National Park Service
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Natural Resource Program Center

Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/230

THIS PAGE:
Bison graze on Antelope Flats, below the Teton Range, which rises more than 2,100 m (7,000 ft) above the floor of Jackson Hole. Tectonic forces raised the Teton Range and dropped Jackson Hole along the Teton fault.

National Park Service photograph by R. Wiles.

ON THE COVER:
Visitors at the Mountain View Turnout take in the stunning views of the Cathedral Group covered in snow.(L to R: Teewinot Mountain, Grand Teton, Mount Owen) .

National Park Service photograph

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Natural Resource Program Center
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August 2010

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Ft. Collins, Colorado

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Please cite this publication as:

KellerLynn, K. 2010. Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/230. National Park Service, Fort Collins, Colorado.

NPS 136/105347, 642/105347, August 2010

Contents

List of Figures

List of Tables

Executive Summary

This report accompanies the digital geologic map data for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway in Wyoming, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

The NPS Geologic Resources Division held a Geologic Resources Inventory (GRI) scoping meeting for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway on June 21–22, 2005. This report expands upon the scoping summary (Covington and Ransmeier 2005) and ties geologic issues, features, and processes to the geologic maps of the park and parkway.

During scoping, participants prioritized the following geologic issues:

1. Geologic hazard assessment and response, particularly as related to earthquakes
2. Streamflow, stream channel morphology, and dynamics
3. Glacial and climate change monitoring
4. Disturbed lands restoration.

This report addresses these issues, which are characterized as follows:

- Seismic Activity. The Teton fault is the most important factor contributing to the spectacular topography and scenery of the Teton Range. The topographic relief between Jackson Hole and the summits of the Teton Range was probably caused by numerous (10–50) magnitude-7 or greater earthquakes during the past 25,000 to 75,000 years. The most likely seismic hazards in the Teton region are ground shaking and deformation, and associated secondary effects, including rock and snow avalanches, landslides, and flood inundation of low-lying areas.
- Mass Wasting. The conditions that produce landslides in the park and parkway are (1) vulnerable rock, (2) slopes parallel to dipping strata, (3) saturated ground, (4) seismic activity, and (5) removal of base support by undercutting of the slope toe. In addition to landslide deposits, talus and related deposits are widespread throughout the Teton Range.
- Fluvial Features and Processes. The Snake River and its tributaries make up the fluvial system at Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. The Snake River has both roaring rapids and gentle meanders. The high rates of aggradation and lateral migration of the Snake River system confound attempts to restrict the flow path to fixed bridge openings. Levee control along segments of the river has changed sedimentation patterns and habitat.
- Glaciers and Climate Change. The 1968 USGS topographic map of Grand Teton National Park shows nine named glaciers and approximately 136 undifferentiated glaciers or perennial snow fields. A thorough inventory of the park's glaciers, however, has not been conducted to date, and long-term documentation is sparse. Past records of glacier extent indicate both advance and retreat, although the overall trend is one of retreat. Models that simulate the response of alpine glaciers in Wyoming to projected climate change predict the near-complete disappearance of Teton Glacier within 30 to 75 years.
- Mineral Resources and Management. Mineral resources of interest in the park and parkway are oil and gas, gold, phosphate, coal, gypsum, building stone, soapstone, and sand and gravel. Most of the abandoned mines in the park are not considered safety hazards to park visitors. Grand Teton National Park contains 38 borrow pits, many of which predate the park. Most have been abandoned, but some are still in use, primarily for storage. The National Park Service has been involved in restoration efforts to reclaim some of the abandoned borrow pits, particularly those that impact wetlands.

Other issues of management interest are bentonite, cave and karst resources, climbing, Jackson Lake Dam, and paleontological resources.

In addition to geologic issues of management concern, this report highlights the distinctive geologic features and processes occurring at Grand Teton National Park, including ancient rocks, young mountains, dikes, geothermal features, glacial features, lakes, loess, oxbows, terraces, unconformities, and volcanic features. Of particular interest for John D. Rockefeller, Jr. Memorial Parkway are geothermal, glacial, and volcanic features.

The glossary contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table. Refer to figure 13 for a geologic timescale.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Program Center.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory website at http://www.nature.nps.gov/geology/inventory/.

Park and Parkway Setting

The iconic peaks of the Teton Range are woven into our nation's identity. They have served as a landmark for American Indians, trappers, prospectors, explorers, scientists, pilots, and vacationers. More than 2 million visitors have come to the park each year since 1993 to experience this spectacular landscape, which "captures the essence of Grand Teton National Park's and John D. Rockefeller, Jr. Memorial Parkway's importance to our natural and cultural heritage" (National Park Service 1995, p. 7).

Dynamic geologic forces created these dramatic landscape features. Tectonic forces raised the Teton Range and dropped Jackson Hole along the Teton fault. This active fault extends more than 70 km (40 mi) from north to south along the eastern base of the range.

The Teton Range and Jackson Hole are two halves of a landscape meant to be protected and managed as a unit (fig. 1). When Grand Teton National Park was established in 1929, only the Teton Range and six glacial lakes at the foot of the mountains were included within its boundaries. The present-day park evolved through a complicated process requiring three governmental acts and a series of compromises, including (1) protection of existing grazing rights and stock driveways, (2) reimbursement to Teton County for lost tax revenues, (3) provision for the controlled reduction of elk within park boundaries, (4) agreement that future presidential proclamations could not be used to create a national monument in Wyoming, and (5) allowance for continuation of certain existing uses and access rights to forest lands and inholder properties (Skaggs 2000).

Before World War II, strong anti-park sentiment from local citizens, stemming from perceived expansion of government control and loss of personal freedoms, stymied park creation. This sentiment began to change after World War II, as local citizens realized that tourism offered a more attractive economic opportunity than ranching, which was difficult in northern Jackson Hole (Skaggs 2000).

Established in 1972, the 132-km (82-mi) John D. Rockefeller, Jr. Memorial Parkway links Grand Teton and Yellowstone national parks. It commemorates the efforts of John D. Rockefeller, Jr., who supported an integrated national park and in 1927 began to purchase and hold land until it could be administered by the National Park Service (Harris and Tuttle 1990).

The parkway is a mountainous region with moderate to steep slopes. Situated between the volcanic plateaus of Yellowstone National Park and the jagged fault-block mountains of Grand Teton National Park, the geology of the parkway largely reflects influences of extraregional origin. Sedimentary layers of Cretaceous sandstone and shale are present, but lava and ash from Yellowstone volcanic features cover much of the Cretaceous bedrock. The most prominent volcanic event was the caldera eruption that created Yellowstone Lake 600,000 years ago (Rodman et al. 1992). This event deposited thick layers of rhyolite in the parkway. The Teton fault, so significant for Grand Teton National Park, has also uplifted the topography and influenced seismic activity in the parkway. Glaciers originating in Yellowstone National Park entirely covered the parkway during the Pleistocene Epoch (2.6 million to 11,700 years ago), creating its gouged valleys and rounded mountains (Rodman et al. 1992).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway on June 21–22, 2005, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

During scoping, participants prioritized the following geologic issues of concern for management: (1) geologic hazards, including seismic activity and mass wasting; (2) fluvial features and processes; (3) glaciers and climate change; and (4) disturbed lands restoration, described in the "Mineral Resources and Management" section. These issues are presented first, followed by other issues of resource management interest.

Seismic Activity

The Teton fault "is the single most important factor contributing to the spectacular topography and scenery of the Teton Range—hence to the essence of the Grand Teton National Park" (Smith et al. 1990b, p. 1). This major normal fault bounding the east side of the Teton Range is the primary structure responsible for the more than 2,100 m (7,000 ft) of topographic relief along the range front (fig. 2). The Teton Range is part of the upthrown footwall block of the fault, and Jackson Hole is situated on the downdropped hanging-wall block. The Teton fault is a single fault line in some locations, but splits into a number of separate, closely spaced strands in many places (Love et al. 2003). While its development began during the deposition of the Colter Formation (24 million to 13 million years ago; see Map Unit Properties Table), the modern Teton Range and Jackson Hole are largely the results of fault movements within the last 5 million years. The last 2 million years have been particularly significant, given the passage of the Yellowstone hot spot close to the northern end of the Teton Range (Love et al. 2003; see "Volcanic Features" section).

The topographic relief between Jackson Hole and the summits of the Teton Range is probably the result of 10 to 50 magnitude-7 or greater earthquakes during the past 25,000 to 75,000 years (Byrd 1995). Gilbert et al. (1983) and Smith et al. (1990a) estimated offset rates of 1.0 mm to 1.5 mm (0.04 in to 0.06 in) per year. These rates do not indicate constant fault movement; they likely reflect a number of sudden offsets, each accompanied by an earthquake, some perhaps of magnitude-7.5 or greater, that produced the net displacement along the fault (Love et al. 2003).

The isolated population of Jackson Hole reported numerous mild to moderate earthquakes around the time of the 1925 Gros Ventre slide, but no one has felt major seismic shaking along the Teton fault (particularly the northern portion) since Jackson Hole was settled more than 100 years ago (Good and Pierce 1996; Smith and Siegel 2000). The Teton fault probably occupies a zone of seismic quiescence for earthquakes greater than magnitude-3 (Byrd et al. 1994).

A possible implication of the aseismic creep (gradual movement on a fault without the generation of seismic waves) on the Teton fault is that it is currently undergoing stress buildup prior to a large earthquake. This interpretation is consistent with the concept that the seismic quiescence on the Teton fault is a seismic gap that may end with a large-magnitude earthquake (surface wave magnitude [Ms] ≥ 6.3), which would most likely result in significant ground deformation and disruption of roads and structures (Smith et al. 1993).

A preliminary assessment by Smith et al. (1990b) characterized the most probable general seismic hazards in the Teton region:

- Ground shaking accompanying a large earthquake that results in strong acceleration of the ground surface and structures.
- Ground deformation resulting from surface rupture along the fault trace and possible subsidence of the valley floor.
- Secondary effects associated with ground deformation and shaking, including rock and snow avalanches, landslides, and flood inundation of low-lying areas.

In addition, scoping participants identified dam failure (see "Jackson Lake Dam" section), liquefaction of loosely packed sediment or fill, flooding, and building and bridge collapse as risks associated with seismic activity (Covington and Ransmeier 2005).

The development of an earthquake hazard response plan is a high priority for Grand Teton National Park (Covington and Ransmeier 2005). In addition to the National Park Service, U.S. Geological Survey, and academic partners, such planning would likely involve state and local governments, the National Guard, U.S. Forest Service, Bureau of Reclamation, and possibly the U.S. Fish and Wildlife Service. It may also be appropriate to solicit ideas, suggestions, and perhaps leadership from the Federal Emergency Management Agency (FEMA). Scoping participants recommended that the hazard response plan include a review of possible scenarios, strategies for response, an inventory of available resources (human and other), and identification of responsibilities.

As part of the Geoscientist-in-the-Parks (GIP) Program administered by the NPS Geologic Resources Division, Patrice Cobin of Michigan Technological University served a 90-day assignment at Grand Teton National Park in 2009. Cobin updated information on the natural hazards, associated risks, and the state of the park's emergency response preparedness. Park officials intend for this project to prompt a new hazard response plan with engagement of park rangers and the appropriate county officials (Sue Consolo-Murphy, Grand Teton National Park, Chief of Science and Resource Management, e-mail, October 9, 2009).

Other ongoing research and monitoring projects seek to better understand seismic activity in the Teton region. These projects are examining the historic return time of earthquakes on the Teton fault, investigating the intermountain seismic belt as a system, and synthesizing monitoring data to improve earthquake prediction (Jean et al. 2005). Three seismic monitoring stations and one continuously recording GPS receiver are currently in place within Grand Teton National Park (Jean et al. 2005). Real-time data from the seismic monitoring network are available at http://quake.utah.edu/helicorder/yell_webi.htm (accessed October 30, 2009). The monitoring effort is coordinated by the University of Utah Seismograph Stations (UUSS) regional and urban seismic network, and the stations in the Teton region are maintained and operated by the U.S. Geological Survey. Braile (2009) suggested methods for monitoring seismic activity including: monitoring earthquakes, analysis and statistics of earthquake activity, analysis of historical and prehistoric earthquake activity, earthquake risk estimations, geodetic monitoring and ground deformation, and geomorphic and geological indicators of active tectonics.

Mass Wasting

Although the majority of mapped landslide deposits are located in the upland area east of Grand Teton National Park, such deposits also cover areas within the park such as Colter Bay, Moose Creek, and Two Ocean and Emma Matilda lakes. In addition, geotechnical engineers evaluated four slope failures about 1.5 km (0.9 mi) east of Moran Junction (fig. 1). These particular failures are related to a shallow, perched groundwater aquifer, which is concentrated near the surface as a result of an underlying drainage barrier (Prellwitz 1998). Furthermore, while mapping the state's landslide threat, Wyoming officials determined that the Snake River drainage was one of the state's highest risk areas for landslides (Smith and Siegel 2000). Between 1989 and 1991, Marston (1993) documented 53 slope failures in the upper Snake River drainage, including slow-moving deep slumps, earthflows, and debris flows, and rapidly moving shallow debris avalanches and wet debris flows.

In John D. Rockefeller, Jr. Memorial Parkway, Rodman et al. (1992) used slope steepness, evidence of historical landslides, shale bedrock, clay content, and the presence of seeps and water-loving vegetation to identify map units susceptible to landslide hazards. Of the 15 identified map units, four had landslide potential (units 23, 30, 31, and 41). These units cover roughly one-third of the parkway's surface and are characterized by glacial till and weathered bedrock on gently sloping to very steep topography (≤30% to 70% slopes). Predominant bedrock from which these units formed is andesite, rhyolite, sandstone, shale, and limestone.

During the Pleistocene Epoch, when large glaciers advanced and retreated and meltwater ebbed and flowed, mass wasting (landsliding) was prevalent, as evidenced by abundant Pleistocene-aged landslide deposits mapped by Love et al. (1992). However, mass wasting continued after the retreat of the large-scale glaciers, and continues to the present time. The most notorious historic example of mass wasting is the Gros Ventre landslide east of the park boundary on June 23, 1925 (fig. 1). An estimated magnitude-4 earthquake triggered the landslide after several weeks of heavy rain compounded by late snow melt (Smith and Siegel 2000). Some 38 million m^3 (50 million yd^3) of rock (Tensleep Sandstone over the slippery shale of the Amsden Formation) slid 640 m (2,100 ft) down the side of Sheep Mountain (fig. 3) (Alden 1926; Lageson and Spearing 1988; Smith and Siegel 2000). The material traveled 2.4 km (1.5 mi) within 3 to 4 minutes. The fast-moving slide crossed the Gros Ventre River and continued 122 m (400 ft) up the opposite bank, forming a dam across the Gros Ventre River that measured 610 m (2,000 ft) in width and 69 m to 76 m (225 ft to 250 ft) in height. In 1927, this natural dam failed, flooding the town of Kelly. The flood killed six people and hundreds of livestock, left 40 families homeless, and washed away the fertile fields on the floodplain, leaving gravel and boulders (fig. 4) in its wake (Lageson and Spearing 1988; Smith and Siegel 2000).

