Geologic Resource Evaluation Scoping Summary Yellowstone National Park

This document summarizes the results of a geologic resource evaluation scoping session that was held at Yellowstone National Park on May 16–17, 2005. The NPS Geologic Resources Division (GRD) organized this scoping session in order to view and discuss the park's geologic resources, address the status of geologic maps and digitizing, and assess resource management issues and needs. In addition to GRD staff, participants included park staff and cooperators from the U.S. Geological Survey and Colorado State University (table 1).

Table 1. Participants of Yellowstone's GRE Scoping Session

Name	Affiliation	Phone	E-Mail
Bob Christiansen	Volcanologist, USGS–Menlo Park	650-329-5201	rchris@usgs.gov
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Monday, May 16, involved a welcome to Yellowstone National Park and an introduction to the Geologic Resource Evaluation (GRE) Program, including status of reports and digital maps. Much of the discussion focused on map coverage of the park and "quadrangles of interest" for the park (see table 2). In addition, the group discussed geologic issues of concern for park managers.

On ***Tuesday, May 17,*** participants completed the previous day's discussion of geologic issues. Afterward, USGS geologists Bob Christiansen and Ken Pierce led a field trip for participants. The selected stops highlighted past glacial activity, past and present volcanic and geothermal activity, and current resource management issues.

Overview of Geologic Resource Evaluation Program

The GRE Program is a collaborative effort of the NPS Geologic Resources Division and the NPS Inventory and Monitoring (I&M) Program with assistance from the U.S. Geological Survey (USGS), state geological surveys, and numerous individual volunteers and cooperators at National Park System units, colleges, and universities. The Geologic Resources Division administers the Abandoned Mine Lands (AML) and Geoscientists-in-the-Parks (GIP) Programs, which also contribute to the inventory. The focus of the collaborative effort is to provide baseline geologic data to assist park managers with geologic resource management issues.

Geology is one of 11 inventories defined by Director's Order 77 (NPS 75): geology, species lists, bibliographies, base cartography, vegetation, water quality, soils, species surveys, species distribution (vascular plants and vertebrates), air quality, and climatic data.

The scoping process includes a site visit with local experts, evaluation of the adequacy of existing maps, and discussion of park-specific geologic management issues. The emphasis of the geologic evaluation is to aggregate existing information and identify where serious geologic data needs and issues exist, not to routinely initiate new mapping projects.

The following are the objectives of the GRE scoping meetings:

- Identify geologic mapping coverage and needs.
- Identify distinctive geologic processes and features.
- Identify resource management issues.
- Identify potential monitoring and research needs.

The scoping process will result in the following outcomes:

- A scoping summary (this document)
- A bibliography
- A digital geologic map
- A geologic resource evaluation report

Status of Scoping and Products

As of July 2005, the NPS Geologic Resources Division had completed the scoping process for 153 of 272 "natural resource" parks. Staff and cooperators have completed digital maps for 56 parks. The U.S. Geological Survey, various state geological surveys, and investigators at academic institutions are in the process of preparing mapping products for 57 parks. Pending ongoing data validation and updates, bibliographies for all parks are in progress. Writers have completed reports for 10 parks, with reports for 65 parks in progress.

Geologic Maps for Yellowstone National Park

During the May 16, 2005, scoping session, Tim Connors (GRD) presented a demonstration of some of the main features of the digital geologic map model used by the GRE Program. The model reproduces all aspects of a paper map, including notes, legend, and cross-sections, with the added benefit of being GIS compatible. Staff digitizes maps using ESRI ArcView/ArcInfo format with shape files and other features, including a built-in help file system to identify map units.

All units of the National Park System have "quadrangles of interests" at one or more of the following scales: 7.5' × 7.5' (1:24,000), 15' × 15' (1:62,500), or 30' × 60' (1:100,000). For the purpose of geologic resource evaluations, GRE staff would like to obtain digital geologic maps of all identified quadrangles of interest at a scale of 1:24,000 for a particular park. Often for simplicity, geologic map makers compile geologic maps at the 1:100,000 scale (30'× 60'), which provides greater consistency and covers more area. In the case of Yellowstone National Park, the U.S. Geological Survey made maps at the 1:62,500 scale.

As discussed during the scoping session, GRE staff will digitize all of the 1:62,500-scale surficial geologic maps from scratch. These maps cover the entire park. Also, GRE staff will convert previously digitized bedrock maps (by the U.S. Geological Survey) and original Mylar films, which GRE staff scanned previously. Staff needs to acquire the bedrock maps from the U.S. Geological Survey (Contact: Ron Wahl). Table 2 outlines the status of the bedrock maps in the overall acquisition and digitizing process.

