National Park Service
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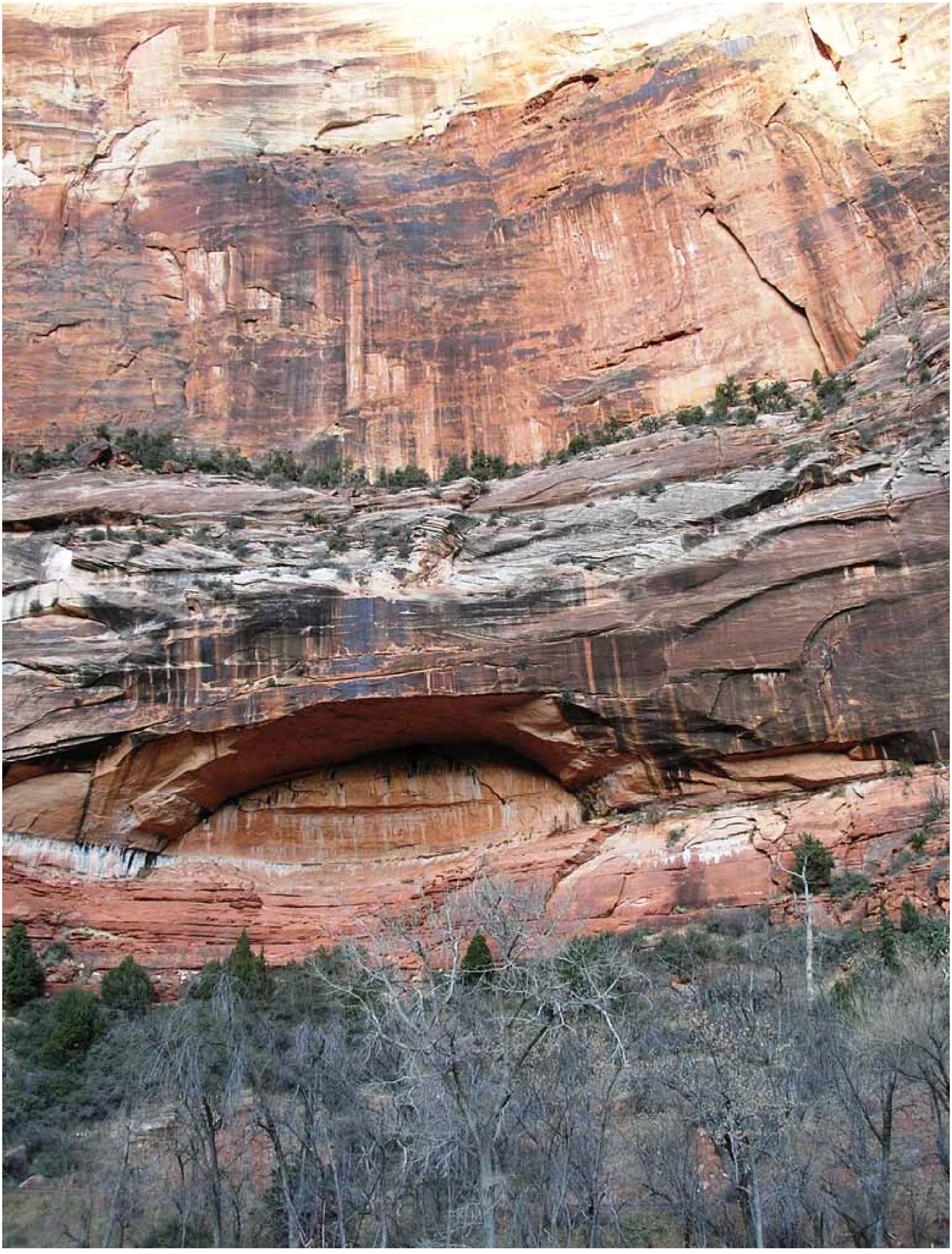
Natural Resource Program Center

Zion National Park

Geologic Resource Evaluation Report

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



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Geologic Resources Division
Natural Resource Program Center
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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."

