National Park Service
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Natural Resource Program Center

Bryce Canyon National Park
Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/002

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Geologic Resources Division
Natural Resource Program Center
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Table of Contents

List of Figures

Executive Summary

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

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

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

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

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

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

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

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

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

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

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

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

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

Introduction

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

Purpose of the Geologic Resource Evaluation Program

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

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

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

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

Geologic Setting

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

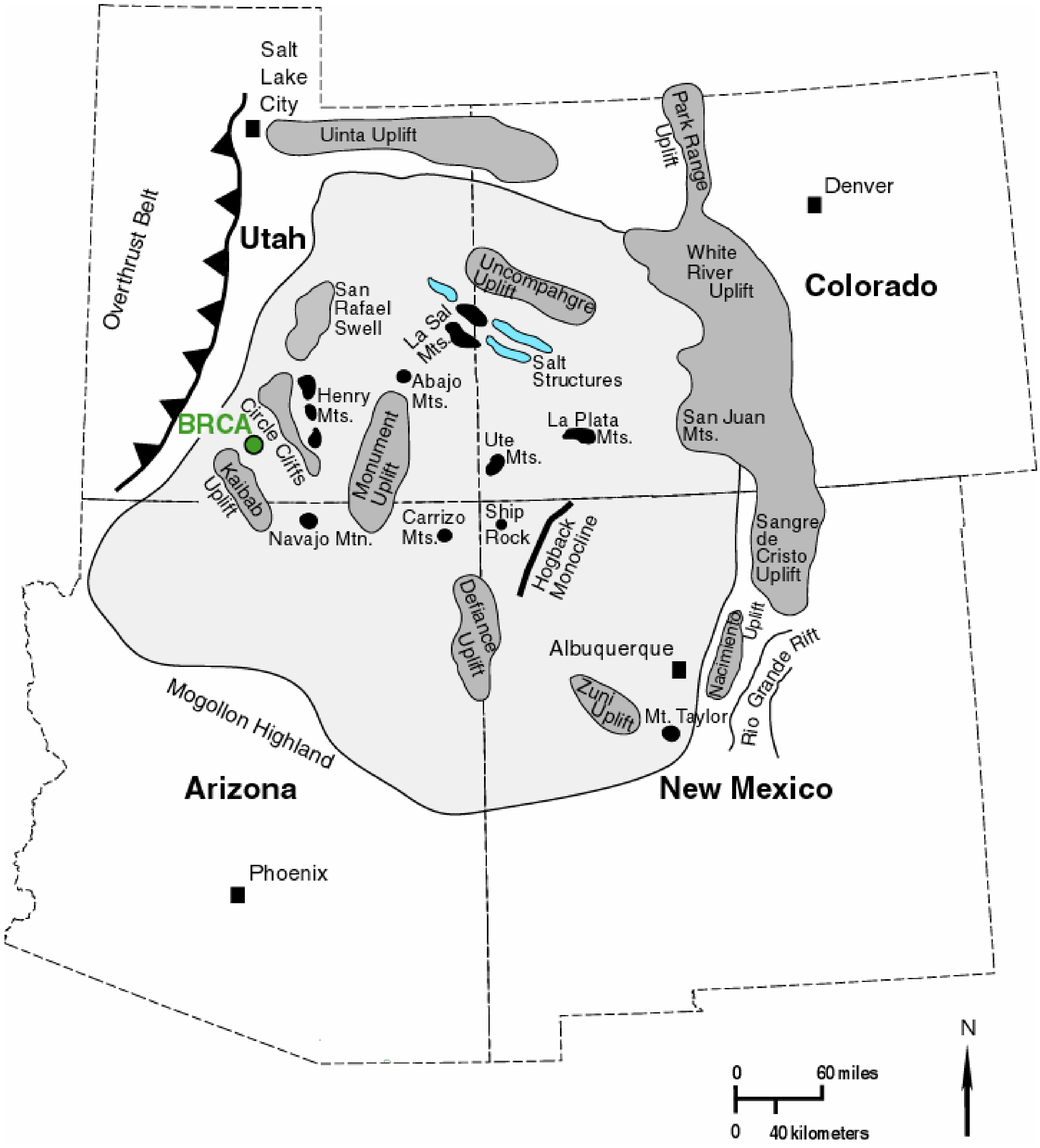

Figure 1: Map of the structural features surrounding Bryce Canyon National Park (BRCA). Light gray area shows extent of the Colorado Plateau while darker gray and black areas indicate regional uplifts and mountains.

