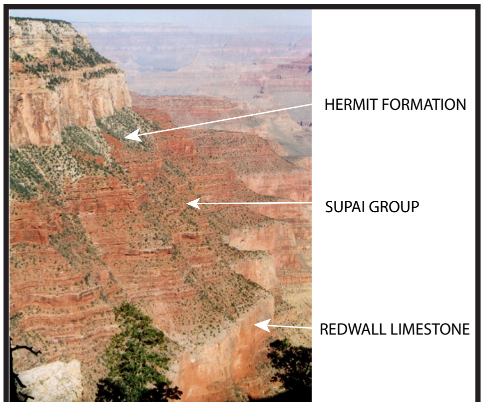
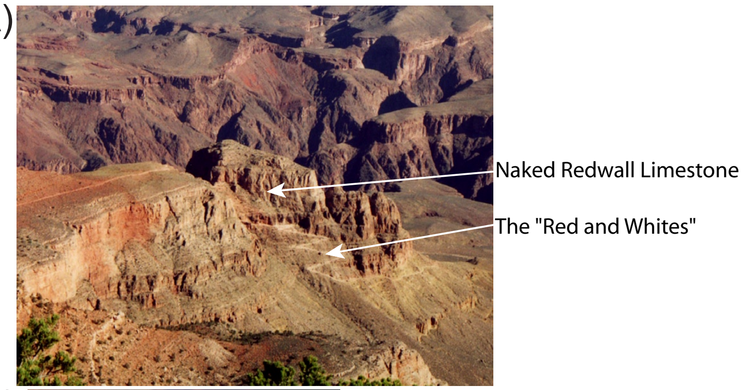


Figure 2.14 – The red rock layers. *The red color in these layers is due to iron oxide (rust) that is in the minerals that make up the rocks. The Redwall Limestone forms a steep cliff, but is not truly red, only stained red by the sediment washed down from the layers above it. The Supai Group is a red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

A)



B)

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 trail 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.*

Redwall Limestone may have been the major groundwater system, channeling water underground through the caves. Today the Redwall Limestone is still a primary aquifer that channels groundwater through the region.

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 over the Redwall Limestone approximately 320 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 parts of some of the 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, including plant fossils, corals, brachiopods, as well as many others (see pages 63-64 for more about fossils).

The Supai Group and Hermit Formation

The layered 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 315 to 280 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, such as schist or basalt. 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 provide 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, slope-forming 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. During the Permian Period, about 275 million years ago when the Coconino formed, the Grand Canyon region was covered with coastal sand dunes.

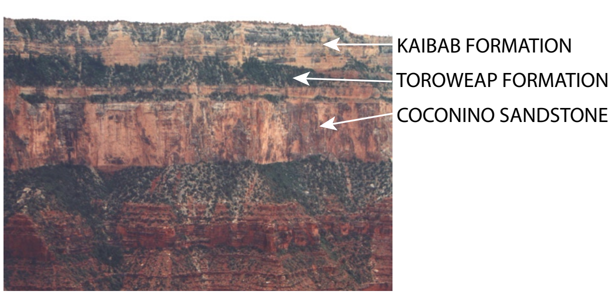


Figure 2.16 – The Permian layers. *The three uppermost layers of Grand Canyon were all deposited during the Permian Period. The Coconino Sandstone forms a massive cliff that is light in color compared to the red layers below it. The Toroweap Formation is a small slope that appears to have more vegetation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

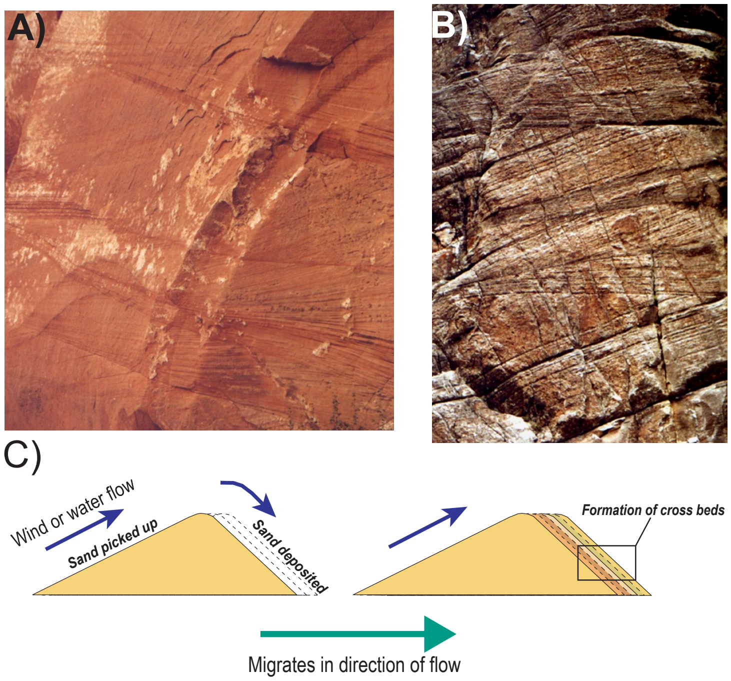


Figure 2.17 – Sand dunes preserved. *Cross-bedding in the Coconino Sandstone is seen here along the South Kaibab Trail (A) and along the Bright Angel Trail (B). It may appear that these layers have been tilted, but the sand was actually deposited at this angle, while the overall sandstone layer is horizontal (called cross-bedding). 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, depositing it at an angle on the down-wind side of the dune, where the wind is not as strong. 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.*

As the sand dunes blew across the land, cross-bedding features were developed and preserved as the sand hardened to sandstone. The preserved cross-bedding gives the layer a tilted appearance because deposition occurred at an angle, however the top and bottom surfaces of the layer are actually horizontal (Fig. 2.17). Also preserved in the Coconino Sandstone are **trace fossils**, which are fossilized traces, such as a track, mold, or footprint without any of the parts of the organism that made it. There are tracks that were formed in the Coconino sand dunes that are thought to be from creatures similar to today's scorpions or millipedes. Interestingly, no remains of the creature have yet been found to confirm what created the tracks.

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, around 273 million years ago. The Toroweap Formation formed in shallow marine, intertidal, 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 transitions. The sedimentary layers at Grand Canyon are often inter-layered and mixed, with no distinction to mark 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 layers usually fade from one into the next, except where there are unconformities.

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 270 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.

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 people speculate! This white coating is called **caliche** or **calcrete**, which is made up of calcium carbonate, the main constituent of limestone. It commonly forms 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 climate.

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.*

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 microscopic 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.

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 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 more 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 the sea was relatively deep and calm to the west when the Fossil Mountain Member was deposited. But in the east the sea was shallower, and the nearby beach and fluvial environments added sand to the limestone. Many fossils have been preserved in this member of the Kaibab Formation, including the fossils along the Rim Trail near the Bright Angel Fault (Fig. 2.20). Another good location for viewing fossils is near the top of the Hermit Trail.

A)

Figure 2.20 – Fossils of Grand Canyon. *A) The fossil site along the Rim Trail, west of the Hermits Road Shuttle Transfer, is adjacent to the Bright Angel Fault. The fault formed during the Precambrian, about 1700 million years ago, and was reactivated about 70 million years ago. It was reactivated again in the last 15 million years. One of the results the fault movement is that fossils in the Fossil Mountain Member (Kaibab Formation) have been exposed at rim level 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 2.20 (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 the original organism. These minerals are mainly calcite (calcium carbonate) or silica.*

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 fossils. They can be distinguished because the top shell is often convex, while the accompanying bottom shell is concave, fitting into the other shell.*
(NPS photos.)

Productid Brachiopod. *This type of brachiopod is usually large, sometimes as large as a human fist. They are quickly identified by the ridge down the middle of the convex, upper shell. (NPS photos.)*

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

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 rings or beads. They would have been stacked to form the stem, with a sea lily-like head called a calyx at the top. When the organism began to decay the individual pieces of the stem broke up.*

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

Stick Bryozoan. *These were once small, tree-like, marine 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. (NPS photos)*

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 organism that was like a thin sheet or sea fan that waved through the water capturing the tiny food particles it needed. (NPS photo)*

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 (chert). As the sponge died and was deposited, tiny silicate minerals from the sea water and sediment bonded to it to preserve 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. (NPS photo.)*

Trace fossils. *These irregularly shaped blobs made up of chert are common at the fossil site, and they are actually trace fossils. Visitors often guess they are bones. They formed 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). Sponges are also often preserved in chert. (NPS photo.)*

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 in the soil throughout the Village and in the residential area.*

The change from the Fossil Mountain Member to the Harrisburg Member is gradual, and the rock types are similar, 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 comes from the Harrisburg Member (Fig. 2.21). **Evaporites** are also found in the Harrisburg Member. They are minerals that were once dissolved in water, but when the water evaporated, the evaporite minerals 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 tectonic environment changed dramatically. Since the Permian Period, the western continental margin of North America has been a site of active plate boundary processes.