The Gros Ventre slide illustrates the landslide-producing conditions in the park and parkway: (1) vulnerable rock, (2) slopes parallel to dipping strata, (3) saturated ground, (4) seismic activity, and (5) removal of base support by undercutting the slope toe. In this case, fluvial undercutting by the meandering Gros Ventre River contributed to the loss of base support. According to Lageson and Spearing (1988, p. 219), "the situation was inevitable; it happened in the past, and will happen again when conditions are right."

In addition to landslide deposits, Love et al. (1992) mapped talus and related deposits. These deposits are widespread throughout the Teton Range, notably along Paintbrush Divide into Paintbrush Canyon, in Granite Canyon, and surrounding Middle Teton, Grand Teton, and Cloudveil Dome (Love et al. 1992). Love et al. (2003, p. 13) described the talus and related deposits as "constant reminders that the land surface is restless;" these deposits are "the ever-changing piles of rock debris that mantle the mountain slopes, the creeping advance of rock glaciers, the devastating snow avalanches and the thundering rock falls."

Loosened by freeze-thaw processes, intense rain storms (Caine 1974, 1986), and seismic activity, angular blocks of talus and abundant smaller rock fragments fall from the cliffs and accumulate on the slopes below. Once deposited, talus can move by the slow process of creep or as part of a snow avalanche (Harris and Tuttle 1990). Flash floods also efficiently move talus deposits: torrents of water running down mountain slopes onto unstable deposits of talus can trigger enormous rockslides and mudflows. During the summer of 1941, for example, more than 100 of these flows occurred in the park. More recently, major slides occurred in Granite and Cascade canyons in the 1980s (Love et al. 2003). Wieczorek and Snyder (2009) suggested five methods and "vital signs" for monitoring slope movements: types of landslides, landslide triggers and causes, geologic materials in landslides, measurement of landslide movement and assessing landslide hazards and risks.

Fluvial Features and Processes

The Snake River and its tributaries make up the fluvial system at Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. Although the Snake River is one of the smallest major drainages in Wyoming, it carries the largest average volume of any river in the state (Kiefling 1978).

The Snake River begins as a trickle within the Absaroka volcanics (Wiggins Formation; see Map Unit Properties Table) near the southern boundary of Yellowstone National Park. The river flows north into Yellowstone, where it meanders westward and is joined by the Lewis River before looping south into John D. Rockefeller, Jr. Memorial Parkway. It flows into Grand Teton National Park at the northern end of Jackson Lake, and empties out of the lake at the Jackson Lake Dam. The river then travels southwest through Jackson Hole.

The Snake River has both roaring rapids and gentle meanders. Marston (1993) characterized the stream channel as having pools (slow, deep water with little or no surface agitation), glides (fast, deep water with little or no surface agitation), riffles (fast, shallow water with surface agitation but no standing waves), and rapids (fast, deep water with considerable surface agitation, including standing waves). Depending on gradient and sediment load, stretches of the river can be meandering, braided, channelized, or have compound channels that are transitional between meandering and braiding (Graf 1988). Sections of the streambed can be bedrock or made of boulders, cobbles, gravel, sand, silt, or clay (Marston 1993).

Sediment load in the system depends on the erodibility of bedrock and the availability of glacial outwash. Mass wasting contributes large volumes of bedload to streams draining from the east (Wyoming State Engineer's Office 1972). Additionally, large alluvial fans of quartzite cobbles provide a ready input of material where Pilgrim Creek and Spread Creek flow into the Snake River (Pierce and Good 1992). The Ditch Creek fan, one of the largest alluvial fans in the western United States, was deposited at the creek's emergence from the mountains east of Jackson Hole. This fan constitutes another significant supply of sediment in the park (Smith and Siegel 2000). Streams crossing alluvial fans are considered chronically unstable because they may shift tens of meters in a single, high-flow event (Mott 1998).

The high aggradation and lateral migration rates of the Snake River system confound attempts to restrict its flow path to bridge openings, such as that over Spring Creek. Future damage may best be avoided by redesigning or relocating this bridge (Mott 1998). Aggradation also causes boat launch areas (e.g., Deadmans Bar) to fill with sediment. The National Park Service allows minor dredging operations in the immediate vicinity of launch areas to provide visitor access to the river (Mott 1998).

Pleistocene topographic features control the course of the Snake River through Grand Teton National Park. It follows the giant glacial scour filled by Jackson Lake, and flows out of Jackson Lake to the east rather than to the west (expected under control of the Teton fault) following a basin excavated by the westward-flowing Pacific Creek glacial lobe during the Burned Ridge glaciation (see "Geologic History" section). The river runs through a rib of glacially eroded bedrock (Mesaverde Formation) just below the mouth of Pacific Creek, and passes through a topographic low between two outwash fans of different glacial phases (Burned Ridge and Hedrick Pond) between Deadmans Bar and Moose (Pierce and Good 1992).

Now, anthropogenic features also control the river's course. Below Moose, the U.S. Army Corps of Engineers built a 48-km- (30-mi-) long system of levees that blocks the river's lateral spread, reducing floodplain width and channel braiding. The levee system also changes sedimentation patterns. Fine material is moved through the system rather than being deposited in lower-energy secondary channels, which would be present in an unmodified system. Bedload is also moved more frequently in the main channel. Furthermore, levee maintenance necessitates almost annual channelization, which is especially destructive to trout habitat (Kiefling 1978).

Another levee system is located along Pilgrim Creek, just east of Jackson Lake Dam. The left abutment of Jackson Lake Dam rests on the alluvial fan deposited by Pilgrim Creek. After construction of the dam, Pilgrim Creek changed course and flowed below the dam to merge with the Snake River. This realignment brought Pilgrim Creek close to the town of Moran, occasionally flooding the town site. The Bureau of Reclamation subsequently built levees to push Pilgrim Creek north into Jackson Lake and alleviate the local flooding problem (Gary Smillie, NPS Water Resources Division, Hydrologist, personal communication *in* Mott 1998, p. 41).

While Bureau of Reclamation concerns over dam safety have served to justify the maintenance of the Pilgrim Creek levee system, such maintenance now may be unnecessary for three reasons: (1) the town of Moran no longer exists in its former town site, (2) flood control on the Snake River can be accommodated through modified dam releases, and (3) armoring of the dam abutment is a viable alternative. The park's desired future conditions for the Snake River system specify that natural processes should be allowed to occur unimpeded to the maximum possible extent, and that existing and future development of facilities should minimize the effects on or alteration of such processes (Sue Consolo-Murphy, Grand Teton National Park, Chief of Science and Resource Management, written communication, 2006). An analysis and declaration by the U.S. Army Corps of Engineers that maintenance of the levee system is unnecessary would allow restoration of the natural migration dynamics associated with Pilgrim Creek (Mott 1998). Lord et al. (2009) suggested six "vital signs" and monitoring methods for fluvial geomorphology: watershed landscape, hydrology, sediment transport, and channel cross section, plan form, and longitudinal profile.

Glaciers and Climate Change

The 1968 U.S. Geological Survey topographic map of Grand Teton National Park (scale 1:62,500) shows nine named glaciers. Mount Moran hosts five of these glaciers: the three Triple Glaciers on the north face, prominent Skillet Glacier on the east face, and Falling Ice Glacier on the southeast face. Teton Glacier lies in the shadow of Grand Teton, and Middle Teton Glacier lies east of the ridge between Middle Teton and Grand Teton (fig. 5). Schoolroom Glacier lies on the park boundary east of Hurricane Pass, and Petersen Glacier is situated above Mica Lake along the park's western boundary. The 1968 map also identifies approximately 136 other undifferentiated glaciers or perennial snow fields.

During a warm period following the Pleistocene ice ages, the glaciers in this region melted completely. Thereby, the park's extant glaciers are not remnants of the large Pleistocene glaciers that once filled the valleys in the Teton Range, but vestiges of ice masses built up during the Little Ice Age (1400–1850 C.E. [Common Era; preferred to "A.D."]). These modern glaciers can be conceived as small-scale models of the great ice masses that shaped and sharpened the Tetons during the Pleistocene (Love et al. 2003). They are also significant reservoirs of water, supplying late-summer agricultural and recreational needs. Moreover, the timing and intensity of peak flow of glacial meltwater affects ecological systems (Elder et al. 1994).

With the exception of Falling Ice Glacier, which has southeast exposure, the glaciers in the national park face north or east. All lie in the shadow of major peaks, "whose sheer walls, rising to the south and west and towering hundreds, or even thousands of feet above them, have furnished the protection without which they would long since have dwindled to snow fields" (Fryxell 1935, p. 385). Falling Ice Glacier persists because of the depth of its cirque and the protection it receives from the huge horns along the southeastern slope of Mount Moran, which block direct sunlight from hitting the glacier's surface for a significant portion of the day (Fryxell 1935).

Snow added to glacier mass is supplied in at least three ways. First, seasonal snow adds mass. These inputs may greatly exceed expected quantities for the region, at least on the Teton Glacier (Elder et al. 1994). Second, avalanches nourish some of the glaciers (e.g., Teton Glacier) (Reed 1964). Third, abundant light, dry winter snow drifts with the prevailing southwest winds and collects in catchment basins on the lee side of the range.

The park's glaciers are often characterized as small or dwindling; anecdotal evidence provided by park employees during scoping suggests that their surface area perceptibly diminishes each year (Covington and Ransmeier 2005). However, a thorough inventory of the park's glaciers has not been conducted to date, and long-term documentation is sparse. Past records of glacier extent show both advance and retreat, although the overall trend is one of retreat.

In 1935, Fritiof Fryxell of Augustana College (Illinois) published his observations of seven glaciers in Grand Teton National Park—Middle Teton, Teton, Falling Ice, Skillet, and the Triple glaciers. The study provided the geomorphic/geographic setting, described the glaciers and glacial features, and presented the history of Pinedale advances in each glacier's valley (Fryxell 1935).

In the mid-1960s, Jack Reed of the U.S. Geological Survey published his observations (sketch maps, profiles, and reports) of the Teton Glacier (Reed 1964, 1965, 1966, 1967). Reed (1966) discussed photographs from 1898 showing the terminus of the Teton Glacier situated level with the crest of the conspicuous terminal moraine that was probably deposited during a Neoglacial advance. At that time, the glacier was about 1,220 m (4,000 ft) long; the terminus retreated about 150 m (500 ft) between 1898 and 1954.

Analysis by Reed (1964) used a 1929 photo by Fryxell (Fryxell 1930) that shows the ice surface of the Teton Glacier at 12 to 15 m (40 to 50 ft) below the crest of the terminal moraine. The change in glacier extent between this 1929 photograph and the photos and map provided by Reed (1964) show that the glacier had retreated about 183 m (600 ft) and stood as much as 61 m (200 ft) below the crest of the terminal moraine in 1963. Between 1963 and 1966, the ice increased in thickness by a few feet and the glacier advanced about 15 m (50 ft).

Findings by Williams (1999) showed that the Teton Glacier was advancing after 31 years (1924–1955) of retreat. Between 1955 and 1998, the Teton Glacier increased approximately 8 m (26 ft) in thickness and 20 m (66 ft) in length. A 5-m (16-ft) increase in thickness in the upper part of the glacier since 1990 suggested that the terminus would continue to advance temporarily (Williams 1999).

In 2009 Glenn Tootle (University of Wyoming) presented findings of a preliminary analysis of aerial photographs and remote-sensing images, suggesting that the Teton Glacier had lost 17% of its areal extent between 1967 and 2006 (Glenn Tootle, University of Wyoming, Assistant Professor, unpublished abstract, September 2009).

Plummer (2004) and Plummer and Cecil (2005) used mathematical models to simulate the response of alpine glaciers in Wyoming to projected climate change. Their findings showed that most of the Teton Glacier will have melted within 30 to 75 years. Karpilo (2009) suggested four "vital signs" and monitoring methods for glaciers: glacier mass balance, glacier terminus position, glacier area, and glacier velocity.

Globally, retreating glaciers provide evidence for the "unequivocal" warming of the climate system (IPCC 2007). For information regarding climate change impacts in the United States, refer to Karl et al. (2009). The 2007 Intergovernmental Panel on Climate Change (IPCC) assessment report contains detailed scientific climate change information, viewable on their website at http://www.ipcc.ch/ (accessed July 30, 2010). The National Park Service Climate Change Response Program website hosts Servicewide climate change information at http://www.nature.nps.gov/climatechange/index.cfm (accessed July 30, 2010).

Mineral Resources and Management

According to Antweiler et al. (1989, p. 12), "the mineral commodities most worthy of study [in the Teton region] are those in sedimentary rocks and include oil and gas, gold in placers derived from conglomerates deposited in Laramide time, phosphate, metals in black shales, coal, gypsum, building stone, sand, and gravel." However, these authors found only low to moderate resource potential for these commodities.

Oil and Gas

Although there are no current oil and gas activities or leases in the park or parkway, development outside park boundaries could impact park resources. For instance, one of the largest onshore natural gas discoveries in the United States is Jonah Field, located in the Green River Basin southeast of the park and parkway. Geologists estimate that this field contains 297 billion cubic meters (10.5 trillion cubic feet) of gas. In 2007, the Bureau of Land Management approved a plan that would allow more than 3,000 wells to be drilled in the field over 75 years. The gas occurs in tight sands, allowing a higher well density for oil and gas recovery than that used in traditional oil and gas field development (Bureau of Land Management and State of Wyoming 2010). The Jonah Field is about 48 km (30 mi) south of Pinedale, Wyoming, and 160 km (100 mi) southeast of the national park, so air quality is the primary resource-management concern (Pat O'Dell, Geologic Resources Division, Petroleum Engineer, e-mail, October 26, 2009).