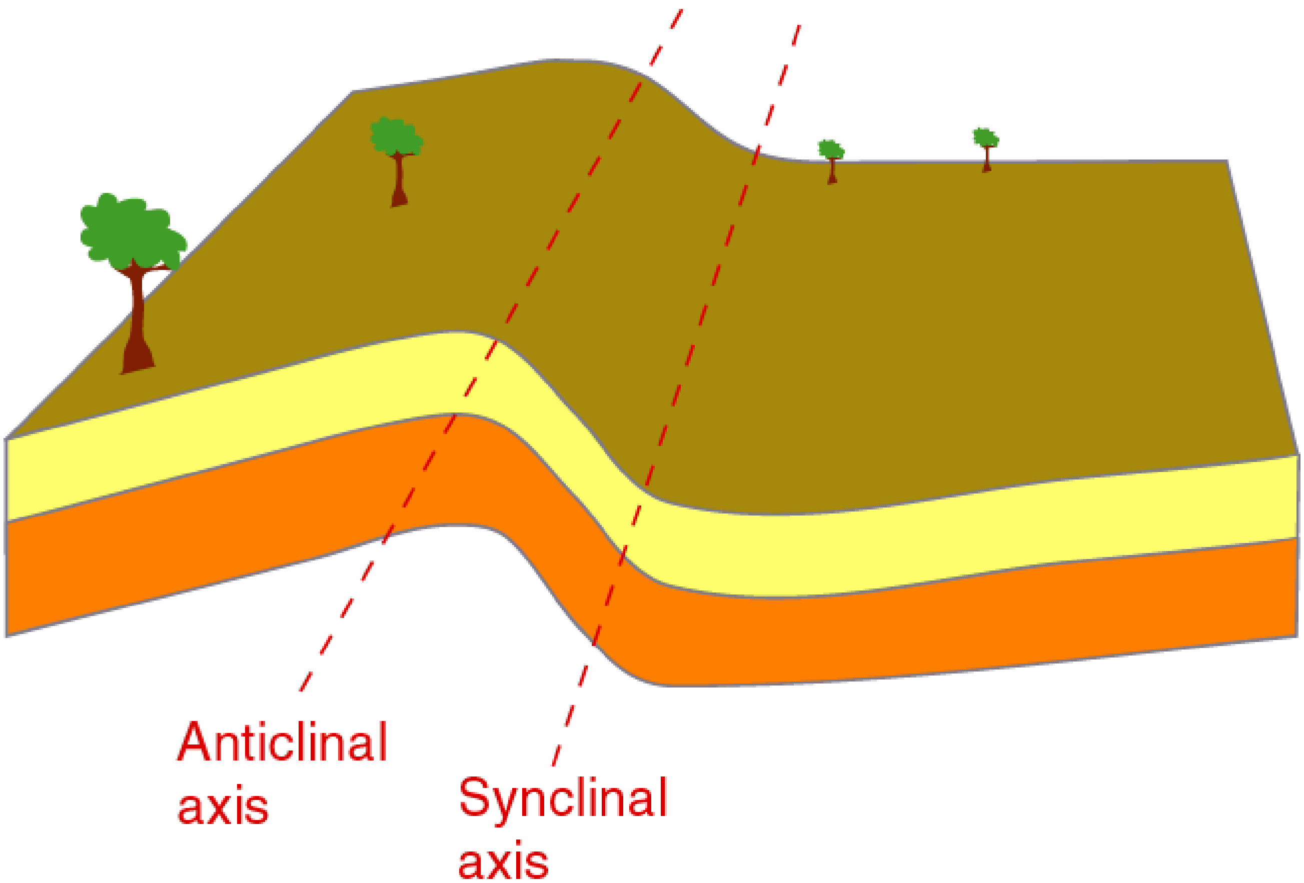

Figure 2: Diagram of a monocline.

Geologic Issues

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

Slope Processes

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

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

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

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

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

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

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

Seismicity and Mining

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

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

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

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

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

Streamflow, Channel Morphology and Sediment Load

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

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

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

Water Issues

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

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

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

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

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

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

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

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

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

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

Hoodoo Formation and Present Condition

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

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

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

Paleontologic Potential

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

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

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

Faulting and Deformation Processes

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

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

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

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

Gravel and Sand Deposits on the Paunsaugunt Plateau

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

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

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

Mining Resources and Issues

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

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

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

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

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

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

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

Marysvale Volcanic Field

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

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

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

Facilities Management

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

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

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

Wind Erosion and Deposition

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

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

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

General Geology

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

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

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

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

Swelling Clays

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

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

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

Geologic Features and Processes

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

Sevier and Paunsaugunt Faults

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

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

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

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

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

Thrust Faults

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

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

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

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

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

Erosion of the Paria Amphitheatre

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

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

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

Formation of Hoodoos

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

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

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

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

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

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

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

Isolated Features

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

Map Unit Properties

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

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

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

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

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

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

Map Unit Properties Table

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

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

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

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

Geologic History

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

According to Gilbert (1877):

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

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

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

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

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

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

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

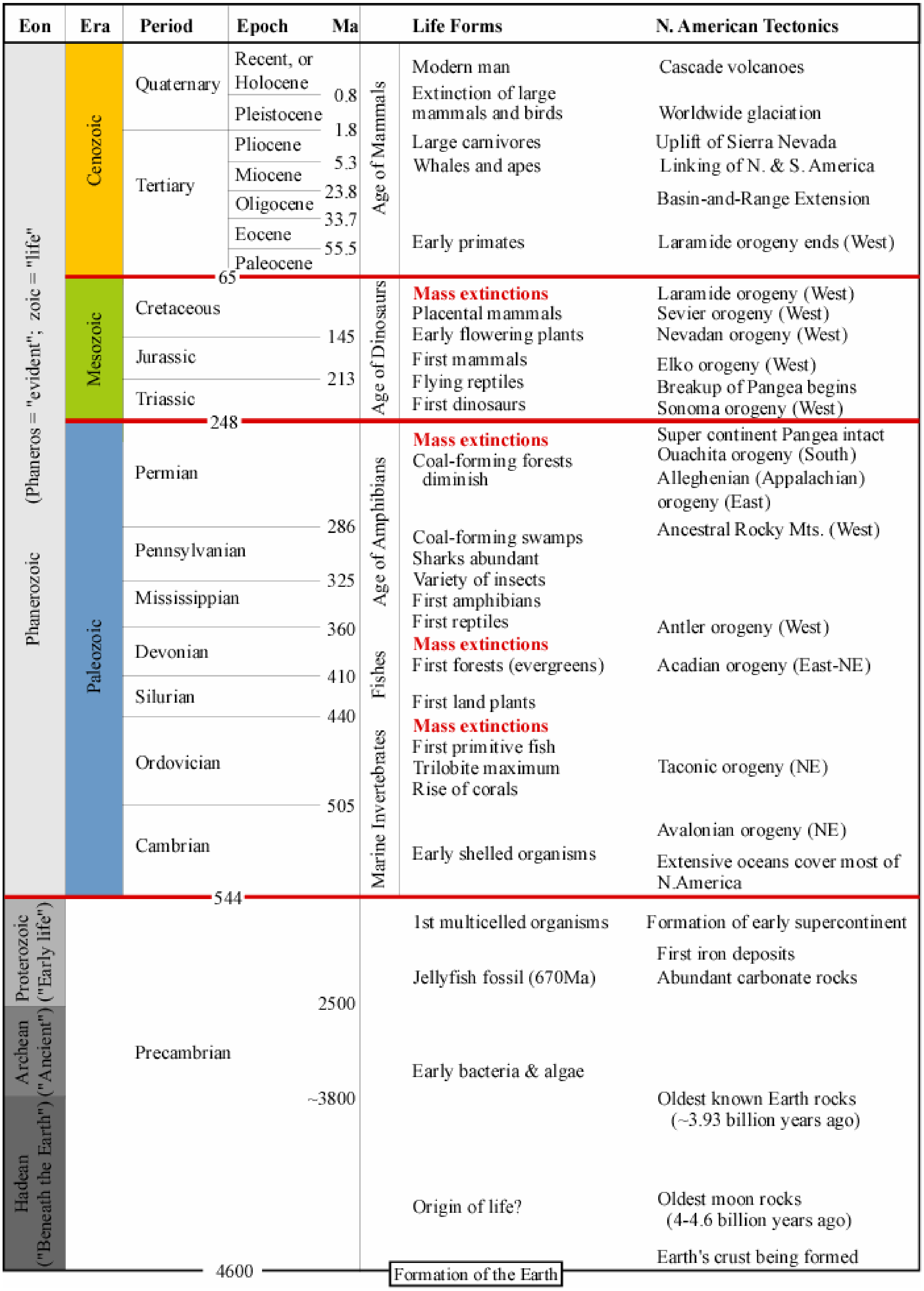

Figure 3: Geologic time scale; adapted from the U.S. Geological Survey. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