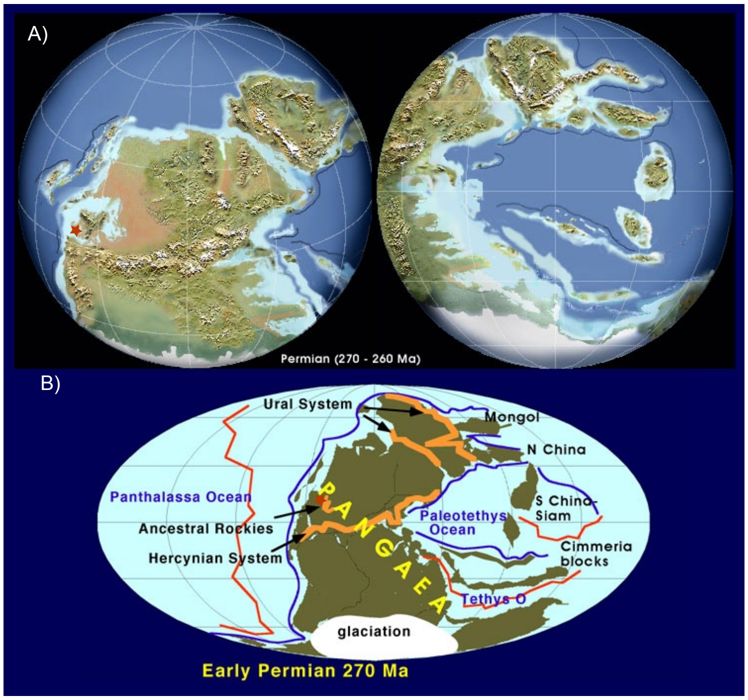


Figure 2.22 – The Earth at the end of the Paleozoic Era. *A) Physiographic depiction shows the topography of the land, and extent of the shallow continental shelves (light blue). B) The outlines of the plates and the plate interactions are shown (blue lines indicate convergence, red lines indicate divergence, and orange lines are mountain chains). On both, the red stars indicate the approximate location of the Grand Canyon region 542 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)*

THE MESOZOIC ERA (251 TO 65.5 MILLION YEARS AGO)

During the Mesozoic Era, the era of "middle life," living creatures recovered and proliferated after the mass extinction at the end of the Paleozoic Era. It was a window of opportunity for the development of mammals, birds, and dinosaurs. Pangea began 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. These rocks are found in many parks in southern Utah, such as Zion, Capitol Reef, Arches, and Canyonlands National Parks. However, in the Grand Canyon region there are few Mesozoic rocks remaining.

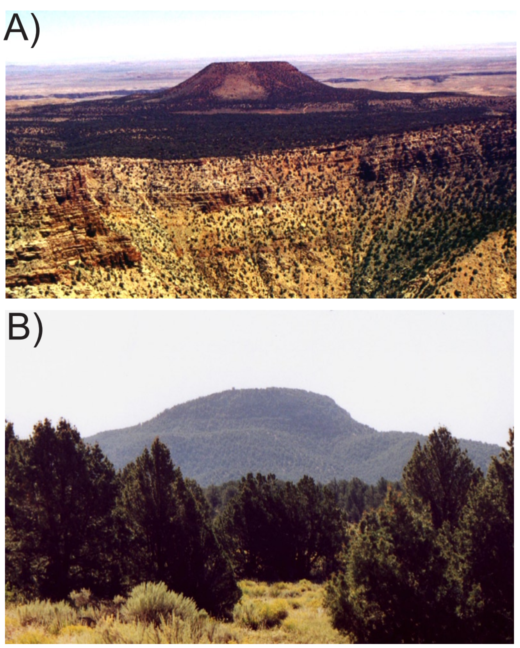


Figure 2.23 – Mesozoic remains. *A) Cedar Mountain is a mesa located near Desert View Point, just east of Grand Canyon. It is composed of the Mesozoic Moenkopi (early to middle Triassic Period) and Chinle Formations (late Triassic Period), which formed between 251 and 199 million years ago. B) Red Butte 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.*

Uplift of the Grand Canyon region that began sometime during or after 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 several Mesozoic layers, which were formed during the Triassic Period (248 to 213 million years ago).

Hypotheses under construction! As you read on about the Colorado Plateau and the incision of Grand Canyon, it's important to know that their development is not well understood. Much of the recent geologic history is still being unraveled and pieced together by geologists. This provides an opportunity to talk to visitors about the **scientific method**, which is the systematic process that researchers follow in order to develop theories that explain any sort of scientific observations. The scientific method begins with detailed observations of some phenomenon, feature, or event. 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 Laramide Orogeny

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, the Colorado Plateau, and the 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 subducting plate no longer extended deep enough to cause melting deep beneath the continent. It also caused deformation to move inland on the North American continent as far as 625 miles (1000 km) from the plate boundary. Geologists

The trouble with uplift. The timing, extent, and amount of uplift of the Grand Canyon region and the Colorado Plateau are very difficult to determine for many reasons. For one, when a region is uplifted, there is often no rocks deposited to leave a depositional record (because it no longer covered by the sea), rather erosion commonly intensifies, removing any clues. Uplift can occur in small regions along faults or over broad, expansive areas with no associated faulting or folding. Without a depositional record or faulting, it is nearly impossible to tell how much land was uplifted and when it was uplifted. The Colorado Plateau and the Grand Canyon region are on a broad area that has been uplifted sometime during or since the Laramide Orogeny, by a number of possible ways. It is important that you know that there are some geologists who believe the region was all uplifted during the Laramide Orogeny, while others think there has been recent uplift in the last 20 to 15 million years that is unrelated to the Laramide Orogeny. Still others see evidence that suggests it could be a combination of events that led to the uplift of the region. This training manual presents some of the different points of view, but there are many other ideas out there. References are provided at the back of the training manual to give you more information on these subjects.

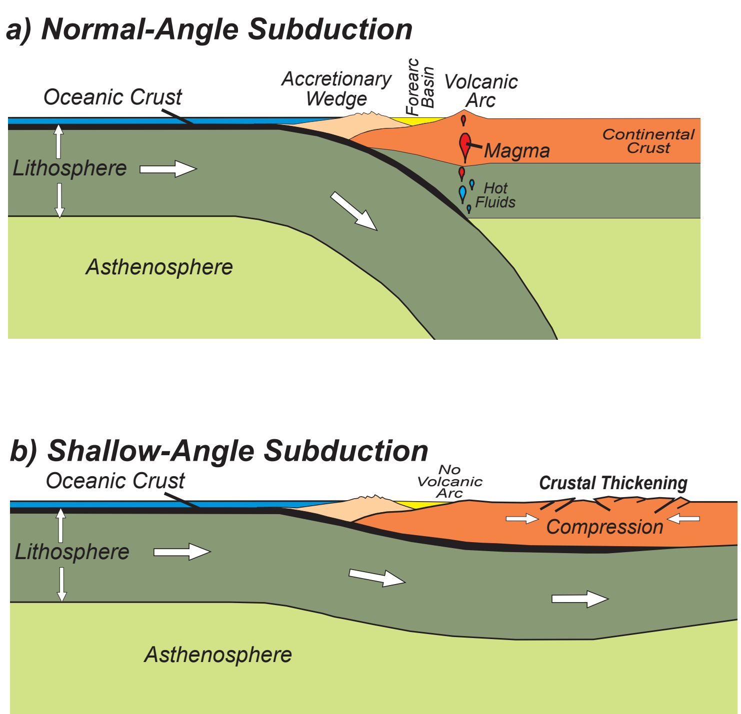


Figure 2.24 – Subduction during the Laramide Orogeny. *a) In a "normal" subduction zone, the down-going plate subducts at a steep angle, causing deformation and volcanism on the overriding plate. As the Farallon Plate subducted beneath the North American Plate it created volcanoes where California is 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)*

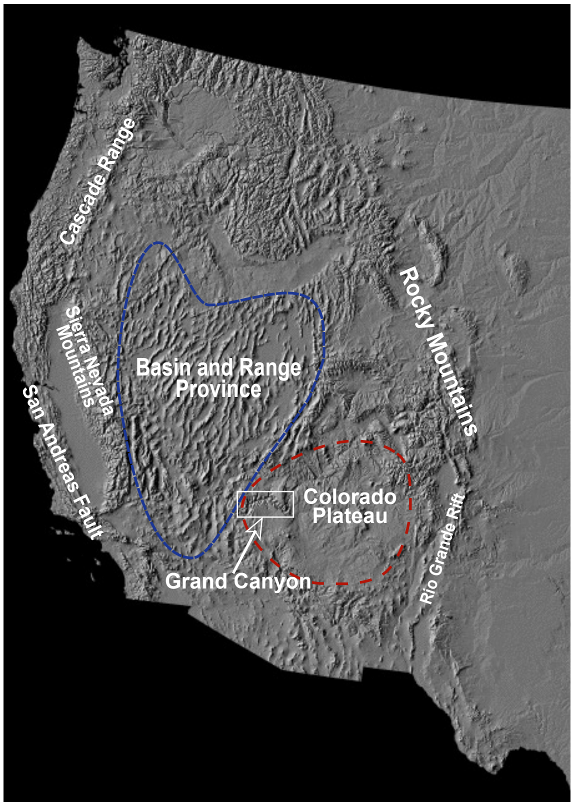


Figure 2.25 – Recent tectonic development of the western US. *The Laramide Orogeny may have initiated the development of many of the geologic provinces identified in this diagram, like the Colorado Plateau and Rocky Mountains. The Colorado Plateau was gradually uplifted and somehow escaped serious deformation, 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, as a result of the Laramide Orogeny.*

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 may have continued for at 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 intensely 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 its crust is 30 miles (48 km) thick, which is thicker than normal continental crust (about 22 miles or 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 may have begun during the Laramide Orogeny as the crust was 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**.

