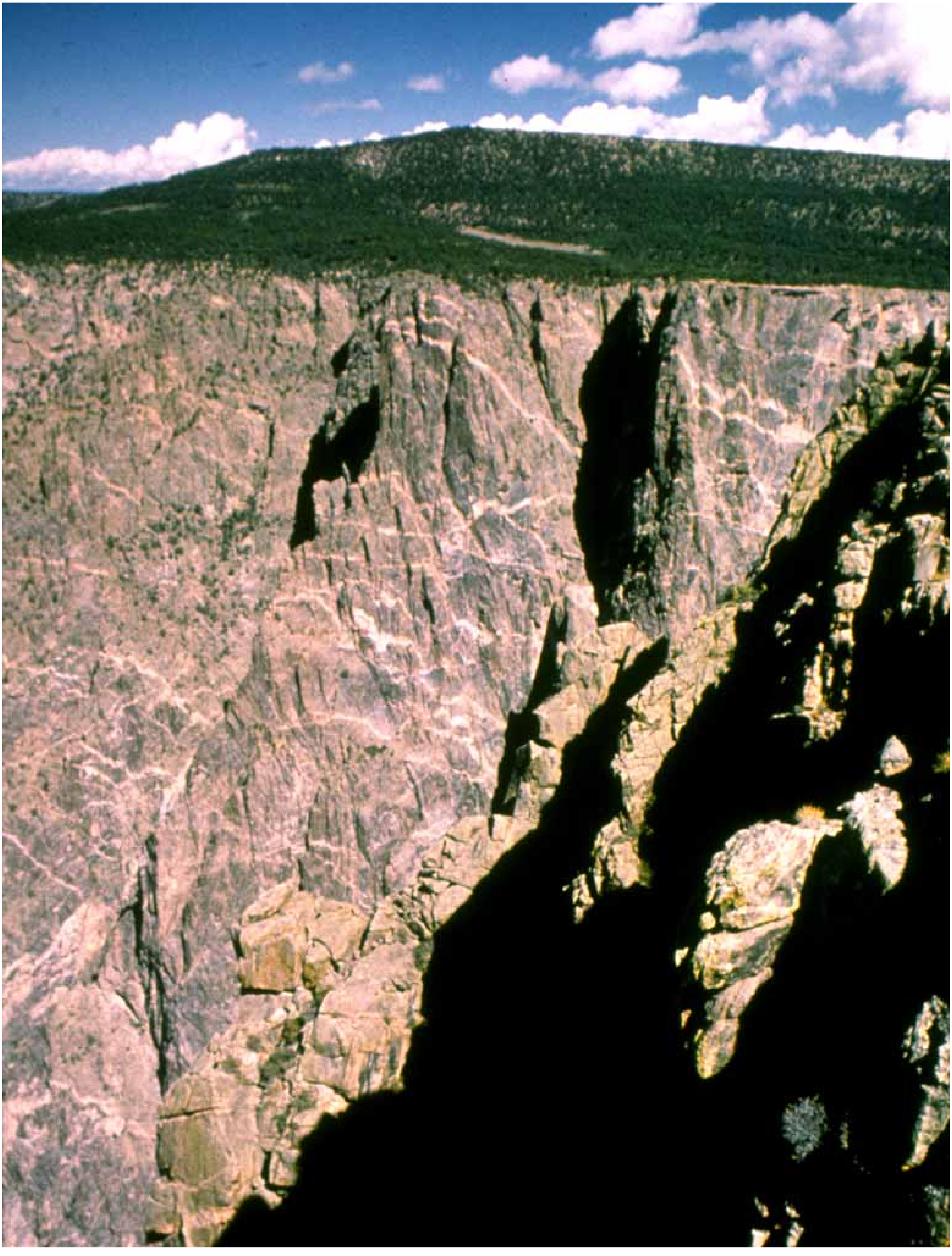
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Black Canyon of the Gunnison National Park & Curecanti National Recreation Area

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/001



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Geologic Resources Division
Natural Resource Program Center
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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Black Canyon of the Gunnison National Park and Curecanti National Recreation Area in Colorado. It contains information relevant to resource management and scientific research.

The Black Canyon of the Gunnison's unique and spectacular landscape was formed slowly by the action of water and rock scouring down through hard Precambrian metamorphic and igneous crystalline rock. Few other canyons in the world combine the narrow opening, sheer walls, and startling depths offered by Black Canyon. It is so deep and narrow that little sunlight reaches the bottom, making the walls look black. In the canyon, the Gunnison River drops an average of 29 m (96 ft) per mile.

Sweeping mesas, deep canyons, and fjord- like lakes abound in Curecanti, attracting recreational enthusiasts from around the world. Curecanti's three reservoirs, named for corresponding dams on the Gunnison River, form the center of Curecanti National Recreation Area. Blue Mesa Lake is Colorado's largest body of water. Morrow Point Lake marks the beginning of the Black Canyon of the Gunnison. Below these two, Crystal Lake is the site of the Gunnison Diversion Tunnel, a National Historic Civil Engineering Landmark.

Geology provides the foundation of the entire ecosystem. Mesas are topped with layers of Tertiary volcanics and the depths of the Black Canyon are walled with hard, crystalline Precambrian rocks. Slumps, slides and block falls line the bottom of the canyon with recent, unconsolidated sediments.

Understanding the geology of Black Canyon - Curecanti enhances one's understanding of the unique relationship between geology and the environment. In Black Canyon - Curecanti geologic surface exposures consist primarily of Precambrian, Jurassic, Cretaceous, and Tertiary age rocks. These rocks record the coming and going of oceans, the blowing of desert sands, and the passing of lakes and rivers.

Geologic processes initiate complex responses that give rise to rock formations, surface and subsurface fluid movement, soil, and canyon formation. These processes develop a landscape that can either welcome or discourage human use.

Preservation of the canyons, ledges, and assorted mesas that make up Black Canyon of the Gunnison National Park and Curecanti National Recreation Area is absolutely necessary to inspire wonder in visitors to the sites. Geologic resources and the natural history of the area deserve emphasis and should be interpreted to enhance the visitor's experience.

The incredible canyons and reservoirs of Black Canyon – Curecanti attracted over 1,066,754 visitors in the year 2002. These visitors place increasing demands on the resources available each year. In recent history, humans have modified the landscape surrounding Black Canyon and consequently altered its geologic system. This system is dynamic and capable of noticeable change within a human life span. It is not surprising then that some of the principal geologic issues and concerns for Black Canyon – Curecanti pertain to protecting geologic resources and features.

The following features, issues, and processes are of primary geological importance and have the highest level of management significance to the parks:

- Uranium and mining issues. The region within and surrounding Black Canyon – Curecanti has been a source of mining interest since the 1870's. The metamorphic and igneous Precambrian age rocks are host to gold, silver, titanium, copper, vanadium, and other metallic ores. The Jurassic Morrison Formation contains uranium deposits. Mining activity can lead to water contamination that may impact the parks' ecosystem.

- Slope failures and processes. Dry environments are especially susceptible to slumping and landslide problems during intense seasonal storms due to the lack of stabilizing plant growth. In addition, road and trail construction can impact the stability of a slope. Mudstone- rich units such as the Mancos Shale and Morrison Formation are typically found in outcrop as slopes. These slopes are prone to fail when water saturated. Slope failure also occurs along the incredibly steep walls of Black Canyon where large blocks break loose every year.

- Water Issues. Western Colorado receives on average only 8 to 10 inches of precipitation per year. This defines the semi- arid climate that makes water such an important resource. The Gunnison River watershed is relatively confined to the area immediately surrounding the river. This is due to the Gunnison Uplift which diverts tributaries away from the Gunnison. Managing the 3 reservoirs of Curecanti National Recreation Area ensures an ample, reliable water source for the surrounding areas. This source must be protected and monitored for quality.

Other geologic parameters and issues such as swelling clays, wind erosion and deposition, and paleontological resources, were also identified during scoping sessions as critical management issues for Black Canyon of the Gunnison National Park and Curecanti National Recreation Area. These are detailed on pages 11- 14.

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 (NPS) 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 called for in Natural Resources Inventory and Monitoring Guideline (NPS-75) and the NPS Strategic Plan.

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

Black Canyon of the Gunnison National Park and Curecanti National Recreation Area consist of 30,244 acres and 41,972 acres, respectively that straddle the Gunnison River in west- central Colorado between the towns of Gunnison and Montrose. Black Canyon of the Gunnison National Monument was established on March, 2, 1933 and was elevated to National Park Status through a proclamation by President Bill Clinton on October 21, 1999. Curecanti National Recreation Area was established in 1965 with the completion of Blue Mesa Dam.

Black Canyon of the Gunnison National Park and Curecanti National Recreation Area straddle the locally indistinct boundary between two physiographic provinces, the southern Rocky Mountains to the east and the Colorado Plateau to the west. The area displays complex geologic features, such as broad flat- topped mesas, sharp ridges, and canyons, which are in many ways representative of both provinces (Hansen, 1965).

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. This physiographic province is also known for its laterally extensive monoclines (figure 1). Basins adjacent to the steep limbs of the monoclines have been filled with sediment eroded from these folds. The characteristic uplifts and basins of the Colorado Plateau formed as a result of the Upper Cretaceous- mid Tertiary Laramide orogeny. The structural fabric of gently warped, rounded folds in the Colorado Plateau contrasts with the intense deformation and faulting of bordering terranes.

Located to the northeast and east of the Colorado Plateau are the jagged peaks of the Rocky Mountains. The laccolithic peaks and volcanic mesas of the West Elk Mountains border the park to the northeast, with high points at Mt. Gunnison, Mt. Lamborn, and West Elk Peak. The Gunnison River cuts through the Gunnison uplift, a relatively recent geologic addition to the landscape (Hansen 1965).

The San Juan Mountains and the anticlinal Monument Upwarp lie to the south of Black Canyon and Curecanti forming the western border of Blanding Basin, a coincident synclinal downwarp. Locally rock layers, while gently folded into anticlines and synclines, remain relatively undisturbed by faulting except in areas associated with salt structures or dissolution of salt structures.

Giant monoclines, laccoliths, and other features present in the Colorado Plateau – Rocky Mountain area today were molded by the processes of erosion. The destructive forces of wind and rain, running water, and freezing temperatures continue to breakdown the uplifts and volcanoes characteristic of this area.

The effects of erosion were probably negligible while the land lay very near sea level in the Early Tertiary Period. However, following a fairly abrupt increase in elevation from near sea level to several thousand feet above sea level in the Late Tertiary, the pace of erosion accelerated. During this time erosion worked to carve down the rocks and carry away the strata.

This erosion created incredible topographic relief. For example, from High Point in Black Canyon of the Gunnison National Park, the Uncompahgre Valley sits some 762 m (2,500 ft) below (Hansen, 1965). This effectively dissected the topography and created the modern landscape known today as Black Canyon – Curecanti.

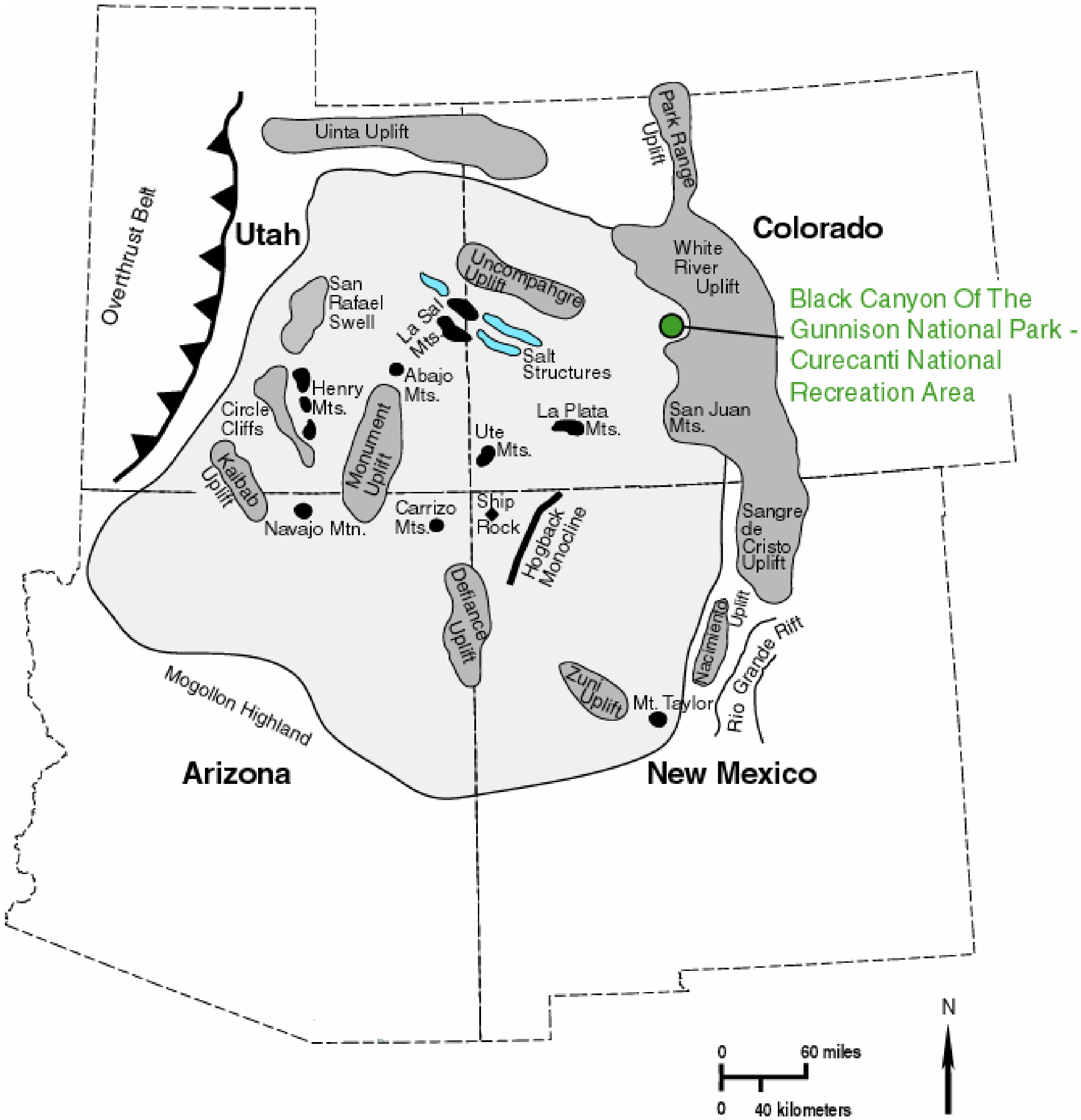


Figure 1: Location of Black Canyon of the Gunnison National Park – Curecanti National Recreation Area relative to Colorado Plateau and Rocky Mountain physiographic features. The light gray area signifies the aerial extent of the Colorado Plateau. Dark gray and black areas represent uplifts and mountains.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Black Canyon of the Gunnison National Park and Curecanti National Recreation Area on August 26, 1998, 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.