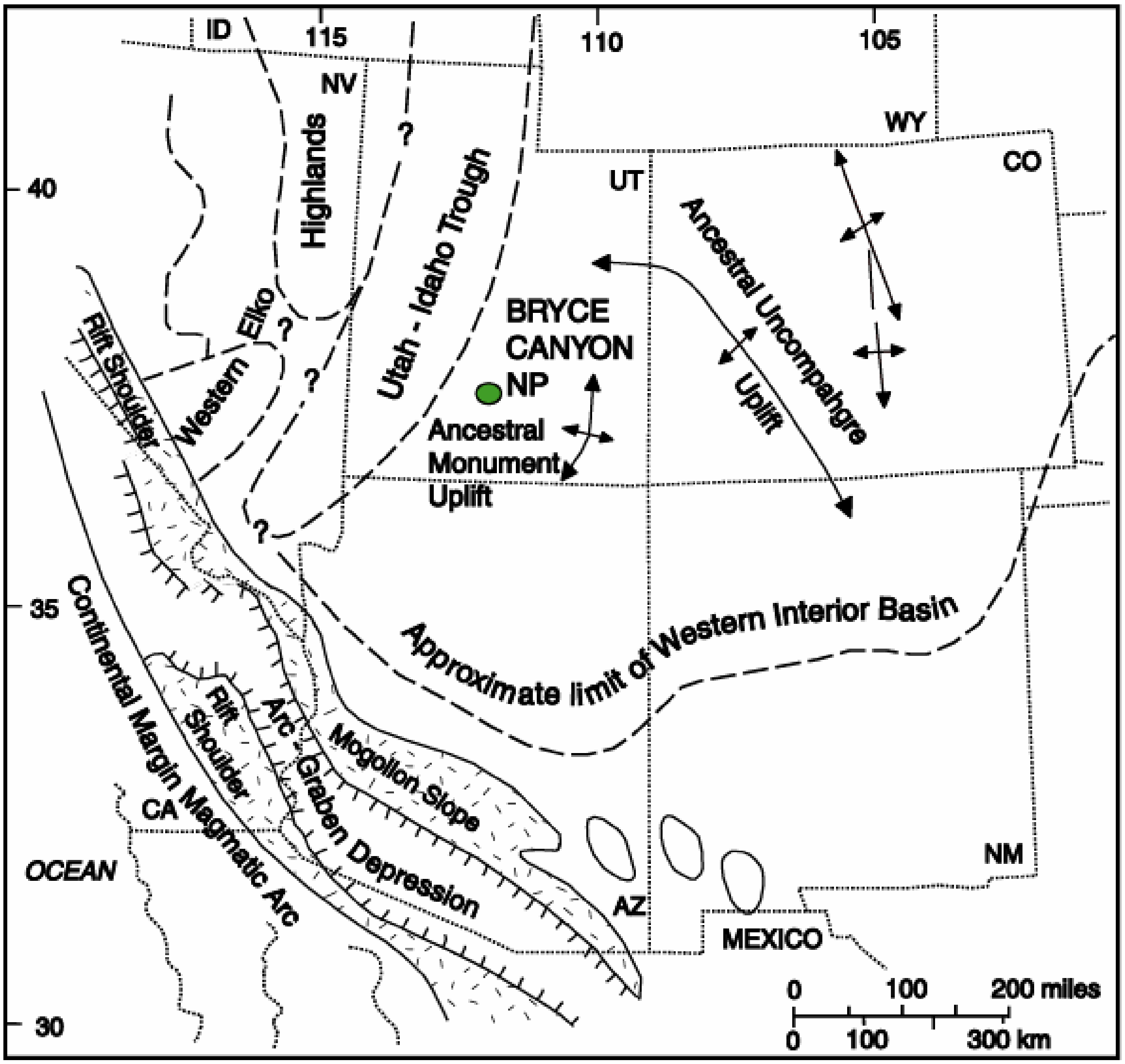

Figure 4: Main Jurassic structural elements affecting sedimentation onto the Colorado Plateau. The arc-graben depression probably did not exist in Late Jurassic time. Eastern Elko highlands rose out of the Utah-Idaho trough in latest Middle and Late Jurassic time. Modified from Peterson (1994).

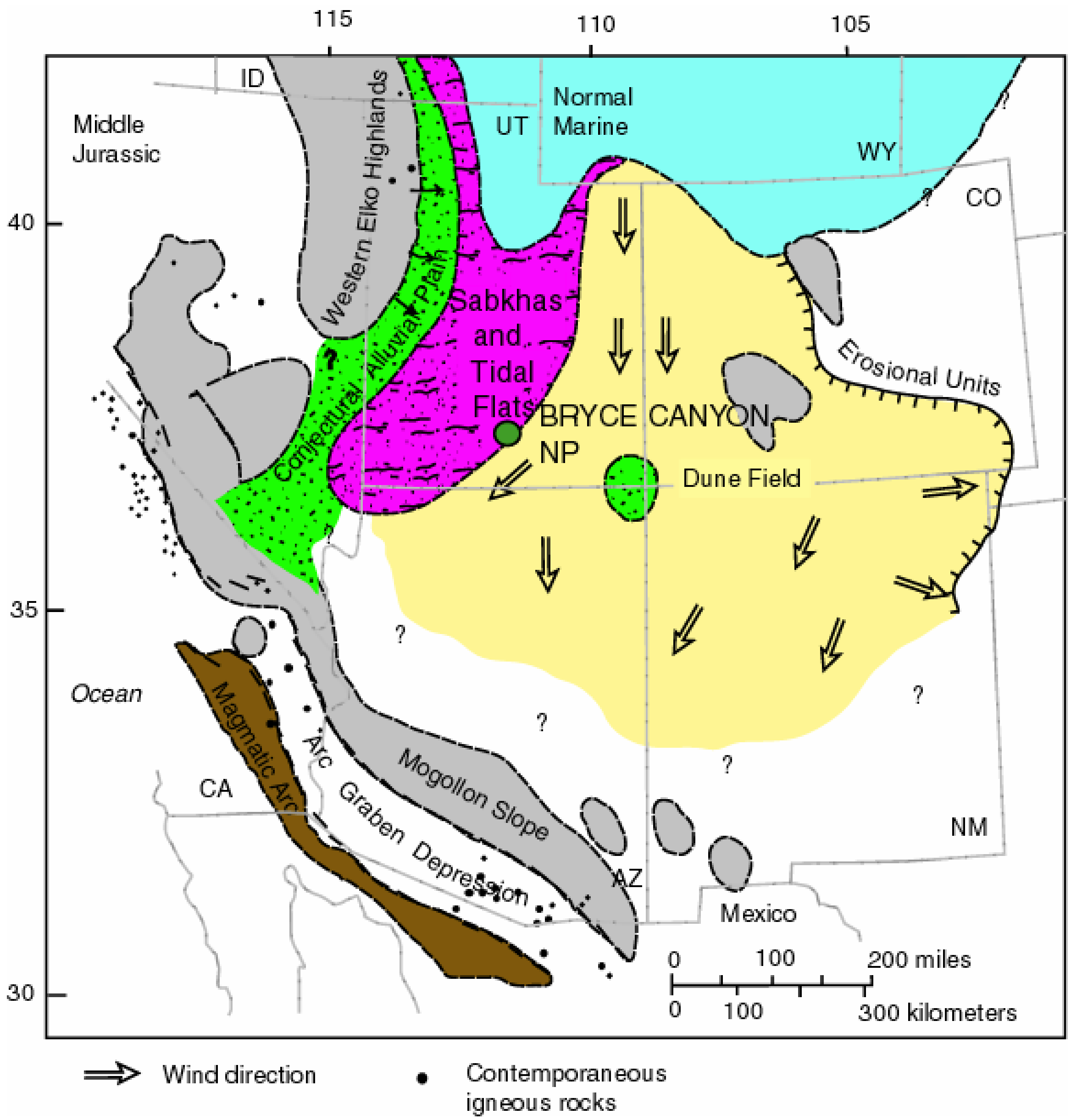

Figure 5: Middle Jurassic paleogeography during deposition of the Entrada Sandstone. Modified from Peterson (1994).