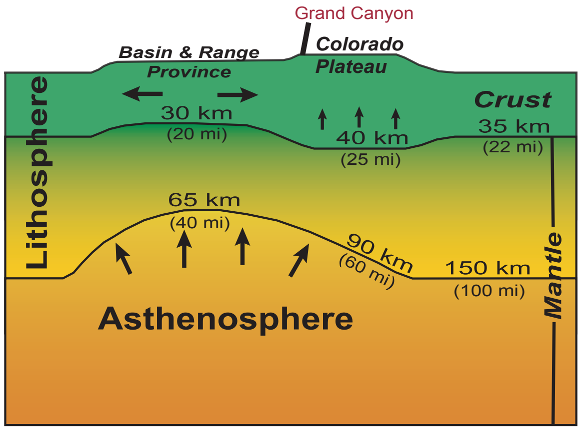


Figure 2.26 – High elevation of the Colorado Plateau. *The Colorado Plateau remains at a relatively high elevation due to both the thick crust beneath the Plateau, and the thin lithosphere of the Basin and Range Province. It is suspected that the thick crust may have developed during the Laramide Orogeny, 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 may be 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.*

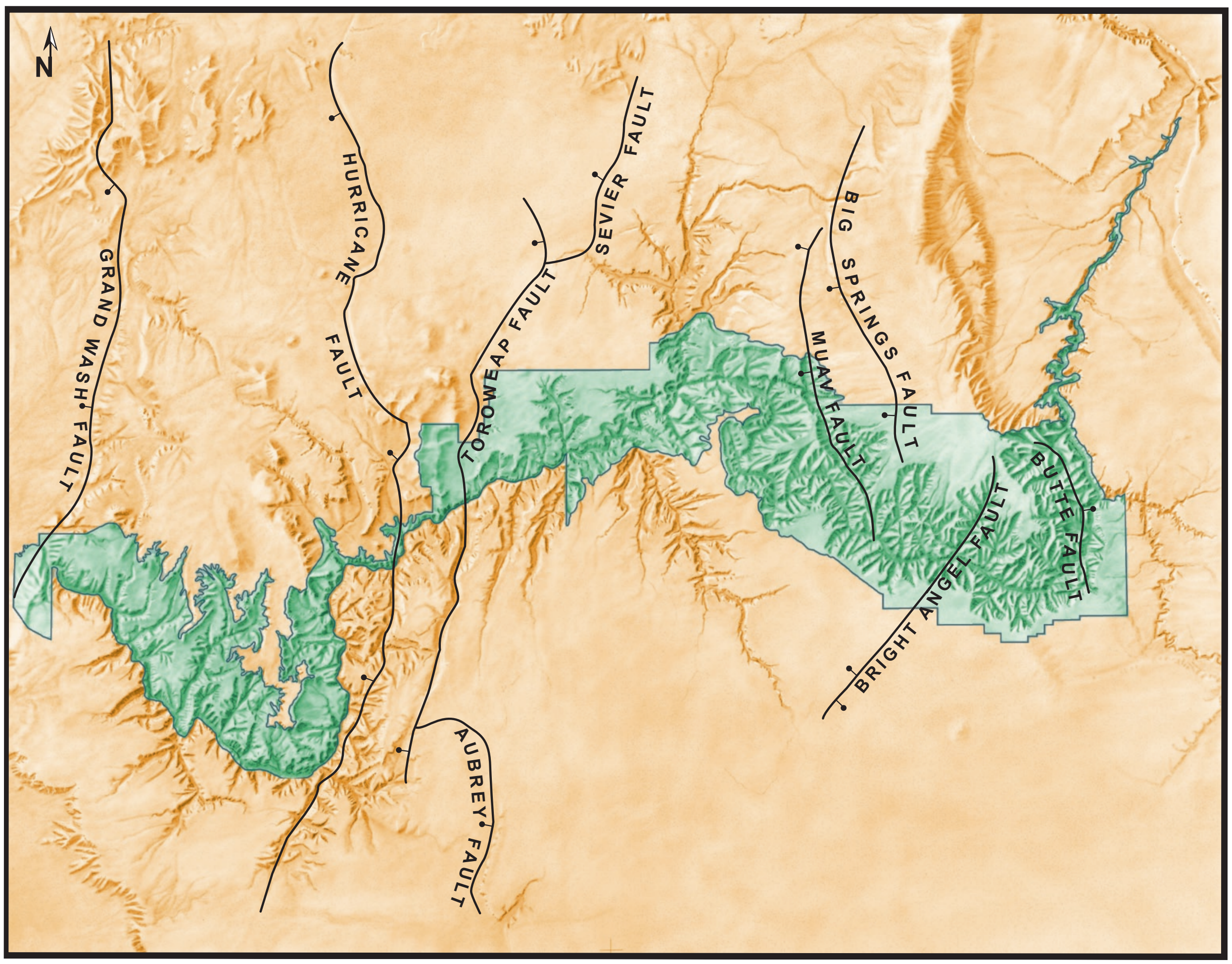


Figure 2.27 – Map of faults in Grand Canyon. *A few of the prominent faults in Grand Canyon are shown on this diagram. Most of these faults formed during the Precambrian and were reactivated during the Laramide Orogeny. Some of them, such as the Toroweap and Hurricane Faults, were reactivated again as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

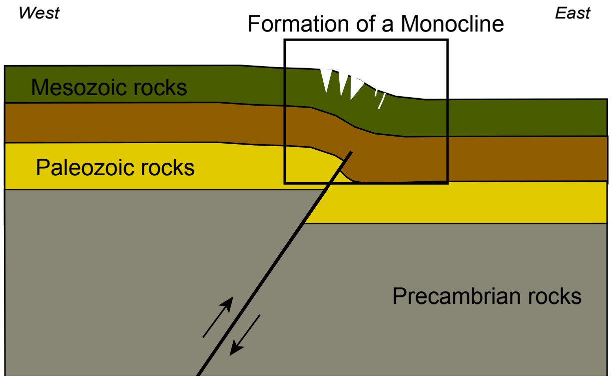


Figure 2.28 – Formation of monoclines at Grand Canyon. *The Precambrian faults deep beneath the Paleozoic and Mesozoic sedimentary layers were zones of weakness reactivated during the Laramide Orogeny. As the reactivated faults ruptured in the Precambrian rocks, they broke through some of the older, 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.*

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 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 is folded, the crust gets broken up and crumbles 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 (see pages 90-93 for more suggestions). 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 intensely deformed during the “crash,” the plateau remained relatively 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 near the Yucatan Peninsula (Mexico) creating a crater 180 miles (290 km) wide. 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, which included the dinosaurs.

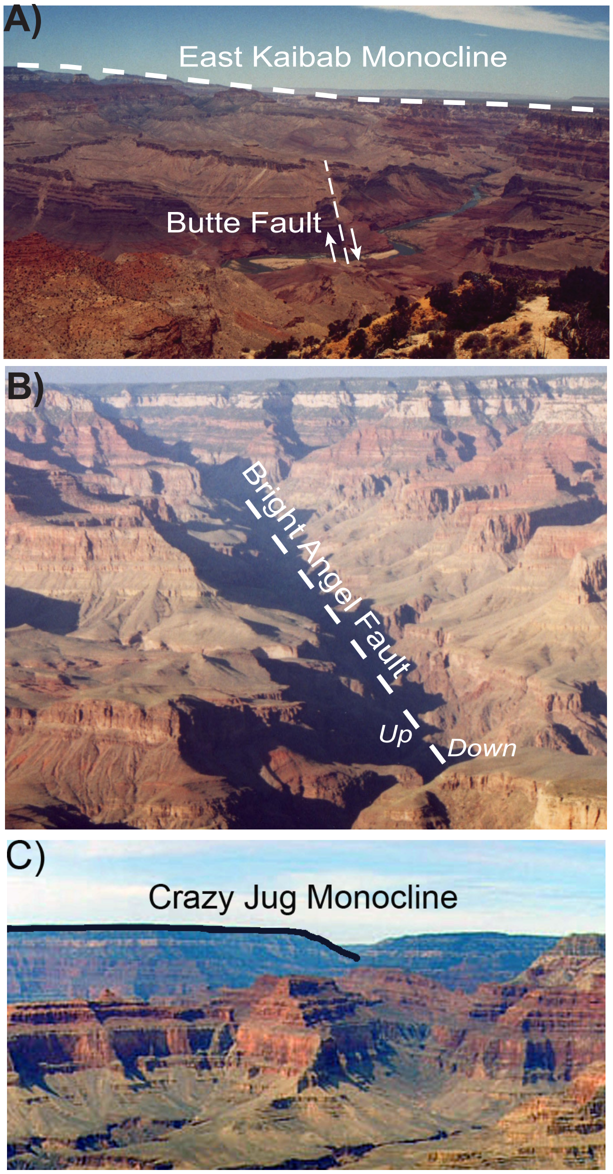


Figure 2.29 – Faults and folds of the Laramide Orogeny. *A) At Desert View, the Butte Fault folded overlying sedimentary layers, creating the East Kaibab Monocline. The arrows show the direction of movement along the fault during the Laramide Orogeny. This photo was taken from Desert View. B) The Bright 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 from 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. NPS photo.*

THE CENOZOIC ERA (65.5 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 all over 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 generally 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, the global climate fluctuated more dramatically than ever before in Earth's history and erosion was greatly intensified. Many of the Mesozoic and Cenozoic rocks in the Grand Canyon region were eroded away. Also, west of the Grand Canyon region, the Basin and Range Province began to rip apart approximately 20 to 15 million years ago. On top of that, a period of volcanism began around 20 million years ago along the southwestern boundary of the Colorado Plateau, which initiated some of the volcanism in the western Grand Canyon region. Around 9 million years ago, the San Francisco Peaks were active volcanoes 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 create an illusion of uplift in the east. This may be one possible explanation for the apparent recent uplift – the land in the west is simply dropping down. There are, however, a number of other hypotheses, and some geologists that suggest that there is no recent uplift. It is a hot topic of research and debate that geologists are struggling with today.

