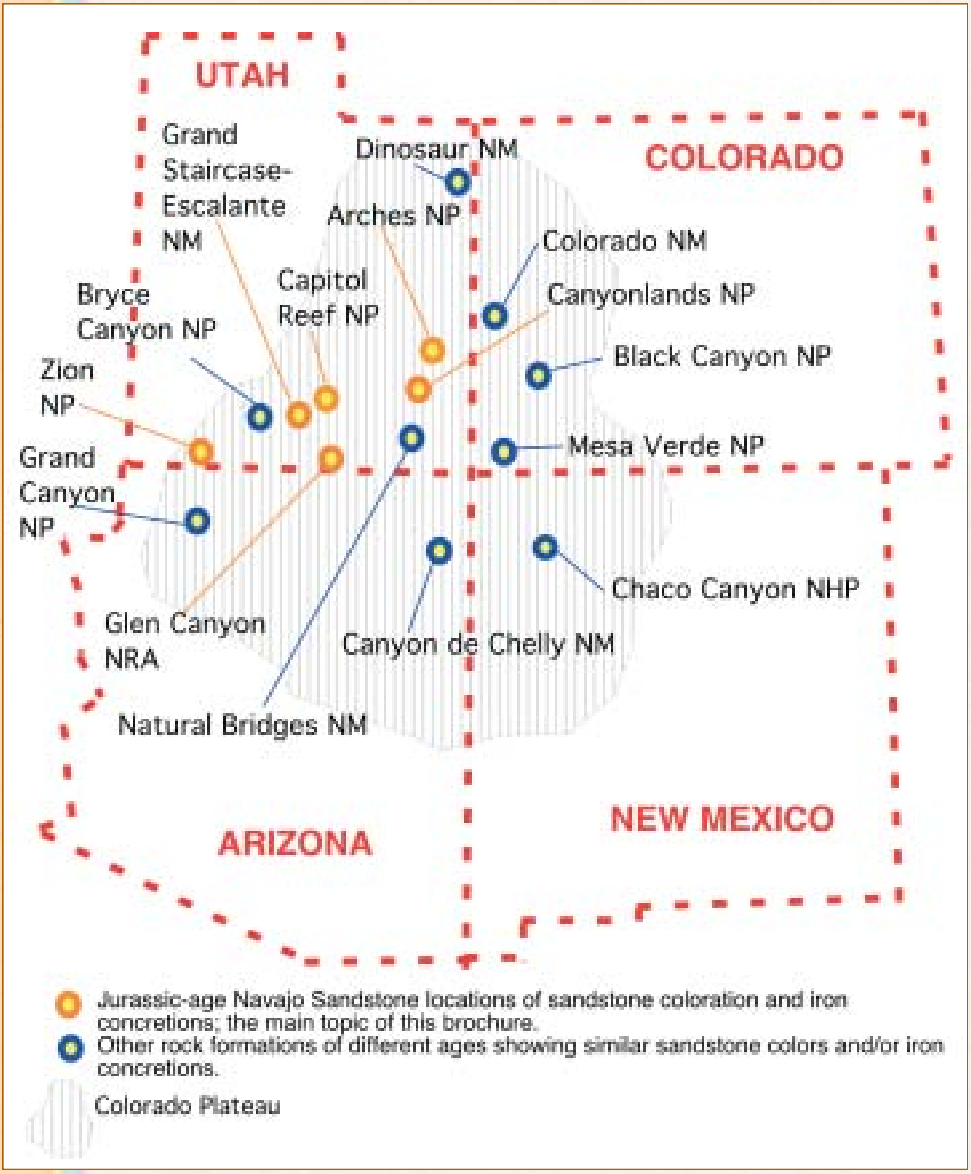
Rainbow of Rocks

Mysteries of Sandstone Colors and Concretions in Colorado Plateau Canyon Country

By Marjorie A. Chan and William T. Parry



Colorado Plateau region centered around the Four Corners where the states of Utah, Colorado, Arizona, and New Mexico meet. Red rock canyon country is particularly well exposed in southeastern Utah. Localities are not inclusive, but are examples where sandstone coloration and concretions are found. NP= National Park; NM = National Monument; NHP=National Historical Park; and NRA=National Recreation Area.

Cover photo: Glen Canyon National Recreation Area and Lake Powell, with colored Jurassic-age sandstones by the Utah-Arizona border. Photo courtesy of Doug Sprinkel.

Brochure design by Vicky Clarke.

Introduction

Sunrise illuminates Colorado Plateau's canyon country. In the early morning light, cliffs radiate a rich red glow, and a sculptured panorama of sandstone is revealed in a rich palette of crimson, vermilion, orange, salmon, peach, pink, gold, yellow, and white. Nearby are black, spherical rock marbles (iron concretions) collecting in small depressions, like puddles of ball bearings. These natural spherical balls have been called various names such as iron nodules, iron sandstone balls, or moki marbles. However, we use the name "iron concretion" to describe both the composition (iron oxide that is the dark mineral which cements the sandstone grains) and the formed shape (concretion).

What paints the sandstone such rich colors? Why is red a dominant color? Where do the black marbles come from? How did the black marbles form? Is there a relationship between sandstone colors and the marbles? This booklet explores the answers to these questions and poses other questions yet unanswered.

The Jurassic-age Navajo Sandstone exhibits a wide range of colors from shades of red to stark white.

In a privately owned area near Moab (southeastern Utah), the Navajo Sandstone is a pale orange, unbleached color. Only 10 miles (15 km) to the northwest of this picture, the upper portion of the Navajo Sandstone formation is bleached white.

The Boulder-Escalante area (south-central Utah) exhibits broad expanses of white Navajo Sandstone.

In Zion National Park (southwestern Utah), the upper Navajo Sandstone is mostly white with shades of yellow.

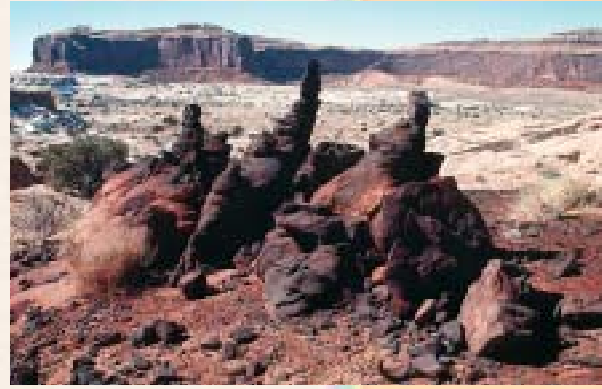
Both pale orange and bleached white sandstone coloration in Grand Staircase - Escalante National Monument, Utah.

Iron concretions in the Navajo Sandstone.

Discrete, small, pea-sized "marbles" accumulated on a flat sandstone surface. Scale card = 6.5 inches (16.5 cm) long. Location: Grand Staircase-Escalante National Monument, Utah.

Partially developed iron concretions that resemble spotted measles dotting a sandstone outcrop. Scale card = 6.5 inches (16.5 cm) long. Location: Antelope Island, Lake Powell, Glen Canyon National Recreation Area, Utah.

Grapefruit-sized, in-place, iron concretion balls (arrow). Location: Antelope Island, Lake Powell, Glen Canyon National Recreation Area, Utah.

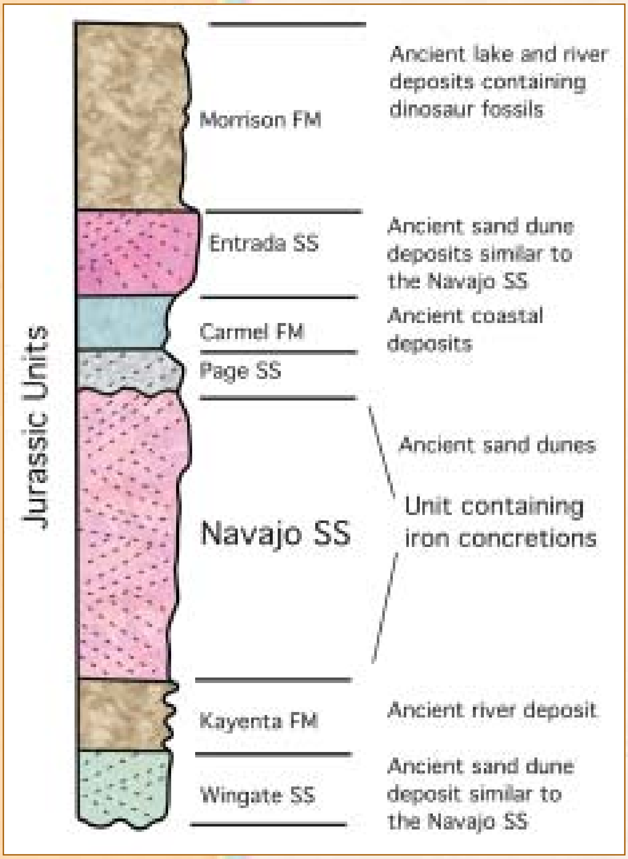


Columns of iron-cemented sandstone. Location: 10 miles (15 km) northwest of Moab, Utah.

Crinkly sheet of iron-cemented sandstone within the ancient sand dune bedding (outcrop is 10 feet or 3 m high). Location: Grand Staircase-Escalante National Monument, Utah.

Red Rock Country

Sandstone can exhibit many colors, but landscapes of the American Southwest that exhibit such striking shades of red have been informally called "red rock country" (portions of which are also called "canyon country" where deeply incised canyons exist). The rock unit called the Navajo Sandstone features prominently in this landscape, and contains some of the largest and most abundant iron concretions found anywhere in the world. The Navajo Sandstone was named for the "Navajo country" of Arizona, Utah, and New Mexico. The red rock country on the Colorado Plateau where the Navajo Sandstone and other relat-



Some Jurassic rock formations in the Four Corners region of southeastern Utah, with emphasis on the Navajo Sandstone. The ancient environments represented in the rock units are given at the right. Modified after Hintze (1988). SS=Sandstone, FM=Formation

ed rock formations are prominently exposed is centered around the Four Corners region where the states of Utah, New Mexico, Colorado, and Arizona meet. This story of the red rocks started millions of years ago. In the next section "Long Ago and Far Away," we address the following six questions.

1. Blood of the Living Rocks: What colors the sandstone red?
2. The Crimson Source: What is the origin of the red pigment?
3. Big-Time Bleaching: What happened to make some red sandstone turn white?
4. The Iron Baby: Where did the red pigment go, and what do iron concretions have to do with this?
5. The Light of Day: How were the sandstones exposed at the surface in the present landscape?
6. The Time Machine: When did all of this happen?

Long Ago and Far Away

This story begins millions of years ago in a world and landscape very different from today: during the Jurassic Period (144-206 million years ago) when the North American continent was at a different latitude, and Utah was close to the equator in a belt of strong trade winds. These winds moved quartz sand to build dunes that covered an area bigger than the Sahara Desert. An accumulation of desert sand dunes is called an erg or sand sea. The largest erg to ever exist in North America is preserved in the Jurassic-age Navajo Sandstone (approximately 180-190 million years old) that is up to 2,500 feet (750+ m) thick. The Navajo Sandstone was deposited over a broad area of the Colorado Plateau and is now well exposed in national parks and monuments such as Zion, Capitol Reef, Arches, Canyonlands, Grand Staircase-Escalante, and a number of surrounding areas. Other rock formations such as the Wingate Sandstone and Entrada Sandstone (see figure of Jurassic units) are also ancient sand dune deposits that show similar coloration and iron concretions. However, the Navajo Sandstone is the focus of this booklet because it displays such a wide range of color (from white to many shades of red) and contains some of the greatest variety of iron concretions found anywhere in the world.

1. Blood of the Living Rocks

What colors the sandstone red? The red color is caused by a union of iron and oxygen (an iron oxide) known as hematite (Fe_2O_3), a mineral named from the Greek word for blood. Iron is a powerful pigment present in many sediments and rocks, thus it commonly imparts color to the rocks. Although red is the common pigment color, not all iron oxides are red; some are brown or yellow (minerals - limonite or goethite), and some are black (mineral - magnetite). Some iron minerals are metallic yellow (mineral - pyrite consisting of iron sulfide) or green (minerals - chlorite or clay consisting of iron silicate).

Although geologists have long understood that sandstone coloration is a function of varying amounts of iron, it is only recently that scientific studies (partly presented here) detail how this happens.

2. The Crimson Source

What is the origin of the red pigment in sandstone? The origin of the color is due to a chemical reaction similar to rusting of a nail. An iron nail appears silver in color and metallic. When a nail rusts due to the addition of water molecules and oxygen, two or three iron electrons are lost to oxygen (the iron is oxidized). The remaining electrons, together with the oxygen, absorb all of light's colors except red and brown. But iron nails don't color sandstones red.

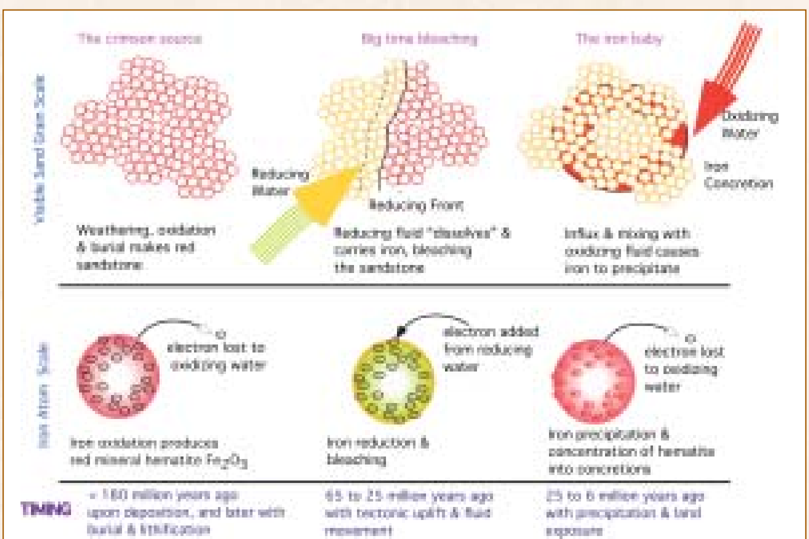
Sandstone originates from the breakdown of older rocks, a process called weathering. Granite, for example, is a type of igneous rock that commonly breaks down in weathering to produce sand grains that later make up sandstone. The older "parent" rocks often have minerals that contain some iron, but these minerals are green or dark brown. Water in contact with the atmosphere absorbs oxygen. Dissolved oxygen in water is very aggressive in removing electrons from iron to produce rust (oxidized iron). As the iron-bearing minerals weather and react with oxygen and water from the atmosphere, the iron is released and forms very thin, paint-like coatings of hematite on the quartz sand grains. Iron in hematite that has lost three electrons absorbs most of the visible colors of light and only red is transmitted to produce the mineral's red coloration. Sands deposited in deserts gradually redden as iron minerals break down and lend their red coloration to the sand. The reddening continues after burial as more overlying sedimentary units are added. Over millions of years, these loose sand grains are compressed and cemented into the rock called sandstone. In these red sandstones, microscopic, oxidized iron films of the mineral hematite spread and coat the quartz grains. The amount of hematite is very small, but since iron is a powerful pigment a little red goes a long way!

Modern desert sands in Western Australia showing an early red coloration from thin coats of oxidized iron around individual sand grains. Photo courtesy of Dick Ojakangas.

3. Big-Time Bleaching

What happened to make normally red sandstone white? Sandstone is porous and permeable because there are holes or spaces between sand grains. Sand dunes make particularly permeable sandstone because wind effectively sorts the grains to create a homogeneous deposit with uniform grain size and not much fine-grained pore fillings. Given enough pressure and force, water moves relatively easily through porous sandstone almost like water through a sponge. Even during heavy rains with much surface runoff, some water infiltrates the sandstone. Under certain conditions, iron pigment will dissolve in water and be removed, or be rendered colorless by chemical reactions with the water. This is much like a bleaching detergent permeating a red cloth, removing color as it spreads. (However, household chlorine bleach won't take out iron rust stains because chlorine is not chemically able to move iron).

How does bleaching happen chemically? Some waters contain reducing agents (electrons are added to the iron atom and oxygen is removed) that make the iron soluble (dissolvable) in water. To make iron soluble, the water can restore one of the electrons that was lost by iron during early weathering and oxidation. Fluids such as hydrocarbons (petroleum), weak acids (vinegar-like), or those with hydrogen sulfide (gas that smells like rotten eggs) can also restore an electron to iron, thus these are called reducing waters. This water can dissolve and remove nearly all of the hematite and bleach red sandstone to white.



Summary of the timing of events related to the sandstone coloration and iron concretions.

Sandstone Coloration is:

- *A function of varying amounts of iron (mineral hematite - Fe_2O_3) that imparts red color.*
- *Initially red, soon after sand grains are deposited and buried.*
- *Red where thin scattered films of hematite coat sand grains, and white where the thin films of hematite have been removed by bleaching.*
- *Facilitated by how easily fluids can move through a sandstone due to different textures of the sandstone (e.g., how loosely or tightly sand grains are packed together).*
- *Variable even on a scale of fractional inches where thin red layers alternate with white layers. This is again a function of microscopic textures in the sandstone.*
- *Affected by oxidizing fluids that encourage hematite precipitation (red color) as well as reducing fluids that bleached the sandstone by removing the hematite (white color).*
- *A property that may have changed over time and involves fluids and processes that occur over tens of millions of years.*

Sharply contrasting sandstone coloration within the Navajo Sandstone.

Navajo Sandstone within Snow Canyon State Park exhibits red sandstone with only small bleached white areas (upper center). Photo by Bruce Simonson.

North of St. George near Snow Canyon State Park (southwestern Utah), the upper Navajo Sandstone is white with some irregular pockets of red sandstone that likely represent the original sandstone color before bleaching.

Navajo Sandstone within Snow Canyon State Park exhibits bleached sandstone with a swath of red sandstone that likely represents the original color before bleaching. Photo by Bruce Simonson.

4. The Iron Baby

After bleaching, (A) where did the red pigment go, and (B) what do sandstone marbles have to do with this?

(A) The red pigment is essentially "dissolved" but still carried by reducing water. So the iron that was bleached out of the sandstone is "held" by the reducing water. On a chemical level, critical changes may occur in the water that has dissolved the iron pigment.

(B) Once the reducing water carrying the dissolved iron meets and mixes with oxygenated water, the oxygen immediately removes an electron from the dissolved iron and drastically reduces its solubility. Thus, a new iron mineral, hematite containing fully oxidized

Navajo Sandstone coloration where the fluid movement and hence the colors are controlled by inherent rock properties displayed in Grand Staircase-Escalante National Monument, Utah.

Bleached white and yellow coloration where reducing water bleached the lower white sandstone.

Red and white "striping" coloration from preferential movement of fluids through sandstones.

iron, is immediately precipitated in the spaces between the grains of the sandstone to form the iron concretions. This is like a marriage where opposites attract and the end product is a new "baby"; the mixing of water causes new iron minerals to grow or precipitate.

Now, instead of thin iron coatings on the sand grains, the iron is concentrated as a thick hematite cement, like a glue, that surrounds the quartz sand grains. Thus, the most abundant iron concretions are typically found in areas where the sandstone is bleached, most likely because the iron for the concretions is actually some of the same iron that formerly made the sandstone red.

Precipitated iron can cement sandstone into many different sizes and shapes of concretions. Pea- to marble- to baseball-sized iron concretions are some of the most striking

Marble to golf ball-sized iron concretions from the Navajo Sandstone, Grand Staircase-Escalante National Monument, Utah. Total length of scale bar = 2 inches (5 cm).

Nearly perfect spherical balls of hematite-cemented sandstone.

The inside of spherical balls. Pink sandstone makes up much of the interior, and the outer dark rind is cemented by iron oxide (hematite).

Other fantastic shapes of iron concretions.

forms, but buttons, columns, pipes, towers, and even corrugated sheets or layers are some of the other shapes that can form. The precipitated hematite can be so concentrated that it looks black in reflected light, but it is still red in transmitted light when viewed under a microscope.

We don't know why some iron concretions are so round, but perhaps some "seed" or nucleus alters local chemistry to precipitate iron in a uniform (spherical) manner. In the concretions, the nucleus could be organic matter or other material that enhances chemical reactions and precipitation. Precipitation is most easily accomplished when some nucleus is present. However, if no nucleus is present, then there may be some optimum physical spacing of concretions that grow by drawing and pulling in their chemical components for precipitation from a local vicinity. Thus, when reducing water carrying soluble iron meets with oxidizing water, the concentrated hematite may precipitate in spaced-out spherical concretions.

All of this iron dissolution and transportation takes place underground. Even mixing with oxygenated water is a subsurface process. The precipitation of the iron in concretions takes place hundreds of feet or more below ground.

The ancient dune sandstones, because of their porosity and permeability, are a good medium for transmitting fluids. Water transport can also be facilitated along weaknesses and cracks in the rock (like faults and joints).

Over the long history of these rocks, enormous amounts of water have flushed through this porous sandstone. The formation of one golf-ball-sized iron concretion requires many times its volume of water.

5. The Light of Day

How was the sandstone exposed in the present landscape? Originally, much of the sandstone was deposited as sand dunes in a desert 180 million years ago. Other rocks about the same age were deposited near the ocean when this region was near sea level. Why is the area now at considerable elevation above sea level and what processes or events led to its present elevation? Strong forces responsible for uplifting buried rocks are commonly attributed to the interactions between large outer pieces of the Earth's crust; a field of study called plate tectonics. Interaction of the Pacific plate (beneath the Pacific Ocean) and the North American plate (largely the continent of North America) thickened the crust and uplifted the Colorado Plateau 80 to 50 million years ago. Uplifted rocks were gradually removed by weathering and erosion, exposing the formerly buried rocks.

More uplift related to rising magma (molten rock) occurred on the Colorado Plateau about 25 million years ago (Ritter and Smith, 1996; Wendlandt and others, 1996). Igneous rocks resulting from the rising magma form prominent landmarks such as the La Sal Mountains, Abajo Mountains, and the Henry Mountains in Utah; the San Francisco Mountains in Arizona; and Shiprock in New Mexico.

During these episodes of uplift, and later during accelerated erosion beginning about 6 million years ago (Hunt, 1969; Lucchitta, 1979), the sandstone formations have been carved and sculpted by flowing water and river systems, including the Colorado River and its tributaries. Weathering and erosion have helped further expose sandstone cliffs over the past several million years.

Iron Concretions are:

- *Natural balls and other shapes formed in a porous sandstone.*
- *Made up of hematite (iron oxide) cement that precipitates around quartz sand grains.*
- *Likely comes from iron that was bleached out of red sandstone.*
- *Formed from the mixing of different fluids: reducing water carrying iron interacted with oxidizing water that induced the iron precipitation.*
- *More resistant to weathering (i.e., harder) than the quartz sandstone host rock.*
- *Unusual and can look "out of this world," but are formed by Earth processes over many tens of millions of years.*

Iron concretions are also known by other names (not inclusive) such as:

- *Hematite or iron nodules*
- *Iron sandstone balls*
- *Moki or moqui (term used by early Spanish) marbles*

Continued uplift and river cutting help to create the canyon country of the Colorado Plateau. The hard, spherical iron concretions are more resistant to weathering than the lightly cemented sand grains of the surrounding or encasing rock. Discrete, individual concretions, that are now loose like marbles, became concentrated on the surface because all the surrounding rock weathered away over a long period of time.

6. The Time Machine

How far back in time must we travel to see all of this happen? The sand dunes first piled up in the Jurassic deserts some 180 million years ago. The sands were red when they accumulated, and reddening continued for tens of millions of years during burial, compaction and cementation to form rock. The bleaching of sandstones probably occurred between 65 and 25 million years ago. The precipitation of iron concretions occurred after bleaching, likely between 25 and 6 million years ago.

We can apply basic principles of geology to deduce the relative time of bleaching. Regional rock colors follow the original layered patterns and have been later cut by rivers, to suggest that bleaching occurred before river erosion. However, some bleaching likely occurred after the formation of faults that provided easy pathways for fluid movement and localized bleaching along the faults and other fractures in the rocks.

A variety of scientific methods can be used to deduce the age of events in millions of years. Specific ages of rocks can be determined from the constant decay of radioactive elements in the rock minerals. A clay mineral called illite occurs along the faults that act as major conduits for fluid movement and bleaching of sandstones. The illite contains potassium, and thus its age can also be estimated. Potassium and argon age analysis of illite from the Moab fault (northwest of Moab, Utah) suggests that bleaching occurred as early as 50 million years ago when the fault developed, well before the time of the iron concretion precipitation.

Radiometric dating of minerals associated with iron concretions can help tell us when the minerals were precipitated. Measurements of potassium and argon in associated manganese minerals (Chan and others, 2001) yield ages of 25 to 20 million years, and suggest a similar timing for some of the iron precipitation.

Paleomagnetic dating is a technique that relies on the memory that rocks have for the Earth's magnetic field. Iron minerals in rock act like a magnet and align themselves with the Earth's magnetic field, and the magnetic field has switched poles throughout geologic time. Measurement of the magnetism that remains in the rocks can indicate when they were deposited, and magnetism that remains in bleached rocks is an indication of the time of bleaching. Magnetic measurements (R. Garden, written communication, 2000) suggest the iron reduction and bleaching happened 65 million years ago or less.

Use of Iron Concretions

Iron concretions have a place in human history as well as geologic history. Findings of small spherical to irregular iron concretionary nodules are commonly cited in many archeological reports covering the prehistoric Four Corners area. At Canyon De Chelly National Monument in Arizona, iron concretions found at ancestral puebloan villages range in size from a few centimeters in diameter to large nodules with grinding facets on multiple surfaces. These are believed to be part of medicine bundles used for ceremonial purposes during both prehistoric and historic periods (Judd, 1954). Some concretions also may have been used as cooking stones (Barnett, 1973), hammerstones and ornaments (Mathien, 1997), or simply as unmodified nodules collected as "... curiosities and in part as objects of veneration (Cattanach, 1980)." Ancient people collected iron concretions and softer, stained mudstone and soil that was ground for the dye color that could be obtained from the iron.

Native American pictographs using the hematite pigment, likely from either iron concretions or iron-rich sediments. Location: Horseshoe Canyon, Canyonlands National Park, Utah.

Ground hematite was mixed with water to make paint and pigment for use on rock and plaster walls (Schaffsma, 1980). This pictograph artistry of the Native Americans is strikingly preserved on cliffs and within prehistoric buildings of the Four Corners region.

Over the Rainbow

What a mind-boggling idea: in some bright white sandstones of canyon country, all the scattered iron that originally made the sandstone red has been bleached and concentrated into compact iron concretions instead! Lots of reducing water had to push through the porous sandstone to bleach and remobilize hematite (some probably moved along fault conduits). Upon meeting up with oxidizing water, hematite was re-precipitated as some of the fantastic iron balls, buttons, pipes, and columns that can be seen in sandstones of the southwestern national parks and surrounding landscapes. Large regional patterns of sandstone coloration reflect different types of fluids that have moved through the rocks in the past, and the chemical element iron is the telltale sign.

Bleached, reduced zone of light-colored sand around a cemented piece of organic root material, Navajo Sandstone in Navajo Canyon area of Lake Powell, Glen Canyon National Recreation Area. Scale card = 6.5 inches (16.5 cm) long.

In addition to the large regional patterns of sandstone coloration, many rock formations contain localized coloration in sandstone that could be due to the presence of organic matter. Typically the host sandstone or mudstone is a red to yellow color, again from early oxidation and evenly scattered iron. Ancient pieces of plant material or even large trees and roots in the host rock can be areas of locally reducing conditions because of the organic acids originally contained in the living matter. Thus, the organic material provides a locally reducing environment that may cause the host rock surrounding the organic material to be light green to white in color. In other instances, organic matter can locally enhance iron precipitation, as seen in iron-cemented burrows of Chaco Culture National Historical Park, New Mexico. Here, burrowing organisms (some similar to shrimp) may have dug into shoreline sands. The organic matter in the fecal pellets of the organisms may have provided the right local conditions of mixed reducing and oxidizing waters to precipitate the iron. Some of the concentrated iron in the burrows may actually be the iron that was originally disseminated and distributed in the shoreline sands.

Why does the Navajo Sandstone have the most abundant concretions compared to some of the other Jurassic sand dune deposits? The Navajo Sandstone is a special rock unit that has relatively consistent properties of porosity and permeability that make it one of the best reservoirs (rock that can hold fluids) and one of the best aquifers (rock through which fluids can flow) of the Colorado Plateau. The reason why the Navajo Sandstone contains such varied coloration and has abundant concretions is certainly related to the fact that it was a unit through which a variety of fluids could easily move.

The story is not over. Although we now have begun to

Other rock units on the Colorado Plateau show a variety of iron concretions. A unit younger than the Jurassic formations contains ancient shoreline sandstones exposed in the Cretaceous-age Mesa Verde Group, Chaco Culture National Historical Park, New Mexico.

Outcrop of iron-oxide concretions (dark areas) in light-colored sandstone.

Other odd concretionary features (not burrow related).

Ancient burrows made by a shrimp-like organism are later cemented by iron oxides, including hematite. Organic matter related to the burrow organisms provides a locally reducing environment that mobilizes the iron. Iron is precipitated at the interface upon contact with oxidizing water.

Remaining Mysteries
Scientists are still working on:

- *Why are sandstone marbles so spherical?*
- *What determines the concretion size and shape? Why are some concretions nearly solid hematite cement, and other concretions have only a hematite-cemented rind with an "uncemented" sandstone interior?*
- *Is there any nucleus or seed that starts a marble growing, and if so, what is it? In some cases, iron may be preferentially attracted to areas that contain organic matter.*
- *What determines the clustering and spacing of concretions?*
- *What are the large-scale distributions and controls on both sandstone coloration and concretions?*

understand the sandstone coloration and the creation of iron concretions, there are still many remaining questions, such as the specifics of forming the round sandstone marble shapes. As new scientific techniques are developed, and future geologic studies of these sandstones are broadened, geologists will continue to probe into the mysteries at the end of the colorful sandstone rainbow.

NOTE: Special written permission and permits are required to collect or remove any rocks or concretions from protected areas such as parks and monuments.

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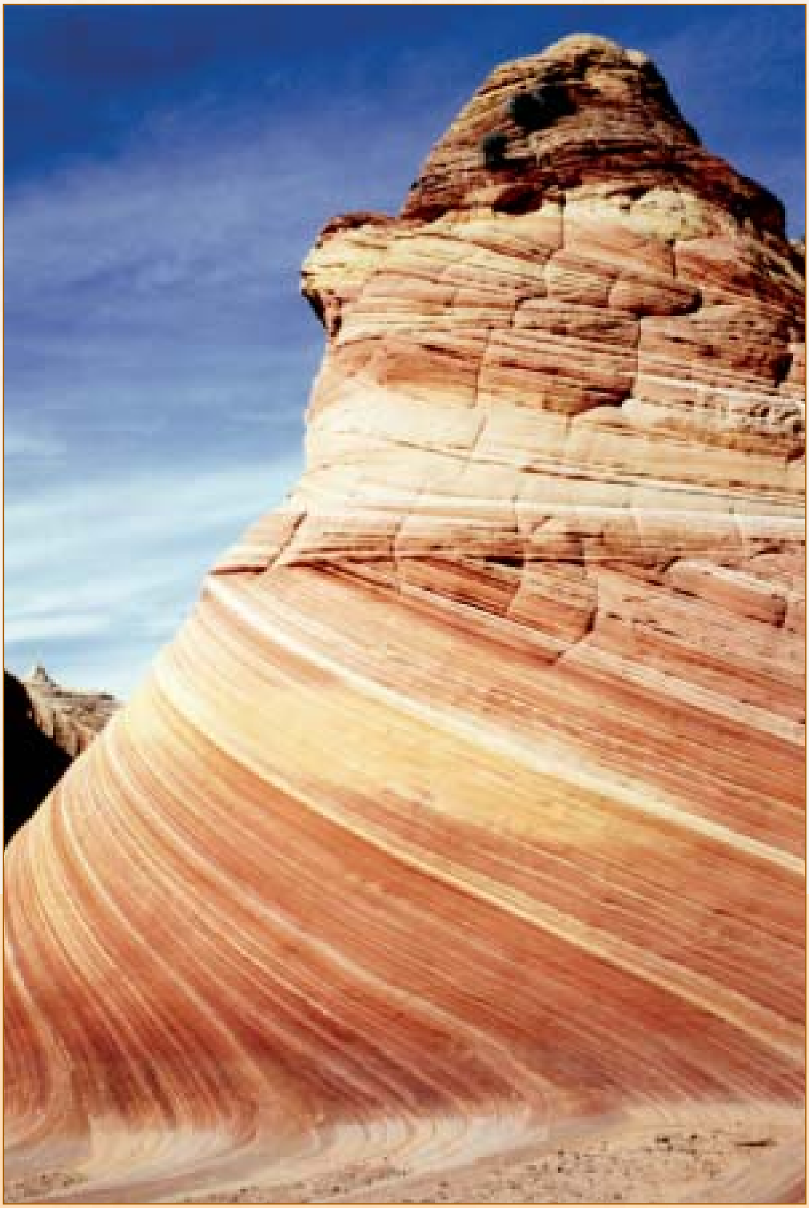

Rainbow of colors in the Navajo Sandstone, Coyote Buttes - Paria Wilderness Area, Utah-Arizona border.

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Table of Contents

List of Figures iv

Executive Summary 1

Introduction 3
Purpose of the Geologic Resource Evaluation Program 3
Geologic Setting 3

Geologic Issues 7
Slope Processes 7
Seismicity and Mining 7
Streamflow, Channel Morphology and Sediment Load 8
Water Issues 8
Hoodoo Formation and Present Condition 9
Paleontologic Potential 10
Faulting and Deformation Processes 10
Gravel and Sand Deposits on the Paunsaugunt Plateau 10
Mining Resources and Issues 10
Marysvale Volcanic Field 11
Facilities Management 11
Wind Erosion and Deposition 11
General Geology 11
Swelling Clays 12

Geologic Features and Processes 13
Sevier and Paunsaugunt Faults 13
Thrust Faults 13
Erosion of the Paria Amphitheatre 14
Formation of Hoodoos 14
Isolated Features 15

Map Unit Properties 16
Map Unit Properties Table 17

Geologic History 21

References 33

Appendix A: Geologic Map Graphic 39

Appendix B: Scoping Summary 40

Attachment 1: Digital Geologic Map (CD)

List of Figures

Figure 1: Map of the structural features surrounding Bryce Canyon National Park. *5*
Figure 2: Diagram of a monocline. *6*
Figure 3: Geologic time scale *25*
Figure 4: Main Jurassic structural elements affecting sedimentation onto the Colorado Plateau *26*
Figure 5: Middle Jurassic paleogeography during deposition of the Entrada Sandstone *27*
Figure 6: Late Jurassic paleogeography *28*
Figure 7: Upper Cretaceous paleogeography at the time of Dakota Sandstone deposition *29*
Figure 8: Location of Bryce Canyon National Park on a tectonic map *30*
Figure 9: Early post-Laramide map *31*
Figure 10: Generalized graphic overview of geologic evolution of Utah *32*
Figure 11: Geologic map coverage of Bryce Canyon National Park at 1:31,680 scale and larger *48*
Figure 12: Geologic map coverage of Bryce Canyon National Park at 1:42,240 and larger scale *49*

Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Bryce Canyon National Park. It contains information relevant to resource management and scientific research.

Understanding the geology of Bryce Canyon enhances one's understanding of the unique relationship between geology and their environment. Geology provides the foundation of the entire ecosystem. In Bryce Canyon National Park, surface exposures consist primarily of Jurassic, Cretaceous, and Tertiary age rocks. The stratigraphy is exposed by the dramatic erosion of the Paria and Sevier Rivers and records clues to ancient environments. In the stratigraphic record, oceans came and went, desert winds blew sand, and lakes and rivers flowed through the region. Understanding the geologic history of Bryce Canyon National Park is necessary to appreciate, manage, and preserve what is there today.

Geologic processes initiate complex responses that give rise to rock formations, surface and subsurface fluid movement, soil, and alcove formation. These processes develop a landscape that welcomes or discourages our use. The preservation of the canyons, spires, alcoves, bridges, and assorted hoodoos of Bryce Canyon National Park is a high priority and emphasis of geologic resources should be encouraged so as to enhance visitor experience.

The Paunsaugunt Plateau, part of the Colorado Plateau Physiographic Province, attracted over 899,220 visitors in the year 2002. They were dazzled by the myriad of fantastic rock columns, spires, hoodoos, fins, windows, pedestals, bridges, alcoves, and canyons, made even more beautiful by the array of colors ranging from pure white to deep red. Nevertheless, these visitors are placing increasing demands on the resources available at Bryce Canyon National Park.

Bryce Canyon National Park hosts some of the most spectacular geologic features on earth. The combination of tectonic forces and erosion have created elegant features on the Bryce landscape. It is not surprising then that some of the principal geologic issues and concerns pertain to protecting these features. Humans have modified the landscape surrounding Bryce Canyon and consequently altered geomorphic responses in the system. This system is dynamic and capable of noticeable change within a human life span (less than a century). The following features, issues, and processes were identified as having the most geological importance and the highest level of management significance to the park.

- Slope Processes. Arid, desert environments are especially susceptible to slumping and landslide problems due to poor soil cohesion, high slope angle, lack of stabilizing plant growth and the occurrence of intense seasonal rainstorms. These storms produce runoff that dramatically alters the landscape, creating new hazard areas in the process. Road and trail construction can also affect the stability of a slope. Mudstone rich units such as the Tropic Shale are typically found in outcrop as slopes. These slopes are prone to fail when water saturated. The more resistant units in the park are exposed on precipitous slopes creating a situation that exposes large blocks of jointed and faulted sandstone and limestone to the force of gravity. The potential for rockfalls and slope failure is occurs almost everywhere along the roads and trails of Bryce Canyon National Park.

- Streamflow and channel morphology. In the arid climate of southern Utah, seasonal runoff and flash floods from intense, short duration rainstorms may impact channel morphology. These seasonal events also result in changes in the sediment load and the deposition of sediment in the canyons and along riverways. These changes affect aquatic and riparian ecosystems. Sediment loading can result in changes to channel morphology and overbank flooding frequency. The canyons are also discharge points for local groundwater flow systems, manifested as seasonal springs at Bryce Canyon National Park.

- Water Issues. The mountains of southern Utah receive on average about 8 - 10 inches of precipitation per year with higher altitudes receiving more. This defines the arid climate that makes water such an important resource. Water, which does not flow as surface runoff, percolates through the soil and rock, eventually making its way along fractures, and fissures, replenishing aquifers. The water source for Bryce Canyon National Park primarily comes from wells drilled into the Claron Formation, Wahweap, and Straight Cliffs Sandstones aquifers. These aquifers are contained in fractured rock that provides groundwater conduits and deep enough to be relatively impervious to drought conditions. Some surface sources alleviate some of the demand; however, they are unreliable during severe drought years. The hydrogeologic system is not well understood and should be studied further.

- Seismic and mining activity. The park was created to preserve and protect some of the most spectacular and fragile erosional spires and other features in the world. The area around Bryce Canyon National Park is near major faults and still seismically active. Vibrations from earthquake activity as well as blasting from nearby mines are putting these features at risk. Earthquakes are a natural process and can not be controlled, however, mining effects can be prevented.

Other geologic issues such as the paleontological potential of the area, wind erosion, gravel and sand deposits on the Paunsaugunt Plateau, swelling clays, facilities management, understanding the controls of hoodoo formation, faulting and deformation processes, and the story of the Marysvale Volcanic Field, were also identified as critical management issues for Bryce Canyon National Park.

In addition to the management of resoures, the understanding of the geologic story at Bryce Canyon is invaluable to park visitor appreciation.

The rock units in the park record the history of the region. Gently folded Cenozoic limestones, sandstones, conglomerates, and recent unconsolidated deposits cap Mesozoic limestone, dolomite, sandstone and shale. These strata dip gently northeastward, dissected by several major normal faults in addition to some recently categorized thrust faults on the northern end. The regional dip of beds ranges from ½° to 3° to the north, northeast, and east.

The few departures from this regional trend are minor faults, small- scale upwarps, and some gentle folds (Gregory, 1951; Marine, 1963). The geomorphological processes of erosion and weathering create the dramatic canyons, hoodoos, amphitheatres, and cliffs. It is the interaction of the variety of rock types present with the topography created by uplift and erosion that must be understood to assess potential hazards and best protect the environment and the visitors to the park. The Map Unit Properties section (see page 16) details the different units and potential resources, concerns and issues associated with each.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation program.

Purpose of the Geologic Resource Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and an understanding of geologic resources yields important information needed for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. Ultimately, the inventory and monitoring of natural resources will become integral parts of park planning, operation and maintenance, visitor protection, and interpretation. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resources Division. The goal of the GRE Program is to provide each of the identified 274 "Natural Area" parks with a digital geologic map, a geologic resource evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and is designed to be user friendly to non- geoscientists. In preparing products the GRE team works closely with park staff and partners (e.g., USGS, state geologic surveys, and academics).

GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss specific geologic issues affecting the park. Park staff are afforded the opportunity to meet with experts on the geology of their park during these meetings. Scoping meetings are usually held for individual parks although some meetings address an entire Vital Signs Monitoring Network.

Bedrock and surficial geologic maps and information provide the foundation for studies of groundwater, geomorphology, soils, and environmental hazards. Geologic maps describe the underlying physical habitat of many natural systems and are an integral component of the physical inventories stipulated by the National Park Service (NPS) in its Natural Resources Inventory and Monitoring Guideline (NPS- 75) and the 1997 NPS Strategic Plan. The NPS GRE is a cooperative implementation of a systematic, comprehensive inventory of the geologic resources in National Park System units by the Geologic Resources Division, the Inventory and Monitoring (I&M) Program of the Natural Resource Information Division, the U.S. Geological Survey, and state geological surveys.

For additional information regarding the content of this report please refer to the Geologic Resources Division of the National Park Service, located in Denver, Colorado with up- to- date contact information at the following website: http://www2.nature.nps.gov/geology/inventory/

Geologic Setting

Bryce Canyon was designated as a National Monument in June 1923, and later as a National Park in September 1928. It was set aside to preserve and protect an incredible collection of geomorphological shapes such as hoodoos, spires, fins, pinnacles, canyons, and mazes. The intense erosion of the colorful sandstones, mudstones, and limestones of the Tertiary age Claron Formation left behind these fantastical remnants on the landscape.

Located in south- central Utah, Bryce Canyon National Park encompasses about 56 square miles (35,835 acres) in Kane and Garfield Counties. The elevation in the park varies from a low of 2300 m (7600 ft) to 2760 m (9100 ft) at Rainbow Point in the southern end of the park. The park is located on the divide between the Paria River, one of the tributaries of the Colorado River, and the East Fork of the Sevier River, which drains into the Great Basin to the north.

Bryce Canyon is part of a geological feature called the High Plateaus subprovince of the Colorado Plateau Physiographic Province. Covering parts of Colorado, Utah, Arizona, and New Mexico, the Colorado Plateau is a region of high plateaus and broad, rounded uplands separated by vast rangelands (Figure 1).

> Gilbert (1875): "The province of plateaus is characterized by a system of tabular reliefs, consisting of strata little disturbed....The simplicity of its structure, the thoroughness of its drainage,...its barrenness, and the wonderful natural sections exposed in its cañons, conspire to render it indeed 'the paradise of the geologist'."