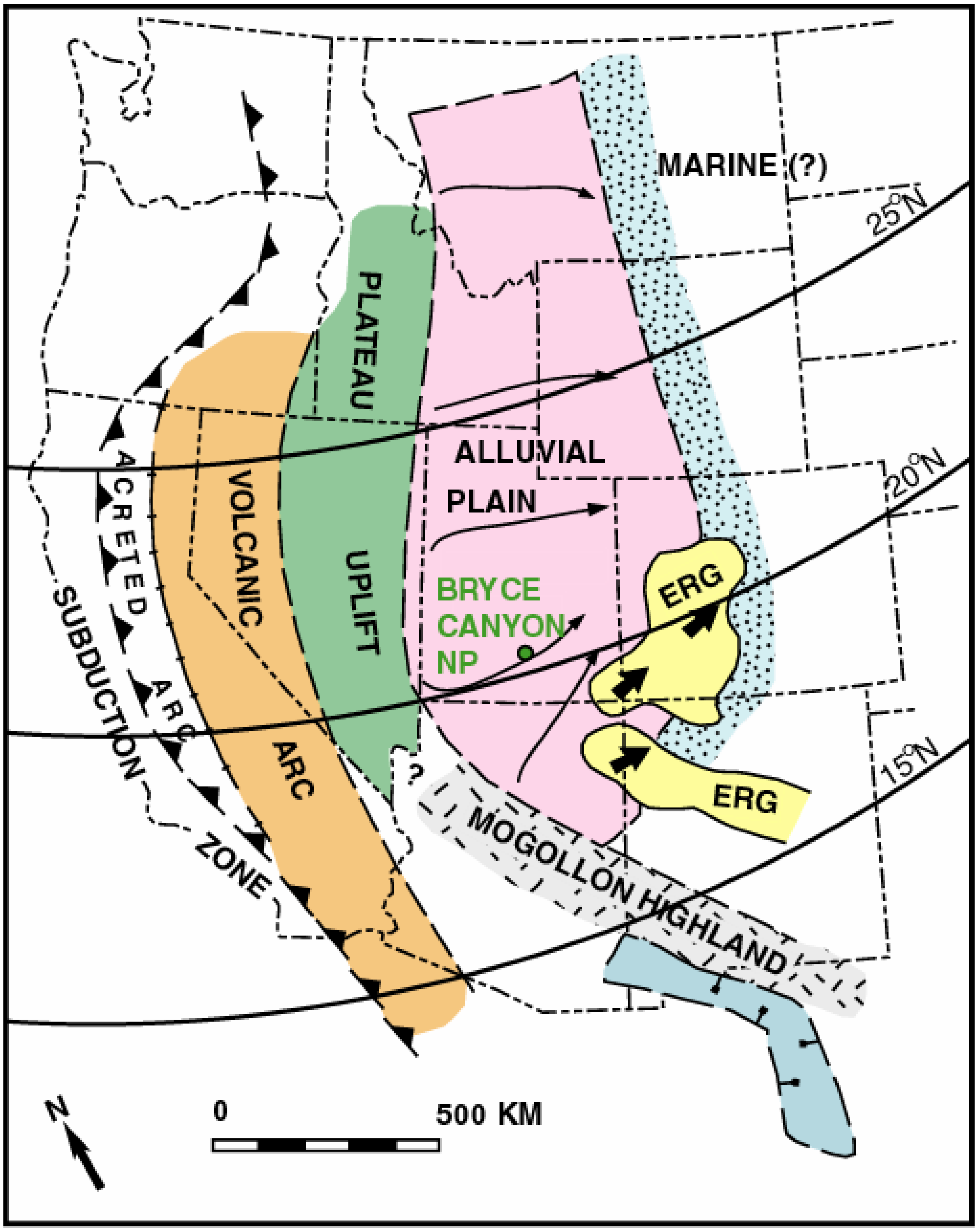

Figure 6: Late Jurassic paleogeography. Thin arrows indicate fluvial dispersal. Thick arrows indicate wind directions. Saw teeth indicate the location of the subduction zone with the teeth on the overriding, upper lithospheric plate. The alluvial plain expanded to the east with time. Modified from Lawton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