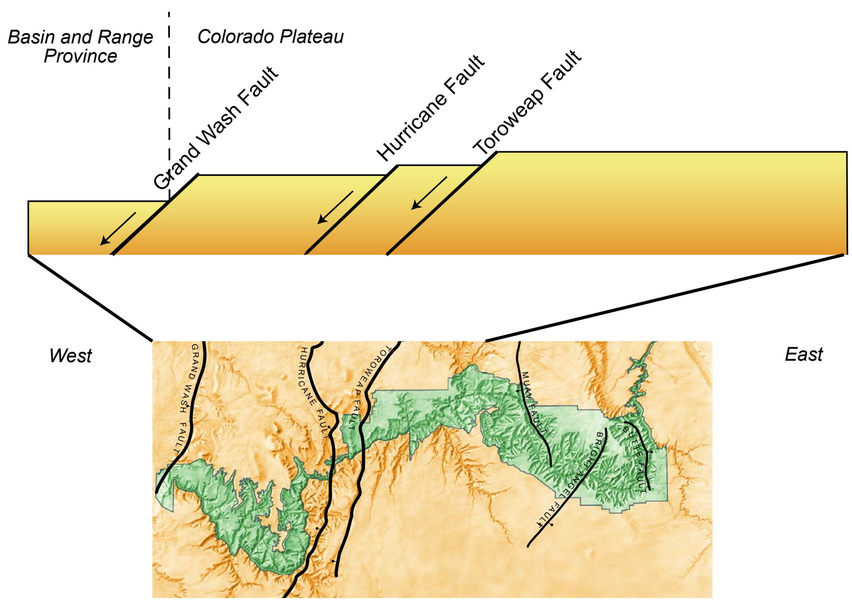


Figure 2.30 – Down-dropping along normal faults. *The upper diagram is a cross-section of what the Earth may look like in western Grand Canyon. The rocks on the west side of the faults drop down in response to the extension and rifting of the nearby Basin and Range Province. The boundary of the Colorado 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 are still being uplifted.*

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!
- 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 overlying canyon layers are comparatively soft

sedimentary rocks, rather than very hard metamorphic or igneous rocks, it may have been 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 tilted and deformed rocks and it would probably have taken a different course over and around the rocks. Also if the rocks were not flat-lying, the canyon would not have the continuous, visible layers of alternating cliffs and slopes that it does today.
- Grand Canyon exists in this location in part 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 15,000 years ago) the massive, continental glaciers did not reach as far south as northern Arizona (but there were small, alpine glaciers on the San Francisco Peaks). However, melting of glaciers in regions far upstream 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. Faults do *cross* the canyon, but do not run parallel to it along its length. An earthquake could not have created the canyon because, again, 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. Finally, 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 clear 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. Unfortunately, so many critical pieces of the puzzle are missing and gone forever. There are just too many gaps 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.

Geologists are stuck working with very little data to help them resolve the history of a complicated river system. One of the biggest problems they face when trying to understand the history of a river is that the river itself tends to wash away much of

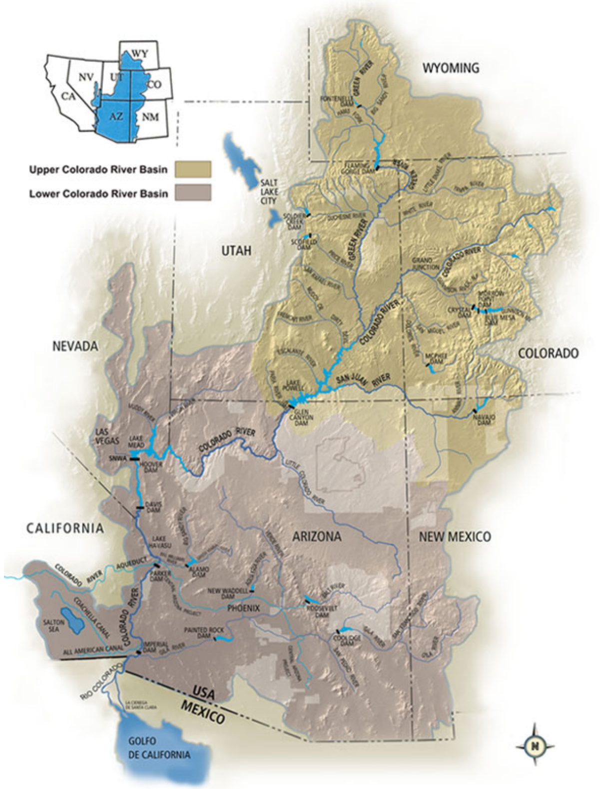


Figure 2.31 – The Colorado River Basin. *The Colorado River begins in the Rocky Mountains of Colorado more than 10,000 feet (3000 m) above sea level. It drains an area of about 242,000 square miles (627,300 square km) of North America.*

the 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. Often times what evidence is found is inconclusive and only serves to create more questions. An additional problem is that the study area, which includes Grand Canyon and the entire Colorado River drainage system, is enormous (Fig. 2.31). The whole Colorado Plateau and some of the surrounding land must be thoroughly covered looking for any small, helpful clue. 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 large amount of time that has passed and the intense erosion that has occurred since the uplift of the Colorado Plateau and the formation of the Colorado River. The river system could be as old as the Colorado Plateau (as much as 70 million years old) as suggested by early geologists like John Wesley Powell and G.K. Gilbert. It is also possible that the river flowed in other locations before entering the Grand Canyon region, and the river has since changed its course. The past 70 million years worth of erosion and other geologic processes has severely hindered the establishment of a solid hypothesis for 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, weathering processes, such as ice wedging and mass movements, as well as by its tributaries. As you look out today at the massive cliffs of rock, like the Coconino Sandstone and Redwall Limestone, know 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 is 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. They continue to research and collect evidence that can help prove or disprove some of the hypotheses. It cannot be emphasized enough that this topic is still under great debate and may never be resolved due to the lack of necessary, physical evidence and data available in this dynamic river system.

The evidence that has been collected so far suggests that the northeastern part of the Colorado River (upper part; in Colorado and Utah) is slightly older, while the southwestern portion (lower part; in Arizona, Nevada and California) 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 of the oldest evidence that may be from the ancestral Colorado River is river gravel found near Grand Junction, CO at Grand Mesa. It is associated with dated volcanic rocks that are approximately 10 million years old. There is another possible Colorado River gravel deposit further upstream near Glenwood Springs, CO, that may indicate the river in that region is at least 7 million years old. It is not exactly clear if the gravels are from an ancestral Colorado River, or some other river, but it is some of the only data available so far. Evidence in the reach of the young Colorado River (discussed in next paragraphs) indicates that between 5 and 6 million years ago, the older and the younger parts 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 was likely an important factor in its development. Undoubtedly, the land looked very different than it does today, in part because there was a thick sequence of Mesozoic rocks overlying the Grand Canyon region, little of which now remains. The shape of the landscape then (which is unknown because it has been eroded away) probably determined the present course of the Colorado River.

In eastern Grand Canyon, one landscape obstacle apparent today that seems impossible for a river to cross is the **Kaibab Plateau**, which is a broad, elevated area that was uplifted along the East Kaibab Monocline (Fig. 2.32). The Kaibab Plateau begins where the Colorado River makes a sharp turn to the west, near Desert View. How the river has managed to cut right through this large area of upwarped land is unknown. As you know, water 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 could have been relatively flat and easy for the river to cross, and then the plateau may have been uplifted 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 could have established its channel right through the plateau (Fig. 2.33b).

Looking at clues in western Grand Canyon, geologists suspect that mountains

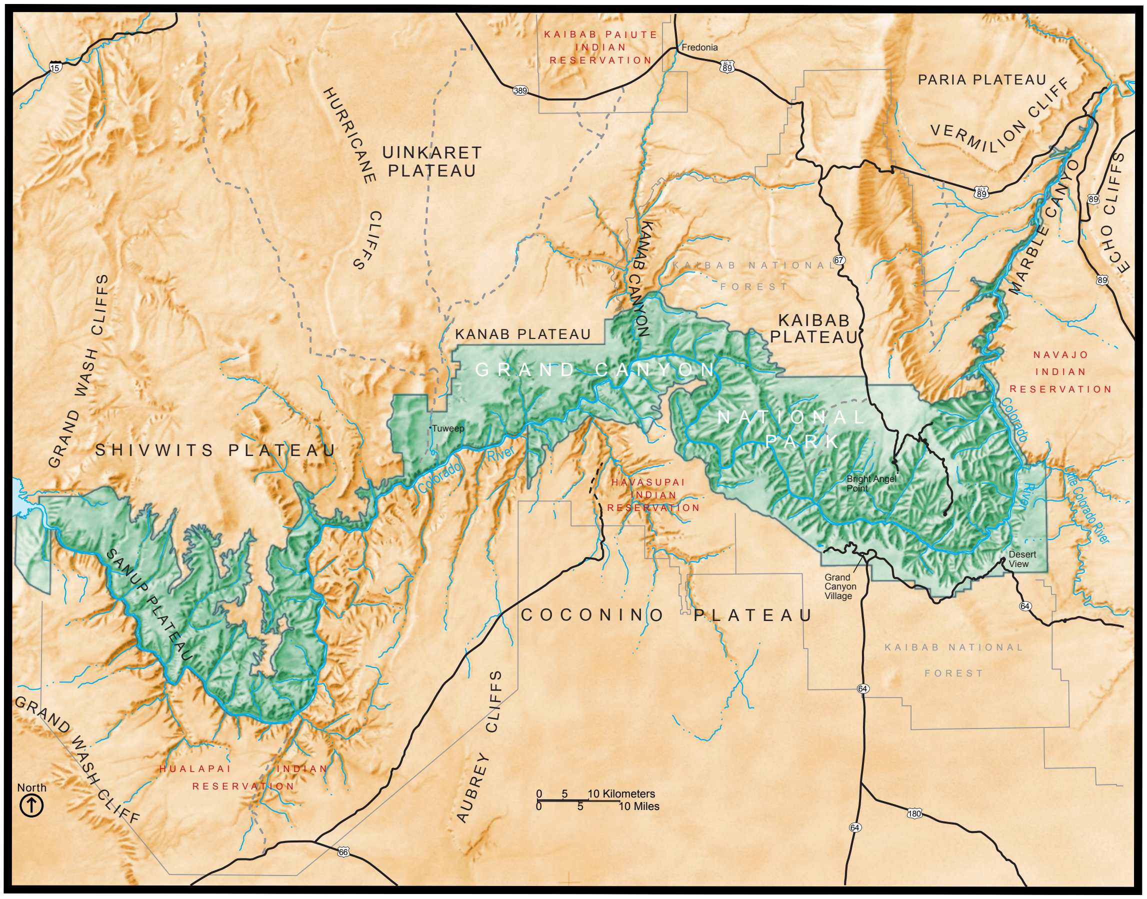


Figure 2.32 – Colorado River and Grand Canyon. *Evidence shows that the northeastern reaches of the Colorado River are older than the southwestern part of the river, which is about 5-6 million years old. These findings suggest that the entire Colorado River through Grand Canyon did not form as one connected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