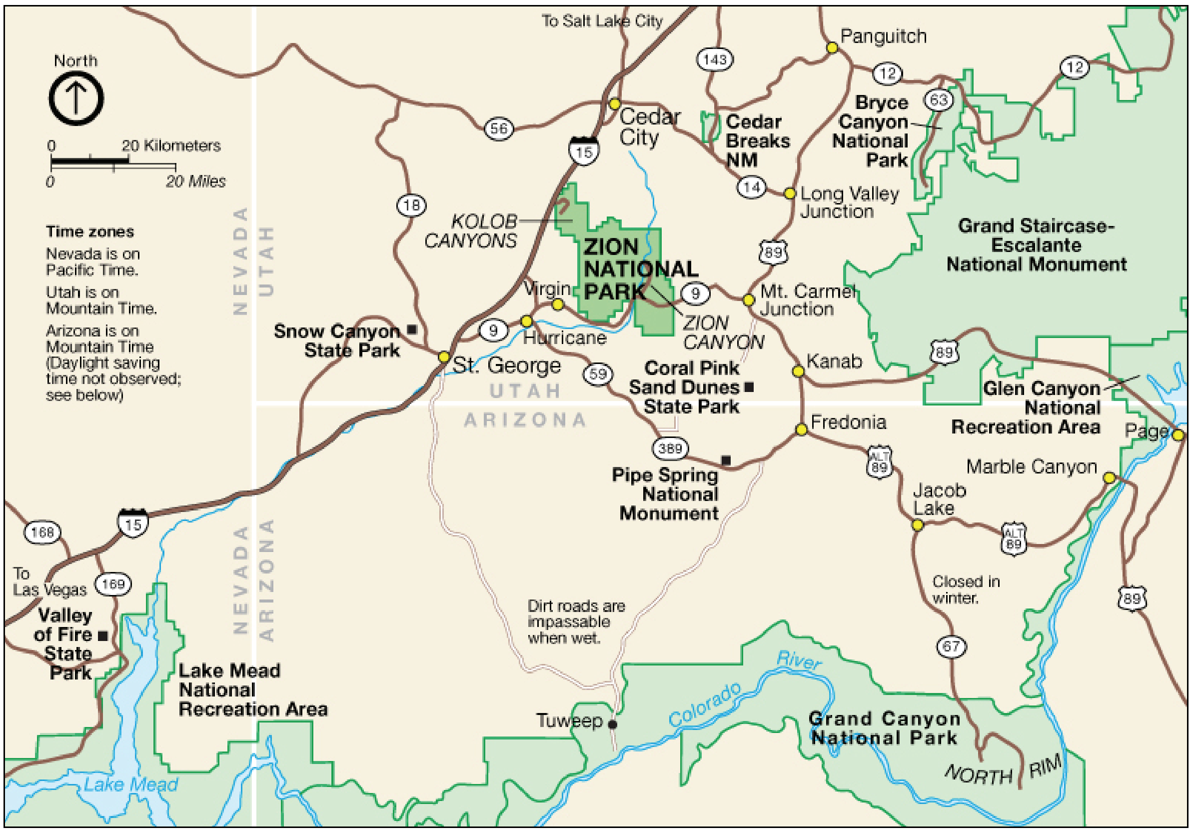


Figure 1. Location map of Zion National Park.

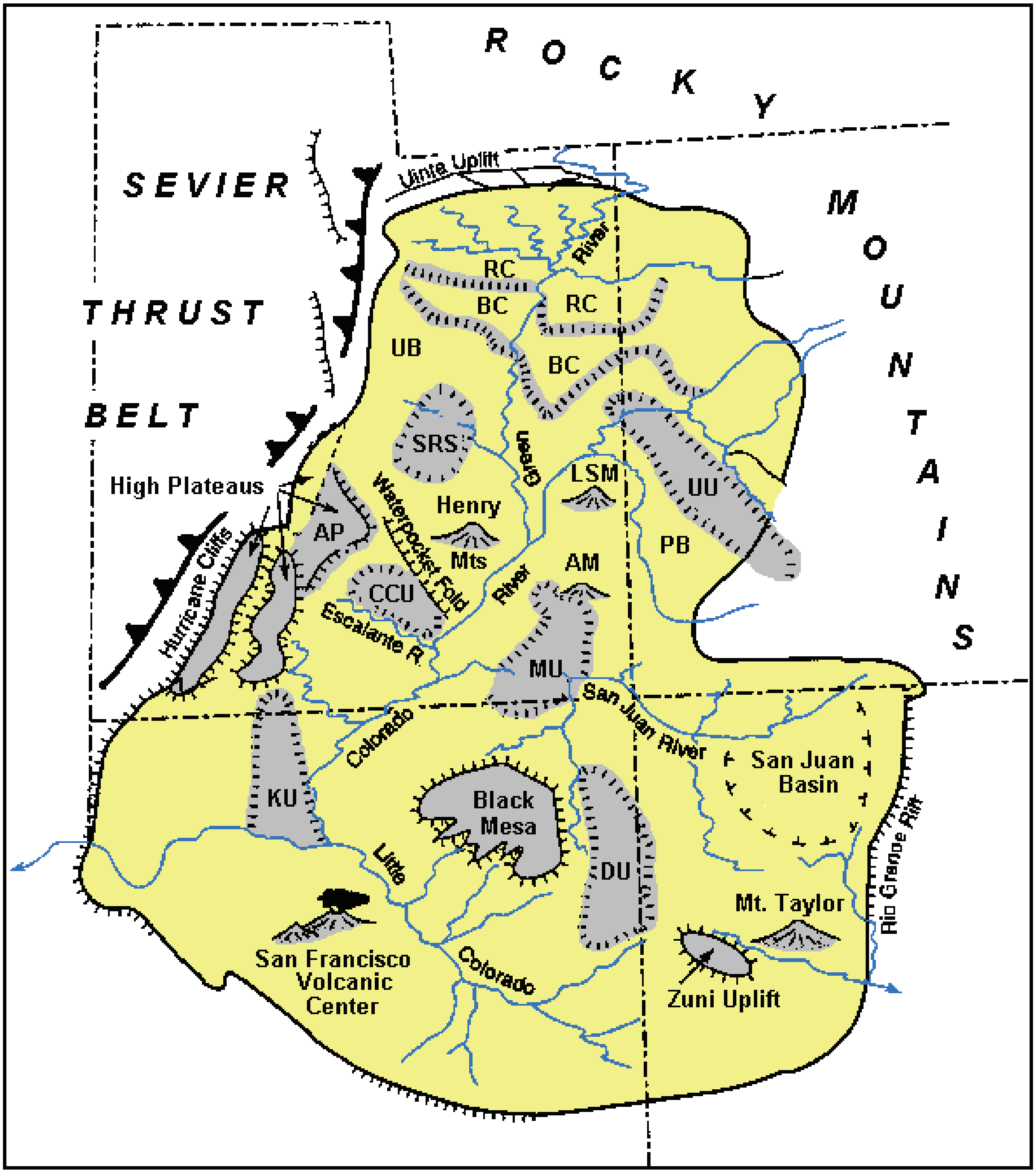


Figure 2. Location of Zion National Park on the Colorado Plateau, showing some of the significant uplifts, basins, faults, volcanic centers, and rivers. High areas are shown in gray: AM, Abajo Mts.; AP, Aquarius Plateau; BC, Book Cliffs; CCU, Circle Cliffs Uplift; DU, Defiance Uplift; KU, Kaibab Uplift; 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.