Uranium and Mining Issues

The Paradox Basin, southwest of Black Canyon has been the site of uranium mining for nearly nine decades. The principal host rocks for the radium, vanadium, and uranium deposits exposed at Black Canyon of the Gunnison and Curecanti National Recreation Area are the Jurassic Morrison Formation, the Cretaceous Dakota Sandstone, and Precambrian pegmatite. In the Morrison, gray, poorly sorted, fine- to coarse- grained, calcareous, arkosic, quartz sandstone of the Salt Wash Member contains uranium ore. Historically, over 1.2 million kg of uranium oxide have been produced from the Gunnison area, mostly from the Cochetopa and Marshall Pass districts. Uranium deposits are often associated with fault and shear zones in the Mesozoic rocks of the area. Local occurrences are in pegmatites and shear zones in Precambrian rocks and some Tertiary sandstones (Goodknight 1981).

A threat specific of uranium mining is that of radon gas exposure. Radon is a product of uranium's radioactive decay. This tasteless, odorless gas is a known carcinogen that usually concentrates in low lying areas like basements and mine shafts.

In addition to uranium resources, the Precambrian rocks exposed at Black Canyon contain deposits of metal ores such as gold, silver, copper, manganese, vanadium, sulfides, and tellurium. Additionally, low- grade niobium, titanium, and vermiculite deposits are associated with the carbonatite and pyroxene of the Iron Hill stock (Hedlund and Olson, 1975). At least 98 thorium- bearing veins and dikes have been examined and found to have radioactive levels 2- 250 times background. At the Little Johnnie mine, the thoria content of high- grade samples is as much as 4 percent (Olson and Wallace, 1956). Thorium veins are commonly located along shear and breccia zones within Precambrian rocks. The thorium vein system west of the Old Lot mine, about 3 miles north of Powderhorn, follows a fault for about 8,000 feet. Rare earth elements and niobium are found in elevated amounts in the thorium- bearing veins (Hedlund and Olson, 1975).

Veins containing gold, silver, copper, and telluride minerals occur in the Dubois Greenstone in a zone across the northern part of the area called the Gunnison gold belt. The scant production from these veins probably totaled several hundred thousand dollars, chiefly from the Good Hope- Vulcan mines. These mines, located near the northeast edge of the Powderhorn quadrangle, were worked from 1898- 1904 and during several other short periods. Mining extended down to approximately 700 feet. At a depth of about 90 feet the shafts were reported to have penetrated a pocket of native sulfur, which then graded into massive pyrite at the water level, about 105 feet below the ground surface (Hedlund and Olson, 1975).

South and southeast of Spencer, are the Headlight, Gunnison, Anaconda, and Ironcap Mines. The Headlight mine was excavated chiefly for its copper, whereas the other mines yielded relatively small tonnages of gold-bearing ore. About one- half mile east of Midway, Colorado is the Ute Trail mine. This mine was developed in a quartz vein that runs along a nearly vertical breccia zone near the contact of chloritized granite and felsite (Hedlund and Olson, 1975).

Vermiculite is sporadically distributed in altered pyroxenite as random segregations and in dike- like (linear) bodies. The vermiculite deposits, which are most likely a weathering product of biotite in the pyroxenite, occur in plates as much as 4 inches across. Most of the surface stripping for vermiculite has been between North Beaver and Deldorado Creeks and at the head of Stone Gulch (Hedlund and Olson, 1975).

Abandoned mines pose a serious potential threat to any ecosystem. Even in semi- arid environments, surface water and groundwater can become contaminated with high concentrations of heavy metals, leached from mine tailings. Heavy metals may also contaminate nearby soils. Contaminated soil and water are likely to have negative impacts on both plant and animal life in the surrounding ecosystems.

Inventory, Monitoring, and/or Research Needs

- Conduct periodic water (surface and groundwater) and soil monitoring for uranium. Drinking water is especially important to sample, test, and monitor.
- Research uranium bearing beds throughout the park-recreation area. Include descriptions, uranium content tests, and locations, i.e. where the beds are exposed and accessible to the public, flora, and fauna.
- Complete inventory of the uranium content in modern unconsolidated deposits and soils as well as uranium bearing stratigraphic units (Morrison Formation).

- Monitor heavy metal concentrations in surface and groundwater.

- Monitor any new mining activity in the area.

- Install new monitoring wells around the park-recreation area to better determine contaminant levels in drinking water aquifers.

Alluvial Reaches

The Black Canyon of the Gunnison River includes several characteristics of an alluvial river in addition to its gorge- like features. Several reaches of the river exhibit fluvially deposited banks and bars, riffle- pool channel geometry, and accompanying riparian ecosystems. These ecosystems and the alluvial reaches they depend on are sensitive to changes in streamflow. Sediment sources for these areas include debris from talus slopes, rockfalls, and minor tributary debris which are reworked and redeposited for riparian vegetation growth (Elliott and Hammack, 1999).

Inventory, Monitoring, and/or Research Needs

- Determine where alluvial reaches exist, and monitor yearly changes based on a GIS derived map.

- Collect geomorphic and sedimentologic data at all alluvial reaches in the Black Canyon. Calculate the entrainment potential of a large range of sediment sizes and correlate them with the underlying geomorphic surfaces.

- Use estimates of water- surface elevations, flow depths, and hydraulic conditions to determine the hydrologic regime in alluvial reaches.

- Monitor streamflow over several years to establish a pattern at specific alluvial reaches and monitor sensitive vegetation changes within the riparian ecosystems.

Slope Failures

Landslide and rockfall potential exists along most roads and trails at Black Canyon of the Gunnison National Park and Curecanti National Recreation Area. Highway 50 is subject to ongoing slides and Route 92 has potential slides on the north side of the park.

These events can endanger the public and cause road problems or closures in the parks. Certain cliff forming units such as the Entrada and Dakota Sandstones, and the Burro Canyon Formation are especially prone to landslides and rockfalls when undercut by a road or trail.

Slumps and other forms of slope failure are common for units that are not necessarily associated with cliffs. Rocks rich in mudstone for instance, like the Morrison Formation and the Mancos Shale, are especially vulnerable to failure when exposed on a slope. Torrential rains which produce flash flooding in the Black Canyon area also act to mobilize material on slopes that lack stabilizing plant and tree roots. The rock and soil, when suddenly saturated with water, can slip down slope causing a slump, mudslide, or flow.

The precipitous slopes of Black Canyon make for arduous and potentially dangerous hiking. Rockfalls and slides are continuous slope processes that affect all levels of the canyon. In the hard Precambrian rocks exposed on the walls of Black Canyon, numerous faults, joints, and other fractures combine with frost action and root wedging to weaken the integrity of the units and increase the potential for block falls into the canyon. Any earthquakes (seismic activity) can increase this hazard.

Inventory, Monitoring, and/or Research Needs

- Perform a comprehensive study of erosion/weathering processes active at Black Canyon of the Gunnison National Park and Curecanti National Recreation Area, taking into account rock formations, slope aspects, location, and likelihood of instability.

- Create a rockfall susceptibility map using rock unit versus slope aspect in a GIS. Use the map to aid planning efforts for future developments and current resource management of trails, buildings, and recreational use areas.

- Perform a shoreline investigation for slumps and rockfalls at Curecanti. A slope classification map could be derived from digital elevation data.

- Use high resolution Global Positioning System (GPS) to detect current movement, swelling, and collapsing in areas of the parks.

- Obtain access to regular seismic activity reports or a seismometer to measure activity in the area.

Swelling Clays

Swelling soils associated with bentonitic shales of the Morrison and Mancos Formations may be a concern to present and future developments and management at Black Canyon of the Gunnison National Park and Curecanti National Recreation Area.

Bentonite, a clay derived from altered volcanic ash deposits, is responsible for road failures at Mesa Verde National Park and in numerous other locations. Bentonite has the ability to absorb large quantities of water into its structure causing it to swell when wet and shrink upon drying. Any structures, roads, trails, facilities, etc., found on soils with large concentrations of this mineral will be profoundly impacted and potentially destroyed by the force exerted by the clays shrinking and swelling.

This shrink- swell characteristic of bentonite produces interesting construction and road maintenance problems. Nonetheless, bentonite is valuable to the oil industry which uses the clay to cool drilling bits and seal fractures.

Inventory, Monitoring, and/or Research Needs

- Determine which trails, roads and buildings are underlain by bentonitic units using GIS.
- Identify high risk areas where future development should be avoided.
- Perform an exhaustive mapping study to locate specific bentonitic beds in the Morrison Formation and Mancos Shale. This will allow for more precise hazard assessment.

Paleontological Issues

A detailed description of the paleontology and biostratigraphy of Black Canyon of the Gunnison National Park and Curecanti National Recreation Area is beyond the scope of this inventory. It is however important to note that the fossil rich Morrison Formation is exposed within Black Canyon - Curecanti and that dinosaur fossils continue to be found locally in this formation. Other units, such as the Mancos Shale and the Dakota Sandstone, also contain fossils that should be catalogued.

Inventory, Monitoring, and/or Research Needs

- Encourage research projects that would help identify the paleontological resources of the park as an aid to the GRD paleontological survey.

Water Issues

Today as in the past surface water and groundwater play key roles in defining and shaping the Black Canyon-Curecanti landscape. Flowing water carves the deep canyons and forms the mesas and spires that are so prevalent on the Colorado Plateau. Groundwater dissolves the cement that binds individual grains together and transports the cementing elements out of the system through seeps and springs. Erosion undercuts cliffs forming alcoves and causing rocks to topple to the base of canyons. Groundwater and surface water also expand and contract, as part of the freeze thaw cycle, widening joints and fractures in the bedrock and causing the eventual breakdown of even the most resistant rocks. In addition, the quality and quantity of water dictates biodiversity and the success of human occupation in an area.

The climate of Black Canyon - Curecanti is one of relatively low precipitation and high evaporation rates. Consequently, recharge to groundwater aquifers is low. Precambrian crystalline rocks contain water only in fractures and consolidated sedimentary rocks yield little or no water to wells at Curecanti. Wells drilled into Tertiary age volcanic rocks generally yield less than 5 gallons of water per minute. Unconsolidated Quaternary age deposits yield as much as 50 gallons per minute to wells, but again, these near surface sources are easily depleted and slow to recharge (Boettcher, 1971). This lack of a plentiful and stable water supply prompted construction of the three dams at Curecanti to provide for the needs of the region.

The three dams in Curecanti National Recreation Area work as a system to store water, produce electricity, and regulate water flow for downstream irrigation and flood control. This system of dams has dramatically altered the natural environment by placing checks and regulations on the once wild Gunnison River. Because the river dominates the area, the hydrogeologic system has completely changed as a result of these dams. Dam maintenance and integrity in turn play a large role in management concerns at Curecanti.

Inventory, Monitoring, and/or Research Needs

- Conduct hydrogeologic studies to delineate subsurface flow patterns, regional and local flow systems, and the conductivity and transmissivity of the strata at Black Canyon - Curecanti.
- Monitor water quality on a multiple sample location basis within the parks; drinking water sources are especially important.
- Develop an understanding of groundwater and surface water flow in relation to erosion rates.
- Identify the hydrology of the area and of seeps along with the water quality, to establish a baseline for comparison.
- Install additional wells for testing and drinking water access.
- Determine the impacts of heavy metal and uranium mining on water quality.
- Identify and study potential sources for impacts to groundwater quality.
- Install transducers and dataloggers in wells.
- Investigate additional methods to characterize groundwater recharge areas and flow directions.

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 in the Black Canyon area and can be affected by human activities. Ecosystem health is dependent on the retention of soil and soil resources, accelerated losses of these resources can indicate degradation of arid- land ecosystems.

Sand and soil from disturbed surfaces can blow onto undisturbed ground, burying and killing vegetation. Even biological soil crusts can be damaged or destroyed by wind blown sediment, exposing more soil to erosion. Because park management practices limit or prohibit off- road travel, human impacts within the parks are primarily associated with off- trail hiking in high- use areas. Where livestock grazing or trailing is still permitted, accelerated soil erosion can be more extensive. However, wind erosion and sediment transport in Black Canyon – Curecanti may be strongly impacted by land- use practices outside park boundaries.

Inventory, Monitoring, and/or Research Needs

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

General Geology and Interpretation

The unique geology of Black Canyon of the Gunnison National Park and Curecanti National Recreation Area lends itself to potential scientific research projects addressing Precambrian rocks, Mesozoic and Cenozoic stratigraphy, the regional and local hydrology, and weathering/erosion rates. The incredible geologic exposures within the Black Canyon and along the mesas at Curecanti offer an unparalleled record of geologic history for investigation.