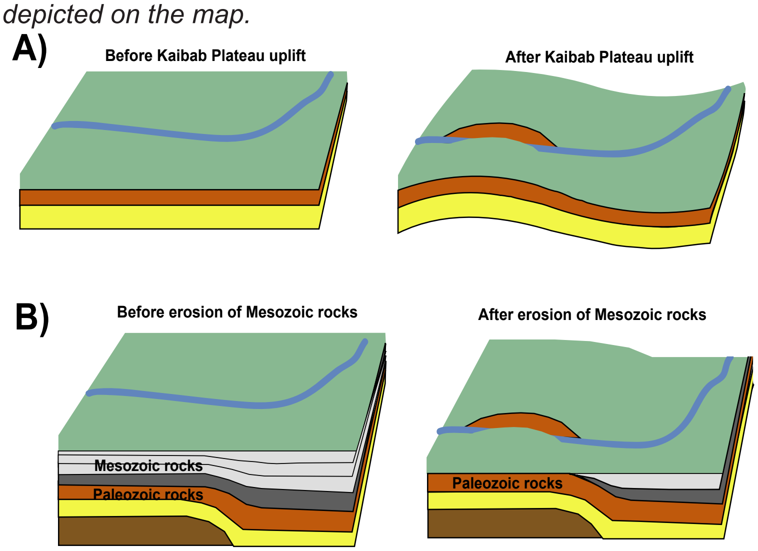


Figure 2.33 – The Kaibab Plateau. *The Kaibab Plateau may not have been an obstacle for the early Colorado River, as it seems to be today. A) One hypothesis is that the Colorado River may have flowed over a relatively flat region prior to the Kaibab Plateau uplift and development of the East Kaibab Monocline. After the Colorado River established its channel, the Kaibab Plateau developed. This suggests there has been recent uplift and the river 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 mildly folded or flat-lying 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 being affected by the upwarped land below.*

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 those mountains that existed on the southern edge 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.

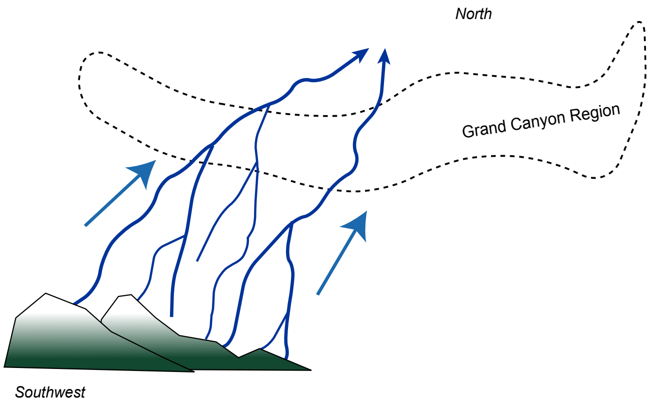


Figure 2.34 – Former highlands near Grand Canyon region. *A mountainous region likely existed south/southwest of the Grand Canyon region, prior to Grand Canyon forming. North flowing streams ran off the mountains over the Grand Canyon region, and deposited sediment known as rim gravel. As the Basin and 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.*

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. Occasionally, 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 5 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 south-

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 less than 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.*

ward to where it is today.

Basalt that flowed from the Vulcan's Throne area provides further clues to the rate and timing of the canyon carving (Fig. 2.35). At this location, lava (basalt) has flowed into the canyon, and down to the present river level. The $^{40}K/^{40}Ar$ 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. Some of the newest $^{40}Ar/^{39}Ar$ radiometric ages for these rocks suggest that they are actually much younger, only about 700,000 years old (0.7 million years). This means that the canyon was not incised to its present level until rather recently, geologically speaking.

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 puzzle pieces that have been pieced together so far indicate the following:

- An ancestral Colorado River may have existed in Colorado and eastern Utah by 10 million years ago, while around that time in the Grand Canyon region small rivers were flowing north onto the Colorado Plateau.
- Grand Canyon did not exist prior to 6 million years ago indicated by rim gravels and dated basalt.
- The Bouse Formation suggests that by 5 million years ago the Colorado River had reached the sea at the Gulf of California, therefore, between 5 and 6 million years ago the Colorado River was established as a through flowing drainage from the Rocky Mountains to the Gulf of California.
- The river had formed Grand Canyon and incised down to the present depth by 700,000 years ago.

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 improve.

Hypotheses for the Puzzle

There are an incredible number of hypotheses and variations of those hypotheses for 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 concluded. Only a few of the many different hypotheses are discussed here.

- **The Little Colorado River Hypothesis:** All of the hypotheses about the Colorado River and Grand Canyon development have to address the apparent difference in age of the upper and lower reaches. 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 ancestral Colorado River, prior to about 5.5 million years ago, flowed in its present channel, coming from the northeast toward the Kaibab Plateau. In their hypothesis, the river then followed the path of the Little Colorado River, joining the Rio Grande, and finally ending in the Gulf of Mexico (Fig. 2.36a). As the young Colorado River worked its way toward the Kaibab Plateau by headward erosion, it intersected the ancestral Colorado River about 5.5 million years ago and captured its waters (Fig. 2.36b). A problem with this hypothesis is that there is no evidence to show that the ancestral Colorado River flowed out to the Gulf of Mexico through the Little Colorado River channel.

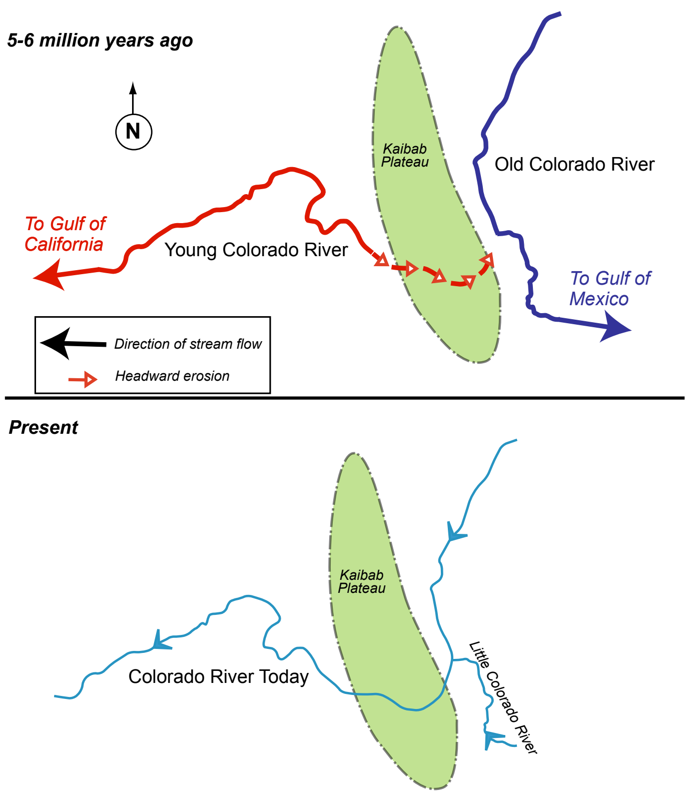


Figure 2.36 – The Little Colorado River hypothesis. *McKee and others (1967) suggested this model for the development of the Colorado River through Grand Canyon. In the top diagram, the "old Colorado River" (blue) flowed to the Kaibab Plateau, then turned to the southeast, and flowed down the channel 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.*

- **The Northwest Flowing River Hypothesis:** A hypothesis by Ivo Lucchitta (1975, 1984) suggests that the ancestral 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 ancestral Colorado River crossed the Kaibab Plateau, then flowed northwest along a valley parallel to an uplift, such as the Kanab, Uinkaret, or Shivwits Plateaus (Fig. 2.32). Lucchitta's hypothesis is similar to McKee and others, as he suggests that the ancestral 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.

