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Geology of Grand Staircase-Escalante National Monument, Utah

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ABSTRACT

The 1.9-million-acre Grand Staircase-Escalante National Monument was created September 18, 1996 by President Clinton and was the first national monument to be placed under the management of the U.S. Bureau of Land Management. Located in southern Utah, the monument contains an array of geological, paleontological, historic, archaeological, and biological resources. It lies in a remote area comprised of canyons, plateaus, mesas, and cliffs set in an environment of colorful geologic formations.

The monument is surrounded by several national and state parks, a primitive area, and a national recreation area. It can be divided into three geographical sections: from west to east these are the Grand Staircase, Kaiparowits Basin, and Escalante Canyons sections. Rock formations exposed in these sections range in age from Permian to Cretaceous comprising more than 200 million years of Earth's history. Structurally, these rocks dip gently northward, and are deformed by mostly north-south-trending faults, anticlines, synclines, and monoclines.

The monument area contains known coal, oil and gas, and mineral resources and potential resources which are generally undeveloped because market areas are distant and because ways of transporting the commodities out of the region have never been in place. As a national monument, the area will provide many future opportunities to study a region of remarkably well-exposed geology.

INTRODUCTION

Grand Staircase-Escalante National Monument was established by presidential proclamation on September 18, 1996 to protect an array of geological, paleontological, historic, archaeological, and biological resources. Following the creation of the monument, Congress passed the Utah Schools and Land Exchange Act, which transferred ownership of all trust lands administered by the Utah School and Institutional Trust Lands Administration (SITLA) (176,699 acres) and trust mineral interests (24,000) acres within the monument boundaries, to the Federal Government. In exchange for these interests, and other lands and interests within national parks and monuments in Utah, the State of Utah received title to federal lands elsewhere, mineral royalties from other federal lands in Utah, and a one-time cash payment. It is the first national monument managed by the U.S. Bureau of Land Management (BLM), incorporating the principles of the Federal Land Policy and Management Act (FLPMA). The proclamation governs how the provisions of FLPMA will be applied within the monument. FLPMA directs the BLM to manage public land on the basis of multiple use and in a manner that will protect the quality of scientific, scenic, historic, ecological, environmental, air and atmospheric, water resources, and archaeological resources (U.S. Department of Interior, 2000).

The monument covers about 1.9 million acres of land in south-central Utah (figure 1). About 68 percent of the monument is in Kane County, while the remaining 32 percent is in Garfield County. Conversely, about 49 percent of Kane County and 18 percent of Garfield County lie within the monument boundaries. The monument is primarily surrounded on three sides by national forest and national park lands, as well as other BLM administered lands to the south and west. Kodachrome State Park also adjoins the monument near Cannonville. For more information on monument management and use restrictions, the reader should refer to the approved management plan (U.S. Department of Interior, 2000)

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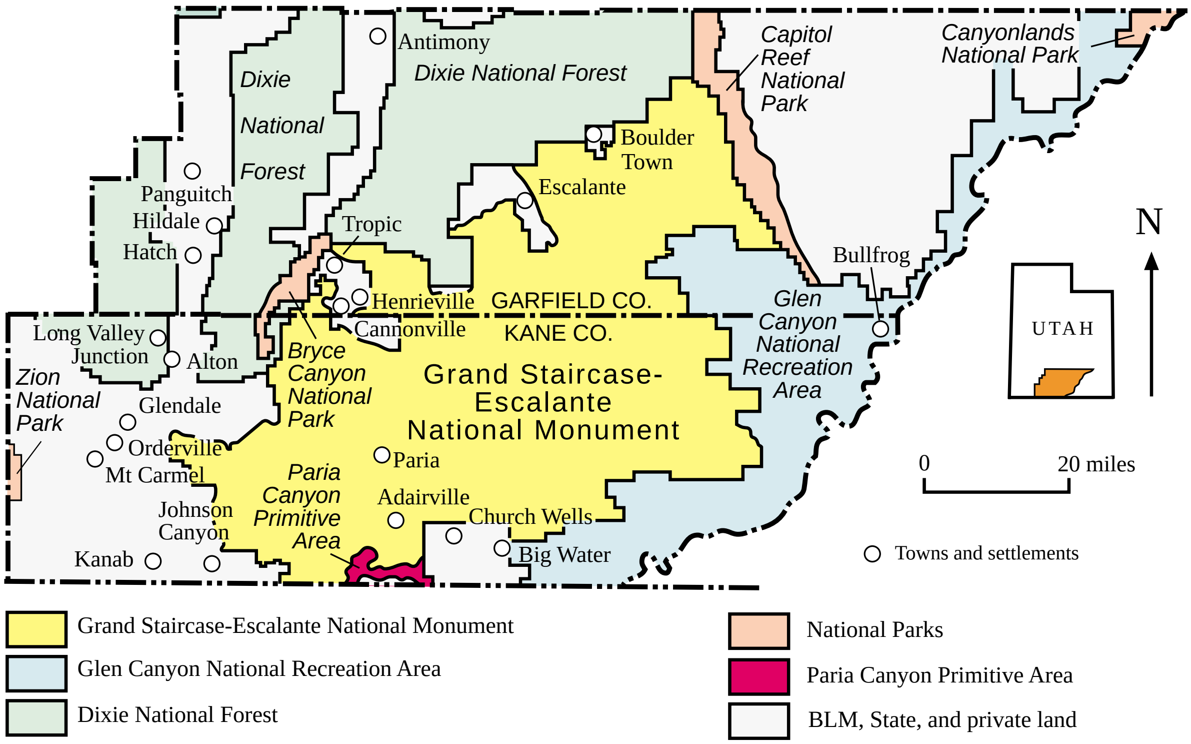

Figure 1. Index map for Grand Staircase-Escalante National Monument in Garfield and Kane Counties, Utah. The 1.9-million-acre monument is encircled by national parks, a national recreation area, a primitive area, and a national forest. Four state parks, Coral Pink Sand Dunes, Kodachrome, Escalante Petrified Forest, and Anasazi Indian Village State Parks are also in the area, west of Kanab, near Cannonville, near Escalante, and near Boulder Town, respectively.

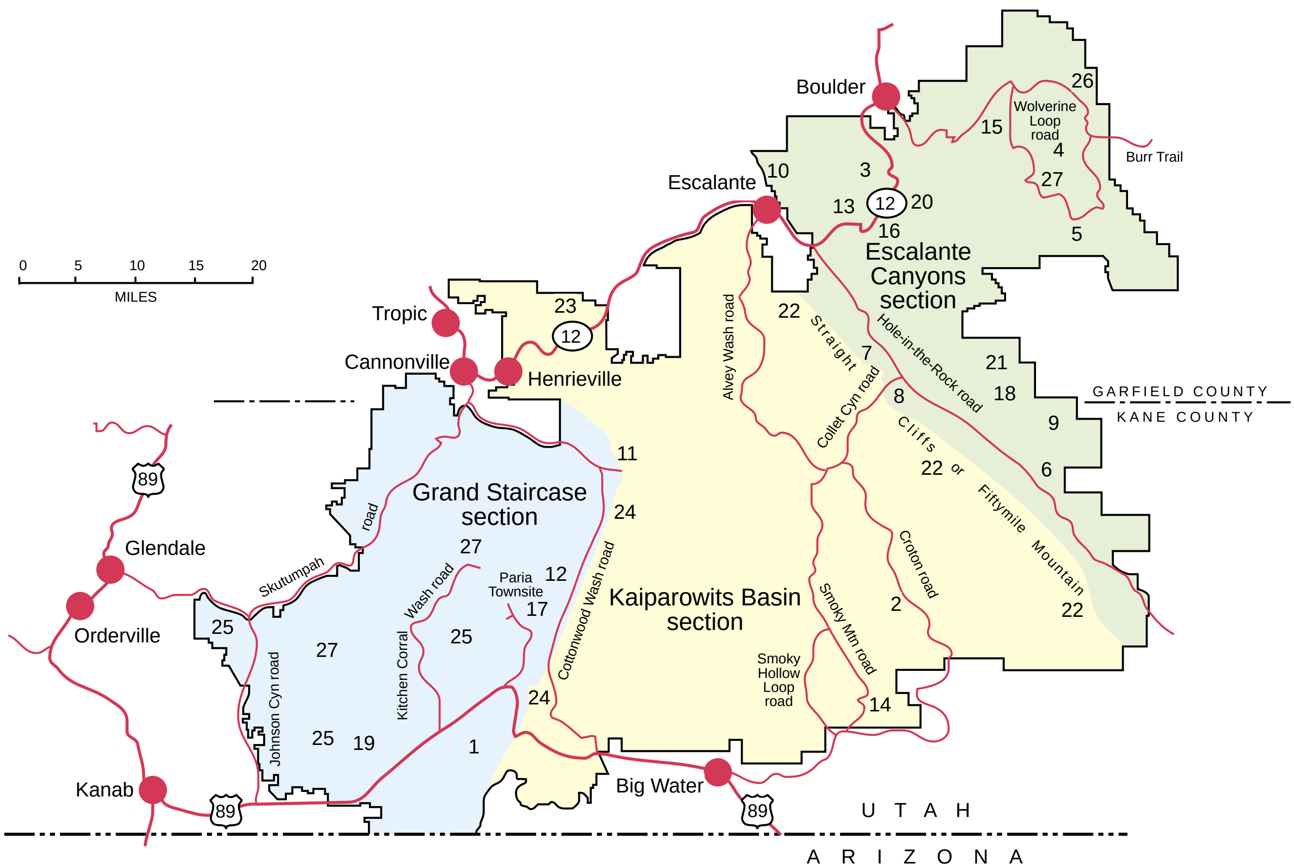

Figure 2. Map showing the locations of the classic geologic sites (numbers) within Grand Staircase-Escalante National Monument in southern Utah. See text for descriptions of these sites. Also, the Grand Staircase section is shown in blue, the Kaiparowits Basin section in yellow, and the Escalante Canyons section in green.

GEOGRAPHY

Grand Staircase-Escalante National Monument is located within the Colorado Plateau physiographic province, near its western margin. It is bordered by the gateway communities of Boulder, Escalante, Henrieville, Cannonville, Tropic, Glendale, Kanab, and Big Water (figures 1 and 2). Annual precipitation in the region varies from about six inches at the lowest altitudes near Lake Powell (4,000 ft), to about 25 inches at the highest altitudes near Canaan Peak (9,280 ft). The variations in altitude and precipitation produce three climatic zones: upland, semi-desert, and desert. At the highest altitudes, precipitation falls primarily during the winter. The majority of precipitation in the semi-desert and desert areas occurs during the summer months.

The monument may be divided into three broad areas: from west to east these are the Grand Staircase, Kaiparowits Basin, and Escalante Canyons sections (figure 2). **The Grand Staircase section** is a broad feature that encompasses the western third of the monument, and consists of a series of topographic benches and cliffs that, as its name implies, step progressively up in elevation from south to north. The risers correspond to cliffs and the steps correspond to the benches, terraces, or plateaus in the staircase (figure 3). The bottom of the staircase commences at the top of the Kaibab uplift, which correlates with and is in the same stratigraphic position as the highest bench of the Grand Canyon in Arizona. The first riser above this bench is the Chocolate Cliffs, which are not well developed in the Grand Staircase section and consists of the Upper Red Member of the Lower Triassic Moenkopi Formation capped by the Upper Triassic Shinarump Member of the Chinle Formation. Descriptions of these formations are given in the stratigraphy section of this paper. Discontinuous Shinarump outcrops explain why this riser is not well developed in the monument. The next step is known as the Shinarump Flats. This bench is mostly developed on top of the hard Shinarump Member and the overlying soft Petrified Forest Member of the Chinle Formation. The Vermilion Cliffs form the next riser, which is well developed in the monument. The cliffs are made up of the resistant red sandstone beds of the Lower Jurassic Moenave and Kayenta Formations. The Wygaret Terrace forms the next step and includes the soft upper part of the Kayenta and the lower parts of the Lower Jurassic Navajo Sandstone. The imposing White Cliffs form the next riser and consist of the upper part of the Navajo Sandstone and the Middle Jurassic Co-op Creek Limestone Member of the Carmel Formation. The bench on this riser is the Skutumpah Terrace built on the remaining soft parts of the Carmel Formation and the overlying Entrada Sandstone. The Gray Cliffs are a series of low cliffs formed by hard Cretaceous sandstone beds. Several benches have formed between these cliffs in the softer shales and sandstones of the Tropic, Straight Cliffs, Wahweap, and Kaiparowits Formations. The final riser, mostly north and west of the monument, in Dixie National Forest and Bryce Canyon National Park, is formed by the Pink Cliffs. The Pink Cliffs consist of lower Tertiary limestones and marls that are sculpted into the beautiful natural features found in Bryce Canyon. The cliffs culminate as the Paunsaugunt Plateau, which is the uppermost bench or step of the Grand Staircase.

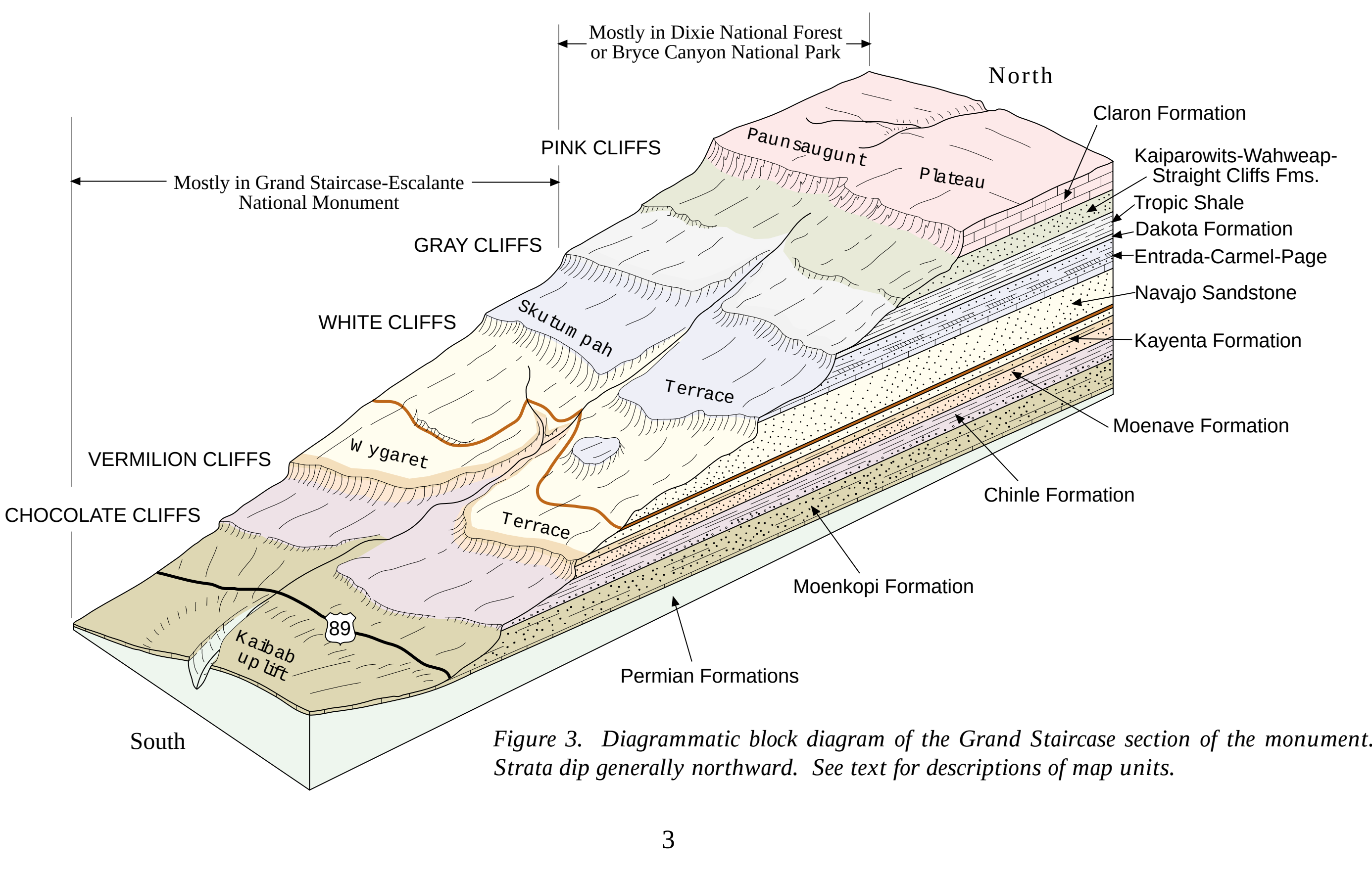

Figure 3. Diagrammatic block diagram of the Grand Staircase section of the monument. Strata dip generally northward. See text for descriptions of map units.

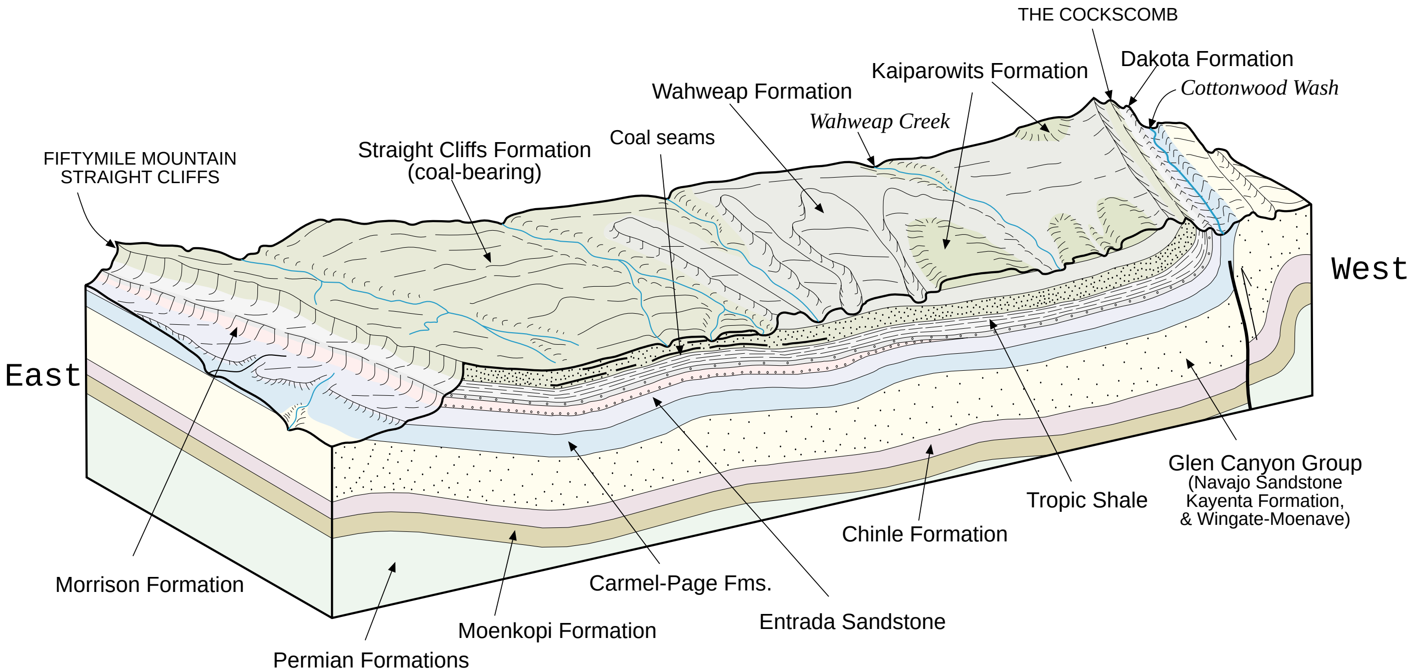

Figure 4. Diagrammatic block diagram and east-west cross section across the Kaiparowits Basin section of the monument. View is from the north looking south. The deepest part of the basin is aligned north-south along Wahweap Creek. The strata dip generally northward, but north-south-trending anticlines and synclines warp the block. The Straight Cliffs mark the east boundary and the Cockscomb marks the west boundary of the section.

The boundary between the Grand Staircase and Kaiparowits Basin sections is The Cockscomb, a series of hogbacks along the East Kaibab monocline, where strata are folded sharply downward to the east. The Cockscomb trends approximately N. 20° E. from the Arizona border to Grosvenor Arch (No. 11 on figure 2) as a sharp fold in the strata. Dips diminish and become more gentle as the trend wraps northwesterly north of the towns of Henrieville, Cannonville, and Tropic. The character of rocks stratigraphically higher than the Tropic Shale is like that in most of the Kaiparowits Basin section and should be considered a part of that section.

The Kaiparowits Basin section is centrally situated in the monument and is mostly exemplified by the Kaiparowits Plateau. Doelling and Davis (1989) described this section as “a series of plateaus, buttes, and mesas carved in Cretaceous rocks that reflect the structures of the underlying geologic strata.” The Kaiparowits Basin covers about 1,650 square miles in the central part of the monument (figure 4). The feature is a broad structural basin; however, the topographic expression is that of a northward-tilted, highly dissected plateau that has been modified by generally north-south-trending folds. The Aquarius and Table Cliff plateaus lie northward and topographically above the Kaiparowits Plateau.

The Kaiparowits Plateau is bounded by the base of the Cretaceous strata (Hettinger and others, 1996) or the base of the Dakota Formation. The Straight Cliffs form a prominent escarpment that rises 1,100 feet or more and extends for more than 50 miles northwest to southeast above the Dakota and Tropic Formations. The cliffs roughly mark the plateau’s east boundary with the Escalante Canyons section of the monument. Some Jurassic strata are exposed in the Kaiparowits Basin section of the monument, along its southern boundary, below the Cretaceous cliffs. These Jurassic rocks have a “Canyonlands” character and, indeed, make up the canyonlands above Glen Canyon of the Colorado River.

The Escalante Canyons section provides a web of multi-hued, steep, narrow canyons and “slickrock,” sculpted in the drainage basin of the Escalante River (figure 5). The section is bounded on the southwest by the Straight Cliffs, on the north by the Aquarius Plateau and Boulder Mountain, on the east by the Waterpocket Fold, and on the south by Glen Canyon of the Colorado River. The Escalante Canyons section can be subdivided into two landscapes based on physiography: Escalante canyons and benchlands, and the Circle Cliffs uplift. The latter is a large doubly plunging anticline, the core of which is eroded into a large kidney-shaped physiographic basin surrounded by the imposing vertical cliffs of the Wingate Sandstone.