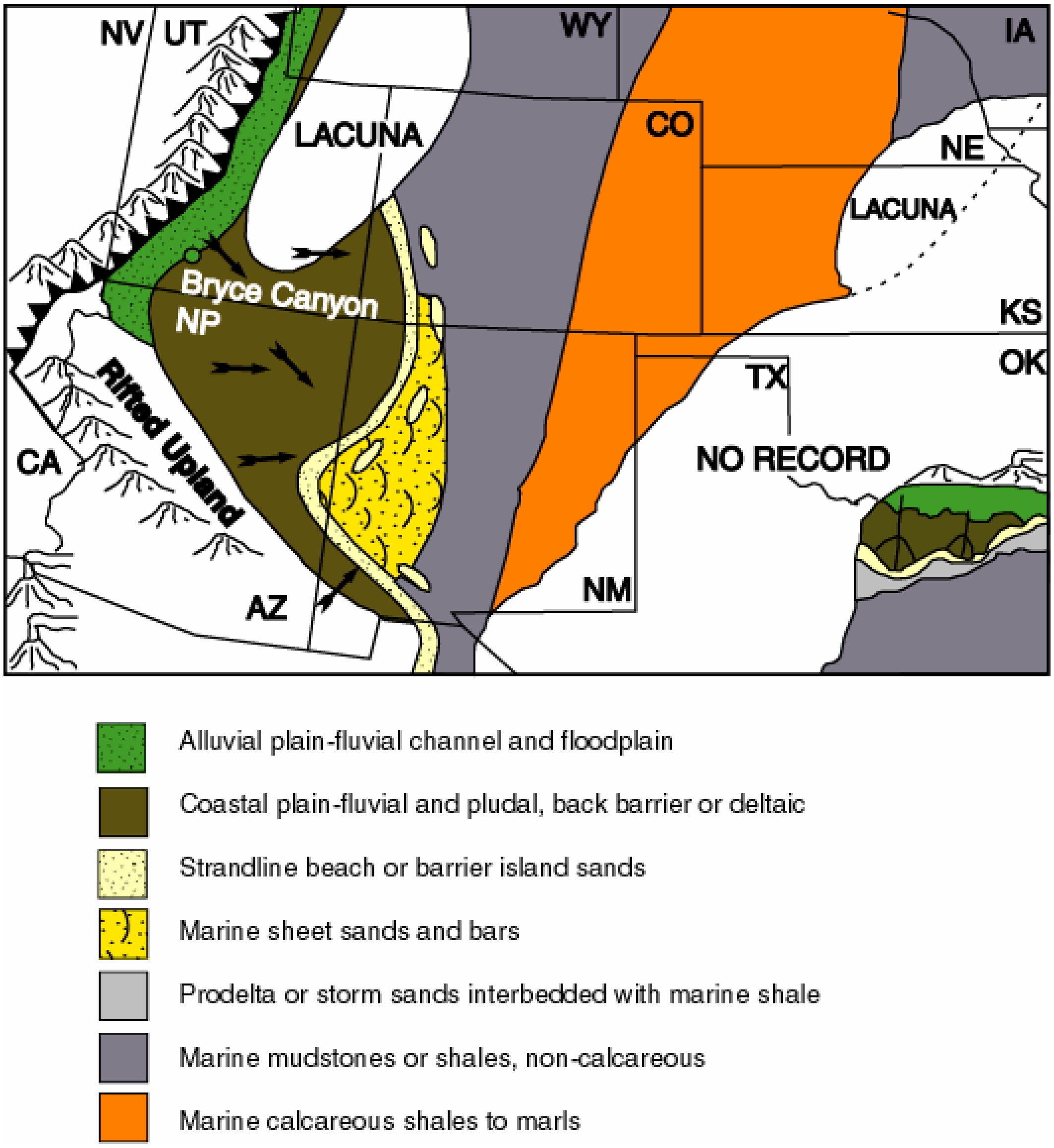

Figure 7: Upper Cretaceous paleogeography at the time of Dakota Sandstone deposition. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. Arrows indicate direction of sediment transport. Modified from Elder and Kirkland (1994).

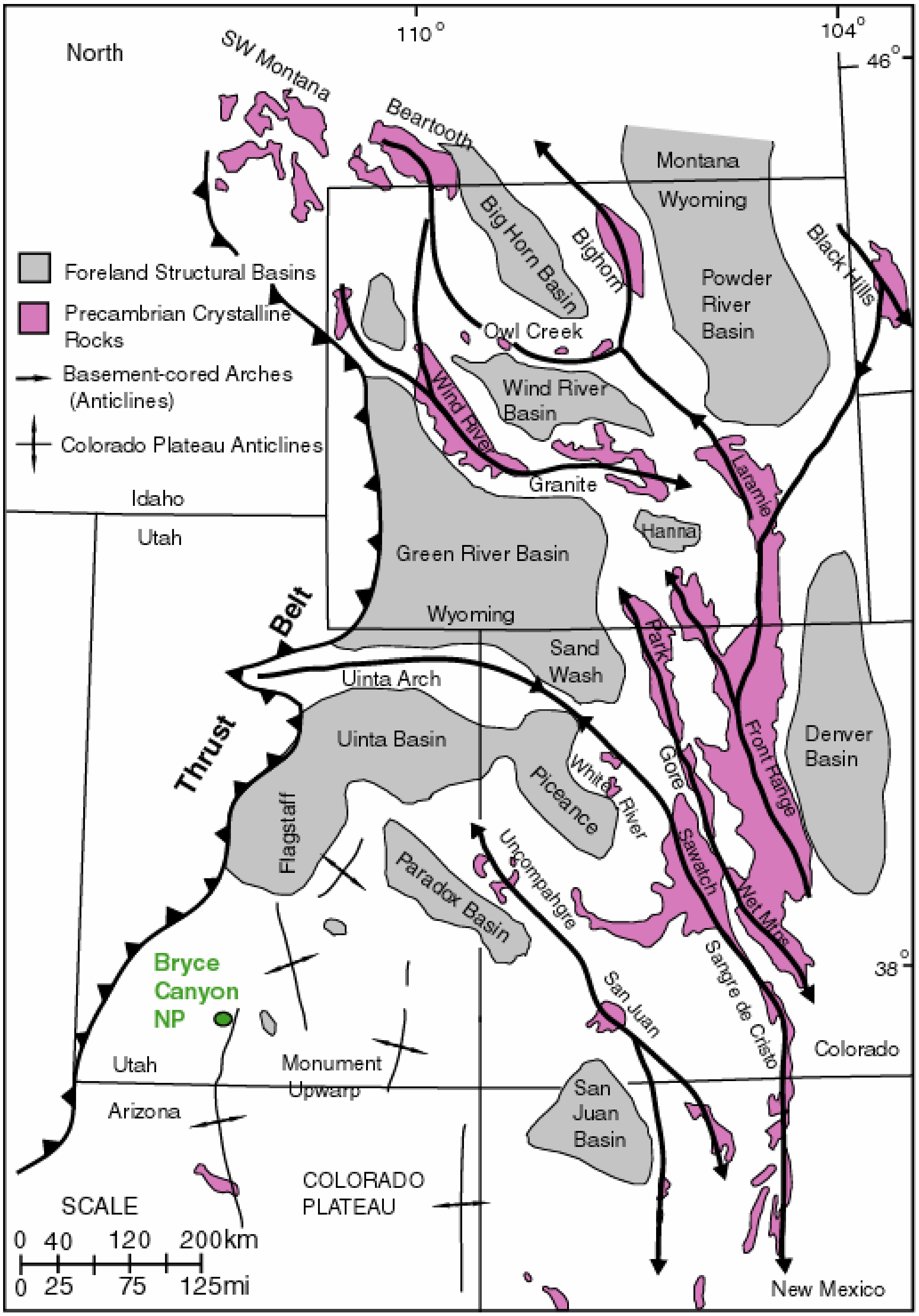

Figure 8: Location of Bryce Canyon National Park on a tectonic map showing Laramide-age structures on the Colorado Plateau. The map illustrates the anastamosing nature of the basement-cored arches (regional-scale anticlines) and the spatial relationships with the adjacent thrust belt, Colorado Plateau,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