Oil and gas activity, including coal bed methane development, is currently taking place just northeast of the park boundary in the Bridger-Teton National Forest. The potential for hydrocarbon occurrence is high in the four Forest Service management areas of the Bridger-Teton National Forest: the Hoback, Moccasin, Wind River, and Green River basins (USDA Forest Service 1997).

The Hoback Basin drains directly into the Snake River, but the confluence of these rivers is downstream from Grand Teton National Park. The Moccasin, Wind River, and Green River basins lie immediately east of the Snake River drainage and abut the drainage divide, which is composed of carbonate strata (Noland and Miller 1995; Mott 1998). Cave systems could allow interbasin transfer of groundwater, carrying contaminants generated by drilling and oil and gas production outside the park to springs within the Snake River drainage and Grand Teton National Park (Mott 1998).

Gold

Exploration for gold in the mid- to late-1800s was minimally successful in the Teton region, and did not generate a "rush" to the area. Most gold prospectors engaged in placer mining, which left little lasting impact on the landscape. A few abandoned mine structures, pits, and ditches used in placer mining are the only remaining evidence of this past mining activity.

Phosphate

The Permian Phosphoria Formation contains large deposits of phosphorite (calcium phosphate) that is commercially mined in Wyoming, Idaho, Utah, and Montana for the manufacture of fertilizer and the production of phosphorus. The Phosphoria Formation crops out in the northern part of the park near Jackass Pass and Harem Hill (Love et al. 1992).

Coal

Miners had more success with coal extraction than with gold in this region. Coal in the Bacon Ridge Sandstone and Sohare Formation has economic potential (Antweiler et al. 1989). The Frontier and Mesaverde formations also contain coal, but the beds are thin and the coal is impure (Antweiler et al. 1989). Within the park, subbituminous coal was excavated from an area near the Jackson Lake Dam during construction and from a mine on Blacktail Butte.

Gypsum

The Chugwater and Gypsum Springs formations contain gypsum (used in drywall), but the beds exposed in the Teton–Jackson Hole area are thin and inaccessible compared to the large deposits in the Bighorn and Wind River basins to the southeast (Antweiler et al. 1989).

Building Stone

The Cambrian Flathead Formation and Mississippian Madison Limestone can serve as attractive building stones for patios, walkways, and garden walls. The geologic map shows two areas where outcrops are accessible from U.S. Route 89: Madison Limestone crops out north of Moose Junction, and the Flathead Formation is accessible near the picnic area northwest of Arizona Island, along the shoreline of Jackson Lake.

Residents of Teton County have also used Huckleberry Ridge Tuff for building stone; it is colorful (red, orange, pink, purple, and gray), lightweight, moderately durable, and easily cut and shaped. Significant sections of U.S.

Route 89 were cut through the Huckleberry Ridge Tuff in John D. Rockefeller, Jr. Memorial Parkway (Appendix A). The Bureau of Reclamation opened a large quarry at the northwestern end of Signal Mountain that produced riprap for the adjacent Jackson Lake Dam (Antweiler et al. 1989).

Mineral Crystals

Rock collectors may be tempted by the soapstone in the park, as well as mica- and garnet-studded gneiss and pegmatite. American Indians were the first to mine soapstone (talc) in this area. Scientists have documented several archaeological sites associated with these mines in the Teton Range, at least one of which is within the park (Sue Consolo-Murphy, Grand Teton National Park, Chief of Science and Resource Management, written communication, 2006). Soapstone is dark green or black, serpentinized, and heavy. Rock collectors remove soapstone pebbles from streams draining the west side of the Tetons, cut and polish them, and sell them as "Teton jade" (Love et al. 2003). Ultramafic rocks ("Wu" on Map Unit Properties Table and Appendix A) are the source of Teton jade.

Pegmatite is an exceptionally coarse-grained rock with interlocking crystals. Some pegmatite contains plates or tabular crystals of silvery white mica (muscovite) up to 15 cm (6 in) wide, which can be split easily into transparent sheets. Other forms of pegmatite contain dark-brown mica (biotite) in thin, blade-shaped crystals. In Garnet Canyon, some pegmatite bodies contain scattered red-brown garnet crystals. These crystals have a distinctive "soccer ball" shape and range from roughly 8 mm (0.3 in) to more than 8 cm (3 in). The garnets are fractured and many are partly altered to chlorite (a dull-green micaceous mineral), so they are of no value as gems (Love et al. 2003). The Archean Mount Owen Quartz Monzonite, granitic rocks of the Gros Ventre Range, and Webb Canyon Gneiss all contain intrusions of pegmatite (Love et al. 1992).

To protect these resources from unauthorized collecting, scoping participants suggested that park staff monitor the accessible areas known to contain these minerals (Covington and Ransmeier 2005). Several soapstone prospects are located west of the park, near Rammel Mountain (Love et al. 2003). Garnet Canyon hosts garnets of geologic interest, and mica occurs in pegmatite exposures.

Sand and Gravel

According to the Federal Highway Administration (1991), Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway contain 396 km (246 mi) of roads. This road system is maintained by the National Park Service in cooperation with the Federal Highway Administration and Wyoming Department of Transportation. Road maintenance requires aggregate (i.e., sand and gravel). An estimated 1.4 million m^3 (1.8 million yd^3) of suitable materials is required over a 20-year period to preserve and maintain the integrity of roads and other infrastructure in the park and parkway (Federal Highway Administration 1991). Ironically, glacial deposits and the Snake River tributaries supply an abundance of these materials within the park, but there is a shortage of external commercial sources within reasonable hauling distance (National Park Service 1986). NPS policy prohibits the development of new borrow pits on NPS lands and stipulates that present borrow pits not be utilized unless economic factors make it impractical to import materials.

In 1987, 30,582 m^3 (40,000 yd^3) of material were excavated from the Gros Ventre River on National Elk Refuge lands immediately upstream from the bridge over U.S. Route 89. Future aggregate needs may be satisfied by materials from the Spread Creek drainage on USDA Forest Service lands adjacent to the park (Mott 1998). The Spread Creek drainage area covers about 280 km^2 (108 mi^2) and enters the Snake River about 13 km (8 mi) downstream from Jackson Lake Dam. The upper reaches of Spread Creek cut through landslides and transport large volumes of alluvial material downstream. Transported material is deposited behind and downstream of a diversion structure located 1.6 km (1 mi) upstream of the park–national forest boundary, adjacent to the proposed mining site (National Park Service 1997). The stream gradient decreases, water velocity slows, and sediment (i.e., sand, gravel, and cobble) deposition increases below the diversion. The proposed extraction and staging area is outside the base floodplain on an elevated glacial outwash deposit (National Park Service 1997). Environmental assessment of future aggregate mining in the area does not anticipate any impacts to wetlands (Mott 1998).

Abandoned Mine Lands

The National Park Service Abandoned Mine Lands (AML) database (accessed August 11, 2010), there are 40 AML features at 39 sites within Grand Teton National Park. One feature at one site is listed for John D. Rockefeller, Jr. Memorial Parkway. Most of the abandoned mines in the park are not considered safety hazards to park visitors. However, scoping participants suggested that the National Park Service evaluate the Webb Canyon adit for possible closure (Covington and Ransmeier 2005). Such an inspection could be completed by staff from the NPS Geologic Resources Division.

Grand Teton National Park contains 38 borrow pits from which at least 76 m^3 (100 yd^3) of material have been excavated. The pits range in size from 0.04 ha to 16 ha (0.1 ac to 40 ac) (National Park Service 1986). Many of these pits predate the park, and most have been abandoned. However, some borrow pits are still in use, primarily for storage of aggregate and other materials, vehicle storage, and construction staging (John Moeny, Grand Teton National Park, Biologist, e-mail, February 19, 2010).

The National Park Service has been involved in restoration efforts to reclaim some of the abandoned borrow pits, primarily those that impact wetlands (Covington and Ransmeier 2005). For example, the Snake River pit (lower) was a gravel mine from the 1960s through 1990s; the National Park Service is currently restoring the former borrow pit to a wetland, although a 2-ha (5-ac) portion will be retained as road-construction staging (John Moeny, Grand Teton National Park, Biologist, e-mail, February 19, 2010).

John D. Rockefeller, Jr. Memorial Parkway managers are restoring a 3-ha (8-ac) abandoned gravel mine on the Snake River floodplain to a mosaic of willow thickets, marshes, wet meadows, ponds, and associated uplands. The restored site will provide important wildlife habitat for grizzly bears, trumpeter swans, moose, sandhill cranes, western boreal toads, and many other wildlife species (Wagner 2009). In spring and early summer 2010, Intermountain Aquatics, an NPS contractor, planted approximately 130,000 nursery-grown, native wetland grasses and sedges, as well as willow stakes as part of this ongoing restoration effort (Joel Wagner, NPS Water Resources Division, Wetland Program Leader, e-mail, July 29, 2010).

Bentonite

Chemical weathering alters volcanic ash into bentonite, a claystone with the ability to absorb large quantities of water by greatly increasing in volume (Neuendorf et al. 2005). Rocks containing bentonite swell when wet and shrink when dry, causing the ground surface to heave and buckle. Such shrink-and-swell processes can impact structures, roads, and trails constructed on bentonite beds, producing heaved sidewalks and roads, cracked and failed foundations, and slippery and treacherous trails. Bentonitic clays occur near the park boundary in the Toby Pass area and in isolated lenses near Ditch Creek and Lost Creek (Covington and Ransmeier 2005).

Covington and Ransmeier (2005) stated that the corner of the Jackson Lake Lodge built on the Teewinot Formation had apparently been affected by bentonite shrink and swell. However, neither Love et al. (1992) nor Antweiler et al. (1989) identified bentonite in the Teewinot Formation. Heaving and subsidence may thus be a result of other factors, such as the location of building sites on improperly compacted fill material or improper drainage around foundations (Pete Biggam, Geologic Resources Division, Soil Scientist, e-mail, February 23, 2007). A site visit by a soil scientist could confirm the source of the problem. The proper identification of areas with clay soils is especially important for future infrastructure development. Rock units with bentonite beds can serve as salt licks for deer and elk. For example, bentonite in the Frontier Formation contains a bitter salt, and ungulates have licked 0.6-m (2.0-ft) holes into some hillside sites (Antweiler et al. 1989).

Bentonite is also a mineral resource, although the bentonite lenses in the rocks of the Teton region are probably insufficiently thick, pure, or accessible for economic use (Antweiler et al. 1989).

Cave and Karst Resources

Because the central Teton Range is composed almost completely of insoluble Precambrian rock, it does not contain cave or karst features. However, thick sequences of Paleozoic strata north and south of the central range contain soluble limestone and dolomite. These rocks—notably the Madison Limestone, the Death Canyon Limestone Member of the Gros Ventre Formation, and the Bighorn Dolomite—are known to contain caves. The National Park Service has documented 17 caves within Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway (Ron Kerbo, NPS Geologic Resources Division, Cave Specialist, personal communication *in* Covington and Ransmeier 2005, p. 10).

Most of the caves south of the crystalline core (uplifted Precambrian rocks) are located outside of Grand Teton National Park in the Targhee National Forest, but Plantz (1978) identified caves in the Death Canyon–Spearhead karst area in the southern part of the park. Rendezvous Peak Cave, the deepest known cave in Wyoming, is also located in this southern limestone area (Hill et al. 1976). This vertical cave formed in the Death Canyon Limestone Member of the Gros Ventre Formation. Plantz (1978) also identified caves in The Wall and Moose Basin Divide limestone areas north of the crystalline core.

Most of the caves are small and only Hole-In-The-Wall Cave receives significant traffic and requires management (Plantz 1978). Plantz (1978) found evident damage to speleothems in the cave that constitutes an ongoing management concern.

In addition to cave resources, karst topography and associated hydrologic conditions are present to the north and south of the central Tetons. Sound and responsible infrastructure planning requires awareness of groundwater flow patterns and areas susceptible to sinkhole formation (Covington and Ransmeier 2005). Toomey (2009) suggested 11 “vital signs” and monitoring techniques for caves and kart landscapes: cave meteorology, airborne sedimentation, direct visitor impacts, permanent or seasonal ice, cave drip and pool water, microbiology, stability, mineral growth, surface expression and processes, groundwater levels and quality, and fluvial processes.

Climbing

The Teton Range has played a pivotal role in the development of climbing and mountaineering in the United States. Authors have called the region “the home of American mountaineering” and “the center of United States alpinism,” highlighting its importance in the evolution of American climbing (Jones 1976).

The designation of appropriate climbing equipment for use in Grand Teton National Park is currently a matter of intense debate. Many climbers believe that the installation of permanent hardware (e.g., pitons and bolts) along climbing routes compromises the integrity of the rock and poses a potential safety risk. Drilling to install hardware is not allowed in the park, nor are scarring, chiseling, or gluing holds. Included in “good climbing practices” at Grand Teton National Park are not leaving fixed protection and anchors and pre-trip planning of climbs, including review of route descriptions to determine the locations of rappels, belay stations, and fixed pitons (National Park Service 2010).

The changing conditions of glaciers and snowfields can endanger climbers. While alpine climbers in the park are accustomed to planning for daily and seasonal changes in snow and ice conditions, glacial retreat due to long-term changes in climatic conditions may remove the support provided to unconsolidated moraine material and cliff walls by glacial ice. These landscape changes could prove hazardous to unsuspecting climbers.

Jackson Lake Dam

Jackson Lake is the largest piedmont lake in Jackson Hole. In 1906, the Bureau of Reclamation modified the natural lake by damming the outlet with a small timber crib dam, which failed in 1910. The following year, the Bureau of Reclamation replaced the dam with a larger structure and associated concrete spillway and earthen embankments. Huckleberry Ridge Tuff supports the south end of the concrete section, but the long dike to the north was built on unconsolidated sediments at least 180 m (600 ft) thick (Gilbert et al. 1983).

The Teton Dam, located on the Teton River west of the Teton Range, ruptured in 1976. The resulting catastrophic flood killed 11 people. This disaster prompted the Bureau of Reclamation to evaluate the safety of other dams in the area, including the Jackson Lake Dam. The ensuing study revealed that the Jackson Lake Dam was susceptible to failure during an earthquake larger than magnitude-5.5. The upper 30 m (100 ft) of glacial fill contains sand beds that are subject to liquefaction (Pierce and Good 1992). Hence, between 1986 and 1989, the Bureau of Reclamation upgraded the dam to withstand the maximum credible earthquake, which is magnitude-7.5 on the Teton fault (Bureau of Reclamation and National Park Service 1984). The liquefiable sediments were strengthened by a combination of dynamic compaction, achieved by repeatedly dropping a 27,000-kg (30-ton) weight from a height of 30 m (100 ft), and by in-situ injection and auger mixing of cement to form concrete pilings (Pierce and Good 1992). Structural improvements to the dam in the late 1980s have greatly reduced the possibility of its failure (Mott 1998).

