National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Timpanogos Cave National Monument

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/013

THIS PAGE:
Chimes room - urchin, Timpanogos Cave NM.

Photos by: NPS

Timpanogos Cave National Monument

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/013

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

July 2006

U.S. Department of the Interior
Washington, D.C.

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the NPS conservation and environmental constituencies. Manuscripts are peer-reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and is designed and published in a professional manner.

Natural Resource Reports are the designated medium for disseminating high priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability. Examples of the diverse array of reports published in this series include vital signs monitoring plans; "how to" resource management papers; proceedings of resource management workshops or conferences; annual reports of resource programs or divisions of the Natural Resource Program Center; resource action plans; fact sheets; and regularly-published newsletters.

Views and conclusions in this report are those of the authors and do not necessarily reflect policies of the National Park Service. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the National Park Service.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available from the Geologic Resource Evaluation Program website (http://www2.nature.nps.gov/geology/inventory/gre_publications) on the internet, or by sending a request to the address on the back cover. Please cite this publication as:

Thornberry-Ehrlich, T. 2006. Timpanogos Cave National Monument Geologic Resource Evaluation Report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/013. National Park Service, Denver, Colorado.

NPS D-30, July 2006

Table of Contents

List of Figures

Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Timpanogos Cave National Monument in Utah. It contains information relevant to resource management and scientific research.

Geology and geologic processes provide the foundation of the ecosystem at Timpanogos Cave National Monument. Extreme relief dominates this landscape where the American Fork River has cut down through the layers of rock concurrent with regional uplift of the Wasatch Mountain Range. The prominent scarp of the Wasatch normal fault defines the western margin of the Wasatch Mountains. This dynamic area is geologically active and understanding the geology is useful for predicting hazards to visitors and better preserving, restoring, and showcasing park resources.

Geologic processes initiate complex responses that give rise to rock formations, surface and subsurface fluid movement, soil and cave formation. These processes develop a landscape that influences patterns of human use. The preservation of the caves, speleothems, and geology of Timpanogos Cave National Monument is important for the inspiration of wonder in visitors to the monument, and emphasis of geologic resources enhances the visitor's experience.

Timpanogos Cave National Monument in American Fork Canyon, a limestone gorge with spectacular cliffs, avalanche chutes, pinnacles, and caves, attracts over 100,000 visitors every year. These visitors place increasing demands on the resources of the monument as their numbers swell.

As the name suggests, Timpanogos Cave National Monument hosts some spectacular cave related (speleological) geologic features. Some of the principal geologic issues and concerns for the monument pertain to protecting these features. Humans have modified the landscape surrounding Timpanogos Cave and consequently have modified its geologic system. This system is dynamic and capable of noticeable change within a human life span. The following features, issues, and processes have a high level of geological importance and management significance for the monument:

- Cave management and restoration. The monument was set aside to preserve and protect the caves and the features therein. In a dynamic cave system, changes in water level, water quality, air quality, humidity, airflow, light, etc. all have profound effects on the entire ecosystem and these parameters must be monitored to determine the best way to regulate them and accommodate visitors. Management is concerned about the changing environmental conditions and the effects on speleothem formation, growth, and decay. Management also wants to improve understanding of cave origins, evolution, and age.

  An effort was launched in 1993 to remove some 250 tons of artificial fill in Hansen Cave, left from the construction of the tunnel connecting Hansen Cave with Middle Cave. This was done to restore the Hansen Cave Entrance to its natural state, restore hydrologic flow paths, and to improve the aesthetic quality of the room (Horrocks 1995). Restoring the caves to their natural condition also includes providing lighting which does not promote the growth of foreign microorganisms.
- Water Issues. Northern Utah mountains receive on average 25- 30 inches of precipitation per year. Thus water is an abundant resource and its quality is of high significance. Water that does not flow as surface runoff, percolates through the soil and rock, eventually making its way along fractures and fissures into cavities and caves. The hydrogeologic system present at the monument is not well understood and given the dynamic nature of the equilibrium relationship between water and caves at Timpanogos, may warrant further study.
- Slope failures and processes. Alpine environments are especially susceptible to slumping and landslide problems due to the lack of stabilizing plant growth and the young age of the canyon. Yearly snowmelt and intense seasonal storms produce runoff that dramatically alters the landscape, creating new hazard areas in the process. Road and trail construction also impact the slope stability. Mudstone rich units such as the Manning Canyon Shale are typically found in outcrop as slopes.

  These slopes are prone to fail when saturated. In addition to this hazardous situation, the more resistant units in the monument are exposed on precipitous slopes. This creates a situation exposing large blocks of jointed and faulted sandstone and limestone to the force of gravity. Rockfall and slope failure is a potential almost everywhere along American Fork Canyon.
- Seismic activity. The region around Timpanogos Cave National Monument is seismically active. The dynamic Wasatch normal fault system therefore places the cave features at risk. The closest segment of the Wasatch fault is among the most rapidly moving portions. In addition to possibly triggering catastrophic mass wasting along the canyon, seismic movements may lead to the destruction of speleologic features and partial or total collapse of the caves.
- Streamflow and channel morphology. In the climate of northern Utah, seasonal runoff, intense seasonal rainstorms of short duration, and subsequent flash floods in the American Fork River may impact channel morphology, pose a hazard to visitors, and destroy

park facilities and roads. These seasonal events also result in changes in the load and deposition of sediment in the canyons. These changes affect aquatic and riparian ecosystems. Sediment loading can result in changes to channel morphology and flooding frequency. The canyons are also discharge points for local groundwater flow systems.

- Overall Park Geology. The rock units present at the monument record the history of the region that can be explained in the monument's interpretive programs. The Precambrian basement rocks contain layers as much as 3,050 m (10,006 ft) thick of quartzite and coarse conglomerate with some calcareous shale and slate interbedded. Cropping out over most of the region are folded Paleozoic strata. These strata are dissected by myriad normal, thrust, and reverse faults at many scales.

Other geologic parameters and subjects such as the paleontology and paleoclimate of the area, wind erosion, and mine topics, have been identified as geologic management issues for Timpanogos Cave National Monument.

The predominant lithologies of Paleozoic age are limestone and dolomite. Mesozoic age strata include sequences of limestone, dolomite, sandstone and shale. Tertiary age rocks include quartz monzonite (intrusive igneous rock rich in quartz), sandstones, and conglomerates as part of the Tibble Fork Formation. Pleistocene age glacial moraines and other glacial landforms are located in many of the high mountain valleys in the American Fork Canyon and composed of clasts of the aforementioned rock types (Mayo and Loucks 1995). Stratigraphic units are present at the monument in generally south dipping layers. The geomorphological processes of erosion and weathering created and continue to shape the caves and cliffs of the dramatic American Fork Canyon. Understanding the interaction of the rock types and the topographic landscape created by uplift and erosion is essential to assessing potential hazards and improving protection of the environment and visitors to the monument. The Map Unit Properties section of this report details the geologic units in the area and potential resources, concerns, and issues associated with each unit.

Introduction

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

Purpose of the Geologic Resource Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and an understanding of geologic resources yields important information for park decision making. The National Park Service (NPS) Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. Ultimately, the inventory and monitoring of natural resources will become integral parts of park planning, operations and maintenance, visitor protection, and interpretation.

The Geologic Resource Evaluation (GRE) Program, which the NPS Geologic Resources Division administers, carries out the geologic component of the inventory. Staff associated with other programs within the Geologic Resources Division (e.g., the abandoned mine land, cave, coastal, disturbed lands restoration, minerals management, and paleontology programs) provide expertise to the GRE effort. The goal of the GRE Program is to provide each of the identified 270 "natural area" parks with a digital geologic map, a geologic resource evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and is designed to be user friendly to non-geoscientists.