The Colorado Plateau is a broad area of relative structural stability between the Rocky Mountains and the Basin and Range physiographic provinces. The Rio Grande Rift in New Mexico forms the southeast border. Curiously, the Colorado Plateau remains somewhat of a tectonic mystery and has suffered relatively little geologic deformation compared to these surrounding regions (Graham et al., 2002). It is roughly circular in shape, and extends about 483 km (300 miles) in an east- west direction and 644 (400 miles) in the north- south direction.

The Colorado Plateau ranges in altitude from about 762 m (2,500 ft) along the Colorado River, to about 3,962 m (13,000 ft) in some of the isolated peaks throughout the region. The principal tectonic elements of the plateau are basins, uplifts, monoclinal flexures, domes of igneous intrusion, platforms, slopes and broad saddles, and fold and fault belts (Kelley and Clinton, 1960).

Perhaps more than any other structural feature, the Colorado Plateau is characterized by a number of monoclines which, if lined up from end to end, would comprise an aggregate length of nearly 4,023 km (2,500 miles) (Kelley, 1955). The term monocline, as defined by Powell in 1873, describes a double bend consisting of anticlinal and synclinal curves involving local steepening in otherwise gently inclined beds (Figure 2).

The monoclines in the Colorado Plateau area are gentle or steep, narrow or broad, open or closed, level or plunging, over- turned, buckled, broken, etc. In short almost every type of deformational intensity manifested as a monocline is present across the Plateau. It is accepted that the principle monoclines of the Colorado Plateau accommodated deformation and uplift during the Late Cretaceous- Early Tertiary Laramide Orogeny (Kelley, 1955; Kelley and Clinton, 1960).

Relative age dating of movement along the monoclines is restricted to those that show a juxtaposition of deformed and undeformed rocks of known ages. Most of the monoclines formed through compression whereby a deep- seated thrust fault does not rupture the surface, but instead folds and deforms the rock column into a monocline.

Surrounding Bryce Canyon National Park are various uplifts, monoclines, and mountains. To the southwest, the Kaibab (monoclinal) Uplift dominates the area. The Circle Cliffs, Monument Uplift, and San Rafael Swell are to the northeast as well as the Henry Mountains (igneous domes or laccoliths) and the Miner's Mountain monocline.

The Marysvale Volcanic Field borders the Bryce Canyon region on the northwest side. The Paunsaugunt Plateau comprises the western side of the Paria or Tropic Amphitheatre at the edge of the High Plateaus province. The east and northeast sides of the amphitheatre are composed of the Table Cliff Plateau and the Kaiparowits Plateau, respectively.

The Paunsaugunt Plateau also contains the headwaters of the East Fork of the Sevier River at its southern end. Bryce Canyon National Park includes part of the plateau, the rim and the foothills bordering the plateau at lower elevations (Marine, 1963).

Essentially, the plateau is a pile of flat- lying or slightly tilted sedimentary rocks that lies between two large, north- south trending faults (Gregory, 1951). It is approximately 45 km (28 miles) long and ranges in width from 24 km (15 miles) on the northern end to as little as 10 km (6 miles) near the southernmost tip (Lindquist, 1980). Dutton (1880) described it as follows:

> "The Paunságunt Plateau is a flat- topped mass, projecting southward in the continuation of the long axis of the Sevier Plateau, bounded on three sides by lofty battlements of marvelous sculpture and glowing color. Its terminus looks over line after line of cliffs to the southward and down to the forlorn wastes of that strange desert which constitutes the district of the Kaibabs and the drainage system of the Grand Cañon of the Colorado River."

As the Paunsaugunt Plateau was uplifted, the eroding streams have been actively downcutting. In some places, the erosion has nearly left the surface flat; in other places it is vigorously scouring and in still others, just barely begun. The length of Bryce Canyon National Park shows this erosive progression from the north, where erosion has removed the bulk of the hoodoo rock cover, to the central park area where the mature hoodoos are most extraordinary, to the south where erosion has not yet completed carving the landscape.

Visitors who flock to the park each year are rewarded with stunning vistas such as Fairyland, Bryce, Fairview, Sunrise, Sunset, Inspiration, Rainbow, and Yovimpa Points, and Paria View and Natural Bridge. These same stunning features no doubt inspired wonder in all past occupants and travelers. When viewing these wonders many visitors yearn to understand what they see, to deepen their intimacy with the landscape by understanding how it formed. This fundamental human compulsion to know the world is stimulated at Bryce Canyon (De Courten, 1994). This environment must be preserved in all its dynamic glory, including proper trail management and an understanding of the underlying geologic processes affecting the trails and other visitor facilities to better enhance the overall experience of Bryce Canyon National Park (Rocky Mountain Regional Office and Bryce Canyon National Park, 1987).

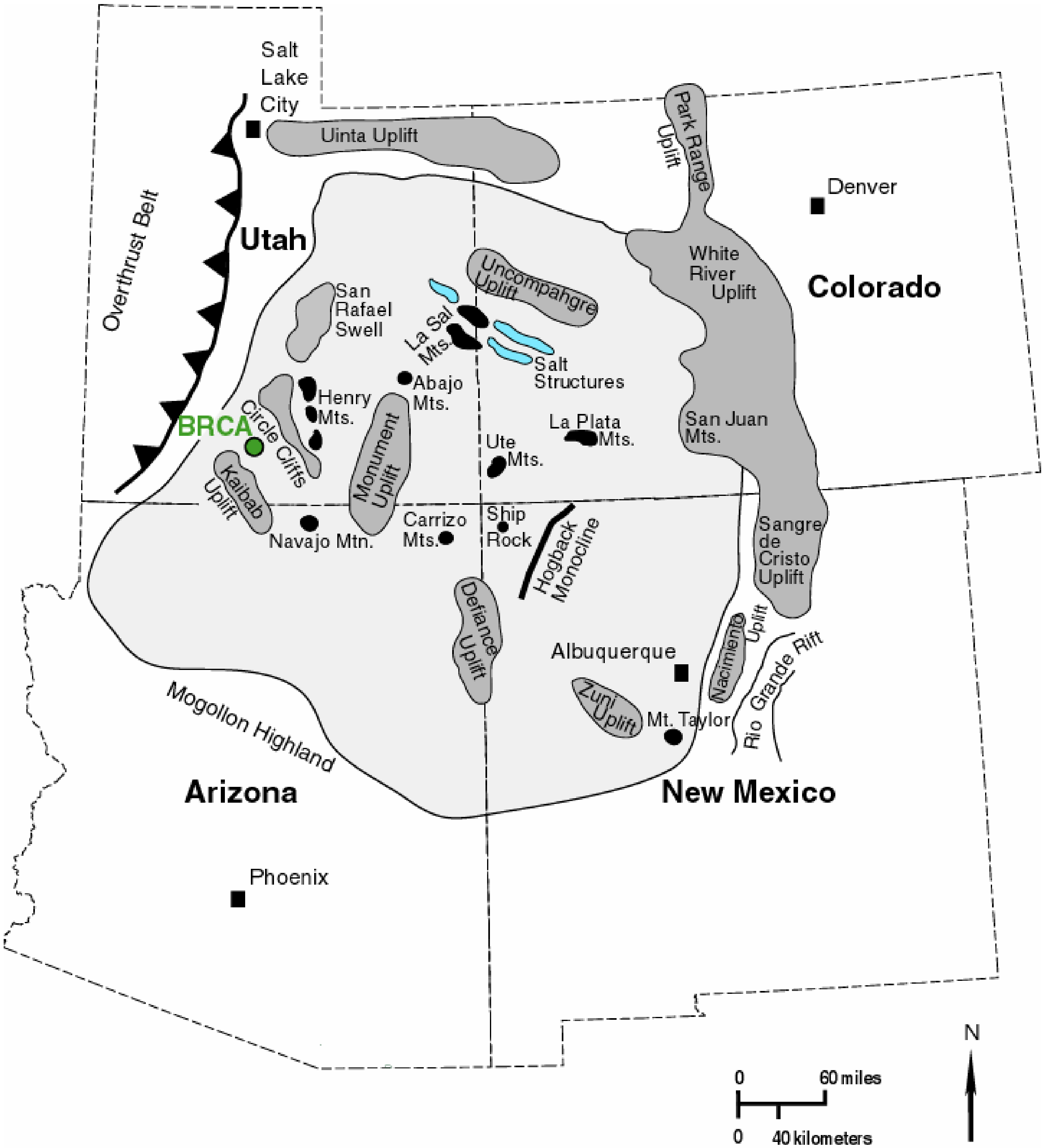

Figure 1: Map of the structural features surrounding Bryce Canyon National Park (BRCA). Light gray area shows extent of the Colorado Plateau while darker gray and black areas indicate regional uplifts and mountains.

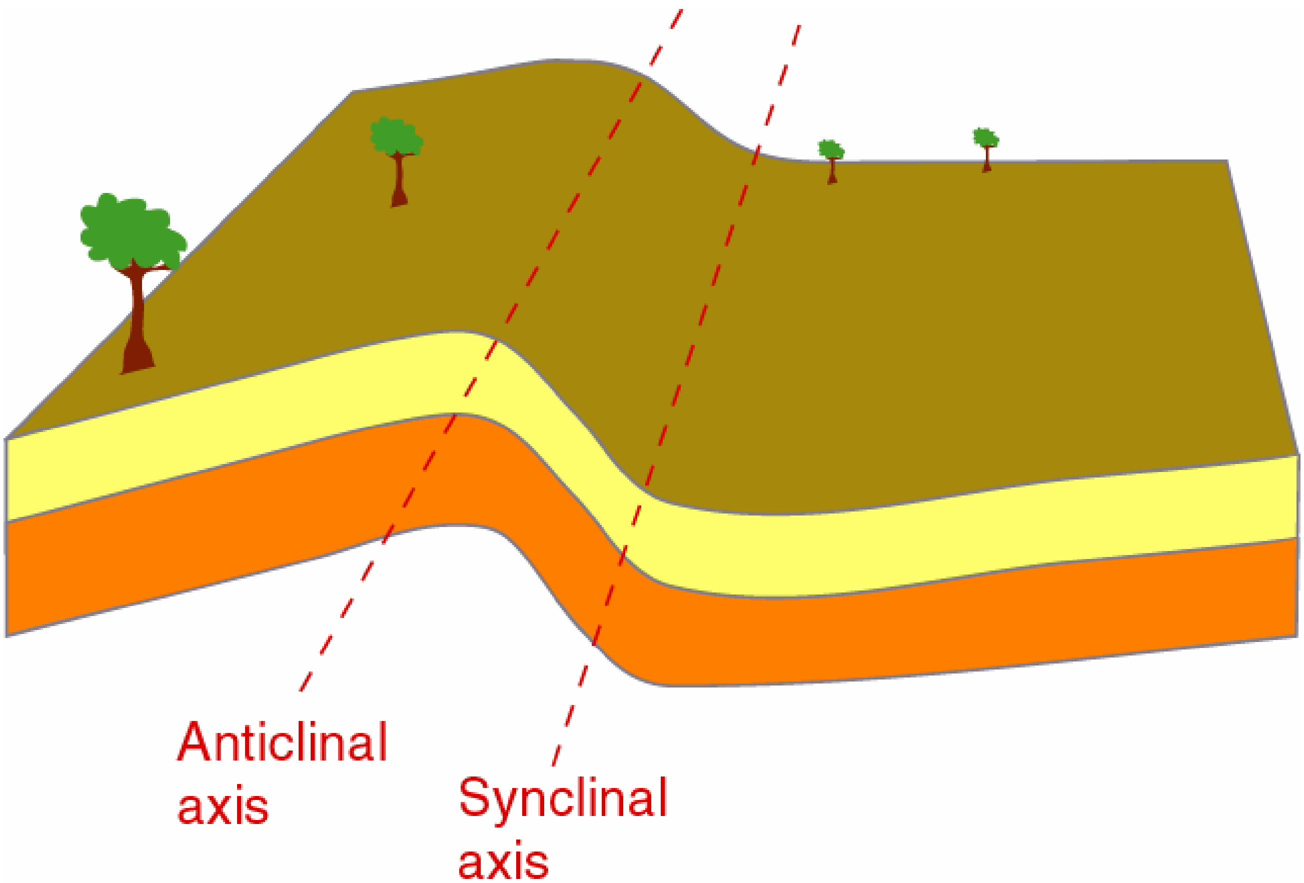

Figure 2: Diagram of a monocline.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Bryce Canyon National Park on July 13- 14, 1999, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Slope Processes

The intense erosion of the relatively soft Tertiary Claron Formation is responsible for the vast array of hoodoos and canyons present at Bryce Canyon National Park. Erosional processes such as mass wasting and rockfalls are two of the most important geological resource management issues.

The walls of the Paria amphitheatre have steep slopes. This renders them highly dangerous because of the likelihood of rockfalls, landslides, slumps, and slope creep. This is a major concern in the weaker rock units such as the Pink Member of the Claron Formation. Stronger rock units such as the White member of the Claron Formation and the Conglomerate at Boat Mesa are highly fractured due to the degree of faulting in the area. This makes rockfall hazards highly probable in these formations.

Slope failures are common for units that are not necessarily associated with cliffs. Unconsolidated alluvial deposits, for instance, are especially vulnerable to failure. The torrential rains that produce flash flooding at Bryce Canyon suddenly saturate the slopes resulting in huge slumps, mudslides and mud flows.

Many trails in the park, including the Navajo Loop trail lead visitors through spectacular desert scenery. However, these trails are at extreme risk for rockfalls and landslides. In less visited areas of the park, slope processes are also creating an impact. For instance, in Cretaceous units, mudslides are produced in Yellow Creek and other watersheds in the backcountry.

Inventory, Monitoring, and/or Research Needs for Slope Processes

- Conduct a landslide inventory and analysis. The purpose is to collect information that will aid in understanding the distribution, timing, and relative size of mass wasting processes in Bryce Canyon. The intent is to evaluate and map the potential for delivery of mass wasting hazards. From this inventory a detailed analysis can address the specific problems identified. In particular, the relationships between land use activities and landslide processes.

  From the inventory, a mass wasting hazard potential map can be derived. Potential hazards from mass wasting are assigned to mass wasting map units. The ratings are determined on the basis of occurrence of landslides in the past and the relationships among management practices and instability processes. In addition, it addresses the likelihood that debris or sediment will be delivered to sensitive locations.
- Create a rockfall susceptibility map using rock unit properties versus slope aspect in a GIS format. Use this map to determine the location of future developments and to manage current developments including trails, buildings, and recreational use areas.
- Monitor the rockfall potential in the Paria amphitheatre, and relate this to slope stability and deposits of loose rock around the amphitheatre.
- Inventory and monitor debris flows potential near picnic areas, and correlate them to slope stability and loose rock deposits.
- Inventory areas susceptible to flash floods, and relate to climatic factors and areas of stream confluence
- Perform trail stability studies and determine which trails are most at risk and in need of further stabilization.
- Monitor the areas where facilities will be sited for fractures and potential for sloughing.

Seismicity and Mining

The Basin and Range and Colorado Plateau are still seismically active. Small- scale earthquakes occur frequently in Nevada and Utah. Most of these are so small that they can only be detected by a seismometer.

Bryce Canyon National Park is also near several mines that employ blasting practices to remove overburden and to extract coal, metallic ore, and other mineral resources. In addition, the vibrations from seismic exploration for oil and gas and from drilling rigs can affect the delicate features in Bryce. These vibrations essentially behave like seismic waves, pulsing through the earth, causing profound shaking of the surface.

The presence of delicate hoodoos in Bryce Canyon National Park is the major reason the area was set aside for preservation and protection. Given the potential for severe ground shaking in the area from both natural and man- made sources, the effect on the geomorphology at Bryce Canyon is a significant resource management issue.

Inventory, Monitoring, and/or Research Needs for Seismicity and Mining

- There is a need for a comprehensive study of the faulting and seismic processes active at Bryce Canyon National Park, taking into account rock formations, slope aspects, location and likelihood of instability.
- The rim of the Paria amphitheatre is prone to slumping and sliding (see Map Unit Properties table). The slopes of this area would likely fail in a moderate to large seismic event. Care must be taken when planning trails and other visitor access routes along steep canyon walls beneath obvious rockfall prone areas.
- Seismic activity in the Bryce Canyon area should be monitored by cooperating with local agencies including the USGS and Utah Geological Survey. (UGS Contact: Kent Brown, Salt Lake City, UT)
- A study is needed to determine the effects of nearby mining practices, including blasting, on the delicate features at Bryce Canyon. How does this relate to natural seismicity in the area?
- An exhaustive study of active faults in close proximity to the Bryce Canyon area is needed. This should include the mapping of small scale faults and fracture zones.

Streamflow, Channel Morphology and Sediment Load

Bryce Canyon National Park is located within the boundaries of two major drainages, the Paria River and the Sevier River. In the high desert climate of southern Utah, intense, short duration, seasonal rainstorms and subsequent flash floods profoundly impact channel morphology. These intense seasonal events may also result in periodic deposits of thick sediments. Sediment loads and distribution affect aquatic and riparian ecosystems, and sediment loading can result in changes to channel morphology and overbank flooding frequency. The canyons are also discharge points for local groundwater flow systems. The deep canyons dissect the region into a discontinuous series of ranges and canyons and disrupt local groundwater flow paths. If recharge is sufficient, the alcoves and gullies may contain local groundwater flow systems that discharge as springs.

Inventory, Monitoring, and/or Research Needs for Streamflow, Channel Morphology and Sediment Load

- Monitor seasonal springs including location, water quality, and maximum flow.
- Study the response of channel morphology to intense seasonal flashfloods and erosional processes.
- Inventory current channel morphology and monitor changes.
- Conduct an assessment of current hydrologic conditions to identify actual and potential "problem reaches" for prioritized monitoring.
- Once "problem reaches" are identified, monitor with repeat aerial photographs.
- Research effects of land use and climatic variation on streamflow.
- Investigate paleoflood hydrology.
- Conduct research on ungaged streams for sediment storage and load.
- Measure sediment load on streams of high interest for comparative assessment. Data will provide information for making management decisions.
- Study the structural controls on the course of the Paria River that direct it towards Bryce Canyon.
- Use diffusion modeling to help map drainage patterns (consult geomorphologist at University of Arizona).

Water Issues

Water is principally responsible for the formation of the wondrous shapes present at Bryce Canyon and continues to play a critical role in sculpting the present landscape. Rain at Bryce Canyon commonly falls in local torrential showers. The sudden violence of the showers in a country almost barren of soil and vegetation results in severe erosion (Gregory and Moore, 1931). During intense seasonal thunderstorms, rain acts like a sledgehammer on unprotected soil, knocking apart individual soil particles and washing unconsolidated sediment into the canyons. Dutton (1880) stated:

> "The lessons which may be learned from this region are many, but the grandest lesson which it teaches is EROSION. It is one which is taught, indeed, by every land on earth, but nowhere so clearly as here...The land is stripped of its normal clothing; its cliffs and cañons have dissected it and laid open its tissues and framework, and 'he who runs may read' if his eyes have been duly opened...Nowhere on the earth's surface, so far as we know, are the secrets of its structure so fully revealed as here."

Rainwater also combines with carbon dioxide in the atmosphere to form carbonic acid, a weak acid. Carbonic acid is very effective at dissolving calcite ($CaCO_3$) present limestones rock layers and as intergranular cement. Lindquist (1980) discovered that the freeze and thaw action of water in the rocks at Bryce Canyon was perhaps the most effective weathering process.

There are four distinct drainage systems on and around the Paunsaugunt Plateau; 1) The Sevier River system draining the western escarpment of the plateau, 2) tributaries of the Colorado River of the southern escarpment, 3) tributaries of the Paria River drainage of the eastern escarpment, and 4) the East Fork of the Sevier River draining the plateau surface (Lindquist, 1980). Two of the primary, perennial surface streams in the Bryce Canyon area are the East Fork of the Sevier River, running up the axis of the Paunsaugunt Plateau, and the Paria River, along the eastern edge of the plateau (Marine, 1963) (see Appendix A). Their drainages are divided by the rim of the Paunsaugunt Plateau (Brox, 1961). The East Fork of the Sevier River flows north. The Paria River flows southward as part of the Colorado River system, across a longitudinal valley and into narrow, deep canyons.

Topography suggests the river system should be gathered in the House Rock Valley at the base of the Kaibab Plateau slopes, but the current pattern (described above) does not reflect present topographic controls. Evidence suggests that the drainage of the Paria and its main tributaries was established on Tertiary deposits and became superimposed on the underlying Cretaceous structures after erosion of the Tertiary layers (Gregory and Moore, 1931).

The East Fork of the Sevier River is responsible for the gently concave surface of the Paunsaugunt Plateau. The drainage is curved radially inward and the direction of flow conforms to the overall, gently north dipping rocks. The summit topography differs radically from the deeply carved canyons below the plateau rim, consisting of mature slopes and graded flats. Some of the streams from the lowlands have diverted drainage from the Sevier River when they erode far enough to breach the rim of the plateau (Gregory and Moore, 1931).

There are numerous small springs arising from the intersection of an aquifer or groundwater conduit with the surface. These are especially common along very steep slopes. Among these springs are Shaker, Trough, Whiteman, Yellow Creek, Campbell Canyon, and Bryce Springs. The two types of springs in the Bryce Canyon area are alluvial and bedrock springs. Alluvial springs are near surface water pockets in unconsolidated sediments. Bedrock springs flow along fractures and bedding planes within lithified rock.

Water is scarce on the Paunsaugunt Plateau, as it is for southern Utah in general. A groundwater study was initiated in 1957 because Trough and Shaker Springs (both former water sources for park facilities) had dried up. Water needed by the park for the mid- May to mid- October tourist season was estimated to be 1.3 million cubic feet. The study showed that, even at that time, the resources necessary to maintain an adequate water supply at the park were hard to come by (Marine, 1963). Much of the water used at the park comes from wells drilled to aquifers in the Claron Formation, the Wahweap Sandstone and the Straight Cliffs Sandstone. Aquifers must be deep enough to be relatively unaffected by drought conditions and be contained in fractured rock so as to provide groundwater conduits to the well. Some of the water demand is alleviated by the East Fork of the Sevier River, Yellow Creek Spring and other nearby springs as well as by wells drilled in the unconsolidated alluvial deposits of East Creek Valley (Marine, 1963). However, these surface sources are unreliable during severe drought years.

Inventory, Monitoring, and/or Research Needs for Water Issues

- Determine the nature of the park's watershed by compiling baseline watershed, surface, and subsurface hydrogeologic data.
- Monitor water quality on a multiple sample location basis within the park, especially drinking water sources.
- Install additional wells for testing and for drinking water.
- Identify the impacts of nearby mining. (see above mining issues discussion)
- Identify and study potential sources for groundwater quality impacts at the park.
- Install transducers and dataloggers in wells.
- Investigate additional methods to characterize groundwater recharge areas and flow directions
- Study groundwater recharge mechanisms and shallow subsurface flow in carbonate terrains in southern Utah.
- Conduct a study of the permeability and quantity of water present for the entirety of Bryce Canyon National Park.

Hoodoo Formation and Present Condition

Preserving the hoodoos and other geomorphological landforms and maintaining their natural environment is a key resource management issue at Bryce Canyon National Park. The relationship between rock units and erosional process is quite dynamic. Changes in climate, especially precipitation have a profound effect on the entire system. Determining the balance between visitor access and preservation of these features is a difficult task.

Inventory, Monitoring, and/or Research Needs for Hoodoo Formation and Present Condition

- Study the progressive evolution of hoodoos, and examine the morphology, stratigraphy, and structure for interpretive value.
- Monitor and inventory human signatures in the park, including any cultural resources.
- Study the role of enlarging fractures through solution weathering and freeze- thaw cycles.
- Study how different lithologies respond to weathering and erosion.
- Study rates of edge migration, erosion, retreat of rim, rates of downcutting of streams at the canyon bottom, aggradation of fill at bottom, and slumping in the Tropic Shale (i.e. all processes affecting landscape evolution).
- Comprehensively study and monitor the atmospheric conditions and hydrology in the park
- Develop a detailed 3- dimensional cartographic survey of the Paria amphitheatre including features (hoodoos and other spires).
- Study the effect of the location of the local fold (syncline) on hoodoos with regards to their formation, preservation and distribution. Are there direction patterns and correlations?
- Study hoodoo fluting to see if it is vertical or if it is affected by bedding.

Paleontologic Potential

The desert landscape at Bryce Canyon contains more than just a collection of hoodoos; it contains a record of prolific ancient life. Fossils at the park include snails, clams, turtles, ammonites, oysters, plants, corals, and dinosaurs. These preserved specimens should be protected and catalogued for scientific study, future generations, and increased visitor appreciation of the entire park.

Inventory, Monitoring, and/or Research Needs for Paleontologic Potential

- Study the Cretaceous rocks to determine if dinosaurs are present in the backcountry.
- Perform a comprehensive inventory and study of the paleontologic resources at Bryce Canyon National Park.
- Attempt to determine the locations of paleontologic specimens removed from the park as part of private collections to obtain an accurate inventory.
- Draw visitor attention to the fossil resources at Bryce Canyon with graphics, brochures and exhibits.

Faulting and Deformation Processes

The rock units present at Bryce Canyon have undergone multiple phases of deformation resulting in folds, faults, joints and other fractures. These features compromise the strength of any rock unit. These weaknesses have many effects on the features present at Bryce Canyon. For instance, a fault or fracture can serve to focus surface runoff, eventually widening into a gulley. If parallel gullies have a jointed rock column between them, water will run through that joint, separating a spire from the rest of the column.

Deformation is still occurring at Bryce Canyon. Rocks are responding to pressures within the earth and recent small- scale fractures and joints attest to this. Understanding the nature of these features allows predictions of where weathering and erosion are likely to be concentrated making this knowledge indispensable to resource management.

Inventory, Monitoring, and/or Research Needs for Faulting and Deformation Processes

- Study the role of jointing versus faulting (both strike-slip and thrust faulting).
- Determine extent of Cretaceous thrusting above the Paria amphitheatre to the south.
- Study the Markagunt Megabreccia (a rock, which is the result of significant brittle fracturing, usually present along a fault zone) near Cedar Breaks for regional implications.
- Conduct an inventory of all recent fault scarps in the area. These are commonly present in Quaternary surficial deposits.

Gravel and Sand Deposits on the Paunsaugunt Plateau

The Sevier and Paria Rivers are examples of how streams have cut through the uplifted strata of the Colorado Plateau in southern Utah. Matching the fast uplift rate, erosion has kept pace and the amount of sediment being carried by the Sevier and Paria Rivers has deposited vast amounts of alluvium in their river valleys. These deposits are a vast resource of sand and gravel; however, due to their poor cohesion they also pose a threat of sliding when undercut or exposed on high slopes.

Inventory, Monitoring, and/or Research Needs for Gravel and Sand Deposits on the Paunsaugunt Plateau

- Perform a comprehensive study of the sediment deposition processes active at Bryce Canyon National Park, taking into account rock formations, sediment type, slope aspects, location with respect to trails, structures, and facilities, the likelihood of instability, etc.

Mining Resources and Issues

The Paradox Basin has been the site of uranium mining for nearly nine decades. The principal host rocks for the radium, vanadium, and uranium deposits exposed near Bryce Canyon is Triassic Chinle Formation and the Jurassic Morrison Formation. In the Chinle, gray, poorly sorted, fine- to coarse- grained, calcareous, arkosic, quartz sandstone contains uranium mineralization (Chenoweth, 1996).

Closed mines can pose a serious potential threat to any ecosystem. Even in arid environments, surface water, runoff, and groundwater can be contaminated with high concentrations of heavy metals leached from mine tailings. Heavy metals may also contaminate nearby soils that in turn can adversely impact the plant and animal life that live on the soil.

Another threat specific to uranium mining is that of radon gas exposure. Radon is a radioactive progeny of uranium decay. It is a tasteless, odorless gas and a known carcinogen that usually concentrates in low- lying areas like basements and mineshafts.

Coal beds are a common sight in the strata at Bryce Canyon, evidencing the vast prolific swamps and bogs that once covered the area. Development of coal and oil and gas accumulations surrounding the Bryce Canyon area pose a potential threat to the park's viewshed and ecosystem. The influx of drills, rigs and extraction equipment necessary for oil and gas exploration and production can create new road construction, water pollution, noise pollution and a localized population increase.

Inventory, Monitoring, and/or Research Needs for Mining Resources and Issues

- Park staff should remain aware of the potential encroachment of oil and gas exploration in the area of the park.

- Investigate any uranium bearing beds throughout the park including descriptions, uranium content, and locations (i.e. where the beds crop out and are accessible to the public), flora and fauna.
- Complete an inventory of the uranium content in the recent unconsolidated deposits and soils as well as the uranium bearing stratigraphic units.
- Acquire plugging records of oil and gas wells potentially connected to park groundwater systems
- Sample and test surface and groundwater and soil for the presence of uranium. Drinking water is especially important to monitor.

Marysvale Volcanic Field

Bounding Bryce Canyon to the northwest is the extensive Marysvale Volcanic Field. This field formed when local extension allowed a warm plume of molten rock to rise through the earths crust and penetrate the surface with flows and small volcanic cones. The volcanic field is contemporaneous with other volcanic features on the Colorado Plateau including Capulin Volcano. In addition to lava flows in the area, the volcanic field spewed vast blankets of ash over the area that are preserved in the youngest rocks at Bryce Canyon today.

Inventory, Monitoring, and/or Research Needs for Marysvale Volcanic Field

- Date whatever minerals are applicable for the timing of lava flow.
- Determine how much volcanic material was originally in the park and subsequently removed by erosion.
- Use resistivity to locate cavities in flows. These cavities could contain preserved animals, lava tubes, large vesicles and so forth.
- Conduct a detailed study of fractures, faults, and bedding within the area.
- Conduct detailed mapping of volcanic terrain features in the volcanic field.

Facilities Management

The following recommendations are for general facilities management concerns that arose during the scoping meeting at Bryce Canyon National Park.

Inventory, Monitoring, and/or Research Needs for Facilities Management

- The visitor center is not sitting on bedrock and caissons are needed for support.
- Use climate information and topographic information in a GIS to map areas unsuitable for recreational development due to avalanche danger.
- Determine the effects of the Highway 12 dump facility on the ecosystem at Bryce. Monitor water quality with test wells around the dump.
- Find and restore a small cave opening that was dynamited shut in the 1970's because it had vertical openings that posed a safety hazard.
- Research landslide and rockfall potential along all roads and trails at Bryce Canyon National Park. These conditions are extremely hazardous in the monsoonal season when high levels of rapid precipitation saturate the thin desert surficial deposits.

Wind Erosion and Deposition

In addition to water, wind is a major force that can redistribute soil and soil resources (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind is important at Bryce Canyon National Park and can be accelerated by human activities. Accelerated losses of soil and soil resources by erosion can indicate degradation of ecosystems because ecosystem health is dependent on the retention of these resources. In addition, wind erosion and sediment transport may be strongly impacted by land- use practices outside the park. Because park management practices limit or prohibit off- road travel, human impacts within the park primarily are associated with off- trail hiking in high- use areas. Where livestock grazing or trailing is still permitted, accelerated soil erosion can be more extensive.

Inventory, Monitoring, and/or Research Needs for Wind Erosion and Deposition

- Monitor movement of soil materials.
- Investigate ecosystem consequences of sand and silt movement.
- Investigate the natural range of variability of soil movement in relation to landscape configuration and characteristics.

General Geology

An understanding of the geological processes and resources at Bryce Canyon is fundamental to management decision making. This report hopes to further this understanding at Bryce Canyon with ideas and baseline information, including the digital geologic map of the park which will be incorporated into a natural resources GIS for help in management decision making. However, for the scientific community and the general public, the geology of Bryce Canyon National Park offers vast opportunities to further the knowledge of desert erosional processes, geologic and earth history, and Native American culture.

Inventory, Monitoring, and/or Research Needs for General Geology

- Perform rock color studies.
- Identify stratigraphic packages confined by unconformities in order to better define the depositional systems both present and past.
- Use GIS technology for park interpretation, resource management, and maintenance through interpretive mapping, 3- D visualization, virtual field trips, and surface rockfall hazard assessment (McNeil et al., 2002). Develop more graphics and brochures emphasizing geology. These should target the average enthusiast.

- Determine the age and provenance of the Boat Mesa Conglomerate. Is it Oligocene or Pliocene? Is it correlative with the Brian Head Formation?
- Examine the possibility of the presence a Cretaceous-Tertiary (K- T) boundary in the Table Cliffs area and its relation to the Kaiparowits Formation.

Swelling Clays

Swelling soils associated with bentonitic shales of the Tropic Shale may be a concern to the present and future developments and management at Bryce Canyon National Park. Bentonite, a clay derived from altered volcanic ash, is responsible for the road failures at Mesa Verde National Park and elsewhere. This clay swells when wet, causing the ground surface to heave and buckle. Any structures, roads, trails, facilities, etc. located on bentonitic soils will be negatively impacted.

Inventory, Monitoring, and/or Research Needs for Swelling Clays

- Map locations of bentonite occurrence and use GIS to determine if trails, roads and buildings are located on bentonite. Use this information to determine high risk areas where future development should be avoided.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Bryce Canyon National Park.

Sevier and Paunsaugunt Faults

There are two large normal faults at Bryce Canyon, the Paunsaugunt fault and Sevier fault. The Sevier fault trends roughly north- south (average of N30°E) and bounds the Paunsaugunt Plateau to the west, with the downdropped block on the west side of the fault. It runs for approximately 322 km (200 miles) from northern Arizona into the Sevier Valley (De Courten, 1994). Although the throw (vertical displacement) along the Sevier fault is not consistent making an average determination difficult, the estimates range between 91 and 610 m (300 to 2,000 ft) (Gregory, 1951). In places the Sevier Fault zone is several kilometers wide. Its escarpment is brilliantly displayed in the Sunset Cliffs on the west side of the Paunsaugunt Plateau (De Courten, 1994).

The Paunsaugunt fault is the easternmost of the three great faults that have determined the regional structural fabric of southern Utah. In addition to the Sevier fault, the other great fault is the Hurricane Fault, further to the west. The Paunsaugunt fault separates the Paunsaugunt and Sevier Plateaus on the west from the Aquarius and Kaiparowits Plateaus on the east. It trends on average N15°E, extends almost 113 km (70 miles) and its displacement ranges from approximately 183 to 610 m (600 to 2,000 ft). Dips range between 67° and 87° to the SE (Gregory, 1951; Engineers International, Inc. 1980; De Courten, 1994; Davis and Pollock, 2000).

The Paunsaugunt fault runs roughly parallel to the Sevier fault and has the same sense of offset, with the upthrown block east of the fault surface (Marine, 1963). The presence of a plateau between these two faults seems counterintuitive. With two parallel faults having the same sense of offset, a staircase structure, descending westward is expected, but the plateau arises from the extreme weathering of the upthrown block, or footwall block of the Paunsaugunt fault. For this reason, the surface expression of the Paunsaugunt fault is not expressed topographically, but its significant offset at Bryce Canyon is reflected in the rocks juxtaposed on either side of it. At one locality, the Sinking Ship region, rocks of Cretaceous (Straight Cliffs Formation) and Tertiary age (Claron Formation) of strikingly different colors are in contact across the fault.

There are a number of other vertical to subvertical faults in the Bryce Canyon area. Most of them are clean- cut surfaces with little to no accompanying breccia (Gregory, 1951). The Fairyland Fault, a vertical feature, which trends north - south directly under Boat Mesa, has about 6 m (20 ft) of displacement (Lindquist, 1980; De Courten, 1994).

The vertical Bryce Canyon Fault has a strike of N55°W and a vertical displacement that changes from about 2 m (7 ft) on its western end to 14 m (46 ft) on the outermost ridge just south of the mouth of Bryce Canyon. The Bryce Point Fault, a reverse fault with a vertical displacement of 30 m (98 ft) strikes N21°E and dips eastward 60°. The Peekaboo fault runs just west of Bryce Point through a deep gully, has 15 m (49 ft) of vertical displacement and strikes N9°E (Lindquist, 1980; De Courten, 1994). The latter two faults have exerted an influence on escarpment development in local areas of Bryce Canyon National Park (Lindquist, 1980).

Thrust Faults

Until recently, the Paunsaugunt Plateau was believed to contain only near vertical, extensional faults. Geologists have now identified several shallow dipping thrust faults bounding the area to the north. The most prominent of which is the Ruby's Inn thrust fault. It trends roughly east – west just north of the park entrance. The Ruby's Inn thrust fault extends across the plateau and is truncated by the Sevier and Paunsaugunt faults on either end. Along the fault, blocks of older rock from the north have been pushed south, over younger, underlying strata. This phenomenon is strikingly displayed in some small-scale hoodoos just south of the bend in Highway 12. Here the upper caps of some of these hoodoos are composed of a 90 million year old gray rock. Composing the pillars beneath these caps are the Claron Formation's red- pink layers of about 50 million years in age (De Courten, 1994)!

In addition to the prominent Ruby's Inn thrust fault, there are other compressional faults in the area. The Pine Hills thrust fault runs through the Pine Hills, just northeast of the park entrance. It parallels the Ruby's Inn thrust fault except in its sense of offset. Along the Pine Hills fault, the upper block has been pushed to the north instead of the south. The Bryce Point fault also records local compression in the area. Its fault plane is inclined at an angle of 60°. This is too steep to qualify it as a thrust fault; instead, it is a high angle reverse fault (De Courten, 1994).

How these compressional faults came to be is a matter of some debate. It is widely accepted that the major, regional compressional event, the Laramide Orogeny, ended sometime near 35 Ma (Lower Oligocene). Rocks as young as 50 million years old are affected by the local compressional faults in the Bryce Canyon area. These thrust faults are meanwhile cut by the Sevier and Paunsaugunt faults, less than 16 million years old, indicating a relative age bracket (De Courten ,1994).

The thrust faults near Bryce Canyon are not ideally aligned for movement during the Laramide. Laramide compressional stress was directed in a northeast - southwest direction, thus the thrust faults associated with it typically trend northwest – southeast, in other words, perpendicular to the compressive stress direction. The faults at Bryce Canyon are trending east - west. Imagine pushing a rug on a wood floor, any ripples in the rug warp perpendicular to the direction the rug is pushed, not parallel to that direction.

Another theory regarding the thrust faults at Bryce Canyon involves the Marysvale volcanic field to the north and west. This activity occurred between 35 and 15 million years ago. It is surmised that the movement of great volumes of hot molten rock up through the earth's crust, in addition to the incredible localized loading of the crust by volcanic rocks (some 3 km, 2 miles, thick over 1,035 square km, 400 square miles, at Marysvale), may have supplied enough compressive force to induce faulting to the south (De Courten, 1994). The orientation of the faults is better explained with this hypothesis.

Erosion of the Paria Amphitheatre

The Paria Valley is flat- floored and broadly bowl- shaped in the vicinity of Tropic, east of Bryce Canyon National Park. It is floored by relatively soft Cretaceous shale that permits rapid erosion by the Paria River and tributaries. The total erosion at the head of the Paria Valley is enormous, giving Bryce Canyon its characteristic features (Gregory and Moore, 1931). The streams have obliterated the topographic high created by the uplift of the eastern block along the Paunsaugunt to the degree that the uplifted block now appears topographically lower than the downdropped side by almost 610 m (2,000 ft)! From the rim of the plateau to the Paria River, over a distance of 6 km (4 miles) the elevation varies from 2,527 m (8,291 ft) to 1,896 m (6,220 ft).

The steep gradients of the Paria and its tributaries are contrasted to the west by the gentle drainage slope of the East Fork of the Sevier River, running up the axis of the Paunsaugunt Plateau. Both rivers are cutting through essentially horizontal sedimentary strata. This proceeds in such a way that the steep cliffs and terraces are continually perpetuated.

Resistant rocks such as the White Member of the Claron Formation cap the plateau and overly the softer formations. This relationship results in a weathering escarpment where the underlying rocks are eroded back under the lip of the caprock. Eventually, erosion removes enough of the underlying material to cause the caprock beds to collapse. Thus the cliff face moves ever backward. The rate of cliff face retreat at Bryce Canyon is astonishing: 5.6 mm (0.22 in) per year at Bryce Canyon exceeding the rate of retreat at the Grand Canyon (0.6 mm, 0.02 in per year) and at the Drakensburg escarpment in southern Africa (1.7 mm, 0.07 in per year). This extremely high rate is attributed to a combination of factors; 1) the rate of weathering is high, 2) the amount of protective vegetative cover is low, 3) the erosion of soft rocks is rapid, and 4) where the white limestone member may act as a caprock, it is subject to rapid horizontal retreat due to undercutting of the pink limestone member at its base (Lindquist, 1980).

Formation of Hoodoos

Somewhere in the erosional process responsible for the Paria amphitheatre is an intermediate step, one where a small fragment of caprock holds on to a narrow spire of strata. The formation of spires and hoodoos is partly a function of the presence of joints and fractures, where erosion is concentrated. The trends of the walls and ridges of the Paria amphitheatre closely follow the trends of the dominant joints within the still intact rock just to the west (Brox, 1961). Water seeps through the cracks locally and by chemical and mechanical weathering, dissolves and moves material from both surfaces, thus widening the crack. In addition to this, freezing and thawing of water in tight cracks acts as a wedge prying the rocks apart (Lindquist, 1980; De Courten, 1994). This downward weathering, coupled with the headward erosion by the Paria River and torrential rainstorms, lead to the unique geological features found today at Bryce Canyon National Park.

Jointing is not the only primary control on hoodoo formation, however, especially if the rock is not hard and competent. This lack of joint control is considered to result from the combination of weak beds and the overall rapid rate of wall retreat. Because of the extremely high rates of erosional retreat and bedrock weathering, it is unlikely that the joints offer much added weakness. Hoodoos tend to form on the crest of ridges between gullies in the pink limestone member of the Claron Formation near the head of the escarpment. Separating the hoodoo proper from the gully slopes are sharp weathering transitions from rapid slope weathering to the much slower weathering of the bedrock surfaces (Lindquist, 1980). Any hoodoo formation in the slope- forming member is thus a self- enhancing mechanism (Engineers International Inc., 1980). The presence of sedimentary layers of alternating resistance appears crucial in hoodoo development. This variation and alternation is a primary feature of the Claron Formation (Lindquist, 1980).

The pinnacles vary in height from less than 12 m (40 ft) to 61 m (200 ft) or more. The eroded limestone forms an intricate landscape of arches, spires, pinnacles, and natural bridges (Engineers International, Inc., 1980). Some hoodoos extend from the escarpment at right angles and are wall- like. Lindquist (1980) called these "primary hoodoos."

Secondary hoodoos extend at various angles from primary hoodoos or slopes leading to primary hoodoos. Ridge hoodoos form on ridge crests some distance (100's of meters) from the primary escarpment. Hoodoos can form complexes as clusters of shapes with a radiating configuration.

In the northern part of the park, the hoodoos are not as well developed because weathering rates between the surface rock and the slope are about the same. In the middle of the park, the resistant cap rocks are protecting the underlying slope- forming red limestone. These are ideal conditions for hoodoo development and all hoodoo types are represented there.

In the southern portion of the park, occur the greatest overall relief and most extensive erosion by the Paria River drainage. The entire Claron Formation is exposed and the red limestone dominates the landscape.

The hoodoos are short compared to those just north, and the undercutting of the Kaiparowits and Wahweap Formations weakens the overlying limestones causing them to break off in slabs rather than eroding into hoodoos (Engineers International, Inc., 1980).