CLASSIC GEOLOGIC SITES WITHIN THE MONUMENT

This 1.9-million-acre monument in colorful southern Utah undoubtedly has thousands of sites to excite not only professionals in geology, archaeology, botany, zoology, and paleontology, but also any visitor with an eye for the unusual and beautiful features of nature. Nowhere else in the world are the rocks and geologic features so well ex-

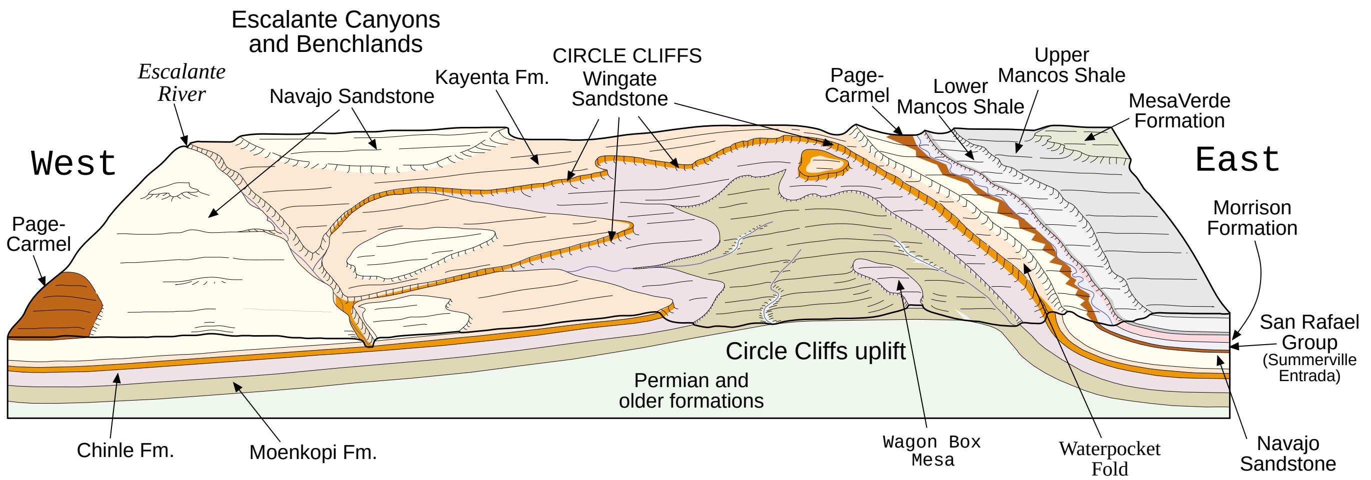

Figure 5. Diagrammatic block diagram across the Escalante Canyons section of the monument. This section consists of two parts. To the west are Glen Canyon Group bench and canyonlands incised by the Escalante River and its tributaries. To the east is the Circle Cliffs uplift, a large doubly plunging, north-south-trending anticline that exposes a fossil oil field in its core. The steeply dipping Waterpocket Fold makes up the east boundary of the uplift and is in Capitol Reef National Park.

posed, so brilliantly colored, and so excitingly displayed. The area is large enough to allow for many new discoveries to be made; certainly to allow for rediscoveries and re-evaluations of geologic features, processes, and theories, whether in the scale of the microscopic or in scales of the vast panoramas that will unfold before you. In an area of this size, not all classic sites can be mentioned because of space constraints. The list below is small compared to what is available for those who will leave their autos, ATVs, and bicycles behind, and venture into the back-country on their own.

The approximate locations of the following classic geologic sites are shown by number on figure 2. They are alphabetically arranged below. Larger scale maps, available from local monument/BLM offices and at the Utah Geological Survey offices in Salt Lake City, will help guide you to these features.

Access descriptions given here are general, and some roads may not be open to the public. Visitors will need to check with Grand Staircase-Escalante National Monument offices, contact stations, and visitor centers in local communities to verify available access routes to these sites.

1. **Buckskin Gulch and the Kaibab uplift**: Buckskin Gulch, a continuation of Kitchen Corral Wash, forms a deep gash through Buckskin Mountain at the north end of the Kaibab uplift in the Grand Staircase section of the monument (figure 6). This gash exposes the oldest rocks (Permian) of the monument: (ascending) the Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone. The Early Triassic Timpoweap Member of the Moenkopi Formation forms a carapace on top of this section which appears as a "whaleback" from U.S. Highway 89. U.S. Highway 89 makes a loop around the uplift, avoiding the inclines of Buckskin Mountain. Access to the top of the deep gash is provided by following a side road (high-centered vehicles only) off the House Rock Valley

Figure 6. Aerial view of Kaibab Gulch with the Vermilion and White Cliffs in the background. Kaibab Gulch is a cut through Buckskin Mountain and exposes the oldest (Permian) rocks in the Grand Staircase section of the monument.

Figure 7. Lower Calf Creek Falls in the Escalante Canyons section of the monument.

road, which extends southward from U.S. Highway 89 just before the highway cuts eastward through the Cockscomb. Hiking through Buckskin Gulch is also worthwhile.

2. **Burning Hills**: This area of reddened and baked rocks is found in the southeastern Kaiparowits Plateau (Kaiparowits Basin section). Here, as coal beds were exhumed by erosion, coal fires were ignited by spontaneous combustion as heat was generated by the oxidation of coal in the atmosphere. The coal was reduced to ash, reducing the volume by more than 90 percent. The overlying rocks collapsed into the space, being fractured in the process. Cracks formed by the collapse propagated to the surface and allowed more oxygen to reach additional coal below the surface, keeping the fires going. The encasing rocks were baked during the burning; shales were altered to varicolored brick and sandstone and iron impurities were oxidized to give a reddened color. Several fires still burn in this area. They are best recognized in the winter, when steam and gases condense at the surface. Even in the summer, however, a strong creosote smell exudes from cracks in the ground. The Burning Hills can be seen from the Croton road (No. 2 on figure 2).

3. **Calf Creek Falls**: Calf Creek is a south-flowing tributary of the Escalante River (Escalante Canyons section) that heads on Boulder Mountain. It has carved a deep canyon into the Navajo Sandstone and the Kayenta Formation, being controlled along a shallow syncline. Two exquisitely beautiful and high waterfalls have formed in the monument and are known as Upper and Lower Calf Creek Falls. Figure 7 gives a view of Lower Calf Creek Falls. Calf Creek forms only one of the many spectacular tributary canyons of the Escalante River. A two-mile hike up the canyon from a campsite off State Road 12 provides access to the base of the lower falls. A view of the upper falls can be obtained by hiking a trail that extends west from State Road 12 a few miles north of the campsite.

4. **Circle Cliffs breached anticline**: Remnants of a large oil field can be seen in the rocks of the Circle Cliffs area (Escalante Canyons section). Oil and gas became trapped in this area after the rocks were deformed or folded into this broad, northwest-southeast elongate dome. As erosion cut through the surface of the dome and into the oil and gas reservoir, the lighter, more volatile fractions of the oil vented to the atmosphere. Left behind were only the heavier, more viscous residues such as heavy bitumen or tar, which saturated the sandstones (tar sands) of the Torrey and Moody Canyon Members of the Triassic Moenkopi Formation. Fractures formed during the folding process, as seen in the Jurassic Wingate Sandstone, probably contributed to the movement of oil and gas into the Moenkopi Formation from Pennsylvanian and Permian source rocks. The 300-foot-high Wingate Sandstone cliffs surround the deeply eroded center of the Circle Cliffs anticline, giving the feature its name (figure 31). Drive the Wolverine loop road to see the tar sands, cliffs, and other features of the anticline.

5. **Colt Mesa mines**: These mines are found at the base of a very thick channel of the Shinarump Member of the Chinle Formation in the south part of the Circle Cliffs area in the Escalante Canyons section of the monument. These mines were opened in the early 1970s for the purpose of producing copper. The ore deposits were quite rich but small and, in addition to copper, contained silver, molybdenum, and cobalt. These mines are highly interesting because the ore minerals are brightly colored and the ore horizon is easily identifiable so that anyone can begin to understand ore emplacement processes. Similar processes were important in the emplacement of the Colorado Plateau uranium ores, which helped usher in the “Atomic Age.” The ore horizon here is a massive, medium-grained sandstone with tiny bits of coal interspersed throughout. The ore is in pods in the lower 6 feet of this sandstone where blue and green copper minerals coat, cement, and, in some cases, replace the sand grains. Minerals that have been identified at this property include chalcopyrite, pyrite, malachite, bornite, chalcocite, and erythrite. Access to the mines is along a road extending south from the Wolverine loop road. Visitors will need to walk about 1/4-

Figure 8. Dinosaur tracks in the Escalante Member of the Entrada Sandstone near Twentymile Wash in the Escalante Canyons section of the monument.

mile from a pullout to the mine site.

6. **Dance Hall Rock**: This prominent monolith within the Gunsight Butte Member of the Entrada Sandstone is located roughly 40 miles southeast of Escalante along the Hole-in-the-Rock Road (Escalante Canyons section). While the Hole-in-the-Rock trail was being forged in 1879, Mormon pioneers camped at Fortymile Spring and held meetings and dances in the shelter of the stage-like erosional feature of the Entrada Sandstone known as Dance Hall Rock. The site was designated a National Historical Site by the U.S. Department of the Interior in 1970. The Hole-in-the-Rock trail was constructed to provide access from Escalante to areas on the opposite side of the Colorado and San Juan Rivers in southeast Utah. The pioneering effort to forge the road, negotiate the sheer cliffs, and to cross the Colorado with wagons and livestock and settle southeast Utah is considered one of the more interesting pioneering achievements in western history. The Gunsight Butte Member of the Entrada Sandstone has a very irregular contact with the upper part of the Carmel Formation in this area. In some places the smooth, rounded, orange-brown sandstone of the Gunsight Butte Member appears to have "sunk" deeply into the bedded Carmel Formation.

Figure 9. Death Hollow, aerial view looking southeast shows deeply entrenched stream channel within Jurassic Navajo Sandstone.

7. **Devils Garden**: At Devils Garden, Mother Nature has sculpted the Entrada Sandstone into goblins, stone babies, monuments, and delicate arches to delight the beholder (figure 24). The features are formed along the contact of the Gunsight Butte and Cannonville Members of the Entrada Sandstone and are accessible along a short side road extending west from the Hole-in-the-Rock Road (Escalante Canyons section). Some of the features are bizarre and visitors have commonly attached their own informal nomenclature to them. When you visit the "garden" have fun doing the same.

8. **Entrada track site**: Normally devoid of fossils, the Escalante Member of the Entrada Sandstone at this site displays approximately 250 tracks of as many as 30 individual dinosaurs (Escalante Canyons section). Most are three-toed tracks of bipedal (two-legged) carnivorous dinosaurs. The site also has a trackway of a quadrupedal (four-legged) sauropod dinosaur (herbivorous) which appears to have left tail drag marks (figure 8).

9. **Escalante Canyons**: Erosion of the Colorado Plateau has resulted in the sculpting of a series of deep magnificent canyons in the Escalante Canyons section of the monument. In mid-Tertiary time (before 15 million years ago), Utah's surface was a little above sea level. To the present that 15-million-year-old surface would have been elevated as much as 15,000 feet had erosion not started to attack the uplift. The ancestral Colorado River and its tributaries have irregularly cut into the rocks of the region leaving high plateaus (some at over 10,000 feet above sea level), cliffs, benches, and deep canyons. A stream eroding a hard rock formation cuts a deep canyon because it cannot erode fast enough to keep up with the rate of uplift. When a stream erodes a soft rock it can form wider valleys. In order to do so it meanders across its valley floor eventually widening the valley. These meanders may become entrenched into harder rocks after the softer rock above is re-

Figure 10. Grosvenor arch is a double free-standing feature cut in the Henrieville Sandstone, Cedar Mountain Formation, and lower part of the Dakota Formation in the Grand Staircase section of the monument.

moved below the stream bed. The Glen Canyon Group of rocks, which consist of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone, are relatively hard and so the tributaries of the Escalante River have cut deep canyons. Locally meanders have been entrenched into the harder rock. The stream may locally be able to erode across loops in the meanders to form rincons after entrenching has taken place, adding interest to the canyons. Locally, natural arches and bridges are encountered in the canyons. Figure 9 shows Death Hollow, a tributary to the Escalante River.

The upper reaches of these canyons are in the monument; the lower and deeper canyons are found in the Glen Canyon Recreation Area. Access for hiking these canyons is from the monument. Favorite canyons accessible from the Hole-in-the-Rock Road include Harris Wash, Twenty-five Mile Wash, Coyote Gulch, Hurricane Wash, Fortymile Gulch, and Sooner Gulch. The upper reaches of the Escalante River, together with the lower canyons of Death Hollow, Sand Creek, Calf Creek, and Boulder Creek are accessible from State Road 12. The Wolverine Loop road and the Burr Trail road provide access to the canyons of Deer Creek, The Gulch, Wolverine Creek, and Death Hollow (figure 9).

10. **Escalante monocline**: The Escalante monocline is a sharp flexure predominantly involving the Jurassic Navajo Sandstone (Escalante Canyons section). This monocline folds strata down to the west and trends N. 30° W. A nice view of this feature can be seen north of the Escalante High School or the Escalante cemetery, east of town, along State Road 12. The Pine Creek road, which extends northward from Escalante, parallels the monocline and offers corresponding views. Most overlying rocks have been stripped off the Navajo Sandstone, which helps to accentuate the flexure. As viewed from high above the town of Escalante (figure 30) the dark rocks in the background, on the Aquarius Plateau and Boulder Mountain (beyond the monument boundary), are mostly Tertiary welded tuffs (volcanic rocks). The Escalante monocline is the steep west limb of the Escalante anticline, the axis of which lies to the east. Anticlines are geologic structures that may trap oil and gas. The north end of the Escalante anticline, beyond the monument boundary, is known to contain carbon dioxide resources.

11. **Grosvenor Arch**: Grosvenor Arch was named after Gilbert C. Grosvenor, the founder of the National Geographic Society. The arch is located near the east boundary of the Grand Staircase section of the monument and is

easily reached along the Cottonwood Wash road about 10 miles east of Kodachrome State Park (Grand Staircase section). It is a double free-standing arch cut in the Henrieville Sandstone, the Cedar Mountain Formation, and the Dakota Sandstone. The unconformities that divide these formations are plainly visible in the arch (figure 10).

12. **Hackberry Canyon:** The Early Jurassic Navajo Sandstone is exposed at the confluence of Cottonwood Wash and Hackberry Canyon. One of the premier hiking locations in the Grand Staircase-Escalante National Monument, Hackberry Canyon offers spectacular views of the Upper Triassic Chinle Formation and overlying Lower Jurassic Moenave, Kayenta, and Navajo Sandstone Formations (figure 11).

13. **Head-of-the-Rocks**: Located along State Highway 12, about 10 miles east of the town of Escalante, Head-of-the-Rocks overlook provides visitors with breathtaking vistas of the terrain typified in the Escalante Canyons section of the monument. The exposed rocks here are mostly of the Lower Jurassic Navajo Sandstone which exhibits large-scale, high-angle cross-bedding. The Navajo Sandstone is believed to represent a coastal to inland dune field by most geologists. Some workers have suggested that the Navajo and equivalent rocks may have been the largest recorded dune field in Earth's history, extending from southern Nevada through Utah into southwest Wyoming.

14. **Kelly Grade**: The Kelly Grade is part of the roadway extending from Escalante to Big Water across the Kaiparowits Plateau (Kaiparowits Basin section). Coal developers, finding themselves in a very remote area in the southern part of the plateau, hired the Kelly Construction Company of Escalante to extend the road from the top of Smoky Mountain, down to the bench below to get access to Glen Canyon City (Big Water) and the then-new Highway 89 extending from Kanab, Utah to Page, Arizona. They were drilling for coal on Smoky Mountain and the way back to Escalante was four or more hours. So in the early 1960s, Kelly took his bulldozer and "pushed" a road down the steep cliff that is still in use today. The top of the Kelly Grade provides a spectacular vista of Lake Powell and all the land below the plateau. The road is narrow and "scary" and eventually uses an old landslide to get down, but passes through the John Henry, Smoky Hollow, and Tibbet Canyon Members of the Straight Cliffs Formation and the Tropic Shale on the way down. A landslide, brightly colored by clinker, is passed on the way down, which is worth the drive on its own. See the discussion about "clinker" in the section on the John Henry Member of the Straight Cliffs Formation. The section of road along which the Kelly Grade is found is known as the Smoky Mountain road.

15. **Land of the Sleeping Rainbow**: Outcrops of the varicolored Petrified Forest Member of the Chinle Formation ring the Circle Cliffs area of the Escalante Canyons section below the Wingate Cliffs. These are especially beautiful

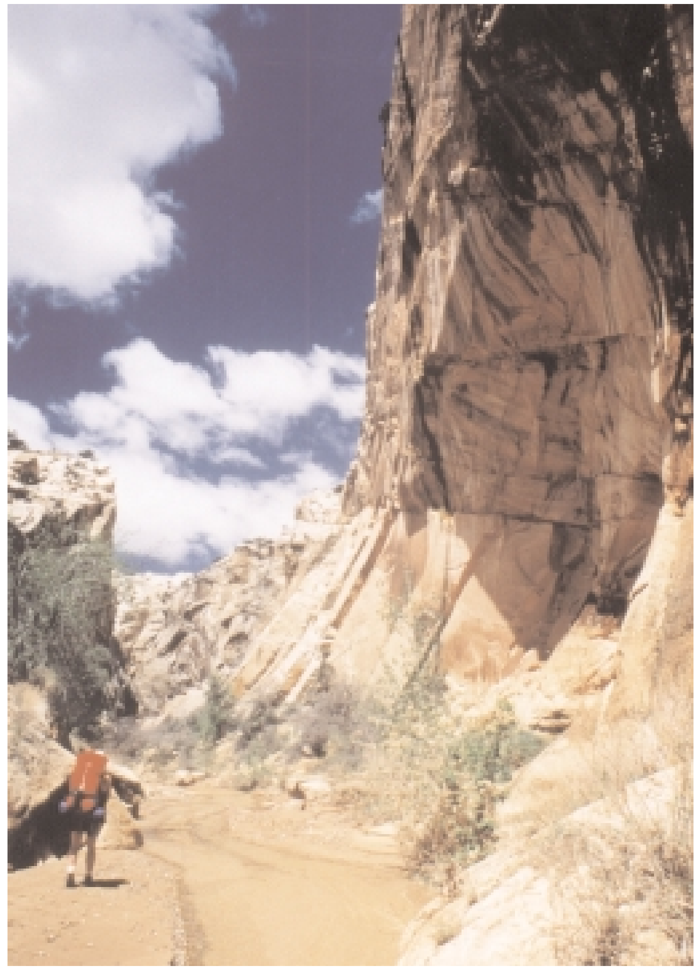

Figure 11. A hiker in Hackberry Canyon. This canyon is located just west of the Cockscomb and is a popular hiking area.

and enchanting as one emerges from Long Canyon into the Circle Cliffs area traveling toward the Waterpocket Fold from Boulder on the Burr Trail road. The name is an interpretation of how the American Indians of the region appreciated these vistas.

16. **Moqui marbles**: Moqui marbles are particularly common in the Navajo Sandstone. It is believed that these ironstone concretions formed near the water table during deposition as iron-froth-coated air bubbles in water-saturated sand. Moqui marbles are abundant in the Spencer Flat area in the Escalante Canyons section of the monument. Collecting Moqui marbles from monument lands is not permitted.

17. **Paria area**: Like the Land of the Sleeping Rainbow, this area is special because of the brightly banded outcrops of the Petrified Forest Member of the Chinle Formation in the Grand Staircase section (figure 19). However, this area is also special for views of the Vermilion Cliffs, steeply dipping Moenkopi strata, channels of the Shinarump Member of the Chinle Formation, faults, the flood plain of the Paria River, the ghost town of Pahreah, Shurtz Gorge, and the movie set (now dismantled) for the film, "The Outlaw Josie Wales," which starred Clint Eastwood. Some regard

Figure 12. The Straight Cliffs extend for fifty miles from Escalante to the Colorado River broken only by the mouths of two canyons. The Straight Cliffs are mostly lenses of beach sand in the Straight Cliffs Formation.

this as the most sublime geologic area in the world.

18. **Peek-A-Boo Gulch**: Narrow slot canyons have been carved into Navajo Sandstone benches by small washes as influenced by joints. During summer monsoon storms, these slot canyons flood with sediment-laden waters which further scour the walls and drill potholes. Peek-A-Boo Gulch and Spooky Gulch are two of the more popular slot canyons within the monument. They are located about 25 miles down the Hole-in-the-Rock Road in the Escalante Canyons section.

19. **Petrified Hollow**: Petrified Hollow is located east of Kanab below the Vermilion Cliffs of the Grand Staircase section of the monument near the Paunsaugunt fault. Petrified wood occurs in the Petrified Forest and Monitor Butte Members of the Chinle Formation. Though collecting is no longer allowed, it was a popular rock-hounding area for many years.

20. **Phipps Arch**: Set in the Navajo Sandstone, this arch stands above Phipps Canyon. Over time the erosive forces of gravity, ice, wind, and water cut this arch through a narrow ridgeline. This arch is located not far downstream from the place where State Road 12 crosses the Escalante River near its confluence with Calf Creek in the Escalante Canyons section.

21. **Sand dunes at Little Egypt**: Wind-blown sand collects as dunes in the Little Egypt area in the Escalante Canyons section. Here, Mesozoic eolian sandstones undergo weathering, erosion, and redeposition to form an active dune field. The source of sand is the Entrada Sandstone. Generally sandy areas are ubiquitous on Entrada outcrops.

22. **Straight Cliffs**: Forming a nearly continuous escarpment for more than 50 miles along the eastern edge of the Kaiparowits Plateau (Kaiparowits Basin section), the Straight Cliffs present a series of stacked marine sandstone layers within the Straight Cliffs Formation. These sandstone layers were probably barrier islands during the Late Cretaceous nearly 90 million years ago. Behind these barrier islands swamps formed that favored the creation of the thick coal beds seen in the Kaiparowits Plateau area. Today, the Straight Cliffs closely follow an ancient shoreline of the Late Cretaceous Western Interior Seaway. Another name for the Straight Cliffs is Fiftymile Mountain. Between Escalante and the Colorado River, a distance of 50 miles, only two canyons break the otherwise straight line of cliffs (figure 12).

23. **The Blues**: The Kaiparowits Formation is an Upper Cretaceous unit that was deposited very thickly in the Kaiparowits Basin section of the monument. It forms outstanding “badlands” topography in the area just south of Powell Point. The gray or gray-blue Kaiparowits Formation is about 2,500 feet thick at the BLM viewpoint along State Road 12. The viewpoint overlooks a nearly complete section of the formation, where it is not covered by vegetation or other debris to mar the view. Known for its abundant fossil record, the Kaiparowits Formation has yielded specimens of small mammals, sharks, crocodiles, turtles, hadrosaurs, theropods, and ankylosaurs.

24. **The Cockscomb**: This feature is the physiographic display of the East Kaibab monocline. This sharp flexure of the earth’s crust is the boundary between the Kaiparowits Basin section and the Grand Staircase section of the monument; it extends 35 miles from the Arizona border northward into Garfield County. The rock strata dip abruptly eastward at angles ranging from 15 degrees to slightly overturned, with an average dip of 40 to 60 degrees in the steepest part of the flexure (figure 29). Rocks on the east side of this flexure have been displaced downward as much as 5,000 feet. The landforms along the monocline consist chiefly of a series of closely spaced hogbacks and strike valleys. Because of the steep folding, the rocks have been locally faulted and attenuated and appear to be thinner than they were originally deposited. The Cottonwood Wash road parallels the feature.

25. **Vermilion Cliffs**: The Jurassic Moenave and Kayenta Formations combine to form the massive Vermilion Cliffs,

Figure 13. View of part of a 90-foot petrified tree trunk in the Wolverine area in the Circle Cliffs.

a riser or step of the Grand Staircase. In the monument, they can be seen north of U.S. Highway 89 from Johnson Canyon to the Cockscomb, but essentially extend along the Utah-Arizona boundary from Washington County, Utah to the Colorado River at Lees Ferry. Iron-oxide cement gives these formations their brilliant color for which they are so well known.