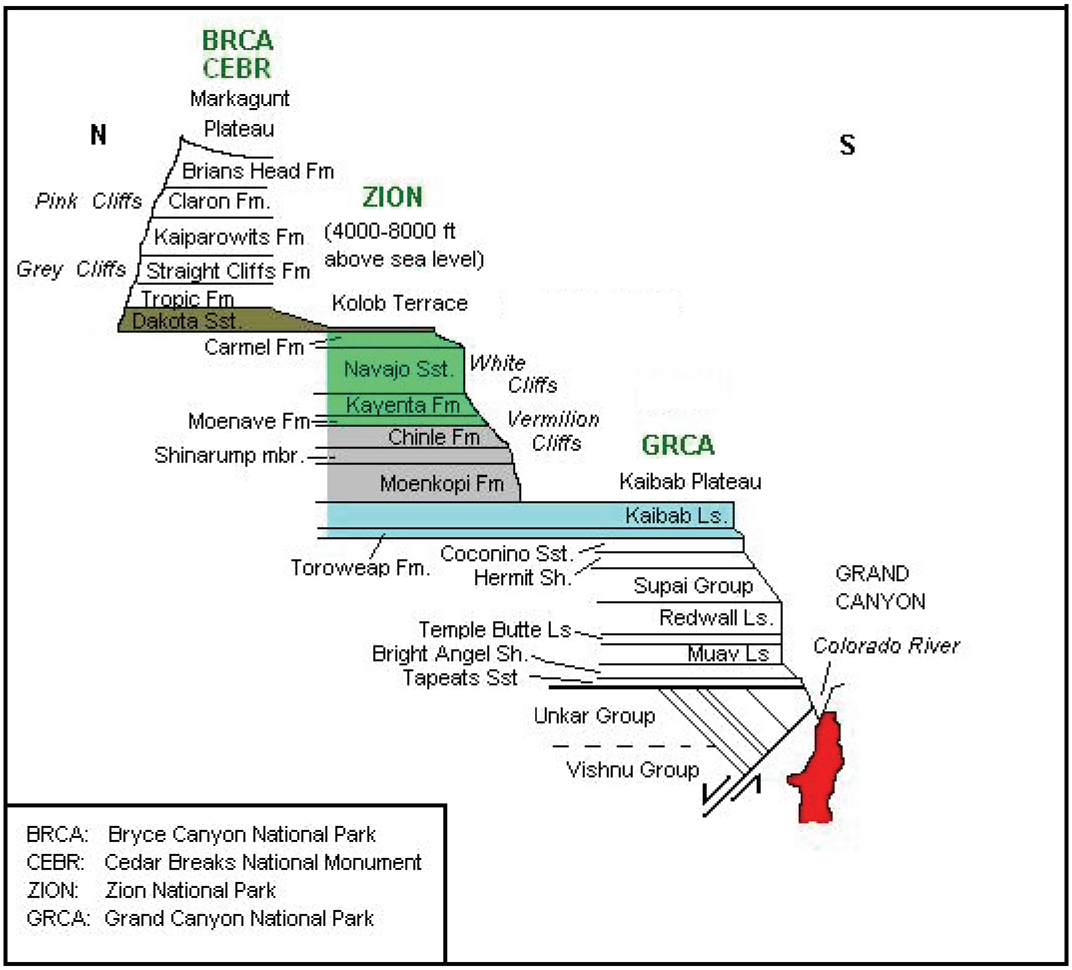


Figure 3. Geologic cross-section of the Grand Staircase from the Grand Canyon to Bryce Canyon National Park and Cedar Breaks National Monument. Diagram illustrates the lithologic correlation from south to north. Modified from the geologic cross section published by the Zion Natural History Association,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