Isolated Features

- The Pink Cliffs of the Claron Formation are the outstanding scenic feature of the plateau (Brox, 1961).
- There are two natural bridges at Bryce according to the digital geologic map.
- Boat Mesa, entirely composed of conglomerate, stands out on the horizon at Bryce Canyon.
- Sinking Ship is a unique caprock of resistant material atop an erosional surface.
- A remote inverted hoodoo has older rock on top of younger due to a thrust fault.
- Mossy Cave, more of an overhang from discharge, could be a nice hanging garden with ice stalactites and stalagmites.
- Thor's hammer from Sunset Point has a unique dolomite capstone.

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Bryce Canyon National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

Mesozoic age rocks capped by Cenozoic age rocks underlie Bryce Canyon National Park almost entirely. Because of the intense regional erosion, these rocks are on striking display, revealing the details of the history of the area.

The oldest rocks of the area are the Navajo Sandstone, Carmel Formation and Entrada Sandstone of Jurassic age. In the early Cretaceous Era, the sediments deposited include the sand of the Dakota, Kaiparowits and Wahweap Formations, the mud of the Tropic Shale, and, the mixture of sand, mud, limey ooze, and organic matter that lithified into the coal rich Straight Cliffs Formation.

Following the late Cretaceous to early Tertiary compressional Sevier–Laramide orogenic events were the extension of the Basin and Range province and the uplift of the Colorado Plateau.

The Tertiary age Claron Formation is the result of the local basins filling with sediments. The Conglomerate at Boat Mesa was deposited atop the Claron. Uplift and continuing erosion formed these units into the spindly hoodoos, amphitheatres, and other fantastic geomorphological shapes seen at Bryce Canyon today. Pleistocene glaciation, downcutting by streams and landsliding have left Quaternary age deposits on the landscape of Bryce Canyon National Park.

The following page presents a table view of the stratigraphic column and an itemized list of features per rock unit. This sheet includes several properties specific to each unit present in the stratigraphic column including: map symbol, name, description, resistance to erosion, suitability for development, hazards, potential paleontologic resources, cultural and mineral resources, potential karst issues, recreational use potential, and global significance.

Map Unit Properties Table

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Potential for Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
QUATERNARY	Alluvium (Qal), Colluvium (Qc)), Landslide Deposits Qls); Older alluvium and colluvium (Qoac); Pediment Deposits (Qp)	Alluvium is composed of clay, silt, sand, and gravel with some minor colluvium and slopewash as well as poorly sorted flash flood deposits; thickness from 0- 40 ft (0- 12 m.); colluvium composed of slopewash or mass- wasting debris with local talus and slump deposits; thickness between 0- 30 ft (0- 9 m). Landslide deposits consist of slides or mudflows derived from Tropic Shale and slide or slump blocks from Straight Cliffs Formation; thickness 0- 100 ft (0- 30 m). Older alluvium and colluvium include gravels from East Fork Sevier River and other mixed origins; gravels are mostly limestone derived from Claron Formation, with some volcanic clasts. Unit ranges in thickness from 0- 60 ft (0 to 18 m). Pediment deposits comprised of sand and gravel and some alluvial fan deposits; coarse clasts are limestone, chert and quartz in a sandy, calcareous matrix; some terrace deposits locally; unit ranges in thickness from 0- 100 ft (0 to 30 m).	Low to very low	Unconsolidated material may be unstable along slopes and in wet environments such as springs or bogs; high permeability may render this unit unsuitable for waste facility development.	Slumping, sliding, mass wasting and debris flows all possible for these units.	None documented	Native American dwellings or tools possible	None documented	None	Gravel, sand, pebbles, clay and silt deposits	Valleys are floored with this loose material making it available to wildlife habitat	Good for trails, picnic areas and campground, light recreational use	Fine examples of erosional deposits in badland area	Only where clay content is high
TERTIARY	Conglomerate at Boat Mesa (Tbm)	Ranges in thickness between 0- 100 ft (0 and 30 m), white, light brown, tan and gray; contains calcareous sandstone and conglomeratic limestone; coarsest clasts are pebbles of black, gray and tan chert and tan quartzite; cemented with white silica and locally contains volcanic tuff and ash beds.	High to very high	Present only on tops of mesas.; if altered volcanic material present, swelling clays may pose a problem for road development; due to highly fractured nature of unit, waste facility development is not recommended; should be suitable for most other development.	Rockfall hazard is extreme due to plucking of large cobbles and unit's exposure atop mesas in Bryce Canyon National Park.	None documented	Chert pebbles might have been used for tools; outcrop extent may have spiritual significance.	None documented	Not enough carbonate present	Gravel, and potential building material	Plucked cobbles may provide vugs for nesting; forms surface of mesas	Unit can be attractive to climbers; other use is possible	Tertiary unit unique to this area, coarse conglomerate	Only where unit is compromised by fractures
TERTIARY	Claron Formation, White limestone member (Tcw)	Member 0- 300 ft (0 and 91 m) in the BRCA area; homogenous white, light gray or tan cliff- forming limestone; fine- grained to microcrystalline and generally thick- bedded to massive with indistinct bedding structures; local beds of thin purplish gray mudstone present as interbeds with some scant sandstone beds.	Moderate to high	Limited in areal extent, but should be suitable for most forms of development unless highly fractured or eroded which would make waste facility development problematic and slopes unstable.	Rockfall hazard in canyons and on slopes; some block slide potential on slopes	Scant fossils of freshwater snails and clams	Native American legend interpretation	None documented	Karst landforms are present in this unit	Limestone	Forms canyons and caps badland formations for variety of desert wildlife habitat	Not recommended for most recreational use unless unit is intact, climbing possible	Caps BRCA characteristic hoodoos	Delicate hoodoo geomorphology

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Potential for Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
TERTIARY	Claron Formation, Pink limestone member (Tcp)	Ranges in thickness between 400- 700 ft (122 to 213 m), color from pale pink to red, pale orange and tan; very fine- grained, thin to thick- bedded with cyclic sediments ranging from limestone to argillaceous limestone and dolomitic limestone; thin interbeds of gray or tan calcareous mudstones in the dolomites render beds more resistant to erosion; grains are quartz, carbonate, and chert; basal, channelized conglomerate between 0- 40 ft (0- 12 m) occurs locally and contains clasts of quartzite, chert, and limestone.	Moderate to low	Unit responsible for development of hoodoos in the BRCA area, development not recommended, but in intact areas, unit should be stable for most foundations and buildings.	Heterogeneity of formation causes severe rockfall hazards in canyons and along trails; very susceptible to slumping and sliding as mass wasting along slopes.	Abundant root casts and plant fossils: *Physa pleromatis*, *Physa bridgerensis*, *Physa* sp., *Bulinus* sp., *Planorbis utahensis*, *Viviparous trachiformis*, *Goniobasis* sp.	Native American legend interpretation	Hematite responsible for brilliant colors	Karst landforms are present in this unit	Some gravel potential and building material; limestone & hematite deposits	Forms canyons and badlands for desert wildlife habitat; hoodoos provide nesting sites	Not recommended for most recreational use unless unit is intact	Forms incredible hoodoos and other badland formations	Delicate hoodoo geomorphology
CRETACEOUS	Kaiparowits Formation (Kk)	More than 2789 ft (850 m) thick on the nearby Kaiparowits Plateau; composed of light brown, tan and greenish- gray, very fine- grained friable sandstone and buff, fine- grained, lenticular sandstone interbedded with light gray to purplish- gray or tan mudstones and brown, white and greenish limestone; pebble conglomerate lenses locally with pebbles averaging 2.5 cm (1 in) in diameter.	Moderate	Friable sandstones may render unit unstable for foundations, but otherwise unit is suitable for most development unless highly fractured.	Rockfall hazard where unit is present on cliff faces and/or highly fractured; limestone layers may dissolve causing undercutting on slopes; mudstones pose slumping hazard.	Fossil rich with vertebrate bones, petrified wood, invertebrates and concretions: *Dammarites, Podozamites, Platanus, Betula, Menispermites, Cinnamomum, Viburnum, Adocus* sp., *Baena nodosa, Basilemys* sp., *Hadrosauridae, Nodosauridae, Theropoda, Trionychid turtle, Bulinus subelongatus, Campeloma* sp., *Goniobasis subtortuosa, Helix* sp., *Physa reesidei, Planorbis* sp., *Unio* sp., *Viviparus leai*	None documented	Concretions	Not enough carbonate present	None documented	Limestone- dissolved vugs on cliff faces may provide nesting habitat	Good for most recreational use; hazardous for climbers	Abundant Cretaceous fossils	Only if unit is extremely friable
CRETACEOUS	Wahweap Formation (Kw)	Unit ranges in thickness between 0- 700 ft (0 and 213 m); lower part is buff to light brown, fine- grained, lenticular sandstone interbedded with gray to tan mudstone and thin beds of light gray to white siltstone; upper beds are light gray to white fine to coarse- grained sandstone and conglomeratic sandstone; sandstone is crossbedded and locally contains small pebbles of gray chert and tan quartzite; locally cemented with calcite and iron oxide. Some gypsum beds.	Moderate to very high	Suitable for all forms of development unless significant fractures are present; fractures may render unit unsuitable for some septic system development; gypsum- rich beds may dissolve out causing some instability for foundations; sandstones cemented by gypsum may also be friable; iron oxide cements (rusty color) are most stable in unit.	Rockfall hazard where unit is present on cliff faces and/or highly fractured, gypsum rich beds may undermine unit integrity causing sliding.	Petrified wood and fossils: *Neritina* sp., *Physa* sp., *Viviparus* sp., turtle bones, leaf impressions	Chert could have provided Native American tool material	Chert nodules	None	Gypsum, flagstone	None documented	Attractive for rock climbers, good trail base; stable for most uses	Abundant Cretaceous fossils	None documented
CRETACEOUS	Straight Cliffs Formation, Upper Part (Drip Tank, John Henry and Smoky Hollow Member) (Ksu, Ksc)	This unit ranges in thickness between 900 - 1300 ft (274 and 396 m); lowermost beds buff, tan and light- brown in color & consist of very fine- grained to fine- grained sandstone interbedded with gray to tan mudstones; ~100 ft (30 m) above base is a 30 ft (9 m) thick interval of carbonaceous shale with thin coal interbeds; uppermost beds of unit are composed of white sandstone containing lenses of pebble conglomerate; sandstone is thick- bedded to massive, medium- to coarse- grained and crossbedded; upper beds form steep slopes or sandy, gravel covered benches between slopes.	Moderate	Suitable for most construction; may be unsuitable where concentration of mudstone is high and unit forms benches, especially if unit is water saturated; high fracture concentration limits waste facility development and building near slopes.	Slumping potential on gravel covered benches between slopes; rockfall hazard where unit is undercut along a cliff; coal bed fires a possibility during lightning storms; high concentrations of carbonaceous mudstone may render portions of unit unstable if exposed on a slope.	*Admetopsis subfusiformis, Anomia* sp., *Barbatia micronema, Campeloma* sp., *Cardium curtum, Certithium* sp.,*Corbula, Cyrena securis, Fusus venenatus, Glauconia coalvillensis, Gyrodes depressus, Maetra arenaria, Neritina bellatula, Nucula coloradoensis, Ostrea prudentia, Planorbis* sp., *Plicatula hydrotheca, Physa* sp., *Turbonilla coalvillensis, Turritella whitei, Viviparus* sp., *Volsella multilinigera*	None documented	None documented	Not enough carbonate present	Coal, natural gas	None documented	Good for trails, picnic areas & campgrounds, light recreational use	Distinctive coal zone in this unit, equivalent to nearby Henderson coal zone.	None documented

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Potential for Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
CRETACEOUS	Straight Cliffs Formation, Lower Part (Tibbet Canyon Member) (Ksl)	Grades from very fine- grained, flat-bedded to low- angle crossbedded, cliff-forming sandstones, buff and tan in color, to sandstone and carbonaceous mudstone interbeds; interbedded throughout local thin coal beds and two distinctive coal beds with serve as bounding layers between the two parts; uppermost layers are fine- to medium- grained, poorly sorted, crossbedded sandstone white to light- gray and containing lenses of conglomeratic sandstone; locally upper beds contain some pebble conglomerate; pebbles are polished, resembling gastroliths found in association with dinosaur remains; 320 - 400 ft (98 to 122 m).	High	Suitable for most development; if highly banded, may be unstable along slopes; if highly fractured in proposed area, waste facility development is not recommended.	Rockfall hazard where unit is undercut along a cliff; coal bed fires a possibility during lightning storms; high concentrations of carbonaceous mudstone may render portions of unit unstable if exposed on a slope.	Possible gastroliths present throughout unit.	Cliffs of this unit may display petroglyphs and desert varnish	None documented	Not enough carbonate present	Coal	Cliff unit with potential for nesting habitat	Good for most recreational use; if highly interbedded may prove hazardous for climbers	Forms cliffs and escarpments in the BRCA area; may contain gastroliths from dinosaurs.	None documented
CRETACEOUS	Tropic Shale (Kt)	700- 1000 ft (215 to 305 m) thick; gray to olive- gray, sandy to clayey shale; lower part contains very thin beds of tan bentonitic clay and a basal limestone concretion zone; upper beds - thin, very fine- grained sandstone interlayered with mudstone; locally gypsum rich; equivalent to Mancos Shale elsewhere on Colorado Plateau.	Low	Forms unstable slopes, unsuitable for most development, especially roads and buildings; bentonite also makes most development risky.	Slumping and sliding very possible	Very fossil rich unit, especially in basal limestone concretion zone, marine fossils, *Anchura* sp., *Anomia* sp., *Certthium n.*, *Corbula nemtatophora*, *Cyrena aequilateralis*, *Exiteloceras pariense*, *Fusus venenatus*, *Glauconia coalvillensis*, *Inoceramus* sp., *Lima utahensis*, *Liopisha meeki*, *Lunatia* sp., *Metoicoceras whitei*, *Ostrea prudentia*, *Sperula* sp., *Sigaretus textilis*, *Turritella whitei*, *Admetopsis subfusiformis*, *Cyrena* sp., *Legumen* sp., *Lucina* sp., *Maetra* sp., *Tellina* sp., *Volsella multinigera*, *Anatina* sp., *Exogyra olisoponensis*, *Gryphaea newberryi*, *Trochocyathus*.	Possible Native American tool material	Selenite crystals	None	Gypsum, coal, oil shale	Friability allows for burrowing	Possible trail base; unstable for most uses	Abundant fossils, deep marine environment	None documented
CRETACEOUS	Dakota Formation (Kd)	180- 300 ft (55 to 91 m) thick; comprised of interbedded buff to light- brown sandstone, gray to tan mudstone and dark carbonaceous mudstone and some coal beds; local pebble conglomerate in lower beds.	High	Suitable for all forms of development unless significant fractures are present; fractures may render unit unsuitable for some septic system development.	Rockfall potential if sandstone is fractured and exposed along a cliff face	Oyster beds, petrified wood, and macerated fossil plant rich beds	Possible Native American petroglyphs and settlements	None documented	None	Flagstone, coal, fossil fuel reservoir rock	None documented	Suitable for all uses, rock climbing	Widespread Cretaceous unit	None documented
JURASSIC	Entrada Sandstone (Escalante Member) (Je)	See Entrada Sandstone, see below.	See below	See below	See below	See below	See below	See below	See below	See below	See below	See below	See below	See below
JURASSIC	Entrada Sandstone (Cannonville Member) (Je)	300- 500 ft thick (91 to 152 m), light tan to white, locally red banded, very fine- grained sandstone and silty sandstone; generally flat bedded and weakly to moderately cemented with gypsum, rendering it friable; interbeds include red beds, limestone, shale and gypsum.	Low to Moderate	High gypsum content renders unit friable and unstable for most foundations and developments; Okay for light use such as picnic areas, trails, etc.	Unstable on slopes, high slide & slump potential	Fossils not present at BRCA as elsewhere	None documented	Gypsum	Unlikely; some potential in limestone beds	Gypsum deposits, limestone	Vugs in cliff faces may provide nesting habitat	Suitable for trails and picnic areas	Regionally continuous unit	None documented

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Potential for Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
JURASSIC	Entrada Sandstone (Gunsight Butte Member) (Je)	White to red, fine to medium grained, crossbedded sandstone.	Moderate to high	Suitable for all forms of development unless significant fractures are present; fractures may render unit unsuitable for some septic system development.	Rockfall potential where sandstone is exposed on cliffs	Fossils not present at BRCA as elsewhere	Possible Native American petroglyphs and settlements	None documented	None	Flagstone and building material potential	None documented	Rock climbing potential, mountain biking	Regionally continuous unit, with tectonic correlative significance	None documented
JURASSIC	Carmel Formation (Upper Member, limestone marker bed) (Jcu, Jcul)	600- 700 ft (183 to 213 m) thick, composed of red, pale- orange, and white sandstone, silty sandstone and mudstone; all fine- grained; marker bed of light- gray limestone occurs low in unit, about 15 ft (5 m) thick; upper part contains silty sandstone, mudstone and thin tan to white gypsum beds.	Moderate	Suitable for most development unless gypsum is present; limestone and gypsum dissolution as well as highly fractured sandstone beds may render unit unstable and a poor choice for waste facility development.	Unstable slope where gypsum beds are concentrated or limestone dissolved; rockfall where sandstone is fractured	Fossils not present at BRCA as elsewhere	None documented	Gypsum	Unlikely, some potential in limestone beds	Gypsum deposits, limestone	Vugs in cliff faces may provide nesting habitat	Suitable for trails and picnic areas	Regionally continuous unit, with tectonic correlative significance	None documented
JURASSIC	Carmel Formation (Gypsiferous member and Thousand Pockets Tongue of Page Sandstone) (Jcgt)	About 30- 50 ft (9 to 15 m) thick, composed of white, yellowish- gray or rust- colored crossbedded sandstone; interbedded with thick- bedded, massive white gypsum in lower beds which grade upward into gray or greenish- gray mudstone and gypsiferous mudstone.	Moderate	Sandstone- rich beds are fine for most development unless highly fractured; fractures increase permeability making unit poor for waste system facilities; gypsum- rich beds are easily dissolved and unstable for development.	Unstable slope where gypsum beds are concentrated; rockfalls where sandstone is fractured	Fossils not present at BRCA as elsewhere	None documented	Gypsum	None	Gypsum deposits	None documented	Suitable for trails and picnic areas	See above	Only where gypsum dissolution is extreme
JURASSIC	Carmel Formation (Banded member) (Jcb)	Approximately 100 ft (30 m) thick; unit is red, fine- grained sandstone and mudstone with some thin- bedded gray to white sandstone and greenish- gray mudstone interbedded.	Moderate	Unit is suitable for most development; if highly banded, unit may be unstable along slopes.	Rockfall and slide potential where mudstone is highly concentrated	Fossils not present at BRCA as elsewhere	None documented	None documented	None	None documented	None documented	Suitable for all uses	See above	None documented
JURASSIC	Carmel Formation (Lower member, Limestone member) (Jcl)	About 120 ft (37 m) thick, gray, thin- bedded limestone; forms cliffs and is interbedded with thin- bedded blue- gray mudstone, shale and gypsum.	Moderate to high	Suitable for most uses unless high shale content and/or limestone dissolution make it unstable for foundations.	Rockfall potential high if sandstone is undercut by dissolution; slopes unstable if high gypsum content	Fossils not present at BRCA as elsewhere	Possible Native American petroglyphs and settlements	Gypsum	Potentially in limestone rich beds	Gypsum deposits	Vugs in cliff faces may provide nesting habitat	Suitable for trails and picnic areas	See above	None documented

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Bryce Canyon National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

In many ways, Bryce Canyon is shrouded in mystery. Its surrounding canyon's sheer cliffs inspire visitors with a sense of wonder, and yet, Bryce Canyon is more than a scenic attraction; this land of spires and hoodoos is part of the rich geological history of the Colorado Plateau. Chapters to this geological story are scattered throughout the western United States (Figure 3). A brief synopsis is presented here, drawn on various localities on the Colorado Plateau and surrounding regions, to illustrate the interconnectedness of the Bryce Canyon area with the evolution of the North American continent. The recorded surface geologic history of Bryce begins in the Jurassic; however, much occurred before then that had a direct effect on the landscape of the park today. The authors recommend other sources for a summary of the geologic history of Utah prior to the Jurassic, such as is found in Hintze (1988).

The Mesozoic rocks, specifically Jurassic age rocks, at Bryce Canyon begin the record of the surface geologic history in the area. Throughout the 100 million years of the Jurassic, periodic incursions from the north brought shallow seas flooding into Wyoming, Montana, and a northeast- southwest trending trough on the Utah/Idaho border. The Jurassic western margin of North America was associated with an *Andean- type* margin where the eastward subduction of the seafloor gave rise to volcanism similar to that found in today's Andes of South America (Figure 4).

Volcanoes formed an arcuate north- south chain of mountains off the coast of western Pangaea in what is now central Nevada. To the south, the landmass that would become South America was splitting away from the Texas coast just as Africa and Great Britain were rifting away from the present East Coast and opening up the Atlantic Ocean. The Ouachita Mountains, formed when South America collided with North America, remained a significant highland, and rivers from the highland flowed to the northwest, towards the Plateau. The Ancestral Rocky Mountains and the Monument Upwarp also remained topographically high during the Jurassic.

During Jurassic time, the Four Corners region was a time of extensive ergs (sand dune "seas"), similar to the Sahara/Sahel regions today. The region was located about 18° north latitude at the beginning of the Jurassic (about 208 Ma) and moved to 30- 35° north latitude at the end of the Jurassic (about 144 Ma) (Kocurek and Dott, 1983; Peterson, 1994).

This is the latitude of the present day northeast trade wind belt where cool, dry air descends from the upper atmosphere and sweeps back to the equator in a northeast to southwest direction. The cool, dry air that can pick up additional moisture becomes warm, dry air. This is the latitude of intense evaporation. Most modern hot deserts of the world occur within the trade wind belt and during the Jurassic, the climate of the Colorado Plateau appears similar to that of the modern Western Sahara of Africa.

The Western Interior Basin was a broad, shallow basin on the southwest side of the North American craton during this time. The basin stretched northward from its southern margin in Arizona and New Mexico across the Canadian border. The basin was asymmetric with the rapidly subsiding Utah- Idaho trough along the west side and a more gently dipping shelf farther east. The Front Range and Uncompahgre uplifts made up the ancestral Rocky Mountains, but by the Jurassic, these uplifts did not contribute much clastic material to the surrounding region.

The western edge of the continent was marked by a continental- margin magmatic arc, a product of subduction processes that began in the Triassic (Dubiel, 1994) and reached its maximum development in the Cretaceous. Magma formed during the subduction process rose through the crust, exploded into the offshore ocean basin, and eventually developed into subaerially exposed volcanic islands that marked the subduction zone. An arc- graben depression (a basin between two topographically high regions) has been postulated to exist in the middle of the arc in the region of southwestern Arizona (Busby- Spera, 1988; 1990; Marzoff, 1990). Clastic debris eroded from the irregular northeastern shoulder of this arc was deposited onto the Colorado Plateau during much of the Jurassic (Peterson, 1994).

A change from eolian to fluvial (river) deposition is recorded in the sandstones of the Kayenta Formation, just below the exposed Navajo Sandstone at Bryce Canyon. In contrast to the sweeping eolian cross- beds of the underlying beds and overlying Navajo Sandstone, the cross- beds in the Kayenta are only a few feet in thickness. Interbedded sandstone, basal conglomerates, siltstones, and mudstones are typical channel and floodplain deposits.

Paleocurrent studies show that the Kayenta Rivers flowed in a general westward to southwestward direction (Morris et al., 2000). The rocks of the Kayenta Formation display an excellent example of the effects of a climate change that precipitated a reworking of eolian sandstone ergs by fluvial processes.

The Navajo Sandstone records a return to dry, arid conditions and the development of extensive ergs on the Colorado Plateau. Sand dune deposits reaching 240 to 340 m (800 to 1100 ft) gradually overtook the fluvial systems of the Kayenta. The large- scale (18 m, 60 ft), high- angle, cross- beds of the Navajo attest to the presence of Sahara- like sand dunes during the Early Jurassic (Morris et al., 2000). The paleolatitude of Bryce Canyon during the deposition of the Navajo Sandstone was near 20 degrees north latitude, within the northeast trade wind belt (Parrish and Petersen, 1988; Chan and Archer, 2000). Paleocurrent wind directions shifted to more northerly winds that gave rise to subtropical and monsoonal circulation patterns in the region. Studies of the cyclicity in Navajo dune sets suggest that the region experienced contrasts of wetter and drier periods on a decade scale in the Early Jurassic (Chan and Archer, 2000).

At the beginning of the Middle Jurassic Period, the western Elko highlands emerged to the west of the Utah-Idaho trough. The highlands record an irregular, pulsed orogeny that signifies continued compression along the western margin, yet at varied rates of motion (Peterson, 1994). When the pace of west coast collision increased in the Middle Jurassic (about 236 to 240 Ma) to about as fast as fingernails grow, the rock layers on the continental side of the collision, in Utah and western Colorado, deformed in response to the collision to the west. Like a ripple effect on water, only here in rocks, the layers folded upward and over millions of years, this "ripple fold" migrated eastward. As the strata bowed upward, weathering and erosion stripped away the rocks and the time represented by those rocks. The contact between these erosional surfaces and the overlying strata form an unconformity. As plate tectonic activity increased in the west, the sea began to onlap the continent from the north.

Middle Jurassic strata on the Colorado Plateau represent a complex interfingering of marine and nonmarine environments. Broad tidal flats formed marginal to a shallow sea that lay to the west (Wright et al., 1962). The sea encroached into west- central Utah from the north and lay in the Utah- Idaho trough bordered to the west by the Elko Highlands. Flat- bedded sandstones, siltstones, and limestones filled in depressions left in the underlying eroded strata (Doelling, 2000).

Carmel Formation strata represent restricted marine and marginal marine environments. Interbedded sandstones and siltstones, fossil- bearing limestone, and chickenwire gypsum record a period of intermittent marine flooding and evaporation in the area (Morris et al., 2000).

The cross- stratified Entrada Sandstone covers the entire Colorado Plateau and is the most widespread of the preserved late Paleozoic and Mesozoic eolianites on the Colorado Plateau. Marine conditions had retreated to the north by this time (Figure 5) (Kocurek and Dott, 1983; Hintze, 1988). When the groundwater table dropped, the wind whipped the sand into huge dune fields in the Bryce Canyon area and further east. When groundwater or relative sea level rose, the sand grains were held together by water cohesion and became unavailable to wind transport.

As plate tectonic activity increased at the end of the Middle Jurassic and beginning of the Late Jurassic (about 157.1 Ma) due to the onset of the Sevier Orogeny, a major transgression of the inland seaway from the north forever destroyed the vast eolian sand seas that once covered the Colorado Plateau (Figure 6) (Kocurek and Dott, 1983). Tidal flats covered the area as marine environments pushed south. Two additional marine transgression/regression couplets occurred in the Upper Jurassic before the seas finally receded and the extensive Upper Jurassic Morrison Formation was deposited across the subaerially exposed continental Western United States. The Morrison Formation is world renowned for both its dinosaur bones and its uranium deposits. Jurassic dinosaurs bones from the Morrison Formation grace many museums worldwide and are preserved *in situ* at Dinosaur National Monument. About 50% of the uranium resources of the United States are found in the Morrison Formation (Peterson, 1994).

The climate must have changed as the area drifted northward with the breakup of Pangaea, but there is not universal agreement regarding this climate change. Whether tropical or semi- arid, the Morrison environments were quite varied. Sediments were deposited in mudflats, overbank floodplains, stream channels, small eolian sand fields, and scattered lakes and ponds (Peterson, 1994).

Today, little vegetation grows on the banded pink, green, and gray "rainbow" shales of the Morrison Formation that paint a vivid landscape over parts of the Colorado Plateau.

As the mountains rose in the west and the roughly north- south trending trough east of those highlands expanded, the Gulf of Mexico separating North and South America continued to rift open in the south, and marine water began to spill northward into the basin. At the same time, marine water began to transgress from the Arctic region. As the shallow sea advanced onto the continent, the currents redistributed the sediments deposited from river systems in much the same way sediments are redistributed along the shorelines of North America today. With the sediments redistributed, more space was available for depositing more river sediments, and the basin continued to subside.

The seas advanced, retreated, and readvanced many times during the Cretaceous until the most extensive interior seaway ever recorded drowned much of western North America. The Western Interior Seaway was an elongate basin that extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4827 km (3,000 mi) (Kauffman, 1977). During periods of maximum transgression, the width of the basin was 1600 km (1,000 mi) from western Utah to western Iowa. The basin was relatively unrestricted at either terminus (Kauffman, 1977). The western margin of the seaway coincided with the active Cretaceous Sevier orogenic belt, but the eastern margin was part of the low- lying, stable platform ramp in Nebraska and Kansas. Consequently, sedimentation into the basin from the rising mountains on the western margin was rapid compared to the slow sedimentation from the craton on the eastern margin into the basin. Rapid sedimentation led to further sediment loading and downwarping along the western margin.

By the Late Cretaceous, the Four- Corners area had migrated northward into a subtropical climatic zone. Although the seaway was not physically restricted at either end, water circulation appears to have been periodically disrupted. A variety of depositional environments would have existed up and down the basin as sea level rose or fell. These included brackish estuaries, deltas, beaches, deeper water, coal swamps, fluvial systems, and so on. Over time, these changes in deposition environment with sea level would be reflected in the vertical section of rocks and fossils.

The Dakota Sandstone in Utah and western Colorado is a heterogeneous mixture of a variety of terrestrial and shallow marine environments (Figure 7). The Dakota strata in Utah are Upper Cretaceous in age whereas the Dakota Sandstone deposits in eastern Colorado are Lower Cretaceous, which illustrates the time-transgressive nature of the advancing sea into Utah. The sea invaded eastern Colorado earlier than it did eastern Utah. Marine waters encroached across the Bryce Canyon region as the area subsided in response to thrust faulting in western Utah. Consequently, the Cedar Mountain Formation was draped with a blanket of high energy, nearshore sandstones.

As the interior seaway widened, the Dakota environments changed westward from a fluvial-dominated system to one dominated by a broad, swampy coastal plain. Widespread carbonaceous shales and fine- to medium- grained sandstones in the upper Dakota indicate an environment of coastal swamps, lagoons, and beaches (Condon, 1991).

The uppermost Dakota sandstone bed is fairly continuous and the sedimentary structures and fossils reflect processes indicative of a rising sea level. The fossils, inferred energy conditions, and sandstone geometry indicate a beach deposit that has been reworked by processes similar to today's Gulf Coast beaches (Ekren and Houser, 1965).

The stratigraphy of the Dakota Sandstone, therefore, records a transition from fluvial to marginal marine to marine shoreface to open marine conditions as sea level rose and covered the Bryce Canyon region (Morris et al., 2000). These marine conditions are further recorded by the deep water facies of the thick Tropic Shale at Bryce Canyon.

During the Midddle to Late Cretaceous, the Sevier orogeny, as referred to earlier, was characterized by relatively thin slabs of older, upper Precambrian and lower Paleozoic sedimentary rocks being shoved eastward, over younger, upper Paleozoic and lower Mesozoic rocks, from a continental collision to the west. It formed a roughly north- south trending thrust belt that is well defined in present- day southern Nevada, central Utah, and western Montana. Collision caused deeply buried rocks to the west to be thrust over younger rocks in Utah and Wyoming and to be stacked piggyback style on top of one another.

As a result of uplift and thrusting, several processes acted in concert to change the landscape of the Western Interior Basin. When layers of rock are stacked into mountains atop other continental rocks, the area ahead of this additional rock mass responds by bending, folding, and flexing downward. When the large piles of rocks accumulated to form mountains, they simultaneously began being eroded away.

Volumes of cobbles, pebbles, sand, silt and clay were transported from the west to the east and into this down- flexed and expanding Western Interior basin. The sediments added more weight to the basin and caused it to subside even more. This increased foreland sedimentation giving rise to several late Cretaceous age rock units across the Colorado Plateau region.

The Kaiparowits Formation represents one of these synorogenic, fluvially deposited units derived from the Sevier fold and thrust belt. Some of the volcanic and rare metamorphic grains in the Kaiparowits suggest a source area in southeastern California and southern Nevada where extensive volcanism and metamorphism had taken place prior to and during the Sevier orogeny. A fluvial system deposited sand and mud in a meandering river pattern towards the east and northeast (Goldstrand, 1990; 1991).

The laterally extensive conglomerates of the Canaan Peak Formation indicate that an east to northeast directed, braided fluvial system was draining the highlands created during the Sevier orogeny. They record the northward progression of postorogenic isostatic uplift and the inherent erosion of the new highlands (Goldstrand, 1990). The drainage during Canaan Peak Formation deposition was structurally controlled between the Paunsaugunt Plateau and uplifts to the east. The subsequent diversion of the braided river system from east to north- northeast, as recorded in paleocurrent data, may signal the initiation of the Laramide orogeny (Goldstrand, 1990; 1991).

The Late Cretaceous to early Tertiary rocks at Bryce Canyon, including the Kaiparowits and Canaan Peak Formations, record the Sevier orogenic deformation and its evolution into Laramide- style deformation (Goldstrand, 1990). For about 35 million years during the Laramide Orogeny, from roughly 70 Ma to 35 Ma, the collision of the tectonic plates transformed the extensive basin of the Cretaceous Interior Seaway or foreland basin into smaller, internally drained, non- marine, intermontane basins (Figure 8) (Goldstrand, 1990; Ott, 1999; Graham et al., 2002). This style, contrasting with earlier Sevier deformation, involved thick, basement-cored uplifts along shallowing downward thrust faults, and extensive folding.

According to Gilbert (1877):

> "It seems as through the crust of the earth had been divided into great blocks, each many miles in extent, which were moved from their original positions in various ways. Some were carried up and others down, and the majority were left higher at one margin than at the other. But although they moved independently, they were not cleft asunder. The strata remained continuous, and were flexed instead of faulted at the margins of the blocks."

The Pine Hollow Formation unconformably overlies the Canaan Peak and Kaiparowits Formation and from paleocurrent data, it reveals two different source areas, from the west and northeast. This partitioning could indicate the partitioning of the basin into smaller basins during the Laramide deformation (Goldstrand, 1990; 1991). The alluvial fan deposits represented by the coarser grained beds of the Pine Hollow, grade laterally into sheet- flood sandstones and mudflats and eventually laminated lacustrine limestones in the center of the basin. This new basin was bounded by the development of the Johns Valley anticline and the Circle Cliffs uplift (Goldstrand, 1990).

The variety of rock types preserved in the Tertiary age Claron Formation, including fluvial, deltaic, and lacustrine deposits overlap the paleotopographic highs (anticlines) of the Pine Hollow Formation. This overlap indicates the cessation of the Laramide deformation by the Middle Eocene period. No longer were tectonic forces beveling of highlands by erosion; the Claron was deposited over the surface with lacustrine and limestone deposits transgressing north and northeastward from the Pine Valley Mountains to the west of Bryce Canyon National Park (Goldstrand, 1990).

The Claron Formation was deposited within an intermontane basin bounded by the basement- cored uplifts produced during the Laramide Orogeny (Figure 9) (Goldstrand, 1990; Ott, 1999). The lower pink member was deposited in a shallow, low- energy, low gradient lake margin, resulting in the slow alteration and pedogenesis (extreme bioturbation) of the primary sediments. The upper white member signals the re-establishments of continuous lacustrine sedimentation punctuated by rare pedogenic events (Ott, 1999). The upper layers, which might bear record of the desiccation of the lacustrine environment, have been eroded from the Bryce Canyon area.

The Quaternary Period is subdivided into two epochs: 1) the Pleistocene, which ranges from about 1.6 Ma to 10,000 years before present (B.P.), and 2) the younger Holocene Epoch that extends from 10,000 years B.P. to the present. The Pleistocene Epoch is known as the Ice Age and is marked by multiple episodes of continental and alpine glaciation. Great continental glaciers, thousands of feet thick, advanced and retreated over approximately 100,000- year cycles. Huge volumes of water were stored in the glaciers during glacial periods so that sea level dropped as much as 91 m (300 ft) (Fillmore, 2000). The carving of a rugged mountain landscape by streams, frost action, and glaciers has been the principal geologic activity in this region from late Tertiary time to the present.

The Holocene, of course, is the Age of Humans and our impact on our global ecosystem is complex. With the retreat of the glaciers and the end of widespread glaciation about 12,000 years ago, the climate continued to warm and global sea level rose. In some local areas (i.e., the coast of Maine), however, relative sea level lowered as the land rebounded from the weight of the glaciers. Local tectonism, sediment input, global warming, and global cooling are some of the factors affecting global sea level and their relative importance, and humans' influence on them, continues to be debated today (Graham et al., 2002).

Geologically, the High Plateaus area has not changed much during the Holocene. The area as a whole has been subjected to some extension and uplift associated with the Rio Grande Rift, and streams have carved new landscapes since the end of the ice age, but 11,000 years is but a geological instant. Figure 10 summarizes the geologic history from the Proterozoic to the present at Bryce Canyon.

Eon	Era	Period	Epoch	Ma		Life Forms	N. American Tectonics
Phanerozoic (Phaneros = "evident"; zoic = "life")	Cenozoic	Quaternary	Recent, or Holocene	0.8	Age of Mammals	Modern man Extinction of large mammals and birds	Cascade volcanoes
			Pleistocene	1.8			Worldwide glaciation
		Tertiary	Pliocene	5.3		Large carnivores	Uplift of Sierra Nevada
			Miocene	23.8		Whales and apes	Linking of N. & S. America
			Oligocene	33.7			Basin-and-Range Extension
			Eocene	55.5		Early primates	Laramide orogeny ends (West)
			Paleocene	65			
	Mesozoic	Cretaceous		145	Age of Dinosaurs	**Mass extinctions** Placental mammals Early flowering plants	Laramide orogeny (West) Sevier orogeny (West) Nevadan orogeny (West)
		Jurassic		213		First mammals Flying reptiles	Elko orogeny (West) Breakup of Pangea begins
		Triassic		248		First dinosaurs	Sonoma orogeny (West)
	Paleozoic	Permian		286	Age of Amphibians	**Mass extinctions** Coal-forming forests diminish	Super continent Pangea intact Ouachita orogeny (South) Alleghenian (Appalachian) orogeny (East) Ancestral Rocky Mts. (West)
		Pennsylvanian		325		Coal-forming swamps Sharks abundant	
		Mississippian		360		Variety of insects First amphibians First reptiles	Antler orogeny (West)
		Devonian		410	Fishes	**Mass extinctions** First forests (evergreens)	Acadian orogeny (East-NE)
		Silurian		440		First land plants	
		Ordovician		505	Marine Invertebrates	**Mass extinctions** First primitive fish Trilobite maximum Rise of corals	Taconic orogeny (NE)
		Cambrian		544		Early shelled organisms	Avalonian orogeny (NE) Extensive oceans cover most of N.America
Proterozoic ("Early life")		Precambrian		2500		1st multicelled organisms Jellyfish fossil (670Ma)	Formation of early supercontinent First iron deposits Abundant carbonate rocks
Archean ("Ancient")				~3800		Early bacteria & algae	Oldest known Earth rocks (~3.93 billion years ago)
Hadean ("Beneath the Earth")				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4-4.6 billion years ago) Earth's crust being formed

Figure 3: Geologic time scale; adapted from the U.S. Geological Survey. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

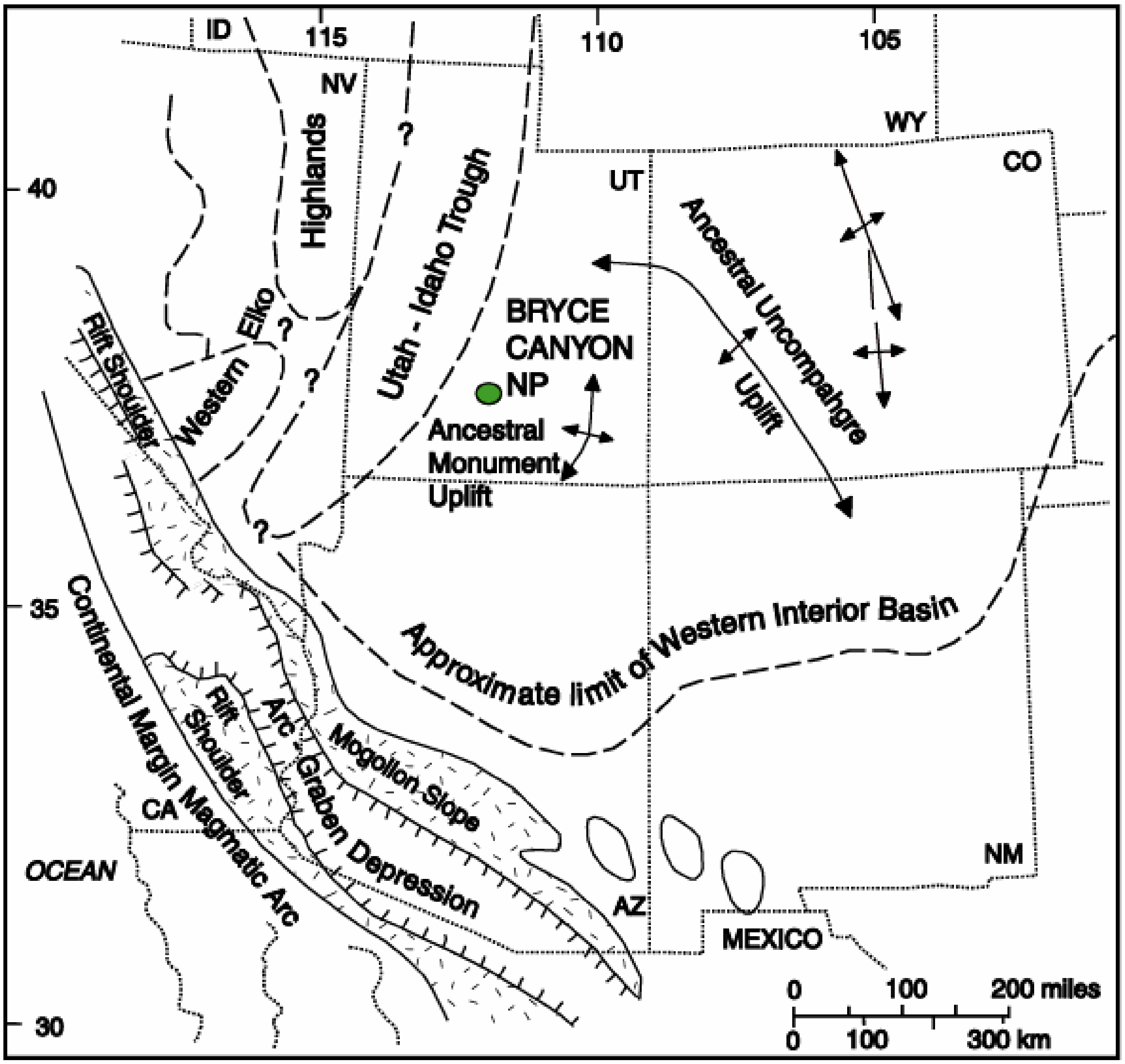

Figure 4: Main Jurassic structural elements affecting sedimentation onto the Colorado Plateau. The arc-graben depression probably did not exist in Late Jurassic time. Eastern Elko highlands rose out of the Utah-Idaho trough in latest Middle and Late Jurassic time. Modified from Peterson (1994).