Failure of the Jackson Lake Dam would flood a 130-km (80-mi) downstream area extending to the Palisades Dam. The town of Jackson, situated away from the river, would not be flooded. However, flooding would impact the area south of town, possibly destroying bridges and impeding access to Jackson. Total collapse of the dam and reservoir would produce an outflow exceeding 11,300 m^3 (400,000 ft^3) per second, with peak flows sustained by the large volume of Jackson Lake (Mott 1998). The reservoir currently covers approximately 10,270 ha (25,370 ac) at full pool, and stores more than 1 billion m^3 (847,000 ac-ft) of water (Mott 1998). If failure occurred during heavy spring runoffs and the Palisades Reservoir downstream was nearly full, the necessary release of large volumes of water from this reservoir could flood agricultural land farther downstream, along the Snake River Plain in Idaho (Smith and Siegel 2000). Flooding could also cause sediment and bacterial contamination of water supply wells (Mott 1998), and destruction of buildings and floodplain vegetation in locations where velocity, depth of flow, and debris movement were significant (Glass et al. 1974).

An earthquake of sufficient magnitude to cause the dam's failure could also produce a seiche on Jackson Lake. The resulting 1.8-m- (6-ft-) high waves (Smith and Siegel 2000) would affect water recreationists and moored boats, as well as people and infrastructure in the vicinity of the lake.

The primary geomorphic changes of the Snake River system due to the impoundment of Jackson Lake are the decline in magnitude and frequency of peak flows and reduced channel avulsion (Marston 1993). These changes occurred after the Palisade Reservoir began operating in 1957 (fig. 6). The decline in peak flows has reduced the Snake River's ability to transport bedloads. The river aggrades and avulses in areas of sediment input (e.g., near cut banks and tributaries), but does not transport sediment from these unstable (more sinuous) areas to stable (less sinuous) areas with less avulsion and lower sediment inputs (Marston 1993; Mott 1998).

These geomorphic changes have altered the distribution and character of riparian resources at Grand Teton National Park. Forested vegetation communities, used by raptors, have expanded at the expense of willow-alder shrub swampland, which constitutes prime habitat for moose (Marston 1993). The decline in channel avulsions has eliminated numerous side channels that formerly served as spawning and rearing habitat for cutthroat trout (Marston 1993).

Paleontological Resources

Tracy (2003) conducted a comprehensive paleontological survey of Grand Teton National Park that listed 160 species: five trilobites, 71 brachiopods, 28 gastropods, three cephalopods, three lagomorphs, four insects, 10 rodents, two artiodactyla, and 34 plants. The plant species included a cycad-like species, gymnosperms, vascular plants with spores, ferns, sequoia, deciduous trees, ficus, flowering plants, tropical chestnut-like trees, and evergreen trees and shrubs. Twenty-eight rock units that occur in the park are considered fossiliferous, and many have yielded fossil specimens (see Map Unit Properties Table). Tracy (2003) inventoried and documented fossil localities in 13 of these rock units.

The oldest fossils discovered in the park are trilobites from the Cambrian Period (500 million years ago) and the youngest are 9,000-year-old gastropods from the Holocene. Paleozoic rocks contain the most fossils (table 1), and the Mississippian Madison Limestone is the most fossiliferous unit in Grand Teton National Park (Tracy 2003).

The 2009 Paleontological Resources Preservation Act outlines a science-based management, education, and interpretation plan for fossil resources, which are nonrenewable. Tracy (2003) identified areas in Grand Teton National Park where paleontological resources are at high risk because of fossil abundance and ease of access. At least one of these areas contained evidence of deliberate fossil poaching. Paleontological resource monitoring strategies should focus on those areas. The sites may also provide opportunities for interpretation and education regarding the National Park Service resource stewardship mission.

The National Park Service has compiled guidance documents to help resource managers manage paleontological resources (National Park Service 2004). Santucci et al. (2009) identified "vital signs" for monitoring impacts to paleontological resources: geologic and climatic variables affecting natural erosion rates, catastrophic geologic processes or geohazards, hydrology and bathymetry (i.e., changes in water level affecting resources near water bodies), and human impacts. Plans to reduce human impacts could include locating future development (e.g., trails and infrastructure) away from fossil localities and increasing the frequency of park-staff presence at these sites. Because paleontological localities vary widely, all of these processes may not be relevant at each fossil site.

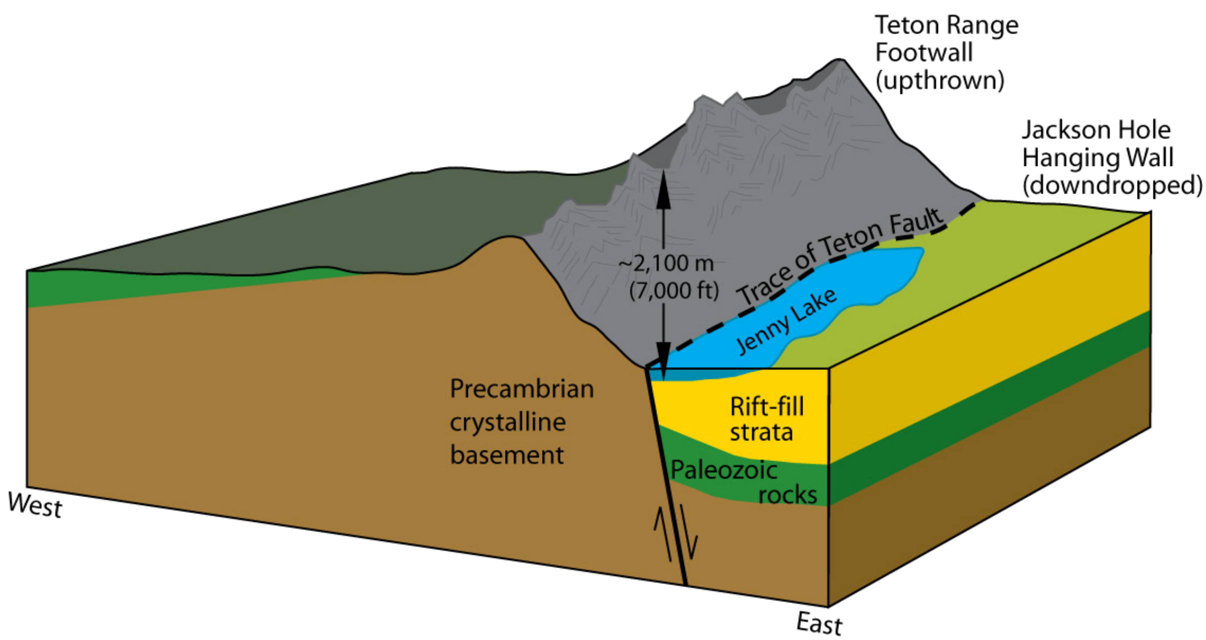

Figure 2. Teton Fault. The Teton Range rises more than 2,100 m (7,000 ft) above the floor of Jackson Hole. The Teton Range is part of the upthrown footwall block of the fault, while Jackson Hole is situated on the downdropped hanging-wall block. Modified from Lillie (2005) by Trista Thornberry-Ehrlich (Colorado State University).

Figure 3. Gros Ventre Slide. The 1925 Gros Ventre slide displaced 38 million cubic meters (50 million cubic yards) of rock 640 m (2,100 ft) down the side of Sheep Mountain. This slide is just east of the park (see fig. 1). National Park Service photograph by Cooper. Available online: http://www.nps.gov/grte/photosmultimedia/photogallery.htm (accessed July 16, 2010).

Figure 4. Gros Ventre Slide Boulders. Large boulders of Tensleep Sandstone are visible near the toe (bottom) of the Gros Ventre slide (fig. 3). U.S. Geological Survey photograph. Available online at the 3-D Geology of National Parks website: http://3dparks.wr.usgs.gov/grte/index.html (accessed July 16, 2010).

Figure 5. Middle Teton Glacier. The present-day glaciers in Grand Teton National Park lie in the shadows of major peaks. National Park Service photograph from 2005 by K. Finch. Available online: http://www.nps.gov/grte/photosmultimedia/photogallery.htm (accessed July 16, 2010).

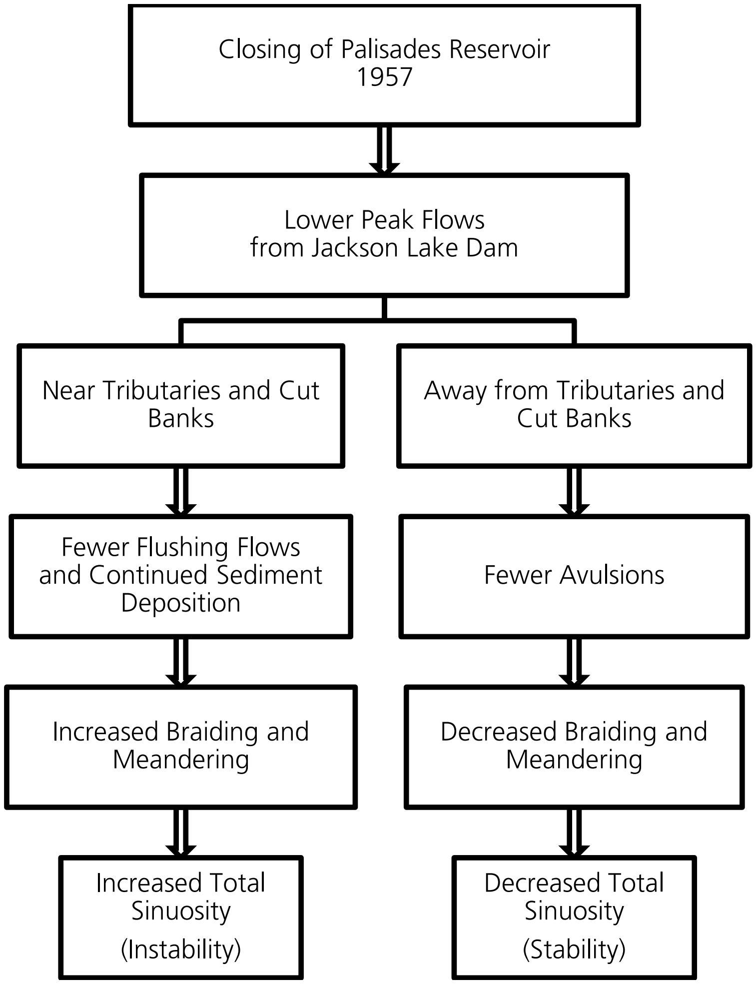

Figure 6. Model of Geomorphic Changes to Snake River System. The primary geomorphic changes to the Snake River system resulting from impoundment of Jackson Lake are the decline in magnitude and frequency of peak flows and decreased channel avulsion. These geomorphic changes have altered the distribution and character of riparian resources at Grand Teton National Park. Graphic from Marston (1993), NPS project no. GRTE-W89-0110.

Table 1. Fossiliferous Paleozoic Strata in Grand Teton National Park

Age	Rock Unit	Fossils
Permian	Phosphoria Formation	Marine fossils (e.g., bivalves) Trace fossils
Mississippian	Madison Limestone*	Bivalves, brachiopods, crinoids, corals, and gastropods
Ordovician	Darby Formation Bighorn Dolomite	Marine fossils: crinoids, brachiopods, and ostracodes Darby Formation also contains stromatolites
Cambrian	Gallatin Formation Gros Vente Formation	Trace fossils, trilobites, and bivalves

Source: Tracy (2003).
*Most fossiliferous unit in Grand Teton National Park

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway.

Ancient Rocks

Although a number of National Park System units host Precambrian (Archean and Proterozoic) rocks, only two contain Archean rocks (the oldest rocks on Earth): Voyageurs National Park in Minnesota (Graham 2007) and Grand Teton National Park. Grand Teton National Park thus contains some of the oldest rocks in the National Park System.

Archean rocks are 4 billion to 2.5 billion years old. During the Archean Eon, masses of rock called cratons formed the initial structures of continents. Today, Archean rocks are found in areas such as the Superior Upland, including Voyageurs National Park, and the Rocky Mountains, including Grand Teton National Park (fig. 7).

The oldest known rocks in the Superior Upland region are between 3.7 and 3.5 billion years old (Peterman 1979). These metamorphic rocks (gneiss) crop out in the Minnesota River Valley between New Olm and Ortonville, Minnesota (Boerboom 1994). However, the oldest rocks yet to be dated in Voyageurs National Park are tonalite, which Goldich and Fischer (1986), Davis et al. (1982), and Davis et al. (1989) dated as 2,729 million to 2,695 million years old.

The oldest rocks in Wyoming, located in the Beartooth Mountains, are 3.3 billion years old (Peterman 1979). Frost and Fanning (2006) obtained dates of 3,253 ± 10 million years old from zircon grains from these gneisses. However, the oldest rocks yet dated in Grand Teton National Park are the Webb Canyon Gneiss, which Zartman and Reed (1998) dated to 2,680 ± 12 million years old.

Both Voyageurs and Grand Teton national parks host rocks that are older than those for which dates have been obtained. The ages of the rocks predating the Webb Canyon Gneiss in Grand Teton National Park and the tonalite in Voyageurs National Park, however, remain unknown.

Young Mountains

In contrast to the age of its rocks, the Teton Range is geologically young. The range is the youngest in Wyoming and among the youngest of the Rocky Mountain ranges. For example, in the vicinity of the park, the Washakie, Gros Ventre, and Gallatin ranges and the Beartooth Mountains formed 70 million to 50 million years ago during Laramide mountain building. The Snake River Range is another young mountain range, although it is older than the Teton Range. Major displacement in the Snake River Range occurred during the Neogene (23 million to 2.6 million years ago) and movement has since ceased (Lageson et al. 1999). By contrast, the Teton Range is seismically active and continues to rise. Although Laramide uplift did influence the Teton Range, its present height was primarily created by uplift during the last 5 million years, as a result of activation of the Teton fault, which elevated the Tetons while dropping Jackson Hole (see "Seismic Activity" section).

A distinctive feature of "young" mountains is their steep slopes, sharp ridges, and pointed peaks yet to be muted by erosion. This craggy appearance contrasts greatly with the mound-shaped peaks, gentle ridges, and gradual slopes of "old" mountains. In the case of the Teton Range, these sharp features were enhanced by the sculpting of alpine glaciers.