Table 2. Quadrangles of Interest for Yellowstone National Park

30 × 60 quadrangle	Bedrock map reference	Availability of Mylar	Surficial map reference
Bedrock map status: GRE has USGS digital files			
Abiathar Peak	(3024)* Prostka, H.J., Ruppel, E.T., and Christiansen, R.L., 1975, Geologic map of the Abiathar Peak quadrangle, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Geologic Quadrangle Map GQ-1244, scale 1:62,500.	Unknown	(1136) Pierce, K.L., 1974, Surficial geologic map of the Abiathar Peak and parts of adjacent quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-646, scale 1:62,500.
Tower Junction	(3018) Prostka, H.J., Blank, H.R., Christiansen, R.L., and Ruppel, E.T., 1975, Geologic map of the Tower Junction quadrangle, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Geologic Quadrangle Map GQ-1247, scale 1:62,500.	Unknown	(1150) Pierce, K.L., 1974, Surficial geologic map of the Tower Junction quadrangle and part of the Mount Wallace quadrangle, Yellowstone National Park and adjoining area, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-647, scale 1:62,500.
Pelican Cone	(3249) Prostka, H.J., Smedes, H.W., and Christiansen, R.L., 1975, Geologic map of the Pelican Cone quadrangle, Yellowstone National Park and vicinity, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1243, scale 1:62,500.	Unknown	(1149) Richmond, G.M., and Waldrop, H.A., 1972, Surficial geologic map of the Pelican Cone quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-638, scale 1:62,500.
Canyon Village	(3254) Christiansen, R.L., and Blank, H.R., 1975, Geologic map of the Canyon Village quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1192, scale 1:62,500.	Unknown	(1137) Richmond, G.M., 1977, Surficial geologic map of the Canyon Village quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-652, scale 1:62,500.
Norris Junction	(3257) Christiansen, R.L., 1975, Geologic map of the Norris Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1193, scale 1:62,500.	Unknown	(1147) Richmond, G.M., and Waldrop, H.A., 1975, Surficial geologic map of the Norris Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-650, scale 1:62,500.
Madison Junction	(3256) Christiansen, R.L., and Blank, H.R., 1974, Geologic map of the Madison Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1190, scale 1:62,500.	Unknown	(1142) Waldrop, H.A., and Pierce, K.L., 1975, Surficial geologic map of the Madison Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-651, scale 1:62,500.

Eagle Peak	Unpublished	Unknown	(1138) Richmond, G.M., and Pierce, K.L., 1972, Surficial geologic map of the Eagle Peak quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-637, scale 1:62,500.
Frank Island	(6348) Blank, H.R., Prostka, H.J., Keefer, W.R., and Christiansen, R.L., 1974, Geologic map of the Frank Island quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1209, scale 1:62,500.	Unknown	(1139) Richmond, G.M., 1974, Surficial geologic map of the Frank Island quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-642, scale 1:62,500.
West Thumb	(3260) Christiansen, R.L., 1974, Geologic map of the West Thumb quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1191, scale 1:62,500.	Unknown	(1152) Richmond, G.M., 1973, Surficial geologic map of the West Thumb quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-643, scale 1:62,500.
Old Faithful	(3255) Christiansen, R.L., and Blank, H.R., 1974, Geologic map of the Old Faithful quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1189, scale 1:62,500.	Unknown	(1148) Waldrop, H.A., 1975, Surficial geologic map of the Old Faithful quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-649, scale 1:62,500.
Two Ocean Pass	(2644) Smedes, H.W., M'Gonigle, J.W., and Prostka, H.J., 1989, Geologic map of the Two Ocean Pass quadrangle, Yellowstone National Park and vicinity, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1667, scale 1:62,500.	Unknown	(1145) Richmond, G.M., and Pierce, K.L., 1971, Surficial geologic map of the Two Ocean Pass quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-635, scale 1:62,500.
Mount Hancock	Unpublished	Unknown	(1144) Richmond, G.M., and Pierce, K.L., 1971, Surficial geologic map of the Mount Hancock quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-636, scale 1:62,500.
Huckleberry Mountain	Unpublished	Unknown	(1141) Richmond, G.M., 1973, Surficial geologic map of the Huckleberry Mountain quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-639, scale 1:62,500.