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

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

For additional information regarding the content of this report, please refer to the Geologic Resources Division of the National Park Service, located in Denver, Colorado. Up- to- date contact information is available on the GRE website (http://www2.nature.nps.gov/geology/inventory/).

Geologic Setting

The Timpanogos Cave system is located high in the south wall of the American Fork Canyon, about 16 km (10 miles) northeast of the town of American Fork and 24 km (15 miles) north of Provo. The American Fork Canyon area is one small part of the deeply dissected Wasatch Front (the western face of the Wasatch Range) of northern Utah. The Wasatch Front is one of the steepest mountain ranges on earth (Horrocks and Tranel 1994). Rugged mountain faces and narrow, east- west trending, steep- sided canyons characterize the Wasatch Range. Due to rapid regional uplift many of the streams that drain the west side of the Wasatch Front have eroded headward, carving back their canyons, until they now reach the mountain crests.

American Fork Canyon, a steep and narrow streamcut channel in the southern Wasatch Range of North Central Utah, trends east- west, subparallel approximately 32 km (20 miles) to a fault zone responsible for the formation of the Timpanogos Cave complex. Timpanogos Cave National Monument comprises ~0.5 square miles (~250 acres, with an addition of 37 acres per the Timpanogos Interagency Land Exchange Act of 2002) of this canyon in the Uinta National Forest. Displayed on the walls of the canyon and the surrounding peaks are rocks illustrating the history of the area from the Proterozoic Eon to the present day. Although created in 1922 under the 1906 Antiquities Act by President William G. Harding (Proclamation No. 1540) to preserve the speleological treasures deep within the limestone, the monument also preserves a rich history that records the dynamic geologic processes that shaped Earth into its present morphology. The monument, formerly under management of the U.S. Forest Service, was included in the National Park Service in 1934.

The Wasatch Range is an uplifted crustal block that extends approximately 200 km (125 miles) between Malad City, ID south to Nephi, UT. The range is 13 to 26 km (8 to 16 miles) wide and is bounded dramatically on the west by the prominent scarp of the seismically active Wasatch Fault. The scarp, referred to as the Wasatch Front rises dramatically, some 2,134 m (7,000 ft) in places, from the valley floor below. This front separates the geologic province of the Basin and Range to the west from the Middle Rocky Mountain province to the east.

The Wasatch Range is geologically complex (figure 1). It is characterized by the normal faults along which Basin and Range deformation occurred. Normal faults form when material above the fault surface drops relative to the rocks below the surface. These faults develop as a result of tensional stress in the earths crust and have angles of dip usually between 45- 90°. Because of this relatively high angle, movement along major normal faults often results in dramatic fault scarp surfaces. In addition to the Wasatch Front, this type of fault scarp is demonstrated in the splendid setting of Grand Teton National Park in Wyoming.

There are many parallel ranges throughout the Timpanogos region due to the extensional tectonics pulling the crust apart in a roughly east- west oriented pattern. The Cedar, Oquirrh, and Promontory Ranges to the west of the Wasatch, and the Cricket Mountains, Pavant, and Confusion Ranges to the south and southwest are examples of similar parallel ranges. Basins such as the Tule, Snake, and Great Salt Lake Valleys to the west, and Cedar, and Little Valleys, and Sevier Basin to the southwest are typical examples of fault- bound basins in the Basin and Range province.

Many westward- flowing, high- gradient, nearly parallel streams are dissecting the Wasatch fault scarp into isolated peaks separated by deep, narrow canyons. Mount Timpanogos is one of the more prominent of these isolated peaks, rising to an elevation of 3,581 m (11,750 ft). The slopes of the mountain descend quickly to the valley floor at an elevation of 1,463 m (4,800 ft). The north and east slopes of the mountain are punctuated by a roughly horizontal feature called the Sagebrush Flats, at 2,438 m (8,000 ft).

Timpanogos Cave System

The cave system is composed of three caves called Hansen, Middle, and Timpanogos Caves. They are connected by a series of manmade tunnels to facilitate visitor access. The total combined length of the caves and tunnels is about 1,706 m (5,600 ft), this includes 488 m (1,600 ft) for Hansen Cave, 335 m (1,100 ft) for Middle Cave, and 884 m (2,900 ft) of Timpanogos Cave. The cave elevation is 2,300 m (7,546 ft) above sea level in a nearly vertical southern face in limestone cliffs (St. Clair et al. 1976).

Understanding the geology of the Timpanogos Cave system, the central feature of Timpanogos Cave National Monument, enhances one's understanding of the unique relationship between geology and the environment. The caves consist of high, narrow passageways and rooms developed along an array of minor faults. These faults are just a part of the much larger, complex fault structure near the intersection of the north- south trending Wasatch front and the east- west trending Uinta Mountain fold system to the north of Timpanogos, in northeastern Utah.

The caves have formed in the Deseret Limestone and contain limestone speleothems and are spectacular examples of solution cave dissolution and precipitation processes. The persistent work of acidic water through limestone carved caves into the Wasatch Front. Limestone caves form along ground- water paths of concentrated flow.

During the uplift of the Wasatch Range, 17 Ma, deformation of the Deseret Limestone along faults created the initial fractures and surfaces necessary to start the cave formation (Mayo et al. 2000). Once dissolution of the limestone began, the cave system continued to enlarge along joints, faults, and bedding planes in the rock until it reached its present size and shape. When the cave was later uplifted above the water table, the process of cave decoration began by precipitating limestone into the stalactites, columns, helictites, anthodites, and stalagmites that make the cave famous.

From the geologic map of the Timpanogos Quadrangle one can see that the local geology is extremely complex (see Appendix A). The cave lies in an area of block faulting. Some blocks have been displaced nearly 305 m (1,000 ft). In the area around the cave, the minor faults within the blocks dip 15° to 20° to the south. Dipping sediments in the cave suggest that the entire block may have been tilted since cave formation (White and Van Gundy 1974).