26. **White Canyon Flat tar seep**: Most of the tar exposed in the Circle Cliffs breached anticline is in the Moenkopi Formation, but locally, some is found in sandstone channels of the Shinarump Member of the Chinle Formation. Located along the east edge of the monument (Escalante Canyons section) at White Canyon Flat, tar drips from sandstone pore spaces in the summer. The oil originally filled the bottom of the Shinarump channel and was probably derived from the same source as that in the Moenkopi Formation.

27. **White Cliffs**: The Jurassic Navajo Sandstone is often described as a fossilized desert because of its eolian origin. In the Grand Staircase section, the 1,800-foot-thick Navajo consists of three parts, based on post-depositional groundwater coloring action. The lower part is brown and cliff-forming. The middle part is pink and forms both cliffs and slopes. The upper part is white and forms a magnificent 500- to 600-foot cliff or riser of the Grand Staircase called the White Cliffs (figure 20). The White Cliffs are a line of cliffs extending from Zion National Park eastward to the Cockscomb and lie above the Vermilion Cliffs. Take a short drive north of U.S. Highway 89 on the Kitchen Corral Wash road through the Vermilion Cliffs to get excellent views of the White Cliffs.

28. **Wolverine petrified wood area**: The Wolverine petrified wood area is located in the Circle Cliffs (Escalante Canyons section). The Petrified Forest Member of the Chinle Formation contains numerous petrified logs, at least one of which measures 6 feet in diameter and is nearly 90 feet long (figure 13). The logs represent conifer trees covered by volcanic-ash-derived stream sediments. Silica from the ash replaced much of the original organic matter in the logs during the process of petrifaction. *Araucarioxylon* and *Woodworthia* are the most common plants represented by the petrified wood.

HISTORY

Geologic

Nearly 270 million years of geologic history is revealed in the exposed rocks and paleontology of the monument (Baars, 1972; Hintze, 1988). The oldest rocks record a time when the North American plate was situated such that the equator angled northeasterly from southern California and across the southeast corner of Utah. The area was a marginal marine lowland of streams, flood plains, and tidal flats. The sea lay to the west, but it occasionally spread eastward across the area, depositing limestone beds containing diverse shells, sponges, and other fossils between the red beds of sandstone and mudstone that were being deposited on adjacent lowlands. The Hermit Shale, Toroweap Formation, Kaibab Limestone and Moenkopi Formation (Blakey and others, 1993; Blakey, 1996), which crop out in the Circle Cliffs and at Buckskin Mountain, record the events of the first 35 million years of exposed geologic history in the monument. A missing record of nearly 20 million years separates the last record of the Permian Period from the Triassic Period in the monument (figure 14). Evidence for climatic regimes, environments of deposition, and other paleohistoric data are available only from the rocks that we currently see in the monument, or only 43 percent of the 270-million-year interval.

One might ask what happened during the remaining 57 percent of time. Strata may have been deposited only to be eroded before the next sequence was laid down. They may have been deposited or eroded in environments that differ from those recorded in the rocks that are present. Unfortunately the missing intervals are generally not recorded in neighboring localities; the events that affected the monument affected the region similarly. Nevertheless there is a wealth of information found in the 43 percent of the rocks that are present and much information remains to be gleaned from them.

The Upper or Late Triassic-age rocks in the Circle Cliffs section have remarkable specimens of petrified wood, including logs exceeding 90 feet in length. These logs represent conifer trees that were left as driftwood on river flood plains. Cellular organic tissues were replaced by silica derived from volcanic ashes which were deposited as part of the Chinle Formation (Dubiel, 1994). Fossils of other kinds of plants, fish, amphibians, and reptiles, tracks of early dinosaurs, and freshwater clam and gastropod shells also give hints about the environment and life in the monument during Late Triassic time (Foster and others, 1999).

Following the Late Triassic, and a period of 5 to 6 million years of non-deposition and erosion, sand was deposited during Early Jurassic time (208 to 187 million years ago). In the Escalante Canyons section this sand was initially deposited in a sand-dune desert (Wingate Sandstone). The desert environment changed for a time and streams deposited sand in channels and overbank deposits on flood plains (Kayenta Formation). The desert climate returned and sand was again deposited in a huge area of sand dunes (Navajo Sandstone). In the Grand Staircase section, Lower Jurassic tidal flats (lower Moenave Formation) gradually changed to flood plains (upper Moenave and Kayenta Formations), and finally ended in a wind-blown sand environment (Navajo Sandstone). These Lower or Early Jurassic-age rocks form the Vermilion and White Cliffs in the Grand Staircase section and make up the walls of the canyon and tributary canyons of the Escalante River. Many people consider these Lower Jurassic rocks to be the most interesting and scenic of the monument. Though generally devoid of fossils, these rocks commonly exhibit tracks of small to medium-sized dinosaurs (Hamblin, 1998).

Middle Jurassic time in the monument is mostly represented by the Carmel and Entrada Formations. The Carmel was deposited near the south margin of a shallow sea that advanced into the area from the north. Carmel limestones contain marine mollusks, brachiopods, crinoids, coral, and algae. Desert sand dunes (beach and back-beach sands of the Entrada Sandstone) were deposited on Carmel sediments and limestones in the wake of the retreating Carmel sea. Another 3 to 5 million years elapsed between the time the Entrada sands were deposited and Upper Jurassic Morrison Formation sediments were laid down. In the Escalante Canyons section, the Morrison was deposited by northeast-flowing streams. The sluggish meandering and anastomosing streams of Morrison time developed broad flood plains. Dinosaurs roamed the monument in profusion and "sloshed" across the streams and through the ponds and lakes that developed on the flood plain.

Late Jurassic to early Tertiary compressive forces in the Earth's crust formed high mountain ranges in western Utah and eastern Nevada which peaked in the Late Cretaceous. This mountain-building event is known as the Sevier orogeny. Simultaneously, an epicontinental sea spread to the foot of these mountains and inundated the monument area. The sea covered most of the interior of the North American continent from the Arctic Ocean to the Gulf of Mexico, dividing the continent into two parts. At its maximum extent the sea stretched to the Cedar City area in southwest Utah, west of the monument. Sediments, provided by the erosion of the Sevier mountains, were carried eastward by rivers and streams to the sea. Dakota Formation sediments were deposited in coastal areas ahead of the encroaching sea. The Tropic Shale represents the muds deposited at the bottom of the sea, and the Straight Cliffs, Wahweap, and Kaiparowits Formations represent sediments deposited on a piedmont belt between the mountains and the sea after the sea retreated east of the monument area. The west part of the monument area was elevated before sediments were deposited during the transgressive and regressive stages of the epicontinental sea. In the west part of the monument all Upper Jurassic and a good part of the Middle Jurassic rocks were removed by erosion before the Cretaceous sediments were deposited (see figure 14).

The thickness, continuity, and broad temporal distribution of the Kaiparowits Plateau stratigraphy provide opportunities to study the paleontology of Late Cretaceous time. Significant fossils, including marine and brackish-water mollusks, turtles, crocodilians, lizards, di-

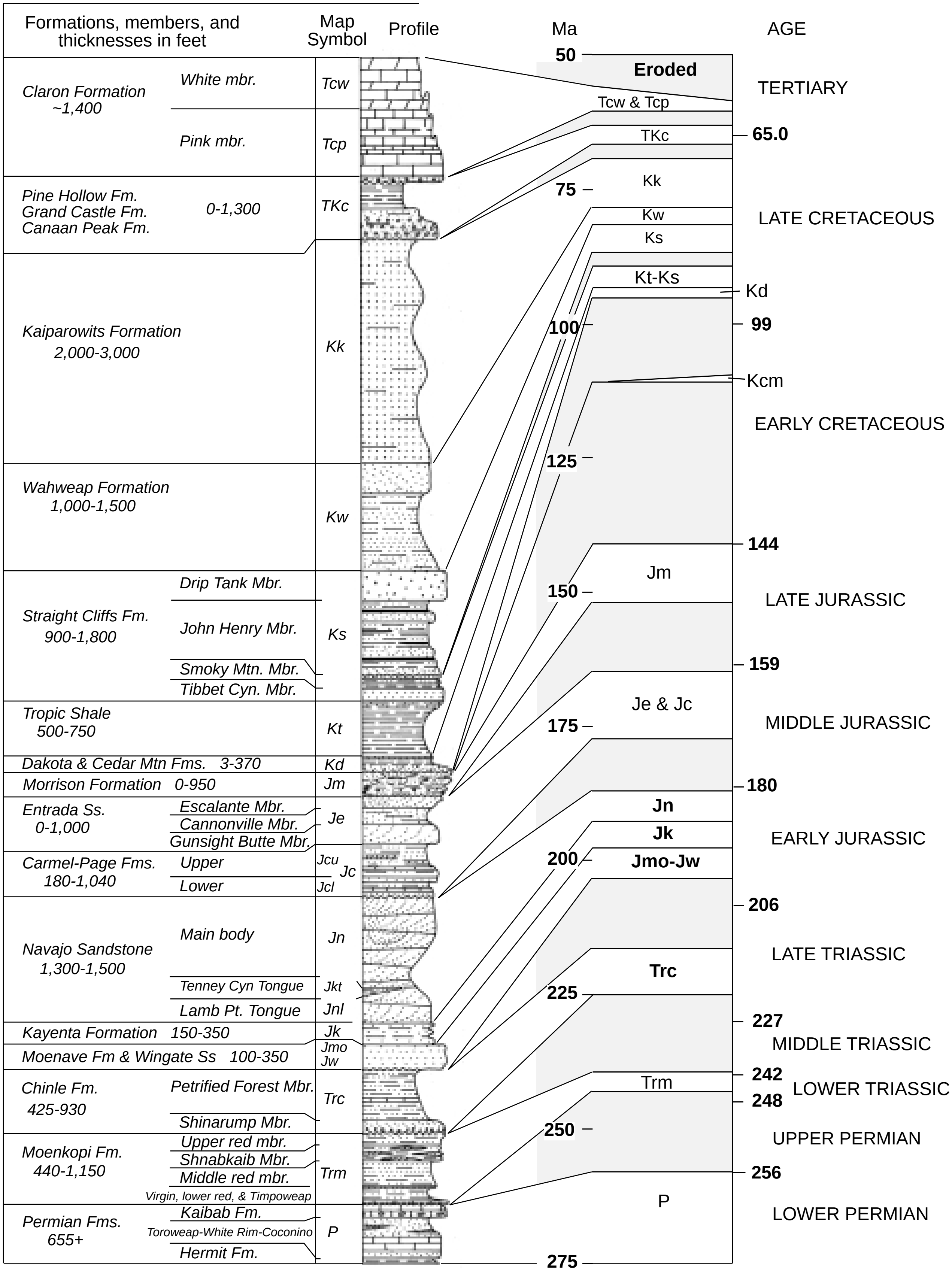

Figure 14. Age, thickness and names of formations and members of geologic units exposed in the Grand Staircase-Escalante National Monument. Symbols are those used on the geologic maps shown in figures 7, 8, and 9. Profile-lithology plot shows true relative thickness (averages) as compared with geologic time. Gray areas denote time with missing rock records. Je includes Romana Mesa Sandstone and Henrieville Formation. Ma stands for millions of years ago. Numbers between period designations indicate age of time boundary.

nosaurs, fish, and mammals have been recovered from the Dakota Formation, Tropic Shale, Straight Cliffs, Wahweap, and Kaiparowits Formations. These formations provide evidence of a diverse terrestrial vertebrate fauna, especially for mammals and dinosaurs, in the 20 million years after the retreat of the epicontinental sea. This sequence of rocks in the monument contains one of the best and most continuous records of Late Cretaceous terrestrial life in the world (Kirkland and others, 1998; Eaton and others, 1999). The research on these strata is still in its earliest stages.

The Canaan Peak Formation straddles the boundary between Cretaceous and Tertiary time. Dinosaurs became extinct during its deposition and changes in depositional environments followed. The Sevier mountains to the west were gradually removed by erosion by early Tertiary time and several large lakes occupied areas extending from southwestern Wyoming to southwestern Utah. The Claron Formation, which forms the Pink Cliffs at Powell Point and Bryce Canyon National Park, was deposited in a lake which covered much of the monument area.

Much volcanic activity took place in central Utah in middle Tertiary time. Today, volcanic rocks cap the Aquarius Plateau and Boulder Mountain north of the monument, but volcanic boulders litter benches in the north part of the Escalante Canyons section. All during the middle Tertiary Utah and surrounding areas lay at low elevations, not far above sea level. A general rise of the landscape and tectonic activity (faulting) occurred in latest Tertiary time and continues into the present. The Colorado Plateau uplift began about 15 million years ago. In western Utah the uplift was accompanied by faulting brought on by crustal extension (stretching). This faulting formed grabens, horsts, and tilted fault blocks that form the north-south-trending basins and ranges in western Utah and Nevada. The monument is located at the east edge of this basin-and-range faulting. The Johnson Canyon and Paunsaugunt faults are the easternmost of the basin and range faults. Although detailed fault and seismic studies are necessary, the Johnson Canyon and Paunsaugunt faults may be active and may relate to small earth tremors and earthquakes that have been experienced in the area (Doelling and Davis, 1989; University of Utah Seismology Catalog, 1986). The Grand Canyon uplift occurred simultaneously with the Colorado Plateau uplift and its specific effect extends into the monument area as the Kaibab uplift (McKee & McKee, 1972; Lucchitta, 1972).

The Colorado Plateau is still rising. The Colorado River and its tributaries cut deep canyons into the landscape and into the colorful formations deposited in late Paleozoic and Mesozoic time. The basin-and-range faults continue to move and affect the Grand Staircase section of the monument. The unconsolidated fluvial and wind-blown deposits that are temporarily lodged in the hollows of the eroding formations, and on their way to the ocean, hold the secrets of the events of the last few million years and hold most of the evidence of human habitation for the last few thousand years.

Cultural

Archaeologists have divided the cultural history of the monument into six generalized periods. They are the Paleo-Indian period (11,500-9,000 years ago), Archaic period (9,000-2,000 years ago), Early Agricultural period (2,000-1,500 years ago), Formative period (1,500-700 years ago), Late Prehistoric-Protohistoric period (700-150 years ago), and the Historic period (150-0 years ago) (Spangler and Metcalf, in preparation).

The Paleo-Indian period began at the Pleistocene-Holocene boundary or at the end of the last Ice Age. The inhabitants of this time period hunted big game animals such as mammoth, bison, camel, and horse. Evidence of their existence has been found throughout the Colorado Plateau region in the form of large Clovis and Folsom spear points.

The Archaic period began after post-Pleistocene warming was complete and many of the larger mammals had become extinct. These inhabitants adapted to a gathering and small-game hunting way of life.

In the Early Agricultural period, corn and squash farming was introduced into the region and by 1,200 years ago became the dominant means of making a living.

The Formative period is the most obvious and studied cultural period in the monument area. The inhabitants constructed more permanent storage facilities and dwellings, they made pottery, and the population reached a high level. Formative people were farmers and small-game hunters as were those of the two previous periods. Two different groups of people were present at this time: the Fremont culture in the northeast part and the Anasazi culture in the southwest part of the monument.

During the Late Prehistoric period, between 1300 and 1500 A.D., both Anasazi and Fremont cultures left the region, most likely because of extended periods of drought (Gieb and others, 1999).

The first written accounts of native American cultures in this region were made by Fathers Dominguez and Escalante as they passed through the region on a Spanish expedition in 1776. Their accounts describe the inhabitants of the Protohistoric period. These explorers noted an Indian culture that was later named the Southern Paiute culture. No other explorers ventured near the monument until Mormon settlers began colonizing southern Utah in the 1850s.

The last and most recent period, known as the Historic period, commences with the Mormon colonization of southern Utah. Journals of these settlers described the Southern Paiute Indians as nomadic people that moved with the seasons to maximize their hunting and gathering activities. This time period coincides with the great western expansion of the United States of America. In the years that followed, several famous surveyors and explorers traveled through the monument region. These include Jacob Hamblin, John Wesley Powell, Almon H. Thompson, Clarence Dutton, G.M. Wheeler, and G.K. Gilbert. In the

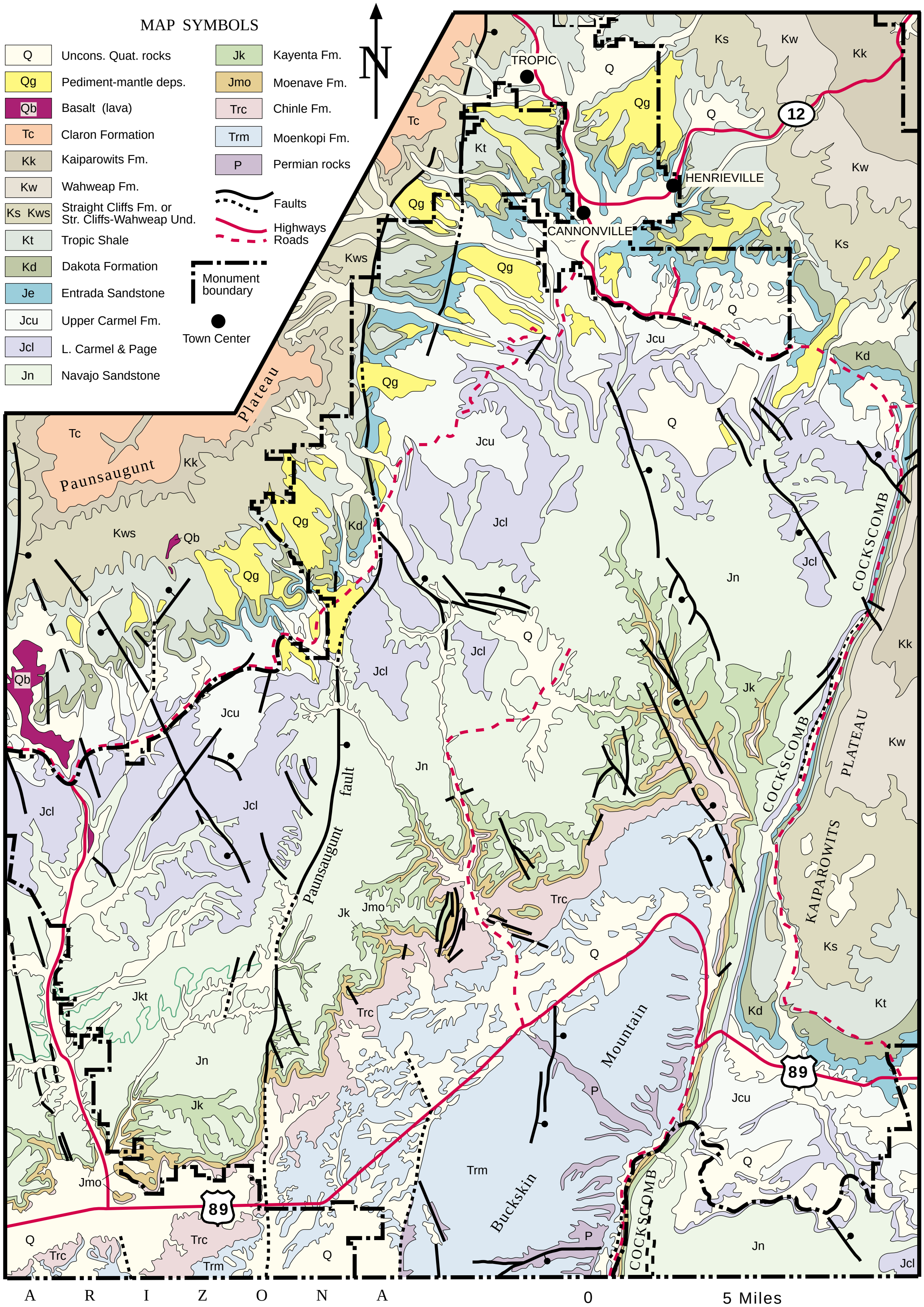

Figure 15. Generalized geologic map of the Grand Staircase section of the monument. The "Grand Staircase" is named for a series of cliffs. The lowermost Chocolate Cliffs are aligned along the Moenkopi-Chinle (Trm-Trc) contact. The Vermilion Cliffs are aligned along the Moenave-Kayenta (Jmo-Jk) outcrops; the White Cliffs are aligned along the upper third of the Navajo Sandstone (Jn); the Gray Cliffs are here aligned along the Dakota Formation (Kd), and the highest Pink Cliffs are aligned just above the Kaiparowits-Claron (Kk-Tc) contact. See text for descriptions of map units.

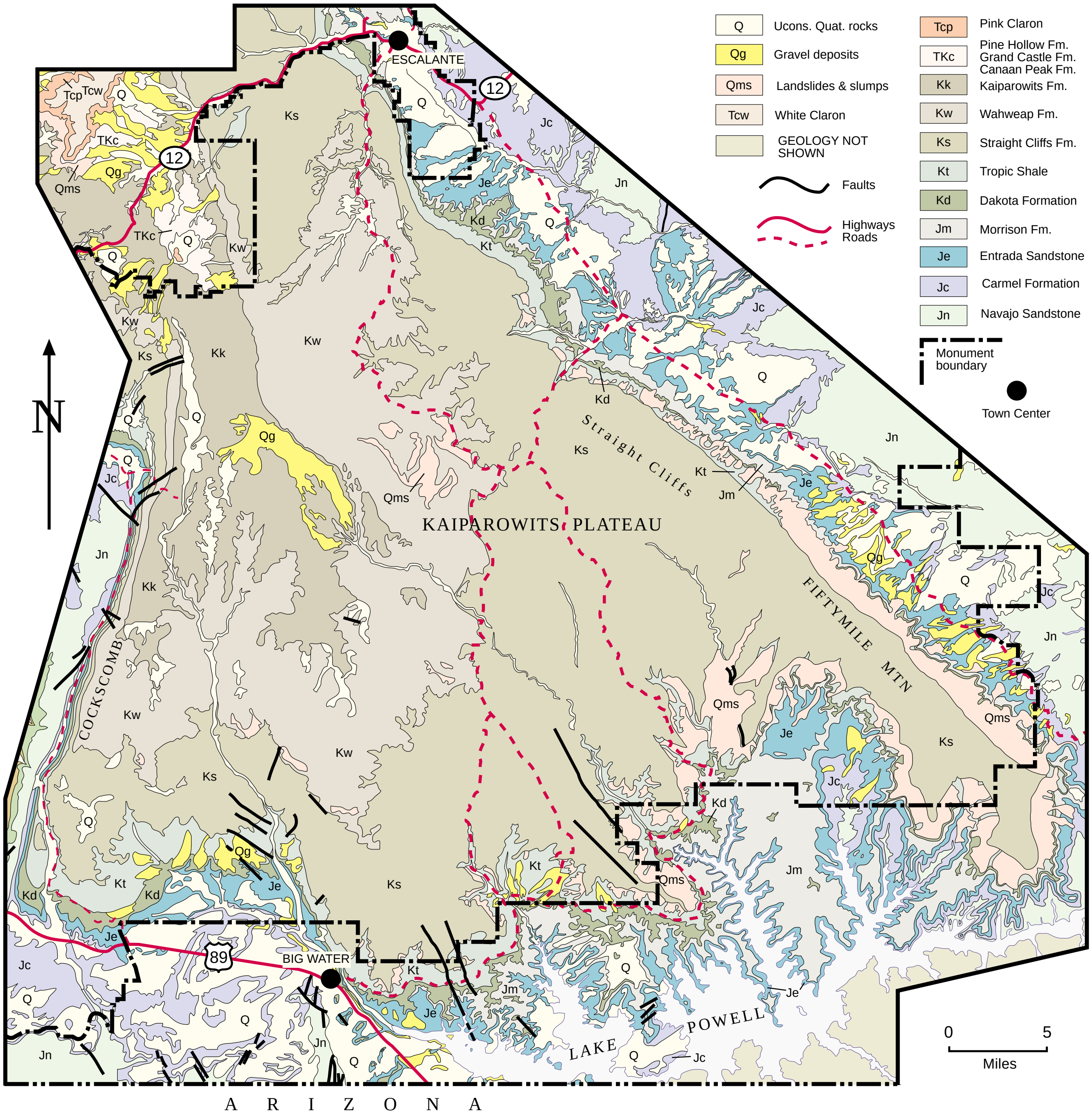

Figure 16. Generalized geologic map of the Kaiparowits Basin section of the monument. This section represents a large structural basin, but is topographically high. Part of the Escalante Canyons section is represented northeast of Fiftymile Mountain. See text for descriptions of map units.

early 1900s, H.E. Gregory began the first detailed geologic study of the region. In more recent times, the lure of precious metals, oil, gas, coal, uranium, and other minerals drew prospectors, miners, and energy companies into the region that produced more detailed reports on the geology, natural resources, and unique sites of the region. Due to its harsh and remote character, the monument area was one of the last places in the continental U.S. to be mapped. Today, the area is largely unpopulated except for the small and scattered communities found along the edges of the monument (Cassity and Truman, in preparation).