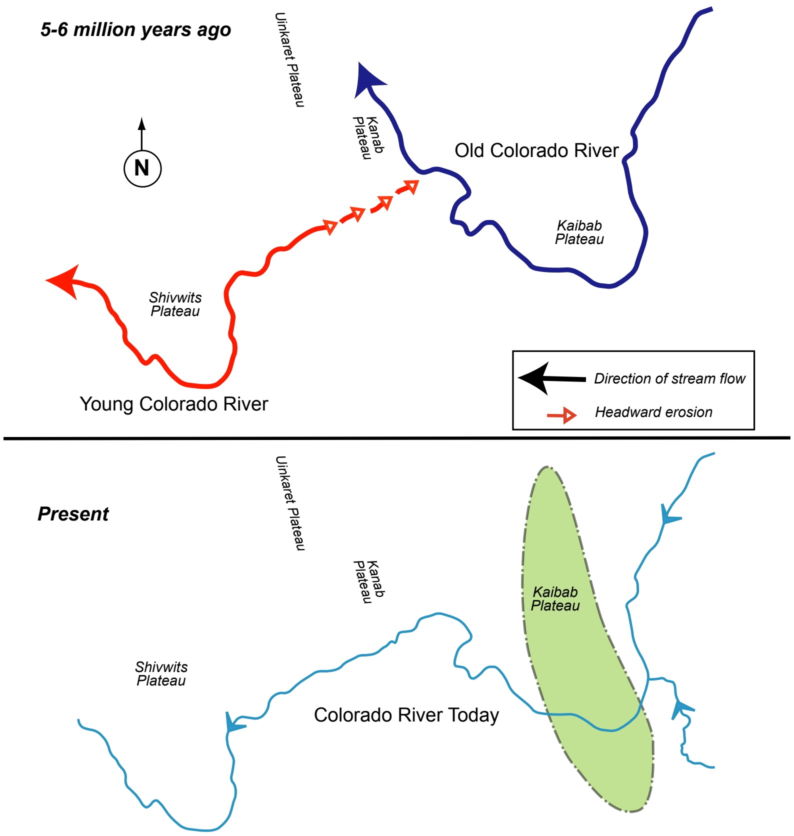


Figure 2.37 – The northwest flowing river hypothesis. *Ivo Lucchita's hypothesis is that the "old Colorado River" flowed northward along a ridge after it crossed the the region where the Kaibab Plateau is today. The diagram at top shows one such possibility. It also may have flowed along the Kanab, Uinkaret, or Shivwits Plateaus. In his hypothesis, either the Kaibab Plateau was not as big as it is today, or it 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.*

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, between 5 and 6 million years ago, the Colorado River began to carve this spectacular landscape we know today as Grand Canyon.

- **The Lake Hypothesis:** A few geologists believe that the ancestral 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.

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 a lake existed 16 million years ago, but it may or may not have any direct relationship to the development of Grand Canyon. One flaw in this hypothesis is that the volume of sediment that was deposited in the lake is not enough to be associated with the Colorado River. Much more sediment would have likely been deposited if the lake were a temporary hold for a sediment laden river such as the Colorado River.

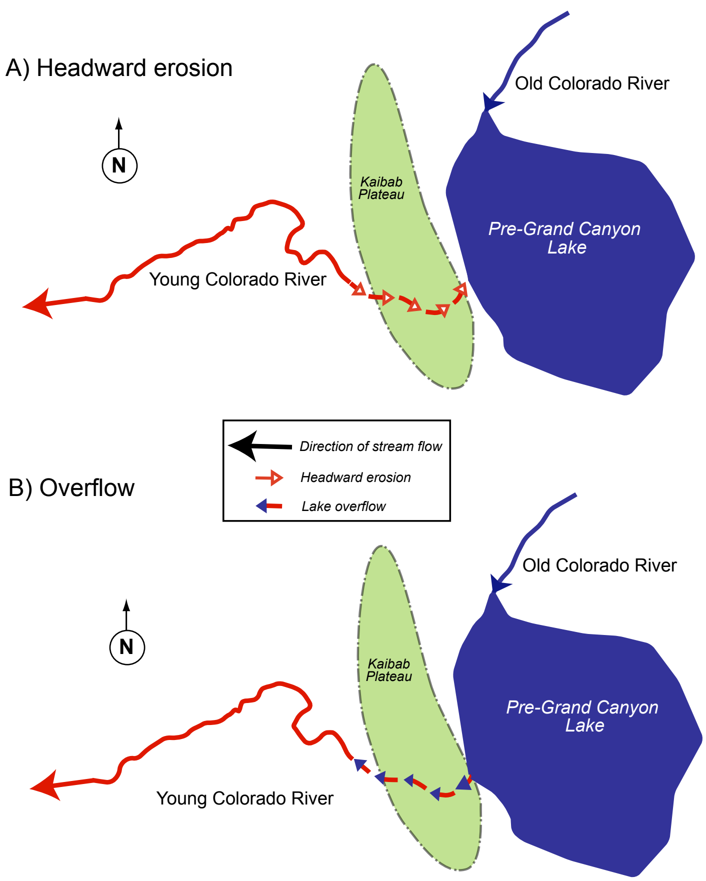


Figure 2.38 – The lake hypothesis. *Some geologists believe that the "old Colorado River" was dammed behind the Kaibab Plateau to form a lake until the lake either: A) was drained as the "young Colorado River" eroded headwardly through the Kaibab Plateau, essentially capturing the water from the lake;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

There are other hypotheses about how 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 pieced together in just the right way – yet!

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, creat-

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 about scientific facts. As an interpreter 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.” Also 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 NPS 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.”

ing 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 large, continental glaciers melted about 15,000 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 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, volcanoes in the western Grand Canyon have erupted basalt into the canyon and may have at times completely dammed the river. Some of the dams may have been over 2000 feet (610 m) high and up to 84 miles (135 km) long! Huge lakes may have formed behind these dams, as the Colorado River backed up. It would have filled side canyons and deposited sediment. Amazingly, the river was

The very basics. When it comes to discussing how the canyon formed with visitors, one of the most important concepts to convey is that all of the rocks formed long before the canyon formed – more than 270 million years before. After the rocks formed, the next major event was the uplift of the 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 in time between these events.*

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.*

able to overcome any of the 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.

Chapter 3: OTHER TIPS FOR INTERPRETERS

FREQUENTLY ASKED GRAND CANYON GEOLOGY QUESTIONS

As an interpreter, you will encounter some of the same geology questions quite often. 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?').

Q. What is the oldest rock in Grand Canyon? The youngest rock?

A. 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 270 million years old. In western Grand Canyon, there are basalts that may be as young as 1000 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!")

Q. How did the canyon form?

A. 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 270 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 movements of rock, as well as tributary streams, 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).

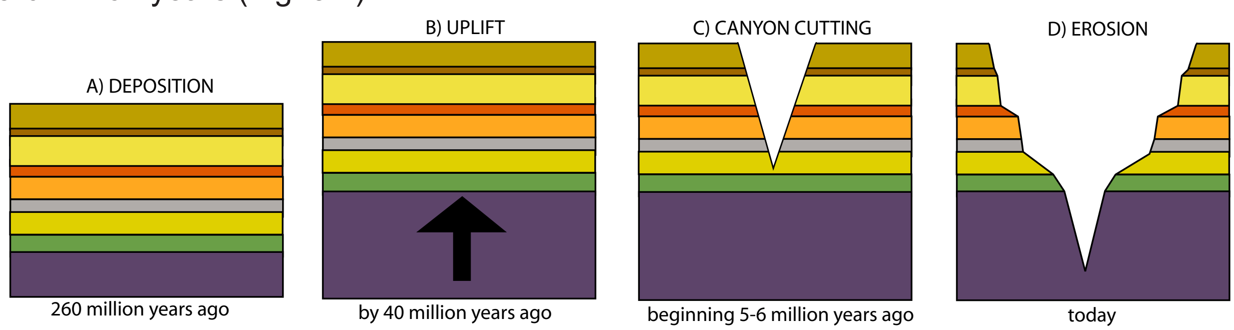


Figure 3.1 – Simplified story of how Grand Canyon formed. *a) The rocks that make up the walls of Grand Canyon were first deposited by water or wind. b) The rocks were then uplifted. c) Much later, the Colorado River began to carve Grand Canyon. d) Over time, the canyon walls have fallen in and eroded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

Q. Why is Grand Canyon here?

A. 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 ***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 monsoon 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!**

Q. Is the canyon getting bigger?

A. 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. The river has also 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.

Q. Where did all the rocks that once filled the canyon go?

A. 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,

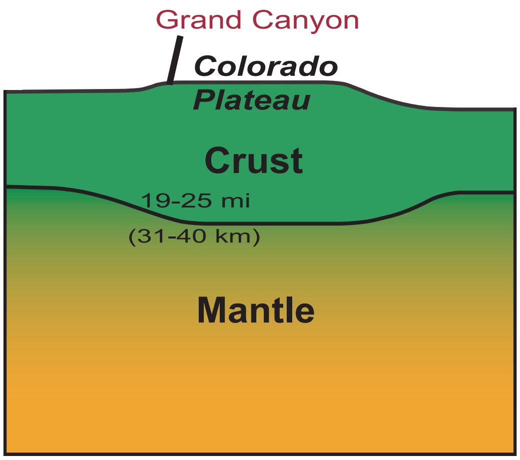


Figure 3.2 – Below Grand Canyon. *This schematic cross-section of the Earth below Grand Canyon shows that the crust is about 19 to 25 miles (31 to 40 km) thick. Most of the crust is solid rock material composed of silica-rich minerals similar to the metamorphic and igneous rocks found in the inner canyon.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

in the past the Gulf of California was much further north than it is now, near Needles, California (Appendix 1). Sediment that was once in Grand Canyon has been 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.

Q. What lies beneath Grand Canyon?

A. 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).

Q. How are the rock layers and fossils dated?

A. The igneous and metamorphic rocks of Grand Canyon have been dated using the decay radioactive isotopes. For example, minerals in the Precambrian 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. The various techniques of dating the rocks at Grand Canyon have helped geologists understand how Grand Canyon fits into the overall geologic history of the Earth (Fig. 3.3).