Grassy Lake Reservoir	(6351) Christiansen, R.L., Blank, H.R., Love, J.D., and Reed, J.C., 1978, Geologic map of the Grassy Lake Reservoir quadrangle, Yellowstone National Park and vicinity, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1459, scale 1:62,500.	Unknown	(1140) Richmond, G.M., 1973, Surficial geologic map of the Grassy Lake Reservoir quadrangle, Yellowstone National Park and adjoining area, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-644, scale 1:62,500.
Bedrock map status: Digitization in progress by Bob Christiansen (completion slated for early 2006)			
Mammoth	Unpublished	Unknown	(1143) Pierce, K.L., 1973, Surficial geologic map of the Mammoth quadrangle and part of the Gardiner quadrangle, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-641, scale 1:62,500.
Mount Holmes	Unpublished	Unknown	(1146) Pierce, K.L., 1973, Surficial geologic map of the Mount Holmes quadrangle and parts of the Tepee Creek, Crown Butte, and Miner quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-640, scale 1:62,500.
Bedrock map status: Bedrock map not digitized			
Cutoff Mountain	Unpublished	Unknown	(1136) Pierce, K.L., 1974, Surficial geologic map of the Abiathar Peak and parts of adjacent quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-646, scale 1:62,500.
Mount Wallace	Unpublished	Unknown	(1150) Pierce, K.L., 1974, Surficial geologic map of the Tower Junction quadrangle and part of the Mount Wallace quadrangle, Yellowstone National Park and adjoining area, Wyoming and Montana: U.S. Geological Survey, Miscellaneous Investigations Series Map I-647, scale 1:62,500.
Gardiner	Unpublished but 7.5-minute quadrangle exists as Fraser, G.D., Waldrop, H.A., and Hyden, H.J., 1969, Geology of the Gardiner area, Park County, Montana: U.S. Geological Survey Bulletin 1277, 118 p., 1 map (in pocket), scale 1:24,000.	Unknown	(1143) Pierce, K.L., 1973, Surficial geologic map of the Mammoth quadrangle and part of the Gardiner quadrangle, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-641, scale 1:62,500.

Miner	Unpublished	GRE has scanned copy	(1146) Pierce, K.L., 1973, Surficial geologic map of the Mount Holmes quadrangle and parts of the Tepee Creek, Crown Butte, and Miner quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-640, scale 1:62,500.
Crown Butte	Unpublished	GRE has scanned copy	(1146) Pierce, K.L., 1973, Surficial geologic map of the Mount Holmes quadrangle and parts of the Tepee Creek, Crown Butte, and Miner quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-640, scale 1:62,500.
Tepee Creek	(3020) Witkind, I.J., 1969, Geology of the Tepee Creek quadrangle, Montana-Wyoming: U.S. Geological Survey Professional Paper 609, scale 1:62,500.	GRE has scanned copy	(1146) Pierce, K.L., 1973, Surficial geologic map of the Mount Holmes quadrangle and parts of the Tepee Creek, Crown Butte, and Miner quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-640, scale 1:62,500.
West Yellowstone	Unpublished	GRE has scanned copy	(1153) Waldrop, H.A., 1975, Surficial geologic map of the West Yellowstone quadrangle, Yellowstone National Park and adjoining area, Montana, Wyoming, and Idaho: U.S. Geological Survey Miscellaneous Investigations Series I-648, scale 1:62,500.
Buffalo Lake	Unpublished	GRE has scanned copy	
Warm River Butte	Unpublished	GRE has scanned copy; however, geology is incomplete	(1151) Richmond, G.M., 1973, Surficial geologic map of the Warm Butte quadrangle, Yellowstone National Park and adjoining area, Idaho and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-645, scale 1:62,500.
Bedrock map status: Unknown			
Pilot Peak	(6380) Pierce, W.G., Nelson, W.H., and Prostka, H.J., 1973, Geologic map of the Pilot Peak quadrangle, Park County, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-816, scale 1:62,500.	Unknown	(1136) Pierce, K.L., 1974, Surficial geologic map of the Abiathar Peak and parts of adjacent quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-646, scale 1:62,500.

Dead Indian Peak	(6381) Pierce, W.G., Nelson, W.H., and Prostka, H.J., 1982, Geologic map of the Dead Indian Peak quadrangle, Park County, Wyoming: U.S. Geological Survey Geologic Quadrangle Map GQ-1564, scale 1:62,500.	Unknown	
Sunlight Peak	Unpublished	Unknown	(1136) Pierce, K.L., 1974, Surficial geologic map of the Abiathar Peak and parts of adjacent quadrangles, Yellowstone National Park, Wyoming and Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-646, scale 1:62,500.