STRATIGRAPHY AND PALEONTOLOGY

Bedrock exposed in the monument ranges in age from Early Permian to Late Cretaceous. Precambrian, Cambrian, Devonian, Mississippian and Pennsylvanian rocks are present in the subsurface. Additionally, there are several types of unconsolidated deposits ranging in age from late Tertiary to Holocene. Since the area is presently one of active erosion, the unconsolidated deposits are geologically temporary, but important with respect to geologic hazards, environmental issues, and human habitation patterns.

The monument is large, a little over 70 miles from its southernmost point to its northernmost point and about 82

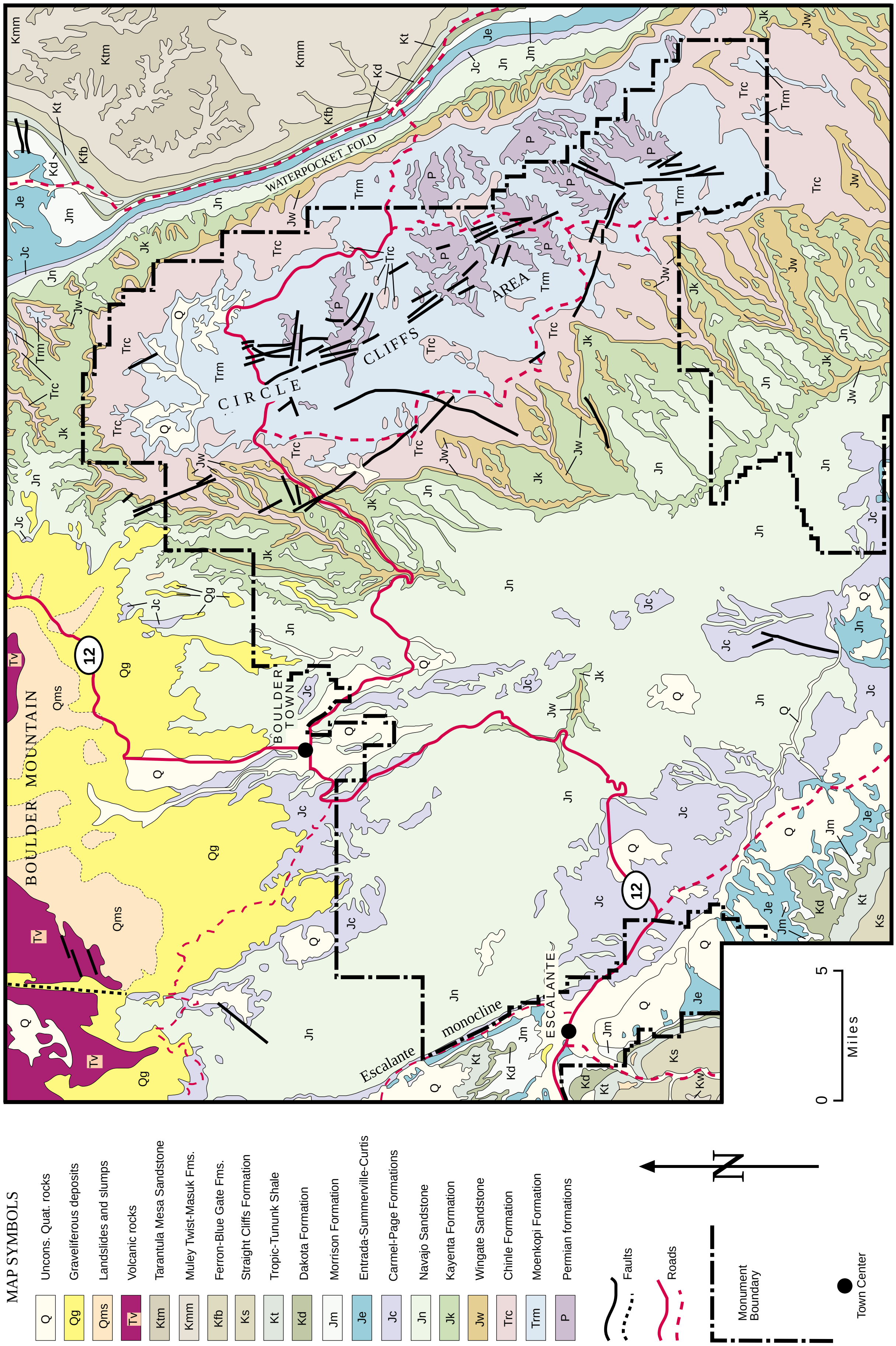

Figure 17. Generalized geologic map of the Escalante Canyons section of the monument. This section is comprised of two parts: the Circle Cliffs area to the east which abuts against the Waterpocket Fold (Capitol Reef National Park) and the Bench-and-Canyonlands area to the west, dominated by Navajo Sandstone benches. See text for descriptions of map units.

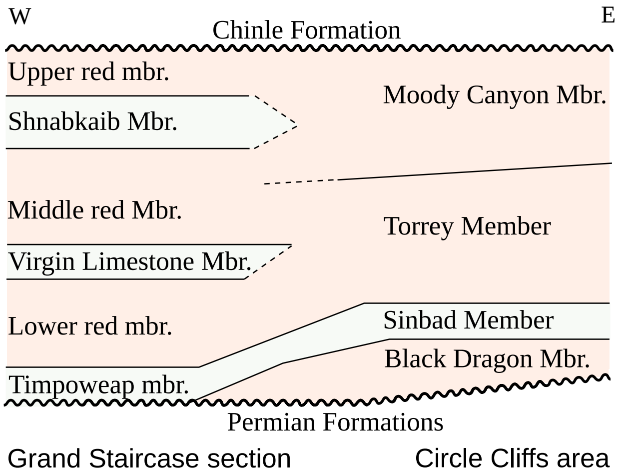

Figure 18. Correlation of the Moenkopi Formation members between the Grand Staircase section and Circle Cliffs area. Green-colored members represent marine encroachments from the west; pink-colored members are red-bed deposits. The Moenkopi thickens westward.

miles from its westernmost point to its easternmost point. Some of the geologic formations undergo significant facies and other changes over these distances. Exposed strata in the Grand Staircase section total from 6,000 to 7,000 feet and range from Permian to Cretaceous in age. Exposed strata in the Kaiparowits Basin section also total from 6,000 to 7,000 feet, but range in age from Middle Jurassic to latest Cretaceous, with a much thicker Cretaceous section. Exposed strata in the Escalante Canyons section total 4,500 to 5,500 feet and range in age from Permian to Late Jurassic. A list of units is given on figure 14 and are shown on the geologic maps, figures 15 to 17.

Permian Rocks (P)

Permian rocks are the oldest rocks exposed in the monument. Outcrops are present in Buckskin Gulch and in adjacent canyons associated with the Kaibab uplift in the Grand Staircase section and are present in scattered places in the core of the Circle Cliffs uplift in the Escalante Canyons section. In the Kaibab uplift the (ascending) Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone are exposed; in the Escalante section-Circle Cliffs uplift the White Rim Sandstone and the Kaibab Formation are exposed.

Hermit Shale

Only the upper 55 feet of the Hermit Shale is exposed in Buckskin Gulch. The Hermit is red silty sandstone, siltstone, micaceous shale, claystone, and minor dolomite. It correlates with the Organ Rock Shale in eastern Utah, which may underlie the White Rim Sandstone in the Circle Cliffs area. Wells indicate the Hermit-Organ Rock ranges from 100 to 600 feet thick, thickening southward under the monument. The unit was deposited partly in a fluvial environment and partly in a tidal-flat environment. As yet no fossils have been found in the Hermit Shale within the monument. Fossils from the Hermit Shale outside the monument include land plants, insects, amphibian footprints, and worm trails (Gillette and Hayden, 1997).

Coconino Sandstone

Less than 64 feet of Coconino Sandstone is present above the Hermit Shale in Buckskin Gulch. There it consists of alternating beds of arenaceous limestone and irregularly bedded fine-grained buff sandstone. The limestones contain poorly preserved marine fossils. At the Grand Canyon it is 330 to 350 feet thick and is a uniform fine-grained, cross-bedded, white to light-gray sandstone with siliceous cement. At Buckskin Gulch it probably interfingers with the lower part of the Brady Canyon Member of the Toroweap Formation. Drill holes indicate it is present only in the south half of Kane County. The Coconino is probably a near-shore deposit grading southward into a beach sand.

Toroweap Formation-White Rim Sandstone

The Toroweap Formation can be divided into two members in Buckskin Gulch: a lower 90-foot section of cliff-forming, cherty, fossiliferous limestone interbedded with calcareous sandstone and 175 feet of slope-forming, mostly yellow preceded by mostly gray to red, very fine and medium-grained (bimodal) gypsiferous sandstone. The upper beds locally contain gypsum, marl or travertine, and intraformational conglomerate. The lower cliff-former is known as the Brady Canyon Member and the upper slope-former is known as the Woods Ranch Member. The Toroweap was deposited in and adjacent to a shallow sea and represents a single marine transgressive and regressive cycle (McKee, 1938).

The oldest exposed geologic unit in the Circle Cliffs uplift is the White Rim Sandstone. There it can be divided into two units. The lower unit, of which up to 108 feet is exposed, is white quartzose cross-stratified sandstone of eolian origin. The grains are very fine to fine, subangular to angular, and are mostly siliceously cemented. The lower unit intertongues with the upper. The upper unit is thin to thick planar-bedded and is 65 to 155 feet thick. It consists of pale-yellow to yellow-brown dolomitic sandstone with a few sandy dolomite beds. Grains are very fine to fine and subrounded to rounded. Some beds contain poorly preserved fossils such as fragments of gastropods and pelecypods. It is assumed that these beds were laid down as a transgressive marine deposit as Permian seas encroached eastward. The White Rim Sandstone in the Circle Cliffs area is a resistant unit.

The Toroweap Formation and White Rim Sandstone grade into each other under the Kaiparowits Basin section. Logs of oil-test wells west of the basin recognize only the Toroweap Formation. Logs of oil-test-wells in the basin generally give thicknesses for the Toroweap or for both the Toroweap and White Rim. East of Fiftymile Mountain, in the Escalante section of the monument, only White Rim thicknesses are reported.

Kaibab Formation

The Kaibab Formation is present under most of the monument, but generally thickens westward. In the Kaibab uplift it is about 160 to 280 feet thick, but the Circle Cliffs outcrops (in the Escalante Canyons section) are at most 60 feet thick. In the Circle Cliffs area the Kaibab is a thin-bedded, light-yellow dolomite. It is absent in the southern part of the Circle Cliffs, where it may have been removed by Late Permian and Early Triassic erosion rather than by just pinching out to the east. The Kaibab has been encountered in oil-test wells east of the monument.

In the Circle Cliffs area the Kaibab is a very fine to fine-grained, oolitic, porous dolomite. Interbedded are a few partings of green glauconitic feldspathic sandstone. It erodes to ledgy slopes and the upper beds contain small quartz geodes, stringers of gray chert, and gray chert nodules and fragments. Locally the beds contain fossils with fossil hash as much as 6 inches thick. The hash includes crinoid columnals, pelecypods, gastropods, productid brachiopods and various spines and spicules (Davidson, 1967).

In the Kaibab uplift (in the Grand Staircase section), the Kaibab Formation can be divided into two members. The lower Fossil Mountain Member is 140 to 200 feet of massive cliff-forming, fossiliferous, cherty gray limestone and calcareous, commonly cherty, well-indurated fine-grained sandstone. The chert is found as nodules, in beds, and in irregular bodies. White spheroidal chert is most distinctive. Some beds are quite fossiliferous, containing a wide variety of marine fossils including branched and fenestellid-type bryozoans, rugosid corals, crinoids, brachiopods and the sponge *Actinoceolia* (Foster and others, 1999).

The upper Harrisburg Member is 15 to 80 feet thick. Beds in the upper member are medium to thick bedded and unfossiliferous. The lower part of the upper member is mostly cherty limestone. Toward the top, sandstone beds become numerous. The unit is capped by a hackly weathering blocky gray limestone bed. The upper half of the bed displays vertical tubes filled with brown, rough-weathering, sandy chert (bioturbation features?). The Fossil Mountain Member was deposited in an advancing sea and the Harrisburg Member in a retreating sea.

Triassic Rocks

Moenkopi Formation (Trm)

The Lower Triassic Moenkopi Formation is divisible into four to six members in the monument. In the Grand Staircase section the members are (ascending) Timpoweap, Lower Red, Virgin Limestone, Middle Red, Shnabkaib, and Upper Red. In the Escalante Canyons section the members are (ascending) Black Dragon, Sinbad, Torrey, and Moody Canyon. A Black Dragon equivalent may not be present in the Grand Staircase section. The Timpoweap Member correlates in time with the Sinbad Member, while the Lower Red, Virgin Limestone and Middle Red Members correlate with the Torrey Member. The Shnabkaib and Upper Red Members correlate with the Moody Canyon Member (Blakey, 1974). In the Grand Staircase section, the Moenkopi Formation ranges from 910 to 1,150 feet in thickness. In the Escalante Canyons section, the Moenkopi ranges from 440 to 730 feet in thickness.

The Moenkopi Formation is bounded above and below by regional unconformities. The lower boundary may be described as a disconformity of low relief. The upper boundary is also a disconformity, but locally, channels of the overlying Shinarump Member have cut deeply into the Moody Canyon and Upper Red Members. Moenkopi Formation member relationships are shown on figure 18 (Blakey, 1974).

Fossils from the Moenkopi are a mix of terrestrial and marine taxa. They include plants, crinoids, brachiopods, gastropods, bivalves, ammonoids, nautiloids, arthropods, fish, reptiles, labyrinthodont amphibians, and reptile footprints (Gillette and Hayden, 1997). Reptile tracks are known from a number of localities in both the Grand Staircase and Escalante Canyons sections of the monument (see Hamblin, this volume). Horseshoe crab tracks have been found in the Circle Cliffs area (Foster and others, 1999).

Black Dragon Member: The Black Dragon Member is exposed in the north Circle Cliffs area in the Escalante Canyons section of the monument where it ranges up to 40 feet in thickness. It is not present in the area south of the Burr Trail road. Typically the member consists of laminated to very thin-bedded siltstone and silty sandstone. It is locally ripple marked and intercalated with thin-bedded, very fine-grained, micaceous sandstone. Commonly the base of the member contains chert or quartz pebbles and locally chert-pebble conglomerate. It forms a steep slope and weathers flaggy or earthy. Locally, some gypsum may be found in this unit. It is thought that the unit was deposited on a mudflat or tidal flat and in associated lagoons (Blakey, 1974).

In the Grand Staircase section, the Timpoweap Member rests directly on the Harrisburg Member of the Kaibab Formation. In a short gulley being eroded into the side of the steep flank of the Kaibab uplift, a very thin section of tan and red sandy siltstone is found between the top of the Kaibab and normal Timpoweap Member beds, which may correlate with the Black Dragon Member.

Sinbad Member - Timpoweap Member: The Sinbad Member overlies the Black Dragon Member in the Circle Cliffs area in the Escalante Canyons section of the monument. The Sinbad Member is up to 55 feet thick in the Circle Cliffs area, thickening to the northwest. It is missing in the southeast part of the Circle Cliffs, but its outcrops extend a little farther southeastward than those of the Black Dragon Member. On the Kaibab uplift (Buckskin Mountain) the Timpoweap Member forms a thin but resistant 20- to 50-foot carapace over the uplift whaleback.

In the Circle Cliffs area the Sinbad Member consists of yellow-gray to pale-orange-brown weathering limestone, dolomite, and calcareous siltstone. The beds are thin, weather platy, and form bench-forming ledges. It intertongues with the Black Dragon Member below and the Torrey Member above. Some limestone beds are fossiliferous, containing mostly poorly preserved pelecypods and gastropods. The Meekoceras zone has been correlated into the Sinbad-Timpoweap Members, but no truly recognizable cephalopods have yet been found so far in either unit in the monument (Davidson, 1967; Blakey, 1974).

At Buckskin Mountain, the Timpoweap Member consists of highly resistant carbonate rocks, sandstone, chert breccia, and siltstone. Some of the sandstones are pebbly. The overall color is light brown to yellow gray and the individual beds are thin to thick bedded and blocky. The upper half is more resistant than the lower part. The contact between the Kaibab and Timpoweap is difficult to discern, but the Timpoweap is generally slightly darker than the very light Kaibab Formation beds. The Sinbad-Timpoweap Member was deposited in a marine environment representing a transgression that extended the farthest east in the Moenkopi depositional basin. The thin, even beds in the Circle Cliffs might indicate quiet water deposition, whereas the chert breccias in the Timpoweap might indicate deposition in more turbulent waters.

Lower red member: The lower red member of the Moenkopi laps onto the lower parts of the Kaibab uplift whaleback, where it is 140 to 220 feet thick, thickening westward. It consists of red to chocolate-brown, interbedded and thin-bedded siltstone and fine-grained sandstone. The unit is earthy weathering and forms slopes with slight ledges. The sandstones are silty, arkosic, and micaceous. The ledges weather platy and display abundant ripple marks. The lower red member was deposited on a tidal flat traversed by meandering streams (Irwin, 1976). It correlates with the lower part of the Torrey Member in the Circle Cliffs area.

Virgin Limestone Member: The Lower Red Member is overlain by the Virgin Limestone Member around the Kaibab uplift south of Paria. The unit is only 10 to 30 feet thick, and thickens to the west. It is conspicuous because it is ledge forming. It consists of interbedded yellow-brown sandstone, siltstone, and limestone. The limestone, a minor constituent here, is very sandy and grades into calcareous sandstone in eastern sections. The pinchout of the Virgin Limestone Member probably is not far to the east of Buckskin Mountain. It is not fossiliferous in the monument where it marks the eastern limit of a Moenkopi marine incursion. The Virgin Limestone Member correlates with part of the Torrey Member in the Circle Cliffs area.

Torrey Member: The Torrey Member overlies the Sinbad Member in the Circle Cliffs uplift in the Escalante Canyons section of the monument. There it is 240 to 310 feet thick and like the other members in the uplift, thickens northwesterly. The very fine to fine-grained sandstone and silty sandstone forms thin- to medium-bedded ledges, cliffs, and slopes. The slope-forming constituents are generally quite micaceous and the ledge formers display ripple marks, load casts, drag structures, and even animal trails. A few mud-pebble conglomerate lenses and mudstone lenses are also present in the unit. The color of the member ranges from pale red-brown to gray red where not saturated with tarry hydrocarbons. Locally hydrocarbons have bleached the Torrey Member, making it pale yellow-brown to gray and even black, according to the degree of saturation.

The Torrey Member correlates with the Lower Red Member, Virgin Limestone Member, and lower part of the Middle Red Member in the Grand Staircase section of the monument. The Torrey Member was deposited in a deltaic and shoreline environment. The upper contact with the Moody Canyon Member is intertonguing to gradational and sometimes difficult to place.

Middle red member: The middle red member overlies the Virgin Limestone Member in the area between the Vermilion Cliffs and the Kaibab uplift in the Grand Staircase section of the monument. Much of it is covered by Quaternary unconsolidated deposits (alluvium and colluvium). It is the thickest of the Moenkopi members in this section and the least resistant to erosion. Its soft and slope-forming nature has induced many of the local drainages to flow along its strike. It is 280 to 400 feet thick and probably thickens westward.

The middle red member consists of interbedded medium-brown to chocolate-brown mudstone and siltstone and light-brown, tan, or gray-green, fine-grained silty sandstone. Many of the beds are criss-crossed with gypsum veinlets. The more resistant thin-bedded sandstones are commonly rippled. The amount of gypsum in the member increases upward. It was probably deposited in mudflat and tidal flat environments. Blakey (1974) correlated the lower middle red member with the upper part of the Torrey Member and the upper part of the middle red member with the lower part of the Moody Canyon Member in the Circle Cliffs uplift.

Shnabkaib Member: The Shnabkaib Member overlies the middle red member in the area between the Vermilion Cliffs and Kaibab uplift in the Grand Staircase section of the monument. There it is 150 to 250 feet thick, thickening westward. It is a ledge- and slope-forming unit consisting of ledges of white to light green silty gypsum and light-brown very fine-grained sandstone and slopes of earthy weathering very fine-grained sandstone and red and green-gray siltstone. The lower contact is placed just under the first thick gypsum bed and the upper just above the uppermost thick gypsum bed.

The Shnabkaib was probably deposited in restricted embayments of a sea surrounded by low tidal-flat and mud-flat areas. The open sea lay to the west and encroached eastward from time to time, carrying in a fresh supply of calcium and sulfate ions needed to precipitate the gypsum.

Upper red member: The upper red member is the uppermost member of the Moenkopi Formation and overlies the gypsiferous Shnabkaib Member in the area between the Vermilion Cliffs and the Kaibab uplift in the Grand Staircase section. It is 90 to 180 feet thick, thickening to the west. It is a dark chocolate-brown to red-brown unit. The lower half forms a steep slope and the upper half weathers into ledges. The chocolate-brown ledge- and cliff-forming characteristic at the top of the member, coupled with the overlying cliff-forming Shinarump Member of the Chinle Formation form the **Chocolate Cliffs** riser of the Grand Staircase. However, the Chocolate Cliffs are better developed to the west, between the Hurricane and Paunsaugunt faults on the Arizona strip. In the monument, the Shinarump is discontinuous and does not form a conspicuous and continuous line of cliffs.