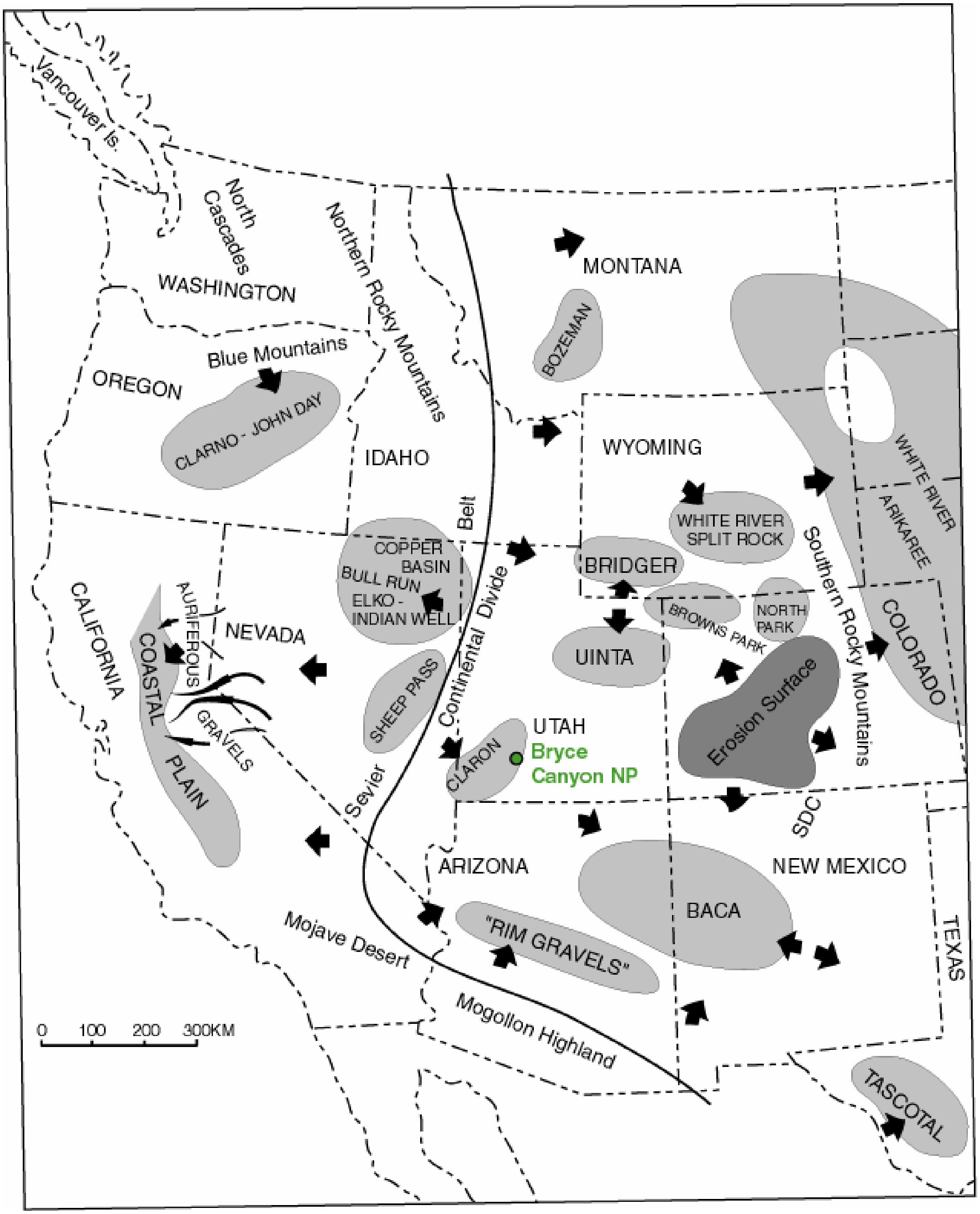

Figure 9: Early post-Laramide map showing the probable location of the continental divide, major depositional basins, erosional features, and stream systems in the western U.S. Light gray areas denote basins (note Claron Basin), dark gray areas indicate highlands and arrows indicate probable directions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

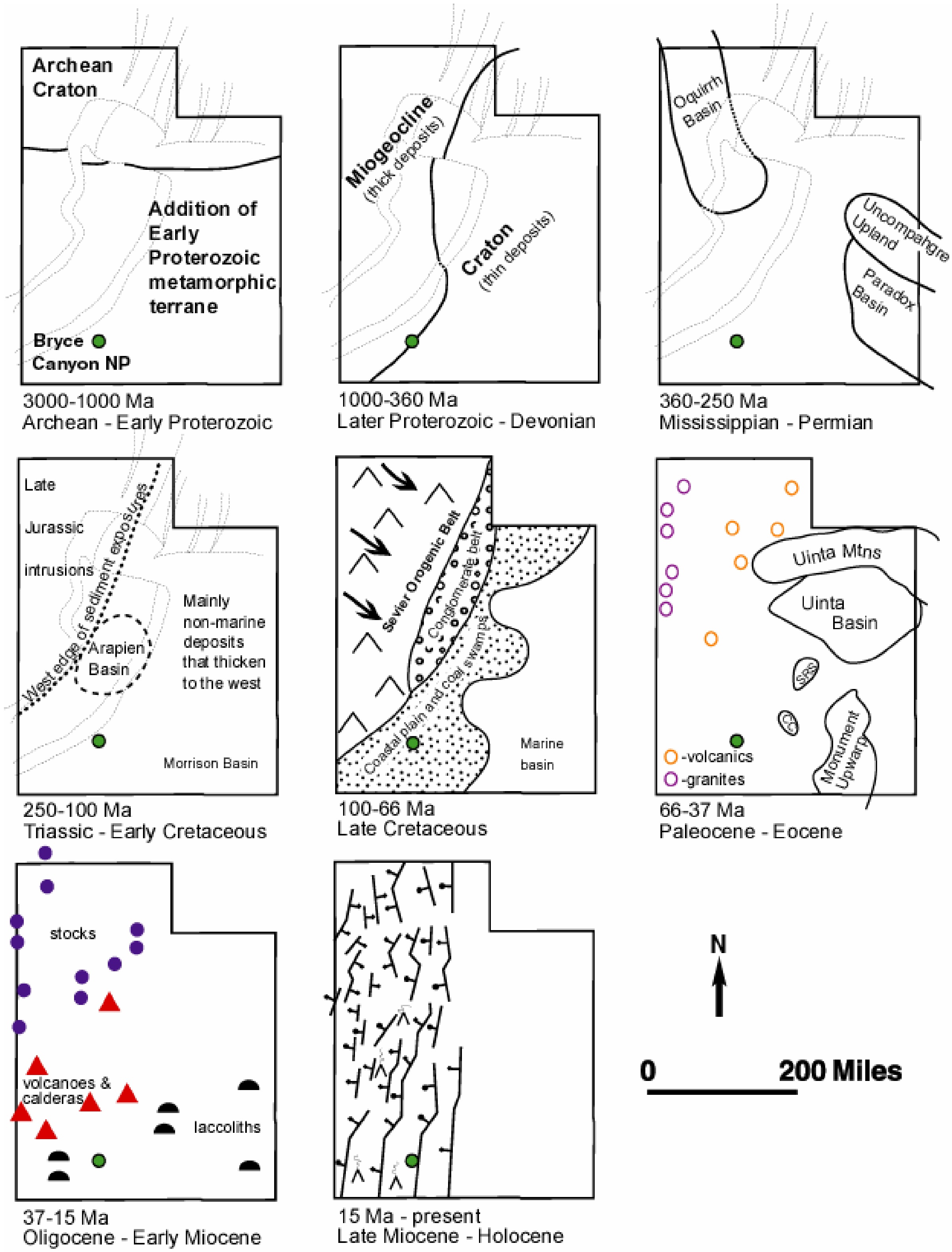

Figure 10: Generalized graphic overview of geologic evolution of Utah from the Archean Eon to the Holocene Epoch (adapted from Hintze 1988).