*The numbers in parentheses represent the USGS GMAP identification code, which are cross-referenced with the GRE database.

Geologic Resource Evaluation Report

Typically GRE reports include sections about geologic resources of concern for management (referred to as "issues"); geologic features and processes; the park's geologic history; a map unit properties table that highlights the significant features and resource concerns of each map unit in the park; references (different from the bibliography); and various appendices (e.g., map graphics and scoping report). During the May 16 meeting, GRD staff showed examples of completed GRE reports to participants. The staffing situation at Yellowstone is unique with two geologists on staff; most park staffs do not include geologists. Under these circumstances, GRD staff wanted to make sure that the final report product would be useful for staff geologists.

Participants concluded that the report would not necessarily be useful for addressing "crisis" situations, which park geologists address on a regular basis. However, participants deemed the report in its present outline to be useful for explaining geologic resources to audiences such as maintenance, law enforcement, and interpretation. Participants suggested one addition to the current report template: a section about digital map products and how they are useful. In particular, participants wanted the report to make a connection between digital maps and ecosystems for these audiences. The report should also include a discussion of how existing geologic hazards affect law enforcement and public safety, as well as the hydrologic and geologic implications of road construction for maintenance staff. Rob Daley suggested that an appendix to the report might be a user guide that includes "real life" examples and case studies for using digital data.

Geologic Features, Processes, and Issues in Yellowstone National Park

The scoping session at Yellowstone provided the opportunity to capture a rough outline of particular features and processes operating in the park, which will be highlighted and expanded in the GRE report. Some of these features and processes may be of concern for park mangers. Park staff determined that the "top three" resource management issues at Yellowstone are (1) geothermal resource protection, (2) geothermal hazards, and (3) volcanic hazards, including associated earthquakes and landslides.

External threats to park resources include potential geothermal development in Known Geothermal Resources Areas (KGRA) outside the park, for example in Island Park (west of Yellowstone National Park). The sensitivity of geyser basins is shown by earthquakes thousands of miles away affecting them. For example, the Denali fault earthquake of November 3, 2002, not only triggered small earthquakes almost 2,000 miles (3,218 km) away at Yellowstone National Park but also changed the timing and behavior of some of Yellowstone's geysers and hot springs (see reference below). In addition, historical observations (e.g., during the Hebgen Lake earthquake and an earthquake “swarm” in 1985) indicate a connection between geyser basins in the Yellowstone area. Therefore, fluid and heat withdrawn in the KGRA could affect the park’s hydrothermal resources.

Husen, S., Taylor, R., Smith, R.B., and Heasler, H., 2004, Changes to geyser eruption behavior in remotely triggered seismicity in Yellowstone National Park produced by the 2002 M 7.9 Denali fault earthquake, Alaska: Geology, v. 32, no. 6, p. 537–540.

North of the park, in a controlled groundwater area in Montana, park management has an agreement in place with the State of Montana. This agreement allows park staff to review proposals for geothermal development north of the park. Hence, the National Park Service is part of the review process in which developers must prove no impacts to park resources. Park managers would like to have similar agreements with Idaho and Wyoming.

Potential for oil and gas development exists in surrounding national forests (e.g., Shoshone National Forest). Generally speaking, fluid depletion would affect geothermal resources. Park staff is seeking to improve the working relationship between the National Park Service and the USDA Forest Service with respect to oil and gas development in the vicinity of Yellowstone National Park.

Finally, a proposed golf course on Bull Lake moraine, north of West Yellowstone, is evidence of development encroachment on Yellowstone National Park.

Participants also discussed the following features and processes:

Caves and Karst

Although investigators have performed a preliminary inventory of caves and karst in Yellowstone National Park, a thorough inventory and additional research are needed to fully understand these resources. With the present level of knowledge, participants assume that most of the karst features exist in the Mammoth Hot Springs area; some caves are associated with Absaroka volcanics, but little is known about caves in the Madison Formation. Caves in the Mammoth area pose hazards for health and human safety because of potentially lethal carbon-dioxide and sulfur-dioxide accumulations. In addition, karst may cause building instability and accumulation of radon in enclosed structures. Sporadically throughout the park’s administrative history, managers have tried to move building structures out of karst terrain, with limited success, however. For instance, new construction in the Mammoth area continues to date. An inventory of karst features would be useful for infrastructure planning.

The following are other issues related to caves and karst:

- The proper disposal of waste water, including watering lawns, which dissolves travertine and causes sinkholes. Participants noted that travertine has a higher potential for resulting in solution features than other types of limestone.
- Improving awareness of the relationship between solution and geothermal features (90% of groundwater distribution is unknown).
- Endangered species (bats) in caves.