The upper red member is composed of interbedded siltstone and sandstone. The siltstones are dark chocolate brown to red brown, micaceous and sandy, and shaly to thin bedded. The sandstones are light brown to red brown, very fine grained, micaceous, and calcareous. The principal ledges are medium to thick bedded but weather blocky, platy, or shaly. As in most Moenkopi members, many sandstone beds are ripple marked and mud cracked. The upper red member is mainly a tidal flat deposit.

Moody Canyon Member: The Moody Canyon Member is 200 to 330 feet thick in the Circle Cliffs uplift area of the Escalante Canyons section, thickening to the west. It is mostly a slope former composed of red-brown interbedded siltstone and mudstone. Dolomite, gypsum, and sandstone are minor constituents. It is finely to poorly laminated to thin bedded, but is generally earthy weathering. The Moody Canyon Member correlates with the upper red member, Shnabkaib Member, and upper half of the middle red member in the Grand Staircase section of the monument. The Moody Canyon is believed to have been deposited in shallow quiet water, such as in ponds or lagoons on a tidal flat (Blakey, 1974).

Chinle Formation (Trc)

The Upper Triassic Chinle Formation in the Colorado Plateau consists of several members, some of which are present in the monument. The most well-known of these are the Shinarump and Petrified Forest Members. All the members (ascending) include the Temple Mountain, Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock Members. These members are not present in every location, and for the newcomer, may be difficult to differentiate. The simplest subdivision of the Chinle is into its lower ledge-forming and upper slope-forming parts.

The Chinle is a lithologically heterogeneous unit composed of varying amounts of fluvial and lacustrine interbedded sandstone, mudstone, claystone, siltstone, limestone, gritstone, and conglomerate. It is 500 to 930 feet thick in the Grand Staircase section of the monument and 425 to 750 feet thick in the Circle Cliffs area. There are no detectable thickness trends in the monument and changes in thickness of 150 feet or more are common across short distances.

The most abundant fossil in the Chinle Formation is petrified wood (see Petrified Forest Member discussion), mostly the wood of conifers, ferns, and cycads. Others include bivalves, fish, labyrinthodont amphibians, phytosaurs, dinosaurs, and dinosaur tracks. Discoveries of vertebrate skeletal material has been sparse in the monument area, but vertebrates are well represented by fossil tracks (Hamblin, this volume).

Temple Mountain Member: This member has only been recognized in the Circle Cliffs area of the monument. There it is up to 50 feet thick, averaging 15 to 20 feet thick. It forms slopes and ledges between the Moody Canyon Member of the Moenkopi Formation and the resistant cliff-forming sandstones of the Shinarump Member. It rests on an erosional surface at the top of the Moenkopi Formation that exhibits an average of two feet of relief.

The most distinctive thing about the Temple Mountain Member is its mottled appearance. The dominant colors are maroon and white, but yellows, reds, purples, and blacks are common. It is a paleosol (ancient soil) and vertical bleachings probably represent root casts. It consists of well-cemented siltstone containing scattered medium and coarse angular grains of quartz. Considerable amounts of dark minerals, notably tourmaline, are present, indicating the source of the siltstone was not the Moenkopi Formation. It is mostly a fluvial deposit that was highly weathered before the Shinarump and later sediments were deposited.

Shinarump Member: The Shinarump Member of the Chinle Formation is primarily a stream-channel deposit. Streams meandered northwestward across an old Moenkopi surface where local thick soils had developed. The streams locally cut deep channels into this surface. The Shinarump Member is found mostly southwest of the Henry Mountains and does not correlate with basal members of the Chinle in the Paradox basin (Moab area). In the Kanab to St. George area, the Shinarump becomes a blanket stream deposit. During Chinle time, southwest Utah may have been an area of interior drainage, with the Shinarump streams depositing their loads of suspended materials over a broad flat that had developed on the old Moenkopi surface. The Shinarump has been recognized both in the Circle Cliffs area in the Escalante Canyons section and in the Paria area of the Grand Staircase section of the monument. In both places it is discontinuous. In the Paria area, it is channel-form and, in the vicinity of the old Paria movie set, rests in scours directly on the top of the upper red member of the Moenkopi Formation. There is generally a few feet of bleached Moenkopi beneath the channel. The Grand Staircase section Shinarump is up to

Figure 19. Gingham Skirts Butte in the Paria area, Grand Staircase section. The colorful banded Petrified Forest Member of the Chinle Formation is breathtaking to the beholder. Similar color is also displayed in the Circle Cliffs area, Escalante Canyons section, in the Petrified Forest Member.

155 feet thick and averages 55 feet. In the Circle Cliffs area the Shinarump was deposited in channels and as a blanket deposit. Some of the larger and deeper channels of this member have cut through the Temple Mountain Member into the Moody Canyon Member of the Moenkopi. Larger Shinarump channels in the Circle Cliffs, such as those preserved in the Stud Horse Peaks, are as much as 190 feet deep and as much as 8,000 feet wide. In the Circle Cliffs area the flow direction of the ancient paleo-rivers that deposited the Shinarump Member was primarily from the southeast to the northwest.

In the Paria area the Shinarump Member consists of very pale orange, gray orange, yellow gray, or very light gray sandstone and conglomeratic sandstone and some partings of green or gray mudstone. It is lenticular and massive, cliff forming, well cemented, with cobbles as much as 3 inches in diameter. The cementing material is commonly calcareous. Conglomeratic sandstones contain scattered fragments of petrified wood. The sandstone is quartzose, mostly medium to coarse grained, and trough cross-bedded. In the Circle Cliffs area the Shinarump can be subdivided into three units. There is a lower interbedded, medium-grained, very thick bedded sandstone; an intermediate interlayered, thin-bedded sandstone, siltstone, and mudstone and an upper poorly sorted, slabby, thin- to thick-bedded sandstone. The colors are the same as in the Paria area. The sandstone is feldspathic and composed of quartz, feldspar, kaolin, and flakes of muscovite and biotite. The grains are poorly sorted and cemented with kaolin. Fragmentary plant material and small uranium-copper deposits have been found in the Shinarump Member in the Circle Cliffs area.

Monitor Butte Member: The Monitor Butte Member overlies the Shinarump Member in the monument and intertongues with its neighbors above and below. It forms ledgy slopes and is commonly included with the Shinarump because of its dominant gray coloration. The member may be up to 185 feet thick in the Paria River area with most sections averaging 60 to 70 feet. In the Circle Cliffs area it is 100 to 200 feet thick.

In the Paria area it is light-colored sandstone with interbeds of gray silty mudstone or siltstone. The sandstones are thin bedded to massive, fine to medium grained and some are gritty and pebbly. Toward the top of the member, mudstone, sandstone, nodular-weathering brown limestone and gritty conglomeratic sandstone are complexly interbedded and highly lenticular. Generally the unit becomes less resistant, but more coarsely grained upward. It locally contains abundant petrified wood in the form of logs, branches, and fragments. North of the Paria cemetery it contains carbonaceous shales and coal beds.

In the Circle Cliffs area the Monitor Butte Member is a green-gray bentonitic mudstone interlensed with gray sandstone and brown conglomerate. The mudstone consists of a mixture of bentonitic claystone, silty claystone, and clay-rich siltstone. The sandstone beds are gray to light brown, very lenticular, moderately to well sorted, very fine grained to fine grained, micaceous, and are locally conglomeratic. The sandstone and conglomerate beds contain scattered petrified wood fragments. Generally, sandstone beds are more common in areas overlying channels of the Shinarump Member, indicating that stream courses established by Shinarump streams were maintained during Monitor Butte time.

Monitor Butte sediments were deposited on the flood plains of streams. Locally lakes and ponds developed on these plains, which were lined with abundant vegetation. Vegetal matter accumulated in long-lived lakes, forming peat bogs and eventually coal.

Petrified Forest Member: Whereas the lower three members of the Chinle Formation generally form cliffs or ledgy slopes, the upper three members generally form slopes, steep slopes, and higher in the section, ledgy slopes. These three members are the Petrified Forest, Owl Rock, and Church Rock Members. The most conspicuous characteristic of the Petrified Forest Member is its bright coloration (figure 19). It displays a spectacular variety of color, usually differentiated in bands, that on a sunny day have inspired such names as The Land of the Sleeping Rainbow, Gingham Skirts Butte, and Calico Peak. The beauty of the member is partly blemished by the fact that this unit contains abundant swelling clays and is, therefore, extremely prone to slope and foundation failures. Numerous landslides in the region are rooted in this member. In developed areas the member is known as the "blue clay." Houses built upon it and not firmly anchored in something more "solid," suffer structural damage as walls and foundations settle differentially, brick walls develop cracks, and the like. Piping is another problem. Roads built upon it commonly develop chuck holes deep and large enough to swallow tires and small vehicles. The beautiful coloration invites hikers to walk upon it, but the steep slopes are hard and unyielding in dry weather and more slippery than ice after a rain.

In the Grand Staircase section of the monument, the Petrified Forest Member is the first formation beneath the Vermilion Cliffs. In the Escalante Canyons section the member is exposed beneath the Circle Cliffs (Wingate Sandstone), although not directly beneath. In the Circle Cliffs area the Owl Rock and Church Rock Members overlie the Petrified Forest Member beneath the Wingate Sandstone cliffs. Perhaps the best place to observe the Petrified Forest Member in the Grand Staircase section is on the approach to the old Paria town site at Gingham Skirts Butte and, in the Escalante Canyons section, at the head of Long Canyon at The Land of the Sleeping Rainbow. In the Grand Staircase section the Petrified Forest Member is also exposed in Hackberry Canyon.

The Petrified Forest Member is mainly bentonitic mudstone, friable muddy sandstone, and minor conglomerate. A small amount of brown- or nodular-weathering limestone is also present. Bentonite, or montmorillonite, is a type of clay produced from the decomposition (devitrification) of volcanic ash. It swells dramatically when wet. Bentonitic character can be recognized by peculiar "popcorn" surfaces of outcrops. The bentonitic character seems to disappear in the upper parts of some sections. It is common to have the normal steep colorful slope replaced by a hummocky landslide surface on which angular boulders and fragments of overlying sandstone formations "swim."

The Petrified Forest Member was deposited on a fluvial plain largely as overbank deposits. The plain was dotted with lakes and ponds. At times, as the sediments accumulated, volcanic ash settled on the plain, which was altered to clay and locally into siliceous brown nodules. Local layers in the Petrified Forest Member contain abundant fossil wood. In the Circle Cliffs area, silicified logs as much as 6 feet in diameter and 90 feet in length have been found. The petrified wood was locally mined in the Grand Staircase section of the monument (before the monument was established). These logs are brightly colored and were avidly sought by collectors for cutting and polishing. A half-inch slab of a log with a diameter of 9 inches, polished to a high sheen, could be purchased in a Berlin, Germany rock shop for $2,000 in 1990. Remember that collecting is forbidden in the monument. The unit has been aptly named.

Owl Rock Member: The Owl Rock Member was identified by Davidson (1967) in the Circle Cliffs area as overlying the Petrified Forest Member. It crops out in the steep slope formed by the three upper units of the Chinle Formation. It is 150 to 250 feet thick. Some investigators indicated they believe that the less bentonitic upper part of the Petrified Forest Member near the Paria ghost town is correlative with the Owl Rock Member (Stewart and others, 1972; Blakey 1974).

The Owl Rock Member is composed of thin lenticular beds of green limestone interbedded with red, brown, and green-gray sandstone and mudstone. The limestone beds are hard and resistant, generally forming ledges. Whereas the Petrified Forest Member contains abundant bentonitic mudstone, this unit contains much less. It too was deposited in a fluvial environment on a plain dotted with lakes.

Church Rock Member: In eastern Utah the Church Rock Member consists of red-brown to orange-brown sandstone and silty sandstone. Some of the upper sandstones are resistant and blocky weathering. About 15 to 25 feet of such sandstones underlie the vertical cliff of the Wingate Sand-

Figure 20. A part of the White Cliffs in the Grand Staircase section of the monument. The upper white part of the Navajo Sandstone is capped by a thin layer of Co-op Creek Limestone Member of the Carmel Formation.

stone in the Circle Cliffs area. The sandstone is fine to medium grained, massive to thick bedded, and it is cross-stratified on a small scale. The sediments were deposited in lakes and by streams on an alluvial plain that sloped away from the Uncompahgre uplift in eastern Utah during Late Triassic time (Stewart and others, 1972).

Jurassic Rocks

Lower, Middle, and Upper Jurassic rocks are exposed in the monument; the formations of each series are separated by significant regional unconformities (Pipiringos and O'Sullivan, 1978), shown as wavy lines on the lithologic profile, figure 14. Lower Jurassic formations include (ascending) the Wingate Sandstone-Moenave Formation, Kayenta Formation, and Navajo Sandstone. These are sometimes combined as the **Glen Canyon Group**. Middle Jurassic formations include (ascending) the Page Sandstone, Carmel Formation, Entrada Sandstone, Henrieville Sandstone, and Romana Mesa Sandstone that are sometimes combined as the **San Rafael Group**. Upper Jurassic rocks consist of members of the Morrison Formation.

Erosion beneath a regional unconformity at the base of the Cretaceous rocks has successively cut out Upper and Middle Jurassic units down to the Carmel Formation from the east to the west. Relationship and facies changes in the Middle Jurassic formations are evident across the monument.

Wingate Sandstone - Moenave Formation (Jw-Jmo)

The name "Circle Cliffs" originated from the bounding rim of Wingate Sandstone cliffs that encircle this area (figure 31). The Wingate Sandstone forms prominent, massive, vertical cliffs; locally, joints pass from the top to the bottom of the 230- to 350-foot cliff. At times a slab made up of the entire thickness of the formation crashes

Figure 21. Wilsey Hollow and Mollies Nipple, erosional forms in the Navajo Sandstone in the Grand Staircase section.

and disintegrates into rubbly rock fall at its base. Parting surfaces are rare in the unit. Close examination, however, reveals the presence of large-scale cross-beds and cross-bed sets.

The sandstone is orange brown, very fine to fine grained, very well sorted, and quartzose. In many parts of the Circle Cliffs area, the Wingate Sandstone is yellow-gray, presumably reduced by hydrocarbons. It is commonly moderately to well cemented with carbonate. The beds are planar and trough cross-bedded in sets 40 to 60 feet thick. Nevertheless, the bed and set boundaries are not selectively weathered or eroded more than the rock between them, thus maintaining the smooth cliff face. The Wingate Sandstone was deposited in eolian (sand dune) and sabhka environments. Few fossils have been found in the Wingate Sandstone. A single dinosaur track site is present in the Circle Cliffs area. This site exhibits about 10 Gralator-type tracks, five of which form a trackway (Hamblin, this volume).

The Wingate Sandstone is not recognizable in the Grand Staircase section of the monument, and is replaced by the laterally equivalent Moenave Formation. The two formations intertongue in the subsurface of the Kaiparowits Basin, and a tongue of the Wingate persists under the Moenave for a considerable distance westward. Some of the lower sandstones in the Moenave Formation in the Grand Staircase section are reminiscent of the Wingate. The Moenave is divisible into (ascending) the Dinosaur Canyon Member and Springdale Sandstone Member. West of Johnson Canyon, a third member appears between the Dinosaur Canyon and the Springdale (Whitmore Point Member). The Whitmore Point Member is not recognizable in the monument.

Dinosaur Canyon Member: The Dinosaur Canyon Member forms the **lower part of the Vermilion Cliffs** and varies in thickness from 100 to 220 feet in the Grand Staircase Section of the monument. The member forms steep slopes, ledgy slopes, and cliffs.

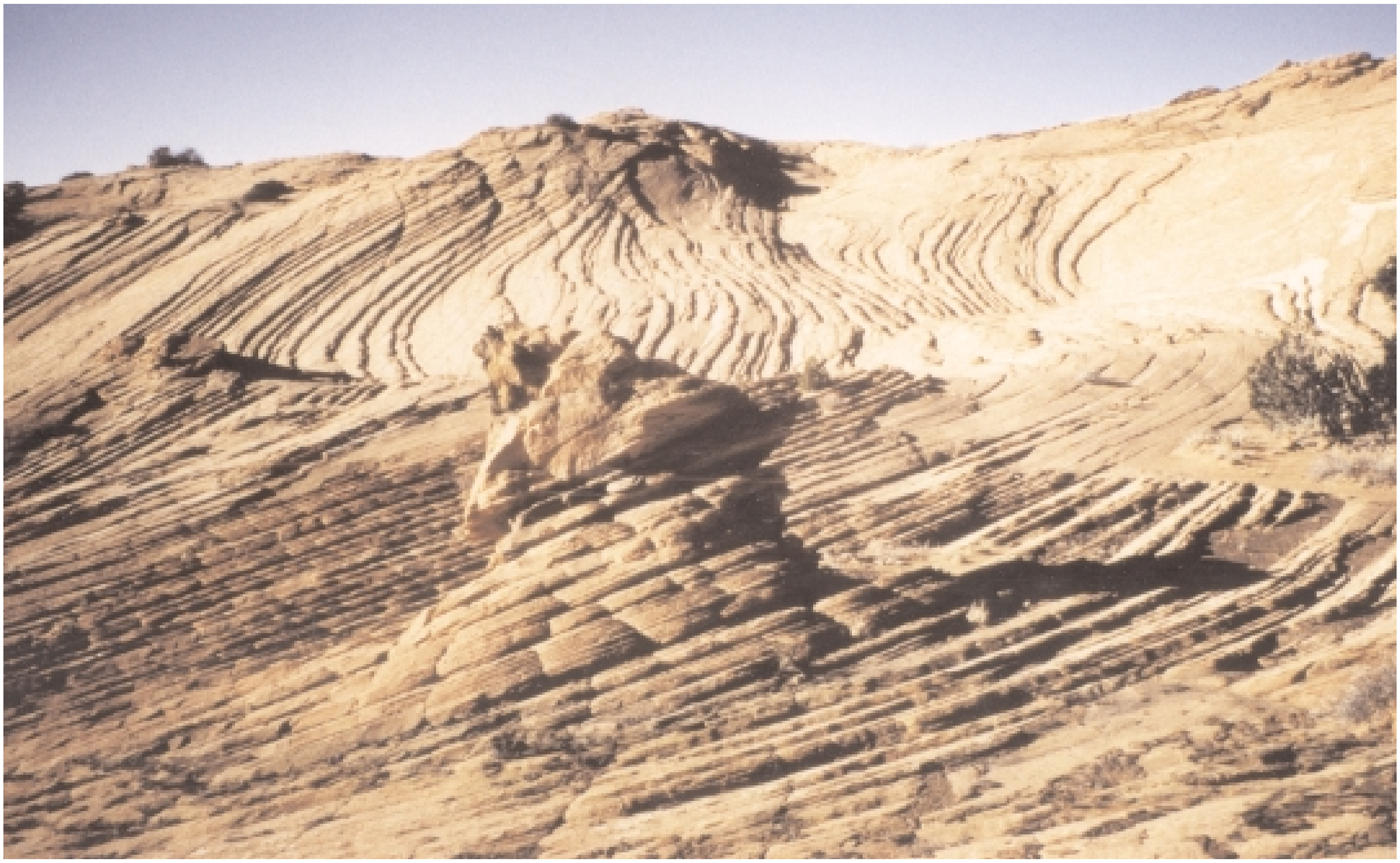

Figure 22. Etched-out cross-beds in the Navajo Sandstone on the benches in the Escalante Canyons section.

This member is mostly red-orange to red-brown siltstone with lesser amounts of red, very fine grained sandstone, claystone, and conglomerate. The percentage of sandstone and coarse siltstone increases to the northeast. These form thin to thick tabular beds, ledges, and cliffs. The finer constituents form laminae to very thin beds and steep slopes. The Dinosaur Canyon was deposited on a lake-covered flood plain and mud-flat dominated environment on which a few small rivers flowed. Fossils found in the monument include fish remains and vertebrate dinosaur tracks (Foster and others, 1999).

Springdale Sandstone Member: The Springdale Sandstone Member is a red-brown to orange-brown cliff former that forms the **middle part of the Vermilion Cliffs** and is about 100 to 230 feet thick in the Grand Staircase section of the monument. It commonly exhibits a yellow-gray upper surface at its contact with the Kayenta Formation that is a few inches to a foot thick.

The Springdale is mostly fine- to very fine grained and consists of relatively uniform, lenticular, overlapping beds of cross-bedded sandstone. Partings and thin beds of siltstone and claystone separate the thick to massive beds. Locally, it contains intraformational conglomerate lenses of claystone pellets and angular fragments of siltstone in a quartz sand matrix. The sandstone exhibits trough cross-stratification, ripple marks and mud-cracked surfaces. The environment of deposition was similar to that for the Dinosaur Canyon Member in the Grand Staircase section.

Kayenta Formation (Jk, Jkt)

This unit forms the **upper part of the Vermilion Cliffs** and the surface of part of the Wygaret Terrace in the Grand Staircase section of the monument. In the Escalante Canyons section, the Kayenta is a bench former. Many mesas and buttes held up by the Wingate Sandstone are capped by this ledgy formation. Whereas underlying and overlying formations are massive, commonly smooth-weathering sandstones, the Kayenta forms thick ledges of sandstone. This ledgy habit contrasts conspicuously with the smooth cliffs of the Wingate, Navajo, and Moenave. It is 150 to 350 feet thick in the Escalante Canyons section and 190 to 340 feet thick in the Grand Staircase section.

Red, brown, lavender, and purple are the colors most commonly used to describe this formation, but some individual beds are light yellow, buff, and gray, though they are commonly stained from the red-browns and dark purple-reds of the majority of beds. The Kayenta is a succession of lenticular, mostly medium grained, fluvially cross-bedded, thick-bedded sandstone with thinner red interbeds of siltstone and mudstone, subordinate thin to medium beds of gray or lavender-gray limestone, and thin to thick beds of intraformational pebble conglomerate.

The environment of deposition of the Kayenta Formation is dominantly fluvial, but lacustrine and eolian beds are interbedded, notably in the upper part of the unit. Dinosaur tracks are locally common in the Kayenta Formation. Other fossils occurring in the monument include petrified wood and undiagnostic vertebrate bone fragments.

The upper part of the Kayenta intertongues with the Navajo Sandstone. Usually the tongues are insignificant; that is, they cannot be reliably correlated over long distances. However, significant intertonguing is present west of the Paunsaugunt fault in the Grand Staircase section. Here a tongue of the Kayenta extends eastward into the Navajo Sandstone, pinching out just before reaching the Paunsaugunt fault. That part of the Kayenta participating in the tongue is called the Tenney Canyon Tongue. That part of the Navajo Sandstone beneath the Tenney Canyon Tongue is called the Lamb Point Tongue of the Navajo Sandstone.

Lamb Point Tongue of the Navajo Sandstone (Jnl): This tongue is typically like the main body or upper part of the Navajo Sandstone. It is white, tan, or gray eolian cross-bedded cliff-forming sandstone with minor thin, red-brown siltstone and gray limestone. It is 250 to 350 feet thick in the monument.

Lamb Point sandstone is mostly fine to medium grained with mostly rounded to subrounded frosted quartzose grains. A small quantity of chert and feldspar grains are also present. Carbonate cementation is loose and irregular so that the rock may be quite friable. It is an excellent aquifer and wells in it supply the culinary water for Kanab and Fredonia. The Lamb Point Tongue exhibits thick cross-bed sets (as much as 25 feet thick) and cross-bed angles locally exceed 36 degrees. Toward the top the cross-beds are commonly contorted.