Dikes

Cross-cutting dikes form distinctive lithologic features at Grand Teton National Park. It is impossible to miss the "ribbonlike black dikes" (Love et al. 2003, p. 9) that splice the east face of Middle Teton or the "glittering mica-studded dikes" (Love et al. 2003, p. 8) along the Cascade Canyon Trail to Hidden Falls and Inspiration Point. Perhaps the most impressive dike in the park is exposed on the face of Mount Moran (fig. 8). As a result of differential erosion, this diabase dike protrudes from the surrounding gneiss. In contrast, diabase dikes on the Middle Teton are recessed in the surrounding granite. Dikes in the park cut across rocks as old as the Webb Canyon Gneiss (Archean) and as young as Cody Shale (Cretaceous). Tertiary basalt breccia also forms some dikes and flows (Love et al. 1992).

Dikes form when magma wells up into fissures in the country rock, cutting across the bedding or foliation of preexisting rocks. Composed of various types of igneous rock, dikes can be diabase, like that on Mount Moran, or pegmatite, such as those in Cascade Canyon.

Geothermal Features

Geothermal features—primarily hot and warm springs and associated pools—are present in Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. The Jackson Hole area hosts Huckleberry, Jackson Lake, Granite, and Astoria hot springs, as well as Kelly, Teton Valley Ranch, Abercrombie, and Boyles Hill warm springs, North Buffalo Fork Springs, and Camp Creek and Driggs wells (Love et al. 2003). Granite and Astoria hot springs have been commercially developed, and Teton Valley Ranch Warm Springs is privately owned. The two geothermal wells were encountered during oil and gas exploration. The map by Love et al. (1992) identifies "the hottest spring in the hot-springs area" on the western shore of Jackson Lake (fig. 9).

In 2004 the National Park Service conducted an inventory that documented 103 geothermal features. These features were located primarily at Huckleberry Hot Springs, but also at Polecat Hot Springs (both in John D. Rockefeller, Jr. Memorial Parkway), and at Jackson Lake Hot Springs, Kelly Warm Springs, and Abercrombie Warm Springs in Grand Teton National Park (Ann Rodman and Carrie Guiles; Yellowstone Center for Resources, Resource Information Exchange; Supervisory GIS Specialist and Cartographic Technician; PowerPoint presentation, 2006). The pH of these features varied from 6.5 to 7.9, and the temperature varied from 26°C to 67°C (79°F to 153°F). The investigators measured electrical conductivity ranging from 100 to 2,000 micromhos per centimeter (Ann Rodman, Yellowstone National Park, Supervisory GIS Specialist, e-mail to Sue Consolo-Murphy, 2005). Electrical conductivity is a measure of the concentration of dissolved minerals in the water; higher concentrations of dissolved materials produce higher electrical conductivity. The investigators also documented these features with digital photography, written descriptions, and GPS location data. These data are now part of the park's GIS (Sue Consolo-Murphy, Grand Teton National Park, Chief of Science and Resource Management, e-mail, October 9, 2009).

Some springs (e.g., Huckleberry Hot Springs) formed where groundwater is heated by igneous rock bodies at shallow depths, while others (e.g., Kelly Warm Springs) are probably heated by the downward movement of groundwater along permeable rock layers to depths where the increased temperature is sufficient to heat the water and cause it to rise toward the surface, possibly along faults (Love et al. 2003). Previous studies associated the thermal springs on the west side of Jackson Lake with the Teton fault (National Park Service 1986).

Glacial Features

"The Teton Range is unique and spectacular, not because it has been glaciated, for almost all mountains in the Rockies have been glaciated, but because of the tremendous magnitude of glacial carving" (Lageson and Spearing 1988, p. 212). Second only to faulting, glacial processes shaped the topography of Grand Teton National Park. Glaciation, particularly associated with the Pinedale glaciation (30,000 to 12,000 years ago), also created the topography and surficial features of the John D. Rockefeller, Jr. Memorial Parkway. Glacial ice completely covered the parkway during this time. Alpine glaciers sculpted the canyons and peaks in the Teton Range and larger glaciers flowed south through Jackson Hole.

Arêtes, Cirques, and Horns

Mountains that are, or have been, surrounded by glaciers tend to exhibit characteristic sharp ridges, craggy spires, and basins created by glacial sculpting (fig. 10). Glaciers carved canyons on all sides of the mountains in Grand Teton National Park, creating the striking glacial horns of Grand Teton, Middle Teton, and South Teton. Steep, straight ridges, called arêtes, often link horns, for example between Grand Teton and Mount Owen (the two highest peaks in the park). Arêtes also separate glacially gouged valleys.

Glacial cirques—amphitheater-like hollows eroded into a mountain mass—head many valleys in the park. The extant small glaciers occupy cirques once excavated by their large predecessors. For example, the Teton Glacier lies in a cirque at the head of Glacier Gulch, shaded by the arêtes of Grand Teton, Mount Owen, and Mount Teewinot.

Erratics

In many glaciated areas, large boulders called erratics become stranded when glaciers recede. These out-of-place rocks, some with glacial striations (see "Polish and Striations" section), demonstrate the effectiveness of glacial erosion and transport. They also exemplify glacial deposition, as they are scattered on bedrock surfaces different from their own lithologies. During the Bull Lake glaciation (160,000–130,000 years ago, and perhaps as early as 190,000 years ago), glaciers flowed out of the Tetons and joined the huge south-flowing glacier in Jackson Hole. The smaller valley glaciers left a train of erratics composed of Precambrian crystalline rock along the west side of Jackson Hole (Love et al. 2003).

Hanging Valleys

Few landscape features are more aesthetically beautiful than a hanging valley with a cascading waterfall spilling over its lip. Before glacial and fluvial sediment began to fill Jackson Hole, hanging valleys cut into the Teton Range above the main glacial valley of Jackson Hole. Today, however, the distribution of such hanging valleys above main valley floors is restricted to smaller, higher-elevation valleys in canyons such as Avalanche and Garnet. The discordant levels of the valley floors and their size differences are due to the greater erosive power of the main, trunk glacier. Differential erosion (between rock units of differing resistance) also contributed to the creation of the "stair steps" of Avalanche Canyon (Good and Pierce 1996).

Moraines

A glacier carries all sizes of debris at its base, surface, and within its body of ice, and deposits this material along its sides and snout. "Till" is the general term for the poorly sorted mixture of fine to coarse rock debris deposited directly from glacial ice. The most obvious landforms composed of till are moraines. Moraines can be rounded mounds or sharp ridges, depending on the presence of surrounding topographic features that may have constrained a flowing glacier, the duration of a glacier's stability in a particular position, and the amount of erosion that has taken place since deposition.

An end moraine forms at the lower end of a glacier. A terminal moraine is a form of end moraine that extends across a glacial valley and marks the farthest advance or maximum extent of a glacier. An end moraine commonly dams meltwater to create a lake. Such moraines impound the piedmont lakes at the base of the Teton Range. Jackson Lake was originally impounded by a terminal moraine, which is now supplemented by a dam constructed by the Bureau of Reclamation. The islands in Jackson Lake (Elk, Dollar, and Marie islands, and Donoho Point) are composed of debris of the Jackson Lake moraine (Love et al. 1992).

Lateral moraines form along the sides of glaciers and merge with an end moraine. Notable lateral moraines in the park occur along Buffalo Fork. Recessional moraines are end or lateral moraines formed during a temporary but significant pause in the final retreat of a glacier. Such moraines extend across the floor of Jackson Hole south of Jackson Lake (Love et al. 1992).

Outwash and Kettles

Meltwater "washes out" sediment from a glacier and deposits the material in a flat area in front of the glacier's snout. Glacial outwash covers Antelope and Baseline flats. In some areas of the park, outwash material is so thick (60 m [200 ft]) that it obscures the underlying deposits of previous glaciations (Elias 1996).

Depressions called kettles commonly pockmark outwash plains, such as in the Potholes area of the park. Kettles form when a block of stagnant ice becomes wholly or partially buried in outwash and ultimately melts, leaving behind a pit. Kettles can be a few or hundreds of feet long, but are generally wider or longer than they are deep. In many cases, water eventually fills the depression and forms a kettle pond or lake. Hedrick Pond, for which the middle advance of the Pinedale glacial phase was named, is a kettle lake (Pierce and Good 1992). Cow Lake, part of the hummocky pothole terrain seen from Jackson Point Overlook on Signal Mountain (Smith and Siegel 2000), is another example of a kettle lake.

Polish and Striations

Rocks and sediment adhering to the base and sides of glaciers act like sandpaper, scratching and smoothing the rock surfaces over which they pass. Though small in scale, glacial polish exemplifies glaciation in Grand Teton National Park. Striations are multiple, generally parallel, scratches inscribed on a rock surface that mark a glacier's flow path. Both smoothly polished and scratched rock faces below Inspiration Point identify glacial ice as shaping this landscape.

U-shaped Valleys

Stream-cut valleys are typically V-shaped prior to the appearance of glaciers. A glacier's movement down a valley straightens and widens it into a U shape. Avalanche, Garnet, Cascade, and Paintbrush canyons are classic examples of U-shaped glacial valleys. When glaciers retreat, the bottoms of U-shaped valleys commonly become flat, as they are filled by sediment deposited in lakes impounded by the terminal moraines.

Lakes

More than 100 lakes are nestled in the alpine area of Grand Teton National Park. These lakes range in size from 0.4 ha to 24 ha (1 ac to 60 ac) and occur primarily above 2,700 m (9,000 ft) of elevation (Mott 1998).

The piedmont ("foot-of-the-mountain") lakes of Jackson, Leigh, String, Jenny, Bradley, Taggart, and Phelps comprise the majority of surface water at Grand Teton National Park (Mott 1998). The largest of these, Jackson Lake, originally covered about 6,920 ha (17,100 ac) (National Park Service 1986). Jackson Lake Dam has expanded the lake to 10,336 ha (25,540 ac) at full pool (Mott 1998) (see "Jackson Lake Dam" section).

Additionally, approximately 75 kettle ponds of less than 0.2 ha (0.5 ac) to more than 14 ha (35 ac) punctuate the glacial drift south and east of Jackson Lake (Mott 1998).

Glacial processes during the three phases of Pinedale-age glaciation created these lakes and ponds. The trough along the front of the Teton Range, which formed during Miocene activation of the Teton fault, initiated the formation of the deep Jackson Lake basin. An ancestral Jackson Lake may have existed during the Miocene (Smith and Siegel 2000). A combination of faulting and glacial scouring created the deepest part of Jackson Lake (i.e., the western trough), which is 133 m (437 ft) deep. The shallowest eastern trough, which is 43 m (142 ft) deep, was primarily carved by glaciers (Smith et al. 1993; Smith and Siegel 2000).

Loess

Loess (windblown dust) commonly forms when winds blow across exposed outwash deposits. The geologic map of Grand Teton National Park shows notable loess deposits on Timbered Island and between Phelps and Taggart lakes (Appendix A) (Love et al. 1992). Loess deposits near the Snake River are thicker than 3 m (10 ft) (Glenn et al. 1983), and those on the high terraces south of Jackson reach 6 m (20 ft) in thickness (Good and Pierce 1996).

Although loess is underrepresented on most geologic maps, investigators of Quaternary climate change have renewed scientific interest in this sediment type (Madole 1995). Thick loess sequences contain detailed records of Quaternary glacial-interglacial cycles. Like the foraminiferal oxygen isotope record of deep-sea sediments, these loess deposits document long-term climate change (Muhs et al. 1999). Loess is also a direct record of atmospheric circulation, supplying paleowind data that researchers can use to test atmospheric general circulation models (Muhs et al. 1999). In addition, widespread eolian deposits are important sources of information for reconstructing the history of aridification in the interior of North America during the Quaternary (Madole 1995).

Soil development, mapped moraine sequences, and loess data allowed investigators to correlate local Munger glaciation deposits with the regional Bull Lake glaciation (Pierce and Good 1992). In Grand Teton National Park, these deposits are characterized by a well-developed soil that is commonly buried by loess of the Pinedale glaciation (Pierce and Good 1992).

Oxbows

The influence of the Teton fault on the Snake River system is illustrated by the unusually deep water (5 m [15 ft]) at Oxbow Bend. "This deep, tranquil stretch of the Snake River may result from backtilting on the Teton fault, elevating the bedrock threshold just downstream from where Pacific Creek joins the Snake River" (Pierce and Good 1992, p. 38) With the exception of depth, the oxbows at this location are classic examples of this geomorphic form. As the river migrates across the floodplain, it creates closely looping stream meanders. The piece of land left between the two endpoints of the meander is the "ox's neck." Eventually, the stream will cut across the narrow neck, abandoning the meander and creating an oxbow lake. An abandoned oxbow thus marks a former course of the river.

Terraces

The gravel terraces along the Snake River are among the most striking geomorphic features in Grand Teton National Park. These ancient floodplains flank the Snake River as it flows south through Jackson Hole, rising 43 m (140 ft) on either side of the river (figs.11 and 12).

Terraces are evidence of the dynamic nature of the Snake River over thousands of years and reflect the active history of glaciation and tectonic movement in Jackson Hole (Marston 1993). During glacial advances, excessive debris in meltwater streams leads to rapid aggradation of their beds through thick accumulations of sand and gravel. When glaciers retreat, streams swollen with meltwater cut trenches into the accumulated outwash, thereby deepening their channels and producing terraces. Terrace tops are therefore built during glacial advances, and terrace faces are cut during glacial retreat (Harris and Tuttle 1990). Paired terraces on opposite sides of the stream channel represent the same former floodplain. Unpaired terraces indicate the erosional removal or depositional burial of the terrace on one side of the valley. Tectonics may also disturb terrace forms.

Love et al. (1992) mapped the terraces in Grand Teton National Park as terrace gravel (Qtg) and outwash gravel forming terraces graded to the Burned Ridge (Qo4b) and Jackson Lake moraines (Qo4j). Notable examples of these deposits comprise Baseline and Antelope flats; older terrace gravel (Qtg) underlies Jackson Hole Airport.

Marston (1993) constructed 11 topographic profiles across the Snake River between Deadmans Bar and Moose to identify the relative ages of the terraces. The exercise tentatively identified 10 terrace levels based on relative position below the uppermost geomorphic surface, which corresponds to the end of Pinedale glaciation. Each level represents a period of river incision, which can be triggered by a drop in river base level or a change in climate that shifts the balance between water and sediment discharge.