Coastal Processes

Coastal areas include shorelines along lakes. In general, the erosion along Yellowstone Lake’s shoreline is related to inflation-deflation cycles of the caldera (Pierce and others, 2002). Increased water level in exceptionally wet years is also a factor in shoreline erosion. From 7,000 years ago to the present, Yellowstone Lake was mostly below its present level. Hardy Rapids, a threshold point, provides evidence of changes in water level as do other topographic features. For example the fishing cone at West Thumb, a popular visitor attraction, was subaerially deposited but is now above water level. Present lake levels cover relict landforms (e.g., barrier beaches) and cultural resources on the north side of the lake. At past Geological Society of America (GSA) meetings, University of Arkansas professor, Stephen K. Boss, and graduate student, Barbara E. Pickup, have presented their research findings regarding shoreline changes at Yellowstone Lake. The most recent presentation was in 2005 (see reference below). Studying coastal processes could provide insight into natural processes that shape coastal shorelines and assist the National Park Service in developing long-term management plans to preserve shoreline processes and the abundant archaeological sites found along the shoreline.

Pierce, K.L., Cannon, K.P., Meyer, G.A., Trebesch, M.J., and Watts, R., 2002, Post-glacial inflation-deflation cycles, tilting, and faulting in the Yellowstone Caldera based on Yellowstone Lake shorelines: U.S. Geological Survey Open-File Report 02-0142, 30 p.

Pickup, B.E., and Boss, S.K., 2005, GIS modeling of shoreline change at Yellowstone Lake, Yellowstone National Park, USA: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 332.

Park staff has used riprap to protect infrastructure from coastal erosion, in particular along roads and overlooks near Lake Hotel. Staff also has attempted to protect the marinas at Grant Village with concrete barriers.

Disturbed Lands

Past land use has resulted in disturbed-land sites in Yellowstone National Park. Formerly cultivated lands at the northern boundary were added to the park in the 1930s, so the park “inherited” a legacy of agricultural land use. Park staff has re-vegetated these fields with native plants, but reestablishment of the original habitat has been difficult.

Recent development at the wildland-urban interface has resulted in the desire to reduce “combustibles” and protect structures. Park managers initiated a GIS study of the wildland-urban interface by contracting a private group of landscape architects to identify structures and reduce fuel hazards around these structures. However, the survey did not include slope, aspect, or geologic materials. As a result, cutting of trees destabilized some slopes, resulting in landslides. Cheryl Jaworowski assisted with this study in summer 2002 (i.e., post-landsliding), in particular in the vicinity of the park’s east entrance. As a result, trees were thinned, rather than clear-cut, taking into account fuel reduction and slope stabilization.

In the past (1920s and 1960s) researchers drilled holes to depths between 215 and 1,088 feet (65 and 330 m) in order to measure physical conditions in the shallow parts of the hydrothermal system. For more information, see the following reference:

White, D.E., Fournier, R.O., Muffler, L.J.P., and Truesdell, A.H., 1975, Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 892, 70 p.

More recently, researchers proposed to drill into the deeper part of the hydrothermal system within the Yellowstone Caldera. The drill holes would be placed in gravel pits, which are already disturbed sites, but this proposal has never gained acceptance (see reference below).

Yellowstone National Park Task Group to the Continental Scientific Drilling Committee, 1987, The objectives for deep scientific drilling in Yellowstone National Park: Washington, D.C., National Academy Press, 69 p.

Other modifications to the surface and surficial processes include roads, coal mines, gravel quarries, borrow pits, and waste dumps. The following list highlights some of these disturbances:

- Road rehabilitation at Gibbon Canyon will require the expertise of a geomorphologist, as restoration will be a geotechnical challenge.
- Park staff is in the process of reclaiming the original road in the Turbid Lake area.
- Questions remain as to sustainable replacement of roads in the Mammoth Hot Springs area.
- Minor mineral extraction of low-grade coal from the McMinn bench occurred in the past; the area has been reclaimed, though coke ovens still exist.
- The park has thousands of borrow pits. In the early 1990s, Roger Andresic (former park staff) supervised the inventory of the park's borrow pits. Mary Hektner (current staff) probably has a copy of this inventory report. The State of Wyoming provided funding from its AML program to help reclaim the pits. Most of the pits were used for construction and road materials (park use) and range between 1 and 10 acres (0.4–4 ha). Today, about half a dozen pits are still in use for storage (i.e., "bone yards" for waste materials, slash, and old picnic tables) not mining (Dan Reinhart, Yellowstone National Park, oral communication, October 4, 2005).
- With the change in grizzly bear management (and the end of open-pit dumping), park staff reclaimed many of Yellowstone's dumps (e.g., Trout Creek and Rabbit Creek) during the 1970s.