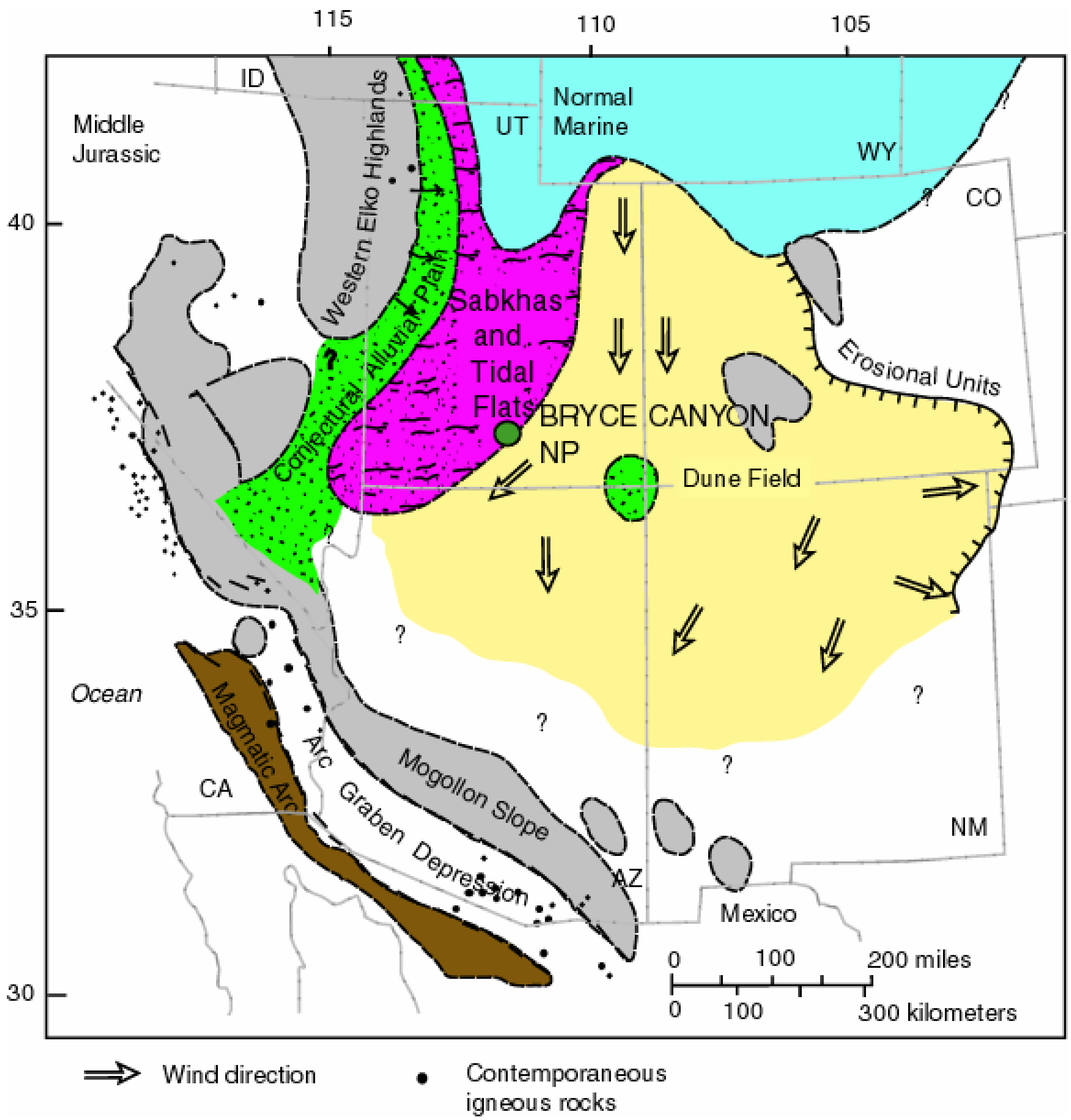

Figure 5: Middle Jurassic paleogeography during deposition of the Entrada Sandstone. Modified from Peterson (1994).

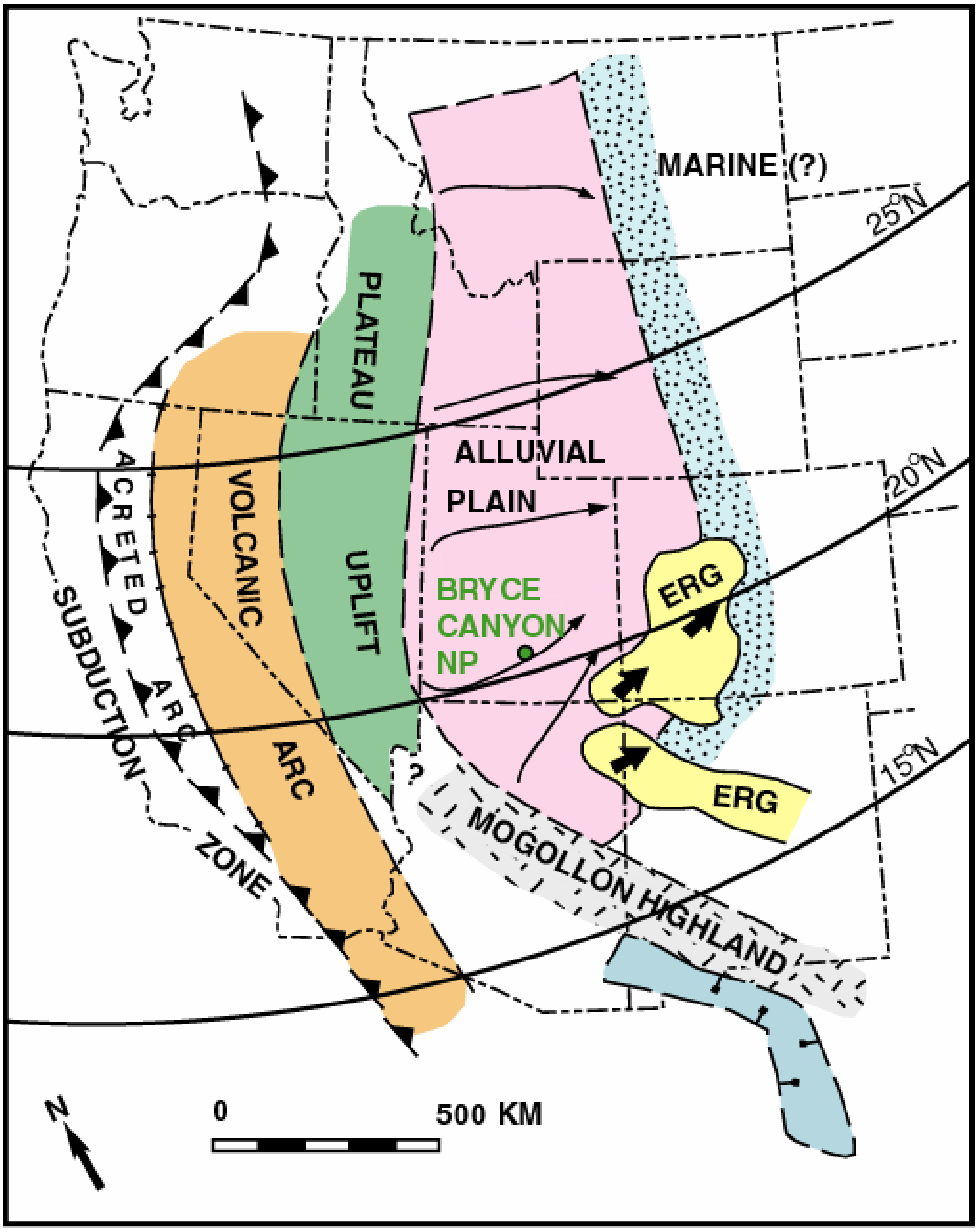

Figure 6: Late Jurassic paleogeography. Thin arrows indicate fluvial dispersal. Thick arrows indicate wind directions. Saw teeth indicate the location of the subduction zone with the teeth on the overriding, upper lithospheric plate. The alluvial plain expanded to the east with time. Modified from Lawton (1994).

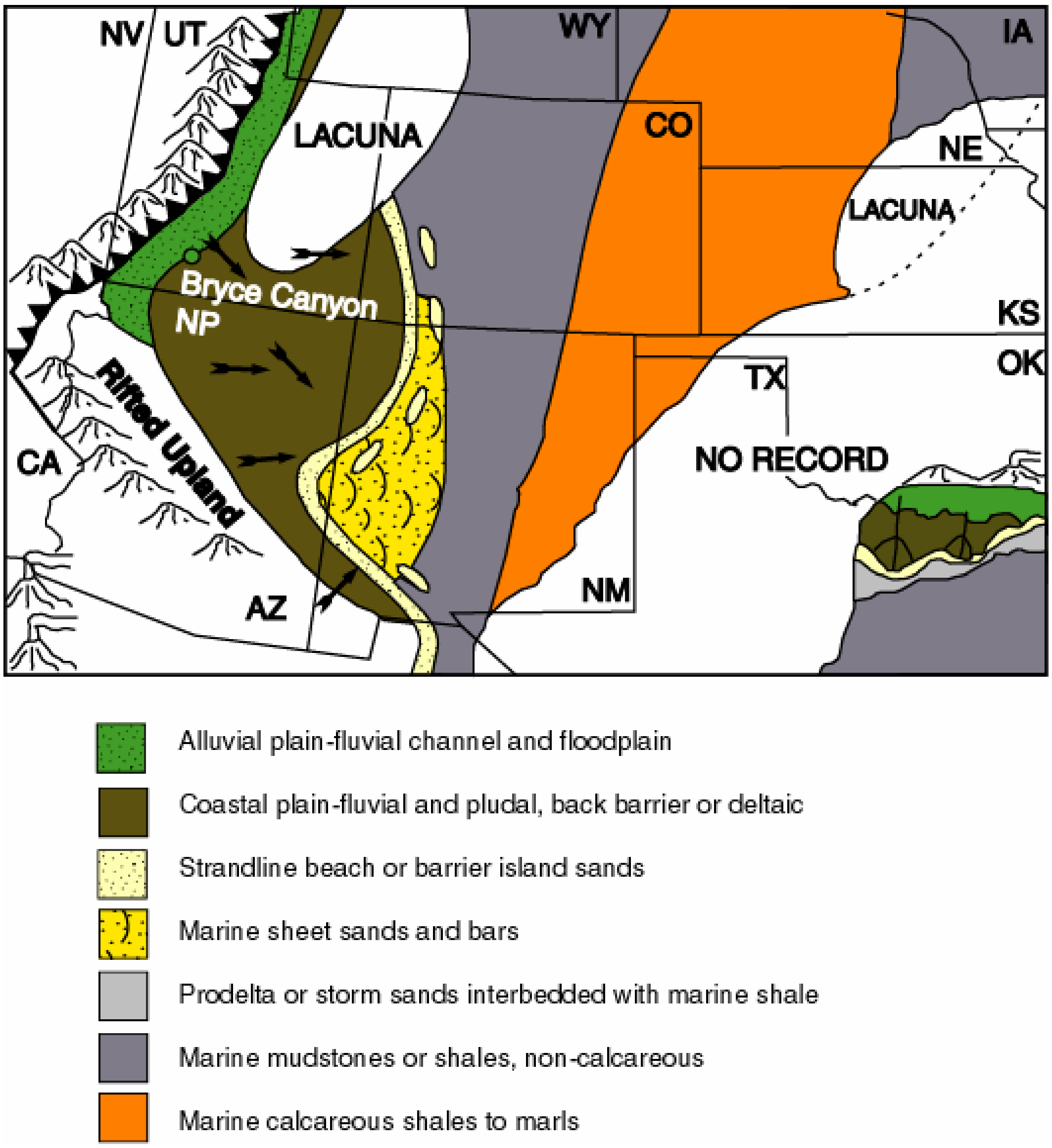

Figure 7: Upper Cretaceous paleogeography at the time of Dakota Sandstone deposition. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. Arrows indicate direction of sediment transport. Modified from Elder and Kirkland (1994).

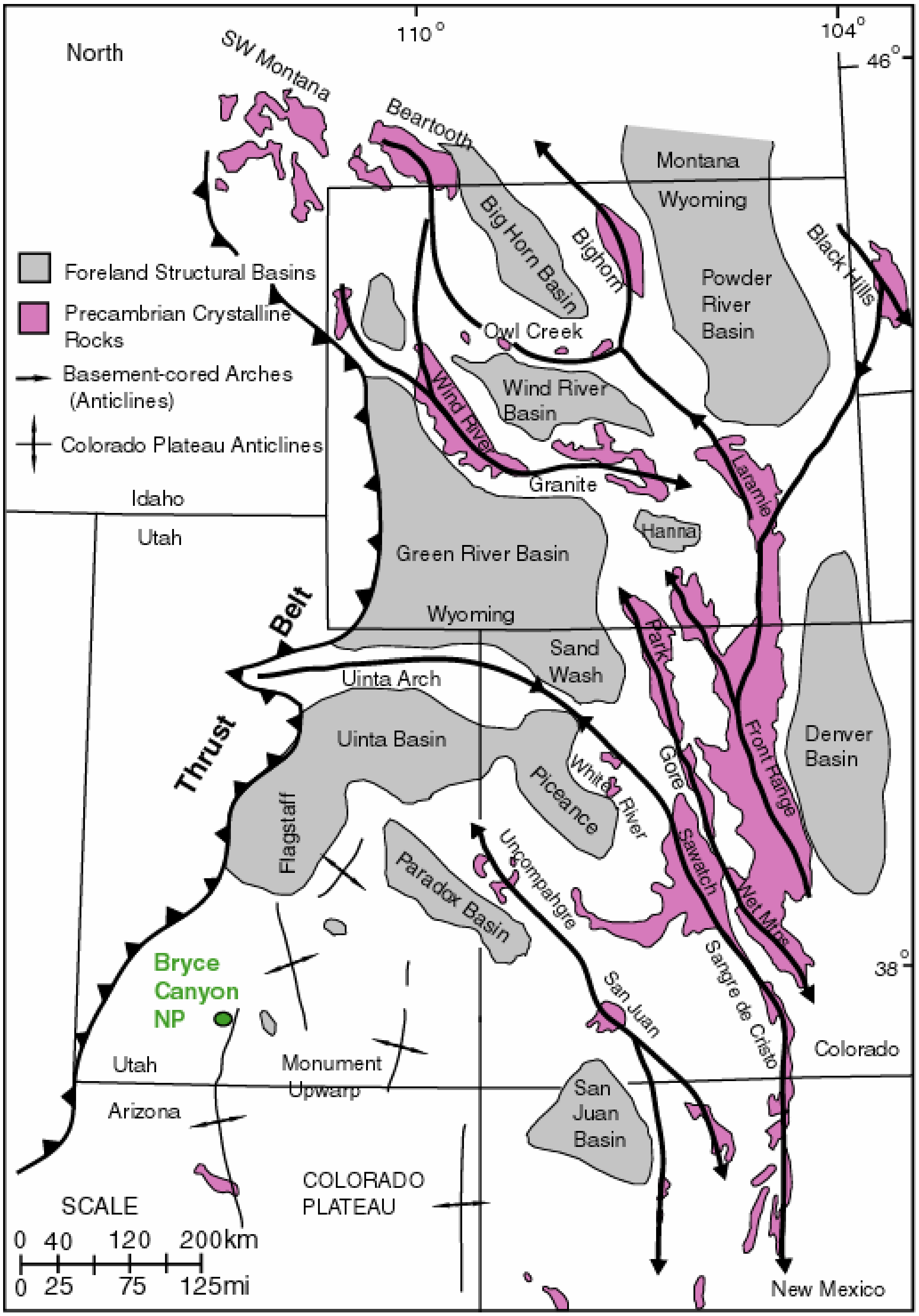

Figure 8: Location of Bryce Canyon National Park on a tectonic map showing Laramide-age structures on the Colorado Plateau. The map illustrates the anastamosing nature of the basement-cored arches (regional-scale anticlines) and the spatial relationships with the adjacent thrust belt, Colorado Plateau, and North American craton. The 'Thrust Belt' marks the eastern extent of the Sevier Orogeny. From Gregson and Chure, 2000.

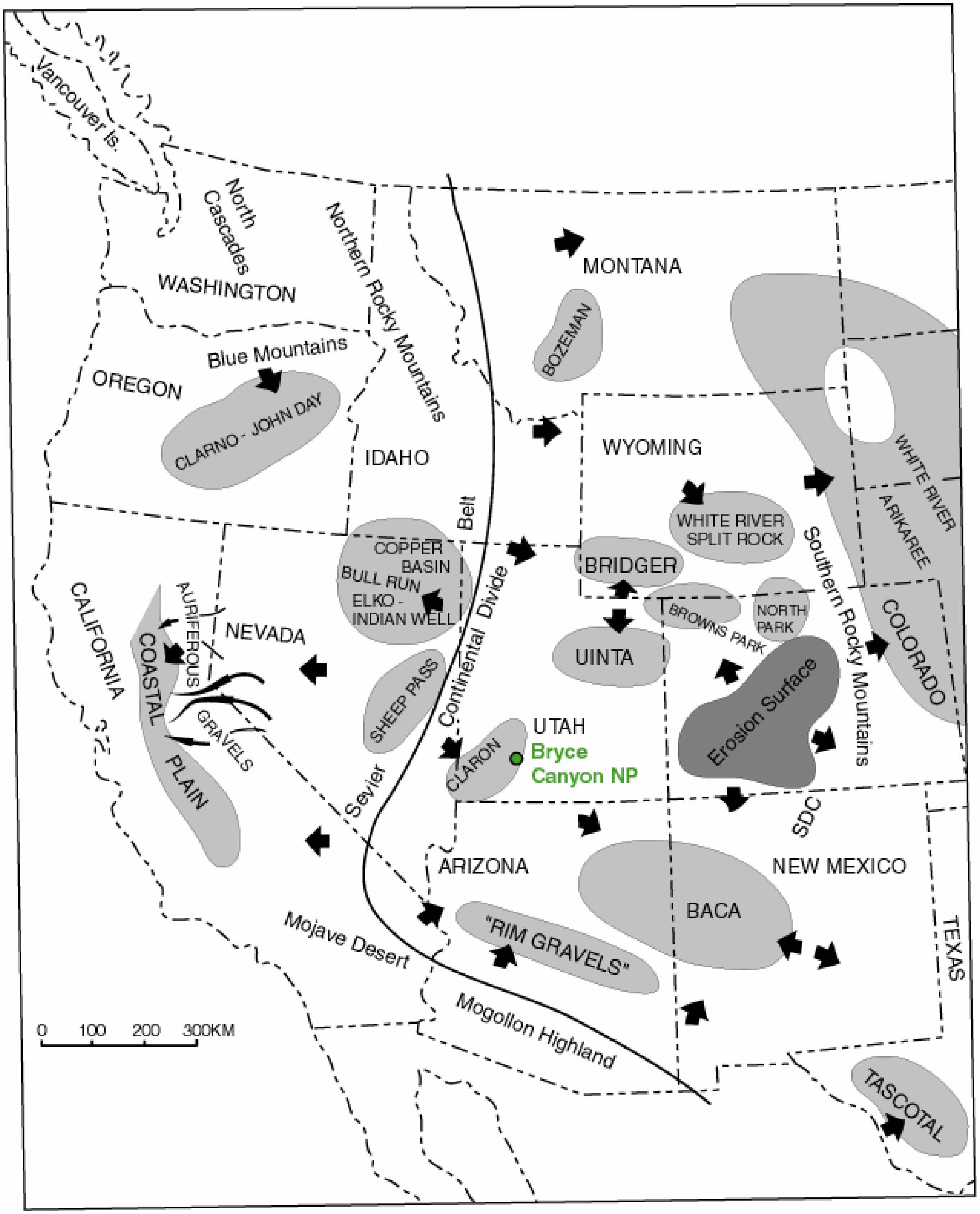

Figure 9: Early post-Laramide map showing the probable location of the continental divide, major depositional basins, erosional features, and stream systems in the western U.S. Light gray areas denote basins (note Claron Basin), dark gray areas indicate highlands and arrows indicate probable directions of sediment transport into the basins and away from the continental divide. SDC, Sangre de Cristo Mountains; SJ, San Juan Mountains. Modified from Christiansen and others, 1992.

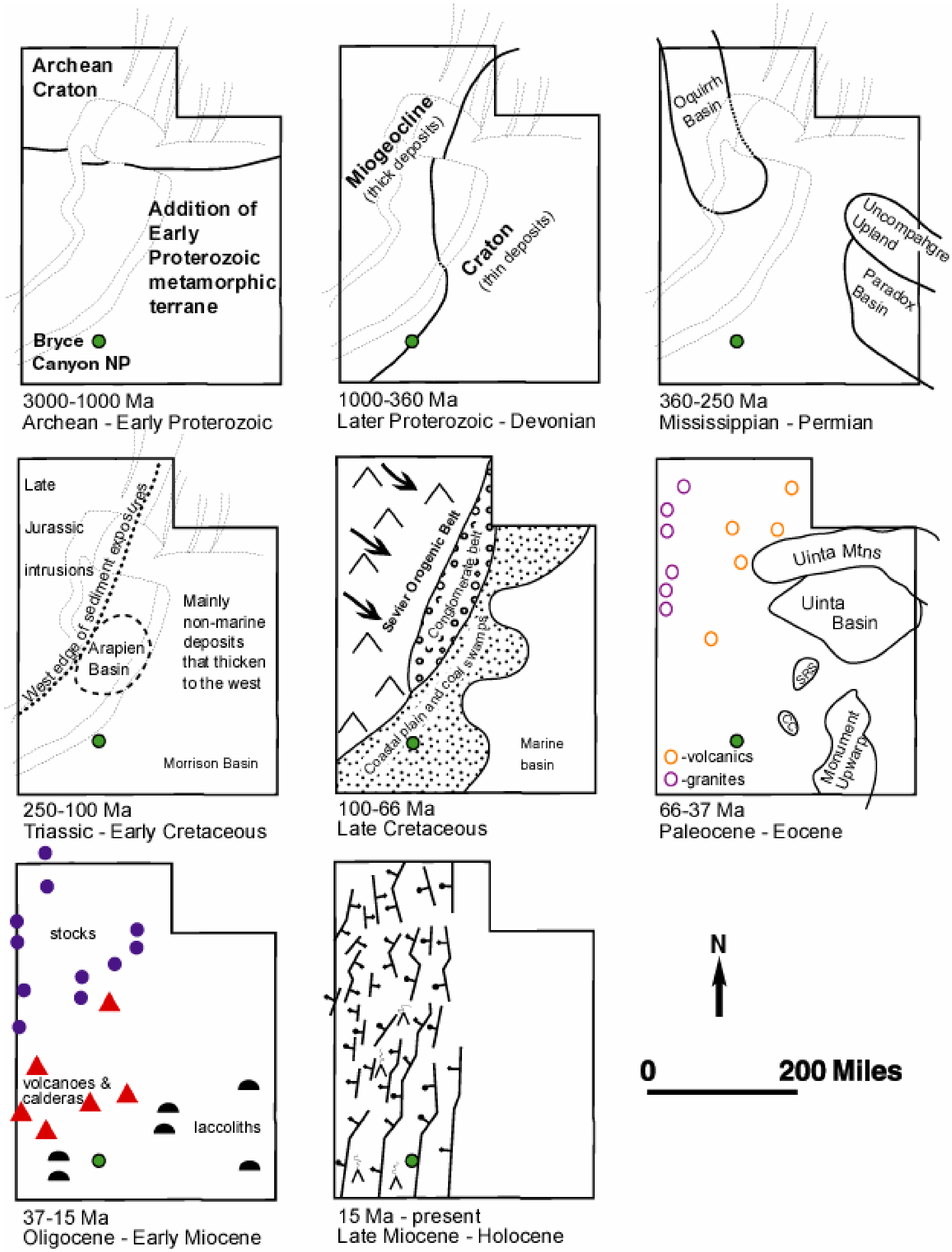

Figure 10: Generalized graphic overview of geologic evolution of Utah from the Archean Eon to the Holocene Epoch (adapted from Hintze 1988).

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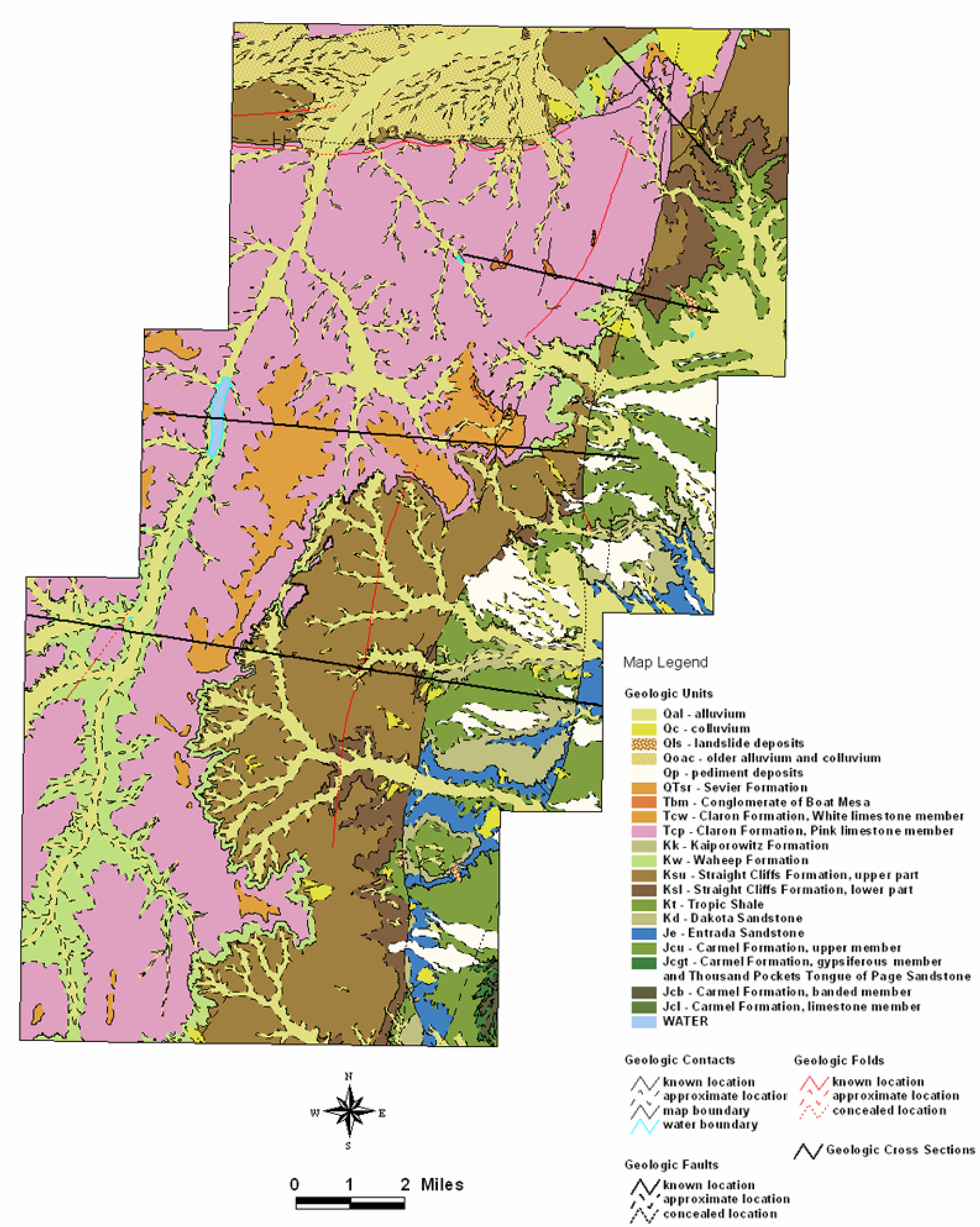
Appendix A: Geologic Map Graphic

This image provides a preview or "snapshot" of the geologic map for Bryce Canyon National Park. For a detailed digital geologic map, see included CD.



The original map digitized by NPS staff to create this product was: Bowers, W.E., 1990, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah, U.S. Geological Survey, Miscellaneous Investigations Series Map I-2108, 1:24000 scale. For a detailed digital geologic map and cross sections, see included CD.

Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Bryce Canyon National Park. The scoping meeting occurred on July 13- 14, 1999; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

Executive Summary

An inventory workshop was held at Bryce Canyon National Park on July 13- 14, 1999 to view and discuss the park's geologic resources, to address the status of geologic mapping by both the Utah Geological Survey (UGS) and the United States Geological Survey (USGS) for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Bryce Canyon NP and Natural History Association, UGS, USGS, University of Arizona and Waterworks Consultants, were present for the two- day workshop.

Day one involved a field trip co- led by University of Arizona geology professor George Davis and USGS geologist Pete Rowley.

Day two involved a scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the Geologic Resources Division, and the ongoing Geologic Resources Inventory (GRI) for Colorado and Utah. Round table discussions involving geologic issues for Bryce Canyon NP included interpretation, the UGA Millennium 2000 guidebook featuring the geology of Utah's National and State parks, the status of cooperative geologic mapping efforts, sources of available data, geologic hazards, potential future research topics, and action items generated from this meeting. Brief summaries of each follow.

An on- line slide show of the highlights of these field trips can be found at http://www.nature.nps.gov/grd/geology/gri/ut/brca/field_trip_brca

Overview of Geologic Resource Evaluation

After introductions by the participants, Steve Fryer (NPS- NRID) presented an overview of the NPS I&M Program, the status of the natural resource inventories, and the geological resources inventory.

He also presented a demonstration of some of the main features of the digital geologic map for the Black Canyon of the Gunnison NM and Curecanti NRA areas in Colorado. This has become the prototype for the NPS digital geologic map model as it ideally reproduces all aspects of a paper map (i.e. it incorporates the map notes, cross sections, legend etc.) with the added benefit of being a GIS component.

It is displayed in ESRI ArcView shape files and features a built- in help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the map. The cross section lines (ex. A- A') are subsequently digitized as a shape file and are hyperlinked to the scanned images

For a recap on this process, go to: http://www.nature.nps.gov/grd/geology/gri/blca_cure/ and view the various files in the directory.

The geologists at the workshop familiar with GIS methods were quite impressed with this method of displaying geologic maps digitally; Joe Gregson is to be commended for his accomplishments.

Bruce Heise (NPS- GRD) followed with an overview of the Geologic Resources Division and the Geologic Resource Evaluation program and the main goals summarized below:

- to assemble a bibliography of associated geological resources for NPS units with significant natural resources,
- to compile and evaluate a list of existing geologic maps for each unit,
- to develop digital geologic map products,
- to complete a geological report that synthesizes much of the existing geologic knowledge about each park. The emphasis of the inventory is not to routinely initiate new geologic mapping projects, but to aggregate existing information and identify where serious geologic data needs and issues exist in the National Park System.

Interpretation

The GRE also aims to help promote geologic resource interpretation within the parks and GRD has staff and technology to assist in preparation of useful materials including developing site bulletins and resource management proposal (RMP) statements appropriate to promoting geology. Jim Wood (GRD) and Melanie Moreno (USGS- Menlo Park, CA) have worked with several other NPS units in developing web- based geology interpretation themes, and should be considered as a source of assistance should the park desire.

The UGS has the Geologic Extension Services available for help to the NPS for creating interpretive brochures and for seasonal employee training. The UGS also has programs for applied geology (hazards), economic geology, archeology and paleontology. Pete Rowley and George Davis have generously offered their services and are also available for any assistance the park may need regarding geologic issues and interpretation.

Doug Neighbor presented the most asked question of interpreters at Bryce Canyon as follows:

Q: Why aren't there any fossils in the Claron Formation?
A: Oxidized environment didn't promote fossil preservation; soil pedogenesis churned and obliterated any life forms

Q: Is the Claron freshwater or marine?
A: Freshwater; marine seas had retreated in late Cretaceous

From these questions, the major interpretive struggle at BRCA is trying to present a modern analogue for the Claron depositional setting. Because the Claron is so well exposed here, it certainly makes for a great place to attempt to answer these questions.

Doug also mentioned that Jan Stock (Chief of Interpretation) and Rob Danno (Chief Ranger) are relative newcomers to the park (June 1999) and weren't able to make the field trip or scoping session.

Bryce Canyon Natural History Association

Gayle Pollock mentioned that the Bryce Canyon Natural History Association (NHA) is currently developing an extended web page for http://www/nps.gov/brca with a "GeoDetective" theme aimed at 2nd- 4th graders. It was suggested that perhaps Jim Wood (GRD), Melanie Moreno (USGS), or Sandy Eldredge (UGS) would be interested in reviewing the site for their perspective into the geology and interpretation portions; Gayle welcomed such assistance and will furnish the web link when it comes on- line.

The NHA has a very active role at Bryce Canyon, and it's nice to see that a geologist is heading this organization. When Gayle Pollock came to BRCA in October 1995, a major focus was to get universities more active in geological research for partnerships. The approach was to target senior level students and try to convince them to do MS or Ph.D. research at BRCA. Several students have been funded by the NHA since 1995. Gayle supplied meeting participants with informative folders pertaining to the status of research, geologic maps, and other useful material; he is to be thanked for putting these brochures together.

The NHA is responsible for distributing funds for park proposals from BRCA for research, whether geologic, biologic, or education/outreach (Debbie Cantu handles most of this as an NPS employee funded by the NHA). Bruce Heise mentioned also that funding for geologists- in- the- parks (GIP) and student conservation association (SCA) might also be available to assist the NHA.

UGA Guidebook on Utah's National and State Park Areas

Grant Willis of the UGA announced that a guidebook treating the geology of 27 of Utah's national and state parks and monuments would be compiled for publication in September 2000. This compilation will be a snapshot into the geology of each park and covers most facets of what the GRI is trying to develop for each park for a final report (i.e. cross sections, simplified geologic map, general discussions of rocks, structure, unique aspects of park geology, classic viewing localities). The only NPS unit in Utah that will not be treated will be Golden Spike National Historic Site.

Funding for this publication is coming jointly from the UGA, NPS, BLM, USFS and Utah state parks; it is hoped that the publication will be sold for under $30.

Each author will be encouraged to get with NPS staff interpreters to develop a product that aims at a wide audience (the common visitor, the technical audience and the teaching community). Bryce Canyon NP authors will be our field trip leader (George Davis, who has also tried to enlist the services of Gayle Pollock into the project).

Park authors are strongly encouraged to get with NPS staff to make sure that any trail logs do follow maintained trails and do not take visitors into unauthorized areas, or places where resources are fragile and would be disturbed by increased visitation (i.e. areas with crytptogamic soils).

Also, a CD- ROM will be distributed with the publication featuring road and trail logs for specific parks as well as a photo glossary and gallery. The photo glossary will describe certain geologic features (i.e. what is crossbedding?). These will also be available as web-downloadable Adobe Acrobat PDF files. The UGA cannot copyright this material because it is funded with state money, so it can be distributed widely and freely, which will also benefit the purposes of the GRI. Additional reprints are not a problem because of the digital nature of the publication and the UGA board is committed to additional printings as needed. UGA normally prints 1000 copies of their publications because they become dated after about five years; that will probably not be an issue for this publication. Prices for the full- color guidebook are estimated to be approximately $25/copy, and sales are expected to be high (exact estimates for Capitol Reef NP were 125 copies/year). A website for the guidebook is forthcoming in October 1999.

Field Trips will be held in September 2000. Currently, four field trips are scheduled:

- Arches NP, Canyonlands NP, Dead Horse Point State Park (SP)
- Antelope Island SP and Wasatch Mountain SP
- Zion NP, Bryce Canyon NP, Snow Canyon SP and Quail Creek SP
- Dinosaur NM, Flaming Gorge NRA, and Red Fleet SP

Many other benefits are anticipated from this publication and are enumerated below:

This type of project could serve as a model for other states to follow to bolster tourism and book sales promoting their state and its geologic features.

Sandy Eldredge (UGS) will be targeting teaching communities for involvement in the field trips; hopefully teachers will pass on what they have learned to their young audience.

The language is intended to appeal to someone with a moderate background in geology and yet will be very informative to the educated geologist.

The publication may be able to serve as a textbook to colleges teaching Geology of National Parks (in Utah).

A welcomed by- product could be roadlogs between parks in Utah for those visiting multiple parks, perhaps with a regional synthesis summarizing how the overall picture of Utah geology has developed..

Natural Resources

Doug Neighbor (BRCA) is working closely with Llyn Doremus (Waterworks Consultants) on various water issues surrounding the Bryce watershed. He may also wish to consult with Dean Tucker (NPS- WRD) for additional assistance. Doug also mentioned that both the NPS- WRD and USGS- WRD are doing research in southwestern Utah for water rights.

Llyn told the group that her project involves water sampling for chemistry and streamflow measurements to model and prepare a hydrologic budget for the park. She believes general groundwater flow to be northward. Alluvial sediments supply water for the park. Also, it seems that the volcanic rocks associated with the Marysvale Complex are contributing iron to the water chemistry at various springs within the Claron Formation. The Straight Cliffs seem to act as a sink for groundwater, and structures are contributing to discharge at Mossy Cave. Infiltration, rather than run-off seem to be the general rule for the Claron; specific conductivity of 150 feet per day has been observed.

Gayle Pollock is interested in having a Paleontological Survey conducted for BRCA. Similar studies have been done at Zion, Yellowstone and Death Valley. Vince Santucci (NPS- GRD Paleontologist) needs to be contacted for his input on this matter. Gayle mentioned that Bill Cobban (USGS) also has done extensive work on the marine fauna of the region, and that currently a student from Northern Illinois University is searching for vertebrates in the area.

Similar surveys have been done for Yellowstone and Death Valley NP's and have shed valuable new information on previously unrecognized resources. These surveys involve a literature review/bibliography and recognition of type specimens, species lists, and maps (which are unpublished to protect locality information), and also make park specific recommendations for protecting and preserving the resources.

The Death Valley Survey will be available soon. The Yellowstone Survey is already available on- line at: http://www.nature.nps.gov/grd/geology/paleo/yell_survey/index.htm and is also available as a downloadable PDF at http://www.nature.nps.gov/grd/geology/paleo/yell.pdf

If a paleontological survey yields significant findings, paleontological resource management plans should be produced for Bryce Canyon involving some inventory and monitoring to identify human and natural threats to these resources. Perhaps someone on the park staff could be assigned to coordinate paleontological resource management and incorporate any findings or suggestions into the parks general management plan (GMP). It would be useful to train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands.

Collections taken from this area that now reside in outside repositories should be tracked down for inventory purposes. Fossils offer many interpretive themes and combine a geology/biology link and should be utilized as much as possible in interpretive programs.

Cumulative Geologic Mapping Efforts for Bryce Canyon National Park

UGS Perspective

Currently, the UGS is mapping in Utah at three different scales:
1:24,000 for high priority areas (i.e. National and State parks)
1:100,000 for the rest of the state
1:500,000 for a compiled state geologic map

The availability of funding for Cedar Breaks and Zion (jointly with the NPS) has made it possible for these higher priority areas to be mapped at 1:24,000 detail. The UGS plans to complete mapping for the entire state of Utah within 10- 15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from "special interest" areas (i.e. areas such as Zion and growing metropolitan St. George). Grant Willis mentioned that the UGS simply does not have enough manpower and resources to do more areas at this scale. He also reiterated that UGS mapping goals are coincident with those of the National Geologic Mapping Program.

In the Zion and Cedar Breaks areas, the UGS has been jointly cooperating with the NPS and USGS for some time on producing these 1:24,000 quadrangles in both paper and digital format. Until 1995, the USGS had done major mapping projects under the BARCO (Basin and Range to Colorado Plateau transition project) mapping program. When the USGS reorganized, many of these projects were put on indefinite hold. Fortunately, their has been mutual cooperation between the UGS and USGS to work together to get these products completed for the NPS. The NPS appreciates the labor of all involved parties and individuals in this cooperative and hopes that many products will result from the combined efforts of all involved agencies.

Because of the adequate coverage for the Bryce Canyon area, the UGS considers this a lower priority area at this time.

USGS Perspective

Pete Rowley (USGS) talked about the immense scope of the BARCO project for preparing 1:100,000 scale maps for earthquake potential, mineral resources and various other themes. Mapping was done at 1:24,000 scale and compiled at 1:100,000 scale. Unfortunately, this project was put on the back shelf because of the USGS 1995 reorganization and many of the original workers have not been able to realize final products for their previous mapping efforts.

Since the USGS now requires digital geologic maps for all of their work, Pete is working with Southern Utah University's (SUU) Dave Maxwell to complete digitizing for some of the BARCO work.

There are many 7.5- minute quadrangles in the BRCA, ZION, and CEBR areas that are in various stages of completion from USGS personnel; Pete Rowley hopes that he will be able to help tidy up some of these unfinished maps and make them ready for publication.

Current Status

Several 7.5- minute quadrangles cover Bryce Canyon NP:
Tropic Canyon
Bryce Canyon
Tropic Reservoir
Bryce Point
Cannonville
Podunk Creek
Rainbow Point (Figures 11 and 12).

These quadrangles have been compiled into the "Geologic Map of Bryce Canyon National Park and Vicinity, Southwestern Utah" by William E. Bowers, USGS Map I- 2108, 1990. This map is 1:24,000 scale, and contains an accompanying pamphlet summarizing the stratigraphy and structure of the area. It is sold in the Bryce Canyon Visitor Center for $3.95. It is not yet available in a digital format.

Bowers map was peer reviewed by Pete Rowley, who thinks it is an excellent map. Bowers has since passed on, and Rowley is attempting to locate the greenlines for digitization; he will keep the NPS posted on what he finds out.

There was general consensus that this map is adequate for digitization at the present time. In the future, with funding and manpower, the following exceptions/enhancements were proposed:

George Davis mentioned that he thought some structural enhancements could be made including more definitive information on faults and folds, and perhaps cross sections showing more detail for the Ruby's Inn and Pine Hill thrust faults.

Gayle Pollock is remapping the Tropic Canyon 7.5' quadrangle because Bowers did not differentiate the various members of the Cretaceous Straight Cliffs Formation; Gayle would like to show the main coal zones. The Straight Cliffs members do not need to be broken out in other areas of the park because not much is exposed, and what is gets covered by mass wasting. He is also putting a major emphasis on the Quaternary geology with landslides and hazards on this quadrangle.

Grant Willis would like to make sure that the Quaternary geology is represented as best as possible; Gayle and Pete Rowley thought that overall, the Quaternary was treated sufficiently by Bowers. Grant thinks the rest of the map is quite good also, and proposes a geologic hazards layer.

Gayle Pollock has a few issues with the orientation of the Paunsaugunt Fault around Little Henderson Canyon that he would like to resolve.

There was also discussion on how to include the Red Canyon corridor into the "area of interest" for Bryce Canyon NP. Red Canyon would include the north end of the Wilson Peak and the Casto Canyon quadrangles, and would be approximately six square miles. It was mentioned that maybe John Anderson has mapped here already, or George Davis may be able to get some students to map the area for inclusion in the BRCA digital map.

Gayle Pollock also thought that additional quadrangles to the north that show thrusting in the Claron Formation are of great interest to BRCA, as well as the volcanic story of the Marysvale Complex. However, these would be more likely useful for the viewshed. Pete Rowley has done extensive mapping in the northern reaches at 1:62,500 scale but has published only a few pieces. Pete Rowley also mentioned that the USGS has agreed to fund the digitization of the Kanab (to the south of Bryce Canyon; see Appendix D, UGS 1:100,000 Quadrangles for entire state of Utah) *1:100,000* quadrangle through SUU, and Pete hopes to begin overseeing this project in the very near future. Kanab greenlines are also available. The Panguitch (encompassing the Bryce Canyon area) *100,000* quadrangle is also being digitized by Florian Maldonado (USGS- Denver) in his spare time. Grant Willis is hoping Pete and Florian will be able to complete this at some point so that this area will be covered thoroughly.