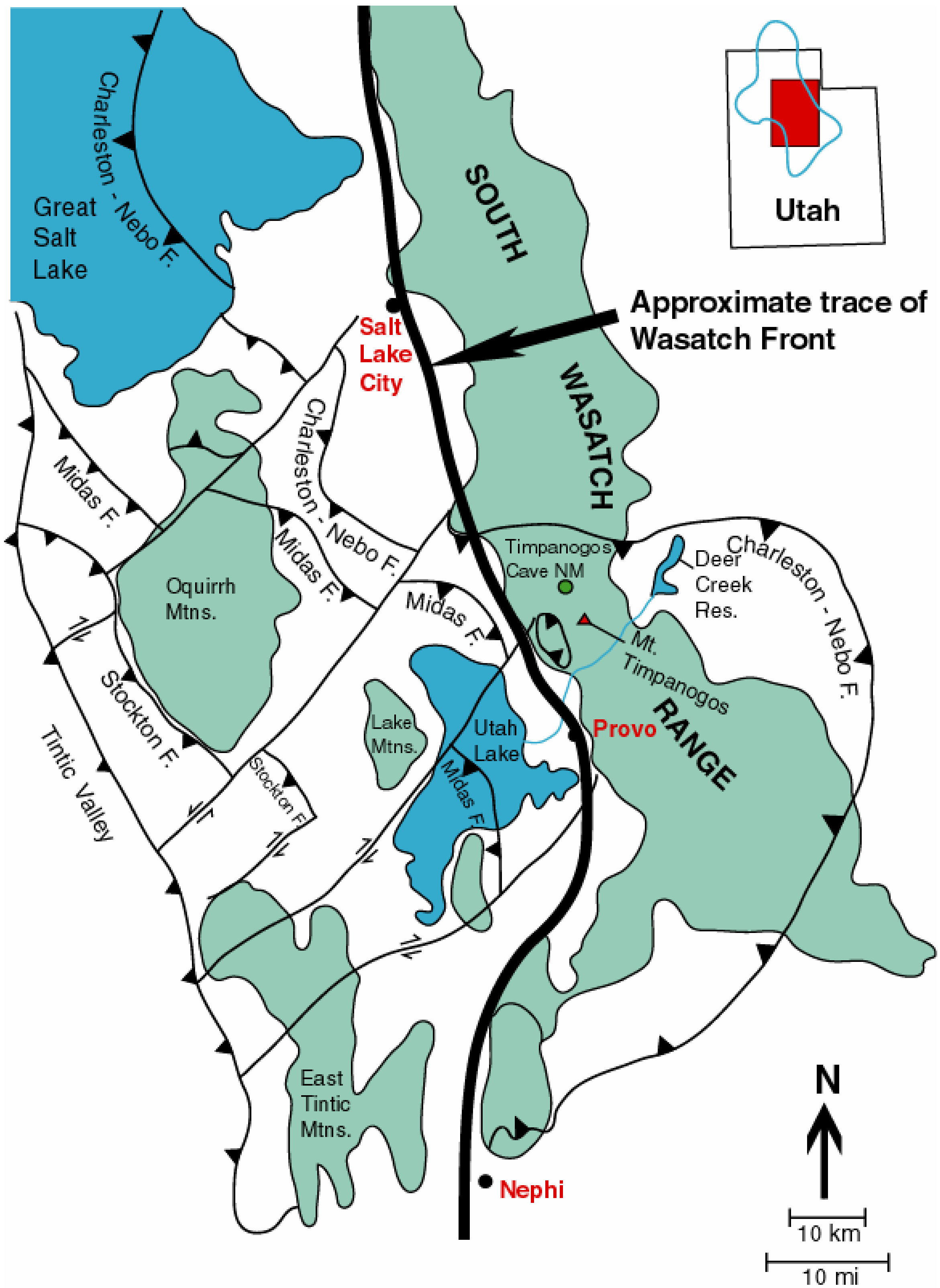


Figure 1. Map of the major faults and other features surrounding Timpanogos Cave National Monument. Uplifts are aqua colored areas. Inset shows boundary of Oquirrh Basin relative to the state of Utah and map extent.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Timpanogos Cave National Monument May 10- 11, 1999, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Introduction

Issues in this section are identified in relative order of resource management significance with the most critical listed first. Topics of general geologic interest and scientific research potential are presented towards the end of this section.

Cave Management and Restoration

Preserving the cave and maintaining its natural environment is the key resource management issue at Timpanogos Cave National Monument. The park's mission statement includes the goal "to preserve the outstanding cave formation, geological processes, and historical values of the Timpanogos Cave System and associated features for the recreational and educational enjoyment, scientific value, and inspiration of this and future generations." Information on the origins, evolution, and age of the caves is helpful to park management and interpretation. Knowledge such as fluid inclusion chemistry, sediment deposition rates and distribution, as well as the rates of growth for cave formations in conjunction with their size allow researchers to date and track the formation of the cave system over time.

Cave systems are quite dynamic. Changes in water level, humidity, airflow, light, etc. all have profound effects on the entire ecosystem. Water level and humidity affect the myriad of speleothems in the process of forming, drop by drop from mineral precipitation. Light sources have caused invasive microorganisms to proliferate in areas of the caves, their presence poses a slippery hazard to visitors and mars the spectacular cave features. Determining the balance between visitor access and cave preservation is a difficult task.

The resource management team at the monument is involved in activities aimed at restoring, preserving, and protecting the cave resources. Each year, Timpanogos Cave National Monument undertakes cave restoration projects that clean accumulated foreign material (mud, hair, lint, algae, etc.) from approximately 279 m^2 (3,000 ft^2) of the cave. These efforts were renewed for FYs 2005 and 2006 with additional funding. New, bat friendly gates were also installed in 2002- 2003. These gates will maintain visitor safety, cave security, and restore natural airflow through the cave system. In 2003, the monument staff began a project to monitor the cave's microbial diversity via a "DNA fingerprinting" technique. In FYs 2003- 2005, the resource management team sought to restore the natural drainage through the cave by minimizing the cave trail's interaction with the natural flow paths and creating maintainable catchments to keep debris such as mud and sand from coating cave formations and decreasing water quality (Timpanogos Cave National Monument website 2006).

Inventory, Monitoring, and/or Research Needs for Cave Management and Restoration

- Measure the concentration of Radon in caves.
- Continue to monitor and inventory human impacts on the cave resources.
- Perform samples of fluid inclusions throughout the cave formations to determine a time- line of water chemistry useful in determining cave age.
- Map and measure sediment thickness, type, and distribution to determine the timing of deposition.
- Determine cave formation rates of growth and comprehensively measure the dates of speleothems throughout the cave system.
- Determine how to prevent and clean up existing algae formation growth due to artificial light in the cave. The illuminated humid cave passageways are creating conditions optimum for microscopic life, such as algae and diatoms. A study by St. Clair et al. (1976) identified twenty- six species of diatom flora in the cave. These life forms obscure the speleothems and are a hazard when present in walkways, making them slippery. This makes visitor access hazardous on trails and cave surfaces.
- Research and develop safe ways of lighting the cave without disturbing the natural environment and encouraging the growth of foreign organisms.
- Determine how best to restore the natural cave climate while providing visitor accommodation and resource demands.
- Continue to comprehensively study and monitor that atmospheric conditions and hydrology in the caves.
- Study palynology and stratigraphy of sediments within the caves.
- Use pressure transducer to study storms moving in and out of cave system to determine pneumatic permeability and the exchange of air within American Fork Canyon.
- Monitor CO_2 concentration within the cave.
- Study cave formation decay due to changing air and water chemistry.

Water Issues

The interaction of water and geology are responsible for the formation of the Timpanogos Cave System. Water continues to play a critical role in sculpting the present landscape of the monument. The erosion of the steep American Fork watershed has cut through thousands of meters of rock creating the V- shaped valleys characteristic of the area.

During intense seasonal thunderstorms, rain pounds unprotected soil, knocking apart individual soil particles and washing unconsolidated sediment into the canyons increasing sediment load and turbidity in the river. Rainwater also combines with organic matter in soils and carbon dioxide in the atmosphere to form carbonic acid, a weak acid. Carbonic acid is effective at dissolving limestone, specifically along cracks where the acidic water is concentrated. The dissolution process increases the size of the cave system with each acidic water influx. As the acidic solution dissolves the limestone, it becomes saturated with calcium carbonate.

When the saturated ground water hits an air filled cavern precipitation of calcium carbonate takes place and over time elaborate speleothems develop. Thus there is a profound relationship between groundwater conditions and cave features. Because of this connection, water quality at the monument is a resource management concern. Potential pollution from septic systems and other human development must be assessed. Understanding the hydrogeologic system and the cave complex watershed of the monument is critical in predicting environmental (and speleological) response to pollution.

Ground water flow systems in the central Wasatch Range of Utah can be described on the basis of rock type and structure (Mayo and Loucks 1995). Among these systems are two found in the American Fork Canyon. They are described as consolidated sedimentary rock systems and fault controlled systems. Consolidated sedimentary rock systems occur in the Paleozoic and Mesozoic age strata and the Tertiary age Tibble Fork Formation in the Timpanogos Cave National Monument area. Water discharges occur typically from bedding planes and minor fractures. Discharge is most common from carbonate and coarse clastic sequences, which overlie less permeable layers of shale. These systems tend to be seasonably stable (Mayo and Loucks 1995).