Unconformities

Unconformities are gaps in the rock record. The absence of rocks of a certain age in a stratigraphic sequence represents a time during which sediment was not deposited or was subsequently eroded. The stratigraphic record in Grand Teton National Park is very comprehensive, representing all but one major divisions of geologic time from the Archean to the present. The Silurian Period is not represented.

The most notable unconformity in the park is between the Precambrian and the Middle Cambrian; this surface represents 2.2 billion years. Other unconformities cover the Lower Ordovician (488 million to 471 million years ago), the entire Silurian Period (443 million to 416 million years ago), the Lower and Middle Devonian (416 million to 385 million years ago), the Middle Mississippian (345 million to 328 million years ago), the Middle Triassic (245 million to 228 million years ago), and the Lower Jurassic (199 million to 175 million years ago). These gaps represent half of all geologic time, most represented by the unconformity between the Precambrian rocks and the Middle Cambrian Flathead Sandstone.

Volcanic Features

The volcanic features at the park and parkway can be divided into four groups. From oldest to youngest, these rocks are related to Absaroka volcanism, Basin and Range extension, the Heise volcanic field, and the Yellowstone hot spot.

Absaroka Volcanics

The present Absaroka volcanic province is an erosional remnant of the largest Eocene (55 million to 33 million years ago) volcanic field in the northern Rocky Mountains, which covered 23,300 km^2 (9,000 mi^2). The rocks within this province belong to the Absaroka Volcanic Supergroup, including the Langford, Hominy Peak, and Wiggins formations in the park and parkway. The Wiggins Formation is the youngest deposit in the sequence.

Today, the Absaroka Range is a rugged, northwest-trending mountain range to the northeast of the park and parkway. The inferred depositional setting was a belt of large andesitic stratovolcanoes flanked by coalescing alluvial fans (Sundell 1993). Zones of Precambrian structural weakness that were reactivated during the Laramide Orogeny (~70 million to 50 million years ago) likely formed two belts of Absaroka volcanic eruptive centers (Sundell 1993). These volcanoes produced highly explosive eruptions that triggered numerous mudflows, called lahars. In addition to mass wasting, fluvial and eolian processes rapidly and continuously reworked and mixed the volcanic material.

Basin and Range Extension

The Colter Formation is a unit of volcanic transition between Absaroka and Basin and Range volcanism. This unit contains recycled fragments of Absaroka volcanic rocks but also represents the beginning of Basin and Range extension, which expanded the western United States by 50% to 100% in the past 15 million years. The Teton Range lies at the eastern edge of the Basin and Range province, while the province's western edge is in

California. Like the Tetons, mountain ranges within the province are typically bounded by normal faults.

As a result of extension, volcanic vents (now buried beneath younger deposits) produced the Colter Formation, which is composed of tuff, basalt, volcanic conglomerate, mafic andesite, and some rhyolitic welded tuff, as well as other rocks such as pumice breccia, flow breccia, scoria, and some flows and intrusive masses of andesite (Love et al. 1992). The vents seem to have initially produced andesitic rocks, then rhyolitic and basaltic compositions as Basin and Range extension became dominant. These vents were likely located along zones of weakness; one of these zones became the locus of the Teton fault (Love et al. 2003).

Heise Volcanic Field

The Heise volcanic field, now buried beneath the Snake River Plain, is the precursor to the present-day Yellowstone Plateau volcanic field. It was actively erupting 5 million years ago. The framework of the field is composed of four rhyolitic ignimbrites formed by ash flows and nuées ardentes. The two youngest ignimbrites occur in the park and parkway: the Conant Creek Tuff is visible at the northern end of the Teton Range and in Jackson Hole, and the Kilgore Tuff is exposed on Signal Mountain and in the Gros Ventre Range (Morgan and McIntosh 2005). Most of the Conant Creek Tuff mapped by Love et al. (1992) is actually a distal facies of the 4.45-million-year-old Kilgore Tuff (Morgan and McIntosh 2005).

Both of these eruptions/rock units help to determine the timing of tectonic events in the Grand Teton–Yellowstone region. The 5.5-million-year-old Conant Creek Tuff includes massive slide blocks that could not have formed or flowed without significant relief, indicating that the Snake River Plain was characterized by such relief at that time. These landslides were probably seismically triggered and flowed catastrophically. The southward flow of the Kilgore Tuff was unrestricted, indicating that the Teton Range was not a significant topographic feature before 4.45 million years ago.

Yellowstone Hot Spot

Like the earlier Heise volcanic field, the Yellowstone hot spot was formed by continental crust overriding a plume of rising mantle material. This hot spot is atypically located in the interior of a continental plate, distant from ocean ridges, volcanic arcs, and other expressions of dynamic plate boundaries. As the North American plate moved southwestward over this stationary plume, massive amounts of volcanic rock were deposited at the surface. The plate’s course is marked by a track of lava (Eastern Snake River Plain) from southeastern Oregon and northeastern Nevada to the plume’s present-day location under Yellowstone National Park. The hot spot first surfaced 16 million years ago, and is likely linked to the extraordinary eruptions of basaltic lava that blanketed much of northern Oregon and southern Washington. Craters of the Moon National Monument and Preserve in Idaho interprets volcanism along the Snake River Plain.

In Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway, three rock units and a portion of a fourth owe their origins to the Yellowstone hot spot. The 2.05-million-year-old Huckleberry Ridge Tuff documents the first major hot spot–related event in the park and parkway. This tuff was probably deposited during a single eruption (Love et al. 2003). Lewis Canyon Rhyolite (900,000 years ago) and Lava Creek Tuff (630,000 years ago) mark more recent eruptions. In addition, the final sedimentary layer of Lake Teewinot (Teewinot Formation) was ash associated with hot-spot activity.

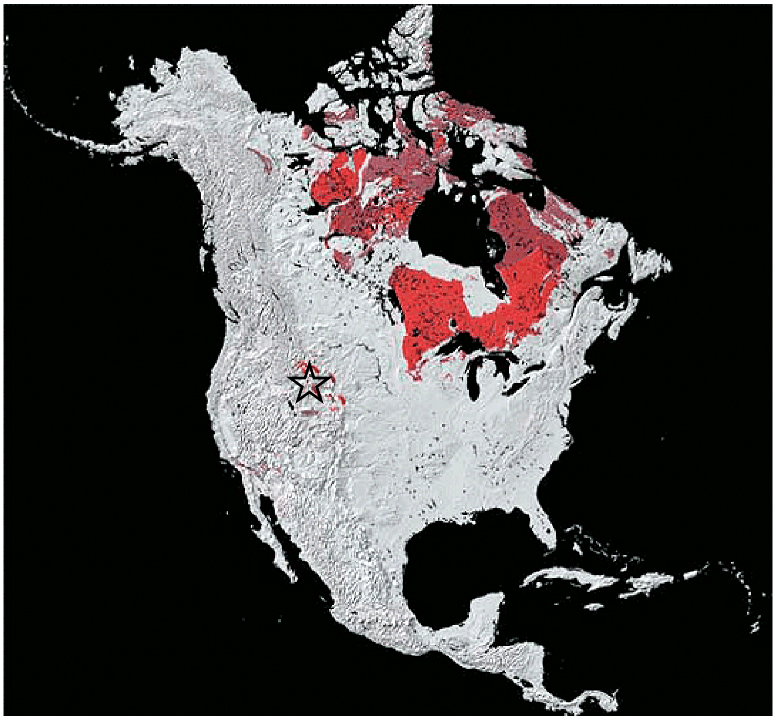

Figure 7. Archean Rocks of North America. The Superior Upland and Rocky Mountains host some of the oldest rocks on Earth. Grand Teton National Park (star) hosts Archean rocks, some of the oldest in the National Park System. Archean rocks span from 4.0 billion to 2.5 billion years ago. U.S. Geological Survey graphic from the North American Tapestry of Time and Terrain website: http://nationalatlas.gov/articles/geology/legend/ages/archean.html (accessed February 22, 2010).

Figure 8. Diabase Dike on Mount Moran. The distinct black feature on the peak of Mt. Moran is a diabase dike (arrow). This previously molten material was injected into cracks of the Archean rocks that form the mountain. The dike is about 46 m (150 ft) wide and cross-cuts the Teton Range for about 16 km (10 mi). U.S. Geological Survey photograph, available online at the 3-D Geology of National Parks website: http://3dparks.wr.usgs.gov/grte/index.html (accessed July 16, 2010).

Figure 9. Jackson Lake Hot Springs. A 2004 survey of the springs obtained pH readings of 6.5 to 7.2 and temperatures ranging from 22°C to 61°C (72°F to 142°F). National Park Service photograph.

Figure 10. Glacially Carved Landscape. During the Pleistocene Epoch, valley glaciers carved horns, arêtes, cirques, and U-shaped valleys in the Teton Range. National Park Service photograph.

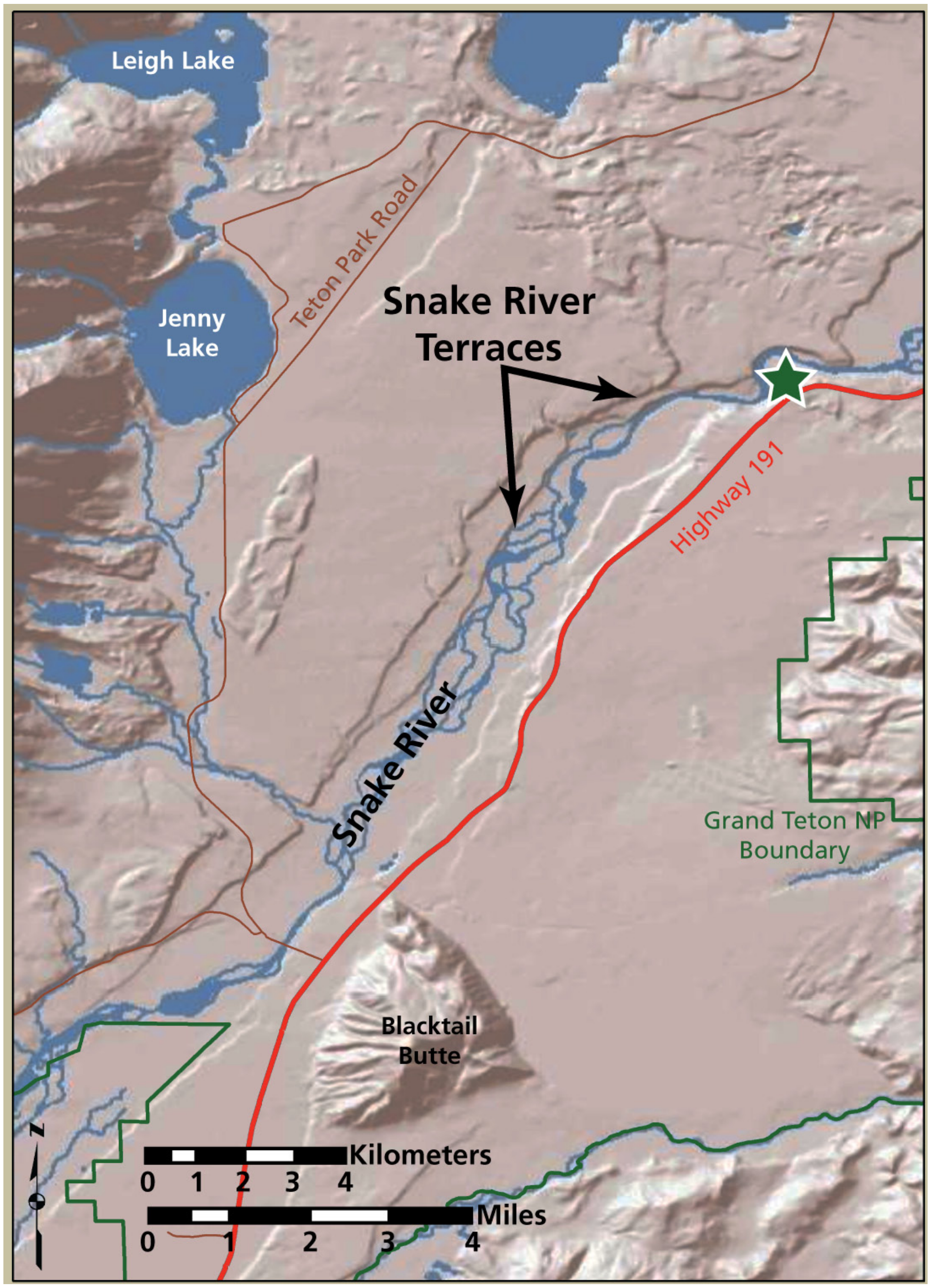

Figure 11. Snake River Terraces. Representing past floodplains, terraces flank both sides of the present-day, actively migrating Snake River in Grand Teton National Park. The green star marks the location of the Snake River Overlook (fig. 12). Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI ArcImage Service, World Shaded Relief Imagery.