Inventory, Monitoring, and/or Research Needs

- Perform a comprehensive study of the canyon wall rocks to determine the Precambrian history of the area.
- Identify unconformity- bounded stratigraphic packages in order to better define past depositional systems.
- Investigate geomorphological changes driven by raising and lowering the reservoir level.
- Develop an exhibit depicting the geologic history of the rock formations, including the depositional environment surrounding visitor center.
- Date talus cones inside the canyon using lichen growth.
- Determine the age of rim gravels with regards to the timing of downcutting, and their chemical alteration.
- Develop more graphics and brochures emphasizing geology, targeting the average enthusiast.
- Develop an informative trail guide based on the detailed GIS- NPS geologic map which has been published for Black Canyon - Curecanti. This would accent the strong geological component of the park and enhance the visitor's experience while at the parks.
- Determine a timeline of canyon incision on the Colorado Plateau. The timing of canyon incision on the Colorado Plateau is an important topic of discussion among Quaternary geologists. Incision and erosion are directly related to weathering rates and regional tectonic regimes.
- Perform rock color studies.
- Complete maps of areas north of Curecanti, possibly an EDMAP project

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Black Canyon of the Gunnison National Park and Curecanti National Recreation Area.

Black Canyon

The park's namesake, is the dominant feature of the landscape. In contrast to most of the canyons in the western United States, the Black Canyon is in many places deeper than it is wide (Figure 2). The average depth of the canyon is 610 m (2,000 ft), with a maximum width of 823m (2,700 ft), just north of Warner Point to a minimum of 533 m (1,750 ft) at The Narrows. The Gunnison River has an usually steep gradient over the length of the gorge. It falls about 655 m (2,150 ft) from the canyon head at Sapinero to the mouth at the junction with North Fork, a distance of just 80 km (50 miles). This is an average drop of 13 m (43 ft) per mile (Hansen, 1965). For comparison, the Colorado River in the Grand Canyon only descends an average of 2.3 m (7.5 ft) per mile.

Many geologic processes acted in concert to create the precipitous depths of the Black Canyon. The most obvious processes evident today include the turbidity of the river carrying mud and debris, occasional rockfalls from high cliffs, and the relentless movement of landslides into the depths. Other more subtle processes such as gullying, frost action, and chemical weathering (acid rain) increase the material available for the river to wash away.

The process of erosion is responsible for the excavation of the canyon. However, the coincidental interplay of several other geologic factors was necessary to remove more than 25 cubic miles of rock from the landscape along such a narrow course through incredibly hard metamorphic rocks (Figure 3). Prior to the Gunnison Uplift, the Gunnison River followed a course through relatively soft Mesozoic and Cenozoic volcanic and sedimentary rocks. The present path of the river is controlled by this previous course; it has been impressed on the hard, underlying Precambrian rocks due to relatively rapid Gunnison Uplift event.

Volcanic evidence indicates that the Gunnison River did not begin to incise its canyon until the cessation of volcanic activity in the West Elk and San Juan Mountains. The rocks of the Hinsdale Formation are the youngest to clearly predate the canyon. The age of this formation is generally regarded as Pliocene (about 11 to 1 million years ago). This means the relative age of the Black Canyon is fairly young, making the excavation even more remarkable (Hansen, 1965).

The tributaries of the Gunnison River flow from small catchment basins. If the tributaries were larger, they would tend to widen the canyon and undermine the erosive capability of the main river. Tributary streams such as Grizzly Gulch only flow intermittently.

The erosive power of these tributaries is negligible compared to that of the Gunnison River. The lack of major tributaries is a result of the Gunnison Uplift which diverts larger streams away from the canyon. This makes the Gunnison River the only deep course and helps to create the steep walls of Black Canyon.

Curecanti Dams

The three dams of Curecanti make up what is called the Wayne N. Aspinall Storage Unit. This is one of the four main units of the Upper Colorado River Storage Project (UCRSP). Other notable dams in this project include Navajo Dam in New Mexico, Flaming Gorge Dam in Utah, and Glen Canyon Dam in Utah. The primary purpose of this project is to provide reliable water storage to the Upper Colorado River Basin states of Colorado, Wyoming, New Mexico and Utah.

Blue Mesa Dam

Blue Mesa Dam is a 119 m (390 ft). high earth and rock fill dam. It was built as the first large dam on the Gunnison River in 1965. The largest body of water in Colorado, Blue Mesa Reservoir, is 32 km (20 mi) long with 155 km (96 mi) of shoreline. While Blue Mesa Dam does produce some hydroelectricity, with a power capacity of around 80,000kw, its primary purpose is to store water.

Morrow Point Dam

Completed in 1967, Morrow Point Dam lies 19 km (12 mi) below Blue Mesa Dam creating a deep, narrow reservoir between the steep walls of the Black Canyon. The dam is a concrete, double curvature, thin arch dam 143 m (469 ft). high, the first of its type built by the Bureau of Reclamation. The Morrow Point Dam was built primarily for the production of hydroelectricity. It has two 83,000kw generators, making its power capacity around 172,000kw, almost twice the power capacity of Blue Mesa Dam.

Crystal Dam

Crystal Dam was completed in 1976. This dam, like Morrow Point Dam, is a concrete, double curvature, thin arch dam. Crystal Dam is located 9.6 km (6 mi) below Morrow Point Dam. Just below the dam is the eastern boundary of Black Canyon of the Gunnison National Park through which the river runs unimpeded. The purpose of Crystal Dam is to stabilize the flow of water through the Black Canyon of the Gunnison although it produces some hydroelectricity as well.

Gunnison Uplift

The Gunnison uplift first took form about 60 million years ago during the Late Cretaceous- Early Tertiary mountain building event known as the Laramide orogeny. It is the dominant structural feature of the area and is responsible for the relatively tiny watershed of the Gunnison River. All would be tributaries, are diverted by the swell, while the Gunnison River cuts directly through the Black Canyon.

The Gunnison uplift is mainly an upfaulted but partly arched block. The Laramide orogeny reactivated previous fault block surfaces with new stresses in the Precambrian basement rocks. The crest of the Gunnison uplift is gently bowed and in areas rocks are sharply folded along faults. Locally the block is tilted 5 to 10 degrees to the north- northeast (Hedlund and Olson, 1981).

The uplift was beveled flat by Tertiary erosion prior to regional volcanism (Hansen, 1964; 1965). The core of the uplift is exposed in the depths of the Black Canyon of the Gunnison. The unconformity seen at the canyon rim where ancient Precambrian Rocks are overlain by relatively young Upper Jurassic and Tertiary age rocks remains one of the more impressive geologic and physiographic features of the region.

Curecanti Needle

The Curecanti Needle is located about 7.2 km (4.5 mi) downstream from Blue Mesa Dam near Sapinero, Colorado. It is a spirelike monolith rising nearly 244 m (800 ft,) composed of an intrusive igneous rock called the Curecanti Quartz Monzonite. This name was applied by J. Fred Hunter in 1925. The quartz monzonite is Precambrian in age and forms an irregular, rather flat laccolith, roughly centered around Curecanti Needle. The laccolith is a pluton roughly 5.6 km (3.5 mi) across from west to east and 3.2 km (2 mi) from north to south (Hansen, 1964).

Dillon Pinnacles

The Dillon Pinnacles are comprised of West Elk Breccia. The West Elk Breccia contains solidified lava flows intermixed with coarse fragments of material resulting from the explosive destruction of previous volcanic features. The volume of the West Elk Breccia is enormous, remnants of the formation exceed 305 m (1000 ft) in thickness and conservative estimates of the formations original volume exceed 625 cubic km (150 cubic miles).

Exposures of West Elk Breccia are especially good in the headward part of the Black Canyon, along Highway 92 and U.S. Highway 50. The Dillon Pinnacles typify the erosional formations contained within the West Elk Breccia. Cliffs, crags, pillars, windows and assorted erosional hoodoos abound.

Faults

Dominant high- angle fractures in Black Canyon trend west- northwest and north- northeast. These fractures are minor in comparison to parallel faults in the area. The largest, named the Cimarron Fault, is part of a left- lateral couple in the area, showing lateral displacement and trending west- northwest for at least 64 km (40 mi) (Hansen, 1964). This fault bounds the Gunnison Uplift on the south and is well exposed along the Lake Fork of the Gunnison River, where Mancos Shale is faulted downward against much older Precambrian rocks (Hedlund and Olson, 1981). Laramide movement along the Cimarron Fault resulted in at least 610 m (2,000 ft) of displacement. Red Rocks fault trends north-northeastward 32 km (20 mi) or more from the head of Red Rock Canyon to the west of Blue Creek (Hansen, 1965).

These fault surfaces were present prior to the Laramide orogeny forcing the Gunnison uplift to rise. Movement along these faults ceased before the end of the Tertiary. Most major faults in the area show a high degree of topographic relief across them. This is not due to recent movement, but rather to differential erosion between different rock types on either side of the fault (Hansen, 1965).

Figure 2: View of narrow, deep Black Canyon of the Gunnison. Photograph by Trista L. Thornberry-Ehrlich, Colorado State University.

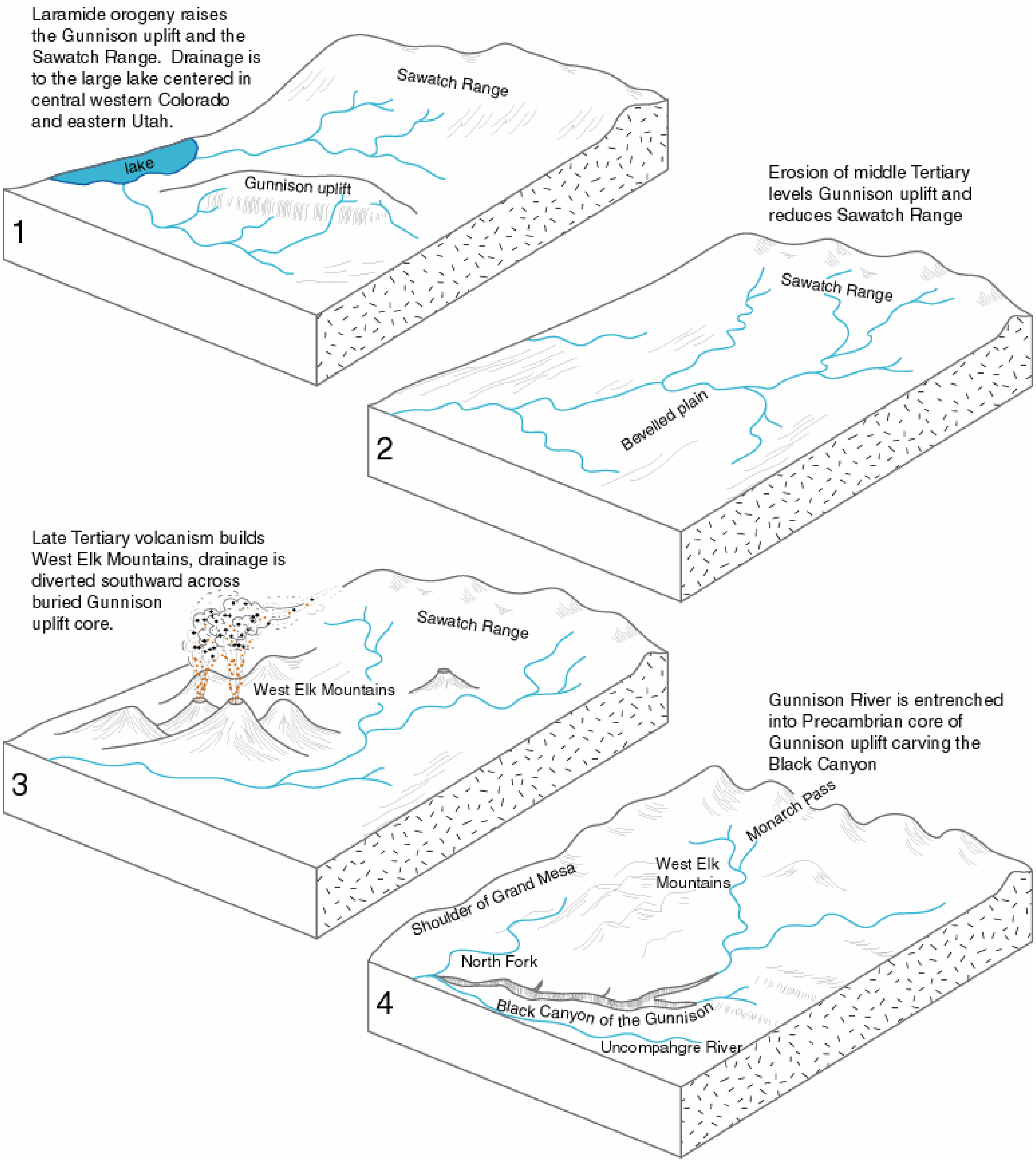


Figure 3: The block diagrams above summarize the sequence of events responsible for the formation of the Black Canyon of the Gunnison. Please note, the diagrams are not to scale.

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 Black Canyon of the Gunnison National Park and Curecanti National Recreation Area. The table in this section 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.

Through incredible erosion, the Gunnison River has exposed a wide range of rock types, from 1.7 billion year old gneiss and schist to Mesozoic – Cenozoic fossiliferous sedimentary rocks and modern unconsolidated sediments.

The steep, "black" walls of the canyon are composed of Precambrian granites, gneisses, gabbros, diorites, pegmatites, and schists (Figure 4). The canyon itself is considered one of the best exposures of these ancient rocks in the world.

Directly atop the Precambrian rocks, lie Mesozoic and Cenozoic sedimentary strata. No Paleozoic sedimentary rocks exist in the Black Canyon – Curecanti area. The absence of Paleozoic strata creates an unconformity, indicating that approximately 370 million years of earth history are missing from this landscape. The Entrada Sandstone, Wanakah Formation, and Morrison Formation represent Jurassic time in the area. The fossils and depositional structures within these rocks record a vast array of Jurassic climates and environments.

Above the Jurassic rocks are the Cretaceous sandstones, shales, and coal beds of the Dakota Sandstone and Burro Canyon Formation. The muds of the Mancos Shale, the volcanic breccia of the Cimarron Ridge Formation, and the brown shales and calcareous sandstones of the Fruitland Formation and Pictured Cliffs Sandstone complete the Cretaceous strata at Black Canyon – Curecanti.

At the end of the Laramide orogeny volcanic activity erupted across the area resulting in large deposits of volcanic ash, tuff, and breccia. These and other Tertiary igneous rocks cap the regions mesas today. Specific formations include West Elk Breccia, Blue Mesa Tuff, Dillon Mesa Tuff, and Carpenter Ridge Tuff.