Each of the caves has a distinct groundwater flow regime which in turn affects the type of speleothems found there. Drip rates in Hansen and Middle Caves respond very quickly to high intensity storms and rapid snowmelt due to unrestricted flow along fractures. Timpanogos Cave is deeper than the other two caves and has slower drip rates and much greater delays between surface recharge events and a change in drip rates.

A study conducted in 1991 revealed that Timpanogos Cave hydrogeology has a larger component of bedding plane flow than either Hansen or Middle Caves. Hansen and Middle Caves are intimately connected to a larger shallow fracture. For the same precipitation event, peak drip rates occurred in Timpanogos Cave 6 months later than in Hansen Cave (Tranel et al. 1991).

Many of the consolidated sedimentary rock systems in the American Fork Canyon are controlled by thrust and extension faults. The discharge rates of fault controlled systems are variable. Travertine deposits often occur concurrent with fault controlled groundwater discharge (Mayo and Loucks 1995). The groundwater reaching the caves is rich in bicarbonate, sulfate, and calcium and magnesium ions ($HCO3^{-2}$, SO^{4+}, Ca^{2+}, Mg^{2+}). Total dissolved solids and pH vary considerable throughout the year in the caves, indicating that mineral precipitation also varies seasonally (Tranel et al. 1991).

Water in the form of glacial ice has left its imprint on the Timpanogos story as well. The glacial sequence in the Timpanogos area has been the subject of only a few studies. Geologists have found evidence for three periods of glacial activity in the area based on the presence of moraines and other glacial till deposits and the degree of weathering and vegetation of those deposits. A large cirque, or bowl shaped depression where a glacier starts, exists on the slopes of Mount Timpanogos. Precipitation data suggest that this cirque could have contained the only Holocene age, also known as the Little Ice Age (mid 1800s), glacier in the Wasatch area. However, deposits found in and around the cirque indicate that only smaller rock glaciers, not ice glaciers, have been in the area since the Pleistocene ice ages (Anderson 1979; Anderson and Anderson 1981).

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

- Determine the nature of the cave complex watershed by compiling baseline watershed and cave hydrogeologic data. Expand upon the cave water quality monitoring project of FY 2003- 2004 (Timpanogos Cave National Monument website 2006).
- Monitor water quality on a multiple sample location basis within the monument, especially drinking water source locations.
- Install further wells for testing and drinking water access.
- The impacts of nearby mining are unknown (see above heavy metal mineral deposits discussion).
- Identify and study potential sources for groundwater quality impacts at the monument.
- Install transducers and dataloggers in wells.
- Investigate additional methods to characterize groundwater recharge areas and flow directions.
- Study groundwater recharge mechanisms and shallow sub- surface flow in carbonate terrains in the Central Wasatch Range.

Slope Processes

The walls of American Fork Canyon have extreme slopes. This renders them highly dangerous because of the likelihood of rock falls, landslides, and avalanches. This issue is a major concern in areas along the canyon walls where structurally weaker rock units including the Manning Canyon Shale are present. Even stronger rock units, such as the Oquirrh Formation, are locally highly fractured due to the degree of faulting in the area making them a hazard in rock fall situations.

Similarly, slumps and other forms of slope failure are common for units that are not necessarily associated with cliffs. Unconsolidated alluvium deposits for instance, are especially vulnerable to failure when exposed on a slope. The torrential rains that occasionally produce flash flooding at Timpanogos Cave National Monument also erode slopes lacking stabilizing plant and tree roots. The rock and soil, suddenly saturated with water can slip down the slope causing a huge slump or mudslide/flow. These conditions are also extremely hazardous in the winter when combined with the high snowfall received in the American Fork area between November and April.

In a cooperative effort, the resource management at the park, the NPS Intermountain Region GIS Support Office, and the University of Denver Department of Geography, developed a digital terrain model (DTM) to use with the park's GIS in determining a spatial rockfall hazard assessment. There is a high frequency of rockfall at the monument. Several rockfall chutes and hazard- prone areas along the visitor trail to the cave are well known. However, the DTM in conjunction with the GIS is a powerful tool to quantify and objectify the rockfall hazard. The relative hazard model uses the DTM to delineate rockfall paths and determine accurate, detailed slope dimensions while taking into account vegetation patterns to account for friction. Velocity of falling rocks can be calculated for every location in a hazard prone area using a mathematical equation accounting for friction, gravity, horizontal distance, and vertical distance of the rock's fall (McNeil et al. 2002). This tool could be expanded to cover larger areas of the monument and surrounding region.

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

- Inventory avalanche chute locations and monitor potential hazards, relate to climate and climate change.
- Perform an exhaustive mapping study of where specific snow accumulation areas are located on the slopes above American Fork Canyon to allow for more precise hazard assessment.
- Use climate information and topographic information in a GIS to map areas unsuitable for recreational development due to avalanche danger.
- Perform a comprehensive study of slope processes active at Timpanogos Cave National Monument.
- Continue to use and refine the rockfall susceptibility map correlating rock unit versus slope aspect in a GIS, in determining future developments and current resource management including trails, buildings, and recreational use areas.
- Monitor rockfall potential in American Fork Canyon, relate to slope and loose rock deposits.
- Inventory and monitor debris flow potential near picnic areas, relate to slope and loose rock deposits.
- Inventory flash flood susceptible areas, relate to climate and confluence areas.

Seismicity

The seismic potential in the monument area is high. Recent movement along the Wasatch fault system has formed fresh scarp faces, 6 to 12 m (20 to 40 ft) high, in unconsolidated, Quaternary age valley deposits. No earthquakes associated with surface rupture faulting have occurred along the Wasatch fault zone during at least the past 133 years. However the recurrence interval, or time between major seismic events, for the Wasatch fault zone is estimated between 50 to 430 years (Swan et al. 1980). The American Fork Segment of the Wasatch fault has slipped an average of 1 mm/year over the past 15,000 years. This is much higher than rates found along most segments of the Wasatch fault zone, which range from 0.1 - 0.2 mm/year (Machette 1987). Evans et al. (1986) measured the uplift rate of the Little Cottonwood Stock along the Wasatch fault to be 0.17 mm/year prior to 10 Ma and 0.76 mm/year starting from 10 Ma to the present. A series of scarps can be traced from the southern edge of the Timpanogos Cave quadrangle to the mouth of Willow Canyon. Studies of fault scarp morphology indicate that the American Fork segment experienced significant movement 2,000 years ago (Machette 1987).

The potential effects from seismicity in the Timpanogos Cave area range from damage to cave resources and park facilities to the triggering of mass wasting events such as landslides and avalanches along the steep slopes of American Fork Canyon. Shaking associated with seismic events has the potential to damage the delicate speleothems in the Timpanogos Cave system and cause localized cave collapse. Visitor safety is threatened during a seismic event from landslide potential along the roads and trails at the monument. Park infrastructure and visitor use areas, especially buildings, foundations, and waste treatment facilities are at high risk of damage during a seismic event.

Increased awareness of seismicity in the Timpanogos Cave area would help resource management predict outcomes accompanying an earthquake and prepare potential responses.

Inventory, Monitoring, and/or Research Needs for Seismicity

- Perform a comprehensive study of the faulting and seismic processes active at Timpanogos Cave National Monument, taking into account rock formations, slope aspects, location, and likelihood of instability.

- Evaluate the stability of the Sagebrush Flats area on Mount Timpanogos (see Map Unit Properties table). The slopes of this area would likely fail in a moderate to large seismic event. Use this information for planning trails and other visitor access beneath rockfall prone areas.
- Monitor seismic activity in American Fork Canyon and elsewhere along the Wasatch Front by cooperating with local agencies including the USGS and Utah Geological Survey.