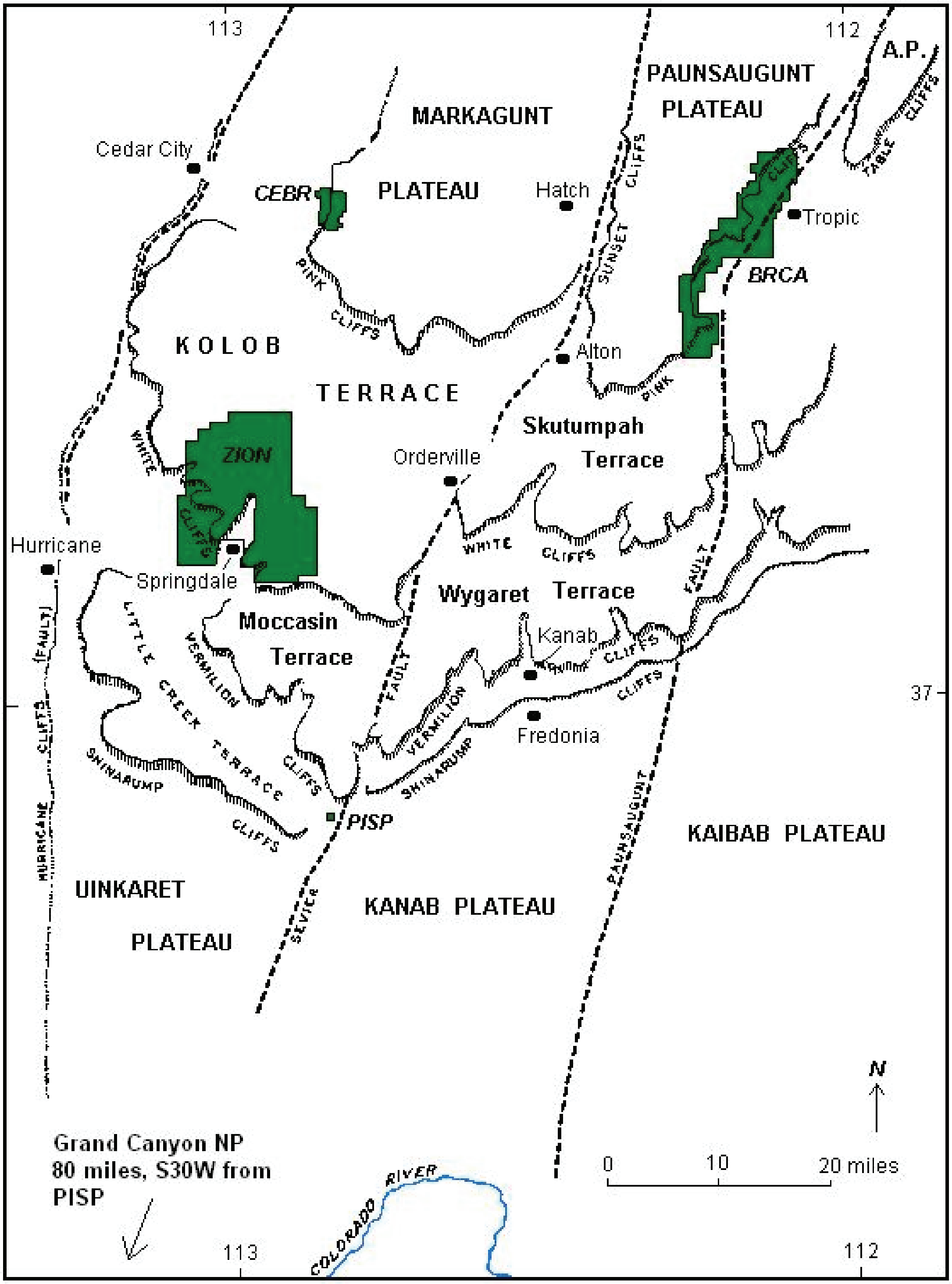
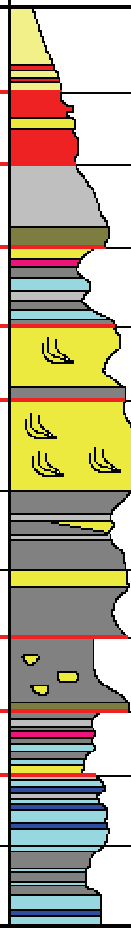


Figure 4. Sketch map modified from Gregory (1950) showing the location of Zion NP and the position of the major plateaus, terraces, cliff lines, and faults in the Zion region. ZION: Zion National Park; BRCA: Bryce Canyon National Park; CEBR: Cedar Breaks National Monument; PISP: Pipe Spring National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