Today, Quaternary silts, sands, and gravels are preserved in the canyons and surface depressions of Black Canyon- Curecanti as terrace deposits, alluvium, and colluvium. They represent only a fraction of the deposits that once spread across this area, only to be subsequently stripped from the region by the relentless process of erosion.

The following pages present a tabular view of the stratigraphic column and an itemized list of features for each map 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
QUATERNARY	Alluvium & surficial deposits (Qa); Alluvial & colluvial deposits (Qac), Eolian deposits (Qe); Fan deposits (Qf); Landslides, mudflows, debris flows (Ql); Active landslide deposits (Qla); Earthflow & mudflow lobes (Qlm); Talus, slope wash & colluvium (Qts); Volcanic ash (Qvb); Travertine (Qtr), Boulder gravel deposits near T50N,R9W (Qbo), Terrace and alluvial fan deposits in Bostwick Park & vicinity (Qtb); Terrace and pediment gravel (Qg); Pediment deposits (Qpa); Highest pediment remnant (Qpb); Older stream gravel (Qsg); Terrace deposits - undifferentiated (Qt); Terrace deposits of Cimarron & Blue Creek drainages (Qtx); Terrace and pediment deposits of Alkali Creek, Onion Valley and Crystal Creek (Qtax); Terrace and pediment deposits related to the Uncompahgre River (Qtux); Boulder gravel deposits - Bostwick Park (QTbg); High level gravel remnants (QTg); Older landslide deposits on Waterdog Peak (QTl)	Unconsolidated sands, silts, clays, pebbles, gravels and boulders; refer to BLCA GLG.hlp (Windows help file) included with the digital geologic map coverages on the accompanying CD	Low	Unconsolidated surficial deposits, should be fine for most development; very permeable	Potential for slumping, mass wasting and other slope processes	Recent fossils	Foundations for dwellings; tools & other artifacts; campsites possible	Metamorphic and igneous pebbles	None	Sand, silt, gravel, and clay	Ground cover, burrows, vegetation base	Ground surface for trails, picnic areas, mountain biking, etc.	Precisely defines Quaternary sequence
TERTIARY	Hinsdale Formation (Th), gravel (Thg); Carpenter Ridge Tuff (Tc); tuffaceous breccia (Tcb); nonwelded pumiceous tuff (Tcn); vitrophyre (Tcv); Tuff of Long Gulch (Tlo); Rat Creek Tuff (Tr); Fish Canyon Tuff (Tf); nonwelded tuff (Tfn); vitric tuff (Tfv), coarse gravel (Tfg); Sapinero Mesa Tuff (Ts); nonwelded tuff (Tsn); black vitrophyre (Tsv), gravel (Tsg); Dillon Mesa Tuff (Td), tuff breccia (Tdb); vitrophyre (Tdv), gravel (Tdg), Blue Mesa Tuff (Tb); black vitrophyre (Tbv); gravel (Tbg); Gravel Deposits Undifferentiated (Tg); Talus, slope wash, or colluvium, undivided (Tgt); Jasper or siliceous sinter (Tj); Travertine (Ttr); Lake Fork Formation- hornblende rhyo dacite flows (Tl), andesite flows and autobreccia (Tla); andesitic to quartz- latitic breccia (Tlb); porphyritic andesite (Tlba); rhyodacite dikes (Tld); quartz latite flows and breccia (Tll); rhyodacite flows (Tlr); pumiceous tuff (Tlt); coarse gravel (Tlg).	Volcanic deposits; various welded, to non- welded tuff with phenocrysts; some unconsolidated gravel deposits; refer to BLCA GLG. hlp file for individual unit descriptions	Moderate	None	Some rockfall potential	None	None	Phenocrysts of olivine, feldspar, etc. in tuffs	None	Gravel	Vugs in tuffs may provide nesting habitat	Climbing is not recommended on tuff units	Age dating
	West Elk Breccia (Tw), ash- flow tuff (Twa), brecciated rhyodacitic flows (Twf), volcanic conglomerate (Twc), laharic volcanic and tuff breccia (Twt), coarse gravel (Twg)	Volcanic deposits; Relatively thin flows of pyroxene and hornblende andesite and hornblende dacite and associated flow breccias, tuffs, and gravels	Moderate	None	Some rockfall potential	None	None	Phenocrysts of olivine, feldspar, etc in flows	None	None	Vugs in tuffs may provide nesting habitat	Climbing is not recommended on tuff units	Age dating
CRETACEOUS	Cimarron Ridge Formation (Kcr), Camptonite (Kc), Fruitland Formation (Kf), Pictured Cliffs Sandstone (Kpc)	Kcr - volcanic breccia; Kc - lamprophyric sills; Kf - carbonaceous brown shale; Kpc - calcareous sandstone	Moderate	Shale beds may fail when exposed on a slope if weathered	Some rockfall potential, and slumping	Kf and Kpc contain coal beds with plant fossils	None	Labradorite and various igneous minerals	Some in calcareous sandstone beds	Coal beds locally in Kf	None	Fine trail base	Age dating; coal beds
	Mancos Shale (Km)	Dark- gray silty clay shale with lenses of friable gray sandstone and scattered calcareous siltstone concretions	Low	Bentonite beds (swelling clays) render unit unstable along slopes; slippery when wet	Potential for slumping, mass wasting and other slope processes	Scaphites depressus, Exiteloceras jenneyi, Didymoceras cheyennense, idymoceras nebrascens, marine mollusks	None	Large gypsum crystals; concretions	Some in calcareous siltstone beds	None	Friable units provide burrows	Swelling clays render this unit unstable; slippery when wet	Widespread unit in southwestern Colorado
	Dakota Sandstone and Burro Canyon Formations (Kdb)	Generally light- brown, medium- to coarse- grained sandstone; upper reaches, carbonaceous shale beds generally less than 6 inches thick interbedded with silty sandstones	Moderate to high	None	Some rockfall potential where unit is undercut	Some plant impressions, worm burrows, petrified wood	Chert source for tool making	Pebble conglomerate	Some in carbonaceous shale beds	Coal beds locally	None	Fine trail base	Widespread coal beds

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
JURASSIC	Morrison Formation (Jm)	Mudstone, siltstone, thin lenticular sandstone beds; upper part is light-green to gray mudstone and siltstone with very thin intercalated silty sandstone beds; lower half red to purple mudstone with thin lenticular sandstone beds	Low to moderate	Bentonite beds (swelling clays) render it unstable along slopes; very slippery when wet	Potential for slumping, mass wasting and other slope processes	Dinosaurs, other reptiles, and a variety of plant fossils	Chert source for tool making	Fossils	Some in carbonaceous siltstone beds	Uranium ore	Friable units provide burrows	Swelling clays: unstable and slippery when wet; uranium ore may deter recreation.	Dinosaur fossils still being uncovered
JURASSIC	Wanakah Formation ((Jw), Junction Creek Sandstone Member (Jwjl)	Interbedded sandstone, siltstone, gypsum, and mudstone in upper beds; Jwj is a discontinuous fine-grained friable highly cross- bedded light- gray to light- yellowish- gray to pink eolian sandstone, mapped locally	Moderate to high	Gypsum and mudstone beds may fail on weathered slopes.	Potential for slumping, mass wasting and other slope processes; rockfalls where unit is undercut	Fossil algae, fresh-water clams, snails	Chert source for tool making	Gypsum crystals and nodules	None	Gypsum	None	Fine trail base	Index fossils for dating
	Entrada Sandstone (Je)	Yellow fine- grained sandstone with some scattered medium to coarse, well- rounded grains; basal conglomerate, detritus from underlying Precambrian rocks	High	None	Some rockfall potential where unit is undercut	None	Possible petroglyphs along cliff faces	None	None	Flagstone	Cliffs provide nesting sites and big horn sheep habitat	Climbing and mountain biking	Correlation across southern U.S.
PRECAMBRIAN - CAMBRIAN-ORDOVICIAN	Diabase dikes (OCd) Trachyte & Trachyte Porphyry Dikes(CpCt); Intrusive breccia (CpCbx); Iron Hill Alkaline complex (CpC); Carbonatite (CpCc); Nepheline syenite (CpCns); Pyroxenite-nepheline syenite hybrid rock (CpCps); Ijolite (CpCi); Melanite-orthoclase rock (CpCmo); Magnetite- ilmenite- perovskite dikes (CpCmt): Pyroxenite (CpCpy); Rocks altered to fenite (Caf).	Various intrusive igneous rocks present as dikes, breccias, and irregular veins and complexes; Refer to BLCAGLG.hlp for specific descriptions for individual units	High	None	Some rockfall potential	None	None	Pegmatites	None	Th, Mn, V, Au, Ag, & Cu sulfides; Te Nb, Ti; vermiculite	Cliffs provide nesting sites and big horn sheep habitat	Steep for trails	Age dating
PRECAMBRIAN	Fine- to Medium- grained Granite (pCfg); Syenite & Related Rocks (pCxx); Granite & quartz syenite of Wolf Creek (pCwe); Quartz syenite, syenite, & granite (pCsy); Fine- grained melasyenite (pCfs); Porphyritic augite syenite (pCas); Biotite syenite (pCbs); Gray porphyritic syenite (pCps); Melasyenite (pCms); Biotite syenite and hornblende syenite (pCcs); Leucosyenite (pCls); Minette (pCmi); Curecanti Quartz Monzonite (pCe); Lamprophyre (pCl); Vernal Mesa Quartz Monzonite (pCv); Gabbro (pCga); Olivine Pyroxenite (pCop); Undifferentiated Granitic Rocks (pCx); Metarhyolite (pCmr); Pegmatite (pCp); Quartz monzonite or granite (pCqm); Granite & quartz syenite of Carpenter Gulch (pCcg); Granite, leucogranite, & quartz monzonite (pCg); Granophyre (pCgr); Porphyritic granite (pCpg); Quartz veins (pCqv), Trachyte Dikes (pCt); Powderhorn Granite (pCpo); Granite of Tovlar Peak (pCtp); Quartz Diorite- to- Monzonite of Gold Basin (pCgb); Lamprophyre (pCl); Pitts Meadow Granodiorite (pCpm); Light-colored, gneissic granodiorite or quartz diorite (pCpm): Dark-colored, gneissic granodiorite or quartz diorite (pCpv); Granite of South Beaver Creek (pCsb); Granite to grano- diorite ((pCsb); Granite to quartz monzonite porphyry (pCsbp); Diorite or Quartz Diorite (pCqd); Quartzite & metachert (pCqt); Black Canyon Schist & Gneiss (pCb); Schist and gneiss, undifferentiated (pCsg); Amphibolite (pCa); Quartz- biotite gneiss & migmatite (pCbt); Quartzofeldspathic gneiss (pCf); Migmatitic gneiss (pCgm); Layered quartzitic gneiss (pCgl); Massive quartzitic gneiss (pCgq); Hornblende schist & amphibolite (pCh); Mica schist (pCm); Quartzofeldspathic & quartz- sericite schist (pCqf); Quartzite (pCqt); Quartz- biotite schist, gneiss & migmatite (pCs); Dubois Greenstone (pCdb); Quartz- biotite- calcite schist (pCdb); Amphibolite, metadiorite, & metagabbro (pCda); Amphibolite-granite hybrid rock of Carpenter Gulch (pCdag); Quartzite conglomerate (pCdc); Felsite & felsite porphyry (pCdf), Metavolcanic hornblende schist & amphibolite (pCdh); Quartzite (pCdq), Quartz- sericite schist & quartzite (pCdqs); Interlayered greenstone & metasedimentary rocks (pCds)	Granites, diorites, syenites, quartz monzonite, gabbros, pegmatites, gneisses and other assorted metamorphic and intrusive igneous rocks; Specific unit descriptions are too lengthy to include here, please refer to BLCAGLG.hlp for detailed information about each unit listed. BLCAGLG.hlp (Windows help file) is included on CD with digital geologic map coverages	High	Steep slopes: inaccessible for development	Some rockfall potential	None	None	Pegmatites, metamorphic and igneous rock samples	None	Attractive building stones, gold, copper, silver veins locally contained in quartz; pyrite, chalcopyrite, sphalerite, vulcanite	Cliffs provide nesting sites and big horn sheep habitat	Steep for trails	Age dating; large Precambrian record