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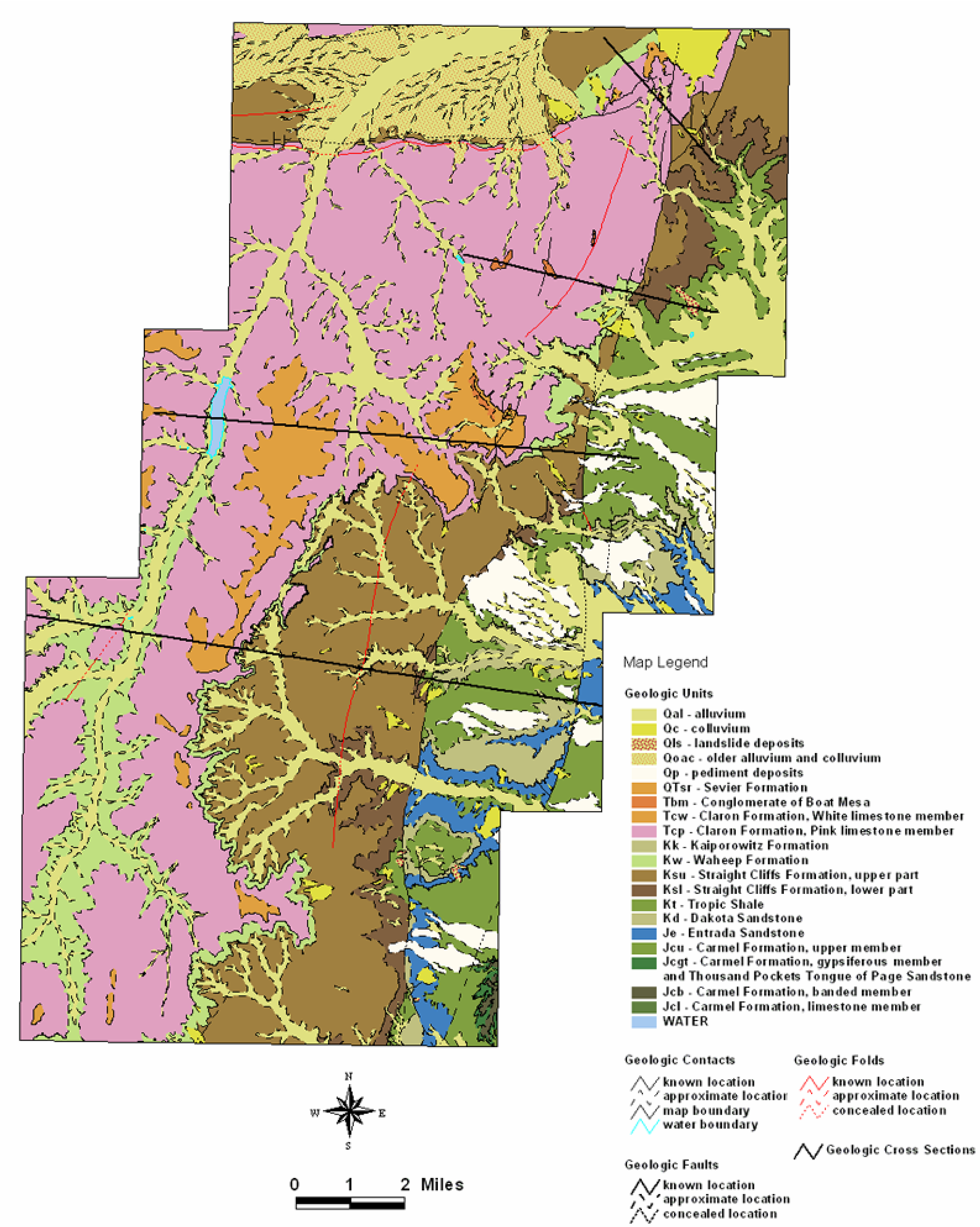
Appendix A: Geologic Map Graphic

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



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

Appendix B: Scoping Summary

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

Executive Summary

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

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

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

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

Overview of Geologic Resource Evaluation

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

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

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

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

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

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

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

Interpretation

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

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

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

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

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

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

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

Bryce Canyon Natural History Association

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

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

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

UGA Guidebook on Utah's National and State Park Areas

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

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

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

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

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

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

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

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

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

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

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

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

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

Natural Resources

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

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

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

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

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

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

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

Cumulative Geologic Mapping Efforts for Bryce Canyon National Park

UGS Perspective

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

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

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

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

USGS Perspective

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

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

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

Current Status

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Other Sources of Natural Resources Data for Bryce Canyon

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

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

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

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

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

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

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

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

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

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

Geologic Hazards

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

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

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

Seismic/active faults in close proximity to BRCA area

Volcanics (Marysvale volcanics)

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

Highway 12 dump

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

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

Potential Research Topics for Bryce Canyon National Park

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

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

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

Study how different lithologies respond to weathering and erosion

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

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

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

Study effects of fluid- rock interactions and results

What is the effect of the syncline on hoodoos

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

Determine extent of Cretaceous thrust above the amphitheater to the south

Study the Markaugunt Megabreccia near Cedar Breaks for regional implications

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

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

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

Permeability and quantity of water assessment for entire Bryce Canyon NP

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

Disturbed Lands

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

Unique Geologic Features

Natural Bridge

Boat Mesa (all conglomerate)