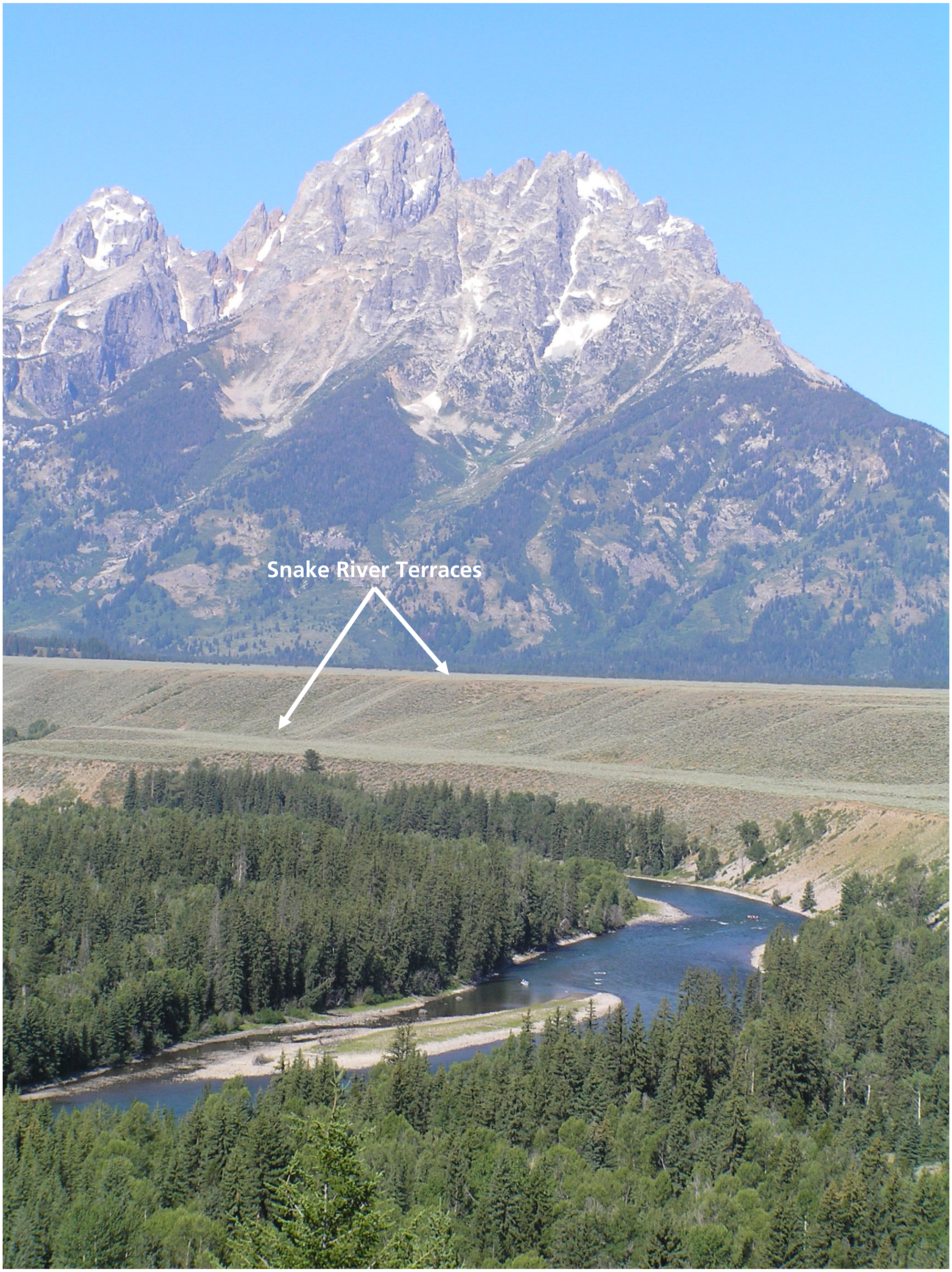

Figure 12. Snake River Overlook. Terraces are plainly visible in this view from the Snake River Overlook (green star on fig. 11). National Park Service photograph, available online: http://www.nps.gov/grte/photosmultimedia/photogallery.htm (accessed July 16, 2010).

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following references provided the source data for the GRI digital geologic maps for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway:

Christiansen, R. L., H. R. Blank, J. D. Love, and J. C. Reed. 1978. Geologic map of the Grassy Lake Reservoir quadrangle, Yellowstone National Park and vicinity, Wyoming (scale 1:62,500). Geologic Quadrangle Map GQ-1459. U.S. Geological Survey, Reston, Virginia, USA.

Love, J. D. 2003. Digital geologic map of the Huckleberry Mountain quadrangle, Yellowstone National Park and vicinity, Wyoming (scale 1:62,500). Unpublished data. U.S. Geological Survey, Reston, Virginia, USA.

Love, J. D., J. C. Reed Jr., and A. C. Christiansen. 1992. Geologic map of Grand Teton National Park, Teton County, Wyoming (scale 1:62,500). Miscellaneous Investigations Series Map I-2031. U.S. Geological Survey, Reston, Virginia, USA.

U.S. Geological Survey. 2007a. Digital geologic map of the Grassy Lake Reservoir quadrangle, Yellowstone National Park and vicinity, Wyoming (scale 1:62,500). U.S. Geological Survey, Reston, Virginia, USA.

The GRI team implements a geology–GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase, shapefile, and coverage GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)–compliant metadata, a Windows HelpFile that contains all of the ancillary map information and graphics, and an ESRI ArcMap file that easily displays the map. These data are included on the attached CD and available through the NPS Data Store at http://science.nature.nps.gov/nrdata/. Data will be available on the Natural Resource Information Portal when the portal goes online. As of September 2010, access is limited to NPS computers at http://nrinfo/Home.mvc.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 13) for the age associated with each time period. In 2009, the International Commission on Stratigraphy updated the international stratigraphic chart, which included an expansion of the length of time covered by the Quaternary Period; therefore, several units listed as

Pliocene on Love et al. (1992) now fall within the boundary of the Quaternary (starting 2.588 million years ago); these units are Huckleberry Ridge Tuff (Th), drift(?) probably related to glaciation 1 (Tg1), and Shooting Iron Formation (Tsi). Similarly the Tertiary Period nomenclature was replaced by Paleogene and Neogene periods. Hence, the Tertiary is now considered an informal time unit (fig. 13).

The following table highlights characteristics of map units in the park and parkway, including susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and use as habitat or for recreation. Some information on the table is conjectural but serves as suggestions for further investigation. Santucci and Wall (1998) and Tracy (2003) provided information about paleontological resources. Antweiler et al. (1989) yielded information regarding mineral resources. Young (1982) provided information about suitability for recreation and infrastructure.

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary	Holocene		Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	0.01		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary – Neogene	Pliocene	2.6		Large carnivores	Sierra Nevada Mountains (W)
			Miocene	5.3		Whales and apes	Linking of North and South America
		Tertiary – Paleogene	Oligocene	23.0			Basin-and-Range extension (W)
			Eocene	33.9		Early primates	Laramide Orogeny ends (W)
			Paleocene	55.8			
				65.5			
	Mesozoic	Cretaceous			Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		145.5		First mammals	Elko Orogeny (W)
		Triassic		199.6		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins Sonoma Orogeny (W)
				251			
	Paleozoic	Permian			Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		299		Coal-forming swamps Sharks abundant	Ancestral Rocky Mountains (W)
		Mississippian		318.1		Variety of insects First amphibians	
		Devonian		359.2	Fishes	First reptiles **Mass extinction** First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian		416		First land plants	
		Ordovician		443.7	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		488.3		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of proto-North America (Laurentia)
				542			
Proterozoic		Precambrian				First multicelled organisms Jellyfish fossil (670 Ma)	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				2500		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean				≈4000		Origin of life?	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust
				4600		Formation of the Earth	

Figure 13. Geologic Timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/, with additional information from the International Commission on Stratigraphy, http://www.stratigraphy.org/view.php?id=25.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

Grand Teton National Park hosts rocks ranging in age from Archean to Quaternary (fig. 13). In John D. Rockefeller, Jr. Memorial Parkway, rocks of Cretaceous age, Tertiary volcanics, and Quaternary sediments have primary significance. The Teton Range consists of an uplifted core of igneous and metamorphic Archean and Proterozoic rocks. Paleozoic and Mesozoic sedimentary rocks surround the central core, excepting the Cenozoic deposits that dominate the land surface immediately east of the core, in Jackson Hole.

Archean and Proterozoic Eons (4 billion to 542 million years ago)

The oldest rocks in Grand Teton National Park are also some of the oldest rocks in the National Park System and the world. These rocks represent Archean (4.0 billion to 2.5 billion years old) crust, part of the North American protocontinent. The Archean suite is composed of gneiss, amphibolites, ultramafic rocks, and metagabbro. These rocks also contain iron formations, which provide evidence for the evolution of oxygen in the atmosphere and hydrosphere.

A major episode of regional deformation and metamorphism occurred at the end of the Archean Eon, when massive amounts of granitic rock intruded older metamorphic rock. Isotopic dating of the Mount Owen Quartz Monzonite shows that this invasion occurred about 2,545 million years ago (Love et al. 2003). The next significant event recorded in the rocks at Grand Teton National Park was the Late Proterozoic intrusion of mafic magma (i.e., diabase dikes). These dikes, which cut across the general metamorphic grain of older Archean rocks, are nearly vertical sheets that range in thickness from a few centimeters to more than 46 m (150 ft) (Love et al. 2003). The most prominent of these dikes is located on the east face of Mount Moran (fig. 8). Analysis of similar rocks from other locations has suggested that the diabase dikes were emplaced about 765 million years ago (Love et al. 2003). These black dikes are the youngest Precambrian rocks in the park and represent the last event of the Proterozoic Eon (2.5 billion to 542 million years ago).

Erosion flattened the Archean and Proterozoic rocks of the Teton region into a relatively flat plain before the deposition of the Flathead Sandstone (510 million years ago), the first Paleozoic rock unit in the park.

Paleozoic Era (542 to 251 million years ago)

At the beginning of the Paleozoic Era, the area of the future Tetons began to subside and a shallow sea advanced from the west. Sedimentation into this basin resulted in the Flathead Sandstone and Gros Ventre Formation (Upper and Middle Cambrian). Exposures of Flathead Sandstone atop Mount Moran attest to later uplift and movement along the Teton fault. The nearshore sands of the Flathead Formation graded into the mud and marine debris of the Gros Ventre Formation as the sea advanced. The three members of the Gros Ventre Formation (Wolsey Shale, Death Canyon Limestone, and Park Shale) reflect transgression and regression of the shallow sea; limestone was deposited in deeper water (>30 m [100 ft]), while shale was deposited in shallower water (<30 m [100 ft]). The shale beds (lithified mud) contain body fossils of brachiopods and trilobites and trace fossils (trails and burrows) of a wormlike creature (Love et al. 2003).

Sea level fluctuated throughout much of the Paleozoic with the deposition of the Gallatin Limestone (Middle to Late Cambrian), Bighorn Dolomite (Middle to Late Ordovician), dolomite and shale of the Darby Formation (Devonian), and Madison Limestone (Mississippian). Corals and other marine animals were abundant in the clear, warm seas when the Bighorn Dolomite was deposited. Fossil scales and bones in the Darby Formation indicate that fish were abundant at that time. The remains of corals, crinoids, gastropods, and brachiopods, which inhabited warm, tranquil seas, became the Madison Limestone (Love et al. 2003).

Volcanic arcs developed toward the end of the Paleozoic (Pennsylvanian and Mississippian periods), and the Ancestral Rocky Mountains rose to the east in what is now central Wyoming. The shallow sea became increasingly restricted, creating a broad embayment between the offshore volcanoes and the rest of North America (Love et al. 2003). Limestone of the Wells and Amsden formations and the Tensleep Sandstone were deposited in this restricted bay. Material from the flanks of the Ancestral Rockies contributed to these formations (Love et al. 2003). The Paleozoic Era ends with the Permian Period, which is represented in Grand Teton National Park by the Phosphoria Formation. This formation accumulated in a shallow-water zone near deep, upwelling, nutrient-rich water (Love et al. 2003).

Mesozoic Era (251 to 65.5 million years ago)

Love et al. (1992) mapped more than two dozen rock units from the Mesozoic Era (Triassic, Jurassic, and Cretaceous periods) with a combined thickness of more than 3,050 m (10,000 ft) in the Teton–Jackson Hole area (see Map Unit Properties Table). Deposition of sediments in relatively shallow seas that covered the Teton area continued throughout the Mesozoic Era, creating alternating beds of sandstone, shale, limestone, and dolomite. The areal extent of the inland seas reached a maximum in the Cretaceous Period when the Cretaceous Interior Seaway extended from the Arctic to the tropics, covering the entire west-central part of the North American continent. The Cretaceous sea left thick deposits of shale and sandstone such as the Thermopolis, Mowry, Aspen, and Cody shales and the Frontier Formation (sandstone). Toward the end of the Cretaceous Period, mountains rose to the west and sedimentation increased with the transition from a marine to a terrestrial setting. This type of sedimentation included conglomerate, which was mostly fluvial; sandstone and shale, which accumulated along muddy coasts; coal formed from organic-rich sediments of marsh environments; and bentonite derived from the alteration of volcanic ash. As the sea retreated, the sediments of the Sohare, Mesaverde, Meeteetse, and Harebell formations, and the Bacon Ridge Sandstone, were deposited along the western shore (Love et al. 2003).

The late Cretaceous and early Tertiary (Paleogene) were characterized by orogeny in the Teton region. This era of uplift and mountain building displaced the interior seaway and ultimately formed the Rocky Mountains (Smith and Siegel 2000). The Sevier Orogeny compressed the terrain and carried massive sheets of sedimentary rock eastward, producing extensive highlands and mountains from which sediment was shed into the Teton region. The Laramide Orogeny formed the Rocky Mountains in Wyoming, Colorado, New Mexico, and southwestern Montana. These mountains differ from those formed by the shallow thrust sheets of the Sevier Orogeny; they are upthrown blocks of sedimentary rock with cores of Precambrian metamorphic rocks and granite. During this time, a large northwest–southeast-trending uplift rose where the Teton and Gros Ventre ranges are today. This probably extended north into the Yellowstone area (Love et al. 2003).

Cenozoic Era (the past 65.5 million years)

Laramide uplift and thrusting continued to shed large quantities of sediment from the highland areas to fill Jackson Hole during the Cenozoic Era (65.5 million years ago to the present time). Jackson Hole subsided as the sediment accumulated in the basin, creating space for a thick sequence of sedimentary rock. According to Love et al. (2003), few other regions of North America contain a thicker or more complete, nonmarine Tertiary (Paleogene and Neogene periods) record. Furthermore, "the character and volume of the Tertiary strata are clear evidence of the instability of the Earth's crust in the Teton region during much of the Tertiary" (Love et al. 2003, p. 62).

Most of the Cenozoic Era at the park and parkway has been characterized by volcanism, excepting the White River Formation, which was deposited in the Oligocene Epoch during a time of quiescence. The Tertiary (Paleogne) volcanics and the Absaroka Volcanic Supergroup (e.g., Langford, Hominy Peak, and Wiggins formations) began erupting 53 million to 43 million years ago during the Eocene Epoch. The Absaroka volcanic field, northeast of the present-day park and parkway, contains huge volumes of volcanic material, including tuff formed from consolidated ash. Some of this material is interbedded with conglomerate and sandstone containing fossilized leaves and petrified wood, notably in the fossil forests of Yellowstone National Park. Volcanism continued in the Miocene Epoch with the deposition of the Colter Formation, as well as flow breccia, dacite, pumice, scoria, basalt, perlite, andesite, rhyolite, and obsidian (Love et al. 1992) related to Basin and Range extension.