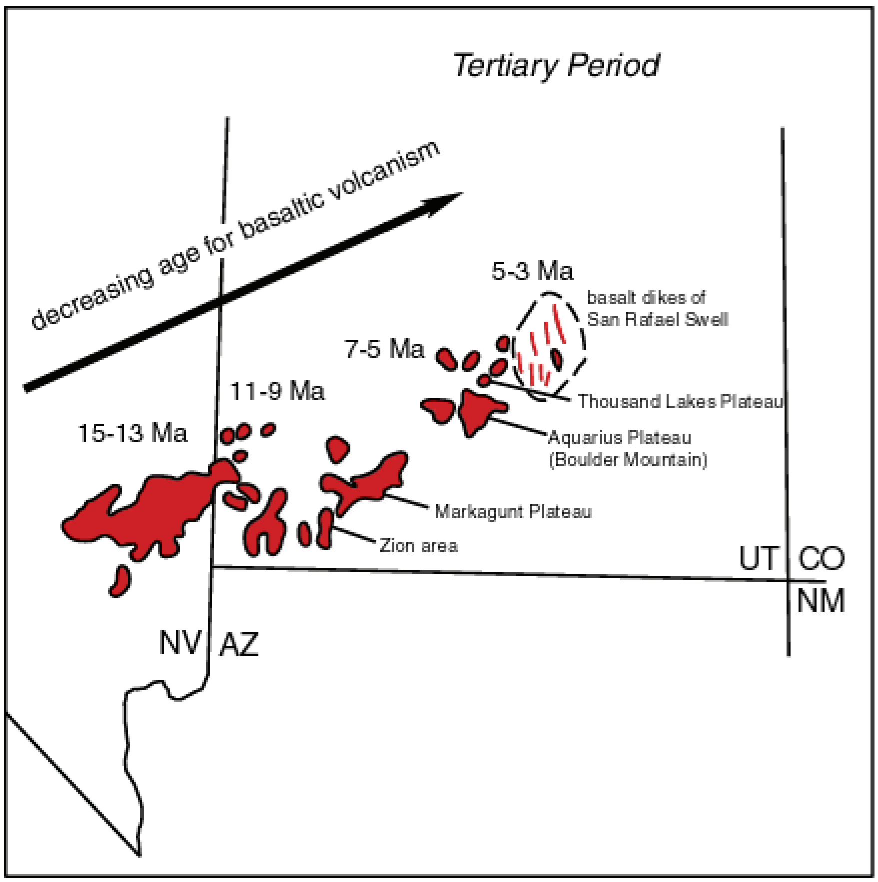


Figure 6. The distribution of young basalts in southern Nevada and southern Utah and their approximate ages. The ages systematically decrease from west to east suggesting the presence of a fixed hot spot in the mantle. Modified from Fillmore, 2000, and Nelson and Tingey, 1997.

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.

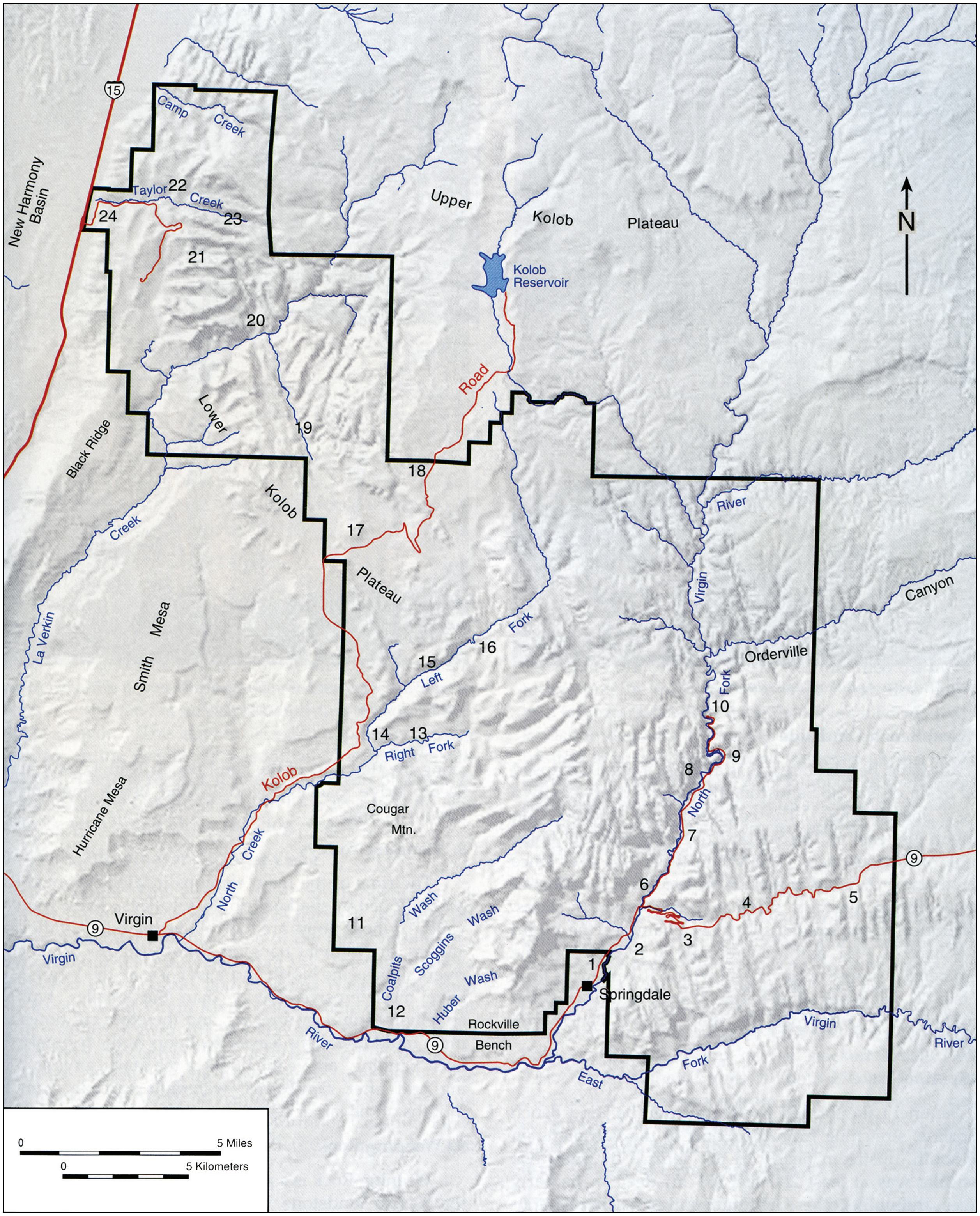


Figure 7. Locations of selected geologic sites in Zion. Image is imported from Biek et al. (2000).

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 1.5x10^5 km^3 (3.6 x10^4 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.