Like the Navajo, the Lamb Point Tongue represents windblown sand converted to rock. High water tables during time of deposition account for the minor, thin, red-brown siltstone and gray limestone beds and partings.

Tenney Canyon Tongue of the Kayenta Formation (Jkt): This tongue of red-brown siltstone, mudstone, and fine-grained sandstone forms either a ledgy slope or a recess between the main body of the Navajo Sandstone and the Lamb Point Tongue between Johnson Canyon and the Paunsaugunt fault in the Grand Staircase section of the monument. Near the Paunsaugunt fault it grades into the eolian beds of the Navajo Sandstone, but the red-brown color persists to the canyon of the Paria River. It is up to 80 feet thick in the monument. It locally contains a thin gray limestone bed. Like the main body of the Kayenta Formation the Tenney Canyon Tongue is a fluvial deposit. Because it is so thin it is shown as a dark green line on the geologic map (figure 15).

Navajo Sandstone (Jn)

The Navajo Sandstone is an easily recognized and prominent unit in Grand Staircase-Escalante National Monument and is present in both the Escalante Canyons and Grand Staircase sections. It is a massive cliff former and **its upper part forms the White Cliffs riser** of the Grand Staircase (figure 20). It generally forms bare-rock outcrops with high-angle cross-beds. It is 1,300 to 1,500 feet thick in the Grand Staircase section and is 1,100 to 1,300 feet thick in the Escalante Canyons section. It generally thickens from east to west.

The Navajo is a light-colored, fine- to medium-grained, massive sandstone. It displays an elaborate array of high-angle cross-beds (figure 22) and forms cliffs, domes, monuments, and other bizarre erosional forms (figure 21). Locally, thin lenses of limestone, dolomite, or dark-red sandy mudstone are also present. Where it does not form cliffs or monuments, its hollows are commonly filled with sand. The light coloration of the Navajo has been described with almost every color; white, tan, buff, salmon, pink, vermilion, brown, red, yellow, cream, orange, and gray. Hematitic cement produces the red colors, limonite the yellows, and ferrous iron minerals the browns and local greens. Most of the grains are subrounded to well rounded, well sorted, frosted, and quartzose. Much of the Navajo is lightly cemented and friable. The upper part, however, is better cemented, either with silica or carbonate cement and is more likely to form cliffs. Cross-beds are in sets as much as 35 feet thick. Locally, and especially near the base (especially in the Lamb Point Tongue), the Navajo includes massive horizontal or planar beds.

The Navajo is dominantly an eolian deposit laid down in dunes above a shallow water table. The thin limestones, dolomites, and dark-red sandy mudstones were deposited in oases, playas, or ponds. As the sands subsided, the water table surface rose and wind commonly blew away sand above it to form a set boundary before the next dune was deposited over it. One might imagine ridges of wandering dunes over a damp surface during Navajo time. Locally, both in the Grand Staircase and Escalante Canyons sections, a thick iron scum or froth accumulated on the tops of the water tables. During diagenesis these hardened to form ironstone sheets within the sandstone. Locally these occur as disk, ball, and dumb-bell forms. At Spencer Flat (No. 16 on figure 2), they occur as spheres known as “Moqui marbles.” It is assumed that air bubbles were forced upward to the water table where an iron scum had accumulated and formed a froth of bubbles. These spheres contain only loose or friable sand in the centers which falls out when the ironstone concretion is broken (Doelling, 1968). Between Hackberry Canyon and Cottonwood Wash (just west of the Cockscomb) iron sheets have been deformed to produce bizarre shapes. Ironstone is also quite common northeast of The Swags at the end of the Kitchen Corral Wash road. Only vertebrate tracks have been found in the Navajo Sandstone: a few on dune faces, most on the thin limestones.

The top of the Navajo Sandstone is a major regional unconformity. In the Grand Staircase section it is overlain by the Co-op Creek Limestone Member of the Carmel Formation. In the Escalante Canyons section it is overlain by the Page Sandstone. In the Escalante Canyons section the lowermost Page may look much like the Navajo Sandstone and is difficult to separate from it. The contact may appear to be a simple set boundary near the top of the Navajo. The base of the Page locally contains angular fragments of chert. Also the Page is generally slightly darker than the Navajo Sandstone. This unconformity (J-2 unconformity of Pipiringos and O'Sullivan, 1978) at the top of the Navajo Sandstone appears to be a flat surface, but undulates with wide amplitude and accounts for differences in the thickness of the Navajo of up to 200 feet or more.

Page Sandstone and Carmel Formation (Jc, Jcl, Jcu)

The Page Sandstone and Carmel Formation intertongue and undergo facies changes from west to east across the monument (figure 23). The Carmel Formation to the west contains marine rocks that intertongue with terrestrial rocks eastward. The Page Sandstone represents beach, back-beach, and dune deposits on the landward side of Carmel deposition. The Carmel sea transgressed southward from Canada in a north-south-trending embayment that terminated in northern Arizona. Rocks exposed in the monument were deposited along the east margin of that embayment. Generally, the rocks thin from west to east.

In the Grand Staircase section the following members and tongues are exposed: (ascending) Co-op Creek Limestone Member, Crystal Creek Member, Thousand Pockets Tongue of the Page Sandstone, Paria River Member, and Winsor Member. The lower two members of the Carmel Formation become very thin east of the East Kaibab monocline (The Cockscomb) where they are combined into one unit known as the Judd Hollow Tongue of the Carmel Formation. Limestone persists in the Judd Hollow Tongue for a few miles beneath the Kaiparowits basin and represents the easternmost extension of the Co-op Creek transgression of the Carmel sea. Thereafter the sea regressed leaving the Crystal Creek Member followed by the Thousand Pockets Tongue of the Page Sandstone in its wake. The Co-op Creek Limestone, Crystal Creek, and Thousand Pockets Tongue units are grouped into the Jcl unit shown on the geologic map (figure 15). On the other two geologic maps (figures 16, 17) the Carmel and Page are mapped as an undivided unit (Jc). A second major transgression followed to deposit the Paria River Member. The sea spread eastward across and beyond the monument area and its deposits are characterized by thin platy limestone and gypsum beds. Though widespread, the sea was very shallow, and was commonly cut off from open-sea circulation. A very gradual retreat of the sea is represented in the Winsor Member, which was also deposited across the entire monument area. Thompson and Stokes (1970) differentiated the Wiggler Wash Member as the youngest member of the Carmel Formation, but we believe this member is a gypsum-bearing facies of the Winsor. The type Wiggler Wash Member has gypsum beds near the top of the Carmel Formation, but gypsum beds can be found region-

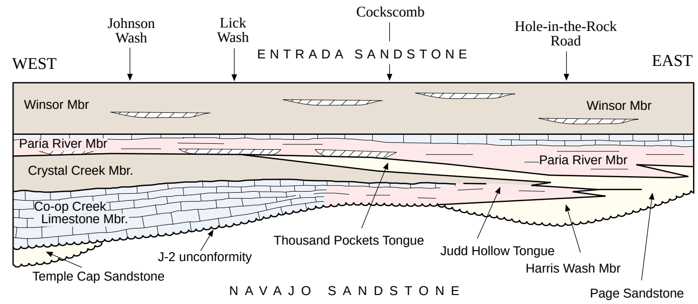

Figure 23. Diagram showing Carmel-Page relationships from west to east across the Grand Staircase-Escalante National Monument.

ally at any level within the Winsor Member.

The Page Sandstone was deposited concurrently with the Carmel Formation east of the Co-op Creek transgression of the Carmel sea and was deposited over much of the monument area prior to the Paria River transgression. East of the monument the Paria River Member grades into Page Sandstone lithologies as does the lower part of the Winsor. The Carmel Formation and Page Sandstone are both exposed along the boundary of the Kaiparowits Basin and Escalante Canyons sections of the monument and subparallel the Hole-in-the Rock road in the Escalante Canyons section. They are eroded from the Circle Cliffs uplift and crop out again in the Waterpocket Fold (Capitol Reef National Park), east of the monument. There the following members are exposed: (ascending) Harris Wash Member of the Page Sandstone, Judd Hollow Tongue of the Carmel Formation, Thousand Pockets Tongue of the Page Sandstone, and Paria River and Winsor Members of the Carmel Formation.

Harris Wash Member (Page Sandstone): This member rests upon the Navajo Sandstone in outcrops that subparallel the Hole-in-the-Rock Road on the east side of the Straight Cliffs (Fiftymile Mountain). It is not present in the Grand Staircase section of the monument. It has the appearance of the Navajo Sandstone, commonly displays high-angle eolian-type cross-stratification in sets 7 to 22 feet thick, and is a massive cliff former.

The contact at the base of the Page Sandstone, the J-2 unconformity of Pipiringos and O'Sullivan (1978), is not a set boundary, but an erosional surface, above which angular bits and pieces of chert are commonly found. The relief on this unconformity may be as much as 70 feet, but is hardly noticeable because the distance between troughs and highs is considerable. The Harris Wash Member is commonly slightly darker in color than the Navajo below and locally contains red-brown, lenticular, very fine grained silty sandstone reminiscent of regressive Carmel Formation deposits. The member is 50 to 120 feet thick along Hole-in-the-Rock Road and is not present on the west side of the Kaiparowits Basin section. The Harris Wash Tongue is mostly light-brown to light-gray, very fine to fine-grained sandstone. It is porous and slightly calcareous.

Co-op Creek Limestone Member (Carmel Formation): The Co-op Creek Limestone Member crops out in the Grand Staircase section of the monument on the Skutumpah Terrace. There it is 35 to 170 feet thick, becoming thicker westward. In the Cockscomb area it may locally be thinner than 35 feet and attenuated. The Co-op Creek Limestone Member forms steep slopes with ledges near the top and bottom. The steep slopes are generally littered with plates, chips, and pencils of limestone.

The Co-op Creek Limestone Member consists of light-gray limestone and olive-gray calcareous shale. Although beds are thin to thick bedded, most are thin bedded. Medium and thick beds are encountered near the base and near the top of the member. Red siltstones and sandstones and even conglomerate may crop out at the base and correspond to the Gypsum Springs Member of the Twin Creek Limestone as found in northern Utah. A few thin gypsum beds have been noted in the Bull Valley Gorge area (Grand Staircase section) above the thin red siltstones near the base of the member. The thicker bedded, ledgier parts of the member are locally fossiliferous and contain pelecypods, gastropods, and the star-shaped crinoid stem, *Pentacrinus.*

Crystal Creek Member (Carmel Formation): This brown-banded silty sandstone forms earthy slopes. The banding is best displayed in steep slopes and fresh road cuts. Like the Co-op Creek Limestone Member, it becomes very thin eastward and becomes part of the Judd Hollow Tongue along the eastern edge of the Grand Staircase Section of the monument. The unit ranges from about 10 to 70 feet and reaches a maximum of about 180 feet west of Kanab. Its outcrop band lies above the Co-op Creek Limestone Member on the Skutumpah Terrace, continuing across the Paria amphitheater to the Cockscomb. It is generally only 10 to 15 feet thick in the Cockscomb area.

The Crystal Creek Member is mostly a silty, very fine grained, friable, poorly cemented sandstone and sandy siltstone. Gypsum is the usual cementing material. Locally, a thin gypsum bed may crop out or a thin bed of coarse-grained sandstone may be present. It is overlain by the Thousand Pockets Tongue of the Page Sandstone east of Lick Wash on the Skutumpah Terrace. It is overlain by gypsum of the Paria River Member west of Lick Wash.

Judd Hollow Tongue (Carmel Formation): Along the Cockscomb the Judd Hollow Tongue is 30 to 60 feet thick, and forms a prominent reddish recess of sandstone, siltstone, and silty limestone, between the Navajo Sandstone and the Thousand Pockets Tongue of the Page Sandstone. Some of the thinner sections may represent thinning due to attenuation along the steeply dipping East Kaibab monocline. A persistent 10- to 15-foot-thick reddish recess above the Judd Hollow may represent another thin Carmel tongue in the lower part of the Thousand Pockets Tongue. Along Hole-in-the-Rock Road, it consists of interbedded ledgy sandstones and reddish silty sandstone 15 to 40 feet thick. This appears to be a zone of intertonguing between the red calcareous sandstones of the Judd Hollow and the yellow-gray sandstones of the Page.

Thousand Pockets Tongue (Page Sandstone): This tongue of sandstone first appears at Lick Wash in the Grand Staircase section, thickens eastward, and in outcrop is thickest along the Cockscomb. It is present, but thin, along the Hole-in-the-Rock Road, at the boundary between the Kaiparowits and Escalante Canyons sections of the monument. It is up to 200 feet thick, including thin Carmel tongues that may appear between its upper and lower contacts.

The Thousand Pockets Tongue is yellow-gray to gray-white, fine- to medium-grained quartzose sandstone that exhibits eolian-type, high-angle cross-bedding. It is mostly massive and cliff or ledge forming. Grains are generally subrounded and well sorted. It is friable and yellow gray in exposures from Lick Wash into the Tropic Amphitheater; it is better cemented and gray-white in eastern sections. South of the Kodachrome State Park area, it is locally (near Rock Springs Canyon) mineralized and coated or disseminated with copper and lead minerals.

Paria River Member: The Paria River Member is a transgressive deposit of the Carmel sea. Although it has far wider distribution than the lower Co-op Creek transgression, and crops out both in the Kaiparowits Basin and Grand Staircase sections, its limestone beds are considerably thinner than that of the Co-op Creek Limestone Member. It reaches a maximum thickness of about 280 feet in West Cove in the southern part of the Cockscomb area. There the upper limestone is completely replaced by a massive yellow-gray resistant beach-sand deposit. The member may be as little as 100 feet thick near the west boundary of the monument; from there it thickens easterly to the area of the Cockscomb, and then thins again, and is only 50 to 100 feet thick along the Hole-in-the-Rock Road.

The member consists of red or red-brown interbedded silty sandstone and sandy siltstone near the base and white or lavender chippy to platy, very thin bedded limestone at the top. The limestone locally contains poorly preserved pelecypods and gastropods and is locally sandy. In the west a very thick, white, massive alabaster gypsum bed lies at the base. This basal gypsum bed is not present in the Cockscomb area and eastward. On the Skutumpah Terrace patches of the 10- to 20-foot-thick basal gypsum bed are present. At Averett Canyon on the west side of the Tropic amphitheater the patchy nature of the gypsum is well illustrated. A thick bed is present on one side of the canyon and is completely missing on the other.

Winsor Member: This member is a steep slope-forming, earthy-weathering unit reminiscent of the Crystal Creek Member beneath it. It is mostly light to medium brown, but yellows are common, especially in the west part of the monument. West of Lick Wash, in the Grand Staircase section of the monument, it is unconformably overlain by the coal-bearing Dakota Formation. To the east of Lick Wash it is conformably overlain by various facies of the Entrada Sandstone. It varies in thickness from about 110 to 320 feet. It is probably 250 feet thick along the west monument boundary. It thickens gradually to the Cockscomb where it reaches maximum thickness, and then thins eastward. Near Fiftymile Point at the south end of the Straight Cliffs, it is only 120 feet thick.

The Winsor Member is mostly light- to medium-brown, very fine to medium-grained sandstone that weathers to an earthy slope. To the east it contains thin to medium beds of varicolored gypsum and gypsiferous sandstones that are gray green. These gypsum beds weather blocky and have locally been extracted to make small sculptings for indoor use. The coloration in the gypsum exhibits pinks, browns, greens, and less commonly blues in thin laminae. Unfortunately, in the open, the gypsum weathers and breaks apart along these thin laminae. Bedding is indistinct in western exposures; to the east a few resistant ledges develop in the member, and together with the gypsum beds, give a good sense of the stratification. The gypsum beds can and do appear at any level within the member.

The Carmel-Entrada contact is thought to be conformable. In most places it is sharp and placed beneath the smooth-weathering (slickrim), bare-rock Entrada outcrop. Locally the contact is uneven because of post-depositional deformation. Especially along the Hole-in-the Rock road, large bodies of the Entrada have "sunk" deeply into the Winsor Member. Winsor strata around these large bodies of Entrada Sandstone are deformed.

Entrada Sandstone (Je)

The Entrada outcrops begin at Lick Wash in the west part of the Grand Staircase section of the monument and extend eastward. West of Lick Wash the Entrada was removed by erosion prior to Cretaceous deposition. East of Lick Wash, on the Skutumpah Terrace extending around the Tropic amphitheater and down the Cockscomb on the west margin of the Kaiparowits Plateau, the Entrada is overlain by the Dakota Sandstone. Between Cannonville and Butler Valley in the Tropic amphitheater, the Entrada is capped by the Henrieville Sandstone, which some investigators believe is merely a hardening at the top of the Entrada Sandstone (Bowers, 1975, 1983). On the southeast and east sides of the Kaiparowits Plateau, the Entrada is overlain by the Romana Mesa Sandstone and Morrison Formation, respectively. The Morrison and Romana Mesa Sandstone are also cut out by the same unconformity that cuts out the Entrada west of Lick Wash. This is evident a few miles east of Big Water along the south margin of the Kaiparowits Plateau. The Entrada was deposited in environments similar to those that deposited the Carmel Formation in its terrestrial environments: tidal flat, sabhka, beach, and back-beach deposits.

The Entrada Sandstone is divisible into three parts: (ascending) the Gunsight Butte, Cannonville, and Escalante Members. The Escalante Member is only present in the north half of the monument, along the north edge of Kane County and in Garfield County.

Figure 24. Two Devils Garden goblins with the Straight Cliffs in the background. The goblins form in the Entrada Sandstone at the contact between the Gunsight Butte and Cannonville Members.

Gunsight Butte Member: The lower member of the Entrada Sandstone is a typical "slickrim" sandstone. It weathers into cliffs and rounded bare-rock smooth-weathering outcrops. The color along the Hole-in-the-Rock Road and in the Tropic amphitheater is orange-brown to red orange. Along the south half of the Cockscomb it is yellow gray and in West Cove has a red band in it. It locally forms very picturesque and conspicuous erosional forms. These include Dance-Hall Rock, Sooner Rocks, Cave Point, and Lone Rock. It is up to 450 feet thick. Along the Hole-in-the-Rock Road it is 200 to 450 feet thick with the thickest sections to the south. Along the Cockscomb the member is 150 to 280 feet thick, but is locally attenuated and faulted out. In the Tropic amphitheater the member is 200 to 300 feet thick.

The Gunsight Butte Member is very fine to fine-grained and silty sandstone that contains sparse medium to coarse, frosted, subrounded to rounded grains of pink and gray quartz. Like the Navajo Sandstone, it exhibits large-scale eolian cross-bedding, but weathers to smooth surfaces. Thin lenses of somewhat darker mudstone interrupt the otherwise massive unit. Much of it is covered by sandy surficial deposits that are largely derived from it (see figures 15, 16, and 17).

The Gunsight Butte Member is a wind-blown deposit probably laid down in dunes. The upper contact with the Cannonville is represented by a change from resistant bare-rock outcrops to bedded, earthy-weathering, slope-forming sandstone. In areas where the "slickrim" is orange-brown, a yellow-gray sandstone overlies it, above which the Entrada becomes earthy weathering. The top of the Gunsight Butte Member locally forms goblins and other interesting erosional forms as is displayed in the Devils Garden along the Hole-in-the Rock road about 17 miles southeast of Escalante (figure 24).

Cannonville Member: The middle or Cannonville Member of the Entrada Sandstone generally forms a steep slope and is banded. In the Tropic amphitheater it displays a yellow-white color with faint red bands. This persists along the Cockscomb. In the area between Escalante and Cat Pasture along the Hole-in-the-Rock Road, the member is prominently banded in shades of brown or red brown. Here large areas of Cannonville outcrop are covered with unconsolidated sandy Quaternary deposits. Between Cat Pasture and Fiftymile Point, the Cannonville Member changes into a medium red-brown, medium to thick-bedded ledgy unit that commonly stands in a cliff above the rounded "slickrim" Gunsight Butte Member. The Cannonville Member is generally 200 to 400 feet thick, but may be only 60 to 80 feet thick along the south edge of the Kaiparowits Plateau. West of Cannonville it thins and is eventually cut out by the sub-Cretaceous unconformity.

The Cannonville Member of the Entrada Sandstone consists of interbedded very fine grained sandstone, silty sandstone, and siltstone. Medium-grained sandstones, some gritty and with a few pebbles, are found in the upper two-thirds of the Cannonville Member. Also deep-red-brown, purple-weathering siltstones are found at widely spaced intervals. At the base is a persistent yellow-gray cliff-forming sandstone.

In the Little Valley area, in the Escalante Canyons section, between Harris Wash and Twentyfive Mile Wash, the banded earthy-weathering nature of the Cannonville Member is well displayed. Here many pipe-like features are present and are quite resistant. One monolithic pipe forms a monument about 40 feet high.

Escalante Member: The upper member forms rounded bare-rock sandstone outcrops and displays high-angle eolian cross-stratification. The upper part is resistant and cliff forming. The lower part is earthy as is the Cannonville Member. It is, however, not banded and mostly yellow-gray to gray-white in color. Tafoni are common in the Escalante Member and is the scientific term for holes lined up along cross-bed striae. Davidson (1967) called these "bird-hole" solution cavities. We prefer "stonepecker" holes (like woodpecker holes) and do not believe they are solution cavities. Our theory is that air "bubbles" lodged in the rock when it was being cemented by ground water prevented the sand from being cemented inside the "bubbles." When erosion cuts into these ancient "bubbles," the sand merely falls out. The member is up to 300 feet thick on the east side of the Straight Cliffs, thickening to the north. It is not identifiable south of Cat Pasture. In the northern part of the Cockscomb and in the east half of the Tropic amphitheater it is up to 40 feet thick (not including the Henrieville Sandstone), and is mostly a slope-forming, earthy-weathering sandstone.

The Escalante Member is mostly fine grained and massive sandstone. The lower half is very friable and forms earthy slopes and ridges. The upper half exhibits rounded to cliffy bare-rock outcrops. The member is calcareous. Dinosaur tracks are locally present in the Escalante Member (figure 8). One site contains over 250. Most are the tracks of bipedal, tridactyl theropod dinosaurs; two are of quadrupedal dinosaurs and include indications of tail drags.

The upper contact of the Escalante Member is abrupt east of Fiftymile Mountain and is taken where the resistant massive yellow-gray sandstone changes to the red-brown siltstone slope at the base of the Tidwell Member of the Morrison Formation. This contact is presumed to be unconformable, but little relief is evident. In the Cockscomb and Tropic amphitheater it is mostly overlain by the Henrieville Sandstone.

Romana Mesa Sandstone

The Romana Mesa Sandstone crops out unconformably below the Morrison Formation and above the Entrada Sandstone along the south and east margins of the Kaiparowits Plateau. It is up to 135 feet thick in the monument. It starts as a feather edge at Cat Pasture and thickens to the south. In the cliffs along the southeast margin of the Kaiparowits Plateau, it looks much like the Entrada Sandstone, except that its color is much lighter.

The rock is mainly gray-yellow-green to yellow-gray, very fine to fine-grained sandstone that normally stands as a cliff. Thin to medium beds of red friable sandstone are commonly found at the base. Locally the sandstones are bioturbated. The Romana Mesa Sandstone correlates with the Cow Springs Sandstone in Arizona and may intertongue with the Summerville Formation as exposed to the east. It is combined with the Entrada Sandstone (Je) on the geologic map of the Kaiparowits basin section (figure 16).