Mine Issues

While there is no mining or oil and gas development in the monument, American Fork Canyon has been the site of mining interest for the past 100 years. Most of the mining took place in the north fork of the canyon in the late 1800s and early 1900s. Mines such as the Silver Bell, Whirlwind, Live Yankee, Queen of the West, Pittsburg, Globe, and Wild Dutchman produced wealth for miners in gold and silver (NPS and USFS 2004). For a few decades, lead, copper, arsenic, zinc, cadmium, and other metals were mined out of the nearby mountains. According to the NPS summary of Abandoned Minerals Lands, Timpanogos Cave National Monument contains at least three abandoned mine sites and three hazardous mine openings.

Mines, including abandoned and inactive mines in the watershed, pose several safety, environmental, and health problems to the Timpanogos Cave area. Foremost among these is metal contamination of groundwater, surface water, and soils. Contamination is defined as the occurrence of metals exceeding probable baseline concentration levels prior to mining activities (Moore and Woessner 2000).

Fluvial sediments can contain metals and mill waste materials. Tailing and other mill waste piles are associated with the potential for collapse and mine openings and dilapidated structures pose safety hazards (Madison et al. 1998). Timpanogos Cave National Monument is located downstream from many mine operations in the American Fork Canyon. Though a lot of the metals drop out of solution in the Tibble Fork Reservoir the potential for acid mine drainage from these mine features is a resource management concern for the park.

Acid mine drainage is a condition resulting from the presence of sulfides reacting with water, in effect lowering the overall pH by producing sulfuric acid (H_2SO_4), sulfate (SO_4^{2-}), and reduced iron (Fe^{2+}). This acidity increases the solubility of some potentially harmful metals. These metals are dispersed from a mine source area by ground and surface water as dissolved ions, suspended sediment, or as part of the fluvial bedload (Madison et al. 1998).

There are at least six components dictating the formation of acid mine drainage conditions (Trexler et al. 1975):

1. availability of sulfides (including pyrite)
2. presence of oxygen and iron- oxidizing bacteria
3. water in the atmosphere
4. availability of metals and minerals (calcite neutralizes acidity)
5. availability of water to transport dissolved components
6. mine and waste area characteristics

These components, if present in mine areas upstream from Timpanogos Cave National Monument have the potential to produce acid mine drainage. Once formed, the acidic water dissolves other minerals including sulfides such as arsenopyrite, chalcopyrite, tetrahedrite, galena, and sphalerite as well as aluminosilicate minerals. Metals such as manganese, silver, arsenic, copper, aluminum, cadmium, mercury, lead, zinc, and iron are then present in the water as ions. When ion concentrations are high enough and pH reaches certain levels, minerals containing these dissolved metals begin to precipitate including ferric hydroxide ($Fe[OH]_3$) (Madison et al. 1998). Precipitates cloud surface water, coat rocks, and deposit in layers in floodplain areas and along streambeds.

These precipitates can have drastic effects on aquatic life. Of particular concern in American Fork Canyon is a fragile population of native Bonneville cutthroat trout. Trout Unlimited (a third party) recently began mine reclamation activities on private lands in American Fork Canyon with an exhibition project allowed by the Environmental Protection Agency (EPA) on landscapes owned or managed by the Snowbird Ski Resort.

The cooperative order between the EPA and Trout Unlimited is the first time the agency has allowed a "Good Samaritan" to restore an abandoned mine. This will hopefully provide a model for federal agencies to enable cooperative conservation efforts with interested third parties.

As part of the reclamation effort, mine wastes with elevated levels of heavy metals will be removed from the abandoned Pacific mine, Blue Rock mine, Scotchman No. 2 mine, and the Pacific mill – all located upstream from Timpanogos Cave National Monument. An expected result of these efforts will be an improvement in water quality in the ten miles of canyon streams that traverse the Uinta National Forest and Timpanogos Cave National Monument (CCC 2006).

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

- Perform a comprehensive sampling study of the concentration of various heavy metals in groundwater and drinking water supplies. Test various stations along the American Fork River and its tributaries relative to locations of former mines.

- Monitor heavy metal concentrations in water sources and in drip water within caves.
- Monitor biota (e.g., aquatic insects) for heavy metal contamination.
- Work with EPA and other third party efforts to remediate mine sites within the monument and in American Fork Canyon.

Speleothems

Speleothems found at Timpanogos Cave National Monument include unique concentrations of helictites, stalactites, stalagmites, flowstone, and moonmilk. Some features are beautifully green and yellow colored by the trace elements including nickel and heavy metals dissolved in the groundwater from the rock units of the area. A recent mapping survey discovered a new type of speleothem found nowhere else on earth. A careful study of the speleothems in the cave would enrich a visitor's experience and add to the knowledge of the speleologic community.

In 2004, a project was funded at Timpanogos Cave National Monument to inventory cave features. Features included were cultural resources, rare or unusual speleothems, water and photo- monitoring stations, and lighting systems. These data were incorporated into the monument's GIS system. Hopefully, this ongoing effort will yield data helpful to park management. A monument wide inventory is planned for FY 2007 to include features such as electrical wiring, historic artifacts, new formations, and park resources and facilities (Timpanogos Cave National Monument website 2006).

Inventory, Monitoring, and/or Research Needs for Speleothems

- Perform a comprehensive inventory of all the speleothems present at Timpanogos Cave National Monument. Review catalog of different types of speleothems catalogued so far for accuracy for inventory and monitoring purposes.
- Determine the best way to display delicate speleothems without rendering them susceptible to damage from visitors.
- Update information regarding speleothems including mineralogy for visitor displays.
- Determine average speleothem growth rates in the cave system noting how they differ on the type of speleothem, and vary seasonally and geographically.
- Use uranium series dating (or C14 if young enough) of U- Pb (if old enough) to determine when active speleological deposition began while extracting paleomagnetic data if possible; determine number of depositional episodes.
- Collect drip waters to determine potential for precipitation (deposition) or dissolution (erosion) by current chemical composition parameters (pH).
- Determine air flow directions in the cave for use in interpreting the direction of deposition of speleothems.
- Conduct a minerals inventory within the cave (aragonite, calcite, etc.).
- Correlate formation locations to geologic features such as faults, hydrogeologic conduits, depth, etc.

Streamflow, Channel Morphology and Sediment Load

Surface water is drained from Timpanogos Cave National Monument by the American Fork River and its tributaries. In the alpine climate of northern Utah, intense, short duration, seasonal rainstorms and subsequent flash floods may impact channel morphology. These intense seasonal events may also result in periodic deposits of deep sediments. Sediment loads and distribution affect aquatic and riparian ecosystems, and sediment loading can also result in changes to channel morphology and overbank flooding frequency. The Tibble Fork Dam was placed in service in May of 1966. Its reservoir covers 13 surface acres and was created to supply irrigation and recreational opportunities. The dam interrupts streamflow and catches sediment, starving downstream areas. In addition, heavy metals, concentrated in the water from acid mine drainage, precipitate out of solution into the sediments behind the dam. The park is interested in understanding the effects of removing the dam on the downstream ecosystem.

The canyon is also a discharge point for local groundwater flow systems. The deep canyons dissect the region into a discontinuous series of ranges and canyons and disrupt local groundwater flow paths. If recharge is sufficient, the mountains may contain local groundwater flow systems that discharge as springs in the canyon. These springs should be inventoried and monitored for groundwater quality data.