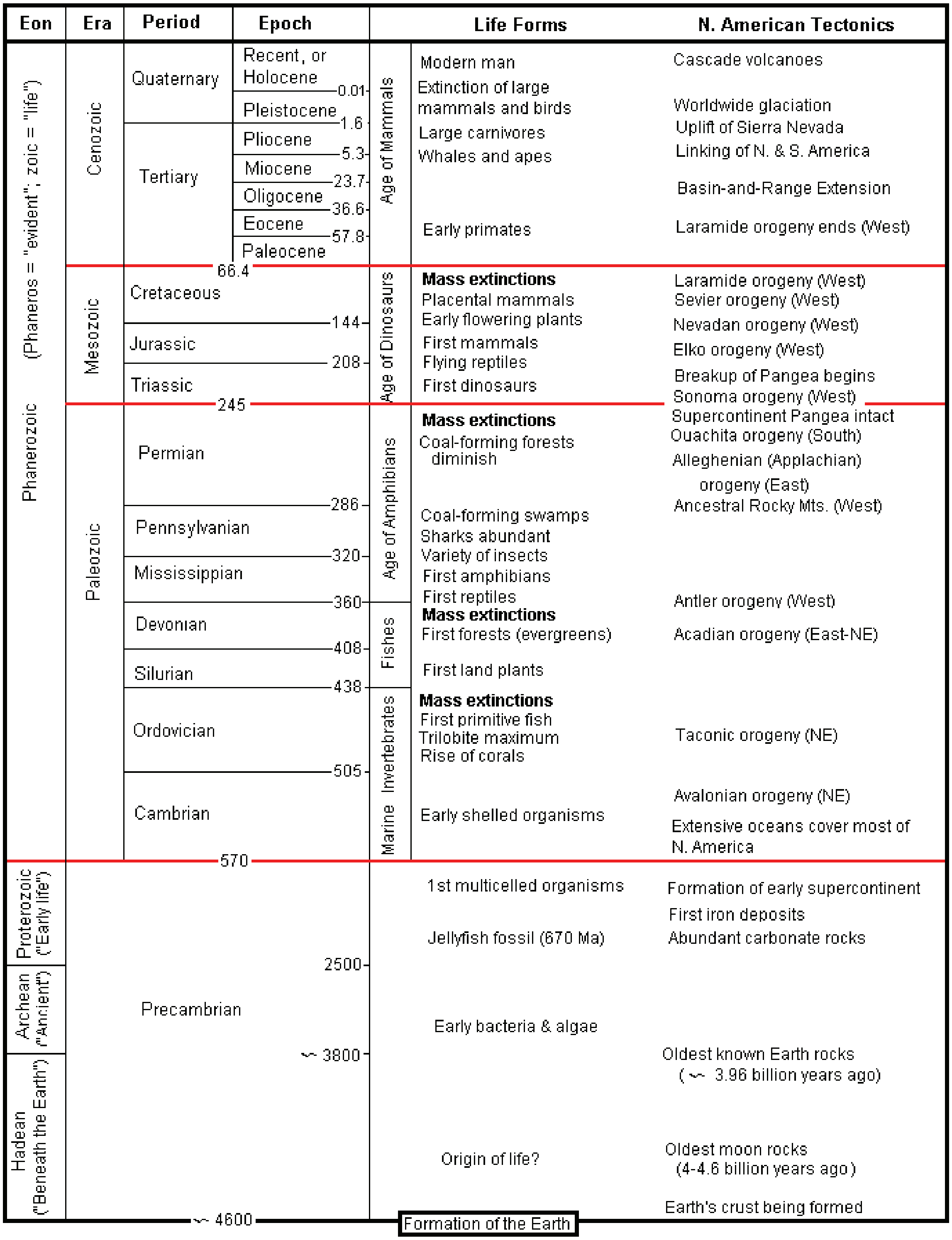


Figure 8. Geologic time scale. Red lines indicate major unconformities between eras. Absolute ages shown are in millions of years. Scale is from the U.S.G.S.

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 Crystal Creek	Jcp Jcx	Marginal marine, arid coastal
			Co-op Creek	Jcc	Open & restricted marine
		Temple Cap	White Throne	Jtw	Coastal dunes
			Sinawava	Jts	Warm shallow marine
	Lower	Navajo	white unit pink unit brown unit	Jnw Jnp Jnb	Coastal eolian dune fields (erg)
		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 Fossil Mtn.	Pkh Pkf	Shallow marine, near-shore envs.
		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.