Henrieville Sandstone

The Henrieville Sandstone crops out in the northeast corner of the Tropic amphitheater between Henrieville and the Cockscomb and is best recognized at Grosvenor Arch of which it forms the pedestals (No. 11 on figure 2 and figure 10). It is generally cliff forming and yellow gray in overall color. It ranges from a feather edge to 234 feet in thickness.

It consists of very fine grained, well-sorted sandstone that is slightly calcareous, porous, and thick bedded to massive. Locally coarse grains of sand are present. It is a cliff former, but locally forms steep slopes. The lower part is planar bedded and the upper part is cross-bedded. Cross-bed sets become thicker upward in the unit. In addition to sandstone, the lower part contains a few siltstone, claystone, and shale beds.

The lower contact with the Entrada Sandstone is wavy and sharp. The upper contact at Grosvenor Arch is a regional unconformity and is also wavy and sharp. Some investigators believe the Henrieville Sandstone is a hardening at the top of the Entrada Sandstone and should be included with that unit (Bowers, 1975, 1983). The Henrieville started out as a fluvially deposited unit and then reverted to an eolian-deposited unit. It is combined with the Entrada Sandstone (Je) on the geologic maps, figures 15 and 16.

Morrison Formation (Jm)

The Upper Jurassic Morrison Formation consists of three members: (ascending) the Tidwell Member, Salt Wash Member, and Brushy Basin Member. In the monument the Morrison is exposed along the east and south margins of the Kaiparowits Plateau. To the west it is cut out by the sub-Cretaceous regional unconformity. Hence, in the Grand Staircase section, no Morrison rocks are exposed and Cretaceous rocks rest directly on the Middle Jurassic Carmel or Entrada Formations.

Tidwell Member: These rocks form a red slope or recess between resistant Salt Wash Member ledges above and resistant cliff-forming sandstones below from Cat Pasture northward to Boulder Mountain (Escalante Canyons section). It is up to 150 feet thick. The outcrop band is quite conspicuous in the vicinity of the town of Escalante.

The member consists of light-colored, fine-grained, ledgy sandstone beds, and red, purple, brown, and green mudstones and siltstones. A few gritstones are also present. The member is strongly calcareous.

Thompson and Stokes (1970) considered the member to be a facies of the Summerville Formation and called it the White Point Member. Doelling also continued to assign these beds to the Summerville Formation (Doelling and Davis, 1989), but has since "changed his mind" after extensive new field mapping. The presence of Morrison-like gritstones in the member and its calcareous nature helped convince him that these beds belong with the Morrison Formation. Zeller and Stephens (1973) assigned these rocks to a lower member of the Morrison Formation. Peterson (personal communication, 1987) believed the beds should be assigned to the Tidwell Member. The beds were deposited in a fluvial environment, on a flood plain dotted with numerous lakes and ponds.

Salt Wash Member: This ledge- and cliff-former ranges up to 700 feet thick in the monument. The member is a heterogeneous complex of sandstone, conglomerate, and mudstone that becomes thicker and has a greater percentage of coarse clastics to the south. It is not present in the Grand Staircase section, being cut out by the sub-Cretaceous regional unconformity, as previously noted.

It is generally a gray, yellow-gray, yellow-brown, lenticular, quartzose sandstone interbedded with conglomeratic sandstone, conglomerate, and red and green silty mudstone. Average grain size increases to the south. The composition is 90 percent quartz; the remainder is chert and milky feldspar. Sandstone and conglomerate exhibit trough cross-bedding and have been deposited as lenses. The mudstones form recesses or slopes and overlying lenses of sandstone commonly break up into large pieces producing a "messy" outcrop.

The Salt Wash Member was deposited in an anastomosing system of braided rivers and streams. Stream-channel deposits are more abundant than the overbank mudstones. The streams flowed from south to north as attested by the greater percentage of lenticular sandstones and conglomerates and the coarser average grain size to the south. Locally, petrified wood is common in the member, some being of polishable quality. Channels in the vicinity of Cat Pasture are mineralized with uranium minerals, but in quantities that rate them as "low grade." Regionally, the Salt Wash Member is famous for its dinosaur fossils, but only bone fragments have been found in the monument. Foster and others (1999) report finding a crocodile tooth, two possible sauropod track sites, and evidence for a possible fossil termite nest.

Brushy Basin Member: This bentonitic slope former is present only along the northeast edge of the Kaiparowits Plateau. It is characterized by variegated colors and the dominance of mudstone over channel sandstones and conglomerates. The Brushy Basin is somewhat inconsistent in thickness because its upper contact with the Dakota Sandstone is unconformable, but it probably also thickens northward at the expense of the Salt Wash Member. Outcrops range in thickness from 0 to about 100 feet.

The Brushy Basin Member consists mostly of red, purple, gray, yellow, green, and white mudstone that is silty, sandy, or clayey with subordinate medium- to coarse-grained and sometimes pebbly sandstone and nodular gray-brown limestone. The mudstones commonly contain much swelling clay that weathers to produce a "popcorn-" like surface on the rounded hills and badlands it forms.

The Brushy Basin Member was deposited fluvially, mostly as overbank deposits and as accompanying lacustrine deposits. It locally contains petrified wood (especially in sandstones) and contains rare dinosaur bone.

Cretaceous Rocks

Cretaceous rocks in the Grand Staircase-Escalante National Monument are mostly limited to the Kaiparowits Basin section. Cretaceous outcrops are present north of the Grand Staircase section and are in Dixie National Forest, in Bryce Canyon National Park, and in Capitol Reef National Park east of the Escalante Canyons section of the monument. In the Kaiparowits section Cretaceous rocks are 5,000 to 6,000 feet thick and were deposited in marine, mixed continental and marine, and continental environments. During this time mountains developed in western Utah and the Western Interior Seaway transgressed and regressed into and out of the monument area.

Cedar Mountain Formation

This formation is the only Early Cretaceous deposit found in the monument. It is discontinuous and found in scattered outcrops, "lodged" between two unconformities along the south margin of the Kaiparowits Plateau, along the Cockscomb, and around the Tropic amphitheater. The outcrops generally consists of resistant conglomeratic

Figure 25. John Henry Member beds in the Kaiparowits Basin section of the monument. A coal bed is commonly found above each thick sandstone bed.

sandstone. Outcrops are up to 50 feet thick, but generally less than 25 feet thick. Because the Cedar Mountain Formation is discontinuous and thin it is included with the Dakota Formation (Kd) on the geologic maps, figures 15 and 16.

The unit crops out as interbedded conglomerate, pebbly sandstone, and sandstone with minor amounts of siltstone and mudstone. Not all of these lithologies are everywhere present. It generally forms ledges or combines with other cliff-forming units above and below. The clasts consist of chert, quartzite, silicified limestone, feldspathic sandstone, and petrified wood and are subrounded to subangular. The rock is generally slightly calcareous. The sandstones are mostly poorly sorted and fine to coarse grained. Sandstone and conglomeratic sandstone commonly exhibit trough cross-bedding and the unit is thought to be of fluvial origin.

The best place to see the Cedar Mountain Formation is at Grosvenor Arch, where it is exposed near the top of this landmark between the two unconformities (figure 10). Pollen found in mudstone partings generally point to an Aptian-Albian (Early Cretaceous) age for these rocks (Doelling and Davis, 1989). Cedar Mountain Formation outcrops were considered to be a part of the Dakota Formation by earlier workers.

Dakota Formation (Kd)

The Dakota Formation crops out around the edges of the Kaiparowits Plateau, and continues westerly around the Tropic amphitheater and along the south margin of the Paunsaugunt Plateau north of the Grand Staircase section of the monument. It generally appears as a medium-gray slope overlain by a resistant cap of sandstone, although locally it has a basal brown sandstone ledge. Thin coal beds are present around the Kaiparowits Plateau, which thicken along the south margin of the Paunsaugunt Plateau. The lower medium-gray slope is 3 to 240 feet thick, thickening to the west. The upper resistant cap is up to 80 feet thick.

The lower member, previously called the middle member by workers who included the Cedar Mountain Formation as their lower member (Peterson, 1969a), consists of interbedded mudstone and shale, sandstone, carbonaceous mudstone, claystone, coal, and conglomerate. The mudstone and shale are gray to nearly black, brown, and olive gray, and shaly to laminated. Mudstone is composed of silty and sandy clay; the clay includes kaolinite, illite, and montmorillonite. Sandstone is orange, yellow gray, and gray. It is mostly fine to fine grained with a few medium- and coarse-grained beds, with subangular, moderately sorted grains. The sandstone beds are thin to thick bedded, calcareous, lenticular and cross-stratified, and resistant, forming ledges between the mudstone slopes. Coal beds surrounding the Kaiparowits Plateau are generally thin, mostly less than 2 feet thick, but locally thicken to 6 or more feet. Nevertheless, some of these coal beds were exploited by early settlers.

The upper member is mostly discontinuous fossiliferous marine sandstone and mudstone with minor shale, carbonaceous mudstone, and coal. The sandstone is yellow, orange gray, or brown in color, ledgy, and forms a hard caprock on top of the formation. It forms the base of the Gray Cliffs north of the Grand Staircase section along the south margin of the Paunsaugunt Plateau. The upper member commonly consists of one or two sandstone ledges, each 5 to 20 feet thick, separated by mudstone and an upper coal zone. Coal beds in the upper member around the Kaiparowits Plateau are also thin, mostly less than 2 feet thick, but locally thicken to 6 feet or more. However, south of the Paunsaugunt Plateau coal beds as much as 16 feet thick are present.

The Dakota Formation is called the Dakota Sandstone in most parts of Utah. However, Lawrence (1965) redefined the Dakota in southern Utah as the coal-bearing beds between the sub-Cretaceous unconformity and the marine Tropic Shale above. Excepting the basal part we now believe is Cedar Mountain Formation, it is the transgressive deposit of the Western Interior Seaway. The lower part of our Dakota Formation shows fluvial influence, but the upper parts become strongly marine in character. The upper ledges of the Dakota are very fossiliferous and commonly include *Ostrea* and *Exogyra* coquinas. The upper Dakota grades into the Tropic Shale.

Tropic Shale (Kt)

The Tropic Shale represents the westernmost deposit of the Western Interior Seaway in Utah. It extended as far west as Cedar City, where "pure" marine shales thin and intertongue with nearshore sandstone and beach sandstone deposits. In the monument area it is exposed around the edge of the Kaiparowits Plateau and ranges from 500 to 750 feet thick. It forms a gray slope commonly covered with mass movement (landslide and slump) deposits.

The Tropic Shale is a thinly laminated to thin-bedded mudstone and shale unit with lesser amounts of sandstone, bentonitic claystone, siltstone, and limestone. The mudstone and claystone are often nodular and chunky when fresh, but shaly and earthy when weathered. Toward the top the Tropic commonly becomes quite sandy and thin interbeds of yellow-gray, very fine grained calcareous sandstone make their appearance, changing the overall color from drab gray to yellow gray.

The muds were deposited on the floor of a shallow sea that had transgressed westward from the midcontinent area. The Tropic is locally fossiliferous and contains key cephalopod faunas that date the unit as Cenomanian-Turonian (Late Cretaceous).

Straight Cliffs Formation (Ks)

The Straight Cliffs Formation was initially named the Straight Cliffs Sandstone by Gregory and Moore (1931) for exposures along the Straight Cliffs (Fiftymile Mountain) on the east side of the Kaiparowits Plateau. Peterson and Waldrop (1965) suggested calling the unit a formation, since the unit contains many rock types other than sandstone. Peterson (1969b) divided the formation into members which are: (ascending) the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members, named after various geographic features in the Kaiparowits Plateau. The entire formation is 900 to 1,800 feet thick in the Kaiparowits Basin section of the monument; the thicker sections are found in the Kaiparowits syncline.

Tibbet Canyon Member: The lowermost member of the Straight Cliffs Formation is a cliff-forming sandstone that crops out above the Tropic Shale all around the margin of the Kaiparowits Plateau. These outcrops locally extend deeply into canyons that cut into the plateau. The member probably ranges in thickness between 70 and 185 feet.

It is mostly yellow-gray to moderate-brown sandstone that coarsens upward. Sorting is poor to moderate in the lower half of the member and the upper half is moderately to well sorted. Gray mudstone and siltstone partings are common in the lower part. The sandstone is calcareous, cross-bedded and thin to thick bedded. Thick beds are more common in the upper part. The lower contact with the Tropic Shale is gradational and is placed at the top of the first medium or thick sandstone bed of the Tibbet Canyon Member.

The member was deposited in beach and shallow-water marine environments. It is locally fossiliferous, containing pelecypods, rare cephalopods, shark teeth, and trace fossils. The unit is locally bioturbated.

Smoky Hollow Member: This is a ledge- and cliff-forming unit of sandstone, gray shale, mudstone and very thin coal. In the northern part of the Kaiparowits Plateau it is difficult to separate from the Tibbet Canyon Member. Several geologic maps show it combined with the Tibbet Canyon and called the lower member of the Straight Cliffs Formation. The Smoky Hollow Member ranges from 25 to 230 feet in thickness.

Sandstone beds of this member are very fine to medium grained, poorly to moderately sorted, cross-bedded and resistant. Mudstone beds are bentonitic, olive gray, and slope forming. Coal, where present, is generally found in the lower part of the member, associated with dark-gray carbonaceous mudstone and thin-bedded sandstone. Near the top is a peculiar white or light-gray, cross-bedded sandstone bed that is about 25 feet thick, fine to coarse grained, poorly sorted, and commonly includes pebbly sandstone.

The Tibbet Canyon and Smoky Hollow Members represent a regressive phase of the Western Interior Seaway and probably correlate with the Ferron Sandstone Member of the Mancos Shale in central Utah. The Smoky Hollow beds were deposited in a variety of nearshore continental environments in lagoons and on flood plains.

John Henry Member: The John Henry Member is a slope- and ledge-forming unit of sandstone, mudstone, carbonaceous mudstone, and coal. It crops out over a large part of the Kaiparowits Basin section of the monument. It ranges in thickness from 590 to 1,100 feet. It is thinner over anticlines and thickens easterly to some extent. It unconformably overlies the Smoky Hollow Member and interfingers with the overlying Drip Tank Member.

The member is dominated by thick-bedded to massive, cliff-forming, yellow-gray to yellow-brown sandstone with interbeds of gray mudstone, thin, friable to blocky sandstone beds, and thin limestone beds (figure 25). The resistant sandstone is mostly fine to medium grained, poorly to moderately sorted, and calcareous. It is commonly cross-bedded. Some of the sandstones, especially to the east, contain significant quantities of titanium and zirconium minerals. Identified minerals in some of the beach deposits include zircon, magnetite, ilmenite, rutile, quartz, calcite, monazite, garnet, sphene, hematite, and anatase (Peterson, 1969b). Locally these minerals may constitute 25 percent of the sand grains in the rock.

Two major coal zones are found in the member and are known as the Christensen-Henderson zone and the Alvey zone. All coal zones are dominated by mudstone, carbonaceous mudstone and shale, claystone, and contain relatively thick coal beds. Kaiparowits Plateau coal beds are commonly 20 feet or more in thickness. The Alvey coal zone is found high in the member and is similar lithologically to the Christensen-Henderson zone. The Alvey coal zone is better developed in the east part of the Kaiparowits Plateau.

The John Henry Member was deposited in lagoons, deltas, and in fluvial environments. Beach sands are also present in the eastern part of the Kaiparowits Plateau. The member exhibits many interesting features attendant with the coal. Natural coal fires are common on the plateau and tend to redden and bake the surrounding non-combustible rocks. Shales and clays are baked into brick in a variety of colors that “clink” when walked upon or are struck with a rock hammer. Hence this material is called “clinker” in the coal-mining industry. Some of the rock has melted and some has metamorphosed under the intense heat of the fires. Fossil oysters and fragments of woody plants have locally been burned black and red in the "clinker."

Drip Tank Member: The highest member of the Straight Cliffs Formation is a prominent cliff-former. Upper surfaces or benches of the Kaiparowits Plateau are commonly developed on the Drip Tank Member. It is 140 to 550 feet thick and probably thickens to the west.

It is mostly yellow-brown to yellow-gray, fine- to medium-grained, poorly sorted, cross-bedded, lenticular sandstone in medium to thick beds. It contains mudstone partings and local pebble conglomerate lenses. Conglomerate becomes more common to the north and west.

The Drip Tank Member is a fluvial deposit. Abundant low-and high-angle, medium-scale trough cross-beds, and cut-and-fill structures all attest to this. Rare petrified wood and vertebrate bone fragments are found in the Drip Tank Member in the monument area.

Wahweap Formation (Kw)

The Wahweap Formation is divisible into a lower, mostly slope-forming unit and an upper, mostly cliff-forming unit. The lower member has generally receded from the cliffy edge of the Drip Tank Member of the Straight Cliffs Formation and intertongues with it and the upper member. The Wahweap Formation is 1,000 to 1,500 feet thick in the Kaiparowits Plateau. The lower slope-forming unit is 800 to 1,100 feet thick and the upper cliff-forming unit is 200 to 400 feet thick.

This formation is composed of interbedded mudstone, claystone, siltstone, resistant and non-resistant sandstone, and conglomerate. In the lower unit slope-forming rocks dominate and in the upper unit resistant rocks dominate. Sandstones are fine to coarse grained, with fairly well sorted, subangular grains. The resistant cliff-forming sandstones are yellow gray and the friable sandstones are yellow, orange, or brown. Both are calcareous. Bedding is medium to massive. Claystone, mudstone, and siltstone are various shades of gray.

The Wahweap Formation is locally fossiliferous and contains petrified wood, vertebrate teeth and bones, and gastropods. These are more common in the upper resistant sandstones. It was deposited under continental conditions in flood plain, fluvial, and lacustrine environments.

Kaiparowits Formation (Kk)

The Kaiparowits Formation is a drab-gray, olive-gray, or green-gray, slope-forming and badlands-forming unit composed of subarkosic sandstone. The sandstone is muddy and gives the appearance of being finer grained. It is best displayed at The Blues (No. 23 on figure 2) where the unit is 2,000 to 3,000 feet thick.

The subarkosic sandstone is mostly very fine to fine grained, and in detail, poorly sorted with a salt-and-pepper appearance. It is weakly cemented with calcite. The grains are mostly quartz, with orthoclase, albite, biotite,

Figure 26. Toreva-type landslide along the Kelly Grade at the south end of the Kaiparowits Plateau. Colors in the landslide material are due to "clinker," shales and sandstones baked by coal that has burned in place in the Straight Cliffs Formation above.

calcite, gypsum, clay, iron, and bits of coal or charcoal. The bedding is poorly defined to lenticular; lenses rarely exceed five feet in thickness. Very thin partings and beds of siltstone and mudstone are also present. A few beds of nodular-weathering brown, green, white, or gray sandy limestone and lime silt are present.

This formation was probably deposited in freshwater or brackish-water lakes and on a subsiding alluvial plain. There are scattered fossils that include freshwater snails, vertebrate bones, and plant fossils (dicotyledons and cycads) (Lohrengel, 1969).

Formations Visible From the monument (TKc, Tcp, Tcw)

The Kaiparowits Formation is unconformably overlain by Upper Cretaceous and Tertiary units that are nicely visible from The Blues viewpoints. These include the Canaan Peak, Grand Castle, Pine Hollow, and Claron Formations. The Canaan Peak and Grand Castle Formations are locally as much as 900 feet thick, the Pine Hollow Formation is locally as much as 400 feet thick, and the Claron Formation may be as much as 1,400 feet thick. The lower three formations (TKc) have only been recognized in the area of Canaan Peak, Powell Point, and the Table Cliff Plateau (Goldstrand and Mullett, 1995) northwest of the Kaiparowits Basin section. The Claron Formation is generally divisible into at least two units: a lower pink unit (Tcp) and an upper white unit (Tcw). The lower pink unit forms the Pink Cliffs north of the Grand Staircase section of the monument where it is sometimes called the "Bryce Canyon Formation."

The Canaan Peak Formation consists of light-brown or gray conglomerate, sandstone, and lenticular mudstone. The rounded cobbles and small boulders in the unit are of quartzite, chert, and dense porphyritic igneous rocks. The formation makes steep gravel-covered slopes. The Pine Hollow Formation consists of gray to red calcareous silt-

Figure 27. A hoodoo rock (demoiselle) on the Tropic Shale along the margin of the Kaiparowits Plateau. Soft shale is protected from erosion by the large boulder that has fallen from sandstone cliffs. Locally whole families of hoodoos are present, especially along the southeast margins of the plateau.

stone, mudstone, and claystone that forms steep, poorly exposed slopes. The pink member of the Claron Formation consists mostly of pink, pale-orange, light-gray, and white limestone that is irregularly to indistinctly bedded to massive. It weathers into the Pink Cliffs that are sculptured into columns, spires, minarets, castles, and other interesting forms. The white member consists of mostly white clastic to microcrystalline limestone, also indistinctly to irregularly bedded, that commonly forms cliffs. It is locally dolomitic.

The four formations have unconformable contacts with one another and were deposited in fluvial and lacustrine environments. The Claron Formation was deposited at the south end of a large lake that covered central Utah during the Paleocene.

Volcanic Rocks

The Aquarius Plateau and Boulder Mountain are capped with volcanic tuffs and basaltic andesite mostly of Oligocene or Miocene age. Tertiary volcanic bedrock units are not exposed in the monument, but large boulders of basaltic andesite are scattered on many of the benches in the Escalante Canyons section of the monument as volcanic terrace alluvium. These were probably deposited on the benches by ancient streams that headed in the highlands. The rock consists of dark-gray to black, vesicular, and porphyritic lava.

Unconsolidated Deposits (Q, Qg, Qms)

Because of the small scale of the accompanying geologic maps (figures 15, 16, and 17), only three divisions are given for the Quaternary unconsolidated deposits. Only the larger deposits are shown on the maps; myriads of smaller areas were omitted. Unconsolidated deposits marked with a Q are deposits of a general nature and are deposits of sand and smaller grain sizes. The Qg designation is given to larger surfaces containing gravel, especially pediment-mantle and terrace deposits. The Qms designation is restricted to larger landslide, slump, and related deposits.

Alluvium

Alluvium is gravel, sand, silt, clay, and other detrital material deposited by running water. If deposited by rivers, streams, or intermittent washes in channels it is called **channel alluvium**. Most channels in the monument are dry washes except during periods of flash flooding brought on by torrential summer rainfall. Some washes fill to as much as 10 feet in depth and move boulders the size of small houses. Generally the floods are only a few feet deep, but have no trouble moving boulders a few feet in diameter. Walk down a few of the larger washes in the monument and you will find evidence of the sizes of materials that can be moved and deposited in the channels. When the volume of water exceeds that which the channel can handle it floods its valley depositing finer grained materials called **overbank or flood plain alluvium**.

In time, streams and washes cut deep valleys or canyons in the rock. As they do so their older deposits are commonly found stranded on benches. Streams meander and commonly abandon earlier channels. These older deposits are known as **terrace alluvium**. Along the larger and longer lived rivers, terrace alluvium is found at several levels above and up to several hundred feet above the present channel level.