Sinking Ship

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

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

Sevier fault at Red Canyon

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

Thor's hammer from Sunset Point; has dolomite capstone

Action Items

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

Interpretation

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

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

UGA Guidebook

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

Natural Resources

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

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

Geologic Mapping

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

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

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

Miscellaneous

Review proposed research topics for future studies within Bryce Canyon NP

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

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

Doug Neighbor needs an upgrade from his existing version of ArcView

List of Scoping Meeting attendees with contact information

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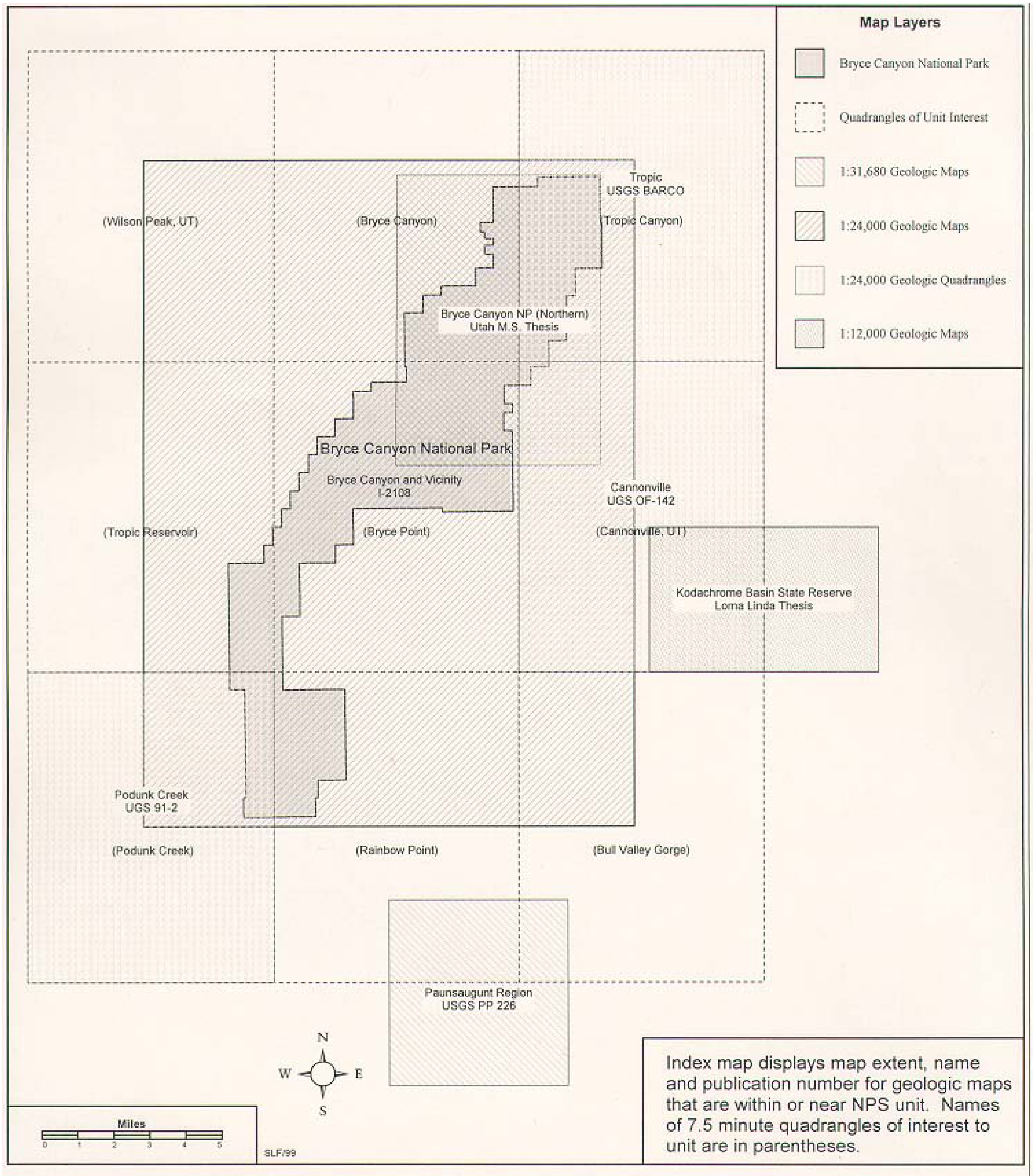

Figure 11: Geologic map coverage of Bryce Canyon National Park at 1:31,680 scale and larger. From GRE Scoping Report

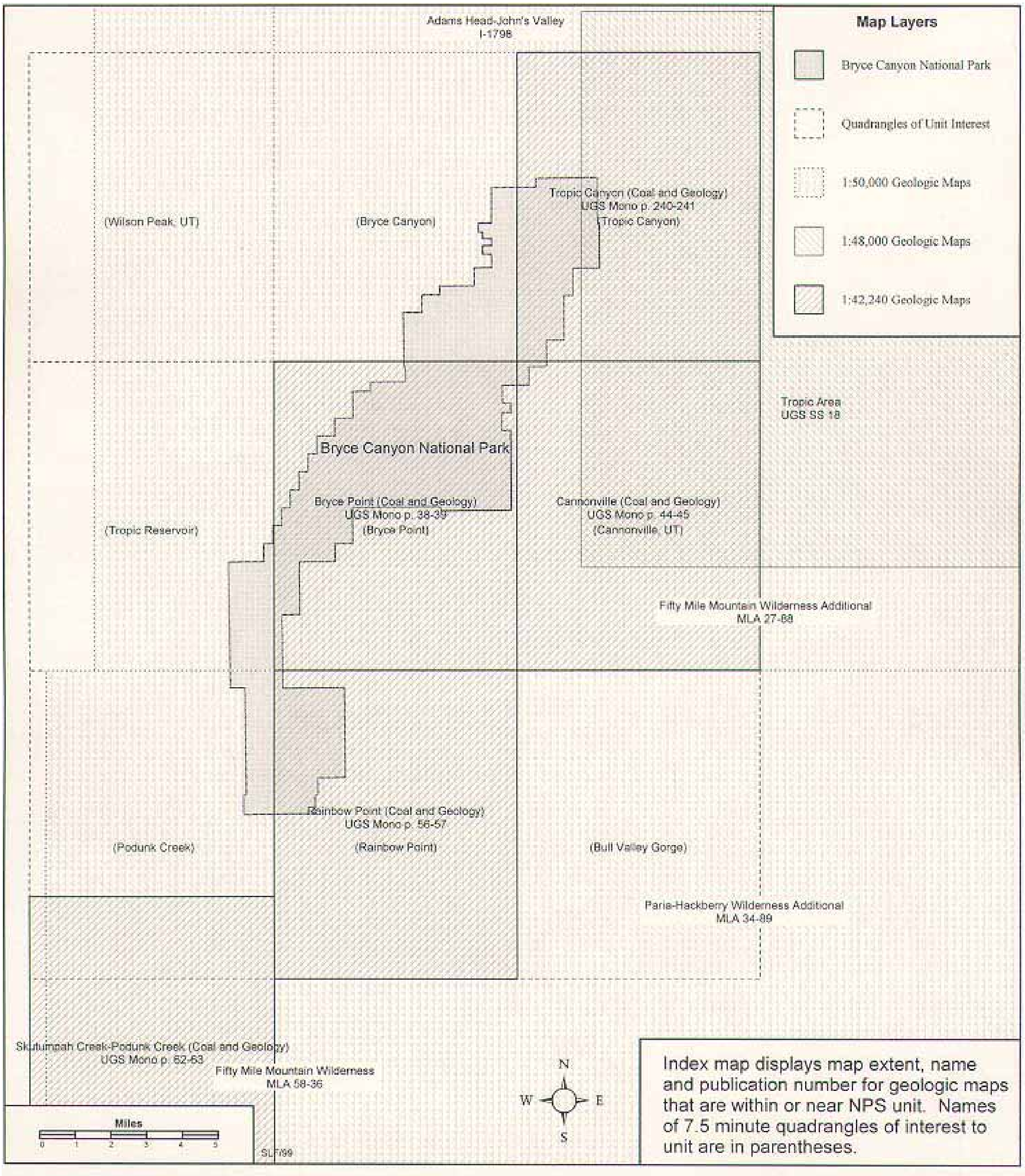

Figure 12: Geologic map coverage of Bryce Canyon National Park at 1:42,240 and larger scale. From GRE Scoping Report

Bryce Canyon National Park
Geologic Resource Evaluation Report

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

National Park Service
Director • Fran P. Mainella

Natural Resource Stewardship and Science
Associate Director • Michael A. Soukup

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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