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

- Monitor seasonal spring locations with regard to their location, water quality, and maximum flow.
- Perform channel morphology studies, about intense seasonal flashfloods. Consult professional geomorphologists regarding erosional processes.
- Inventory current channel morphological characteristics.
- Monitor changes in channel morphology.
- Determine downstream effects of dam removal with GIS (layering topography, flow velocity information, bed structure, etc) and streamflow models.
- Conduct hydrologic condition assessment to identify actual and potential "problem reaches" for prioritized monitoring. Once "problem reaches" are identified, monitor with repeat aerial photographs.
- Research effects of land use and climatic variation on streamflow.
- Investigate paleoflood hydrology.
- Conduct research concerning ungaged stream sediment storage and load.

- Measure sediment load on streams of high interest for comparative assessment. Data will provide information for making management decisions.

Paleontological Resources

Timpanogos Cave National Monument protects more than just a collection of speleothems, it contains a record of prolific ancient life. The oldest fossils are trace fossils from the Precambrian age Mutual Formation. These are among the oldest evidence of life in Utah. Fossils at the monument include ostracodes, plants, corals, brachiopods, trilobites (*Olenellus*), algae, and crinoids in the Cambrian Maxfield Limestone, Ophir Shale, and the Devonian/Mississippian age Fitchville Formation. The cave supporting unit, the Mississippian Deseret Formation, contains a variety of fossilized marine invertebrates, including syringoporoid corals and brachiopods (Santucci 2000).

More recent evidence of life comes from packrat middens. Middens were excavated from several locations in and near the cave system including Organ Pipe Room, Hidden Mine Cave, and Boneyard, as well as a test site in the Grotto. At least two species of packrat, *Neotomacinera* and *Neotoma* sp. were identified (NPS 1999). The middens contained other paleontological remnants found in the cave system including 11 species of mammals (Santucci 2000).

A comprehensive, formal inventory of the paleontological resources has yet to be completed for the monument. These preserved specimens should be protected and catalogued for scientific study, future generations, and increased visitor appreciation of the entire monument.

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

- Perform a comprehensive study of the paleontologic resources at Timpanogos Cave National Monument.
- Compile an inventory of all paleontologic specimens present in the caves and rock formations exposed at the monument.
- Attempt to determine the locations of paleontologic specimens removed from the monument as part of private collections to obtain an accurate inventory.
- Draw visitor attention to the fossil resources at Timpanogos Cave with graphics, brochures, and exhibits.
- Use fossils and speleothems to determine paleoclimate.

Wind Erosion and Deposition

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

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

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

General Geologic Issues and Potential Research Topics

Timpanogos Cave National Monument is a geologic park. The importance of geologic resources to the monument is identified in the *Annual Performance Plan*.

Sedimentary rock layers provide geologists with information to interpret the rock's provenance, depositional setting, paleogeography, diagenetic history, and the tectonic setting present when the sediments comprising the rock were deposited. Interpretations are based on many factors, including the mineralogy (composition) and texture of the rock, and sedimentary structures (e.g., cross- bedding). The fossil record contained within the rocks often best defines stratigraphy, referring to the rock's age, distribution, and position relative to other rock units (Prothero and Schawb 1996).

The thick stack of well- exposed rock layers present in American Fork Canyon contains an incredibly vast sedimentologic and stratigraphic record. The limestones in particular are rich in fossil evidence of past life. Understanding these features is vital to understanding the natural history of Timpanogos Cave National Monument.

Geomorphological processes continue to shape the landscape at the monument. Ongoing research about these processes could help fill in gaps in understanding of their role in the monument. Bringing attention to these processes in the interpretive programs at Timpanogos Cave National Monument will likely enrich visitor understanding and appreciation of the parks unique resources. The American Fork Canyon and River are an example of a steep- sided valley cut by fast moving water through the rapidly uplifting Wasatch Range in north- central Utah. Erosion has kept pace with rapid uplift and as a result the amount of sediment carried by the American Fork River is immense. These deposits are a vast potential resource as sand and gravel, however, they also pose a threat when undercut or exposed on high slopes.

Inventory, Monitoring, and/or Research Needs for General Geologic Issues and Potential Research Topics

- Perform rock color (including speleothems) studies.
- Identify unconformity- bounded stratigraphic packages in order to better define the depositional systems present in the past.
- Continue the study and implementation of geographic information systems (GIS) technology for interpretation, resource management, and maintenance areas of park management through interpretive mapping, 3- D visualization, a virtual field trip, and surface rockfall hazard assessment (McNeil et al. 2002).
- Develop more graphics and brochures emphasizing geology. These should target the average enthusiast.
- Determine age of canyon cutting using apatite fission tracks for peaks and surface exposure ages for minimum age of canyon from the exposed flatirons.
- Date small vugs in other stratigraphic units for timing of deposition; use isotopic composition of CO_3 minerals to determine source (hydrothermal or other).
- Use resistivity to locate cavities in other stratigraphic units
- Conduct a detailed study of fractures, faults, and bedding within the area.
- Conduct detailed mapping of karst terrain features in both the Deseret limestone and other limestone formations in American Fork Canyon (see Geologic Features and Processes section below).
- Perform a comprehensive study of the sediment deposition processes active at Timpanogos Cave National Monument, taking into account rock formations, sediment type, slope aspects, location with respect to trails, structures, and facilities, the likelihood of instability, etc.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Timpanogos Cave National Monument and vicinity.

Charleston Fault Zone

An important structural feature in the southern Wasatch is the Charleston Thrust Fault system. It forms the boundary between rocks of the thick and thin facies of the Carboniferous (a name referring to the Mississippian- Pennsylvanian Periods) for many kilometers northeast and east of Mount Timpanogos. The overriding block moved so far eastward on the fault that widely dissimilar sections of sedimentary rocks were brought together. Indeed, in the fault's hanging wall, the combined thickness of Upper Mississippian, Pennsylvanian, and Permian strata is ten times thicker in the vicinity of Mount Timpanogos and in the nearby Oquirrh Mountains, than in the part of the Wasatch Mountains carved from the fault's footwall. The rocks above the fault (Great Blue Limestone, Manning Canyon Shale, and Oquirrh Formation), called the thick facies by Baker and Crittenden (1961), are the result of essentially continuous deposition during Late Mississippian, Pennsylvanian, and Permian time. The rocks of comparable ages now in the footwall, and called the thin facies (Doughnut Formation, Round Valley Limestone, and Weber Quartzite), appear to be the result of slower, and perhaps intermittent deposition (Baker and Crittenden 1961).

In addition to the large thrust fault, the Charleston Thrust zone also includes an east- west trending corridor of faults and folds. Structural analysis and mapping in American Fork Canyon demonstrates that the zone contains an array of low- angle thrust faults and high- angle reverse (faults with the hanging wall being pushed up relative to the footwall typically at angles greater than ~30°) and normal faults. From local cross cutting relationships, it appears the thrust faults formed first, followed by reverse faults and some normal faults, and finally by a majority of normal faults, a few of which reactivated reverse fault surfaces. The overall pattern of faulting and folding in the area indicate that the zone is a left- lateral strike- slip (analogous to the San Andreas Fault of California where blocks slide past each other along a fault surface) system superimposed on a preexisting imbricate thrust fan (Paulsen and Marshak 1998).

Movement on the Charleston Thrust appears to have occurred in the Late Cretaceous- Tertiary time Sevier - Laramide Orogeny. Its surface trace is overlapped east of the Wasatch Mountains in the Uinta Basin by rocks of earliest Tertiary age, placing a latest age bracket on the last fault movements in the area (Baker, Huddle, and Kinney 1949; Baker and Crittenden 1961; Paulsen and Marshak 1998).