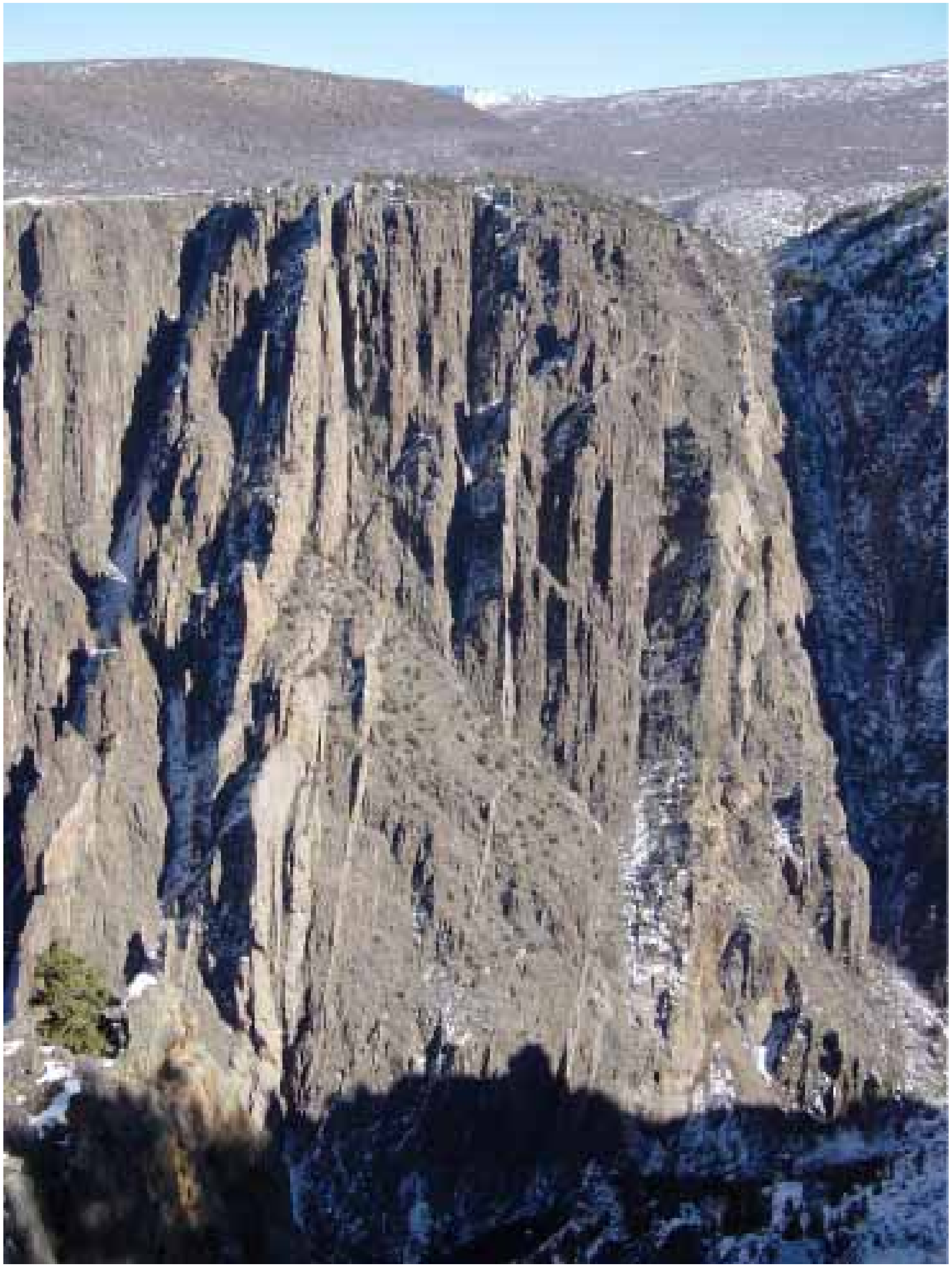


Figure 4: View of the Precambrian rock walls forming Black Canyon of the Gunnison. Photograph by Trista L. Thornberry-Ehrlich, Colorado State University.

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Black Canyon of the Gunnison National Park and Curecanti National Recreation Area 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.

Preserved Precambrian history began in the Colorado Plateau – Rocky Mountain area in the Proterozoic about 1,800 – 2,000 million years ago (Ma) when muddy sandstones (*graywacke*), shales, and volcanic rocks were deposited in a vast oceanic environment. Erupting volcanoes formed a chain of islands in this ancient ocean beyond the southern edge of the North American craton (Reed *et al.*, 1987; Scott *et al.*, 2001). It was in a back- arc basin that volcanic and sedimentary deposits collected between 1,710 and 1,740 Ma. This collection of deposits would later comprise the Black Canyon Precambrian terrane, one of four early Proterozoic terranes identified in Colorado (Knoper *et al.*, 1987)

About 1,740 Ma a period of compressive mountain building folded the Precambrian strata into tight, chevron- like folds and metamorphosed the rocks to gneisses as the volcanic islands collided with the southern end of what is now Wyoming (Hutchinson, 1976; Tweto, 1980; Warner, 1980; Gregson, 1992; Scott *et al.*, 2001). Metamorphosed sedimentary and volcanic rocks over 1,800 million years old are present in exposed terranes throughout Colorado and in the buried basement of the Colorado Plateau (Tweto, 1980). Gneisses, schists, granites, pegmatites, and other rocks that dominate the walls of Black Canyon are all Precambrian in age.

Late Proterozoic rifting created a new continental margin along western North America. During the Late Precambrian and Cambrian, deposits of shallow- water, marine sediments thousands of feet thick accumulated along a passive plate- tectonic margin on the western side of the Transcontinental Arch. The arch was an upland that stretched from northern Minnesota southwestward across Nebraska, Colorado and northwestern New Mexico (Speed, 1983; Sloss, 1988).

Throughout the Paleozoic Era, Africa, and South America were approaching North America as the two great landmasses, Laurasia and Gondwana, collided. The ancient continent of Gondwana included Australia, Antarctica, Africa, South America, and India south of the Ganges River, plus smaller islands. Laurasia, located in the northern hemisphere contained the present northern continents. The union of Gondwana and Laurasia formed the supercontinent, *Pangaea,* which was centered on the equator.

What happened geologically in the Ordovician Period (438- 505 Ma) and the Silurian Period (408- 438 Ma) in southwestern Colorado remains somewhat of a mystery because no Ordovician or Silurian rocks are present there today. It is known that the end of the Ordovician Period (438 Ma) marks one of the five most extensive mass extinctions of all time (see Figure 11).

The other four occurred at the end of the Devonian Period, the end of the Permian Period, at the close of the Triassic, and most recently at the Cretaceous – Tertiary boundary. There is a significant period of time missing from the rock record at Black Canyon where Precambrian rocks are covered by Mesozoic age rocks. This juxtaposition means more than 370 million years of the rock record is missing in central Colorado. The following brief discussion draws from areas surrounding Black Canyon – Curecanti where the rock record is more complete.

By the beginning of the Devonian Period, the seas that had covered most of the continent had receded far to the west. The first pulses of the Antler orogeny in the west and the Acadian orogeny in the east (part of the Appalachian orogeny) began to be felt as landmasses accreted onto both the western and eastern borders of North America. To the west of Colorado, a subduction zone formed. As lithospheric plates collided their rocks were bent, folded, and thrust- faulted into a north- south trending mountain range stretching from Nevada to Canada. The Roberts Mountains Thrust marks the easternmost thrust sheets generated by the Antler orogeny (figure 5).

As the highlands to the west were thrust above sea level at the beginning of the Mississippian Period, warm marine water gave rise to extensive deposits of carbonate rocks (figure 6) (De Voto, 1980A; Poole and Sandberg, 1991). The structural effects of compression on the western margin, however, were evident as far inland as southwestern Colorado where local uplifts caused regression and erosion. Aggressive tectonism in the Pennsylvanian Period built mountains (the Ancestral Rocky Mountains) in Colorado with as much as 3,000 m (10,000 ft) of relief (De Voto, 1980B).

The Permian was a time of worldwide changing environments. In the area southwest of Black Canyon - Curecanti, beyond the Uncompahgre Mountains, broad lowlands extended toward an ocean to the west (Baars, 2000). The close of the Permian also brought the third, and most severe, major mass extinction of geologic time. (Becker *et al.*, 2001). It is hypothesized that a large comet colliding with the earth wiped out 300 million years of history.

In the Early Triassic (240 to 245 Ma), volcanic activity decreased on the western margin of the supercontinent (Christiansen *et al.*, 1994). The depositional environments in the Early Triassic represent a transition from marine and marginal marine environments in western Utah and Nevada to terrestrial (above sea level) environments in western Colorado.

Throughout the Early Triassic the region around Black Canyon - Curecanti remained above sea level and red beds (rocks of terrestrial origin with relatively high iron contents) were deposited over the area (figure 7) (Stewart *et al.*, 1972A; Christiansen *et al.*, 1994; Doelling, 2000; Huntoon *et al.*, 2000).

As Pangaea began to break apart in the late Triassic and early Jurassic, the monsoonal climate changed. The Western Interior of North America was slowly rotating into a position farther north of the equator. Soon, the Colorado Plateau – Rocky Mountain region was to become a Sahara- like desert.

The mesas on the North Rim of Black Canyon along Highway 92 in Curecanti reveal exposures of rocks deposited during the Mesozoic. Just downstream of Black Canyon the thin strip of pink or yellow rock present at the northern lip of the canyon is the Entrada Sandstone. This rock formed when massive sand dunes covered much of this region. Extensive eolian sand seas, called *ergs*, blew across the Colorado Plateau during the Lower Jurassic (figure 8). The region was located about 18° north latitude at the beginning of the Jurassic and about 30- 35° north latitude at the end of the Jurassic (Kocurek and Dott, 1983; Peterson, 1994). This is the latitude of the trade wind belt.

The western edge of the continent was marked by a continental- margin volcanic arc, a product of subduction processes that began during the Triassic (Dubiel, 1994) and reached its maximum development in the Cretaceous. At the beginning of the Middle Jurassic Period, the western Elko highlands emerged to the west of the Utah- Idaho trough recording an irregular, pulsed orogeny (Peterson, 1994).

Middle Jurassic strata in the area represent a complex interfingering of marine and nonmarine environments. The sediments were deposited during five major transgressive- regressive cycles (Peterson, 1994). A picture emerges of broad tidal flats marginal to a shallow sea that lay to the west (Wright *et al.*, 1962). As plate tectonic activity increased at the end of the Middle Jurassic and beginning of the Late Jurassic (about 157 Ma), a major transgression of the inland seaway covered the vast eolian dune fields of the Colorado Plateau region (Kocurek and Dott, 1983). Tidal flats covered the area as marine environments pushed south and the extensive Upper Jurassic, Morrison Formation was deposited across the continental Western United States (figure 9). Morrison depositional environments were quite varied. Sediments were deposited in mudflats, overbank floodplains, stream channels, small eolian sand fields, and scattered lakes and ponds (Peterson, 1994). The best place to find the Morrison Formation in Black Canyon – Curecanti is along the shore of Blue Mesa Reservoir.

During the Jurassic, the subducting oceanic slab (named the Farallon plate - precursor to the Pacific plate) sliding eastward beneath the continental lithosphere is thought to have changed its angle of descent becoming steeper. This change caused the volcanic arc to shift its position farther to the west near the present- day border of California and Nevada. The late Jurassic and earliest Cretaceous magmatic activity associated with this volcanic arc is known as the Nevadan orogeny. The Nevadan orogeny spread volcanic ash across the Colorado Plateau and evolved into the late Cretaceous Sevier orogeny as the rate of lithospheric plate movement increased.

The Sevier orogeny formed a roughly north- south trending thrust belt that is well defined in present- day southern Nevada, central Utah, and western Montana (figure 10). A series of eastward- directed overthrusts carried upper Precambrian and lower Paleozoic sedimentary rocks over upper Paleozoic and lower Mesozoic rocks (Stewart, 1980).

As mountains rose to the west and the roughly north- south foreland trough expanded, the Gulf of Mexico separating North and South America continued to rift open in the south, and marine water began spilling into the basin. At the same time, marine water began to transgress from the Arctic region. The sea advanced, retreated, and readvanced many times during the Cretaceous until the most extensive interior seaway ever to cover the continent 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 4,827 km (3,000 mi) (Kauffman, 1977). During periods of maximum transgression, the width of the basin was 1,600 km (1,000 mi). The basin was relatively unrestricted at either terminus (Kauffman, 1977).

Deposited above the Jurassic Morrison is the Cretaceous Dakota Sandstone. This buff- colored rock forms prominent outcrops in the roadcuts along Highway 50 just west of Elk Creek. Coarse conglomeratic sandstones, cross- stratification, petrified wood fragments, and erosional topography are characteristic of the lower Dakota Sandstone in the Black Canyon – Curecanti area. This suggests that the sediments were deposited by fluvial processes in paleovalleys (Ekren and Houser, 1965; Condon, 1991; Elder and Kirkland, 1994).

At the beginning of Late Cretaceous time, the interior seaway had advanced to cover the eastern third of the Colorado Plateau. Gradually, as sea level rose, the soft, sparsely fossiliferous, dark- gray muds of the Mancos Shale were deposited in the deepening basin above the Dakota Sandstone.

By the end of the Cretaceous, tectonic plates were jockeying for position on the western margin of the North American continent. From late Jurassic to late Cretaceous plutons, of the Sierra Nevada batholith, were emplaced beneath the Sierra Nevada Mountains. Granitic plutons were developing in a southwest-northeast trend from southwestern Colorado to north-central Colorado (Christiansen *et al.*, 1994). The rearrangement of tectonic plates gave rise to the Laramide orogeny, the mountain- building episode that began the development of the modern Rocky Mountains.

The Laramide orogeny began approximately 66 to 70 million years ago, in the late Cretaceous, and continued intermittently until between 35 and 50 million years ago. The Laramide event transformed the extensive basin of the Cretaceous Interior Seaway into smaller interior basins bordered by high arches (anticlines and synclines on the scale of miles). The Gunnison uplift is an example of one of those arches. North of the Colorado Plateau, the stresses caused by colliding plates to the west forced several Precambrian crustal wedges upwards, forming the Colorado Front Range and the Southern Rocky Mountains. However, the Colorado Plateau region appears to have reacted as a single block to the crustal forces that buckled the rest of the central Rocky Mountains as the sedimentary strata on the Colorado Plateau were warped into broad anticlinal and synclinal folds with very little brittle faulting (Dickinson and Snyder, 1978; Chapin and Cather, 1983; Hamilton, 1988; Erslev, 1993).

In some areas Laramide mountain building was accompanied by volcanic eruptions and magma emplacement. Tertiary volcanism deposited vast blankets of material in the Black Canyon area and is responsible for one of the most notable geologic features in Curecanti National Recreation Area, the Dillon Pinnacles. The Dillon Pinnacles, composed of 30 million year old West Elk Breccia, tower above the northern shore of Blue Mesa's Sapinero Basin. The West Elk Breccia formed as a result of a huge volcanic mud flow of ash and volcanic debris that spewed from violent eruptions in the West Elk Mountains.

The West Elk Mountains were among several centers of igneous activity during the Tertiary. From about 26- 35 Ma, in the Oligocene epoch, volcanic activity erupted across the region. The laccoliths that formed the Henry Mountains, La Sal Mountains, and Abajo Mountains were emplaced during the mid- Tertiary. A series of volcanic ash flows from the San Juan Mountains covered much of southern Colorado. The burning- hot ash and glass shards of these flows welded together to form a dense, resistant rock known as welded tuff. Today this serves as a resistant cap rock on the mesas of Curecanti National Recreation Area.