Q. How do we know the age of the canyon?

A. The length of time that it took to form the canyon has mainly 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 overlie rim gravels that were deposited by older streams 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

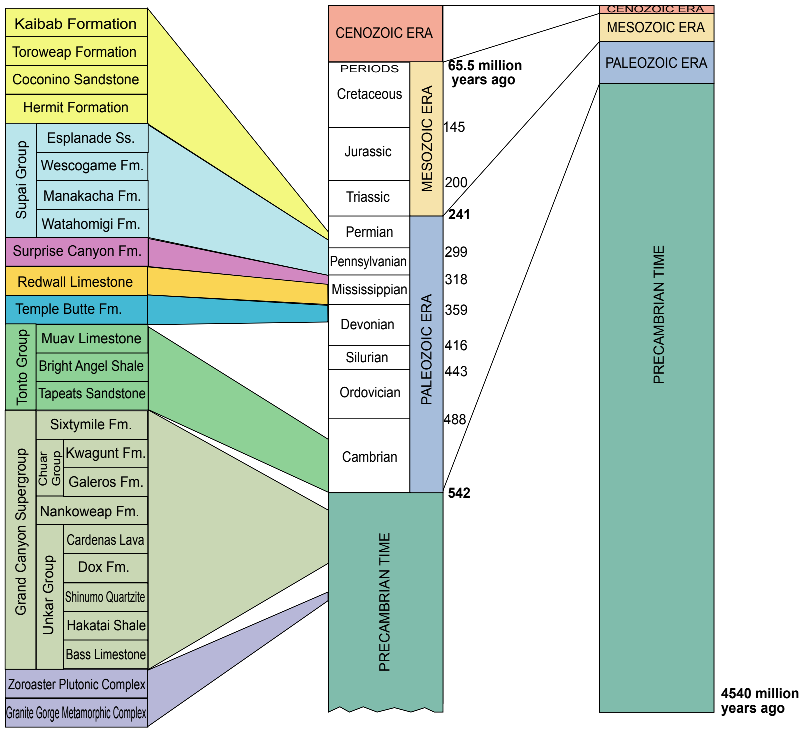


Figure 3.3 – Geologic time scale for Grand Canyon. *The different rock layers of Grand Canyon are depicted to show their approximate ages. The geologic time scale in the middle is not drawn to scale, but the time scale on the right side has the correct proportions. Notice that Precambrian Time covers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

they have been measured to be about 700,000 years old. This tells us that the canyon was as deep as it is now by 700,000 years ago. Also, sedimentary rocks deposited by the Colorado River 5 million years ago near Needles, CA, imply that the Colorado River was flowing through Grand Canyon by that time.

Q. Why are features like mesas, buttes, and temples still standing?

A. 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 a layer that was once continuous, and they are just the last to be eroded away.

Q. Why do the canyon walls have a stair-step shape?

A. 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

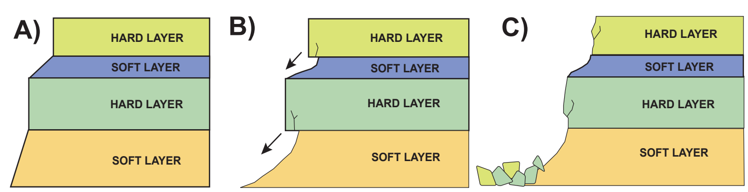


Figure 3.4 – Erosion of canyon walls. *a) Alternating hard and soft rock layers create the stair-step shape of the walls of Grand Canyon. b) Because soft layers erode easier and faster, they undercut the hard layers above, leaving them no support from below. c) The harder rocks eventually break off in 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.*

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).

Q. Is the Colorado Plateau and Grand Canyon region currently being uplifted?

A. 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 explanation 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 Canyon region, activating normal faults as the region is extended and stretched. Along the normal faults in western Grand Canyon, the west side of the faults drops down, causing the western portion 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.

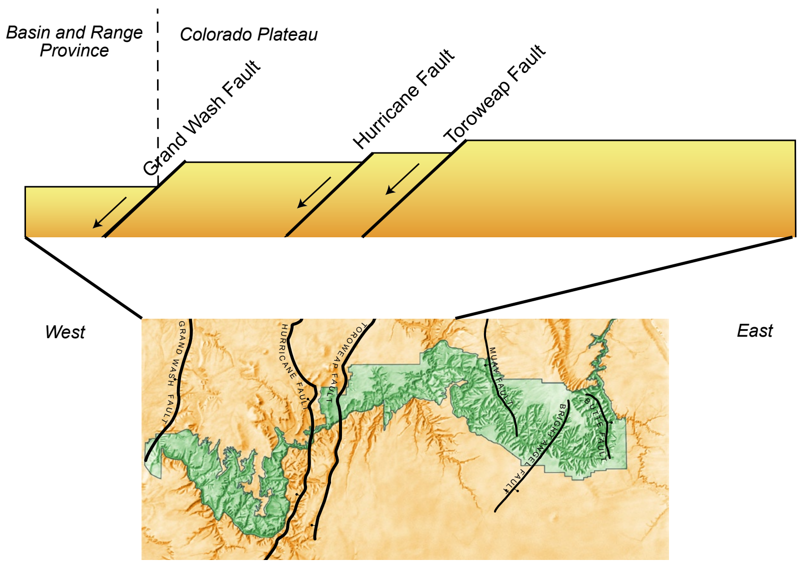


Figure 3.5 – Down-dropping along normal faults. *The upper diagram is a cross-section of what the Earth may look like in western Grand Canyon. The western block of the faults drops down in response to the extension and rifting of the nearby Basin and Range Province. The boundary of the Colorado Plateau 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 is still being uplifted.*

Q. Are the faults in Grand Canyon active?

A. 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). Even as recently as 500,000 years ago there have been significant fault movements where dated basalt has been offset along the Toroweap Fault. Most other faults have not been active since the Laramide Orogeny (70 to 40 million years ago).

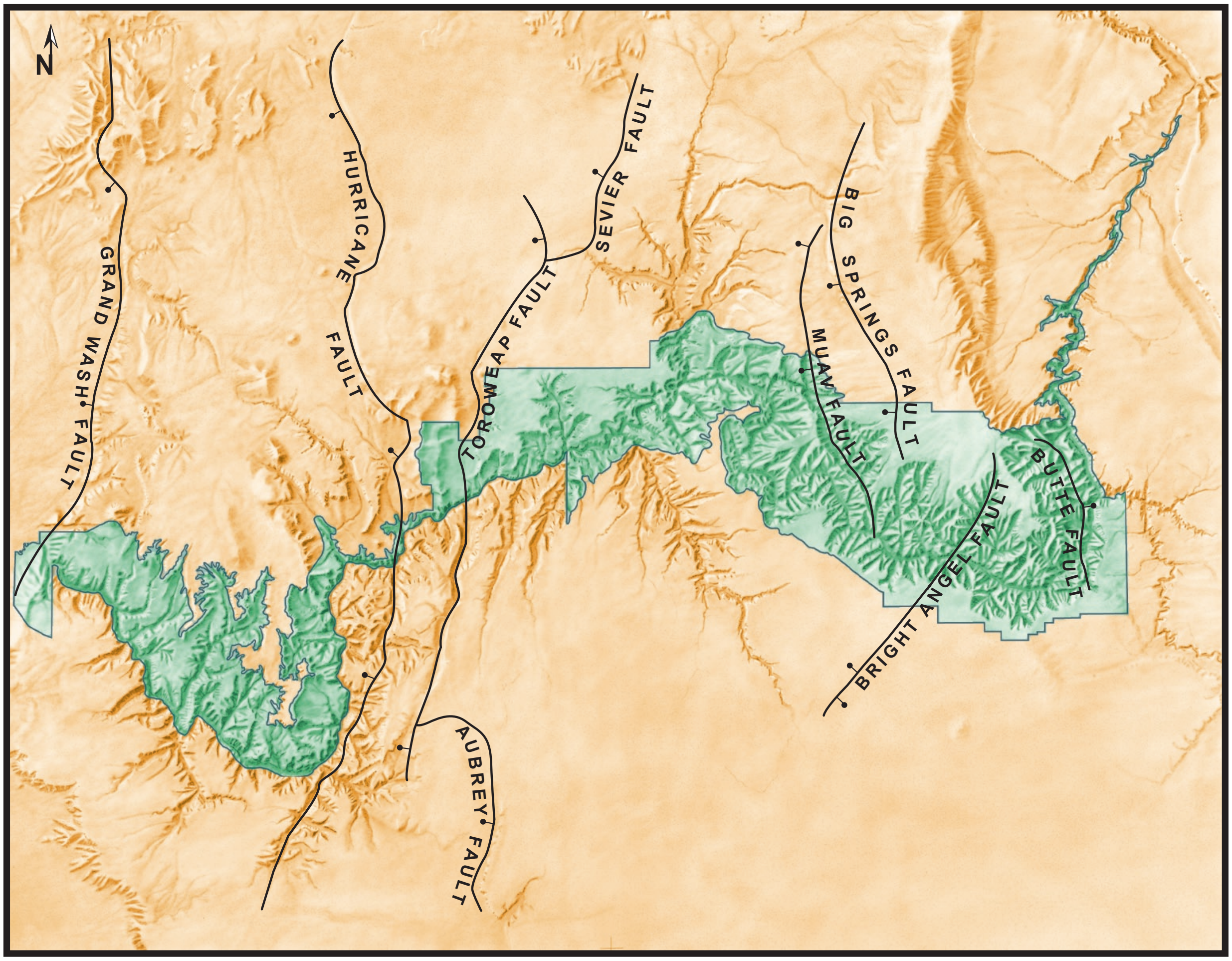


Figure 3.6 – Map of faults in Grand Canyon. *Some of the prominent faults in Grand Canyon are shown on this diagram. Most of these faults formed during the Precambrian and were reactivated during the Laramide Orogeny (70 to 40 million years ago). Some of these faults, such as the Toroweap and Hurricane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

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 sedimentary rock 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.