Pete also mentioned that Richard Hereford (USGS) has mapped the area at *1:100,000* scale and is a Quaternary geologist, should he need consulted.

There are some issues to consider in completing digitization of these quadrangles:
Pete would need some financial assistance in digitizing these maps at SUU. Dave Maxwell is willing and able to get a GIS shop going on NPS and BARCO projects as he has sufficient equipment and personnel. With Pete's oversight and input, it is hoped that many products may result from the SUU GIS department. Dave Maxwell would also like to get with the UGS for his input on how to scope out these digital geology projects.

Pete's salary and time needs to be covered by the USGS to oversee digitization work on this project, as well as potential field mapping projects around Cedar Breaks NM.

A priority list for quadrangles of interest should be developed for SUU and estimates of costs and time to complete the work also need to be ascertained. Grant Willis suggested that a few weeks for a single quadrangle seems like a reasonable amount of time.

Other Sources of Natural Resources Data for Bryce Canyon

The UGS has a significant quadrangle database that they have furnished to NRID for the entire state of Utah.

NRID has compiled a geologic bibliography for numerous parks and monuments, including Bryce Canyon. Visit the website at: http://165.83.36.151/biblios/geobib.nsf; user id is "geobib read", password is "anybody".

Bill Bowers Geologic Map for Bryce Canyon available in the visitor center

The "Shadows of Time: The Geologic Story of Bryce Canyon National Park" by Frank DeCourten is an excellent summary for the layperson and geologist alike; it is available from the visitor center for $9.95

The USGS has compiled large volumes of data on the BARCO project that was halted in 1995; much of this work is unpublished and should be sought out from USGS personnel.

Doug Neighbor was asked if BRCA currently has their ProCite software in place that chronicle any natural resources into a bibliography. Doug says he installed it two years ago.

George Davis mentioned that in September 1999, he will have a GSA Special Paper on the "Structural Geology of the Southern Utah part of the Colorado Plateau with Special Emphasis on Deformation Bands". This will detail major geologic structures of the southern Utah parks and monuments East- West from the Henry Mountains to Zion NP, and North- South from the San Rafael Swell to the Arizona state line.

Much of the paper will be devoted to deformation band shear zones in the Entrada and Navajo sandstone, and plate tectonic descriptions for the Mesozoic and Cenozoic.

George also mentioned a paper on basement cored uplifts featuring the East Kaibab Monocline and Colorado Plateau, featuring detailed cross sections. This will be separate from the GSA Special Paper.

Llyn Doremus will be publishing a water resources report for Bryce Canyon NP sometime in the near future; Pete Rowley would like a copy of this report to review since he's been doing similar work at the Nevada test site, GRD would also like a copy.

Geologic Hazards

The main geologic hazard discussed for BRCA involves mass wasting and rock falls along the most traveled walking trail in the park: the Navajo Loop trail

Trail stabilization receives much attention because of the potential for injuries and such

Siting facilities is also a major issue because of the fractures and potential for sloughing; these areas should be monitored for growth and potential danger.

Seismic/active faults in close proximity to BRCA area

Volcanics (Marysvale volcanics)

Visitor center not setting on bedrock; it's at 28 feet so caissons needed

Highway 12 dump

Mudslides in Cretaceous units in back country causing mass wasting in Yellow Creek, but less visitation in these areas

Doug mentioned a cave that was dynamited shut in the 1970s because it had vertical openings that posed a safety hazard.

Potential Research Topics for Bryce Canyon National Park

Study the progressive evolution of hoodoos; examine morphology and internal stratigraphy and structure for interpretive value

Study the role of enlarging fractures through solution weathering and freeze- thaw cycles

Study the role of jointing versus faulting (both strike- slip and thrust faulting)

Study how different lithologies respond to weathering and erosion

Study rates of edge migration, erosion, retreat of rim, rates of downcutting of streams at the canyon bottom, aggradation of fill at bottom, slumping in the Tropic Shale (i.e. all of which are processes affecting landscape evolution)

Use diffusion modeling to help map drainage patterns (University of Arizona has Geomorphologist who does this)

Study the structural controls on the course of the Paria River that direct it towards Bryce Canyon

Study effects of fluid- rock interactions and results

What is the effect of the syncline on hoodoos

Study hoodoo fluting to see if it's vertical or affected by bedding

Determine extent of Cretaceous thrust above the amphitheater to the south

Study the Markaugunt Megabreccia near Cedar Breaks for regional implications

Determine the age and provenance of the Boat Mesa Conglomerate; is it Oligocene or Pliocene, and if the Brian Head and Boat Mesa correlate to each other.

Determine how much volcanic material was originally in the park and subsequently removed by erosion

Study the Cretaceous rocks to determine if dinosaurs are present in the backcountry; currently have student from Northern Illinois looking for remains on Markaugunt and Paunsaugunt areas

Permeability and quantity of water assessment for entire Bryce Canyon NP

Examine the potential for a K- T boundary in the Table Cliffs area and its relation to the Kaiparowits Formation

Disturbed Lands

Doug says a disturbed lands inventory was conducted at BRCA, but nothing significant was found. No coalmines are within the park boundary either because it is too difficult to extract. There are a few bentonite quarries on Highway 12 in the upper part of the Tropic Shale.

Unique Geologic Features

Natural Bridge

Boat Mesa (all conglomerate)

Sinking Ship

Inverted hoodoo (klippe); but hard to get visitors there (we visited it during field trip)

Mossy Cave (more of an overhang from discharge); could be a nice hanging garden with ice stalactites and stalagmites; only flat trail alongside a stream
Paunsaugunt fault

Sevier fault at Red Canyon

Bryce Point and Boat Mesa normal faults (on Bowers map and Shadows of Time book)

Thor's hammer from Sunset Point; has dolomite capstone

Action Items

Many follow- up items were discussed during the course of the scoping session and are reiterated by category for quick reference.

Interpretation

If desired NHA consult with GRD's Jim Wood (jim_f._wood@nps.gov), UGS Sandy Eldredge(nrugs.seldredge@state.ut.us) or Melanie Moreno at the USGS- Menlo Park, CA (mmoreno@usgs.gov) for additional assistance with various interpretation themes

Gayle Pollock supply web address for expanded web page for BRCA NHA with GeoDetective site

UGA Guidebook

Attempt to plant the seeds of this concept to other states for similar publications involving local area geology. Such publications are especially useful for the GRI

Natural Resources

Llyn Doremus supply to interested parties her report on Water Resources for BRCA; including copies to Pete Rowley and GRD.

Consult with Vince Santucci on the likelihood of a full paleontological survey for BRCA (only the marine has been studied thus far; may yield significant vertebrates)

Geologic Mapping

Attempt to locate Bill Bowers greenlines to digitize from (Pete Rowley is working on this)

USGS address issues relating to funding salaries and other work to ensure BARCO products can be published

NPS and USGS develop for SUU a priority list of quadrangles to digitize from existing Bowers 1990 map, as well as associated estimates of time and material costs.

Miscellaneous

Review proposed research topics for future studies within Bryce Canyon NP

NPS GRD folks make contact with USGS GIS person Jeremy Workman to develop relationship with NPS GIS projects

Have conference call with Gregson, Heise, Connors, Rowley and Maxwell to discuss potential future projects, including possible digitization of the BRCA maps of Bill Bowers (1990)

Doug Neighbor needs an upgrade from his existing version of ArcView

List of Scoping Meeting attendees with contact information

NAME	AFFILIATION	PHONE	E- MAIL
Bruce Heise	NPS, Geologic Resources Division	(303) 969- 2017	Bruce_Heise@nps.gov
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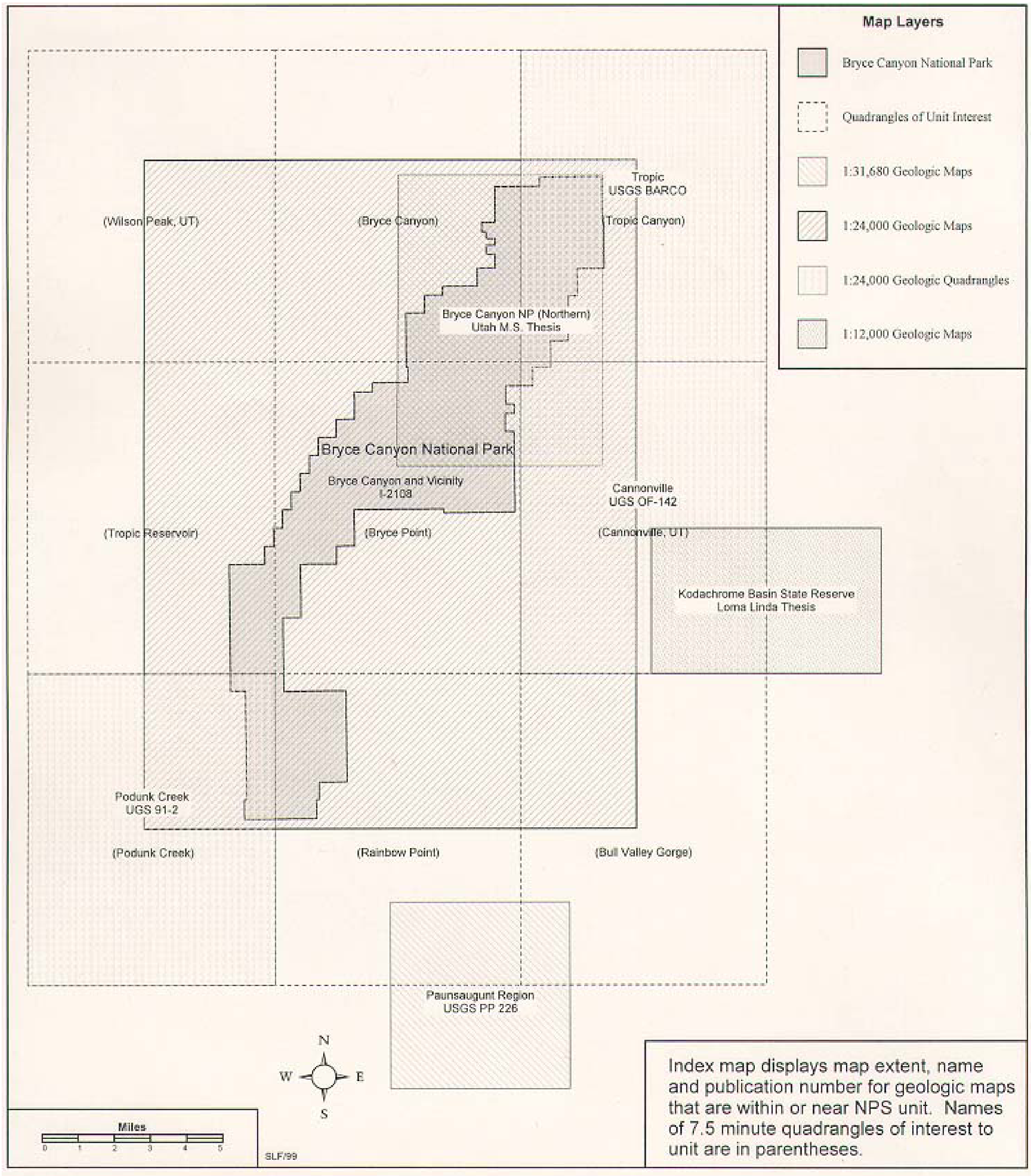

Figure 11: Geologic map coverage of Bryce Canyon National Park at 1:31,680 scale and larger. From GRE Scoping Report

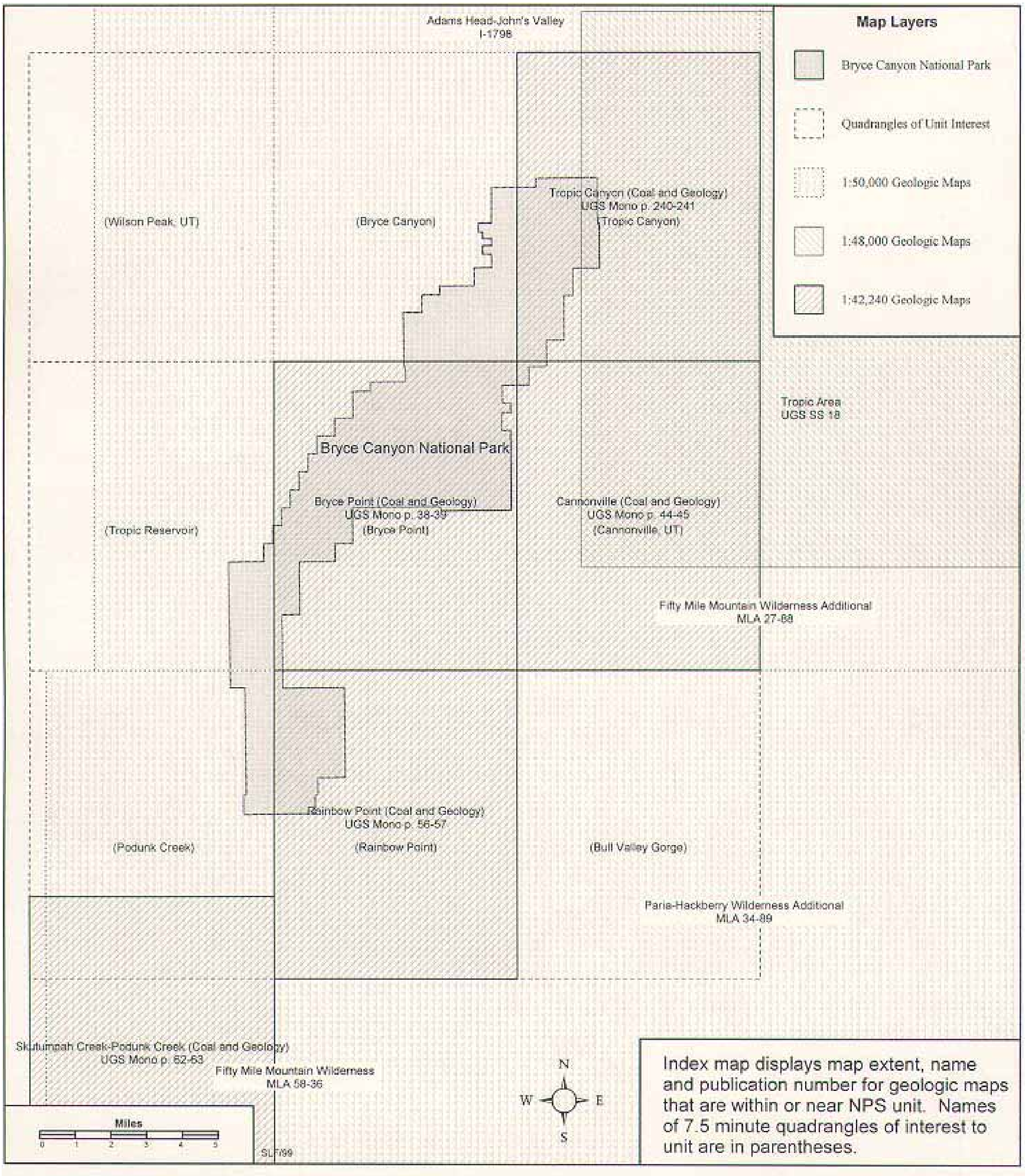

Figure 12: Geologic map coverage of Bryce Canyon National Park at 1:42,240 and larger scale. From GRE Scoping Report

Bryce Canyon National Park
Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/002
NPS D-219, September 2005

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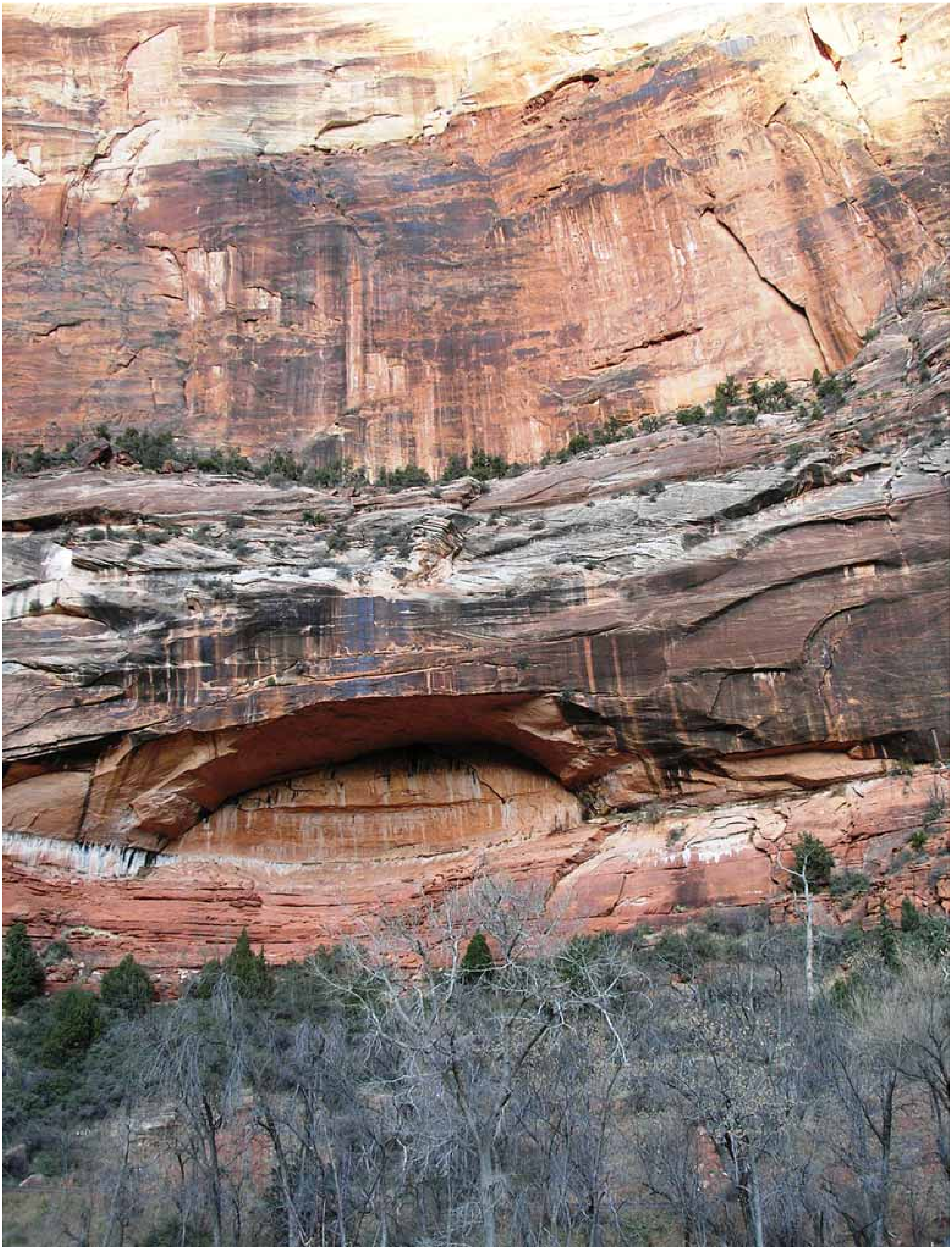
Zion National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/014



Zion National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/014

Geologic Resources Division
Natural Resource Program Center
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Denver, Colorado 80225

March 2006

U.S. Department of the Interior
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Table of Contents

List of Figures iv

List of Tables iv

Executive Summary 1

Introduction 2
Purpose of the Geologic Resource Evaluation Program 2
General Information and Regional Setting 2
Park History 2
General Geology 3

Geologic Issues 9
Landslides and Debris Flows 9
Earthquakes 9
Volcanism 10
Soil 10
Impacts of Mineral Extraction 10
Quaternary Studies 10
Structural Geology Projects 11
Hydrogeology 12
Hydrogeology Projects 12
Paleontology and Palynology 12
Diagenesis 13
Identification of Type Sections 13

Geologic Features and Processes 17

Map Unit Properties 21
Map Unit Properties Table 23

Geologic History 27
Tectonic History 27
Depositional History 28

References 36

Appendix A: Geologic Map Graphic 39

Appendix B: Scoping Summary 41

Attachment 1: Geologic Resource Evaluation Products CD

List of Figures

Figure 1. Location map of Zion National Park 4
Figure 2. Location of Zion National Park on the Colorado Plateau 5
Figure 3. Geologic cross-section of the Grand Staircase 6
Figure 4. Sketch map showing major plateaus, terraces, cliff lines, and faults 7
Figure 5. Stratigraphic column for Zion National Park. 8
Figure 6. The distribution of young basalts in southern Nevada and southern Utah 14
Figure 7. Locations of selected geologic sites in Zion 20
Figure 8. Geologic time scale 33
Figure 9. Depositional environments represented by the strata in Zion National Park. 34
Figure 10. Location of the Cretaceous Period, Western Interior Seaway. 35

List of Tables

Table 1. Quaternary research projects identified in the 1999 Workshop. 15
Table 2. Potential research projects identified in the 1999 Workshop at Zion. 16

Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Zion National Park. It contains information relevant to resource management and scientific research.

The spectacular cliffs, arches, spires, temples, and colorful strata of Zion National Park record changing environmental conditions through 275 million years of geologic time. Zion lies in a transition zone where the High Plateau region of the Colorado Plateau meets the Basin and Range geological province. A visitor to Zion enters a landscape in which the rock layers have been arched upward, tilted, and eroded into plateaus and terraces that form a giant staircase stepping up from the Grand Canyon to the south northward to Bryce Canyon National Park. Under foot, the strata record episodes of both horizontal compression caused by colliding lithospheric plates and extensional tectonics generated as the lithospheric plates pulled away from one another.

The heterogeneous strata of primarily Mesozoic and Cenozoic rocks in the park present potential geologic hazards that fall into five general categories:

- Landslide and debris flows
- Earthquakes
- Volcanism
- Soil instability
- Impacts of mineral extraction

Landslides and debris flows occur in both consolidated and unconsolidated material. Landslides pose a potential hazard especially during and after rainstorms. Erosion and construction projects that oversteepen slopes or undercut cliffs also promote potential landslides.

The potential for damage caused by earthquakes and volcanism is not well defined for Zion. The Hurricane Fault remains active with long- term slip rates of 0.21 to 0.57 mm/year and is capable of producing earthquakes of magnitude 6- 7. Many relatively small episodes of volcanism have occurred in southwestern Utah in recent geologic times. Although there are no indications of imminent eruptions, it is possible that the Zion area will experience some level of volcanic activity in the future.

Soils composed of expandable clays present potential construction and maintenance issues for Zion. Areas containing these types of soils need to be identified. Radon in the soils is another potential problem. A naturally occurring radioactive gas, radon has been identified in soils developed on the Chinle Formation.

An abandoned uranium mine and three abandoned oil wells within park boundaries may pose issues in the future. Both types of operations may impact groundwater and surface water. Tailing piles also present a possible air quality issue.

Based on these issues and specific properties attributed to the geologic formations found in Zion, a list of potential research projects was generated during a Geologic Resource Inventory Workshop held at Zion in 1999. Project topics fell into the following general list:

- Quaternary studies
- Structural geology projects
- Hydrogeology projects
- Palynology
- Diagenesis
- Identification of type sections

These research projects focus on the properties tied to individual formations and the relationship between strata. Erosion potential is high in Quaternary sediments, for example, and also in sandstone units with high porosity and permeability. The Navajo Sandstone and some alluvium act as aquifers, which need to be monitored and studied for water yields, water quality, and potential contamination. Other units, especially in the Kaibab Limestone, are prone to karst development as calcium carbonate dissolves in meteoric groundwater percolating downward through porous formations or along vertical fractures in the rock. There may be an opportunity to locate and preserve a type locality for the Navajo Sandstone. Fossils and archeological artifacts may be associated with features common to certain geological units.

Zion has many geologic features that formed in response to geologic processes that continue to modify the current landscape. Geologic processes that form canyons also promote landslides and illustrate the complex relationship among strata, fractures, and climate. Weathering processes have produced distinctive patterns in cross- bedded sandstone. Hanging valleys and alcoves color the sandstone cliffs. Narrow slot canyons have been cut into bedrock. Dinosaur tracks are preserved in sandstone. The Kolob arch, the world's longest natural arch, spans a distance of 94.5 m (310 ft). All the monoliths, canyon walls, and other geologic resources combine to provide a visitor to Zion with an exceptional experience.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation Program.

Purpose of the Geologic Resource Evaluation Program

Geologic resources serve as the foundation of park ecosystems and yield important information for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resources Division. The goal of the GRE Program is to provide each of the identified 274 "natural area" parks with a digital geologic map, a geologic evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and each is designed to be user friendly to non- geoscientists.

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the geologic issues in the park. Park staff are afforded the opportunity to meet with the experts on the geology of their park. Scoping meetings are usually held in each park individually to expedite the process although some scoping meetings are multipark meetings for an entire Vital Signs Monitoring Network.

General Information and Regional Setting

Protected within the 593 square kilometers (229 square miles) of Zion National Park, the Kolob Arch is the world's largest arch with a span measuring 94.5 m (310 ft), a window height of 101 m (330 ft), and a thickness of 24 m (80 ft) (Biek et al. 2000). In other monuments and parks, this arch would be the centerpiece of a visitor's experience, but Zion is probably best known for Zion Canyon. This narrow chasm with sheer walls of Navajo Sandstone towering 610 m (2,000 ft) above the canyon floor contains blind arches, alcoves, hanging valleys, waterfalls, and colorful surficial stains (desert varnish). Incised into Zion Canyon, the Virgin River is one of the last, mostly free- flowing river systems on the Colorado Plateau. About 2,130 m (7,000 ft) of sedimentary rock records approximately 275 million years of changing environmental conditions in Zion.

Zion National Park is located in the semi- arid desert of southwestern Utah. Interstate 15 passes west of Zion and connects with Utah 9 leading to the park (figure 1). U.S. 89 passes east of the park and connects with Utah 9 to the park.

The lowest elevation in the park is 1,128 m (3,700 ft) above sea level at Coalpits Wash in the southwestern corner of the park while the highest is 2,660 m (8,727 ft) above sea level at Horse Ranch Mountain in the Kolob Canyons section.

Park History

The rugged, dissected topography of the Zion region presented a formidable impediment to early visitors to the region. During the Formative period (A.D. 500-1300), two distinctive horticultural groups, the Virgin branch of the Ancestral Puebloan (formerly Virgin Anasazi) and the Parowan Fremont, settled in the area of Zion National Park. Datable artifacts suggest that Ancestral Puebloan people occupied the southern part of the present park about 750 A.D. while the Parowan Fremont people settled the valleys and plateaus north and west of the park (Eardley and Schaack 1994; Kiver and Harris 1999). The difference between the Ancestral Puebloans and the Fremont cultures can be attributed to geography of their settlements (Dave Sharrow, National Park Service – Zion National Park, personal communication). Both cultures settled around water courses where they occurred, both also left artifacts in upland settings. When the Little Ice Age changed climate patterns about 1200 A.D., crops failed and this area and other drier sites on the Colorado Plateau were abandoned.

The historic period began in the eighteenth century when initial explorations by traders from New Mexico blazed the Old Spanish Trail. During the nineteenth century, the temples and canyons became familiar to the Paiutes who settled this unoccupied land. They compared the canyon of the Virgin River and its tributaries in the Zion area to a "loogoon," or quiver of arrows in which one comes out the way it goes in (Kiver and Harris 1999).

Once the Mormon settlement of the Great Salt Lake area was established in 1847, Brigham Young sent scouts and settlers into the area to seek out arable land and potable water. Small communities sprang up along the Virgin River during the 1860s following Nephi Johnson's exploration of the Great White throne in 1858. Issac Behunin built the first log cabin in Zion Canyon on the fine- grained lake sediments near today's Zion Lodge. Amidst the grandeur and beauty of the spectacular white and pink monoliths and canyon walls, Behunin and the few other Mormon settlers felt as if they were surrounded by a great cathedral or heavenly place. Behunin called the place Little Zion.

Two scientific surveys, the Wheeler Survey and the Powell Survey, were the first professional surveys to investigate the region in the nineteenth century. The Wheeler Survey (1869- 1871) focused on generating a master topographic atlas of the west rather than studying geology. No geologists were involved in the Wheeler survey until the third field season in 1871 when Grove Karl Gilbert joined (Gregory 1950; Stegner 1954).

When Gilbert joined the Powell survey in 1874, he was allowed great freedom to study the geology of the west. Consequently, Gilbert's systematic observations and documentation of the geology of the High Plateau country remain relevant today.

Clarence Edward Dutton, another geologist who joined Powell's survey in 1875, studied the structure and igneous history of the High Plateaus (Gregory 1950). With geologists like Gilbert, Dutton, William H. Holmes, and Charles D. Walcott, the Powell Survey set an elevated standard for the study of geology in America. New geological principals were established, old ones were revised, and illustrations defined processes, structure, and topographic forms of the High Plateaus and Canyon Country of Utah.

Major John Wesley Powell visited the southern Utah region and used the Native American name Mukuntuweep, which means "straight canyon", to describe the spectacular canyon along the upper Virgin River (Kiver and Harris 1999). Photographs and drawings from Powell's expedition ignited the public's interest in these magnificent canyons, rounded domes, arches, and monoliths and spurred the eventual protection of the area in 1909 when the region became Mukuntuweap National Monument.

The name "Mukuntuweap" was not popular with the non- Native American locals, who, like Behunin, considered the grandeur and beauty of the spectacular white and pink monoliths and canyon walls to be reminiscent of a great cathedral or heavenly place. The name was subsequently changed to Zion National Park in 1919. The Kolob section was added in 1937, bringing the park to near its present size.

General Geology

Zion is located at the western margin of the Colorado Plateau, a physiographic province characterized by high plateaus and broad, rounded uplands separated by vast rangelands covering parts of Colorado, Utah, Arizona, and New Mexico (figure 2). The Colorado Plateau is distinctive in that the sedimentary rocks forming the plateau, while having been folded and faulted in places, remain much more intact than in surrounding areas. Also, the Colorado Plateau province contains the highest concentration of parklands in North America. The cliffs and rock temples of Zion are part of the High Plateau section of the Colorado Plateau and it is located near the transition zone between the Colorado Plateau and Basin and Range physiographic provinces.

The rocks of the Colorado Plateau have been arched upward, tilted, and eroded into a feature called the Grand Staircase (figure 3). The first step, in the Grand Canyon, is composed of Precambrian- age rocks, the oldest rocks exposed on the Colorado Plateau. Paleozoic rocks in the Grand Canyon step up to Triassic- age rocks of the Chocolate Cliffs (Moenkopi Formation and Shinarump Conglomerate) and Vermillion Cliffs (Chinle Formation and Wingate Sandstone or locally the lower Navajo Sandstone), then up to the Jurassic- age White Cliffs (upper Navajo Sandstone) at Zion (Kiver and Harris 1999). The Pink Cliffs of Bryce Canyon National Park top the giant staircase with Cenozoic layers of rock (figure 3). The lowest (oldest) rock layer found at Bryce is the top (youngest) layer at Zion, and the lowest (oldest) step at Zion is the top (youngest) layer at the Grand Canyon.

Two platforms, each thousands of square miles in area, dominate the topography in the Zion region (figure 4). The lower platform to the south consists of the Uinkaret and Kanab Plateaus. These plateaus border the Colorado River in Arizona forming the rims of Grand Canyon (Gregory 1950).

Between these large plateaus the Vermillion Cliffs of Navajo Sandstone and Kayenta Formation form a major step. Zion Canyon is cut into the face of this step and the Kolob Terrace sits on top of it (figure 4). The Kolob Terrace is relatively well watered by springs and streams and more accessible than the highest plateaus, making it a desirable summer range for sheep and cattle.

Zion is primarily a Mesozoic park (figure 5). The arid climate and sparse vegetation allow exposure of vast expanses of colorful sedimentary strata ranging in age from the Early Permian Toroweap Formation to the newly recognized late Cretaceous strata. The most abundant rock is sandstone. The cliffs, benches, terraces, and shelves on slopes are composed of massive sandstone. Except for the coarser grained conglomeratic sandstone in the Shinarump Formation of Triassic age and the Cretaceous Dakota Formation, sandstones in Zion are generally fine or medium grained (Gregory 1950). Beds roughly classified as "shale" are, in fact, relatively thin beds of very fine grained sandstone rather than true clay shale. Likewise, the rocks classified as "limestone" could be as easily classified as "calcareous sandstone."

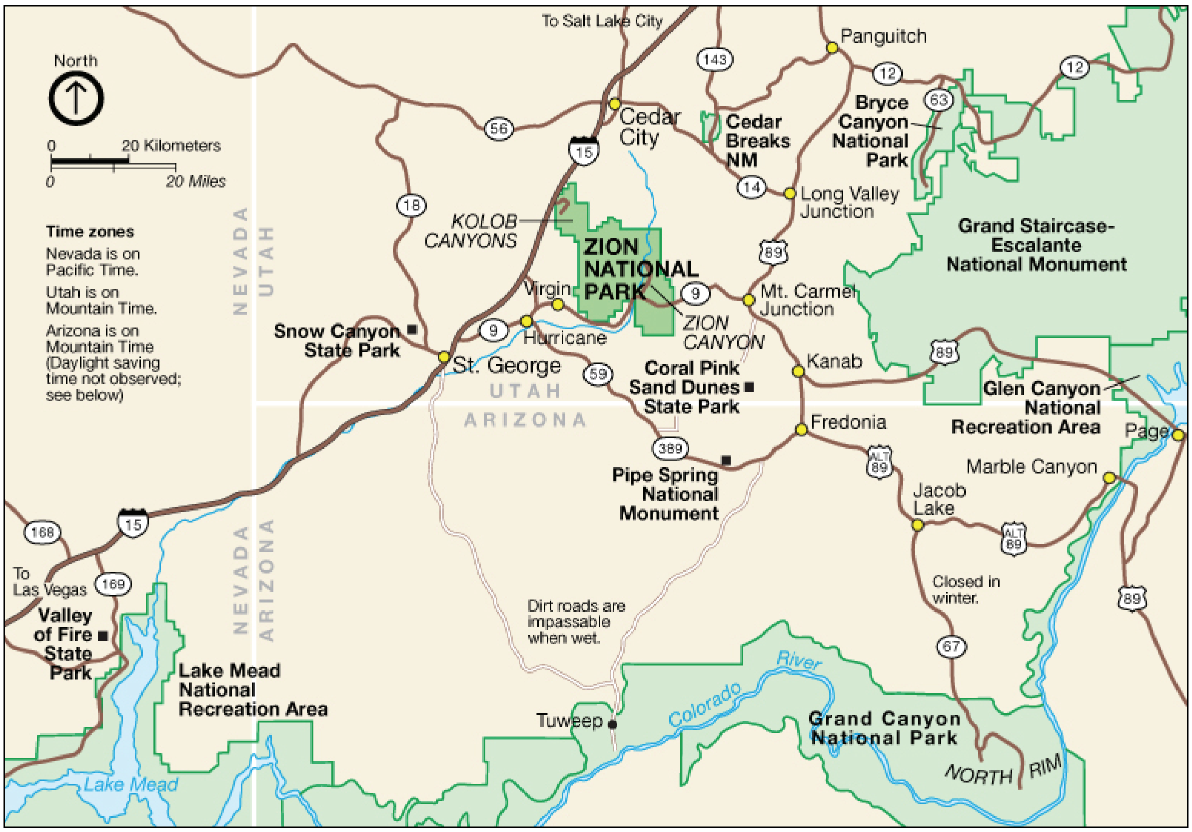


Figure 1. Location map of Zion National Park.

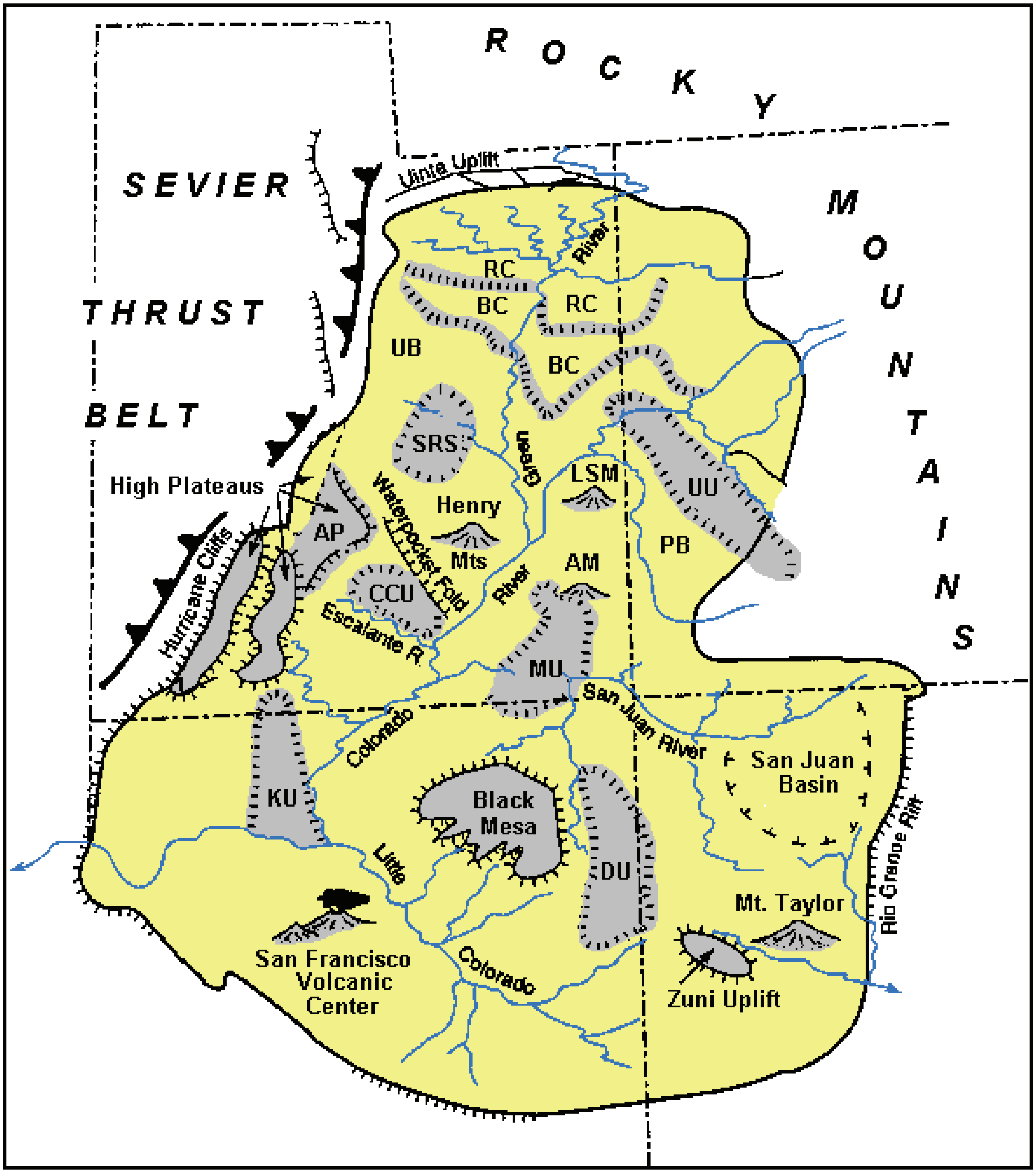


Figure 2. Location of Zion National Park on the Colorado Plateau, showing some of the significant uplifts, basins, faults, volcanic centers, and rivers. High areas are shown in gray: AM, Abajo Mts.; AP, Aquarius Plateau; BC, Book Cliffs; CCU, Circle Cliffs Uplift; DU, Defiance Uplift; KU, Kaibab Uplift; LSM, La Sal Mts.; MU, Monument Upwarp; RC, Roan Cliffs; SRS, San Rafael Swell; UU, Uncompahgre Uplift. Basins: PB, Paradox Basin; UB, Uinta Basin. Leading edge of Sevier Thrust Belt is shown with sawteeth on upper, overriding thrust plate. Modified from Kiver and Harris, 1999.

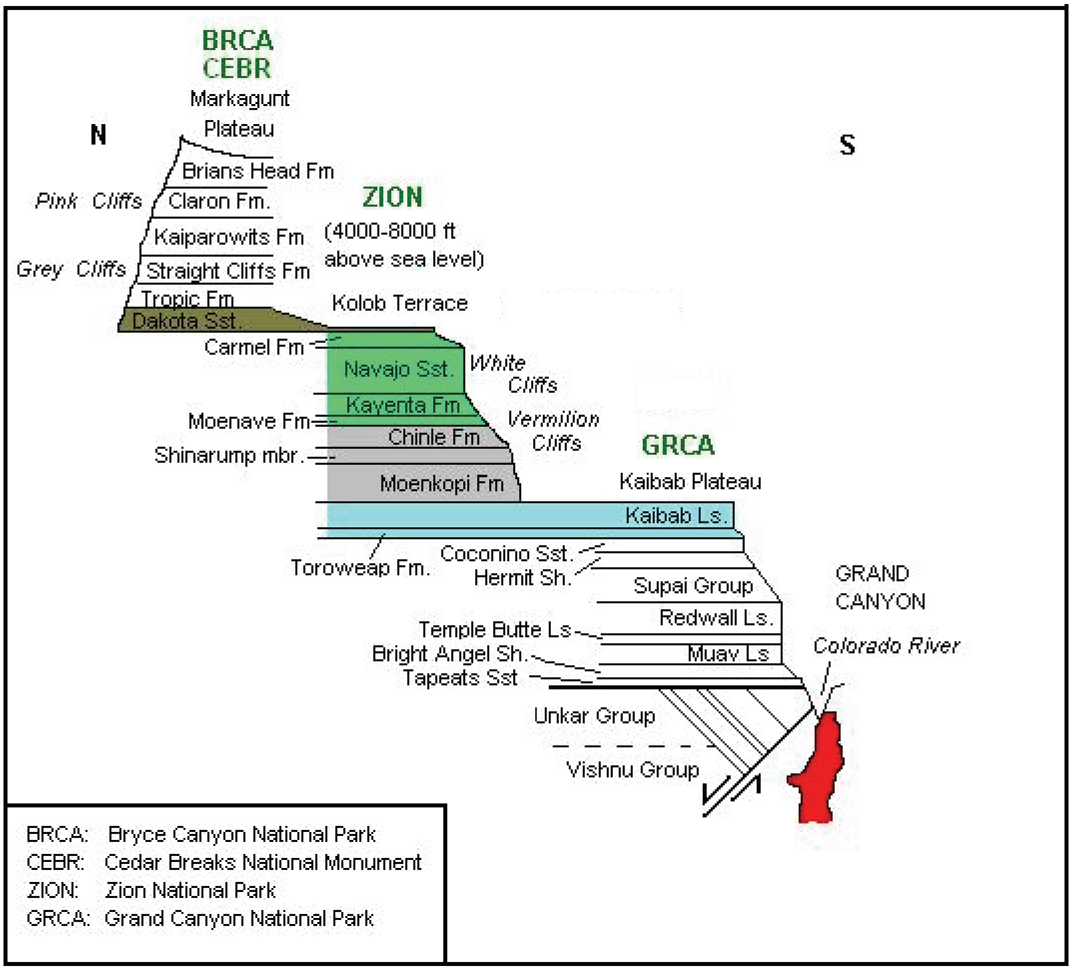


Figure 3. Geologic cross-section of the Grand Staircase from the Grand Canyon to Bryce Canyon National Park and Cedar Breaks National Monument. Diagram illustrates the lithologic correlation from south to north. Modified from the geologic cross section published by the Zion Natural History Association, 1975.