A period of volcanic quiescence followed from about 16 to 19 Ma. During this time, the western United States underwent a radical tectonic transformation wherein the compressional regime that had existed for millions of years became an extensional regime. As the crust was extended, the surface broke into the basin- and- range, block- faulted topography we see today in western Utah and Nevada. Extensional faulting and basaltic volcanism in the western United States continues into the present.

The Tertiary uplift and volcanism established the headwaters for the Gunnison River. Snowmelt from the Sawatch Range to the east, the West Elk Mountains to the north and the San Juan Mountains to the south began to supply water to what would become the Gunnison Basin. The modern Gunnison River first established its current course 10 to 15 million years ago. During the uplift of the Colorado Plateau, between 5 and 10 Ma, the river cut through the thick layers of Tertiary volcanics and Mesozoic sedimentary rocks (Hintze, 1988).

Early in the Quaternary (2- 3 Ma) a broad uplift of the entire region initiated another period of active erosion. It is at this point in geologic history that the profound scouring of the Black Canyon is thought to have occurred. Constrained in its own canyon of Tertiary and Mesozoic rocks, the river began to incise its bed, exposing the much harder Precambrian metamorphic and igneous rocks of the eroded Laramide age Gunnison Uplift. At the rate of approximately one inch per hundred years, the high volume, high- velocity Gunnison River slowly worked its way through the tough rock, as it carved the narrow, steep- sided Black Canyon.

During the cooler, more humid climates of Pleistocene glaciation, streams cut headward into canyons, developing the drainage pattern seen today in the Colorado Plateau – Rocky Mountain area. Meltwater from glaciers brought more gravel deposits into the area. Spring meltwater continues to feed the Gunnison today as it winds through both parks. Today, the climate is drier and the Gunnison River no longer flows freely through the canyon. The three dams of Curecanti hold back the Gunnison’s yearly floods reducing erosion rates in the canyon.

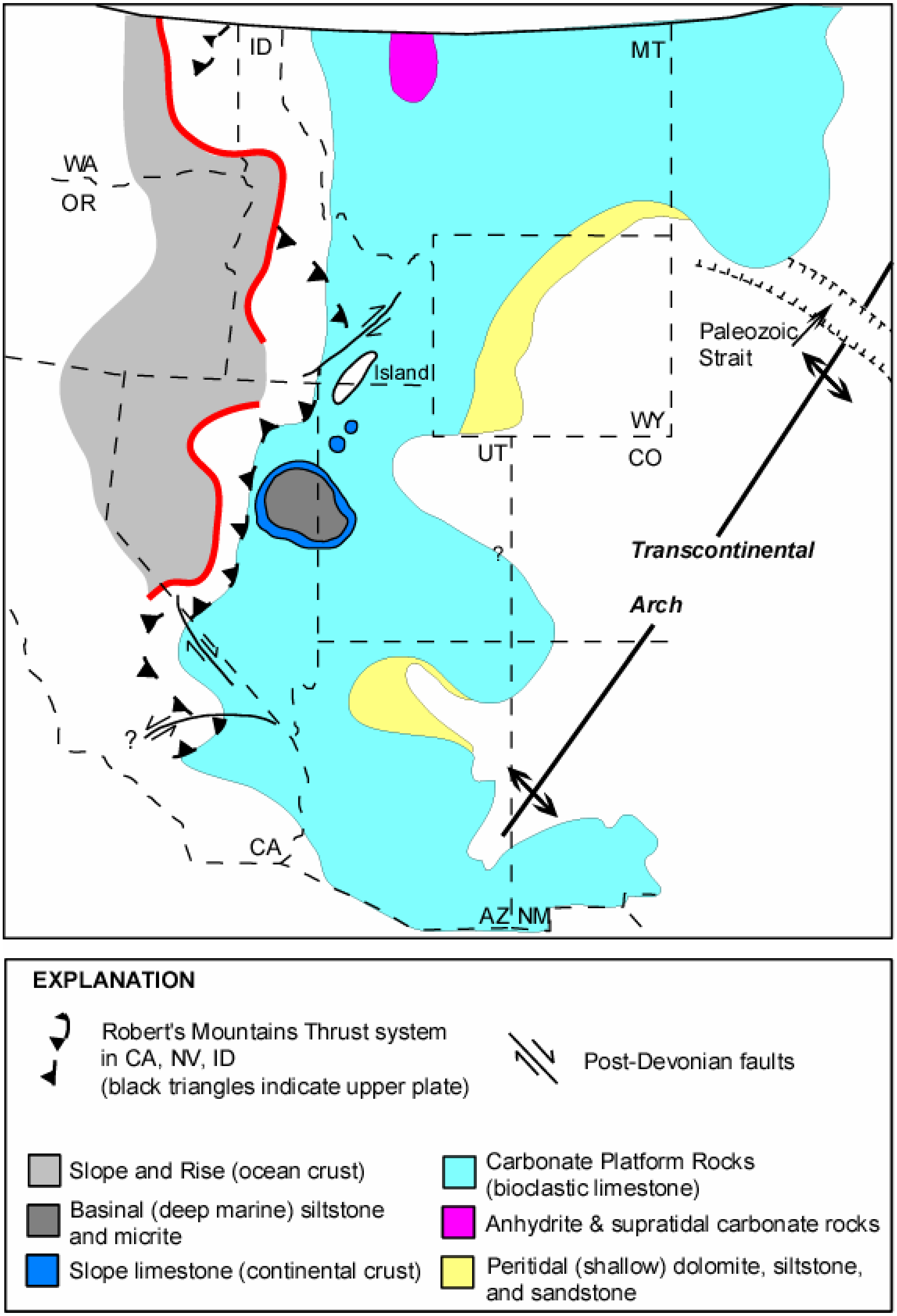


Figure 5: Distribution of lithofacies during the Upper Devonian, Frasnian stage of western United States. The red line is the strontium isotope line wherein $^{87}Sr/^{86}Sr$ = 0.706 and is interpreted to represent the break between continental and oceanic crust. Modified from Johnson *et al.*, 1991.

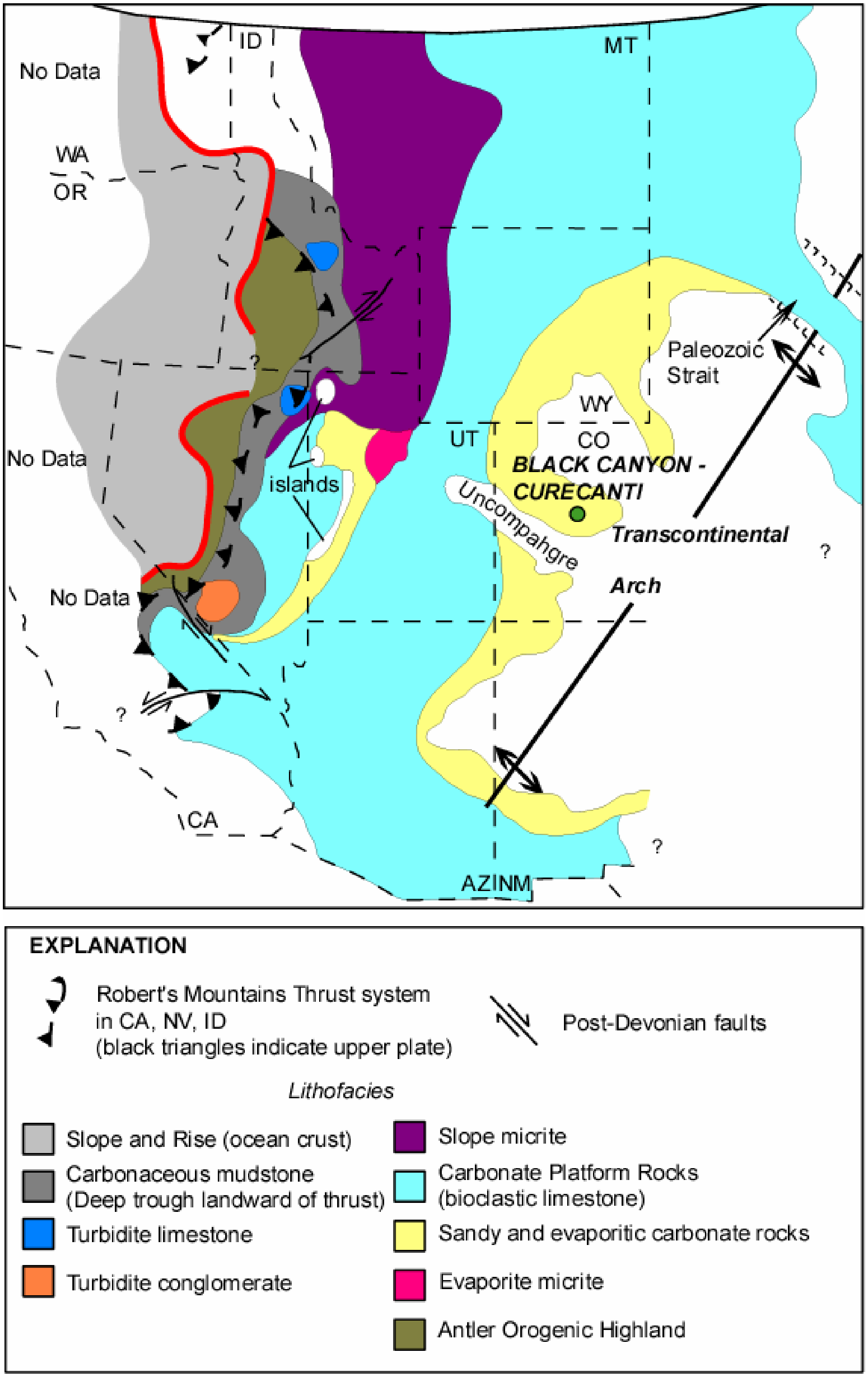


Figure 6: Lithofacies map of the Lower Mississippian Period, Kinderhookian stage of the Western United States. While the lithofacies are complex in the foreland basin adjacent to the Antler orogenic highland, a broad carbonate platform developed to the east. Marine water breached the Transcontinental Arch through the Paleozoic Strait. Any Mississippian rocks that were deposited on the transcontinental Arch or ancestral Uncompahgre highland during this time have been eroded. Modified from Poole and Sandberg, 1991.

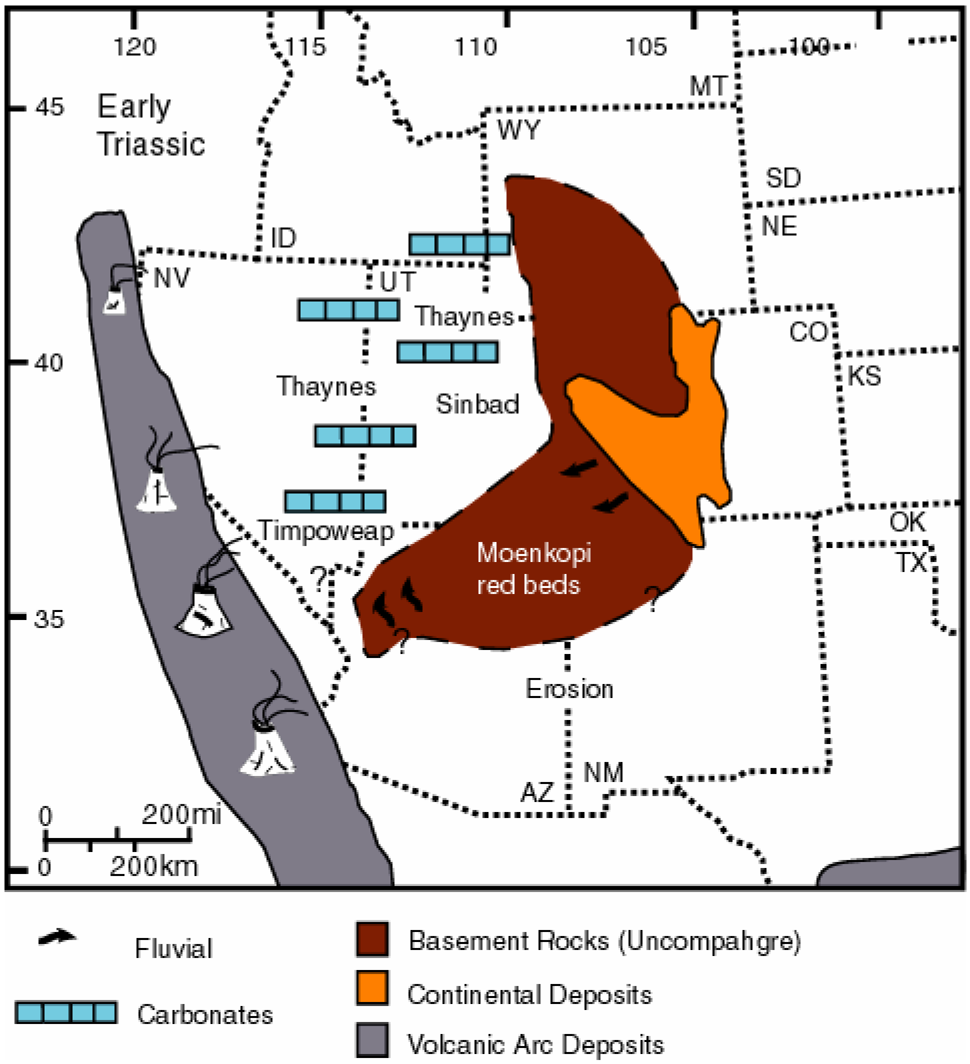


Figure 7: Paleogeographic map of the Lower Triassic, Moenkopi Formation during the second transgressive episode of the Early Triassic. Modified from Dubiel, 1994.