Huge lakes formed during the Miocene and Pliocene epochs. Lake Teewinot (1,800 km^2 [700 mi^2]) formed near the southern boundary of the park during the Miocene. Downwarping of the trough that contained the Colter Formation interrupted south-flowing drainage and impounded the lake. Volcanic ash and richly fossiliferous (e.g., snails, clams, ostracodes, diatoms, pollen, fish bones, and teeth of aquatic mice, beaver, and shrews) sediments accumulated in the lake. Shooting Iron Lake, represented by the Shooting Iron Formation, occupied southern Jackson Hole during the Pliocene (Leopold et al. 2007). Mammal teeth and fossil mollusks indicate a deepwater environment (Love et al. 1992), and pollen data suggest a climate like that of present-day Jackson Hole and the surrounding foothills (Leopold et al. 2007).

The Pliocene Epoch marks another phase of volcanic activity in the Teton region, with the formation of the Heise volcanic field north of Idaho Falls, Idaho. This field preceded the present-day Yellowstone Plateau volcanic field on the Snake River Plain (Morgan and McIntosh 2005). The 5.5-million-year-old Conant Creek Tuff and the 4.45-million-year-old Kilgore Tuff document Heise volcanism in the park and parkway.

The first manifestations of the Yellowstone hot spot in the Teton region occurred 2.05 million years ago, and are recorded in the rock record by the Huckleberry Ridge Tuff and the final layer of ash in Lake Teewinot (Teewinot Formation). The 900,000-year-old Lewis Canyon Rhyolite and the 630,000-year-old Lava Creek Tuff document the continuation of volcanic (hot-spot) activity into the Pleistocene Epoch.

The Laramide Orogeny provided the first uplift of the Teton Range. Compression forces drove a reverse fault (the Buck Mountain fault) that elevated the rocks of the central Teton Range. The range's second uplift occurred after 4.5 million years ago, when significant movement began on the Teton fault (Morgan and McIntosh 2005; Leopold et al. 2007). Seismic activity increased into the Pleistocene, but post-glacial (non-tectonic) displacement may also have contributed to further uplifting of the crest of the Teton Range (Susong et al. 1987; Smith et al. 1990a, 1993). Most (~80%) of the displacement along the Teton fault is a result of the dropping of the Jackson-Hole block along the fault. Uplift of the Teton-Range block along the fault accounts for the remaining 20% of displacement (Love et al. 2003) (see fig. 2). Unlike the Laramide Orogeny, which uplifted the rocks through compression, the rise of the Teton Range along the Teton fault is a result of extension. Laramide deformation caused thrust and reverse faults, while the more recent uplift of the Teton Range occurred along a normal fault.

Although some evidence attests to several periods of glaciation in the Teton–Jackson Hole area during the last 2.5 million years, subsequent glaciations have destroyed most of these older features. Eight or more glaciations may have preceded the Bull Lake glaciation in the region, but little is known about these early processes (Good and Pierce 1996). "Glaciation 1" is represented only by preserved evidence of drift within and east of Jackson Hole (Love et al. 1992).

The Bull Lake (160,000–130,000 years ago, but possibly beginning 190,000 years ago) and Pinedale (70,000–15,000 years ago) glaciers produced most of the U-shaped valleys, jagged peaks, and piled moraines in the region. Geologists named these glaciations for areas in the Wind Rivers of Wyoming where they were first studied and mapped, and the terms now have regional use in Colorado and Utah. Glaciation 2 (Qg2) and glaciation 3 (Qg3) of Love et al. (1992) are Bull Lake deposits. In the Teton region, investigators refer to Bull Lake glacial deposits as "Munger," after Munger Mountain at the southern end of Jackson Hole (Pierce and Good 1992). This glaciation entirely filled Jackson Hole with ice (Pierce and Good 1992). A blanket of loess blown from the bare glacial outwash plains during the subsequent Pinedale glaciation covers most Bull Lake deposits (Love et al. 2003).

Love et al. (1992) mapped Pinedale deposits as glaciation 4 (Qg4). The Pinedale glaciations are divided into three phases in the Teton region: Burned Ridge (70,000–30,000 years ago), Hedrick Pond (~35,000 years ago), and Jackson Lake (ended by 15,000 years ago) (Pierce and Good 1992). Three lobes of ice moved into the Jackson Hole area during Pinedale glaciation: (1) the Snake River lobe entered the region from the north and moved south; (2) the Pacific Creek lobe came from the northeast and advanced to the southwest; and (3) the Buffalo Fork lobe flowed into Jackson Hole from the east and moved west. The size of these three lobes kept changing throughout Pinedale time, with a general trend in mass from east (Buffalo Fork lobe) to west (Snake River lobe). Smaller mountain glaciers also flowed from the Teton Range. North of Jenny Lake, glaciers from the Teton Range joined the south-flowing Snake River lobe. The smaller Teton valley glaciers extended only about 2.5 km (1.5 mi) beyond the mountain front. The surface area of the Teton Range was too small to host the development of large glaciers, so most ice (and outwash debris) came from the much larger area of high terrain to the north and east (Pierce and Good 1992). Significantly, however, valley glaciers carved many glacial features and formed the end moraines that dammed Jenny, Bradley, Taggart, and Phelps lakes. The three lobes of ice also left substantial outwash and enormous quantities of gravel.

During the Burned Ridge (first) phase of Pinedale glaciation, glaciers scoured basins into Jackson Hole valley, including those for Two Oceans and Emma Matilda lakes. These glaciers also deposited abundant outwash debris that covered much of the previous Bull Lake (Munger) moraine material (Pierce and Good 1992). During the Hedrick Pond and Jackson Lake (second and third) phases of glaciation, the south-flowing Snake River lobe completed the excavation begun by faulting, carving the Jackson Lake basin into its present shape. Glacial activity during the Hedrick Pond phase created kettle ("pothole") terrain. Glaciers from the Teton Range carved basins for the other piedmont lakes during the Jackson Lake phase. Moraines from this phase dammed the piedmont lakes, including the southern end of Jackson Lake. This forced the Snake River, which feeds and drains Jackson Lake, to exit on the lake's east side (Pierce and Good 1992; Elias 1996).

According to Love et al. (2003), a complex array of alluvial fans and stream terraces built up during and after glaciers covered most of the Jackson Hole floor. These landforms are situated outside the Pinedale terminal moraines and record much of the latest history of the southern parts of the valley. Alluvium occurs as floodplain deposits and alluvial fans in valleys; it commonly consists of well-sorted beds of silt, sand, and gravel. Much of the alluvium in this area is glacial outwash that has been reworked by modern streams but greatly resembles the parent material. Alluvial fans have formed along the margins of Jackson Hole where streams enter the valley from surrounding uplands. Relatively large amounts of groundwater occur within the alluvium of the park (Cox 1974). Frost action pries loose blocks of exposed rock that tumble down and come to rest in the form of fan-shaped talus aprons draping many of the lower mountain slopes and canyon walls (Love et al. 2003). Landslides form, move, and can temporarily dam rivers and impound lakes. Lakes and wetlands dot the landscape. Debris-rich deposits of clay, silt, and fine sand or thinly laminated white marl, ash, and clay accumulate in kettles. In addition, springs deposit travertine. Love et al. (2003) identified 11 hot springs, warm springs, and thermal wells in and near Jackson Hole.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

aggradation. The building-up of Earth's surface by depositional processes, specifically the upbuilding performed by a stream in order to establish or maintain uniformity of grade or slope.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

alpine glacier. A glacier occurring in a mountainous region; also called a valley glacier.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

amphibolite. A metamorphic rock consisting mostly of the minerals amphibole and plagioclase with little or no quartz.

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

artiodactyla. Any of the order Artiodactyla of ungulates (as camel or pig) with an even number of functional toes on each foot.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

augen. Describes large lenticular mineral grains or mineral aggregates that have the shape of an eye in cross-section. Found in metamorphic rocks such as schists and gneisses.

avulsion. The sudden cutting off or separation of land by a flood or by an abrupt change in the course of a stream, as by a stream breaking through a meander or by sudden change in current whereby the stream deserts its old channel for a new one.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bed load. The part of the total stream load that is moved on or immediately above the stream bed such as the larger or heavier particles (boulders, pebbles, and gravel) transported by traction or saltation along the bottom; the part of the load that is not continuously in suspension or solution.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

biotite. A widely distributed and important rock-forming mineral of the mica group.

block (fault). A crustal unit bounded by faults, either completely or in part.

brachiopod. Any marine invertebrate belonging to the phylum Brachiopoda, characterized by two bilaterally symmetrical valves that are commonly attached to a substratum but may also be free. Range—Lower Cambrian to the present.

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cephalopod. A marine mollusk of the class Cephalopoda, characterized by a head surrounded by tentacles and, in most fossil form, by a straight, curved, or coiled calcareous shell divided into chambers by transverse septa. Range—Cambrian to the present.

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

conodont. One of a small number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition, and commonly toothlike in form but not in function; produced in bilaterally paired, serial arrangement by small marine animals of uncertain affinity. Range—Cambrian (possibly Late Precambrian) to Upper Triassic.

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

coquina. Limestone composed of cemented shell fragments.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

cycad. An ancient group of extant seed plants that flourished during the Jurassic, characterized by a large crown of compound leaves and a stout trunk; resembles palms or ferns in appearance, but is unrelated to either.

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

devitrification. Conversion of glass to crystalline material.

diabase. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules. Diatoms live in freshwater or marine environment.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

drift. All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

facies (metamorphic). The pressure and temperature conditions that result in a particular, distinctive suite of metamorphic minerals.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault).

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

garnet. A hard mineral that has a glassy luster, often with well defined crystal faces, and a variety of colors, dark red being characteristic. Commonly found in metamorphic rocks.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical (e.g., a snail). Range—Upper Cambrian to the present.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

glauconite. A green mineral, closely related to the micas. It is an indicator of very slow sedimentation.

glaze. A fired glassy surface on lava features.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

gypsum. The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

hot spot. A volcanic center that is thought to be the surface expression of a rising plume of hot mantle material.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

ignimbrite. The rock formed by the widespread deposition and consolidation of ash flows and nuées ardentes. The term includes welded tuff and nonwelded but recrystalized ash flows.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

lagomorph. Any of the order Lagomorpha of gnawing, herbivorous mammals having two pairs of incisors in the upper jaw one behind the other and comprising rabbits, hares, and pikas.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

liquefaction. The transformation of loosely packed sediment into a more tightly packed fluid mass.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

loess. Windblown silt-sized sediment, generally of glacial origin.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

mantle. The zone of Earth's interior between the crust and core.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

maximum credible earthquake. The largest hypothetical earthquake that may be reasonably expected to occur along a given fault.

meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

migmatite. Literally, "mixed rock" with both igneous and metamorphic characteristics due to partial melting during metamorphism.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

muscovite. A mineral of the mica group. It is colorless to pale brown and is a common mineral in metamorphic rocks such as gneiss and schist, igneous rocks such as granite, pegmatite, and sedimentary rocks such as sandstone.

neoglacial. Describes the period of glacial readvance during the late Holocene, the most recent being the Little Ice Age (from the 1500s until the mid 1800s).

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

nuée ardente. A swiftly flowing, turbulent gaseous cloud, sometimes incandescent, erupted from a volcano and containing ash and other pyroclastic materials in its lower part.

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition with conchoidal fracture. Can be used as a raw material for arrowheads, jewelry, and art objects.

oolite. A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.

orogeny. A mountain-building event.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

parent material. Geologic material from which soils form.

pegmatite. An exceptionally coarse-grained intrusive igneous rock, with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths.

perlite. A volcanic glass having the composition of rhyolite and generally higher water content than obsidian; commercially used to form a lightweight aggregate (e.g., used in gardening).

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

piedmont glacier. A thick, continuous sheet of ice at the base of a mountain range on land, formed by spreading out and coalescing of valley glaciers from the higher elevations of the mountains.

piedmont lake. An oblong lake occupying a partly overdeepened basin excavated in rock by, or dammed by a moraine of, a piedmont glacier.

pitchstone. A variably colored volcanic glass with a waxy dull resinous luster. Contains a higher percentage of water than obsidian.

plastic. Capable of being deformed permanently without rupture.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

porphyritic. Describes an igneous rock texture characterized by large crystals (phenocrysts) surrounded by a finer-grained groundmass (matrix).

pumice. Solidified "frothy" lava. It is highly vesicular and has very low density.

pyroclast. An individual particle ejected during a volcanic eruption.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

rock. A solid, cohesive aggregate of one or more minerals.

rodent. Any of the order Rodentia of relatively small, gnawing animals (as a mouse, squirrel, or beaver) that have in both jaws a single pair of incisors with a chisel-shaped edge.

roundstone. Any naturally rounded rock fragment larger than a sand grain.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

scour. The powerful and concentrated clearing and digging action of flowing air, water, or ice.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

seiche. An oscillation of a body of water in an enclosed or semi-enclosed basin that varies in period, depending on the physical dimensions of the basin, from a few minutes to several hours, and in height from several centimeters to a few meters. It is caused chiefly by local changes in atmospheric pressure, aided by winds, tidal currents, and occasionally earthquakes.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

speleothem. Any secondary mineral deposit that forms in a cave.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subbituminous. A black coal, intermediate in rank between lignite and bituminous coal. It is distinguished from lignite by higher carbon and lower moisture content.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrace. A relatively level bench or steplike surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

tonalite. A type of plutonic (intrusive) rock.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

travertine. A limestone deposit or crust, often banded, formed from precipitation of calcium carbonate from saturated waters, especially near hot springs and in caves.

trend. The direction or azimuth of elongation of a linear geologic feature.

trilobite. Any marine arthropod belonging to the class Trilobita, characterized by a three-lobed ovoid outer skeleton, divided lengthwise into axial and side regions and transversely into cephalon ("head"), thorax (middle), and pygidium ("tail"). Range—Lower Cambrian to Permian.

tufa. A chemical sedimentary rock composed of calcium carbonate, formed by evaporation as an incrustation around the mouth of a spring, along a stream, or exceptionally as a thick, concretionary deposit in a lake or along its shore. It may also be precipitated by algae or bacteria. A hard, dense variety of travertine.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron and magnesium rich) minerals.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vitrophyre. A porphyritic igneous rock with a glassy matrix.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

vug. A small cavity in a vein or in rock, usually lined with crystals of a different mineral composition from the enclosing rock.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of September 2010.

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Appendix A: Overview of Digital Geologic Data

The following pages show an overview of the digital geologic data for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway. For poster-size PDFs of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications website at http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Appendix B: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Grand Teton National Park and John D. Rockefeller, Jr. Memorial Parkway, held on June 21–22, 2005. The contact information and e-mail addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications website at http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed July 30, 2010.

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NPS 136/105347, 642/105347, August 2010

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