The trace of the Charleston Fault in the Timpanogos Cave Quadrangle is believed to lie concealed in the hanging wall of the Deer Creek Fault, an east- west trending, south- dipping, mid- Tertiary normal fault which crosses the quadrangle near its northern boundary. All but a small area in the northeast corner of the Timpanogos Cave quadrangle is therefore occupied by rocks of the upper plate of the Charleston Fault, characterized by the thick facies.

Cave Formation and Speleothems

The geologic history of the caves at Timpanogos began approximately 340 million years ago (Ma) with the deposition of the Deseret Limestone. After this deposition, the deformation, or faulting and folding, associated with the Sevier and Laramide orogenies created the linear surfaces necessary to concentrate limestone dissolution. About 17 Ma, the Wasatch Range was uplifted and created apertures or openings along the preexisting surfaces, producing the necessary space for cave formation. These fractures acted as preferred conduits for the movement of acidic groundwater, deep below the surface, dissolving the rock slowly and creating larger and larger openings.

Once the caves formed, minerals dissolved in the saturated water began to precipitate, drop by drop, to create the spectacular array of speleothems, or cave formations, present at Timpanogos Cave National Monument.

Bullock (1942) described three distinct geological epochs of cave formation for Timpanogos Cave. The first is the faulting phase where the preliminary fissures were formed to focus the second phase or excavational epoch wherein water dissolves rock away along the fissures. Three faults were involved and all indications point to recent (in geologic time) movement along them (St. Clair et al. 1976). The structural orientations of Hansen and Middle Caves are the same, N55°E, whereas the orientation of Timpanogos Cave is 10° northward from the other two, N45°E. This indicates that Hansen and Middle Caves were most likely developed along the same set of faults whereas Timpanogos Cave was developed along a different fracture (White and Van Gundy 1974). Dissolution was accomplished by pirating of surface water streams infiltrating the fractures within the rock, and groundwater flowing downslope focused along the linear features (St. Clair et al. 1976). The third and final phase of ongoing cave development involves the deposition of sediments and speleothems in the caves.

The caves consist mainly of high, narrow passageways in a linear arrangement, described below (figure 2). The caves are somewhat less developed and excavated than might be expected in a typical karst landscape, the reason for this could be the high concentration of dolomite in the Deseret Limestone around the formation of the cave. Dolomite dissolves much slower than pure limestone (White and Van Gundy 1974). Other reasons could be a lack of sufficient water or properly oriented fractures for dissolution. Additional rooms may remain to be discovered in the Timpanogos cave system.

The caves are composed of a variety of morphologies which indicate their origin in relation to the water table. Vadose origin (above the water table) and phreatic origin (below the water table) cave passages display different features as a function of the role of thoroughgoing water movement. Vadose origin passages show features indicative of ephemeral, fast moving water such as waterfall shafts, stream slots and meanders, small scallops, and directionality of passages to maintain a consistent gradient. Phreatic origin passages, on the other hand, show rounded cross sections, no preferred directionality of passages, an absence of sediment derived from outside the cave, and very gentle scallops indicative of slow water movement.

The Timpanogos Cave system may show both types of passageways, though a vadose origin is questionable. Scallop development in the caves indicates an approximate direction of water flow opposite that of the nearby American Fork River, possibly indicating that the caves formed at a sufficient depth, such that both the location and direction of flow in the American Fork River had no apparent bearing on cave development.

Karst Landforms

Karst landscapes, or those formed by the dissolution of limestone, occupy nearly 15% of the Earth's land area. The term *karst* derives from the Slavic *kars*, which means "a bleak, waterless place." (Summerfield 1991). Karst topography forms in carbonate or gypsum areas where surface water and groundwater dissolve the rock, forming sinkholes and caves similar to the topography found in Florida today (Graham et al. 2002).

Dissolution is possible when there is enough subsurface water flow to remove dissolved bedrock and keep undersaturated water in contact with the soluble walls. Dissolution rates vary directly with flow distance, chemical saturation, and temperature and inversely with initial fracture width, discharge, gradient and pressure of carbon dioxide in solution. An average maximum rate of dissolution, or wall retreat, is 0.01 - 0.1 cm/year. Solutionally enlarged high- angle faults tend to produce fissure- like passages with lenticular cross sections and very angular intersections, hence Timpanogos cave is an angular karst feature (Palmer 1991). The cave is angular, but does not vary much in elevation; the maximum elevation difference between the mouth of Hansen Cave to the southwest end of Timpanogos is only 19 m (61 ft) (White and Van Gundy 1974).

There are some alluvial sediments deposited in flat beds within the caves about 2.4 m (7.9 ft) thick (St. Clair et al. 1976). These sediments are primarily sand and yellow silt (White 1971).

In addition to the cave at Timpanogos National Monument, the landforms of the Wasatch Mountains provide unique examples of alpine karst landforms. There is little soil cover on the precipitous slopes of American Fork Canyon and bare rock ledges are common, making the exposure of the bedrock geology extremely apparent (White and Van Gundy 1974). Less soil is available to pick up carbon dioxide, but the colder temperatures at this altitude allow more solubility of carbon dioxide into the groundwater dissolving the rock into karst landforms (Jasper, personal communication 2006).

At the high altitude of Mt. Timpanogos, rinnenkarren (lit. German for truck ruts, solutional features carved on limestone faces like furrows) and pinnacle karren (solution furrows with intermittent pillars), as well as solutional pans (dissolved depressions) are forming in the Bridal Veil Falls Limestone of the Oquirrh Group during snow melt.

The Deseret Limestone, in addition to hosting the cave system, also supports a pinnacle karst landscape with a relief of several meters (tens of feet) along the canyon walls. The rough pinnacle surfaces indicate that this may be a remnant of Pleistocene climatic conditions because they are weathering rapidly under current conditions (White 1971; White and Van Gundy 1974). Other carbonate units at Timpanogos Cave National Monument, the Maxwell, Fitchville, and Gardison formations do not display much solutional sculpturing (White and Van Gundy 1974).

Cave Formations

Present in the caves are stalactites, stalagmites, drapery, flowstones and other drip stones in a dizzying array of shapes and configurations. Two minerals, calcite and aragonite, make up the majority of the speleothems ranging from stalagmites, stalactites, and draperies to the delicate and intricate anthodites, helictites, soda straws, and frostwork (figure 3).

Trace elements such as nickel, iron, and manganese, play the role of artist in the caves, splashing shades of green, yellow, orange, brown, pink, and black in otherwise white minerals. However, it is the tremendous diversity and number of helictites which makes the Timpanogos Cave system special. Helictites are small speleothems which twist and turn into strange, fantastical shapes as they grow from the cave walls.

The Timpanogos Cave complex is exceptionally well mineralized (figures 4 and 5). More than 42 different types of cave formations have been identified (Horrocks and Tranel 1994). The walls display intricate sculpturing with common wall and ceiling pockets. In addition to this sculpturing, incredible speleothems decorate the cave walls. Even the grandest speleothems begin with a single drop of water saturated with dissolved minerals (figure 6).

The usual calcite dripstone deposits give way to complex helictites and other erratic forms (White 1971). Sample analysis revealed that only three minerals are responsible for the variety of erratic speleothems found in the caves: calcite ($CaCO_3$), aragonite ($CaCO_3$), and hydromagnesite ($4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$) (White and Van Gundy 1974). Aragonite, a calcium carbonate mineral, is common in all areas as needles and anthoditic forms. "Moonmilk," composed of hydromagnesite, occurs locally as tufts of material on the tips of dripstones.

Trace elements may lend their color to the deposits. Nickel in calcite is thought to be responsible for unusual yellow stains whereas nickel in aragonite may result in a unique green cast (White 1971). Trace amounts of iron and manganese often lend a brown or orange cast to the speleothems. Copper and lead also contribute to the vast array of colors in the caves.