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 used 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 used a watermelon to help visitors understand the geologic significance of Grand Canyon. If you never saw the inside of a watermelon but only saw the green and white rind, you would never guess that a watermelon was pink with black seeds inside unless it was cut open. Similarly, the Earth is like a watermelon. Grand Canyon is like a slice into the watermelon, 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) was deposited in a warm, tropical environment near the equator. It may have been similar to the climate of the Caribbean, but with one major difference – NO PLANTS! The Supai Group formed in a semi-arid coastal environment that may have been like southern, coastal Texas, such as Galveston or Padre Island. The rocks of the Kaibab Formation, Toroweap Formation and Coconino Sandstone may have been deposited in an environment similar to a mini-Arabian Desert, with the nearby Red Sea and Persian Gulf.

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. 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 help get visitors (especially children) involved and interested. You have the best visual aid for geology right in your back yard - the canyon itself! Use it as much as possible. Here are a few alternative suggestions you can also try.

Geologic time. Use your arm span as a timeline. Hold your arms out to your side. Designate the tip of your right hand as the beginning of the Earth about 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 wrist, getting closer to today

d) The extinction of the dinosaurs and the uplift of the Colorado Plateau (Laramide Orogeny) began at the 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 your 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!

Shape of Grand Canyon. 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 develop a keen awareness of the landscape of cliffs and slopes formed by the different rock types.

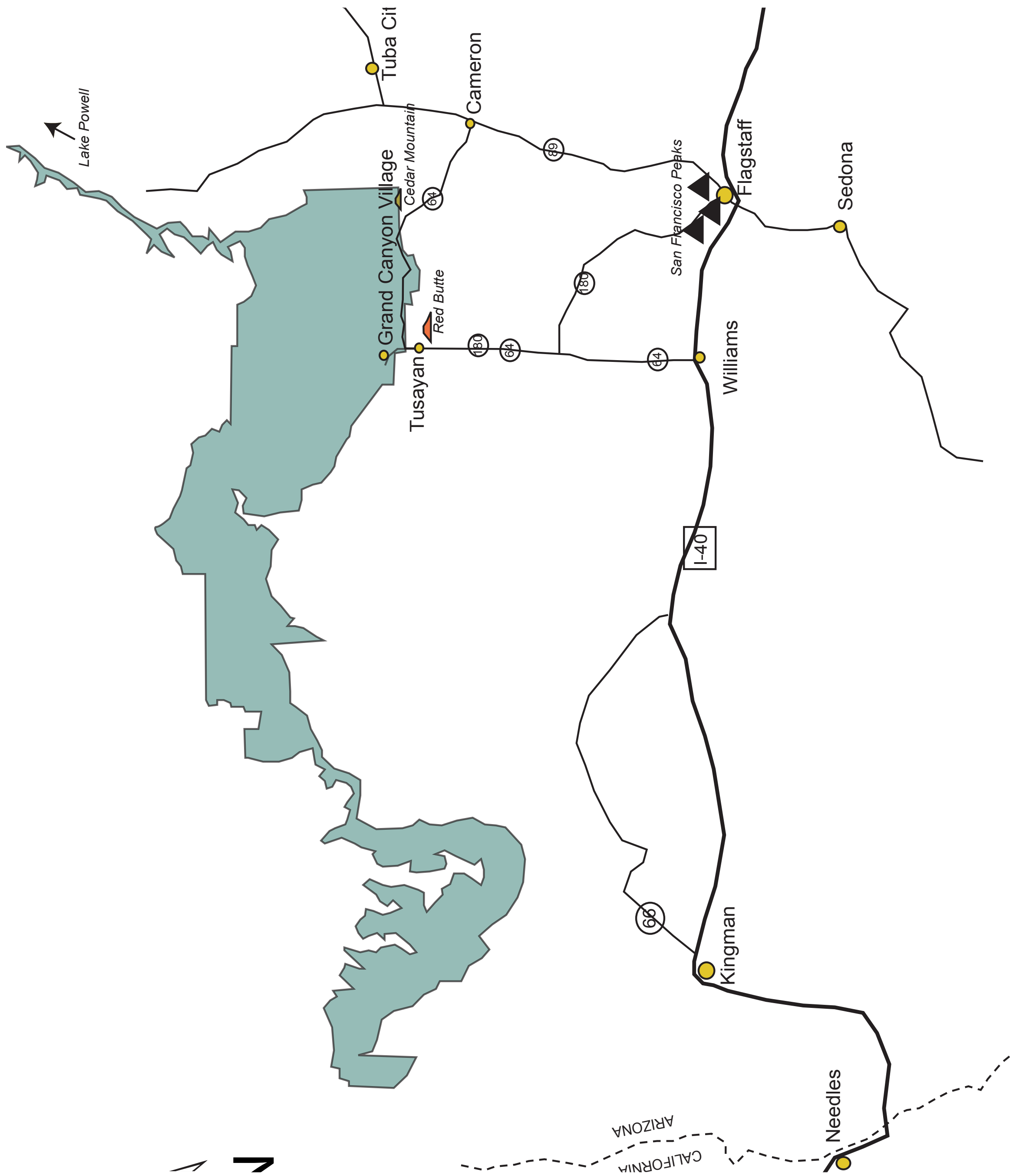
Grand Canyon's rocks. Phyllis Northup also liked to have signs or posters with names of rock layers and their ages. Kids can hold the signs and make a visual timeline.

Geologic time. Interpreters at Dinosaur Ridge National Monument (near Morrison, CO) 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 inches multi-cellular life began to evolve.
- At 4½ inches 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 1/20th inch the first members of the human family of primates appeared.

Grand Canyon geology. Any of the figures used in this training manual are available to you. A CD of the figures is available from the park, and the figures can be printed out for making a poster or presentation.

APPENDIX 1: REGIONAL MAP



Regional Map. *The green area is the approximate area of Grand Canyon National Park.*

GLOSSARY

absolute age – a numeric 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 center 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, fine-grained, extrusive igneous rock composed of 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, generally narrower than a mesa

calcrete – (see *caliche*)

caliche – a hard, white substance composed of primarily calcium carbonate; it forms on the surface of rocks or as a soil layer

chemical weathering – the process by which the chemical composition of a rock is broken down and minerals that in the rock are altered

chert – a hard substance composed of very fine (micro-crystalline) quartz crystals, made of pure silica (SiO_2) that may form irregular shaped nodules and blobs in a rock

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, one plate usually subducts beneath the other causing volcanoes to form on the over-riding plate and earthquakes to occur where the plates are in contact and on the subducting plate; when two continents collide, there may be no subduction zone

convection – the transport and circulation of energy due to differences in density; it is <u>caused by</u> the circulation of hot, <u>less dense</u> material rising 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 visible mineral crystals

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

delta – the fan-shaped 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; named after the shape of the delta symbol.

dike – a vertical intrusive igneous feature formed when magma cuts across or is squeezed into rock

discharge – the volume of water that a river or stream carries in a given time; usually measured in cubic feet per second (cfs)

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, which has distinct, identifying 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 in conjunction with and subsequent to weathering

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

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

evaporite – a mineral that was once dissolved in water, but as the water evaporated the mineral was precipitated 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 platy or prismatic minerals in metamorphic rocks

formation – a mappable rock layer of a distinct and recognizable rock type(s) that can be distinguished from the rocks above and below it; the fundamental stratigraphic unit

fossil – any mineralized remains, traces, or remnants of once living organisms

fracture – (see *joint*)

geology – the study of the Earth and the surface and sub-surface processes that shape it

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

glauconite – a 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 pore spaces within rocks beneath the Earth's surface

group – several stratigraphic formations that represent similar depositional environments in geologic time

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

hypothesis – a testable scientific idea that is an attempt to explain the observations of some phenomenon may have occurred

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 dense iron and nickel-rich minerals

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

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 some may be radioactive

jasper – red chert colored by impurities

joint – a crack in a rock with little or no upward or downward movement in directions parallel to the crack; the rocks simply move apart *perpendicular* to the cracked surface

lava – igneous, molten rock that is erupted onto the Earth surface

limestone – a sedimentary rock composed mainly of calcium carbonate ($CaCO_3$), or "lime," that has chemically precipitated from seawater or composed of the hard parts of some marine organisms; the lime settles 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 or fall

mechanical weathering – (see *physical weathering*)

member – the stratigraphic division of a rock unit in a formation

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

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

plate tectonics – the theory 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 initially 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

relief - the difference in elevation between high points and the surrounding region on the Earth's surface

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

ripple – miniature dune-like features that form as water transports and deposits fine-grained 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 falls freely

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 – technically speaking, shale is a sedimentary rock with a significant amount of clay, but for this manual, shale is used to describe a sedimentary rock composed of very tiny particles of mud, silt, and sand that have been compressed together

silicate – a class of minerals rich in compounds of oxygen and silica

sill – a horizontal layer of igneous rock that forms as magma that is injected and spreads out 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 – (temple) a landscape feature that is tall and slender and usually much taller than it is wide; generally narrower than a butte

stratigraphic column – a cross-sectional representation that shows information about the different rock types and features found in each rock unit, for a given location

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 mats of algae and layers of very fine sediment

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 stratigraphic group of formations

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

theory – a scientifically proven explanation for some phenomenon that began as a hypothesis and was repeatedly tested but not proven wrong

topography – the shape of the Earth's surface

trace fossil – fossilized traces 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

FURTHER READING LIST

Note: There is an enormous amount of published information about Grand Canyon geology, all of which could not be included here. The list below consists of books, papers, and maps that were often referred to as this training manual was written.

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