The debris carried by washes and streams is dropped when the water velocity is decreased, such as at the mouths of canyons along mountain or cliff fronts. The deposit develops a fan shape with the apex at the point where the stream gradient first diminishes. Such landforms are called **alluvial fans**. The most recent deposits lie high on the fan surface. The next flood will choose a lower path on which to deposit its load and so the drainage swings back and forth over the fan surface gradually building it up. If the cliff or mountain front is long, a series of fans may be built up and coalesce to form a **bajada**.

In time, cliffs and mountains retreat because of erosion. Washes and streams may then cut into and through older fans or bajadas. Older fans become dissected and their remnants are then found on the benches between drainages. The bedrock surfaces eroded in the foothills below the cliffs and mountain fronts are pediments (piedmonts) and the deposits that the streams leave on them are **pediment-mantle alluvium**. Alluvial deposits are found in all sections of the monument.

Mixed Eolian and Alluvial Deposits

Streams may meander across a plain developed on benches formed at the top of a relatively hard sedimentary formation. Until the streams can cut through or deeply into this hard underlying formation, alluvium is deposited on the bench in shallow hollows and is temporarily held up from moving downstream. The alluvium may fill these hollows and eventually bury all the rocks. Such alluvium may remain on these benches a considerable length of time. Wind may redistribute its finer constituents (fine sand and silt) and bring in sand from outside of the area, depositing it in sheets on top of the alluvium. These wind-blown deposits may then be covered or mixed by more alluvium, as during wet climatic cycles. Soil may also develop on the surfaces. As part of soil development, a white caliche layer may slowly develop a few feet below the surface. Examples of mixed eolian and alluvial deposits are common on benches beneath the Straight Cliffs (Fiftymile Mountain) and at the base of the Vermilion Cliffs in the Grand Staircase section of the monument.

Eolian (wind-blown) Deposits

Most sandstone beds in the monument are friable and weather to produce loose sand. Such sand is blown by wind to fill shallow hollows in bedrock or to accumulate on the lee sides of cliffs and other impediments. Some sandstone units produce much sand and are commonly covered with wind-blown sand either in sheets or in dunes. In the monument the Entrada Sandstone provides the sand that produces the largest of these deposits. These deposits are most evident left and right of the Hole-in-the-Rock Road. Some of these sheets and dunes are stabilized and no longer move, being held in place by vegetation. Others are active deposits that migrate from one place to another.

Landslides and Slumps

Clay-bearing formations such as the Chinle Formation and Tropic Shale are commonly covered with self-derived landslide debris and slumps. The Petrified Forest Member of the Chinle is conducive to slumping, especially in the Circle Cliffs area, where it contains more clay than in other areas. The Tropic Shale contains much bentonitic clay along Fiftymile Mountain and along the south margin of the Kaiparowits Plateau (figure 26). It too is covered with talus and landslide debris. In places the Tropic has "oozed" down the cliff formed by the Dakota Formation, Morrison Formation, and Entrada Sandstone.

Undercutting produced by the weathering of soft slope-forming units causes vertical cracks to open in the hard cliffs above them. During wet years moisture enters these cracks and eventually reaches permeable and porous material found above or below the clay beds. The water then moves toward the outcrops through the permeable strata, wetting the adjacent clay. Weight above the wet slippery clay causes the overlying rocks to slide, rotate, or slump. Landsliding is the normal way clay-rich rocks are eroded.

The landslides and slumps attendant to the Tropic Shale are some of the largest landslide complexes in the world and are best displayed at the southeast end of Fiftymile Mountain. The poorly sorted jumble of rock material is commonly interestingly eroded to form hoodoo rocks (figure 27). Hoodoo rocks or pedestal rocks are formed when a large boulder rests on easily eroded finer grained landslide debris. The boulder protects the finer grained materials directly beneath it from removal or weathering during rainstorms. Eventually the boulder sits on a pedestal of the finer grained material. In some places whole families of hoodoos delight the sightseer.

Talus and Rock Fall

Rock fall consists of large chunks of rock that become dislodged from escarpments (cliffs and ledges) and drop or roll to more level areas below. Talus is the name given to conical deposits that form at the base of escarpments and is a mixture of rock fall and finer constituents. Talus and rock-fall deposits are ubiquitous in the monument.

STRUCTURAL GEOLOGY

Generally, structural geologic features seen today within the monument region result from two phases (or styles) of deformation. Many of the folds that we see today in the Kaiparowits and Circle Cliffs regions began during the latter part of the Mesozoic (Jurassic-Cretaceous); initiated during the Sevier orogeny and later modified as compression of the region continued through the Laramide event (Cretaceous-Tertiary). During mid-Tertiary, uplift of the Colorado Plateau was accompanied by basin and range extension which affected the western portions of the monument region resulting in the development of the Sevier and Paunsaugunt faults. The uplift of the Kaibab region and folding along the East Kaibab monocline accompanied initial formation of the Grand Canyon starting about 15 million years ago.

Grand Staircase Section

All strata in the Grand Staircase section of the monument dip gently (mostly 2 to 4 degrees) northward in a homocline that is warped and faulted (figures 3 and 12). Hence, the oldest rocks are generally exposed to the south and the youngest to the north. The strata are cut by many

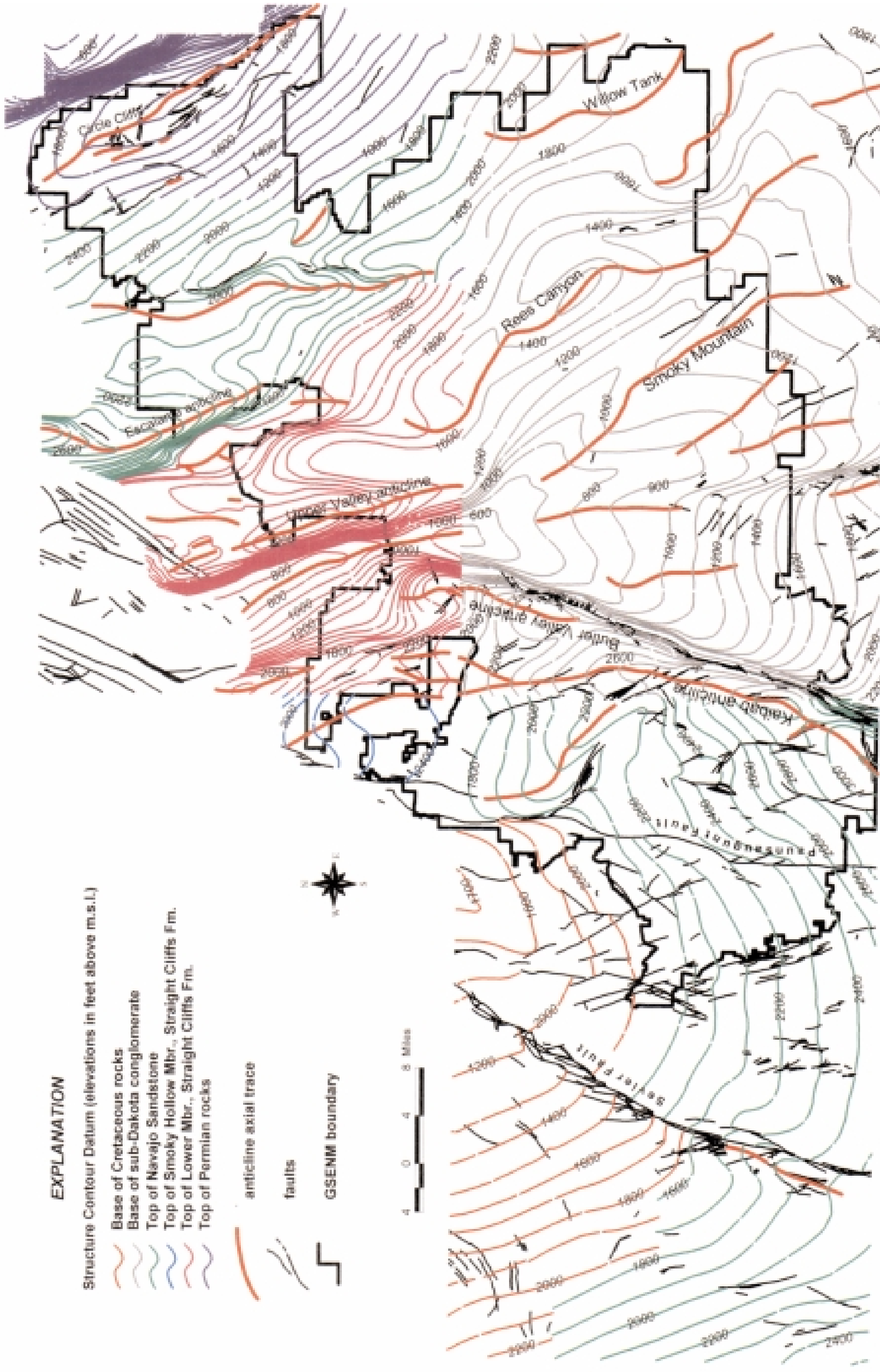

Figure 28. Structure contour map of Grand Staircase-Escalante National Monument.

Figure 29. The Cockscomb is the physiographic expression of the East Kaibab monocline which forms the boundary between the Kaiparowits Basin and Grand Staircase sections of the monument. Ribs of harder formations are found between slope-forming softer units.

normal faults with displacements ranging to about 800 feet (figure 15).

The **Paunsaugunt fault,** which extends from Arizona northward into central Utah, is the most significant of the Grand Staircase section faults (see geologic map, figure 15). The fault is a high-angle normal fault, and the upthrown block is to the east. The displacement decreases southward from about 800 feet near Willis Creek to less than 100 feet near Deer Spring Point. From there to the Arizona border it increases again to approximately 500 feet. The fault plane dips at various angles from 45° E. as a reverse fault to 45° W. Differential erosion of bedrock near the fault has resulted in reverse topography. Because west-side strata generally stand higher in elevation than the east side the outcrops of older rocks are exposed farther north on the upthrown block (figure 28). The northern segment, outside the monument, shows evidence for surface rupture during Quaternary time, but movement along the southern segment during Quaternary is not apparent (Hecker, 1991).

The **Johnson Canyon faults** are present along the west margin of the monument. These faults may be active, however, to date, associated earthquakes have registered very low magnitude on local seismographs (University of Utah Seismology Catalog, 1986). Seismologists have not determined a link between movement on the Johnson Canyon faults and local earthquakes.

Two major faults (**Paria River faults**), 3/4 to 1/4 mile apart, occur on each side of the Paria River just north of the abandoned Paria townsite. These form a graben or down-dropped block, the river generally flowing between them. Each exhibits a maximum displacement of about 250 feet. It is assumed these faults are not tectonic in origin, are shallow and die out not far beneath the surface. The strata on each side of the canyon is thought to be moving riverward due to gravity-induced sliding.

The **Kaibab uplift** is present in the southeast corner of the section. It is expressed as a positive topographic feature known as Buckskin Mountain. The uplift is most easily recognized traveling southward along U.S. Highway 89 between the Paria turnoff and the deep cut through the Cockscomb as a whaleback. The uplift is connected and synchronous with the Grand Canyon uplift in Arizona. The axis of the uplift trends roughly north-south and is known as the **Kaibab anticline**. This anticline extends north to south completely across the monument, generally plunging northward. In the Buckskin Mountain part of the anticline, the east boundary of the uplift or east limb of the anticline (East Kaibab monocline as expressed by the Cockscomb) is steeply dipping and locally overturned.

North of U.S. Highway 89, the Kaibab anticline is very subtle and gentle on both flanks. There it is bounded on the west by the **Paria River syncline** and on the east by the **Hackberry Canyon syncline,** which are also gentle, generally north-south-trending folds.

The east boundary of the Grand Staircase section is the Cockscomb, the topographic expression of the **East Kaibab monocline** (figure 29). It trends north-northeast from the south boundary of the monument nearly to the north boundary and is paralleled by the Cottonwood Wash road. The rock strata dip abruptly eastward at angles ranging from 15 degrees to slightly overturned. The structural relief across the monocline is about 5,000 feet to the south and decreases gradually to the north end of the monument near Butler Valley. Locally, the monocline is faulted and strata are attenuated. It is the most magnificent structural feature in all of Grand Staircase-Escalante National Monument.

Kaiparowits Basin Section

Like the Grand Staircase section, strata in the Kaiparowits Basin section dip gently northward. Because of the displacement on the East Kaibab monocline, Cretaceous outcrops shift southward and dominate the Kaiparowits Basin section. The strata are composed of alternating hard and soft units as in the Grand Staircase section, but the cliffs are all subdivisions of the Gray Cliffs part of the Grand Staircase. Superimposed on the north-dipping homocline are several north-south-trending anticlines and synclines (figure 4). Most of these have gentle limbs, but a few form monoclines.

Figure 30. The Escalante monocline looking north toward Boulder Mountain.

The Kaiparowits Basin section is a structural basin topographically expressed as a high plateau. The deepest part of the basin lies westward near the East Kaibab monocline. The strata gradually rise eastward. The Cretaceous rocks are cut off by erosion along Fiftymile Mountain (Straight Cliffs). West to east, from the East Kaibab monocline to the Straight Cliffs, the principal folds in the basin include the **Coyote Creek-Blue Wash-Table Cliff syncline** (deepest part of the Kaiparowits Basin)**, Tommy Canyon anticline, Wahweap syncline, Nipple Bench anticline, Warm Creek syncline, Smoky Mountain anticline, Last Chance syncline, Upper Valley anticline, Alvey Wash syncline, Rees Canyon anticline,** and **Croton syncline**. Fewer of these folds are present to the north where the plateau-basin is narrower. The folds radiate out southward like the plications of a fan. Folds to the west trend southwesterly; folds to the east generally trend southeasterly.

Escalante Canyons Section

The boundary between the Escalante Canyons and Kaiparowits Basin sections of the monument is placed at the base of Fiftymile Mountain (Straight Cliffs). The dominant structural feature of the Escalante Canyons section is the **Circle Cliffs uplift** (figure 5). It has a gentle southwest limb that extends from the Hole-in-the-Rock Road east-northeast to the axis of the uplift. The east limb of the uplift is the Waterpocket Fold, another steeply dipping monocline like the East Kaibab monocline. The **Waterpocket Fold**, however, is in Capitol Reef National Park. The core of the Circle Cliffs uplift is lined by the prominent vertical and magnificent red-brown or orange-brown cliffs of the Wingate Sandstone. These cliffs "circle" the uplift and are the basis for its name. The core of the uplift exposes Permian and Triassic rocks. The **Escalante monocline** is a north-northwest-trending feature north of the town of Escalante that dips to the west (figure 30).

Several anticlines and synclines are superimposed on the gentle west limb of the uplift. These include the **Collet anticline** and **Red Breaks syncline** to the north, and the **Hurricane Wash syncline, Bridge anticline**, and **Fiftymile Creek syncline** to the south. The Escalante River and its tributaries have cut deep canyons into the gentle west limb that are favorites for hikers. These deep canyons are the basis for the name of the Escalante Canyons section of the monument.

GEOLOGIC RESOURCES

Mineral, oil and gas, coal and other geologic resources are found within Grand Staircase-Escalante National Monument. At the time the monument was created, many thousands of acres of oil and gas leases, coal leases, and mining claims were still valid. Here we discuss the geology of these resources as part of the natural scientific endowment of the monument.

Coal

The Kaiparowits coal field is mostly based on coals found in the Cretaceous Straight Cliffs Formation in the Kaiparowits Basin section of the monument. Thin coal beds are also found in the Cretaceous Dakota Formation. The Straight Cliffs coals were first mined by settlers near Escalante in the late 1800s. Coal studies were initiated by Gregory and Moore (1931). All mining in the coal field ceased in the early 1960s as the local market converted to the use of petroleum products for heating purposes. Only 37,000 short tons were produced during the production history of the coal field (Doelling, 1972; Jahanbani, 1997). Energy companies became interested in developing the resource in the early 1960s to produce electrical energy. Coal leases were obtained by 23 separate companies (Doelling and Graham, 1972). Hundreds of coal test holes were drilled as plans were made to build a 5,000 megawatt coal-fired power plant on Nipple Bench on the Kaiparowits Plateau. Plans were scaled back in the early 1970s to a 3,000 megawatt plant to be built on Fourmile Bench and were eventually dropped altogether because of economic and environmental concerns. One coal company in the Kaiparowits area was actively working to get a mine started when the monument was created.

In the 1960s and 1970s coal drilling and exploration efforts by industry, the U.S. Geological Survey, and the Utah Geological Survey showed that the Kaiparowits Plateau was underlain by thick beds of high-volatile C bituminous coal with heating values averaging 11,000 Btu / lb and sulfur contents averaging less than 1 percent. Estimates of the original coal resource in place in the plateau range from 62 billion short tons (Hettinger and others, 1996) to 15.2 billion tons (Doelling and Graham, 1972). The overburden above coal beds in the Kaiparowits Plateau dictates that the coal would need to be extracted in underground mines. Most of the Kaiparowits coal field is contained within a northwest-trending, 15- to 18-mile-wide band within the John Henry Member of the Straight Cliffs Formation. Coal is found in nearly horizontal to gently dipping seams that have undergone little folding. Very little has been mined in the past, however, because of the remote location of the coal field, the small local market, and environmental concerns. It is, however, the largest relatively untapped coal resource in the lower 48 states.

Coal is also found in the Alton coal field which partly extends into the Grand Staircase section of the monument. The coal in the monument is found in the Dakota Formation and was locally mined by ranchers in the early days. West of the monument the coal is very thick and strip-minable. However, in the monument the Dakota coal beds are generally thin and contain more sulfur and ash than the Kaiparowits coals.

Coal remains an important scientific resource in the monument. The public can see what a natural coal outcrop looks like, how coal burns and oxidizes along outcrop (Burning Hills), the nature of roof and floor rocks, and many other aspects of coal geology. Scientists can study the processes involved in coal-producing environments and better understand the problems that coal producers face. It is a place where the public can learn to understand the geology of coal and its place in the geologic world.

Petroleum

The geology of the monument and surrounding region are favorable for the accumulation of oil and gas. However, the only commercial quantities of oil within the boundaries of the monument are at the Upper Valley field near Canaan Peak. To date 48 wildcat (exploratory) wells have been drilled within the confines of the monument. All of these wells have been capped and abandoned. The number of wells drilled indicates the geologic favorability of the area and the presence of encouraging oil shows.

Figure 31. View eastward across the north end of the Circle Cliffs area from Boulder Mountain. The Circle Cliffs get their name from the nearly vertical cliffs formed by the Wingate Sandstone. The Henry Mountains are in the background.

Anticlines are favorable structures to explore for oil and gas and there are many in the monument. Petroleum generally collects in the elevated areas of reservoir rocks above formation water. Wildcat wells in the monument have mostly been drilled along the anticlinal axes. The anticlinal theory of oil accumulation generally assumes a water table under oil to be level. However, the oil of the Upper Valley anticline was discovered in its steep western flank where the oil-water contact is tilted westward. Apparently, a flood of carbon dioxide, other non-hydrocarbon gasses, and deep ground water drove the oil from the axis into the flank of the anticline (Utah Geological Survey, 1998). Because the flanks of other anticlines in the region have not been thoroughly tested through drilling, some workers believe the monument area may contain undiscovered oil and gas resources.

The Upper Valley oil field was discovered in 1964 by Tenneco, and has since produced nearly 26 million barrels of oil, mostly from the Permian Kaibab Limestone. Citation Oil & Gas Corporation currently operates 22 production wells and 11 water injection wells within the field. Five of the production wells and two injection wells are located in the monument. Production from the wells in the monument represents about 27 percent of the total field production. It is estimated that the total production of the field will amount to about 30 million barrels of oil.

Petroleum has also been discovered at the surface as tar and seeps in the core of the Circle Cliffs uplift or anticline. This oil is asphaltic. The Circle Cliffs anticline would have been a giant oil field had it been discovered before the oil-bearing reservoir rocks had been exposed by erosion. Lighter constituents of the oil have long since evaporated, leaving only the heavier petroleum residues. These residues and the rock in which they are found are called tar sands. They are mostly in the Triassic Moenkopi Formation, but tar sands have also been found in the Shinarump Member of the Chinle Formation. The technology for producing gasoline and other usable products from tar sands is available, but the process is much more expensive than producing oil from wells.

The Circle Cliffs area is a good place to visualize oil reservoirs. Good reservoir rocks have pore spaces or openings between the sand and mineral grains. These spaces are commonly filled with water, oil, or gas. When buried at great depth, rocks are commonly under great pressure and the oil rises when tapped by wells. Drilling through confining impermeable rock allows man to produce and make use of these commodities.

Recently oil companies have developed new concepts in their efforts to discover petroleum resources. The concept that Precambrian rocks might serve as reservoir rocks has been tested in the monument. Conoco, Inc., completed the most recent wildcat well within the monument in November, 1997 on a former SITLA lease on the Rees Canyon anticline in the Kaiparowits Plateau. The well was completed to a depth of 11,911 feet, reportedly encountering shows of natural gas and non-flammable gas (D.A. Sprinkel, verbal communication, November 1999). The well was plugged and abandoned because of subeconomic quantities of natural gas.

Minerals

Various types of metallic mineral deposits are known within the monument. Most are small and of low grade. Manganese was mined in the 1940s from the Petrified Forest Member of the Chinle Formation in the Grand Staircase section because this metal was on the critical list during World War II. Total production was about 300 to 400 tons of ore containing about 40 percent manganese (Buranek, 1945). Manganese is also found in small areas within the Page and Carmel Formations near the Hole-in-the-Rock Road (Doelling, 1975).

Uranium associated with vanadium or copper is present within the Moenkopi, Chinle, and Morrison Formations. The Chinle and Moenkopi-hosted occurrences are in the Circle Cliffs uplift area and along the Cockscomb on the east side of the Kaibab uplift. These deposits are found on the bottoms and sides of paleochannels in the Shinarump Member of the Chinle Formation. Mineralization has locally extended into and bleached the Moenkopi Formation below.

Gold was reported in Permian to Jurassic sedimentary rocks across much of southern Utah, particularly in the Chinle and Moenkopi Formations (Butler and others, 1920). Lawson (1913) reported several early unsuccessful attempts to mine the gold in the Chinle Formation near the ghost town of Paria by hydraulic methods.

The Carmel Formation and Page Sandstone are locally mineralized in the Tropic Amphitheater area in the north part of the Grand Staircase section. Lead, silver, and copper have been found in above-normal quantities. A little lead was produced in the 1930s by grinding sandstone in an *arrastre* at the Rock Spring deposit near Kodachrome basin (Doelling and Davis, 1989). An *arrastre* is a primitive device in which sandstone ore is ground by placing the ore between two hard millstones, the upper being rotated by a mule or ass walking around in a circle. The ground sandstone is then washed through a sluice box to concentrate the heavier ore particles.

A number of heavy-mineral fossil placer deposits containing titanium and zirconium minerals are present in the John Henry Member of the Straight Cliffs Formation in the Kaiparowits Plateau. The deposits occur in a belt extending southward from Dave Canyon, a few miles south of Escalante, to Sunday Canyon, near the south end of the monument. At least 14 fossil beach placers have been identified that contain variable amounts of ilmenite, zircon, monazite, magnetite, rutile, and silicates (Gloyn and others, 1997).

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