Eolian Processes

Eolian (windblown) processes are deflating formally tilled and grazed fields in the northern-boundary area of the park. The combination of ongoing eolian processes and past human impacts makes the establishment of habitat difficult in these areas. Eolian deposits (cliff loess and sand dunes) occur along the shores of Yellowstone Lake and often bury archaeological sites. Ken Pierce noted that in most of Yellowstone National Park, about 6 inches (15 cm) of loess is mixed with top soil; loess is an important resource for retaining soil moisture. This loess topsoil is a non-renewable resource.

Fluvial, Lacustrine, and Mass Wasting Processes

Rivers, lakes, and gravity on slopes are active geologic agents that "fuel" natural ongoing processes. In Yellowstone, these processes are directly impacted by underlying volcanic activity. For example, continual deformation of the Yellowstone Caldera causes shoreline aggradation. Additionally, the outlet of Yellowstone Lake changes over time and impacts the ecology (e.g., drowning trees impacts pelican nesting sites) and cultural sites, which are affected by wave action on shorelines.

In general, the National Park Service strives to let natural processes proceed uninhibited. However, for the purpose of protecting infrastructure, these processes are often disturbed by human activities. For example, park staff has placed riprap along streams in order to protect roads in the park; this activity cuts off meander bends. Also, landslides, particularly after a fire, are natural processes. Nevertheless, the toes of landslides have been cut in the process of clearing debris from roads, causing destabilization of slopes.

The park geologists work with engineers to think more geologically when planning construction projects. Thinking geologically includes designing for catastrophic events and longer time periods (> 5 years). In short, they strive to educate engineers to recognize the power of natural forces over the long term (by coming up with solutions that will not impact [or be impacted by] the geologic processes active in Yellowstone) rather than trying to control natural forces in the short term.

Geothermal Features and Processes

Thermal features are the reason that Yellowstone National Park was established as the United States' first national park. Yellowstone is the site of the largest and most diverse collection of natural thermal features in the world. In accordance with section 115 of the Department of the Interior and Related Agencies

Appropriations Act for 1987, Public Law 99-591, the National Park Service published for review and comment a Proposed Notice in the Federal Register on February 13, 1987 (vol. 52, no. 30, p. 4,700–4710, part II). This notice identified significant thermal features within 22 units of the National Park System, including Yellowstone National Park. The report documents Yellowstone as having a single hydrothermal system that covers the entire park.

Staff geologists emphasized the importance of protecting geothermal resources as a dynamic system, not merely preserving particular geysers, which change over time. The protection process includes identifying anthropogenic impacts from inside and outside the park. For instance, a sewer line collected heat and produced a “hot spot” in front of Old Faithful.

Geothermal features are shown on both bedrock and surficial maps of the park but are typically considered surficial features. Rick Huchinson (former park geologist) started inventorying the park’s thermal features in the mid-1980s. Huchinson died in 1997. This inventory consists of many notebooks and hard-copy maps and black-and-white photos with sketched outlines of the thermal barrens. These hard copies have not been transferred electronically (Ann Rodman, oral communication, October 4, 2005).

Irving Friedman (USGS) compiled an extensive database of geothermal features for the park’s major geyser basins. He conducted geochemical analysis on selected features. His chloride flux monitoring, starting in the 1980s, is the longest record to date (more than 30 years). Friedman sampled water flowing out of the park in the Yellowstone River for chloride, which serves as a proxy for the overall Yellowstone system.

In 1996, an inventory of geothermal features became part of the park’s GIS. The accompanying database currently documents 900 individual features by temperature, pH, location, general description, electrical conductivity, and a digital photo. This information provides a thumbnail sketch or snapshot of Yellowstone’s geothermal resources. Investigators at the University of New Mexico, who are studying microbes on a NSF grant, use and contribute to the database.

In fiscal year 2005, park managers began a formal scientific monitoring program of geothermal resources. Monitoring will encapsulate the entire Yellowstone system (not just individual features). However, it will focus on high-priority areas such as Old Faithful and Norris. Collaborators at Utah State University will use remote sensing for the Upper, Midway, and Lower Geyser Basins. Dave Sauson, USGS hydrologist in Salt Lake City, will measure water levels in wells. In addition, park staff is testing an automatic sampling device to use for continuing (and expanding) the chloride-flux monitoring on all rivers flowing out of the park.