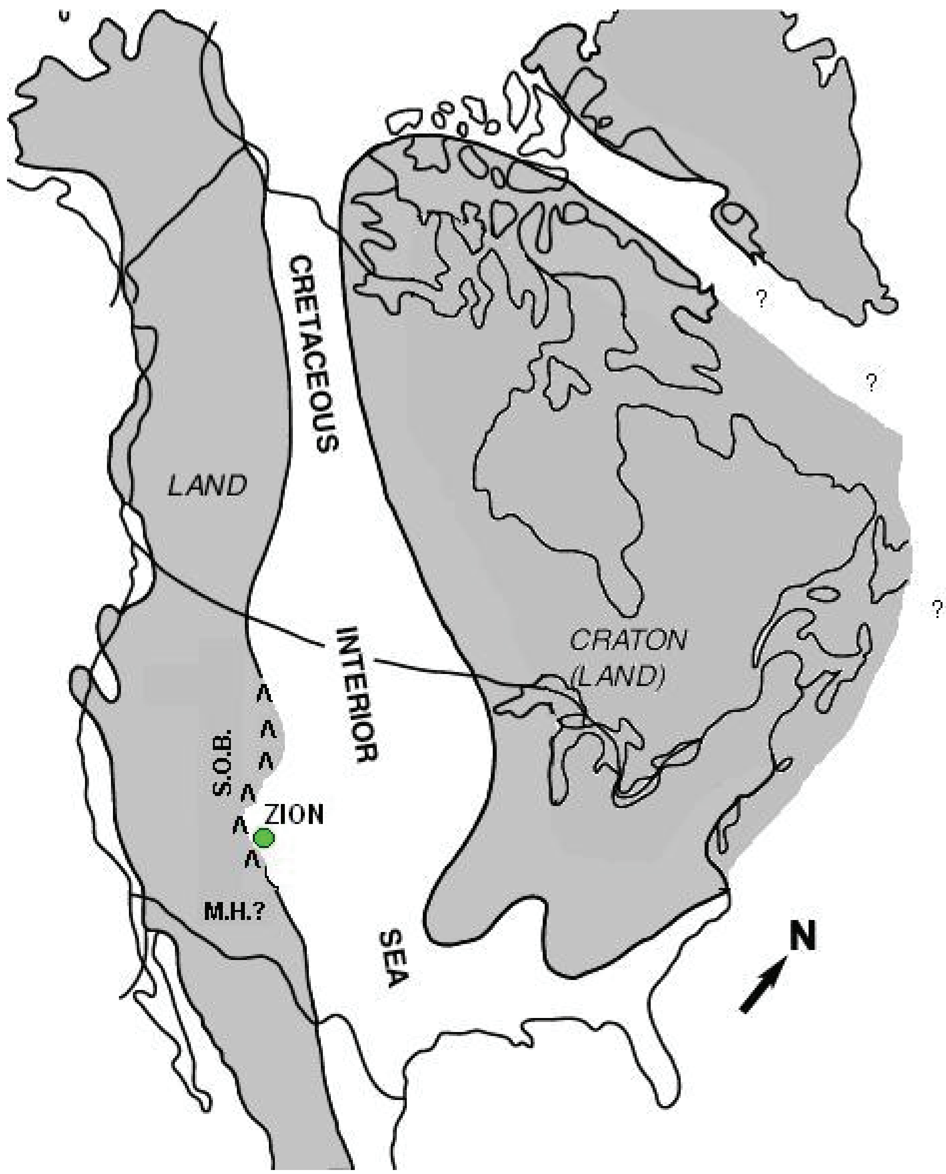


Figure 10. Location of the Cretaceous Period, Western Interior Seaway. Shaded areas indicate land above sea level. North arrow indicates the Cretaceous north. Modified from Rice and Shurr (1983).

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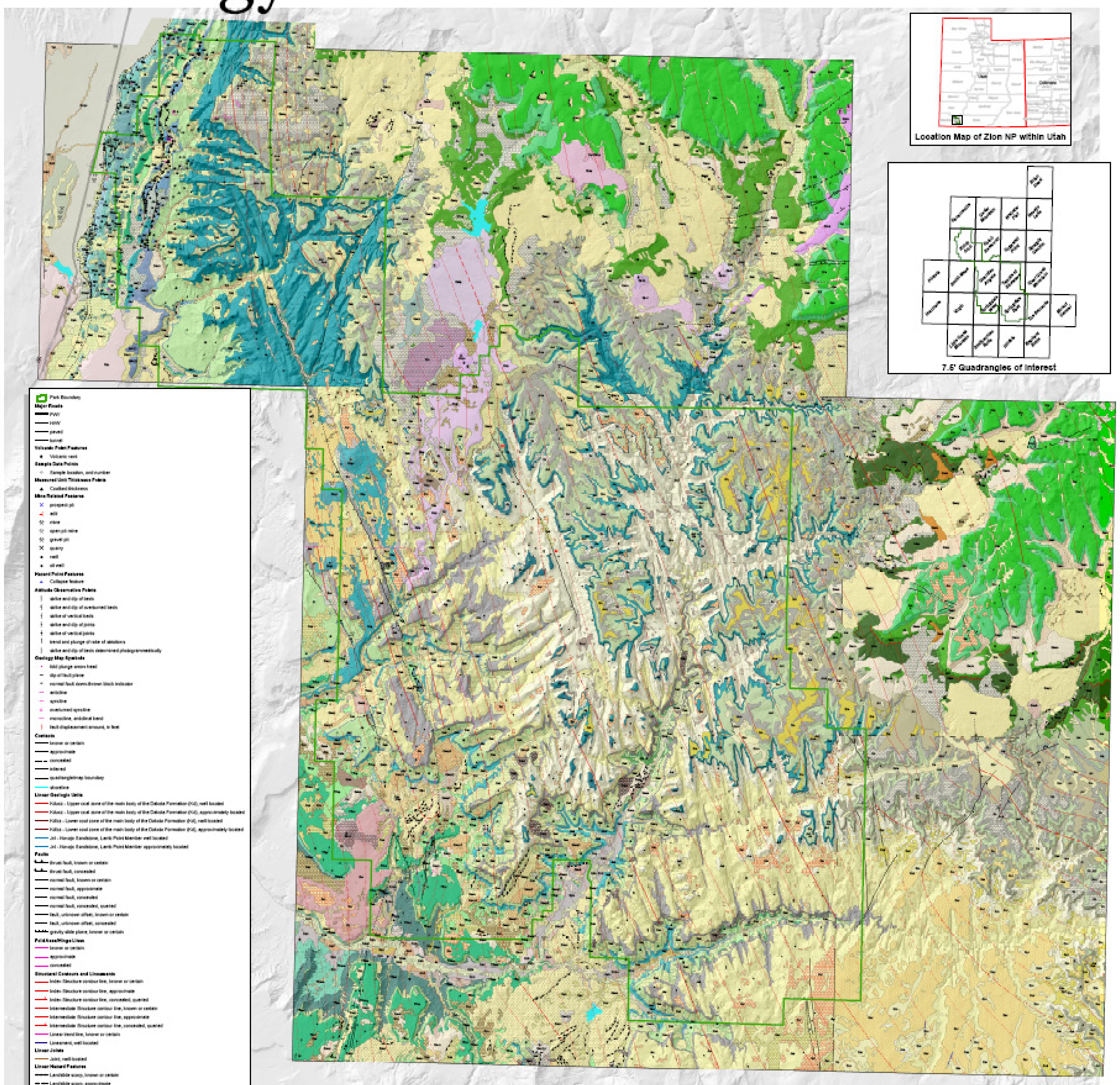
Appendix A: Geologic Map Graphic