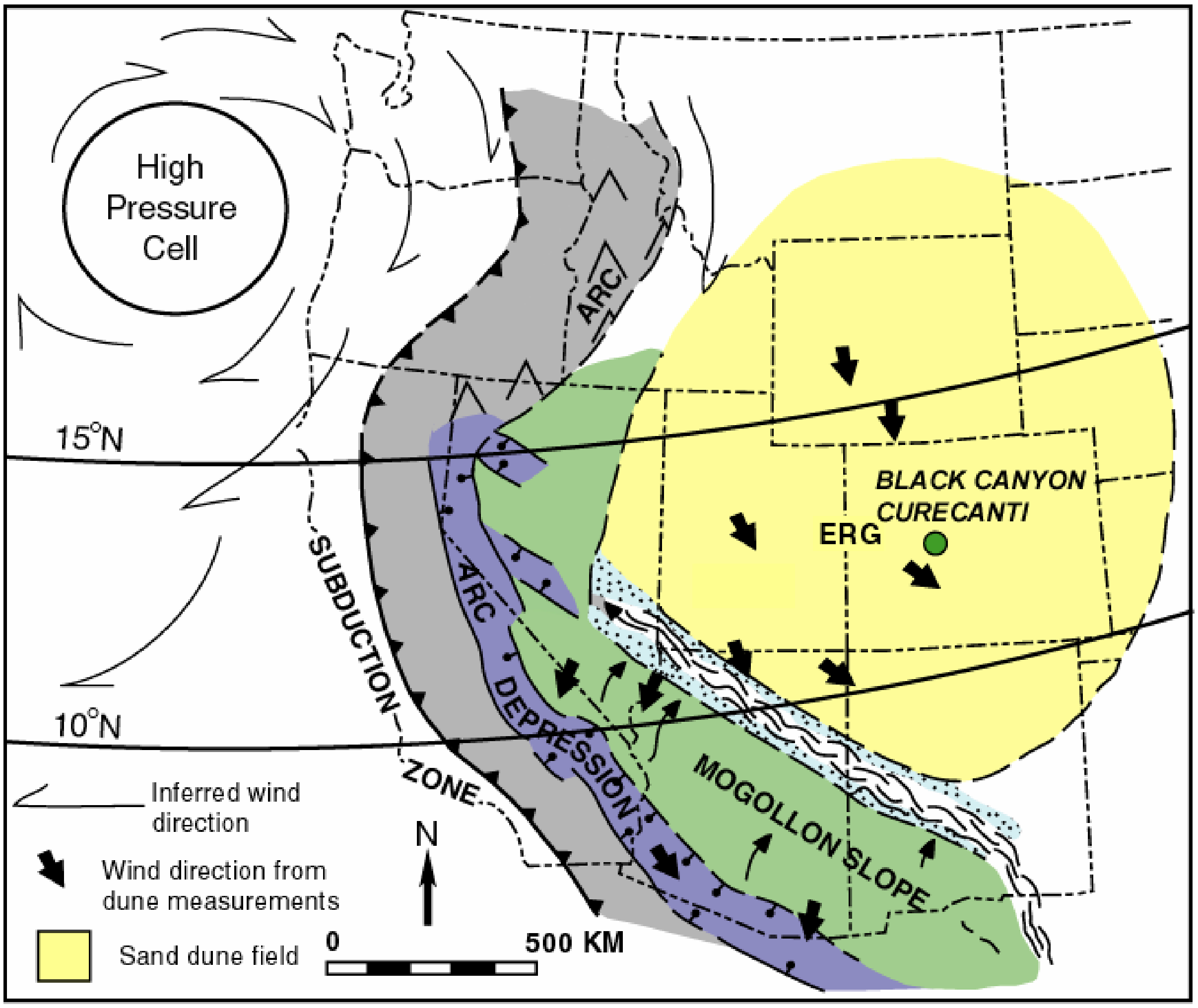


Figure 8: Paleogeographic map of the Lower Jurassic Period. Thick arrows indicate eolian transport of sand. Thin arrows indicate fluvial transport of sediments. Inverted "Vs" indicate the location of the volcanic arc. Solid triangles indicate the location of the subduction zone with the triangles on the overriding, upper lithospheric plate. Modified from Lawton (1994).

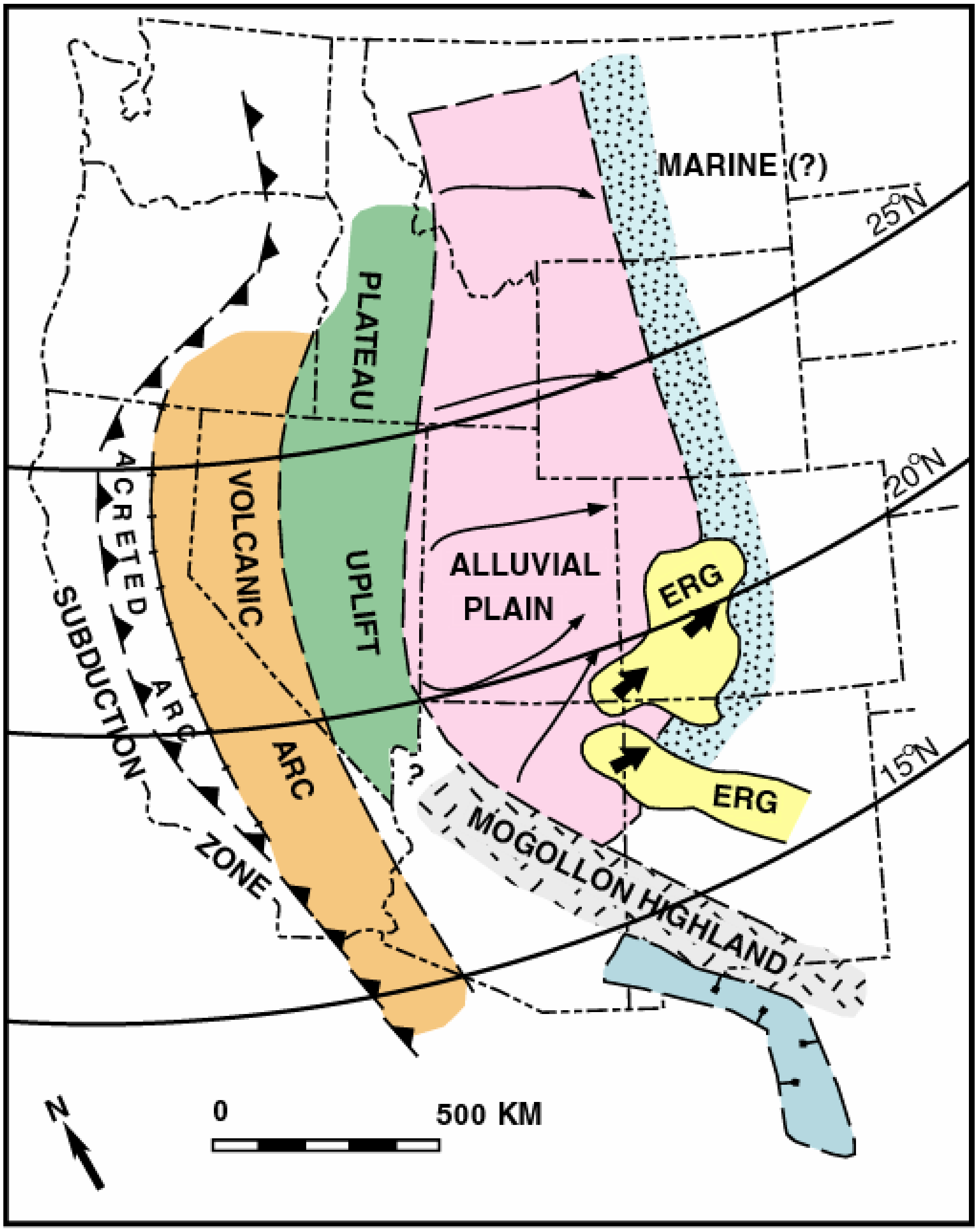


Figure 9: Upper Jurassic Period paleogeography. Thin arrows indicate fluvial dispersal. Thick arrows indicate wind directions. Sawteeth indicate the location of the subduction zone with the teeth on the overriding lithospheric plate. A marine environment possibly covered continental environments to the east. The alluvial plain expanded to the east with time. Modified from Lawton (1994).

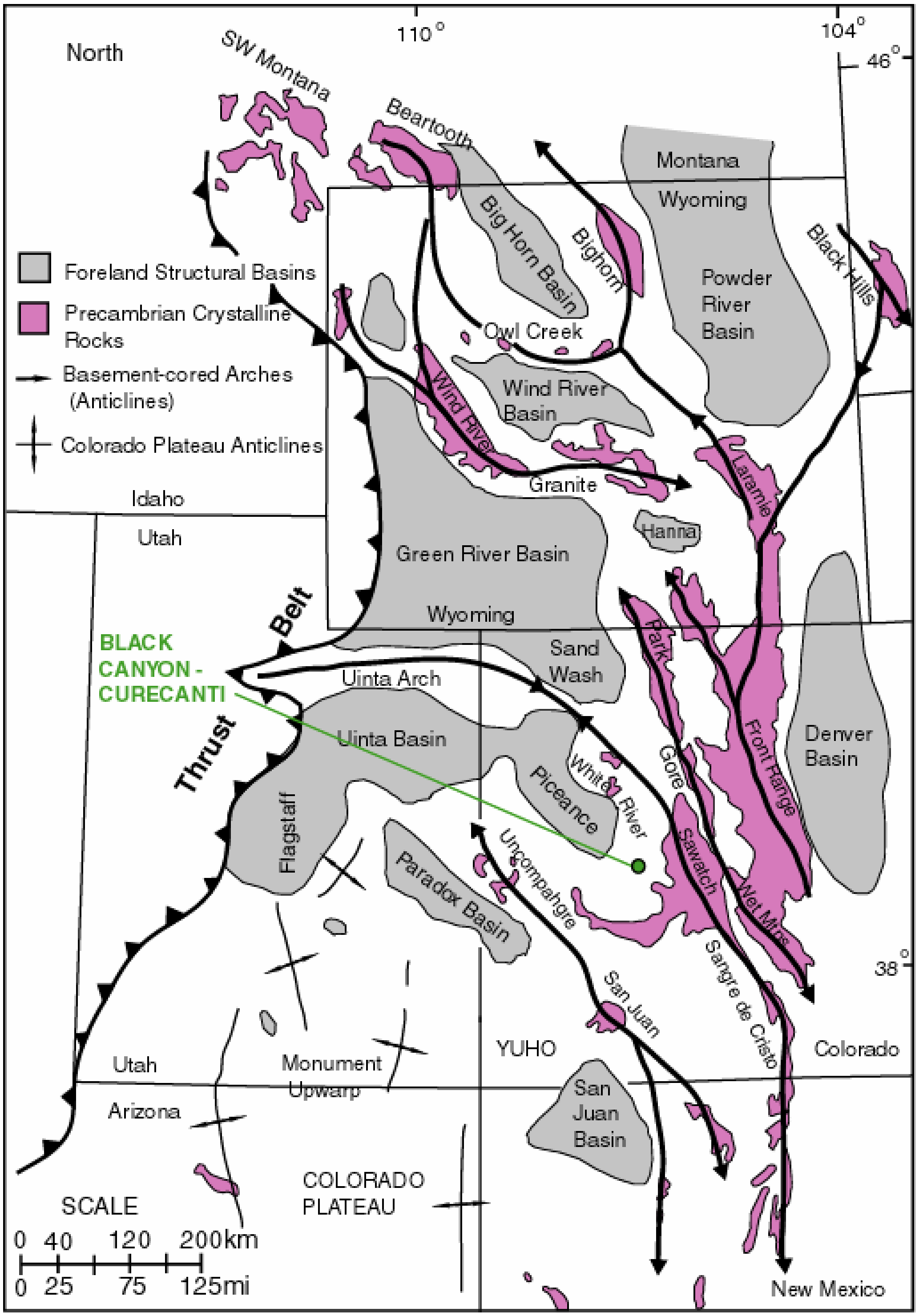


Figure 10: Location of Black Canyon of the Gunnison National Park and Curecanti National Recreation Area on a tectonic map of the Laramide foreland. The map illustrates the anastamosing nature of the basement-cored arches (regional-scale anticlines) and the spatial relationships with the adjacent thrust belt, Colorado Plateau, and North American craton. From Gregson and Chure, 2000.

Eon	Era	Period	Epoch	Age (base)		Life Forms	N. American Tectonics
Phanerozoic (Phaneros = "evident"; zoic = "life")	Cenozoic	Quaternary	Recent, or Holocene		Age of Mammals	Modern man	Cascade volcanoes
			Pleistocene	1.6		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary	Pliocene	5.3		Large carnivores	Uplift of Sierra Nevada
			Miocene	23.7		Whales and apes	Linking of N. & S. America
			Oligocene	36.6			Basin-and-Range Extension
			Eocene	57.8		Early primates	Laramide orogeny ends (West)
			Plaeocene	66.4			
	Mesozoic	Cretaceous		144	Age of Dinosaurs	**Mass extinctions** Placental mammals Early flowering plants	Laramide orogeny (West) Sevier orogeny (West) Nevadan orogeny (West)
		Jurassic		208		First mammals Flying reptiles	Elko orogeny (West) Breakup of Pangea begins
		Triassic		245		First dinosaurs	Sonoma orogeny (West)
	Paleozoic	Permian		286	Age of Amphibians	**Mass extinctions** Coal-forming forests diminish	Super continent Pangea intact Ouachita orogeny (South) Alleghenian (Appalachian) orogeny (East) Ancestral Rocky Mts. (West)
		Pennsylvanian		320		Coal-forming swamps Sharks abundant Variety of insects	
		Mississippian		360		First amphibians First reptiles	Antler orogeny (West)
		Devonian		408	Fishes	**Mass extinctions** First forests (evergreens)	Acadian orogeny (East-NE)
		Silurian		438		First land plants	
		Ordovician		505	Marine Invertebrates	**Mass extinctions** First primitive fish Trilobite maximum Rise of corals	Taconic orogeny (NE)
		Cambrian		570		Early shelled organisms	Avalonian orogeny (NE) Extensive oceans cover most of N. America
Proterozoic ("Early life")		Precambrian		2500		1st multicelled organisms Jellyfish fossil (670Ma)	Formation of early supercontinent First iron deposits Abundant carbonate rocks
Archean ("Ancient")				~3800		Early bacteria & algae	Oldest known Earth rocks (~3.93 billion years ago)
Hadean ("Beneath the Earth")				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4-4.6 billion years ago) Earth's crust being formed

Figure 11: Geologic Time Scale - Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring North American continent. Absolute ages shown are in millions of years and are from the United States Geological Survey (USGS) time scale found at: http://geology.wr.usgs.gov/docs/usgsnps/gtime/timescale.html.