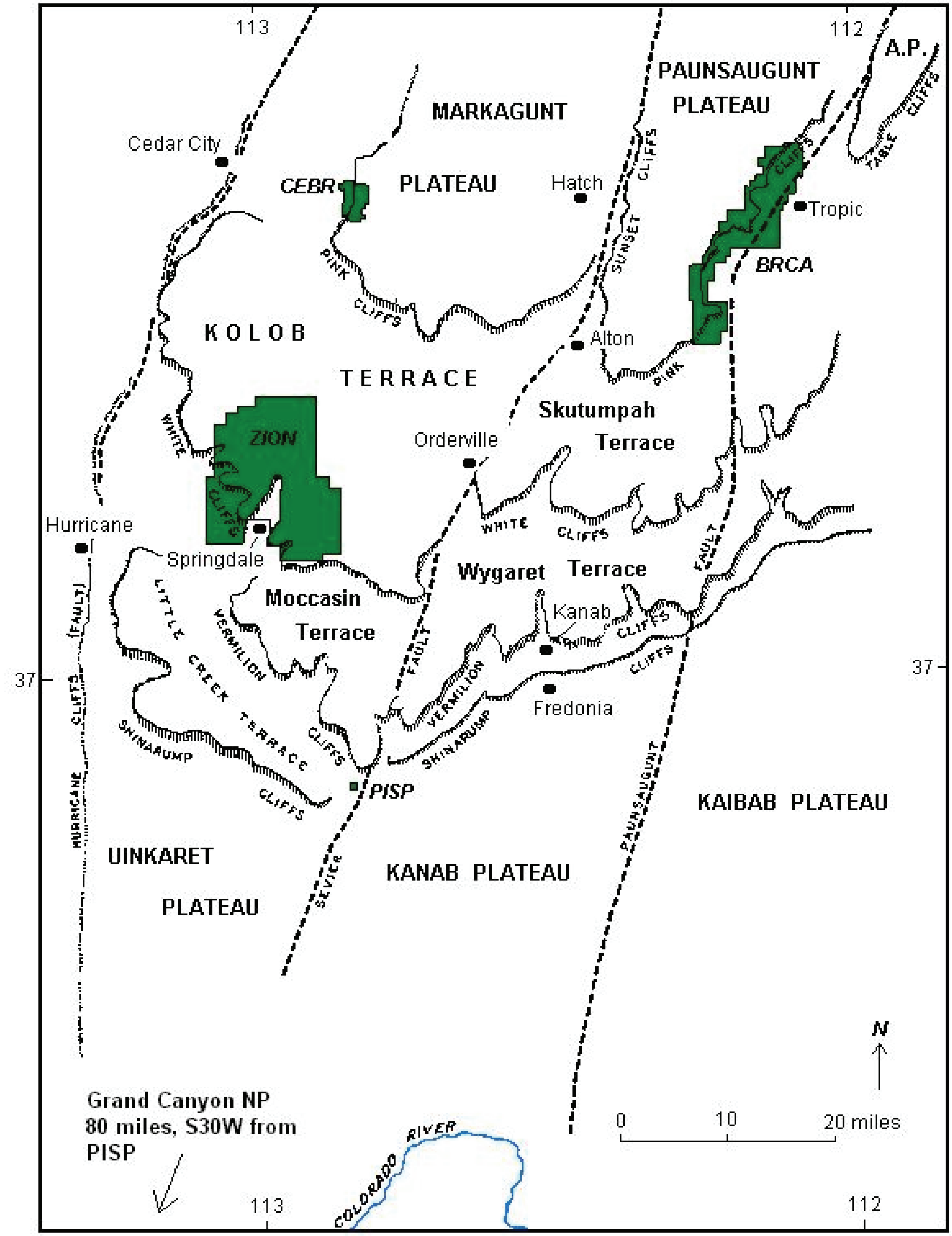
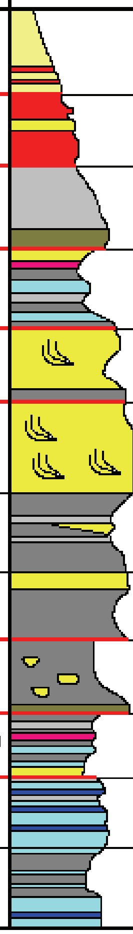


Figure 4. Sketch map modified from Gregory (1950) showing the location of Zion NP and the position of the major plateaus, terraces, cliff lines, and faults in the Zion region. ZION: Zion National Park; BRCA: Bryce Canyon National Park; CEBR: Cedar Breaks National Monument; PISP: Pipe Spring National Monument.

AGE (millions of years)	FORMATION (thickness in feet)	SYMBOL	LITHOLOGY
QUATERNARY (0-1.8)	100 units on map	Q	Unconsolidated material & volcanic rocks
TERTIARY (1.8-65)	3 map units	T	Igneous & sedimentary rocks
CRETACEOUS (65-144)	Dakota? (100)	Kdm	Sandstone, tan, fine-grained, fossil plants and pelecypods.
JURASSIC (144-206)	Carmel (850)	Jc	Limestone, tan & gray; sandstone & siltstone, banded pink & gray; gypsum; sandstone, fine-grained
	Temple Cap (0-260)	Jt	Sandstone, gray & tan, crossbedded
	Navajo Sst. (2000 max.)	Jn	Sandstone, white, gray, yellow, tan, pink, medium to fine-grained, crossbedded
	Kayenta (600)	Jk	Mudstone, reddish brown, siltstone, & sandstone. Dinosaur trackways common.
	Moenave (490)	Jm	Sandstone, mauve, overlying reddish-brown siltstone & mudstone
TRIASSIC (206-248)	Chinle (400)	TRc	Shale, mauve, gray, white, weathered to clay where exposed, with sandstone and limestone lenses.
	Moenkopi (1800)	TRm	Siltstone & mudstone, red & red-brown, w/ many gray gypsiferous shale beds
PERMIAN (248-290)	Kaibab (incomplete)	Pk	Limestone, yellowish gray, massive w/ chert & marine fossils.
	Toroweap (350-400)	Pt	Limestone, cherty limestone, & gypsiferous siltstone



Key

Figure 5. Stratigraphic column for Zion National Park.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Zion National Park April 12- 13, 1999, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Details correlating geologic units to specific park concerns were not defined in the summary report documenting the 1999 workshop. However, significant geologic hazards in Zion were identified. The issues identified at the workshop fall into the following categories:

- Landslide and debris flow issues
- Earthquake issues
- Volcanism
- Soils
- Impacts of mineral extraction

Landslides and Debris Flows

Landslides and rockfalls are common occurrences in Zion Canyon and the rest of the park. A "landslide" is a general term for any mass movement of material, consolidated or unconsolidated. Landslides are prevalent in Zion because the rapid cutting of a deep canyon exposes large cliff faces and slopes to the force of gravity, and many overlying beds rest on strata that are notoriously weak. Landslides and rockfalls are particularly prone to occur during and after rainstorms, or in particularly wet seasons.

The Navajo Sandstone is a relatively friable sandstone containing abundant joints and therefore, has a high erosion potential along fractures and joints. Many of the sandstones in Zion are underlain by shale or siltstone and are prone to undercutting which may lead to landslides and rockfalls.

The North Fork of the Virgin River continues to erode and oversteepen the 180 m (600 ft) high face of Sand Bench. This process has caused periodic reactivation of older landslide material at Sand Bench in the stretch of Zion Canyon located beneath The Sentinel (Biek et al. 2000). Major landslides were documented in 1923, 1941, and 1995.

The most recent significant landslide in Zion occurred on April 12, 1995. At about 9:00 pm, the lower face of Sand Bench gave way and a landslide dammed the North Fork of the Virgin River. The landslide mass was about 150 m (500 ft) long and 45 m (150 ft) wide and transported about 84,000 cubic meters (110,000 yd^3) of material. A 6- m (20- ft) deep pond formed that eventually overtopped the landslide dam. Although no flooding occurred downstream, the river eroded a 180 - m (600 - ft) section of the east bank, washing out Zion Canyon Scenic Drive (Biek et al. 2000). Two days later, a temporary access road was opened on the east side of the river for the more than 300 people stranded at Zion Lodge. Excessive precipitation in the preceding months has been blamed for the landslide by elevating pore pressures and reducing cohesion within the landslide mass. The winters of 1995, 1941, and 1923 that preceded major slides were all exceptionally wet.

Several landslide deposits are mapped in and around the community of Springdale. These deposits can be recognized by tipped and broken strata and irregular hummocky terrain. These slides have all occurred where overlying strata slid on the weaker, more plastic Petrified Forest member of the Chinle Formation. One of the largest recent slides is located just outside the entrance of Zion National Park, and was triggered by a December 2, 1992 magnitude 5.8 earthquake centered on the Washington Fault, about 48 km (30 mi) southwest. Three houses recently built on these slopes were destroyed when the slope dropped 30 m (98 ft) and extended laterally a similar distance over a period of several hours.

Landslide deposits (Ql) are identified on the geologic map (Appendix A and Attachment 1). These areas should be monitored for movement. In addition, old landslides should be studied in detail to determine the size of material moved, the cause of movement, the porosity and permeability of the medium involved in the movement, and the degree of saturation prior to movement. The degree of slope and the potential and real downhill impacts from mass movements should also be documented and inventoried.

Construction or maintenance could potentially cause mass movements, therefore roads and other facilities should be constructed over landslide deposits with the greatest caution.

Earthquakes

A 1992 earthquake scarp in Springdale can be seen at the west entrance of the park. Significant Quaternary offset suggests that the Hurricane fault zone remains an active, north- trending, west- dipping normal fault in the Kolob Canyons area (Biek et al. 2000). The fault zone stretches for at least 250 km (155 mi) from south of the Grand Canyon northward to Cedar City. The fault has been divided into two segments near Zion, the Ash Creek segment and the Anderson Junction segment. Two short lengths of the Ash Creek segment are in Zion. These segments are visible at the mouths of Taylor Creek and

Camp Creek. At both of these localities, the fault is defined by the juxtaposition of Permian Harrisburg and Triassic lower Moenkopi strata on the upthrown block against basin- fill, unconsolidated sediments on the downthrown block. Fault drag has folded the strata on the upper block. At St. George, the tectonic displacement along the fault is about 1,098 m (3,600 ft), and near the latitude of Toquerville, the displacement is about 1,494 m (4,900 ft) (Biek et al. 2000). Near the Kolob Canyons area, the average slip rate for part of the Ash Creek segment is about 0.39 meters/1,000 years (15 in/1,000 yr). The Hurricane Fault marks the western boundary of the Kolob Canyon section.

The Hurricane Fault may be the only active fault in the park. Movement along other faults in the park could be measured by a seismic monitoring system. Possible sources for earthquakes such as groundwater withdrawal, artificial recharge, oil extraction, or tectonic plate movements could be identified and monitored. If the fault trace indicates the direction of movement, the type of fault could be determined.

Volcanism

Though volcanism is not widespread in the area, numerous smaller lava flows have occurred in the vicinity in the recent geologic past. Thirteen lava flows are mapped in and near Zion dating from 1.5 million to 100,000 years ago. More recent flows of less than 10,000 years in age occurred north of Zion and east of Cedar Breaks National Monument. Thus the occurrence of sporadic volcanism can be said to be continuing in the area, but on a human time scale it is more important as a part of the geologic story of Zion than an actual threat. Figure 6 shows the larger patterns of volcanism over the last 15 million years.

Soils

The Triassic Chinle Formation contains the expandable clay, bentonite, formed from volcanic ash. Bentonite has the unique property of incorporating water molecules into its chemical structure and expanding. Upon drying, the structure collapses causing the clay to shrink. This shrink and swell property can have an undesirable effect on roads, buildings, and infrastructure resulting in maintenance and construction problems due to unstable soils.

Soils derived from Chinle Formation should be located and analyzed for their bentonite content, the slope upon which they rest, and their water- holding capacity. If possible, areas containing these soils should be avoided when planning future development. Bentonite soils have also been found on terraces soils derived from sheet flow off of the Moenave Formation.

Radon is present in soils developed upon the Chinle Formation. Radon is a naturally occurring radioactive gas (the only radioactive gas) produced by the radioactive decay of Uranium (U) and Thorium (Th). Radon is colorless, odorless, and tasteless and usually associated with high concentrations of U. High levels of U may be found in granitic rocks, stream sediments, groundwater, or surface waters. Weathering and re- sedimentation may also concentrate U. Faults and shear zones are more permeable and therefore may be enriched with U and consequently elevated levels of radon gas may be present in the overlying soils.

The movement of radon through rocks and soil depends upon the pore space and permeability of the medium through which the gas flows. Radon is moderately soluble in water and can be transported over considerable distances. Fluid transport is especially rapid in limestone and along faults. Radon may enter a building from the ground or via the water supply, especially if the building is supplied by a well.

Park staff may wish to inventory and monitor the amount of radon associated with faults, soils, and rocks in the park. The radon potential of an area can be estimated by soil gas surveys. A soil gas survey should be conducted in stable weather conditions because weather conditions as well as soil permeability affect radon detection levels. Both must be taken into account during a soil gas survey. The data from soil gas surveys can be used to produce maps that show levels of radon in the soil. Different methods may be used to measure and monitor the level of radon in soils. An active monitoring method is a hollow spike hammered into the ground and linked to a gas pump and detection unit. A passive method would be to bury radon detectors in the soil for later recovery.

Impacts of Mineral Extraction

Federal mineral leasing is prohibited within the boundaries of Zion National Park as is the location of new mining claims. Approximately 3,500 acres in the park are non- federally owned and could potentially be the subject of proposals to develop private mineral rights. If that occurred, the NPS would regulate that activity. However, no mineral production on this acreage is taking place at this time. In addition, park resources and visitor values could be adversely affected by mineral development adjacent to the boundary of the park.

Interest in exploiting mineral resources in southwest Utah has been active since 1851 when large deposits of iron and coal were found near Cedar City (Gregory 1950). Most of the prospect holes and milling tests, however, have not been encouraging to commercial mining operations. Widely scattered, small, impure deposits of copper have been discovered in the Kaibab Limestone and the Navajo Sandstone. Lead, zinc, silver, gold, manganese, and uranium are all found in the Chinle Formation. Building stone is also available as a potential resource.

An abandoned uranium mine is located on private lands approximately 100 feet outside the park boundary near the Kolob Canyon Visitor Center. An evaluation of the site was made by a NPS- GRD geologist in 1991 (Burghardt 1991). Potentially hazardous mine openings exist at the site, but since these are located on patented mining claims it is the responsibility of the claimant and the State of Utah to mitigate these hazards. Nevertheless, park staff should be aware of these hazards and discourage entry.

Coal was found by Mormon pioneers in Coal Creek Canyon and on Cedar Mountain north of Zion. In the Zion region, coal is found in Cretaceous formations. Deposits that are thick enough to mine are found in the Tropic Formation, a Cretaceous formation that is not exposed in the park, but is exposed on the slopes of the watershed above the park. Despite protection from development in Zion, coal mining operations in southwest Utah may impact the viewshed of the park and thus, the visitor's experience. Acidic precipitation, over time, would also impact the geological features of the landscape.

Sand and gravel in various amounts are available in alluvial deposits in and near Zion. Although sand and gravel extraction is prohibited in the park, mining operations would target the more abundant deposits outside the park. Park staff should have a map of these deposits if one is not already available.

Pioneer settlers and Paiute Indians knew about the oil seeps in Oil Seeps Wash, on North Creek and in cavities filled with "oily tar" in rocks in the La Verkin, Virgin, and Short Creek Valleys (Gregory 1950). Oil exploration began in 1907 and resulted in the Virgin Oil field located approximately 3 miles west of Zion National Park. The Virgin Oil Field is Utah's oldest oil field, but was never a big producer. It was abandoned in the late 1960's after producing over 200,000 barrels of oil. Oil came from thin beds of sandy limestone in the Timpoweap member of the Moenkopi Formation, which occurs at depths less than 600 feet in the field. Lack of trapping mechanisms and indications of oil degradation from exposure to oxygenated ground water, bacteria, and other nutrients limit future potential for the Timpoweap in the area of Virgin. However, the deepest well drilled in the Virgin Field, the Bardwell No. 1 Venton, bottomed out at 4,538 feet in the Mississippian and had several good shows in the base of the Permian at 3,410 to 3,490 feet."

Though the area around Zion contains all the elements necessary for oil and gas accumulations (source rocks, reservoirs, and trapping mechanisms), past exploration results have been poor. However, advances in exploration technology supported by higher product prices and demand could renew interest in the area. Since much of southwest Utah consist of federal lands, the Bureau of Land Management would be a good source of information on the industry's level of interest at any given time.

In 2001 the Bureau of Land Management proposed the issuance of oil and gas leases for the exploration and production of coalbed methane north of the park in the Virgin River Watershed near the headwaters of the North Fork of the Virgin River and its major tributary Deep Creek. At the request of the NPS, the BLM withdrew the leases from sale at that time. In 2005, BLM consulted with Zion NP on the sale of additional leases located immediately north of the park boundary, just east of Interstate 15. Due to NPS concerns over viewshed and steep slope issues, BLM also removed these leases from the sale. Limited oil and gas leasing has taken place in the Virgin River watershed further to the north and east of Zion. However, exploration in these sites has not resulted in the production of oil and gas (Dave Sharrow, Zion National Park, personal communication 2005).

Three abandoned oil wells exist within the park. If wells are not plugged properly, there may be a conduit for well fluids (oil, brine, etc.) to mix with groundwater and present a water quality problem. Consequently, the park may benefit from knowing:

- the depths wells were drilled and oil zones encountered,
- the drilling, production, and plugging history of the specific wells and the operations (i.e., depth of casing and cementing record) if available, or general practices of the time if specific well records do not provide the details,
- groundwater flow and depth in the area, and
- proximity and water quality of existing water wells.

Other issues and potential research projects include:

- Quaternary studies
- Structural geology projects
- Hydrogeology
- Paleontology and Palynology
- Diagenesis
- Identification of type sections

Quaternary Studies

Quaternary research projects fall into four general topics: lake studies, fluvial and alluvial projects, landslides, and ecosystem management. The 1999 workshop list of research projects involving these Quaternary projects is summarized in table 1 (a subset of table 2).

Structural Geology Projects

Two projects associated with structural geology were identified in 1999:

- determining the history of the Hurricane fault as related to Basin and Range extension
- developing a history of joint formation

Both of these projects would help project future landslides and cliff collapse as well as slippage along the active Hurricane fault zone. Because oil exploration may also impact the park (either directly or indirectly by impacting the viewscape), studies pertaining to structural hydrocarbon traps might also prove fruitful.

Hydrogeology

Aquifer Potential

Most precipitation in the semi- arid Zion region runs off the hard, poorly vegetated surface. If it wets the soil, it is captured by plants and evaporates from the leaves. Such conditions are not favorable for the accumulation of groundwater. About 10 percent of rain and snowmelt seeps into groundwater aquifers. Several formations have the necessary porosity and permeability to accommodate this percolating groundwater.

The Navajo Sandstone serves as the principal aquifer in the region. Large recoverable reserves of excellent groundwater quality are present in the Navajo Sandstone (Gregory 1950; Cordova 1978; Clyde 1987). Porosity of the Navajo Sandstone ranges from 32% on neutron logs run in groundwater wells to 17% from rock samples analyzed in the laboratory. Because the Navajo Sandstone is exposed at the surface, the aquifer is considered to be an unconfined aquifer. Sandstones in the Carmel, Kayenta, Moenave, Chinle, and Moenkopi formations and the Kaibab Limestone also contain recoverable quantities of groundwater but these aquifers may be confined between impermeable strata.

Where impervious shales, limestones, and mudstones inhibit upward or downward flow of groundwater in the more porous sandstones, the water escapes laterally. If the aquifer is exposed at the surface springs or seeps develop. Consequently, the contact between the Navajo Sandstone and underlying, less permeable Kayenta Formation is often marked by springs or seeps. Clyde (1987) provides location maps for both springs and wells in the Virgin River basin.

Alluvial aquifers located in unconsolidated, narrow valley- fill sediments along major drainages are a primary source of water for irrigation in the area (Gregory 1950; Clyde 1987). Loose unconsolidated material ranges from near zero to 61 m (200 ft) in depth. The water table is usually high and groundwater is easily recovered through shallow wells. Deeper, more extensive alluvial aquifers are also found in the Virgin River basin that may extend to 152 m (500 ft). Local aquifers have also been defined in Quaternary basalts and thin sandstone units in the Cretaceous Dakota Sandstone and the sandstone lenses in the Chinle Formation.

Contour maps of groundwater flow are presented in Cordova (1978) and Clyde (1987). The general pattern of groundwater flow follows the surface topography and surface water runoff from higher elevations towards the drainage network of the Virgin River and its tributaries. Of course, groundwater movement may be extremely variable, especially with regard to confined aquifers. Some groundwater will move vertically through permeable and semi- permeable layers while some groundwater will move horizontally due to an impervious barrier and emerge as a spring or seep. Faults can also complicate groundwater flow. Some faults act as barriers to groundwater flow; some act as conduits (Cordova 1978; Clyde 1987).

Groundwater aquifers are naturally recharged in the Upper Virgin River Basin by the infiltration of precipitation (some directly and most from melting snow) and seepage from streams passing over recharge areas of the aquifer outcrops. Much of the recharge takes place at higher elevations where precipitation is greater. Development of recharge areas may impact groundwater levels. A more thorough description of groundwater recharge and discharge properties in the Navajo Sandstone is presented in Cordova (1978) and Clyde (1987).

Hydrogeology Projects

Because water is the most precious resource in a desert, the groundwater studies listed below would have a direct impact on the future development of water resources in the park. Experts in the Water Resources Division of the NPS and the USGS should be consulted regarding the following groundwater issues:

- hydrologic parameters near the Sevier fault zone east of Zion
- fracture flow in the Navajo Sandstone aquifer
- groundwater quality and quantity related to joints
- locations of hydrologic divides in Zion to determine groundwater flow patterns.

Groundwater (GW) Quality

Most of the springs in the Zion region yield water that is relatively low in mineral content. Generally, the longer groundwater is in contact with surrounding rock, the higher its mineral content will be. Springs that feed Oil Seeps Wash and Alkali Wash are also gypsiferous and may taste of oil (Gregory 1950). Otherwise, groundwater is generally fresh while some is fresh to slightly saline.

Paleontology and Palynology

The Utah Geological Survey completed a Survey of the paleontological resources of Zion National Park in 2005 (De Blieux et al. 2005). Among the paleontological resources found in the park are bones, plant materials and imprints, tracks, burrows and other trace fossils, wood, invertebrates, fish, and Quaternary tracks. The abundance of fossils varies considerably by strata from absent to abundant.

Palynology is the study of pollen and spores whether living or fossil. The research projects listed in the 1999 scoping summary (Appendix B) included a proposal to investigate the palynology of various formations. Although specific formations were not identified, the formations associated with recent lake deposits and younger bedrock formations containing strata deposited under terrestrial conditions probably have the better chance for preserved pollen than do ancient marine environments or older formations that were buried to depths wherein the pollen was destroyed by heat, pressure, and chemical reactions.

Diagenesis

Diagenesis is the study of physical and chemical processes that change the sediment upon deposition and burial. These processes may include compaction, cementation, recrystallization, and replacement of one mineral for another. Two diagenetic projects identified during the 1999 scoping meeting (Appendix B) are:

- dating desert varnish
- determining the effects of cementation on the color in rocks with emphasis on groundwater from the Navajo Sandstone and diagenesis

These two topics might make an interesting story for the interpreters at Zion, but park resource staff may also wish to know the diagenetic affects controlling porosity and permeability in potential hydrocarbon reservoirs that lie in the vicinity of Zion. Diagenetic histories are complex, but they may be used to project whether a potential rock unit is a reservoir, for hydrocarbons or for groundwater. Diagenetic studies may also be used to estimate erosion rates and potential slippage along fault and joint planes.

Identification of Type Sections

Geologic formations typically have a designated locality at which the formation was first described and named. The Navajo Sandstone, however, does not have a designated type locality (USGS Lexicon web site). Rather, the formation was named for the "Navajo Country" of Arizona, Utah, and New Mexico. Zion National Park could serve as a type locality for the Navajo Sandstone, and thus, the type locality would be preserved. Table 2 summarizes the 1999 Workshop list of potential research projects (Appendix B).

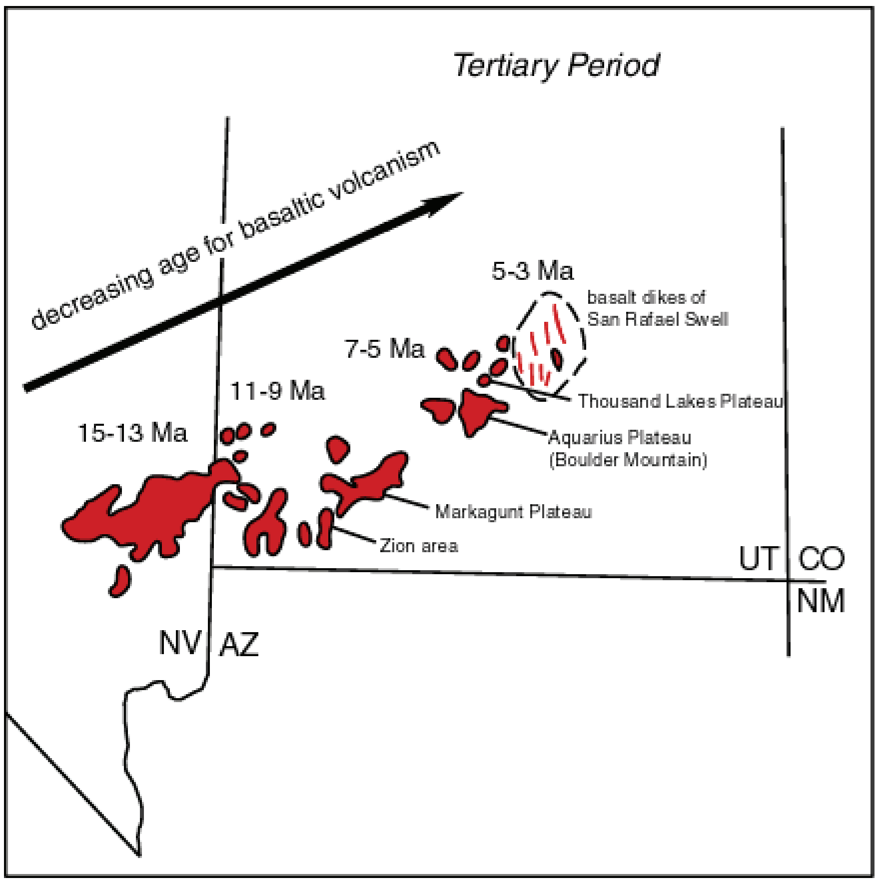


Figure 6. The distribution of young basalts in southern Nevada and southern Utah and their approximate ages. The ages systematically decrease from west to east suggesting the presence of a fixed hot spot in the mantle. Modified from Fillmore, 2000, and Nelson and Tingey, 1997.

TABLE 1. Quaternary research projects identified in the 1999 Workshop.

Quaternary Topic	Research Project
Lake studies	1. Lake development and climate history
	2. Analyze cores taken to the bottom of lake deposits including the core collected by Helmutt Doelling (UGS)
	3. Determine lake chronology using lake sediments
Fluvial/alluvial	1. Alluvial terrace chronology
	2. River system erosion history with emphasis on upstream basalts
Landslides	History of slope instability from landslides (age of landslides)
Ecosystem mgmt.	1. Correlations between vegetation types and rock types
	2. Ecological analysis of pack- rat middens
	3. Study of coalpits lakebed deposits

TABLE 2. Potential research projects identified in the 1999 workshop at Zion.

Category	Potential Research Project
Quaternary Studies	Lake development and climate history
	Analyze any cores collected from lake deposits
	Determine lake chronology using lake sediments
	Alluvial terrace chronology
	River system erosion history with emphasis on upstream basalts
	History of slope instability from landslides (age of landslides)
	Correlations between vegetation types and rock types
	Ecological analysis of pack- rat middens
	Study of coal pit deposits
Structure Projects	Determine the history of the Hurricane fault/Basin and Range extension
	Relate joint formation in Navajo Sandstone to regional tectonics
Hydrogeology	Hydrologic parameters near the Sevier fault zone east of Zion
	Fracture flow in the Navajo Sandstone aquifer
	Groundwater quality and quantity related to joints
	Locations of hydrologic divides in Zion vicinity
Palynology	Palynology of various formations
Diagenesis	Date of desert varnish
	Color in rocks due to cementation
Type Sections	Identifying a type section for the Navajo Sandstone in the park

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Zion National Park.

Biek et al. (2000) identified 24 outstanding geologic features in Zion. These features are summarized below and located on their map, reproduced here as Figure 7.

1. The Springdale Landslide

Triggered on September 2, 1992, by a magnitude 5.8 earthquake, this old landslide has probably moved many times in the past. In 1992, 14 million cubic meters (18 million yd^3) of mostly Moenave Formation slid on the weak claystone of the Petrified Forest member of the Chinle Formation (Biek et al. 2000). Three homes and two water tanks were destroyed, utility lines were disrupted, and Utah Highway 9 was closed.

2. The Watchman Overlook

Millions of years of geologic history are captured in the bedrock units in this view of Zion Canyon. The resistant bench of Shinarump Conglomerate at the mouth of the canyon can be followed vertically upward to the gray limestones of the Carmel Formation high above the Navajo Sandstone. Landslides, joints, pediments, debris flows, and river terraces that help define the erosional history of Zion Canyon can also be seen from this overlook.

3. Zion-Mt. Carmel Highway Tunnel

This tunnel, completed in 1930, was the first million-dollar highway constructed in the U.S. The 1.8 km- long (1.1 mi) tunnel was blasted through the lower 80 m (260 ft) of the Navajo Sandstone.

4. Joints along Zion-Mt. Carmel Highway

Weathering and erosion processes aggressively attack the sandstone faces exposed in near- vertical fractures, or joints, in the Navajo Sandstone and create the spectacular landscape of Zion. The orientation and alignment of side canyons in the eastern part of the park are controlled by the prominent set of north- northwest-trending joints. Excellent examples of these joints can be seen along the Zion- Mt. Carmel Highway.

5. Checkerboard Mesa

Checkerboard Mesa is an example of two weathering processes, one controlled by stratigraphy and one by climate. The "checkerboard" results from the roughly perpendicular sets of grooves in the Navajo Sandstone. The nearly horizontal grooves follow layers of coarse sand that coincide with eolian bedding sets whereas the vertical grooves have been interpreted to be the result of local expansion and contraction of the rock surface due to changes in temperature and moisture (Biek et al. 2000).

6. Sand Bench Landslide

About 7,000 years ago, the relatively thin wall between two closely spaced joints in the Navajo Sandstone collapsed. The resulting Sand Bench landslide blocked Zion Canyon just east of The Sentinel, creating Sentinel Lake. For thousands of years, the Virgin River has been eroding the eastern part of Sand Bench landslide. The result is the river has steepened the landslide creating unstable slopes with the potential for further landslides. Recent landslides in 1923, 1941, and 1995 have temporarily dammed the Virgin River. Prior to the initial Sand Bench landslide, the Virgin River flowed 21 m (70 ft) lower in elevation than it does today.

7. Sentinel Lake

Stretching from the Court of the Patriarchs on the south upstream to the Temple of Sinawava, Sentinel Lake was 61 m (200 ft) deep in its early stages. Horizontal lake sediments that can be seen along the Emerald Pools Trail and the Sand Bench Trail indicate that the lake was probably full of water all year round.

8. Hanging Valleys

During and after rainstorms, waterfalls cascade from the mouths of hanging valleys that rim the main canyons in Zion. These scalloped tributary valleys are alluvial hanging valleys. Large rivers, such as the North and East Forks of the Virgin River, have more erosive energy than the small, typically ephemeral, tributary streams that feed them. The larger rivers cut their canyons faster than streams in the side valleys. Eventually, these tributary valleys are left "hanging" above the floor of the main canyon.

9. Weeping Rock

The effects of groundwater movement along a contact between the permeable Navajo Sandstone and relatively impermeable Kayenta Formation are displayed at Weeping Rock, a picturesque alcove near the base of the Navajo Sandstone, below the mouth of Echo Canyon. Downward infiltration of groundwater directly beneath Echo Canyon is impeded by the Kayenta Formation. Flow is therefore redirected laterally toward the cliff face and ultimately, groundwater seeps out of the rock. The exact path the water follows, and where it discharges, is strongly influenced by joints in the sandstone. A lush hanging garden on the ceiling of the alcove enjoys year-round moisture due to the seeping groundwater. Because the water is alkaline, tufa (calcium carbonate) structures form on the surface of Weeping Rock.

10. The Narrows of Zion Canyon

Beyond the north end of Zion Canyon Scenic Drive, the North Fork of the Virgin River flows for about 16 km (10 mi) through a spectacular gorge cut into Navajo Sandstone. The gorge narrows to a 300- m (1,000- ft) slot canyon at The Narrows where the minimum width of the canyon floor is about 5 m (16 ft).

11. Crater Hill Flow and Cinder Cone

Marking the vent of one of the more voluminous volcanic flows in southwestern Utah, the Crater Hill cinder cone is the largest cinder cone in the park. Flowing southward into Coalpits and Scoggins Washes, basalt from the Crater Hill flow accumulated to a depth of over 122 m (400 ft) in the ancestral Virgin River valley. Volcanic features such as pressure ridges, which form concentric rings and large rafted blocks of basalt are "frozen" in the upper surfaces of the flow. Lake Grafton formed when the flow blocked the Virgin River and Coalpits Lake formed when it blocked Coalpits and Scoggins Washes.

12. Coalpits Wash

Several episodes of recent geologic history and fluvial geomorphology can be seen along Coalpits Wash. In the lower part of Coalpits Wash, basalt plugged the channel of the Virgin River exposing post- basalt gravels, a major debris flow plug, and several young terraces cut by the rapidly adjusting stream. Near the head of the basalt flow, in the upper part of Coalpits Wash, huge chaotic basalt boulders stand as evidence of undercutting and collapse of the flow into the newly formed wash.

13. Trail Canyon Lake

The Pleistocene- age Grapevine Wash basalt flow and a more recent large landslide involving the Kayenta Formation combined to create a dam upstream from the confluence of the Left Fork and Right Fork of North Creek. Lake sediments overlie the landslide deposits. A variety of fossils have been uncovered from these lake sediments including snails, fish vertebrae, and a bison thoracic vertebra.

14. Basalt Stack at Left Fork North Creek

Hiking a short distance east on the Grapevine Springs Trail reveals a spectacular view of 17 cooling units from the Grapevine Wash basalt flow. This flow erupted from a group of vents on the Lower Kolob Plateau at and near Spendlove and Firepit Knolls. Lava flowed southward around sandstone knobs and eventually cascaded into North Creek. The basalt plug is at least 137 m (450 ft) thick and radiometric ages taken from the top and bottom of the flow indicate that all of the flow was emplaced about 270,000 years ago. The entire stack, therefore, is the result of one or more closely spaced eruptions. Accumulation of basalt of this volume in a relatively short period of time is unusual for volcanic deposits on the Colorado Plateau.

15. Dinosaur Tracks at Left Fork North Creek

About 0.8 km (0.5 mi) up Left Fork on the Subway hiking trail lies a large boulder of Kayenta Formation sandstone covered with tracks from a large bipedal tridactyl (three-toed dinosaur).

16. Subway

The Subway is another classic example of differential erosion and the influence of joints on the development of the canyons in Zion. Located on the Left Fork of North Creek, this narrow canyon is wide and rounded at the bottom and narrow and steep- walled at the top because the lower transitional strata of the Navajo Sandstone are less resistant to erosion than the upper strata of the Navajo. The stream in the canyon flows along a series of joints during periods of low flow, thus illustrating the influence of joints on canyon development.

17. Firepit and Spendlove Knolls

The Firepit and Spendlove Knolls are two nearly perfectly conical cinder cones located near the Kolob Road in the west- central part of the park. They mark two of the vents associated with the Grapevine Wash basalt flows. Other, small cones are exposed to the south and west of these two.

18. Old Debris-Flow Deposits

Huge igneous boulders derived from the Pine Valley Mountains form much of the old debris flow deposits west of Little Creek Sinks and to the north on the Upper Kolob Plateau. The boulders are up to 7.3 m (24 ft) long, 6.7 m (22 ft) wide, and reach an estimated 3.7 m (12 ft) thick. These large blocks were transported to the east and northeast at least 16 km (10 mi) and possibly as much as 26 km (16 mi). This movement would be impossible today because of the topographic barrier provided by the Hurricane fault zone. Consequently, the debris- flows must be older than the Hurricane fault zone.

19. Hop Valley

The seldom visited and enchanting Hop Valley lies in the Kolob Canyons portion of Zion (figure 7). Hop Valley "Lake" formed sometime prior to 2,640 years ago when a landslide dammed the mouth of the canyon. Though the sediment trap formed by the landslide performed much like a lake, the sandy nature of the sediments filling the valley indicates that it rarely held standing water. Contrast this with the sediments behind the Sand Bench landslide that are fine silts and clays. Hop Valley is the youngest of the large, landslide- dammed paleolakes in Zion. Sediment deposited in the lake now forms the valley floor that slopes gently north. These valley fill sediments may be as much as 107 m (350 ft) thick.

20. Kolob Arch

Spanning 94.5 m (310 ft) and with a window height of 101 m (330 ft), Kolob Arch is the world's longest natural arch (Biek et al. 2000). The arch is 24 m (80 ft) thick and formed in the middle of the massively cross- bedded Navajo Sandstone. The alignment of the arch suggests that it is related to the north- northwest- trending joint system in the park, and possibly to the exfoliation joints that parallel the East Cougar Mountain fault.

21. Finger Canyons of the Kolob

Eroded into the edge of the Upper Kolob Plateau, the Finger Canyons are a series of west- trending canyons that formed along a series of west- trending joints that isolate large monoliths of Navajo Sandstone. Each canyon resembles a miniature Zion Canyon with a broad canyon mouth where the erodible, pre- Navajo strata are exposed and then taper to a slot canyon in the upper reaches of the canyons.

22. Taylor Creek Thrust Fault Zone

Thrust faults (low angle reverse faults) repeat the strata in the fault zone. The Taylor Creek Thrust Fault Zone is an excellent example of this type of structural geology. The Moenave strata have been repeated along one principal and several lesser east- dipping thrust faults on the east flank of the Kanarra anticline. The thrusts are Sevier- age back thrusts that formed under a west- east compressional regime during the Late Cretaceous to early Tertiary.

23. Double Arch Alcove

Formed in the massively cross- bedded Navajo Sandstone, the Double Arch Alcove illustrates two different processes of arch formation. The lower arch formed by spring sapping and lateral stream erosion and the upper arch was controlled by jointing.

24. Hurricane Fault Zone

The Hurricane fault zone is a major, active, steeply west-dipping normal fault that stretches at least 250 km (155 mi) from south of the Grand Canyon northward to Cedar City. Along the southern boundary of the park, tectonic displacement is about 1,098 m (3,600 ft). Zion rests on the eastern block and as this block was uplifted, the erosive power of streams draining the Kolob Terrace increased to help form the present landscape.

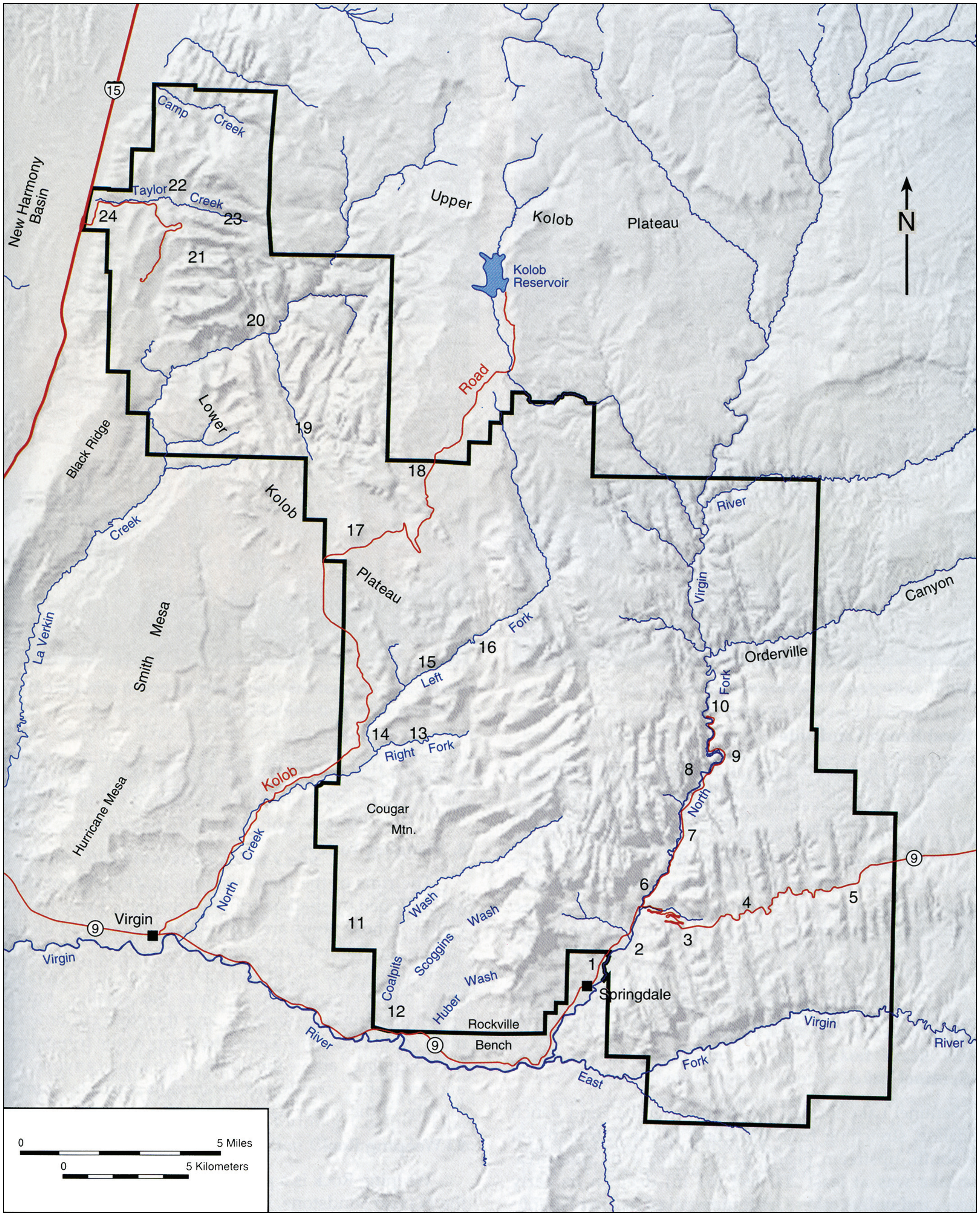


Figure 7. Locations of selected geologic sites in Zion. Image is imported from Biek et al. (2000).

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Zion National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

The following Map Unit Properties Table and accompanying text identifies properties of individual map units that might impact the management of a specific resource. The table is tied to the digital geologic map and the stratigraphic column. Additional information may be gleaned from the cited references.