As a “top three” resource management issue, geothermal features are a significant health and human safety concern. For example, breaking through geothermal crusts causes four times as many human deaths as bear attacks; however, park management focuses on bears, not geothermal hazards. In addition to unstable geothermal crusts, geothermal hazards include hydrothermal explosions that extrude boiling water and mud.

The following are concerns for construction in geothermal areas:

- Wells—Drilling can alter natural hydrothermal workings.
- Road stability—Gravel surface covering, which “breathes,” is a superior alternative to asphalt paving, which covers geothermal features that ultimately buckle roads.
- Two types of hydrothermal deposits have different concerns for construction: (1) silica sinter is highly erodible and crumbles to powder; (2) travertine contains karstic features.

Glacial Features

In the recent geologic past, glacial ice covered all of Yellowstone National Park (Pierce, 1979; Good and Pierce, 1996). The northern margin of glacial ice extended past Chico Hot Springs. The southern margin was at Jackson Lake. The western margin was at West Yellowstone, and the eastern margin extended to the mouth of Clark Fork River. An icecap on the Yellowstone Plateau was so thick that it flowed upward and eroded Mount Washburn to the north. Because the Grand Canyon in Yellowstone was filled with ice, both park staff and the public have perpetuated some misinformation that the canyon was carved by glacial outwash; this is not the case. Other topographic features, such as the Lower Geyser Basin, do have connections to Yellowstone's glacial history. For information about glacial-volcanic interactions, see Christiansen (2001), especially p. G44.

Pierce, K.L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729 F, 91 p.

Good, J.D., and Pierce, K.L., 1996, Interpreting the landscapes of Grand Teton and Yellowstone National Parks, recent and ongoing geology: Grand Teton National History Association, 58 p. (Revised and reprinted 1998).

Christiansen, R.L., 2001, Quaternary and Pliocene volcanism of the Yellowstone Plateau region of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional Paper 729-G, 145 p.

The penultimate glaciation in Yellowstone occurred 140,000 years ago (Pierce and others, 1976), and the last glaciation culminated about 17,000 years ago. Between these glaciations, numerous rhyolite flows were extruded. Moreover, during glaciations, volcanic and geothermal processes interacted with overlying glaciers to create landforms in the park. The last glaciation ended between 12,000 and 15,000 years ago.

Pierce, K.L., Obradovich, J.D., and Friedman, I., 1976, Obsidian hydration dating and correlation of Bull Lake and Pinedale glaciations near West Yellowstone, Montana: Geological Society of America Bulletin, v. 87, p. 703–710.

Ice was thick over the Yellowstone Caldera during the last glaciation, but deglaciation (changes in pressure) did not cause volcanic eruptions. However, catastrophic draining of Yellowstone Lake produced a hydrothermal explosion when 200 feet (61 m) of water filled West Yellowstone basin and flooded the Fall Creek drainage.

The following list highlights significant features of glacial deposits in Yellowstone:

- Most of the grasslands in the park (prime wildlife-viewing areas) occur on glacial—including glacial lake—deposits, in particular the northern range and Gardiner and Hayden Valleys.
- Glacial lake deposits and till are prone to landsliding.
- The water levels in kettle lakes in Lamar Valley have decreased more than 3 feet (0.9 m) since the 1980s, which may be an indicator of long-term climate change.
- As aquifers and aquitards, glacial deposits significantly affect near surface hydrology.
- Many small- and large-scale (5–100 feet [1.5–30 m]) features of Yellowstone's landscape were eroded or deposited by glacial processes.
- Ice-marginal channels between Tower and Mammoth are key topographic features that dictate road placement and animal migration.
- Gravels deposited alongside receding glaciers formed well-drained deposits, which are good places to build roads.

- Talus from glacially oversteepened slopes is locally used for crushed rock aggregate, for example, in the Silvan Pass area.

Paleontological and Archaeological Resources

Because of the current staffing situation at Yellowstone, paleontological resources are treated as cultural resources. Elaine Hale oversees any paleontology-related projects through the archaeological office at the park. Many archeological sites occur in surficial deposits. In the 1990s park staff worked with Vince Santucci to acquire paleontological data for the park; however, no one has completed a thorough inventory of the park's paleontological resources. Park managers have established a process for inventorying fossils if they are unearthed during road construction: academic researchers assist with this process and are able to quickly respond and document resources. The inventory process does not interrupt construction for any significant length of time.