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

Geology of Zion National Park



1 0.5 0 1 2 3 4 Miles

1:63,360

Data Set Credit:
Field mapping and compilation: Utah Geological Survey
Digital mapping: Utah Geological Survey
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

September 2005

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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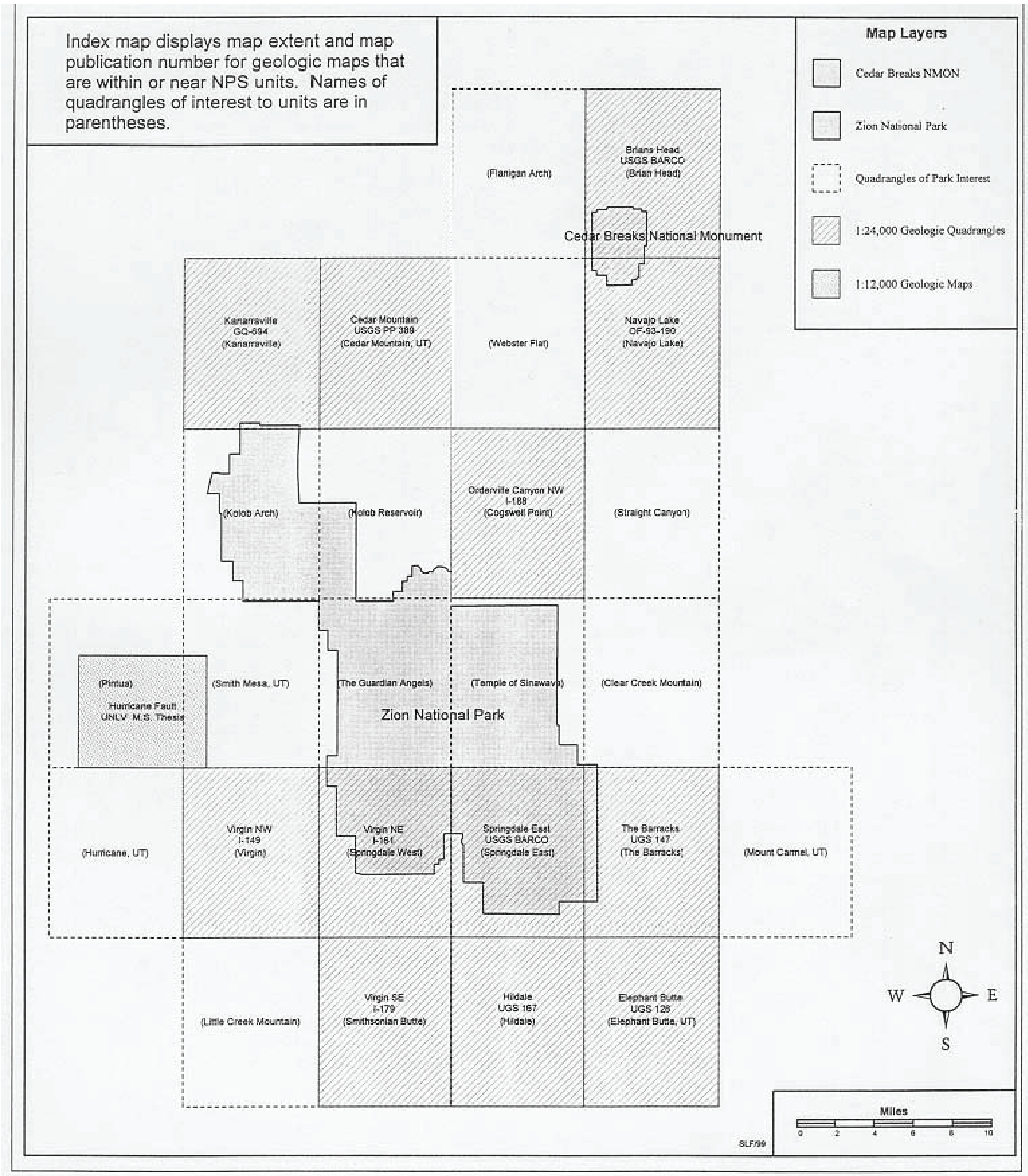

Zion National Park Index of Quadrangle Maps (1:24,000 scale).

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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