Erosion Potential

In general, erosion potential is highest in formations that have abundant siltstone and shale or are unconsolidated. Erosion of less resistant bedrock or unconsolidated sediment tends to steepen slopes and create unstable banks along rivers especially in a semi- arid environment such as in Zion. Erosion of a sparsely vegetated landscape is particularly intense following brief summer thunderstorms.

Erosion potential in sandstone depends on the porosity and permeability of the sandstone and the natural cement that binds the grains together. Calcite cement will dissolve more readily in meteoric water than silica or iron cement. Friable sandstones are those in which the grains of quartz are not firmly cemented together. Erosion of friable sandstones form the rounded knobs and temples of Zion. Fractures in sandstones also tend to promote rapid erosion and tend to create features such as spires and needles.

The Navajo Sandstone is a relatively friable sandstone containing abundant joints and thus, has a high erosion potential along fractures and joints. Many of the sandstones in Zion are underlain by shale or siltstone and are prone to undercutting which may lead to landslides and rockfalls.

Aquifer Yields

Most deliverable water in the Zion area is found in the cross- bedded Navajo Sandstone, Quaternary basalts, and unconsolidated alluvial deposits. Other aquifers have limited value because they either lack porosity and permeability or they are limited in lateral and vertical extent.

Groundwater (GW) Quality

Most of the springs in the Zion region yield water that is relatively low in mineral content. Generally, the longer groundwater is in contact with surrounding rock, the higher its mineral content will be. Springs that feed Oil Seeps Wash and Alkali Wash are also gypsiferous and may even taste of oil (Gregory 1950). Otherwise, groundwater is generally fresh while some is fresh to slightly saline.

Groundwater Contamination

Naturally occurring gypsum is the primary contaminant to groundwater and is found in the Petrified Forest member of the Chinle Formation and the Shinabkaib member of the Moenkopi Formation. Blebs of oil in the cherty conglomerate of the basal Rock Canyon Conglomerate member of the Moenkopi Formation may also impact groundwater.

Landslide Potential

Landslides and their subsequent erosion are the primary processes in canyon development at Zion and throughout the Colorado Plateau. These processes also pose potential hazards in the park. As previously mentioned, the soft Kayenta Formation is easily eroded from beneath the Navajo Sandstone. When the Navajo is undercut, slabs of sandstone collapse and cascade downslope on the weak, underlying shale beds. Fractures in the Navajo help facilitate this movement. Active landslides and old landslide deposits are common features throughout Zion and have a history of damming rivers and creating lakes.

If located on steep slopes, unconsolidated Quaternary deposits have a high probably of movement especially during and after heavy rainfall. If the toe of these old landslide deposits is disturbed, by road- building for example, the landslide will reactivate and flow to another position of relative stability. The velocity of the flow depends on several factors such as the size of the material to be moved, the amount of water, the degree of slope, and vegetation.

Paleontology Resources

A detailed description of the paleontology and biostratigraphy of Zion National Park is beyond the scope of this report. The Map Unit Properties Table summarizes data from Santucci (2000), but a more comprehensive list of fossils discovered by 1950 may be found in Gregory (1950)

The UGS established the following sensitivity classes for each strata in the park representing the presence of fossil resources and their vulnerability to human and natural degradation. These sensitivity classes are referenced in the Map Unit Properties Table.

0) Fossils absent – Formations with rock types, such as igneous or metamorphic rocks, that are very unlikely to contain fossils of any kind.
1) Fossils rare – Formations that contain fossils only in rare instances such that intensive survey is unlikely to uncover noteworthy occurrences of fossils. Additionally, significant sites are known from Quaternary alluvium, but these sites are placed in this category because of the vast aerial extent of these surficial deposits and the low probability of encountering fossils at any particular location.
2) Fossils present – Formations known to contain fossils, but these fossils are unlikely to be of unique scientific importance. For example, formations with abundant marine invertebrate fossils in which disturbance of small areas are unlikely to impact scientifically significant fossils.
3) Significant sites known – Formations from which scientifically important fossil sites are known, but many areas of the formation will not contain significant fossil resources because of either the large aerial extent of the formation or rarity of these sites.
4) Very sensitive – Formations known to contain abundant and significant vertebrate, invertebrate, and/or plant fossils in which a field survey is likely to result in the discovery of scientifically significant fossils.

Extremely sensitive – Formations that can be considered "world- famous" because of the scientifically important fossils they contain. Formations in which unique and scientifically important fossils are very likely to be discovered during field survey and in which there is a good possibility that any disturbance will impact critical fossil resources.

Cultural Resources

Cultural resources may be expected in caves carved into the less resistant shales and siltstones beneath sandstone cliffs. Primary contacts where caves occur are at the Dakota Sandstone- Carmel Formation, Navajo Sandstone- Kayenta Formation, and Shinarump Conglomerate member of the Chinle Formation- upper red member of the Moenkopi Formation.

Two types of caves have been etched by erosion: flat-roofed structures at the base of flat- lying, regularly bedded, and resistant sandstones; and arched roof structures at the base of massive cross- bedded friable sandstones. Flat- roofed caves are found in the Moenkopi shales beneath flat- lying Shinarump conglomerate and in the shales beneath Cretaceous sandstones. Caves with arched roofs and generally flat floors are found in the Navajo.

Karst Potential

The sole formation with significant karst potential is the Kaibab Limestone. Karst features are common in this formation.

Map Unit Properties Table

Age	Unit Name (Symbol)	Features and Descriptions	Erosion Potential	Potential Hazards	Water Resources and Water Quality (WQ)	Potential for Groundwater Contamination	Paleontologic Resources	Mineral Resources	Potential Cultural Resources	Global Significance
Quaternary	Alluvium (Qa)	Unconsolidated sand, mud, gravel; river bank deposits; includes older debris- flow deposits west of Little Creek Sinks on the Upper Kolob Plateau	High	Low	Unconsolidated aquifer; moderate to very large yields; fresh to saline WQ		Bison bones (*Bison antiquus)* (1)	Sand and gravel	Historic and prehistoric settlement, agriculture, pigment	None
	Lake Bed Deposits (Ql)	Lacustrine deposits associated with at least 14 lakes are known in the park. Deposits include sand, clay, limestone, sand- to pebble- size cinders (Coalpits Lake) and peat (Hop Valley Lake)	High	Low	Limited; low aquifer yields; fresh water		Bird and camel track & pollen (2)		Settlement and agriculture	None
	Eolian Sand (Qe)	Unconsolidated sand	Very High	Variable landslide potential; low hazard potential; expandable or collapsing soil	Local aquifer; large to very large yields; fresh water		None documented (0)			None
	Basalt Flows (Qb)	Medium to dark gray, weathering dark grayish brown to black, basalt (basalt, trachybasalt, basaltic trachyandesite, and basaltic andesite); phenocryst poor; scattered white plagioclase, common tiny dark- greenish- brown olivine and black pyroxene phenocrysts; flows typically 3- 12 m (10- 40 ft) thick, but may reach several hundred feet thick where flows fill canyons	Low	Variable landslide potential; Cliff former; potential rockfall	Local aquifer; large to very large yields; fresh water		None documented (0)	Cinders	Tool material, rock art	None
	Landslides and Talus (Qms)	Unconsolidated clastics; variable lithologies	Variable	Very high potential for reactivation of landslide if undercut	Low aquifer potential; variable yields; fresh water	Low	Trace fossils on blocks (1)			None
Tertiary	Old Boulder Gravel Deposits (Tu)	Undifferentiated igneous and sedimentary deposits; widespread to the north, but removed by erosion from ZION	Not in ZION	Not in ZION	Not in ZION	Not in ZION	Not in ZION (1)	Not in ZION	Not in ZION	None
Regional Unconformity										
Upper Cretaceous	Tropic Shale (Kt)	Gray marine shale and sandstone with coal.	High	Very high potential for landslides; expandable or collapsing soils	Low aquifer potential; saline WQ	Low	Ammonites (marine); plesiosaur (2)			Maximum development of Cretaceous Western Interior Sea
	Dakota Sandstone (Kd)	Pebble and cobble conglomerate and tan sandstone; may represent previously unrecognized Cedar Mountain Formation; about 30 m (100 ft) thick	Low	Very high landslide potential; low rockfall potential; expandable or collapsing soils	Limited aquifer potential; small to moderate yield; fresh to saline WQ	Low	Bones and plants, freshwater bivalves, (2)	Coal, Uranium	Tool material	None
Regional Unconformity										
Middle Jurassic	Carmel Fm. Winsor member (Jcw)	Sandstone and siltstone; widely exposed on the Upper Kolob Plateau north and east of the park but is not exposed within the main part of ZION; 55- 85 m (180- 280 ft) thick	High	Very high landslide potential; low rockfall potential	Limited aquifer potential; small to moderate yield; poor WQ	Low	None documented (0)		Alcove beneath Kd cliffs	None
	Carmel Fm. Paria River mbr (Jcp)	Lower three- quarters is ledge and cliff- forming alabaster gypsum with a few thin mudstone or sandstone interbeds; upper part is ledge- forming, thin- bedded, platy- or chippy- weathering micritic and argillaceous limestone; only preserved in the northeast part of the park but widely exposed to the north and east on the Upper Kolob Plateau; 15- 24 m (50- 80 ft) thick	High	Variable landslide potential; low rockfall potential; expandable or collapsing soils	Limited aquifer potential; small to moderate yield; poor WQ	Gypsum	Small, poorly preserved pelecypods, ostracodes, and *Pentacrinus* sp. (star- shaped) crinoid columnals (2)	Gypsum		None
	Carmel Fm. Crystal Creek mbr (Jcx)	Sandstone and siltstone; only preserved in the northeast part ZION near Lava Point and north of Orderville Canyon; 46- 56 m (150- 185 ft) thick	High	Low landslide potential; low rockfall potential	Limited aquifer potential; small to moderate yield; poor WQ	Moderate	None documented (0)			None

Age	Unit Name (Symbol)	Features and Descriptions	Erosion Potential	Potential Hazards	Water Resources and Water Quality (WQ)	Potential for Groundwater Contamination	Paleontologic Resources	Mineral Resources	Potential Cultural Resources	Global Significance
Middle Jurassic	Carmel Fm. Coop Creek mbr (Jcc)	Gray resistant, fossiliferous, limestone; plateau forming veneered by thin layer of unconsolidated reddish- brown loess and residual Crystal Creek sediments; upper unit 30- 33 m (100- 110 ft) thick, lower unit is 46- 53 m (150- 170 ft) thick	High	Low landslide potential; moderate rockfall potential	Limited aquifer potential; small to moderate yield; poor WQ	Moderate	Marine pelecypods, gastropods, *Pentacrinus* sp. crinoid columnals (2)	Limestone		None
Regional Unconformity										
Middle Jurassic	Temple Cap Sandstone White Throne mbr (Jtw)	Sandstone from wind- blown sand dunes; thins westward and pinches out near the Hurricane fault; top was beveled flat by encroaching seas; 0- 58 m (0- 190 ft) thick	Moderate	Low landslide potential; high rockfall potential	Limited aquifer potential; moderate yield; fresh WQ	Low	None documented (0)			None
	Temple Cap Sandstone Sinawava mbr (Jts)	Red mudstone and siltstone; 12- 18 m (40- 60 ft) thick	High	Low landslide potential; moderate rockfall potential	Limited aquifer potential; small to moderate yield; fresh WQ	Moderate	None documented (0)			None
Regional Unconformity										
Lower Jurassic	Navajo Sandstone (Jn)	Moderately well- cemented, well- rounded, frosted, fine- to medium- grained quartz sandstone; weathers to bold, rounded cliffs; large- scale cross- beds; locally exceeds 610 m (2,000 ft); three informal subunits based on color, in ascending order, brown, pink, and white. White subunit: forms highest cliffs in ZION (Great White Throne); highly jointed massive vertical cliffs; top is locally stained red by runoff from the mudstone and siltstone of the overlying Sinawava mbr or the Temple Cap Fm.; 0- 244 m (0- 800 ft) thick. Pink subunit: uniformly stained by iron oxides (hematite); porous and friable; high- angle eolian cross- beds; sheets, concretions, and nodules of ironstone (1- 20 percent iron oxide) litter some outcrops; 183- 305 m (600- 1,000 ft) thick Brown subunit: vertical cliff- former; cemented by iron oxide; hanging valleys form at top; 122- 183 m (400- 600 ft) thick	High erosion potential at fractures	High landslide potential if cliffs are undercut; very high rockfall potential from cliffs	Primary aquifer; Moderate to very large yields; fresh WQ	Low potential for contamination	Poor preservation; tridactyl dinosaur tracks; fossil wood (1)	Copper, oil, glass sand	Alcoves in cliff, rock art, pigment, tool material	Potential for type locality; sand dunes may have been part of the largest erg recorded on Earth
	Kayenta Fm. (Tk)	Red and mauve siltstones, shale, and sandstones; slope- former; commonly covered by talus; Lamb Point Tongue (0- 37 m, 0- 120 ft thick) of Navajo Sandstone forms a ledge about one- third of the way down from the base of the Navajo in Zion and Parunuweap Canyons; lower two- thirds is the main body of the Kayenta and is 88- 110 m (290- 360 ft) thick, upper one- third is the Tenney Canyon Tongue and is 43- 96 m (140- 315 ft) thick; entire formation is 168- 213 m (550- 700 ft) thick	High	High landslide potential; moderate rockfall potential	Springs and seeps; small to moderate yields; fresh to saline WQ	Moderate	Three- toed dinosaur tracks; snail and worm trails; fish scales; invertebrates (5)		Alcoves beneath Jn cliff	None
	Moenave Fm. Springdale mbr (Jms)	Thin, discontinuous lenses of intraformational conglomerate, with mudstone and siltstone rip- up clasts; forms the first significant cliff below the Navajo Sandstone; 27- 46 m (90- 150 ft) thick	High	High landslide potential; high rockfall potential	Limited aquifer potential; small to moderate yields; fresh to saline WQ	Low to moderate	Dinosaur tracks; poorly preserved, petrified and carbonized plants (2)		Tool source material	None
	Moenave Fm. Whitmore Point mbr (Jmw)	Sandstone, siltstone, and reddish- purple to greenish- gray mudstone and claystone and thin dolomitic limestone beds; limestones are bioturbated and contain small, moderate- reddish- brown chert nodules and blebs, algal structures, and fossil fish scales and bones of *Semionotus kanabensis*; slope- former; 18- 24 m (60- 80 ft) thick	High	High landslide potential; moderate rockfall potential	Limited aquifer potential; small yields; poor WQ	Moderate	Dinosaur tracks, fish scales and bones (*Semionotus kanabensis*) (3)			None

Age	Unit Name (Symbol)	Features and Descriptions	Erosion Potential	Potential Hazards	Water Resources and Water Quality (WQ)	Potential for Groundwater Contamination	Paleontologic Resources	Mineral Resources	Potential Cultural Resources	Global Significance
Lower Jurassic	Moenave Fm. Dinosaur Canyon Sandstone mbr (Jmd)	Reddish- brown, thin- bedded, very fine- to fine-grained sandstone and silty sandstone; ripple marks and low- angle cross- bedding; slope former; 53- 64 m (175- 210 ft) thick	High	High landslide potential; low rockfall potential; expandable or collapsing soils	Limited aquifer potential; small yields; poor WQ	Moderate	Burrows, tracks (2)			None
Regional Unconformity										
Upper Triassic	Chinle Fm. Petrified Forest mbr (TRcp)	Variegated gray, purple, and white shale with several layers of light- colored sandstone and limestone; abundant bentonite produces badlands topography of bare clay hills with “popcorn” weathering; paleosols are common; 137- 152 m (450-500 ft) thick	High	Bentonite causes very high landslide potential; numerous building foundation problems with expandable or collapsing soils	Not an aquifer; fresh to saline WQ	High	Bone & teeth from fish, *Metoposaur* sp., phytosaurs, ornithischian and aetosaurs, coprolites, petrified wood: *Araucarioxylon* sp., *Woodworthia* sp., plants, and invertebrate burrows (5)	Lead, zinc, silver, gold, manganese, uranium, bentonite, petrified wood	Tool material	None
	Chinle Fm. Shinarump mbr (TRcs)	Sandstone, pebbly sandstone, pebbly conglomerate; forms prominent east- dipping cuesta in Kolob Canyons area; 18- 41 m (60- 135 ft) thick	Low to moderate	Low landslide potential; very high cliff- forming and rockfall potential	Limited aquifer potential; small to moderate yields; fresh to saline WQ	Moderate to high	Wood	Lead, zinc, silver, gold, manganese, uranium, oil	Rock art, tool material	None
Regional Unconformity										
Lower Triassic	Moenkopi Fm. Upper Red mbr (Trmu)	Reddish- brown siltstone and shale; ripple marks; mudcracks, thin laminated bedding; regressive member; 84 m (275 ft) thick	High	High landslide potential; moderate rockfall potential	Limited aquifer potential; small yields; poor WQ	Moderate to high	Vertebrate tracks (2)		Alcoves beneath TRcs cliffs	None
	Moenkopi Fm. Shnabkaib mbr. (TRms)	Siltstone and shale interbedded with abundant gypsum; thickens westward; transgressive member; 91 m (300 ft) thick	High	High landslide potential; moderate rockfall potential; expandable or collapsing soils	Limited aquifer potential; small yields; poor WQ	Gypsum	Marine invertebrates (2)	Gypsum	Pigment	None
	Moenkopi Fm. Middle Red mbr (TRmm)	Reddish- brown siltstone and shale; ripple marks; mudcracks, thin laminated bedding; regressive member; 61 m (200 ft) thick	High	High landslide potential; moderate rockfall potential	Limited aquifer potential; small yields; poor WQ	Gypsum	Wood and bone? (2)			None
	Moenkopi Fm. Virgin Limestone mbr (TRmv)	Fossiliferous limestone with interbedded mudstone; thickens westward; transgressive member; 30 m (100 ft) thick	Low to moderate	Low landslide potential; moderate rockfall potential	Limited aquifer potential; small to moderate yields; poor WQ	Moderate to high	Marine invertebrates: bivalves, gastropods, ammonites (*Meekoceras* sp.), asteroid starfish (2)			None
	Moenkopi Fm. Lower Red mbr (TRml)	Reddish- brown siltstone and shale; ripple marks; mudcracks, thin laminated bedding; regressive member; 49 m (160 ft) thick	High	High landslide potential; low rockfall potential	Limited aquifer potential; small yields; poor WQ	Moderate to high	Vertebrate tracks, wood and bone (2)			None
	Moenkopi Fm. Timpoweap mbr (TRmt)	Brecciated (fragmented) limestone (result of cave collapse); thickens westward; transgressive member; 9- 24 m (30- 80 ft) thick	Low to moderate	Low landslide potential; moderate rockfall potential	Local aquifer; small to moderate yields; poor WQ	Oil, sulfates	Marine invertebrates (2)	Oil		None
	Moenkopi Fm. Rock Canyon Conglomerate mbr (TRmr)	Two main rock types: 1) rounded pebble and cobble conglomerate found in paleovalleys, 2) widespread, but thin, regolithic breccia; clasts are well-cemented, angular, pebble- to cobble- size chert and limestone from Harrisburg mbr of Kaibab Limestone; fill paleochannels up to several tens of feet deep; poorly developed in ZION; 0- 15 m (0- 50 ft) thick	High	Low landslide potential; moderate rockfall potential	Limited aquifer potential; small to moderate yields; poor WQ	Oil, sulfates	Wood and bone?		Tool material	None
Regional Unconformity										
Permian	Kaibab Limestone Harrisburg mbr (Pkh)	Argillaceous limestone and gypsum; exposed in ZION in two short segments of the Hurricane Cliffs; upper contact is an erosional unconformity that spans 10 to 20 million years; 46- 61 m (150- 200 ft) thick	Low	Highly faulted along Hurricane fault zone; rockfall potential	Limited	Few well or spring data; oil, sulfates potential contamination	Marine invertebrates (2)	Copper, oil, uranium prospects south of ZION		Part of the last major Permian transgression in SW Utah
	Kaibab Limestone Fossil Mountain mbr (Pkf)	Fossiliferous limestone or dolomite; exposed in ZION in two short segments of the Hurricane Cliffs; 73 m (240 ft) thick	Low	Highly faulted along Hurricane fault zone; rockfall potential; karst hazard	Karst aquifer? Moderate to high yields; poor WQ?	Few well or spring data; oil, sulfates potential contamination	Marine invertebrates (2)	Copper, oil, limestone, uranium south of ZION		Part of the last major Permian transgression in SW Utah

Age	Unit Name (Symbol)	Features and Descriptions	Erosion Potential	Potential Hazards	Water Resources and Water Quality (WQ)	Potential for Groundwater Contamination	Paleontologic Resources	Mineral Resources	Potential Cultural Resources	Global Significance
Permian	Toroweap Fm. Woods Ranch mbr (Ptw)	Thick evaporates, red and white quartz arenites, thinly bedded carbonate units; collapse structures; exposed in ZION in two short segments of the Hurricane Cliffs; 46- 61 m (150- 200 ft) thick	Low to moderate	Highly faulted along Hurricane fault zone; rockfall potential	No spring or well data	No spring or well data	None			None
	Toroweap Fm. Brady Canyon mbr (Ptb)	Highly fossiliferous limestone with chert nodules, aphanitic lime mudstone, dolomite, and quartzose dolomite; exposed in ZION in two short segments of the Hurricane Cliffs; 61 m (200 ft) thick	Low	Highly faulted along Hurricane fault zone; rockfall potential	No spring or well data	No spring or well data	Brachiopods, bryozoans, crinoids, corals, foraminifera, stromatolites			None

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Zion National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

This section summarizes the tectonic and depositional history found in Zion Natural Park. The tectonic history includes two major orogenic (mountain- building) events: one that occurred in the Mesozoic and one that began in the Mesozoic and ended in the Cenozoic with uplift of the Colorado Plateau. The depositional history includes a wide variety of depositional environments.

Tectonic History

Folds and Faults

Folds and faults are not abundant in Zion; however, fault locations are important because faults are zones of weakness where earthquakes and mass- movements tend to reoccur. The Hurricane fault, created by Tertiary- age (Miocene) Basin- and- Range faulting, coincides with part of the older Sevier thrust fault. This coincidence suggests that the Sevier thrust fault created a zone of weakness that was reactivated by the Hurricane fault.

The folds and thrust faults in Zion are primarily associated with two Mesozoic to Tertiary orogenic events: the Sevier Orogeny and the Laramide Orogeny. Both orogenies are the result of lithospheric plate collisions and subsequent subduction along the western margin of North America. Compressive forces during the Sevier Orogeny initiated thrust faulting and mountain building to the west during the Cretaceous. The Rocky Mountains were built during the Laramide Orogeny that extended from Late Cretaceous to Eocene. Figure 8 lists some of the important North American tectonic events and life forms that occurred throughout geologic time.

Extending for nearly 64 km (40 mi) from near Toquerville to near Cedar City, the Kanarra anticline has its east limb exposed within Zion (Appendix A). Parts of the crest of the fold are also exposed at the mouths of Taylor Creek and Camp Creek. Strata on the east limb dip from 20 degrees to 35 degrees east (Biek et al. 2000). The dip of the beds flattens abruptly and is nearly horizontal under the great cliffs of Navajo Sandstone. The Hurricane fault zone has sheared off the western limb of the fold as well as parts of the crest and eastern limb along a line roughly parallel with the fold axis.

In the Kolob Canyons area, the Taylor Creek thrust fault zone, which has pushed older strata on top of younger, replicates Jurassic strata on the east limb of the Kanarra anticline (Biek et al. 2000). Taylor Creek thrust faults are back thrusts generated by the regional west to east compression during the Sevier Orogeny. The back thrusts are subparallel to bedding with fault planes dipping to the east (Appendix A) (Hamilton 1987; Biek et al. 2000). In Zion repetition of the resistant, cliff- forming Springdale Sandstone member of the Moenave Formation best illustrates the Taylor Creek fault zone. The Kayenta, Chinle, Moenkopi, and Kaibab strata are also displaced by smaller back thrusts associated with the Taylor Creek fault zone. The strata were displaced about 610 m (2,000 ft) vertically and about 762 m (2,500 ft) horizontally.

Cenozoic- age normal faulting has further disrupted the sedimentary rocks at Zion. While most of the Colorado Plateau was not greatly affected by Basin- and- Range normal faulting, extensional forces broke the western margin of the Colorado Plateau into a series of large blocks bounded by the north- south trending Hurricane, Sevier, Paunsaugunt, and other faults (figure 4) (Gregory 1950; Biek et al. 2000). These large fault systems that parallel the western margin of the plateau demonstrate that Zion, CEBR, and BRCA are in a transition zone between the Colorado Plateau Province and the Basin and Range Province. Zion lies on an intermediate fault block bounded by the Hurricane fault zone to the west and the Sevier fault zone to the east.

Faults of lesser linear extent are also present in Zion (Appendix A). A graben (fault bound valley) is formed by the offset along the East and West Cougar Mountain faults located in the southwest part of Zion. These faults are parallel, northwest- trending, steeply dipping normal faults probably related to Basin- and- Range extension although the timing of the faulting is poorly defined. The faults do not offset the 250,000 year- old Grapevine Wash basalt flows and the youngest rock displaced by the fault is Jurassic (Biek et al. 2000).

Another northwest- trending normal fault is the Wildcat Canyon fault that parallels the Cougar Mountain faults (Appendix A). Temple Cap and Carmel strata in Wildcat Canyon have been displaced about 55 m (180 ft) (Biek et al. 2000). Biek et al. (2000) in their text and Hamilton (1987) on his map interpret the movement along the fault to be down- to- the- east, but Biek et al. (2000) have the offset drawn as down- to- the- west. Determining the correct orientation of this fault may be important in order to predict direction of movement in the future.

The 1.0 million year old Lava Point flow to the north is not offset by the Wildcat Canyon fault. This fault is probably contemporaneous with the East and West Cougar Mountain faults.

The Bear Trap Canyon fault, a northeast- trending, high-angle normal fault, with down- to- the- west movement, and more than 274 m (900 ft) of displacement (Hamilton 1992; Biek et al. 2000) merges with the East Cougar Mountain fault (Appendix A).

Minor folds of limited extent have been mapped in the Kolob area. One fold that is about 151- 172 m (495- 564 ft) long has the Jurassic Kayenta at the surface. Another fold 72 m (236 ft) long is located in Jurassic Moenave Formation through Quaternary deposits. A third fold also affects Moenave Formation strata and extends for about 106- 116 m (348- 380 ft) on the surface.

Joints

In contrast to the limited number of folds and faults, joints are ubiquitous throughout Zion. The joints are exceptionally well developed, and are instrumental in orienting today's canyon network by channeling runoff (Biek et al. 2000). Joints are simply cracks in the bedrock without any significant offset. The most prominent joints in Zion trend north- northwest and are found in the Navajo Sandstone. These joints are nearly vertical and are spaced widely apart with some uniformity. Crushed or sheared zones associated with the joints indicate two diametrically opposite types of crustal stresses: one set related to compression and one set related to tension (Biek et al. 2000). Rogers (2002) suggests that joints were initiated with tension related to Basin- and- Range extension, but that the joints did not propagate until surface erosion began cutting into the rock and preferentially following and facilitation joint development. The result is near parallel, regularly spaced, joint- controlled canyons.

Some joints near rock surfaces formed because of erosion. These joints are termed exfoliation joints and form roughly parallel to the rock face as overlying bedrock and sediments are eroded. Other joints, such as those at Checkerboard Mesa, are thought to form due to local expansion and contraction near the surface of the rock as it is subjected to constant, persistent temperature and moisture changes.

Depositional History

The strata of Zion represent layer upon layer of overlapping and interfingering marine and non- marine depositional environments (figure 9).

Permian Period

About 275 million years ago the Permian equator passed through what is now eastern Utah and Wyoming along the western margin of Pangaea, the supercontinent forming as the globe's landmasses sutured together (Biek et al. 2000; Morris et al. 2000). A dry, high atmospheric pressure climatic belt prevailed in this western part of Pangaea and resulted in restricted marine evaporitic conditions over much of the cratonic shelf seaway (Peterson 1980). Warm, shallow seas and sabkhas (broad, very flat surfaces near sea level) covered the area. Farther to the west, a complex island arc assemblage formed above a subduction zone as lithospheric plates collided (Silberling and Roberts 1962). To the east, in western Colorado, the majestic, jagged peaks (similar to today's Himalayas) of the Uncompahgre Mountains bordered the Utah lowland.

The Toroweap Formation contains evidence of four environments of deposition created by the advance and retreat of the shoreline across northern Arizona and southwestern Utah (Rawson et al. 1980). From west to east, these four environments include an open marine environment, restricted marine, sabkha, and eolian dune environments. As sea level continued to rise during the initial Toroweap transgression, normal marine organisms such as brachiopods, crinoids, corals, and bryozoans entered the Zion area, and their shell material is incorporated in the Toroweap limestones. The fossiliferous limestone, dolomite, and limy sandstone environments record three transgressive pulses (Rawson et al. 1980).

Following the last transgression, the sea withdrew to Nevada and coastal sabkha environments spread over Zion. Eolian dune fields formed east of the sabkhas. One last Toroweap transgressive pulse swept marine environments back into the area from the west.

The Kaibab Limestone records the last in a long series of shallow seas that transgressed over the Zion region throughout the Paleozoic Era. Oolites, disarticulated and broken marine fossil fragments, dolomite, siliceous sponge spicules, and gypsum, all found in the Kaibab, formed under shallow, near- shore, warm and arid climatic conditions (Hamilton 1992). Spherical, modern oolites, similar to those found in the Kaibab Limestone, are currently being formed in warm, shallow marine water where they slowly accrete carbonate mud to their round surfaces as waves gently roll them back and forth over the sea bottom.

The interfingering of the Kaibab with the White Rim Sandstone in the Capital Reef National Park area to the east suggests that the marine facies of the Kaibab migrated eastward in response to a relative sea- level rise, or transgression (Dubiel et al. 1996). The sea moved back and forth across Utah, but by the Middle Permian, the sea had withdrawn and the Kaibab Limestone was exposed to subaerial erosion (Morris et al. 2000). Dissolution of the Kaibab created karst topography and channels reaching 30 m (100 ft) in depth cut into the limestone surface (Morris et al. 2000).

The close of the Permian brought the third, and most severe, mass extinction of geologic time. Although not as famous as the extinction event that exterminated the Dinosaurs at the end of the Mesozoic, the Permian extinction was much more extensive.

Almost 96% of all species were extinct by the end of the Permian (Raup 1991). The most recent hypothesis regarding the Permian event suggests that a comet, about 6- 13 km (4- 8 mi) in diameter, slammed into Earth (Becker et al. 2001), triggering vast volcanic eruptions that spread lava over an area two- thirds the size of the United States.

Triassic Period

During the Triassic (250 to 206 million years ago), the supercontinent Pangaea reached its greatest size. All the continents had come together to form a single landmass that was located symmetrically about the equator (Dubiel 1994). To the west, explosive volcanoes arose from the sea and formed a north- south trending arc of islands along the border of what is now California and Nevada (Christiansen et al. 1994; Dubiel 1994; Lawton 1994).

Shallow, marine water stretched from eastern Utah to eastern Nevada over a beveled continental shelf. As the sea withdrew, fluvial, mudflat, sabkha, and shallow marine environments developed (Lower Triassic, Moenkopi Formation) (Stewart et al. 1972A; Christiansen et al. 1994; Doelling 2000; Huntoon et al. 2000). The Red Canyon Conglomerate, the basal member of the Moenkopi, fills broad east- flowing paleochannels carved into the Kaibab Limestone (Biek et al. 2000). Some of these channels are up to several tens of feet deep and may reach 61 m (200 ft) deep in the St. George area. A thin poorly developed soil or regolith formed over the paleotopographic high areas between the channels (Biek et al. 2000).

The fossilized plants and animals in the Moenkopi are evidence of a climate shift to a warm tropical setting that may have experienced monsoonal, wet- dry conditions (Stewart et al. 1972A; Dubiel 1994; Huntoon et al. 2000; Morris et al. 2000).

At Zion, the limestones and fossils of the Timpoweap, Virgin Limestone, and Shnabkaib members of the Moenkopi Formation document transgressive episodes. Unlike the Timpoweap and Virgin Limestone members, the Shnabkaib contains abundant gypsum and interbedded mudstone resulting from deposition in a restricted marine environment with complex water-table fluctuations (Biek et al. 2000).

Regressive, red- bed layers separate the transgressive strata. Ripple marks, mud cracks, and thinly laminated bedding suggest that these intervening red shale and siltstone units were deposited in tidal flat and coastal-plain environments (Stewart et al. 1972A; Hamilton 1992; Biek et al. 2000).

The Early Triassic is separated from the Late Triassic by a regional unconformity (figure 5). This unconformity marks a change from the shallow marine environments of the Lower Triassic Moenkopi Formation to mostly continental sedimentation in the Upper Triassic Chinle Formation. The Middle Triassic remains a mystery. No rocks that span this time (from 242- 227 Ma) have been preserved in Utah. By the Late Triassic, Utah was part of a large interior basin drained by north- and northwest-flowing rivers (Biek et al. 2000). Braided streams deposited coarse sediments (Shinarump Conglomerate member) in paleovalleys eroded into the underlying Moenkopi Formation (Dubiel 1994; Biek et al. 2000).

High- sinuosity stream, flood plain, and lake sediments (Petrified Forest member) overly the braided stream deposits in the Zion region (Stewart et al. 1972B; Dubiel 1994; Biek et al. 2000). Aquatic crocodile- like Phytosaurs, lungfish, and lacustrine bivalves inhabited a Utah that looked vastly different in the Upper Triassic than it does today. Rather than a semi- arid desert environment, the Zion area was a coastal lowland supporting amphibians, reptiles, freshwater clams, snails, ostracodes, and fish. The moist climate supported conifer trees, cycads, ferns, and horsetails (Stewart et al. 1972B; Dubiel 1994; Biek et al. 2000). Periodically, volcanic ash from the volcanic arc off the continental margin to the west drifted into the area and was subsequently altered to bentonitic clay that today is notoriously susceptible to landslides and for causing foundation problems in southwest Utah.

About ten million years is missing between the Chinle Formation and the Early Jurassic Moenave Formation. This basal Jurassic unconformity extends from central and western Wyoming, through Utah and the Four Corners area, and into northwest New Mexico and the San Juan Basin (Pipiringos and O'Sullivan 1978; Peterson 1994).

Jurassic Period

Throughout the Jurassic's 100 million years, periodic incursions from the north brought shallow seas flooding into Wyoming, Montana, and a northeast- southwest trending trough on the Utah/Idaho border. The Jurassic western margin of North America was associated with an Andean- type margin where the eastward subduction of the seafloor gave rise to volcanism similar to that found in today's Andes of South America. Volcanoes formed an arcuate north- south chain of mountains off the coast of western Pangaea in what is now central Nevada. To the south, the landmass that would become South America was splitting away from the Texas coast just as Africa and Great Britain were rifting away from the present East Coast and opening up the Atlantic Ocean. The Ouachita Mountains, formed when South America collided with North America, remained a significant highland, and rivers from the highland flowed to the northwest, towards the Plateau. The Ancestral Rocky Mountains and the Monument Upwarp also remained topographically high during the Jurassic.

Bordered by these highlands, the Western Interior Basin was a broad, shallow depression on the southwest side of the North American craton. The basin stretched northward from its southern margin in Arizona and New Mexico across the Canadian border. The basin was asymmetric, rapidly subsiding along the west side and more gently dipping farther east.

The Moenave Formation was deposited in a variety of river, lake, and flood- plain environments (Biek et al. 2000). Ripple marks, cross- bedding, reddish and gray siltstone and shale, fossil fish scales, and bones of *Semionotus kanabensis* suggest low energy streams and ponded drainages (Dinosaur Canyon and Whitmore Point members) (Hamilton 1992). The thin, discontinuous lenses of intraformational conglomerate, fine- grained rip- up clasts (mud clasts "ripped- up" by currents and transported elsewhere), and fossil plant fragments found in the Springdale member record deposition in river channels (Biek et al. 2000).

Fluvial processes continued to affect southwestern Utah by the deposition of the Kayenta Formation. Interbedded sandstone, basal conglomerates, siltstones, mudstones, and thin cross- beds are typical channel and floodplain deposits found in the Kayenta. Paleocurrent studies show that the Kayenta rivers flowed in a general westward to southwestward direction (Morris et al. 2000).

Mountains in Nevada and California continued to rise in the Early Jurassic as plate motions forced North America northward. Eventually, this created a rain shadow. Gradually, sand dune deposits reaching 240 to 340 m (800 to 1100 ft) overtook the fluvial systems of the Kayenta. These dune fields became the Navajo Sandstone, part of the world's largest coastal and inland paleodune field (Blakey 1994; Peterson 1994; Biek et al. 2000). The large- scale (18 m, 60 ft), high- angle, cross- beds of the Navajo attest to the presence of Sahara- like sand dunes during the Early Jurassic (Biek et al. 2000; Morris et al. 2000).

Extensive eolian sand seas, called ergs, developed in the Western Interior Basin mainly because the region was located about 18 degrees north latitude at the beginning of the Jurassic and about 30- 35 degrees north latitude at the end of the Jurassic (Parrish and Petersen 1988; Chan and Archer 2000; Kocurek and Dott 1983; Peterson 1994). This latitude marks today's trade wind belt where hot, dry air descends from the upper atmosphere and sweeps back to the equator in a southwesterly direction, picking up any moisture as it goes - the latitude of intense evaporation. Most modern hot deserts of the world occur within the trade wind belt and during the Jurassic, the climate of the Colorado Plateau appears to have been similar to the modern Western Sahara.

In the Sahara, the world's largest desert, only 10% of the surface is sand- covered. The Arabian Desert, Earth's sandiest desert, is only 30 percent sand- covered. The Jurassic deserts that occurred across the Colorado Plateau for roughly 40 million years (not counting the time represented by erosion) contained sand dunes that may be the largest recorded in the rock record (Kocurek and Dott 1983). These ergs formed on a coastal and inland dune field affecting southern Montana, eastern Utah, westernmost Colorado, southwest Colorado, northeastern Arizona, and northwestern New Mexico (Kocurek and Dott 1983; Peterson 1994). The volume of sand in these systems was enormous. Ergs may have covered 106 km^2 (41 mi^2) with as much as $1.5 \times 10^5 km^3$ ($3.6 \times 10^4 mi^3$) of sand being deposited (Saleeby et al. 1992). Two types of cyclicity have been observed in Navajo sandstone. First there are layers of annual deposition where 1 to several meters of sand accumulates on the dune face during strong winds, separated by thinner wedges of sand deposited during light and variable winds. These have been interpreted as deposition during seasonal monsoon winds from the north (Loope et al. 2001). Secondly, studies of cyclicity in the annual dune sets suggest that the region experienced contrasts of wetter and drier periods on a decade scale in the Early Jurassic (Chan and Archer 2000).

Great, sweeping Navajo cross- beds are wonderfully preserved at Zion. As in modern deserts, where ground water reached close to the surface, oases formed. Planar sandstone and limestone beds found in the middle and upper parts of the Navajo represent oasis deposits formed in these active dunefields. One good example of fossil oasis deposits can be seen along the Canyon Overlook Trail (Biek et al. 2000). The top of the Navajo Formation and the end of the Early Jurassic is marked by another regional unconformity.

As the pace of west coast collision increased in the Middle Jurassic (about 160 to 180 Ma) to about as fast as fingernails grow, the rock layers on the continental side of the collision, in Utah and western Colorado, deformed in response to the collision to the west (Sevier Orogeny). The sea began to encroach on the continent from the north. Broad tidal flats and streams carrying red mud (Sinawava member of the Temple Cap Formation) formed on the margins of a shallow sea that lay to the west, and flat- bedded sandstones, siltstones, and limestones filled depressions left in the underlying eroded strata (Wright et al. 1962; Hamilton 1992; Biek et al. 2000; Doelling 2000). Streams eroded the poorly cemented Navajo Sandstone, and water caused the sand to slump. Desert conditions returned briefly (White Throne member), but encroaching seas again beveled the coastline, forming a regional unconformity.

Crinoid, pectin, clam, and oyster fossils of the Carmel Formation were deposited in a shallow inland sea (Biek et al. 2000). Many unique environments were created by the migrating Sevier thrust system and the four members of the Carmel Formation in southwest Utah capture these changing environments (figure 9). Both open marine (crinoids) and restricted marine (pelecypods, gastropods) environments are represented in the Co- op Creek member. Sandstone and gypsum in the Crystal Creek and Paria River members signal a return to desert conditions in a coastal setting (Biek et al. 2000; Morris et al. 2000).

Cretaceous Period

As mountains rose in the west and the roughly north-south trending Western Interior Basin expanded in the Cretaceous, the Gulf of Mexico separating North and South America continued to rift open in the south, and marine water began to advance northward into the basin. At the same time, marine water advanced onto the continent from the Arctic region.

The seas advanced and retreated many times during the Cretaceous until the most extensive interior seaway ever recorded drowned much of western North America (figure 10). The Western Interior Seaway was an elongate basin that extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4827 km (3,000 mi) (Kauffman 1977). The western margin of the seaway coincided with the active Cretaceous Sevier orogenic belt with the westernmost extension of the shoreline in the vicinity of Cedar City, Utah. The eastern margin was part of the low- lying, stable platform ramp in Nebraska and Kansas.

The pebble to cobble conglomerate and tan sandstone that compose the Cretaceous rocks exposed at the top of Horse Ranch Mountain include alluvial- fan and alluvial- plain sediments that grade laterally into coastal plain, marginal marine, and marine deposits (Biek et al. 2000). For the first time in the history of the Mesozoic, the source area for these terrestrial clastic sediments is from the west, a result of the Sevier Orogeny.

Tertiary Period

Explosive andesitic volcanism dominated the area to the west of Zion during Oligocene and early Miocene time and probably inundated the region with hundreds of feet of welded tuff that has since eroded away (Biek et al. 2000). Three of these tuff layers are preserved on top of Brainhead Peak. Some of these enormous cascadia- type volcanoes produced eruptions that exceeded the largest Yellowstone eruptions (Dave Sharrow, Zion National Park, personal communication 2005). About 21 million years ago the Pine Valley laccolith formed. This typical mushroom- shaped laccolith is one of the largest intrusions of this type in the world. Debris- flows carried boulders of this intrusion onto the Upper Kolob Plateau indicating that the Hurricane Cliffs could not have been present at the time.

Quaternary Period

Synthesizing geologic maps for the quadrangles that cover Zion, 100 Quaternary units are mapped on the NPS- GIS digital map. These units are summarized in Biek et al. (2000) who organized the surficial deposits into six main types of surficial sedimentary deposits common in the park:

- alluvium,
- colluvium and residuum,
- talus,
- eolian deposits,
- mass- movement deposits (including landslides and debris flows), and
- lacustrine or basin- fill deposits.

Unlike the consolidated bedrock units, these surficial units are classified according to their interpreted mode of deposition, or genesis. In addition to these (but too small to map), are the rare tufa deposits associated with springs and the basalt flows and cinder cones that stand in stark contrast to the surrounding red- rock strata.

The surficial deposits of Zion speak to an active recent history of the park. Older debris- flow deposits contain subrounded basalt boulders brought in from a western source before the Hurricane fault zone was a significant topographic barrier to deposition. Analyses of the basalt flows and cinder cones reveal an eruptive cycle that may have lasted less than 100 years before going extinct (Biek et al. 2000). The volcanic vents appear to be located along faults and joints, structurally weak zones in the rock.