The following are some interesting fossils at Yellowstone:

- Cambrian trilobites in the Gallatin Range

  Walcott, C.D., 1899, Cambrian fossils, *in* Hague, A., Iddings, J.P., and Weed, W.H. (eds.), Geology of the Yellowstone National Park: U.S. Geological Survey Monograph 32, part 2, p. 440–478.

- Cretaceous-age mososaur

- "Fossil forest"

  Dorf, E., 1960, Tertiary fossil forests of Yellowstone National Park, Wyoming: Billings Geological Society 11th Field Conference Proceedings, p. 253–260.

  Dorf, E., 1964, The petrified forests of Yellowstone Park: Scientific American, v. 210, p. 106–114.

- Diatoms and pollen in ponds and lakes record post-glacial fire–climate–vegetation history.

- From a microbiological perspective, geothermal features have present-day "fossils." The question remains whether an organism that forms in a geothermal feature today, or an animal that falls into one, should be considered fossils. The outcome of this seemingly academic question has implications for resource management.

Permafrost

Permafrost likely occurs in the high country of Yellowstone National Park, though a soil survey must confirm this. Areas with permafrost have the potential to produce patterned ground and solifluction. Ice-cored talus in "permanently frozen areas" yields gravel, which is used for road construction and repair. Extraction for road building has removed an estimated 2,000,000 cubic yards (1,529,110 m^3) of gravel and permafrost from the Sylvan Pass area. Repeated "repair" of slumping roads in permafrost-affected areas (e.g., from Mammoth to Tower) has resulted in the addition of layer-upon-layer (an estimated 15 feet [4.6 m]) of asphalt.

Seismic Features and Processes

Earthquakes are part of Yellowstone's topographic development. The Yellowstone Volcano Observatory is a "distributed" network of seismic monitoring stations with the main monitoring activity located at the University of Utah in Salt Lake City. The University of Utah station measures seismic activity in real time and collects GPS and tilt measurements of surface deformation. The Yellowstone Volcano Observatory records between 1,000 and 3,000 earthquakes annually. A notable example of a large earthquake in the vicinity of Yellowstone National Park is the 1959 Hebgen Lake earthquake, which produced a scarp and caused landslides that altered the landscape. The highest post-glacial fault scarp is at the base of Mount Sheridan.

Earthquakes are a concern for health and human safety and have a significant potential for causing infrastructure damage. Consequently, workers are in the process of restructuring the headquarters building at Mammoth Hot Springs in order to "bring it up to code." An earthquake-generated seiche on Yellowstone Lake could cause changes in pressure of the hydrothermal system, which could trigger a hydrothermal explosion. Such an event would be a major concern for health and human safety.

Type Sections

The participants of the scoping meeting did not think that Yellowstone National Park was the site for any stratotypes (global standard for the definition and recognition of a representative rock unit of a segment of geologic time); however, a number of type sections (original described sequence of strata) occur in the park: Quadrant Formation, Lava Creek Formation, all three Yellowstone tuffs, and other volcanic rocks (mostly Tertiary). If this information is to be included in the GRE report, data needs to be researched and verified.

Volcanic Features and Processes

Lava flows in Yellowstone National Park govern many topographic features; contacts between flows control the locations of lake basins, streams, and hydrologic discharge. The type of lava flow may also be a factor in determining the type of vegetation that grows. For example, porous rhyolite appears to encourage the growth of homogeneous lodgepole pine, as on Rhyolite Plateau. However, before any broad generalizations are made and used for fire management planning, the direct relationship between bedrock and vegetation should include a soil survey (Pete Biggam, NPS Soil Scientist, personal communication, June 8, 2005).

The Yellowstone volcanic system has the potential to erupt. An eruption is a concern for health and human safety and would cause impacts to infrastructure. Most likely, the geologic result of an eruption would be basaltic or rhyolitic lava flows in areas outside the Yellowstone caldera. Somewhat less likely would be large rhyolitic lava flows on the Madison or Central Plateaus, aligned with fault zones outside the caldera. Least likely would be a large caldera-forming eruption within the area of the Yellowstone caldera. Eruptions could also produce ash and increased hydrothermal activity. Bob Christiansen mentioned that the U.S. Geological Survey is preparing a report about volcanic hazards for Yellowstone.

The Yellowstone Volcano Observatory was created as a partnership among the U.S. Geological Survey, Yellowstone National Park, and University of Utah to strengthen the long-term monitoring of volcanic and earthquake unrest in the Yellowstone National Park region.