References

This section provides a listing of references cited in this report. A more complete geologic bibliography is available and can be obtained through the NPS Geologic Resources Division.

Baars, Donald L., 2000, The Colorado Plateau: University of New Mexico press, Albuquerque, NM, 254 p.

Becker, Luann, Poreda, Robert J., Hunt, Andrew G., Bunch, Theodore E., and Rampino, Michael, 2001, Impact event at the Permian- Triassic boundary: Evidence from extraterrestrial noble gases in fullerenes, in Science, Feb. 23, p. 1530- 1533.

Boettcher, A.J., 1971, Evaluation of the Water Supply at Six Sites in the Curecanti Recreation Area, Southwestern Colorado. U.S. Geological Survey, Open File Report 71005, 28 p.

Chapin, Charles, E. and Steven M. Cather, 1983, Eocene tectonics and sedimentation in the Colorado Plateau – Rocky Mountain area, *in* James Lowell, ed., Rocky Mountain Foreland Basins and Uplifts: Rocky Mountain Association of Geologists, Denver, CO., p. 33- 56.

Christiansen, Eric II, Kowallis, Bart J., and Barton, Mark D., 1994, Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior: an alternative record of Mesozoic magmatism, *in* Mario V. Caputo, James A. Peterson, and Karen J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 73- 94.

Condon, Steven, M., 1991, Geologic and structure contour map of the Ute Mountain Ute Indian Reservation and adjacent areas, southwest Colorado and northwest New Mexico: USGS Map I- 2083, Scale: 1:100,000.

De Voto, R. H., 1980A, Mississippian stratigraphy and history of Colorado, *in* Harry C. Kent and Karen W. Porter, eds., Colorado Geology: Rocky Mountain Association of Geologists, p. 57- 70.

De Voto, R. H., 1980B, Pennsylvanian stratigraphy and history of Colorado, *in* Harry C. Kent and Karen W. Porter, eds., Colorado Geology: Rocky Mountain Association of Geologists, p. 71- 102.

Dickinson, W. R., and Snyder, W.S., 1978, Plate tectonics of the Laramide Orogeny, *in* V. Matthews III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America, Memoir 151, p. 355- 366.

Doelling, Hellmut H., 2000, Geology of Arches National Park, Grand County, Utah, *in* D.A. Sprinkel, T.C. Chidsey, Jr., and P.B. Anderson, eds., Geology of Utah's Parks and Monuments: Utah Geological Association Publication 28, p. 11- 36.

Dubiel, R. F., 1994, Triassic deposystems, paleogeography, and paleoclimate of the Western Interior, *in* Mario V. Caputo, James A. Peterson, and Karen J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 133- 168.

Ekren, E.B. and Houser, F.N., 1965, Geology and petrology of the Ute Mountains area, Colorado: U.S.G.S. Professional Paper 481, scale 1:48,000.

Elder, William P. and Kirkland, James I., 1994, Cretaceous paleogeography of the southern Western Interior Region, *in* Mario V. Caputo, James A. Peterson, and Karen J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 415- 440.

Elliott, J.G., Hammack, L.A., 1999, Geomorphic and Sedimentologic Characteristics of Alluvial Reaches in the Black Canyon of the Gunnison National Monument, Colorado. U.S. Geological Survey, Water-Resources Investigations Report 99- 4082, 67 p.

Erslev, E. A., 1993, Thrusts, back- thrusts, and detachment of Rocky Mountain foreland arches, *in* C. J. Schmidt, R. B. Chase, and E. A. Erslev, eds., Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States: Geological Society of America, Special Paper 280, p. 339- 358.

Goodknight, C.S., 1981, Uranium in the Gunnison Country, Colorado, in New Mexico Geological Society Guidebook, 32nd Field Conference, Western Slope Colorado, Epis, R.C., Callender, J.F., eds, p. 183- 190.

Gregson, J., 1992, Geology and tectonics of the Ancestral Uncompahgre Uplift and the Colorado Orogeny, *in* Joe D. Gregson, ed., Uncompahgria Journal: Mesa State Geology Department, Grand Junction, Colorado, p. 19- 46.

Hamilton, W. B., 1988, Laramide crustal shortening, *in* C.J. Schmidt and W.J. Perry, Jr., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America, Memoir 171, p. 27-39.

Hansen, W.R., 1964, Curecanti Pluton, an Unusual Intrusive Body in the Black Canyon of the Gunnison, Colorado. Geological Survey Bulletin 1181- D, 15 p.

Hansen, W.R., 1965, The Black Canyon of the Gunnison Today and Yesterday: U.S. Geological Survey Bulletin 1191, 76 p.

Hedlund, D.C., and Olson, J.C., 1975, Geologic map of the Powderhorn Quadrangle, Gunnison and Saguache counties, Colorado: U.S. Geological Survey, Geological Quadrangle Map GQ- 1178, 1:24,000 scale.

Hedlund, D.C., and Olson, J.C., 1981, Precambrian Geology along parts of the Gunnison Uplift of Southwestern Colorado, in New Mexico Geological Society Guidebook, 32nd Field Conference, Western Slope Colorado, Epis, R.C., Callender, J.F., eds, p. 267-272.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Studies Special Publication 7, 202 p.

Huntoon, J. E., Stanesco, J. D., Dubiel, Russell F., and Dougan, J., 2000, Geology of Natural Bridges National Monument, Utah, *in* D.A. Sprinkel, T.C. Chidsey, Jr., and P.B. Anderson, eds., Geology of Utah's Parks and Monuments: Utah Geological Association Publication 28, p. 233- 250.

Hutchinson, R. M., 1976, Precambrian geochronology of western and central Colorado and southern Wyoming, *in* R. C. Epis and R. J. Weimer, eds., Studies in Colorado Field Geology: Professional Contributions, Colorado School of Mines, p. 73- 77.

Kauffman, E. G., 1977, Geological and biological overview: Western Interior Cretaceous Basin: Mountain Geologist, v. 14, p. 75- 99.

Knoper, M. W; Condie, K. C; Thacker, M.; Lanzirotti, A, 1987, Early Proterozoic tectonic history in Colorado. Program with Abstracts - Geological Association of Canada; Mineralogical Association of Canada; Canadian Geophysical Union, Joint Annual Meeting, vol.12, p.63.

Kocurek, G. and Dott, R. H. Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountain region, *in* Mitchell W. Reynolds and Edward D. Dolly, eds., Mesozoic Paleogeography of the West- Central United States: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 101- 118.

Johnson, J.G., Sandberg, Charles A., and Poole, Forrest G., 1991, Devonian lithofacies of western United States, *in* John D. Cooper and Calvin H. Stevens, eds., Paleozoic Paleogeography of the Western United States – II: Society of Economic Paleontologists and Mineralogists (SEPM), Pacific Section, p. 83- 106.

Lawton, Timothy F., 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States, *in* Mario V. Caputo, James A. Peterson, and Karen J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 1- 26.

Olson, J.C., and Wallace, S.R., 1956, Thorium and rare-earth minerals in Powderhorn district, Gunnison County, CO: U.S. Geological Survey Bulletin 1027- 0, p. 693- 723.

Peterson, Fred, 1994, Sand dunes, sabkhas, stream, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin, *in* Mario V. Caputo, James A. Peterson, and Karen J. Franczyk, eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO., p. 233- 272.

Poole, F.G., and Sandberg, C.A., 1991, Mississippian paleogeography and conodonts biostratigraphy of the western United States, *in* John D. Cooper and Calvin H. Stevens, eds., Paleozoic Paleogeography of the Western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists (SEPM), v. 2, p. 107- 136.

Reed, J. C., Jr., Bickford, M. E., Premo, W. R., Aleinikoff, J. N., and Pallister, J. S., 1987, Evolution of the Early Proterozoic Colorado province: Constraints from U-Pb geochronology: Geology, v. 15, p. 861- 865.

Scott, R. B., Harding, A. E., Hood, W. C., Cole, R. D., Livaccari, R. F., Johnson, J. B., Shroba, R. R., Dickerson, R. P., 2001, Geologic map of Colorado National Monument and adjacent areas, Mesa County, Colorado: U.S. Geological Survey, Geologic Investigations Series I- 2740, 1:24,000 scale.

Sloss, L.L., 1988, Tectonic evolution of the craton in Phanerozoic time, *in* L.L. Sloss, ed., Sedimentary Cover – North American Craton: U.S.: Geological Society of America, Geology of North America, Vol. D- 2, p. 25- 52.

Speed, R.C., 1983, Evolution of the sialic margin in the central western United States, *in* J.S. Watkins and C.L. Drake, eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 457- 468.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972A, Stratigraphy and Origin of the Triassic Moenkopi Formation and related Triassic strata in the Colorado Plateau region: U.S.G.S. Professional Paper 691, 195 p.

Stewart, J. H., 1980, Geology of Nevada: Nevada Bureau of Mines and Geology, Special Publication 4, 136 p.

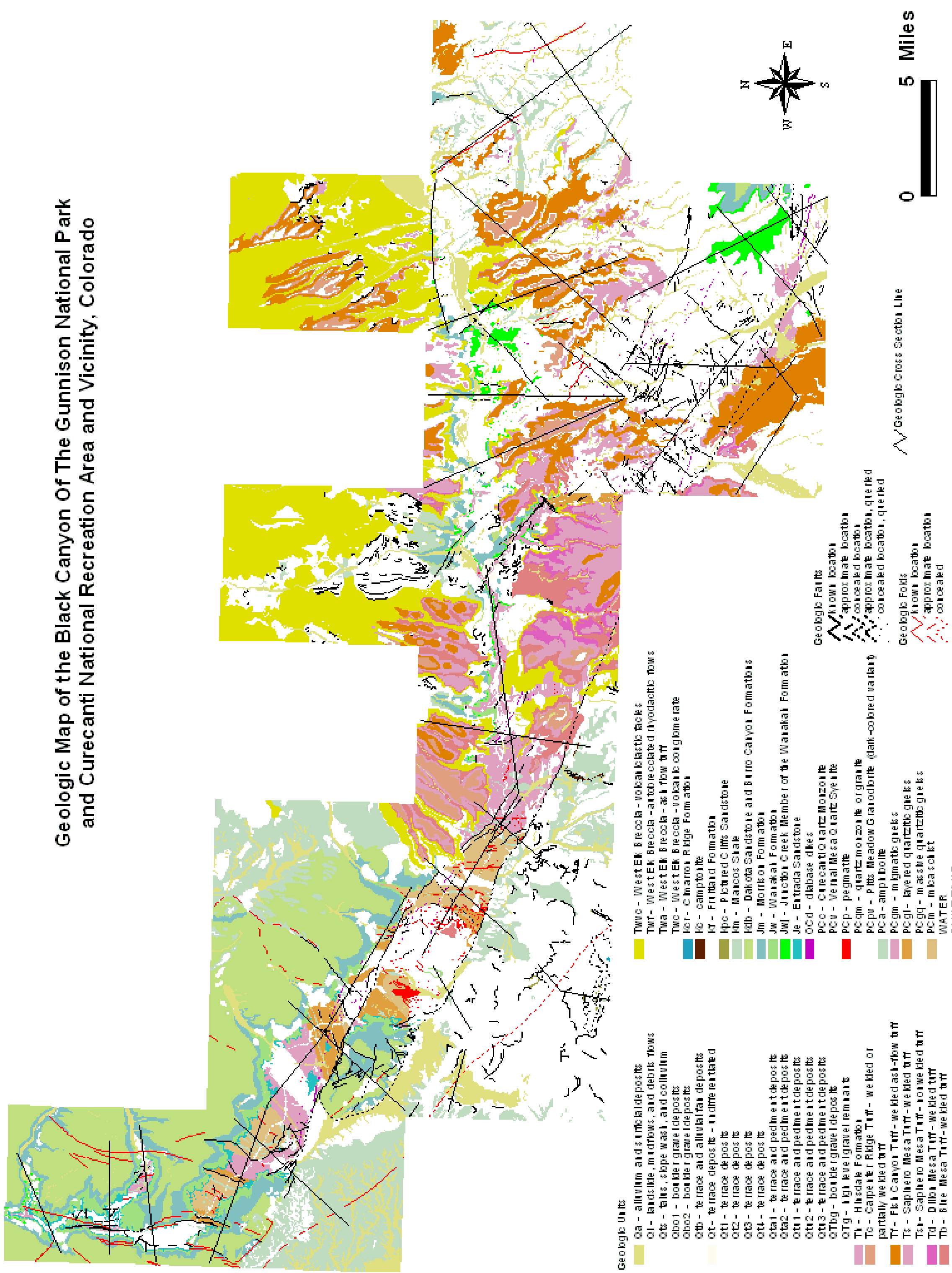
Tweto, O., 1980, Precambrian geology of Colorado, *in* Harry C. Kent and Karen W. Porter, eds., Colorado Geology: Rocky Mountain Association of Geologists, p. 37- 46.

Warner, L.A., 1980, The Colorado Lineament, *in* H.C. Kent and K.W. Porter, eds., Colorado Geology: Rocky Mountain Association of Geologists, Denver, p. 11- 22.

Wright, J.C., Shawe, D.R., and Lohman, S.W., 1962, Definition of members of Jurassic Entrada Sandstone in east- central Utah and west- central Colorado: American Association of Petroleum Geologists Bulletin, v. 46, no. 11, p. 2057- 2070.

Appendix A: Geologic Map Graphic

This image provides a preview or "snapshot" of the geologic map for Black Canyon of the Gunnison National Park and Curecanti National Recreation Area. For a detailed digital geologic map, see included CD.



Numerous original maps were digitized by NPS staff to create this product. Source maps are cited in full in the metadata accompanying the digital geologic map on the included CD.

Black Canyon of the Gunnison National Park & Curecanti National Recreation Area

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2005/001
NPS D-105, January 2005

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup

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