Quaternary basalt flowed down canyons and drainages onto valley floors, just as magma does today. Because basalt is more resistant to erosion than sedimentary rocks, however, erosion has removed the surrounding sedimentary rock that once stood at higher elevations so that the basalt now caps ridges that separate adjacent drainages. Thus, they form an "inverted topography" in which the valleys that were once flooded with basalt are now ridges and plateaus.

Impounded behind landslides and lava flows, small lakes and ephemeral ponds filled the canyons of Zion. About 100,000 years ago, the Crater Hill basalt flow blocked the Virgin River near the present- day ghost town of Grafton. Behind this barrier, Lake Grafton grew to become the largest of at least 14 lakes that have periodically formed in the park.

Zion National Park is a monument to erosion and the impact that water has in a dry, sparsely vegetated landscape. Runoff from precipitation and snowmelt has eroded thousands of feet of strata from the Zion block in the Quaternary. Canyon cutting could only begin in earnest when the Colorado River began flowing through Grand Canyon and on to the sea about 4.5 million years ago. The Virgin River could then link with the Colorado and begin expanding its watershed into the Colorado Plateau. It does this at the expense of the Sevier River drainage, which has less erosive energy because it has a gentle gradient draining to the Great Basin about 4,000 feet in elevation, rather than sea level.

Normally a small, placid stream, easy to wade across, the Virgin River does not seem capable of eroding such an immense canyon as Zion. However, the Virgin River carries away more than 1 million tons of rock waste each year due its steep gradient of about 13 meters per kilometer (69 ft/mi) (Biek et al. 2000). Nearly all of the sediment transport occurs during floods because the capacity of the river to move sediment increases exponentially as the streamflow increases. A ten- fold increase in flow, a common occurrence, results in a 1,000- fold increase in sediment transport. Peak flows, however, are quite variable with a range from 0.6- 256 m^3/sec (21- 9,150 cfs) near Springdale to 0.6- 638 m^3/sec (21- 22,800 cfs) downstream near Virgin. During the wetter Pleistocene past, average sediment transport was probably even greater than it is today.

Downcutting and canyon widening are the two dominant erosional processes forming the canyons at Zion (Biek et al. 2000). Downcutting is represented at The Narrows at the head of Zion Canyon where the North Fork of the Virgin River flows through a spectacular gorge cut into the Navajo Sandstone. Acting like a ribbon of moving sandpaper through The Narrows, the Virgin River has carved a 305 meter- deep (1,000 ft) gorge that, in places, is only 5 m (16 ft) wide at the bottom.

The second dominant erosional process, canyon widening, makes use of the different erosional properties between the Kayenta Formation and the overlying Navajo Sandstone. The thin- bedded siltstone, sandstone, and shale of the Kayenta Formation are softer and more easily eroded than the massive sandstone of the Navajo. Consequently, as the Kayenta is eroded and slips away in landslides, the Navajo cliffs are undercut. Seeps and springs at the contact of the permeable Navajo and relatively impermeable Kayenta further undermine the Navajo cliffs until they collapse in rockfalls and landslides. Failure of the Navajo is facilitated by the vertical joints in the sandstone, as well. During canyon widening the Virgin River acts primarily as a conveyor that transports the material washed off the slopes downstream.

Carved in the Jurassic- age Navajo Sandstone, the sheer walls of Zion Canyon rise 610 m (2,000 ft) from the canyon floor. A narrow slot in its upper reaches, the canyon widens below The Narrows where the North Fork of the Virgin River has cut a wider flood plain in the less resistant beds of the Jurassic Period Kayenta and Moenave Formations (Biek et al. 2000).

The Virgin River has cut down about 396 m (1,300 ft) in about 1 million years. This rate of canyon cutting is about 40 centimenters/1,000 years (1.3 ft/1,000 yr). This is a very rapid rate of downcutting, about the same rate as occurred in Grand Canyon during its period of most rapid erosion. About 1 million years ago, Zion Canyon was only about half as deep as it is today in the vicinity of Zion Lodge (Biek et al. 2000). Definitive evidence is sparse for determining long- term erosion rates of Zion Canyon, but if the assumption is made that erosion was fairly constant over the past 2 million years, then the upper half of Zion Canyon was carved between about 1 and 2 million years ago and only the upper half of the Great White Throne was exposed 1 million years ago and The Narrows were yet to form. Downcutting and canyon widening continue today as the relentless process of erosion continues to bevel the landscape to sea level.

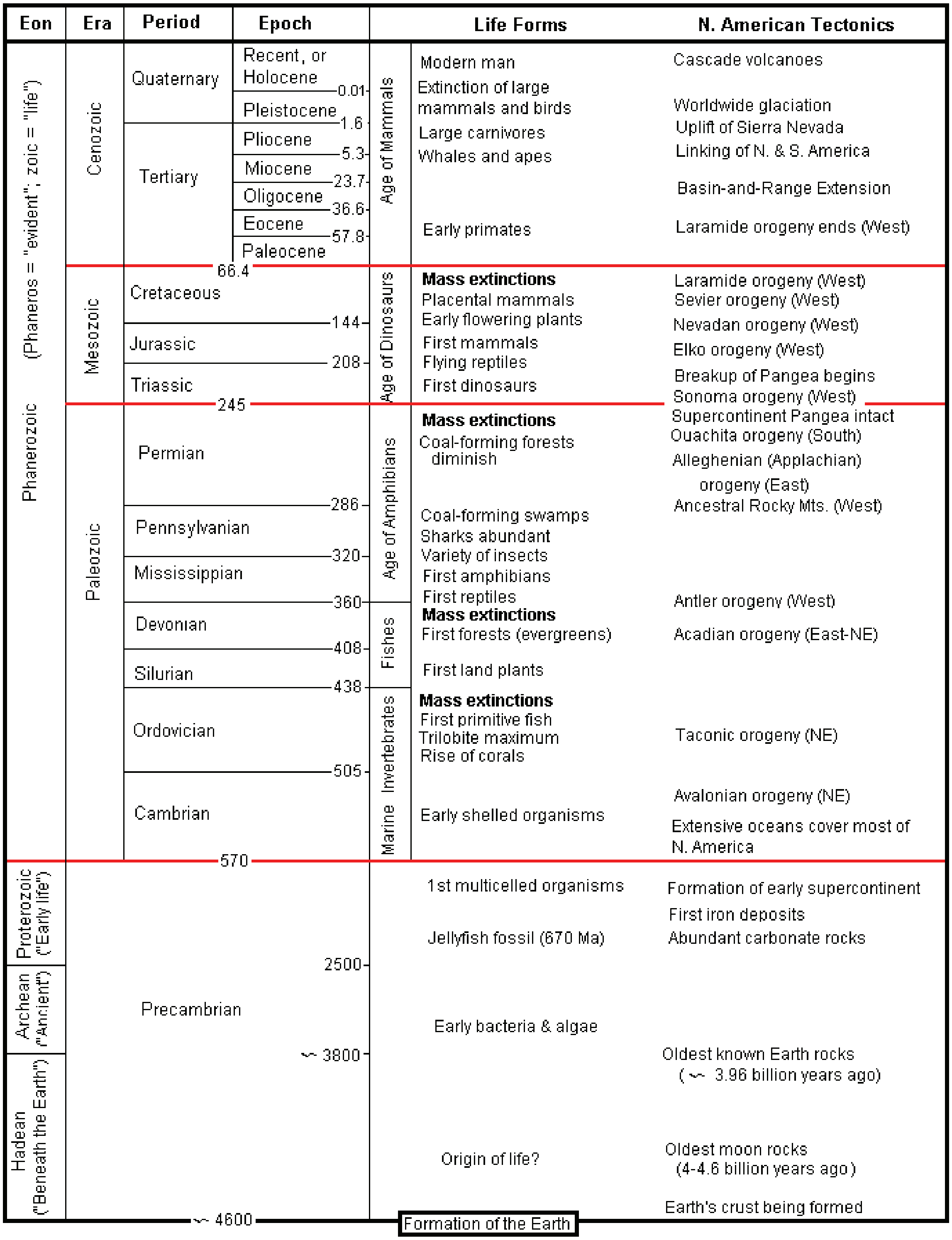


Figure 8. Geologic time scale. Red lines indicate major unconformities between eras. Absolute ages shown are in millions of years. Scale is from the U.S.G.S.

Age		Formation	Member	Symbol	Depositional Environment
Quaternary				Qa	Alluvial
				Qat	Alluvial terrace
				Qe	Eolian
				Ql	Lacustrine
				Qbcr	Debris-flow with boulders
				Qb	Basalt flow
				Qms	Mass-movement (landslide)
Tertiary				Ta	Alluvial fan
				Ti	Qtz monzonite (igneous)
Cret.	Lower	Dakota		Kd	Alluvial fan to marginal marine
Jurassic	Middle	Carmel	Winsor	Jcw	Not in Zion
			Paria River	Jcp	Marginal marine, arid coastal
			Crystal Creek	Jcx	
			Co-op Creek	Jcc	Open & restricted marine
		Temple Cap	White Throne	Jtw	Coastal dunes
			Sinawava	Jts	Warm shallow marine
	Lower	Navajo	white unit	Jnw	Coastal eolian dune fields (erg)
			pink unit	Jnp	
			brown unit	Jnb	
		Kayenta		Jk	Fluvial, playa, some lake
		Moenave	Springdale Sst	Jms	Fluvial channel fill
			Whitmore Pt.	Jmw	Ponds & lakes
			Dinosaur Can.	Jmd	Fluvial, lake, flood plain
Triassic	Upper	Chinle	Petrified Forest	TRcp	Meandering stream, lake, coastal lowland
			Shinarump Cgl.	TRcs	Braided stream, valley-fill
	Lower	Moenkopi	upper red	TRmu	Tidal flat & coastal plain
			Shnabkaib	TRms	Restricted marine
			middle red	TRmm	Tidal flat & coastal plain
			Virgin Lst.	TRmv	Shallow marine
			lower red	TRml	Tidal flat & coastal plain
			Timpoweap	TRmt	Shallow marine
			Rock Can.Cgl.	TRmr	Fluvial channel fill & regolith
Permian	Lower	Kaibab	Harrisburg	Pkh	Shallow marine, near-shore envs.
			Fossil Mtn.	Pkf	
		Toroweap	Woods Ranch	Ptw	Coastal sabkha, eolian dunes, marine
			Brady Canyon	Ptb	Marine

Figure 9. Depositional environments represented by the strata in Zion National Park.

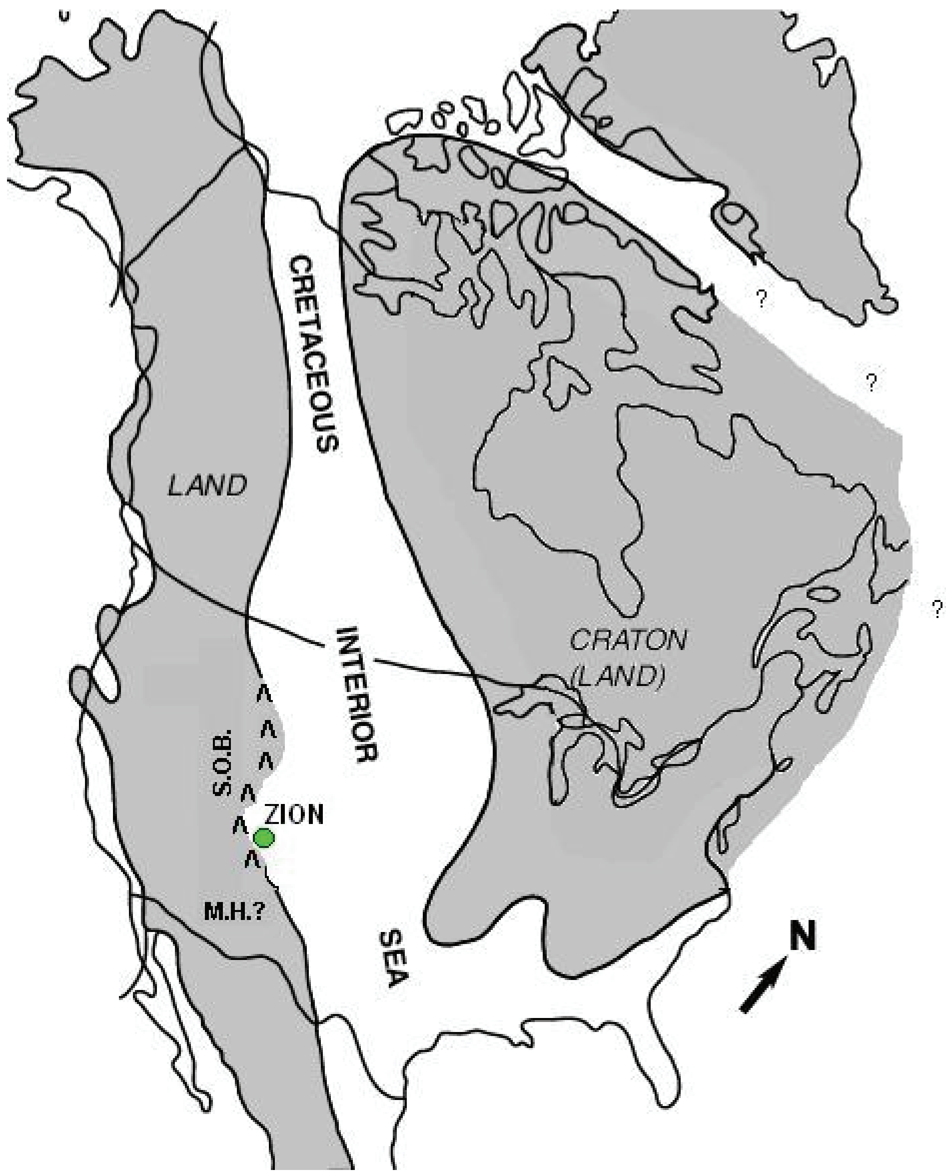


Figure 10. Location of the Cretaceous Period, Western Interior Seaway. Shaded areas indicate land above sea level. North arrow indicates the Cretaceous north. Modified from Rice and Shurr (1983).

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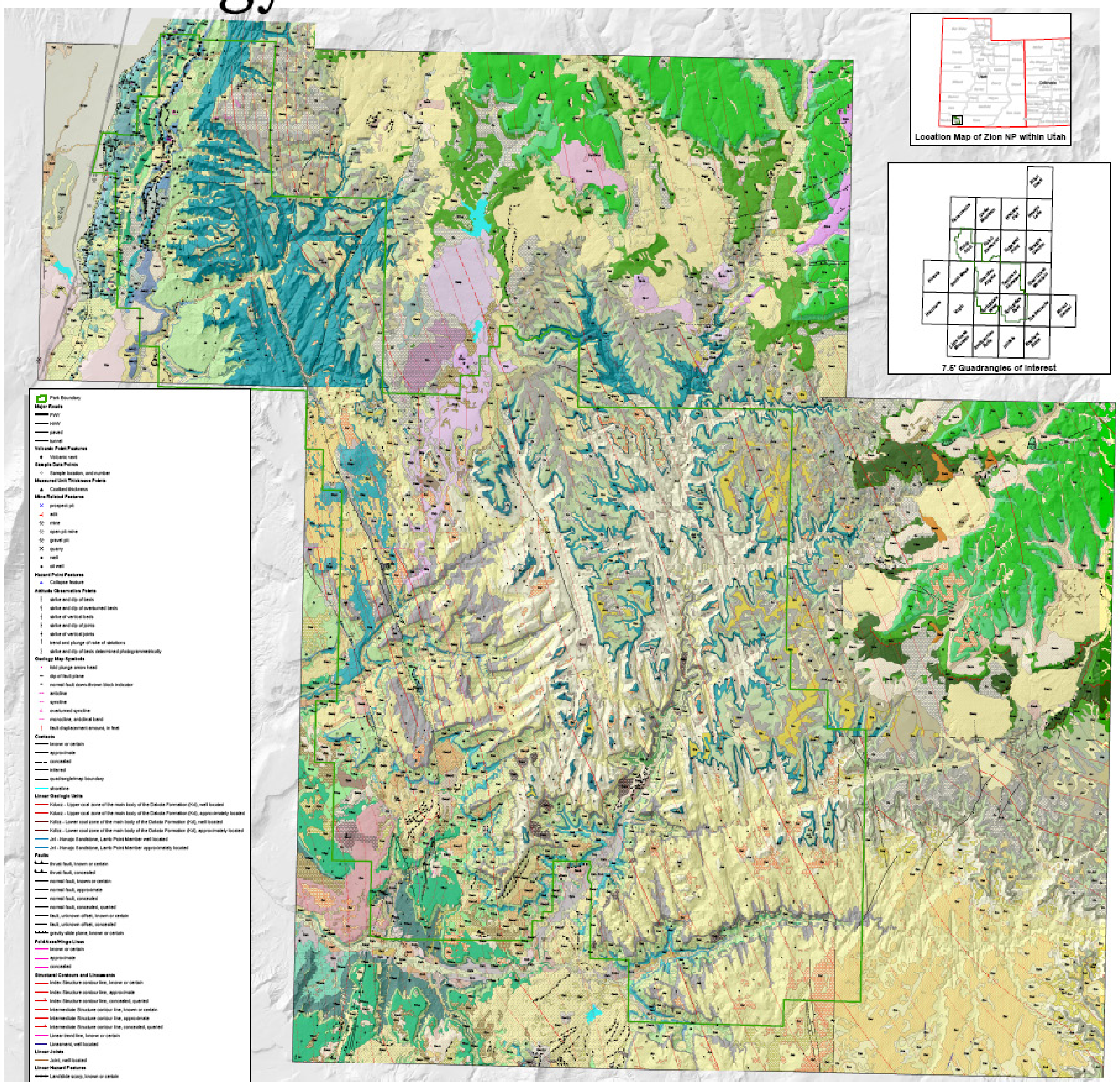
Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Zion National Park. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

National Park Service
U.S. Department of the Interior

Geology of Zion National Park



Map Unit Descriptions

1 0.5 0 1 2 3 4 Miles

1:63,360

Data Set Credit:
Field mapping and compilation: Utah Geological Survey
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Digital conversion: Stephanie O'Meara (Colorado State University) for the NPS Geologic Resources Division

Map Layout Credit:
Tim Connors and Jennifer McCollom with the NPS Geological Resources Division

Produced by National Park Service, Geologic Resources Division, Denver Colorado

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Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Zion National Park. The scoping meeting occurred April 12- 13, 1999; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

Executive Summary

An inventory workshop was held at Zion National Park on April 12- 13, 1999 to view and discuss the park's geologic resources, to address the status of geologic mapping by both the Utah Geological Survey (UGS) and the United States Geological Survey (USGS) for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Zion NP (interpretation), UGS, USGS, Utah Geological Association (UGA) and Utah Bureau of Land Management (BLM) were present for the two day workshop. (see Zion NP Geological Resources Inventory Workshop Participants, April 12- 13, 1999)

Day one involved a field trip led by UGS geologists Grant Willis and Helmut Doelling. Highlights of the field trip included visits to view paleontological resources within the Triassic Moenave Formation (Whitmore Point Member) where dinosaur track sites exist near the visitor center area, the Birch Creek landslide- dammed lake deposits, Crater Hill volcanic deposits, and the structural geology of the Hurricane fault zone and Kannarraville anticline. The field trip was concluded with a "team building" session (barbecue) at USGS Geologist Pete Rowley's new home in New Harmony, UT.

Day two involved a scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the Geologic Resources Division, and the ongoing Geologic Resources Inventory (GRI) for Colorado and Utah. Round table discussions involving geologic issues for Zion NP included interpretation, the UGA Millennium 2000 guidebook featuring the geology of Utah's National and State parks, paleontological resources, the status of cooperative geologic mapping efforts, sources of available data, geologic hazards, potential future research topics, and action items generated from this meeting. Brief summaries of each follows.

Overview

After introductions by the participants, Joe Gregson (NPS- NRID) presented an overview of the NPS I&M Program, the status of the natural resource inventories, and the geological resources inventory.

He also presented a demonstration of some of the main features of the digital geologic map for the Black Canyon of the Gunnison NM and Curecanti NRA areas in Colorado. This has become the prototype for the NPS digital geologic map model as it ideally reproduces all aspects of a paper map (i.e. it incorporates the map notes, cross sections, legend etc.) with the added benefit of being a GIS component. It is displayed in ESRI ArcView shape files and features a built- in help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the map. The cross section lines (ex. A- A') are subsequently digitized as a shape file and are hyperlinked to the scanned images.

The geologists at the workshop familiar with GIS methods were quite impressed with this method of displaying geologic maps digitally; Gregson is to be commended for his accomplishments.

Bruce Heise (NPS- GRD) followed with a presentation summary of the up- to- date results of the Colorado GRI program. The status of each park area for geologic mapping inventories, digitizing maps, assembling bibliographies, preparing reports and defining deliverable dates for the NPS units in Colorado was discussed, as the Utah parks will follow a similar process.

Interpretation

The GRI also aims to help promote geologic resource interpretation within the parks and GRD has staff and technology to assist in preparation of useful materials including developing site bulletins and resource management proposal (RMP) statements appropriate to promoting geology. Jim Wood (GRD) and Melanie Moreno (USGS- Menlo Park, CA) have worked with several other NPS units in developing web- based geology interpretation themes, and should be considered as a source of assistance should the park desire.

Zion interpreters pointed out that the park's newspaper has an excellent article summarizing some aspects of the park's stratigraphy. Also, the park's program entitled "Sedimentary my dear Watson" was illustrated as an example of a successful interpretation program in a park that treats geology.

Zion interpreters said their goal is to educate the public that geology is not boring. A significant GPRA (government performance and results act) goal for the park is that97% of visitors will be able to understand some aspects of the geology, and thus there is an emphasis on simplifying the geology for visitors. To aid in this process, more graphics and brochures related to the geology are desirable and should target the average enthusiast. These could be either black and white or full color (similar to the park's main brochure). It was also noted that supplies of such produced material should be always stocked instead of distributed once in a single mass printing.

It was also noted that the appropriate time to promote geology and convey a geologic message with the visitor is at the time of their visiting experience when they are most receptive to learning, not a week later. This may involve trying to get them to concessions to purchase materials relevant to the geology so that they can further their interest.

Tom Haraden (Zion NP) discussed how interpreters reach the general public. He believes most park visitors want to be around rangers and interpreters when they come to the area. The park has an environmental education person working to educate teachers on the geology so that when they bring their groups in, the teacher becomes the knowledgeable "hero" instead of the park staff. To this means, the park will provide props and other learning materials to facilitate this. Also, the new visitor center will feature a 90- second video display on the geology of the park. This should probably be quality assured/ quality controlled (QA/QC'd) by interpretive staff and geologists for accuracy prior to release. Several wayside exhibits are also planned to emphasize the geology so that the common person can discover geology on their own.

Common questions asked of interpreters that involved geology include the following:

- When is the next rockfall?
- Are the rocks monitored for falls?
- What is responsible for the colors of the rocks?

From an ecosystem management perspective, Zion is at the confluence of important physiographic provinces (Basin and Range and Colorado Plateau), making a case for it as the NPS "poster- child" for promoting the ecosystem management concept. It is a spectacular place to integrate geology with biology, hydrology, geomorphology, vegetation and many other facets of the ecosystem. Flood awareness is also a major theme of interpretation; April 1999 was "Flood Awareness Month" at the park and the staff are sure to warn visitors of the potential for danger from this geologic process.

UGA Guidebook on Utah’s National and State Park Areas

Doug Sprinkel of the UGA announced that a guidebook treating the geology of 27 of Utah's national and state parks and monuments will be compiled for publication in September 2000. This compilation will be a snapshot into the geology of each park and covers most facets of what the GRI is trying to develop for each park for a final report (i.e. cross sections, simplified geologic map, general discussions of rocks, structure, unique aspects of park geology, classic viewing localities). Each author will be encouraged to get with NPS staff interpreters to develop a product that aims at a wide audience (the common visitor, the technical audience and the teaching community). Zion NP authors will be our field trip leaders from the UGS (Grant Willis and Helmut Doelling).

Also, a CD- ROM will be distributed with the publication featuring road and trail logs for specific parks as well as a photo glossary and gallery. The photo glossary will describe certain geologic features (i.e. what is crossbedding?). These will also be available as web-downloadable Adobe Acrobat PDF files. The UGA cannot copyright this material because it is funded with state money, so it can be distributed widely and freely, which will also benefit the purposes of the GRI. Additional reprints are not a problem because of the digital nature of the publication and the UGA board is committed to additional printings as needed. UGA normally prints 1000 copies of their publications because they become dated after about five years; that will probably not be an issue for this publication. Prices for the full- color guidebook are estimated to be approximately $25/copy, and sales are expected to be high (exact estimates for Capitol Reef NM were 125 copies/year). A website for the guidebook is forthcoming in October 1999.

Field Trips will be held in September 2000. Currently, four field trips are scheduled:

1. Arches NP, Canyonlands NP, Dead Horse Point State Park (SP)
2. Antelope Island SP and Wasatch Mountain SP
3. Zion NP, Cedar Breaks NM, Snow Canyon SP and Quail Creek SP
4. Dinosaur NM, Flaming Gorge NRA, and Red Fleet SP

Note: Trips 1 and 2 will run concurrently and Trips 3 and 4 will also run concurrently.

Many other benefits are anticipated from this publication and are enumerated below:

- This type of project could serve as a model for other states to follow to bolster tourism and book sales promoting their state and its geologic features.
- Sandy Eldredge (UGS) will be targeting teaching communities for involvement in the field trips; hopefully teachers will pass on what they have learned to their young audience.
- The language is intended to appeal to someone with a moderate background in geology and yet will be very informative to the educated geologist.
- The publication may be able to serve as a textbook to colleges teaching Geology of National Parks (in Utah).
- A welcomed by- product could be roadlogs between parks in Utah for those visiting multiple parks, perhaps with a regional synthesis summarizing how the overall picture of Utah geology has developed.

Paleontological Resources

The field trip provided glimpses into the little known paleontological resources of dinosaur trackways near the visitor center. Intern Joshua Smith has been locating and studying the tracks and will be giving a summary of his findings to the Zion interpretive staff in the near future. It has been suggested to keep these locations low profile to minimize disturbances and potential theft or vandalism.

Vince Santucci (NPS- GRD Paleontologist) will be co-authoring a "Paleontological Survey of Zion National Park" with Josh and detailing their findings of resources within the park. Plants, invertebrates, and vertebrate tracksites are among the recognized paleontological resources within the Zion area.

Similar surveys have been done for Yellowstone and Death Valley NP's and have shed valuable new information on previously unrecognized resources. These surveys involve a literature review/bibliography and recognition of type specimens, species lists, and maps (which are unpublished to protect locality information), and also make park specific recommendations for protecting and preserving the resources.

The Death Valley Survey will be available soon. The Yellowstone Survey is already available on- line at:
http://www.nature.nps.gov/grd/geology/paleo/yell_survey/index.htm
and is also available as a downloadable PDF at:
http://www.nature.nps.gov/grd/geology/paleo/yell.pdf

Paleontological resource management plans should be produced for Zion involving some inventory and monitoring to identify human and natural threats to these resources. Perhaps someone on the park staff could be assigned to coordinate paleontological resource management and incorporate any findings or suggestions into the parks general management plan (GMP). It would be useful to train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands.

Collections taken from this area that now reside in outside repositories should be tracked down for inventory purposes. Fossils offer many interpretive themes and combine a geology/biology link and should be utilized as much as possible in interpretive programs.

Status of Cooperative Geologic Mapping Efforts for Zion

UGS Perspective:
Currently, the UGS is mapping at three different scales:

- 1:24,000 for high priority areas (i.e. National and State parks)
- 1:100,000 for the rest of the state
- 1:500,000 for a compiled state geologic map

The availability of funding for Zion (jointly with the NPS) has made it possible for these higher priority areas to be mapped at this detail. The UGS plans to complete mapping for the entire state of Utah within 10- 15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from "special interest" areas (i.e. areas such as Zion and growing metropolitan St. George). Grant Willis mentioned that the UGS simply does not have enough manpower and resources to do more areas at this scale. He also reiterated that UGS mapping goals are coincident with those of the National Geologic Mapping Program.

In Zion NP, the UGS has been jointly cooperating with the NPS and USGS for some time on producing these 1:24,000 quadrangles in both paper and digital format. Until 1995, the USGS had done major mapping projects under the BARCO (Basin and Range to Colorado Plateau) mapping program. When the USGS reorganized, many of these projects were put on indefinite hold. Fortunately, there has been mutual cooperation between the UGS and USGS to work together to get these products completed for the NPS. The NPS appreciates the labor of all involved parties and individuals in this cooperative and hopes that many products will result from the combined efforts of all involved agencies.

The UGS has divided their mapping work in Zion into two distinct phases. The first phase involves producing geologic maps for the following quadrangles (see Zion NP Index of Geologic Maps, 1:24,000 Scale):

- The Guardian Angels
- Temple of Sinawava
- Clear Creek Mountain
- Springdale West
- Springdale East

All five quadrangles are field mapped and are presently in the internal review stage by the UGS; some field spot-checking is desirable. Some of the mapping was done using photogrammetric methods and some is hand drawn on Mylar. The UGS expects to deliver both completed paper and digital products by October 1, 1999. The original projected deliverable date was April 1, 1999, however, the UGS has had significant turnover with their GIS personnel and has requested an extension until October 1st.

The second phase is beginning in spring 1999. This will involve geologic mapping for the following quadrangles:

- Kolob Arch
- Kolob Reservoir
- Cogswell Point
- Completion of Smith Mesa, The Barracks, and Navajo Lake

This phase will also involve completing the Smith Mesa quadrangle. Ed Sable (USGS) was the primary worker on this map but was unable to complete it due to health problems. The USGS and UGS are working cooperatively to get make sure this product is completed. The Barracks (southeast Zion NP) and Navajo Lake (south Cedar Breaks NM) are already available as published paper maps and will be digitized as part of this phase. Deliverable dates for this phase should be September 2001 according to Grant Willis. Upon completion of this phase, there will be complete digital coverage for Zion NP.

Some issues have surfaced regarding the correlation of Quaternary deposits across quadrangle boundaries which have caused some delay in matching edges between maps of the USGS BARCO project and those of the UGS. The UGS would like to treat these deposits more in- depth.

USGS Perspective: Pete Rowley (USGS) talked about the immense scope of the BARCO project for preparing 1:100,000 scale maps for earthquake potential, mineral resources and various other themes. Mapping was done at the 1:24,000 scale and compiled at 1:100,000 scale. Unfortunately, this project was put on the backshelf because of the USGS 1995 reorganization and many of the original workers have not been able to realize final products for their previous mapping efforts.

The UGS has essentially inherited much of Ed Sable's work in the Zion area since health problems wouldn't allow him to continue working in the field. Since the USGS requires digital geologic maps for all of their work, Pete is working with Southern Utah University's (SUU) Dave Maxwell to complete digitizing for Ed's BARCO work. It seems like the UGS has the Zion area well in hand, so Pete's energies will be focused on deliverables for the Bryce Canyon and Cedar Breaks areas.

USGS assistance is most welcomed in completing quadrangles in the vicinity of Zion, Cedar Breaks, and Bryce Canyon because the UGS does not have personnel currently assigned to work in these areas. Both the USGS and UGS agree that the main priority is to get these BARCO products into usable forms and give credit where credit is due. The following quadrangles were mentioned as either being partially mapped or important to the regional watershed:

- Straight Canyon
- Flanigan Arch
- Webster Flat
- Mount Carmel
- Glendale
- Orderville
- Long Valley Junction
- North
- Strawberry Point
- Alton
- Yellow Jacket Canyon
- Elephant Butte
- Hilldale
- Cedar Mountain
- Kannarraville
- Smithsonian Butte

While these quadrangles are not necessarily within an NPS boundary, they are part of the regional watershed and would be welcomed products by the NPS. Bob Higgins suggests trying to get NPS Water Resources Division (WRD) to help fund some of the mapping since the bedrock geology is already available and since these involve the watershed.

As the park's hydrologist, Dave Sharrow would like to see some emphasis on studying the quadrangles east of Zion for water issues. From his perspective those closest to the Sevier fault are of most interest to him because of a lack of understanding of the hydrology nearest the fault. Pete has done a similar type of project for Nevada test site and would be willing to further discuss this with Dave Sharrow.

There are some financing issues to consider in completing these quadrangles:

- Pete would need some financial assistance in digitizing these maps at SUU
- An EDMAP project may be a good way to obtain assistance for completing any needed field mapping with SUU students
- Pete's salary and time needs to be covered by the USGS to work on this project
- Other surficial specialists (Van Williams was mentioned) may need to be called upon to help complete the surficial mapping and caliche deposits; also numerous landslides are known for the area and should be mapped appropriately. Salary and time is also an issue for these specialists.

A priority list for quadrangles of interest should be developed for SUU and estimates of costs to complete the work also need to be ascertained.

Other Sources of Natural Resources Data for Zion NP

- The UGS has a significant quadrangle database that they have furnished to NRID for the entire state of Utah.
- NRID has compiled a geologic bibliography for numerous parks and monuments, including Zion. Visit the website at: http://165.83.36.151/biblios/geobib.nsf; user id is "geobib read", password is "anybody".
- The USGS has compiled large volumes of data on the BARCO project that was halted in 1995; much of this work is unpublished and should be sought out from USGS personnel.
- It was suggested that the DOE may have mineral exploration data for the area as there are numerous

mineral resources within the park (copper, iron, uranium, silica, cinders, gravels, coal, as well as hydrocarbon potential).

- A STORET water quality report apparently exists and may be available from the NPS- WRD.
- Wayne Hamilton's 1987 geologic map is digitized because years ago park staff needed a geologic layer for their GMP to define use areas within the park. However, it is expected that the new layers provided by the UGS will make this existing coverage obsolete.
- A soils map apparently exists for the park but could use significant improvement. It contains adequate soil descriptions, but according to Laird Naylor boundaries are poor. It was suggested that the new geology layers can enhance the existing understanding of the soils by comparing layers.
- Both an Archeological and Paleontological (from Josh Smith) database apparently exist, but there is no metadata, rendering it incomplete. Proposed coverages include a layer for floodplains, geologic hazards, and debris flow paths.
- It was rumored that the park may also have a disturbed land sites database featuring many small dams (up to a few acres). It was suggested that GRD begin compiling and tracking this information for their disturbed lands programs as it is a component of the GRI. Suggested park contacts for this database were Laurie Kurth and Darla Sidles. GRD's Disturbed Lands coordinator (Dave Steensen) may want to attempt to contact these folks and obtain any available data.
- Other disturbed land related issues included exotic species and channelization along the river. The river restoration debate involves whether the river should be allowed to run its course. Restoring the stream channel to its natural position is identified in the GMP, and will likely be a very expensive endeavor.

Geologic Hazards

There are numerous issues related to geologic hazards in and around Zion NP. Below is a brief list of some mentioned during the scoping session:

- Landslides of April 1995, 1923, 1941, and September 11, 1998 that resulted in taking out the park road to the Zion Lodge
- Many active landslides are in the park on North Creek with the potential to dam creek and create lake (i.e. above Sunset Ridge headquarters at edge of park boundary)
- A few years ago, from the Kolob Canyon section, portions of Interstate- 15 was washed over and vehicles were actually washed off of the road (this was pointed out to us during the field trip) because of a landslide from a dam collapse
- 1992 earthquake scarp in Springdale at west entrance of park
- The Hurricane Fault marks the western boundary near the Kolob Canyon section of the park; the actual road is built essentially on the fault surface
- The potential for volcanism exists within the Zion area
- Debris flows and rockfalls are constant sources of problems during rainstorms
- Collapsible soil potential from swelling soils within the Triassic Chinle Formation, and windblown loess deposits
- Radon is known from soils developed upon the Chinle Formation
- Abandoned mineral lands (AML) for uranium mining near the Kolob Canyon Visitor Center
- An existing oil well within park boundaries may pose the threat of mixing with groundwater and present a water quality breach
- It was suggested that any future facility siting exercises should focus near Crater Hill

Potential Research Topics for Zion NP

A list of potential research topics includes studies of the following:

- Study the hydrology nearest the Sevier fault zone (east of Zion NP)
- Lake development and climate history
- Study Helmutt Doelling (UGS) core to bottom of lake deposits; take new core to bottom of deposits
- Lacustrine chronology from lake sediments
- History of slope instability from landslides (try to ascertain ages of landslides)
- Alluvial terrace chronology
- River system erosion history with emphasis on upstream basalts
- Fracture flow within the Navajo Sandstone because it is an important aquifer (Pete has student Jonathan Cain doing post- doc work with USGS- WRD)
- Study of Joints for ground- water quality/quantity
- Locations of hydrologic divides (where is the water going ?)
- History of Hurricane fault as related to Basin and Range extension
- Geologic Type section for Navajo Sandstone within the park
- Vegetation type vs. rock type; what are the correlations
- Development of way to date desert varnish ages;(Larry Snee will do it for $500,000; Pete Rowley's wife has worked on similar projects; she is an archeologist)
- Color in rocks due to cementation: Navajo groundwater and diagenesis creating color changes
- Paleobotanic investigations of various formations
- Study Pack- rat middens for ecological analysis
- Coal pit deposits
- History of joint formation
- Also, Tom Haraden should be consulted for his ideas on various interpretation and education topics; consult Wood and Moreno for assistance

Action Items

Many follow- up items were discussed during the course of the scoping session and are reiterated by category for quick reference.

Interpretation:

- More graphics and brochures emphasizing geology and targeting the average enthusiast should be developed. If Zion NP needs assistance with these, please consult GRD's Jim Wood (jim_f_wood@nps.gov) or Melanie Moreno at the USGS- Menlo Park, CA (mmoreno@usgs.gov).
- QA/QC of the new 90 second geology video for the new visitor center by geologic professionals for accuracy

UGA Guidebook:

- Attempt to plant the seeds of this concept to other states for similar publications involving local area geology. Such publications are especially useful for the GRI

Paleontological Resources:

- For now, try to minimize location disclosure of vertebrate tracksites to minimize disturbances and the potential for theft or vandalism
- Develop an in- house plan to inventory, monitor and protect significant paleontological resources from threats; assign staff to oversee
- Locate collections taken from the park residing in outside repositories

Geologic Mapping:

- UGS deliver to NPS all Phase 1 products (paper and digital) by October 1, 1999
- UGS deliver to NPS all Phase 2 products (paper and digital) by September 2001
- Maintain UGS- USGS- NPS cooperation to reap all possible products from existing USGS BARCO work to benefit the NPS GRI
- Consult with NPS- WRD to obtain funding for mapping numerous quadrangles contained in regional watershed
- USGS address issues relating to funding salaries and other work to ensure BARCO products can be delivered
- USGS develop for SUU a priority list of quadrangles to digitize and complete field mapping, as well as associated estimates of time and material costs

Natural Resource Data Sources

- Improve the soils map for Zion NP
- NPS- GRD Disturbed Lands Coordinator should consult with Zion staff about obtaining disturbed lands database

Miscellaneous

- Laird Naylor suggested that Stan Hatfield, Robert Eves, and Fred Lohrengel (all of SUU) and Dave Madsen and Lee Allison (both UGS) should be invited to attend the Cedar Breaks NM meeting in July 1999
- Review proposed research topics for future studies within Zion NP

Budget Items

- The UGS has picked up 70% of the costs of mapping using State Map matching funds.
- NRID I&M paid $79K in FY96 and $59K in FY98 for a total buy- in of $13

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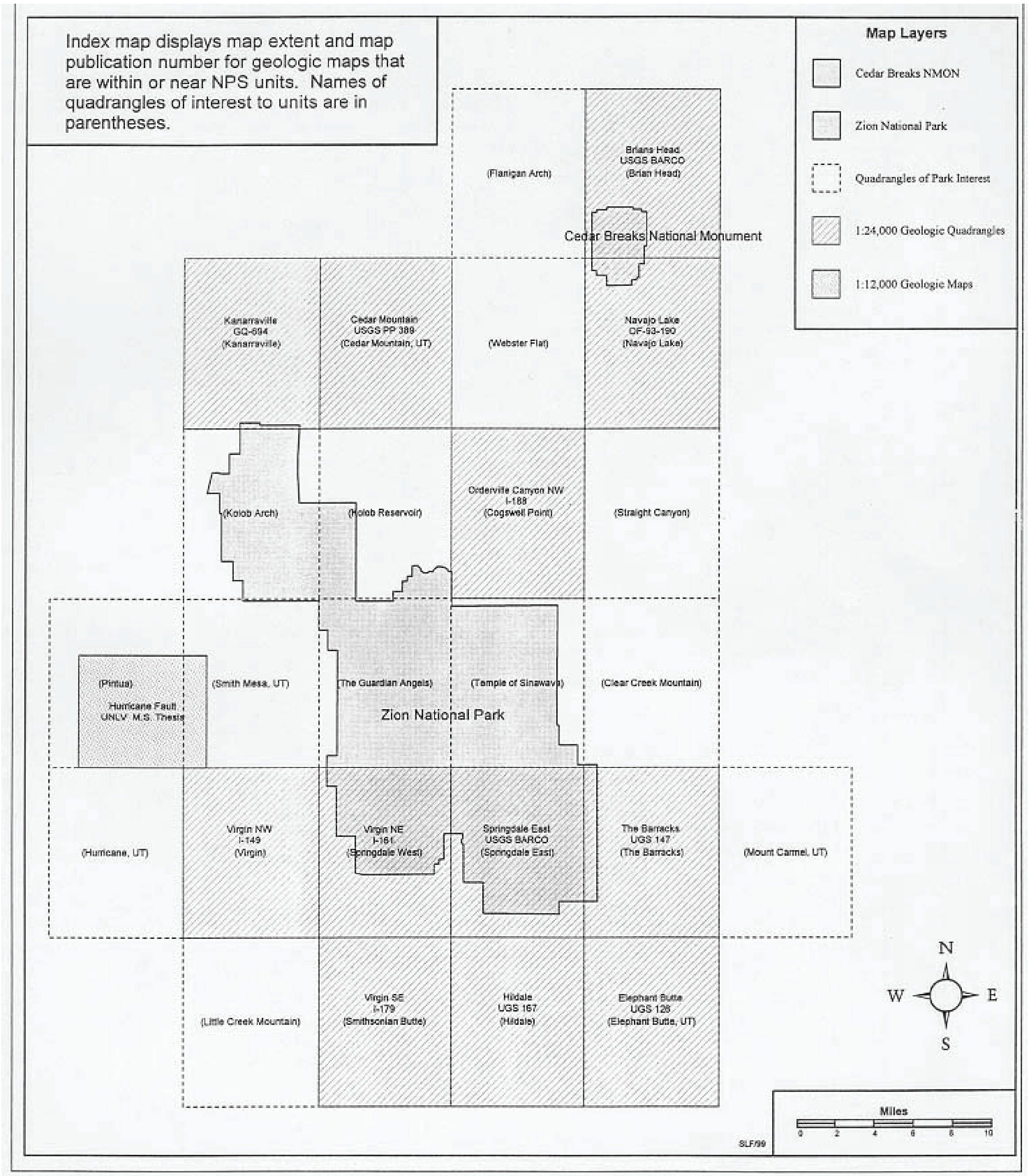

Zion National Park Index of Quadrangle Maps (1:24,000 scale).

Zion National Park

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/014
NPS D-259, March 2006

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

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Natural Resource Program Center

The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring and Evaluation, and the Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross-cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the national park system.

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