The common flowstones and dripstones are typically coarse- grained and white or light brown. They appear to be entirely composed of calcite. Monocrystalline dripstone or soda straw varieties are not commonly present in Timpanogos Cave system (figures 7 and 8). Flowstones in the cave complex can vary in color from deep chocolate brown (such as in the Cascade of Energy) to deep clear yellow. Some of the flowstones are faintly luminescent, but most are unusually lacking in luminescence (the emission of light by a substance that has received energy from an external stimulus) (White and Van Gundy 1974).

There are at least 16 different types of erratic speleothems in the Timpanogos Cave complex. Most of these are different morphologies of dripstone and flowstone. The erratic forms are calcitic helictites, aragonitic helictites, globulites, and spicular aragonite. These forms can occur together, such as in the Chimes Chamber, or separately. Calcitic helictites have smooth exteriors, are often curved and twisted. They form anastamosing branches. Frostwork anthodites tend to be linear, jutting from the walls at all angles. They have rougher surfaces than the calcite helictites. Some calcite can be intergrown with the aragonite in these forms (White and Van Gundy 1974).

Small clusters of acicular aragonite crystals, herein called, spicular aragonite are also known as anthodites. They appear as bush- like clusters of crystals radiating from a common "stalk." Common in the caves are several globular or nodular forms of speleothems. Some appear as spherical lumps on the tips of other crystals. They are incredibly variable in their morphology. Also found tipping aragonite spicular crystals is a loose, white, powdery moonmilk composed of hydromagnesite (White and Van Gundy 1974).

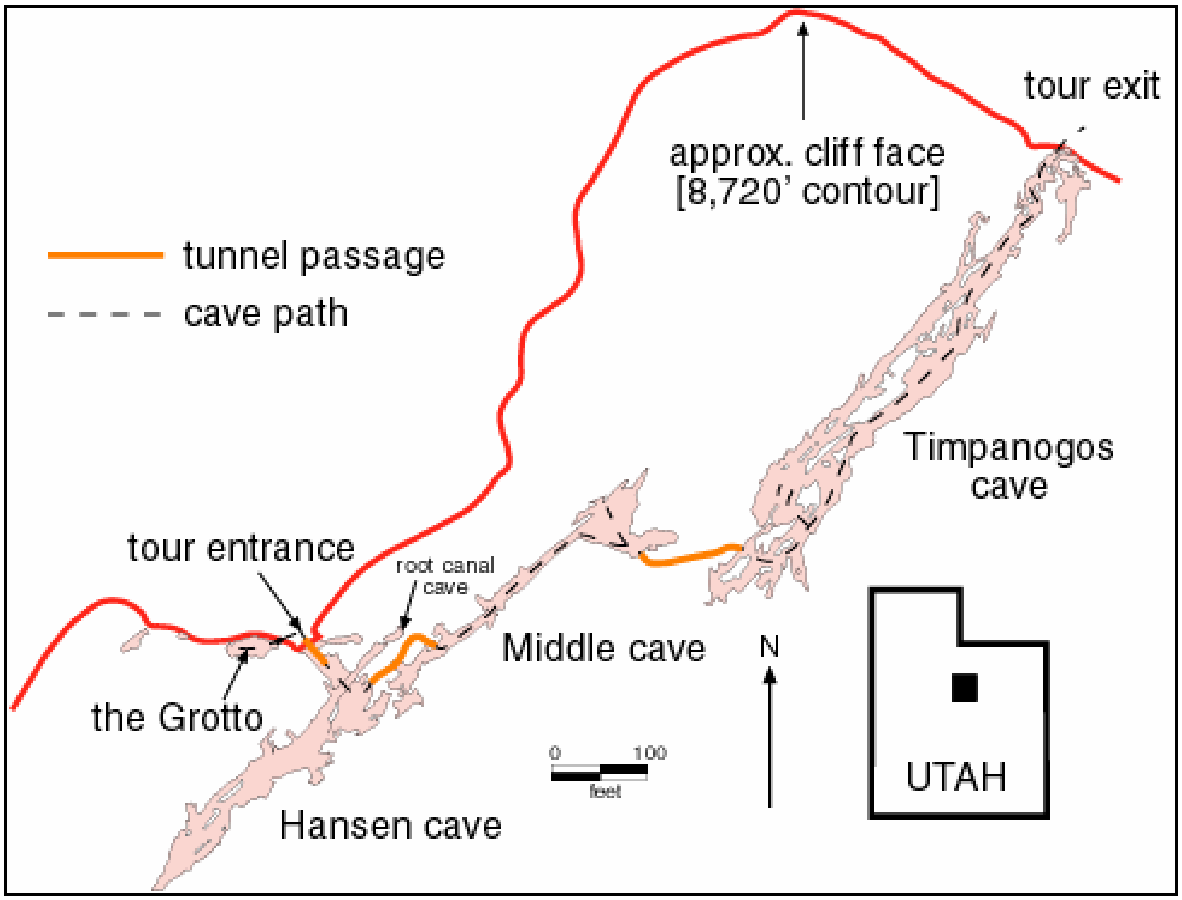


Figure 2. Map of Timpanogos Cave system with trails and man-made tunnels indicated (from Mayo et al. 2000).

Figure 3. Photograph of frostwork on a wall in Timpanogos Cave. Photographic is courtesy of the National Park Service.

Figure 4. Photograph of mineralization and speleothems in a cavern of Middle Cave. Photographic is courtesy of the National Park Service.

Figure 5. Photograph of stalactites in Coral Garden of Middle Cave. Photographic is courtesy of the National Park Service.

Figure 6. A drop saturated with dissolved minerals dripping from a soda straw at Timpanogos Cave National Monument. Photographic is courtesy of the National Park Service.

Figure 7. Photograph of soda straw and helictites speleothems in the Timpanogos Cave. Photographic is courtesy of the National Park Service.

Figure 8. Photograph of two soda straws speleothems at Timpanogos Cave National Monument. Photographic is courtesy of the National Park Service.

Map Unit Properties

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

Timpanogos Cave National Monument is underlain almost entirely by Precambrian and Paleozoic age rocks. Comprising the walls of American Fork Canyon and the surrounding peaks, these rocks are on striking display, indicative of the history of the area from the Proterozoic Eon to the present day.

The oldest rocks of the area, the Big Cottonwood Formation, the Mineral Fork Tillite, and the Mutual Formation, provide a rare glimpse into the tectonic setting of the Proterozoic Eon. In the early Cambrian Era, the sediments deposited include the sand for the Tintic Quartzite, the mud for the Ophir Formation, and, the limy ooze that lithified into the Maxfield Limestone. In the Mississippian, Pennsylvanian, and Permian Eras, the vast Oquirrh Basin formed and in this shallow deposits comprising the Fitchville Formation, the Gardison and Deseret Limestones, the Humbug Formation, Great Blue Limestone, Manning Canyon Shale, and Oquirrh Group were laid down.

Following the late Cretaceous to early Tertiary compressional Sevier–Laramide orogenic events was the uplift of the Wasatch Range and other ranges in the Basin and Range Province. The Tertiary age Tibble Fork Formation is the result of the local basins filling with sediments. Pleistocene glaciation, Lake Bonneville and other geomorphological agents such as streams and landslides have all left recent, Quaternary age deposits on the landscape of Timpanogos Cave National Monument.

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

Map Unit Properties Table

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Suitability for Development	Hazards	Paleontologic Resources	Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation	Global Significance
QUATERNARY	Alluvium (Qal); talus and high angle colluvial cones (Qt); landslides (Qls); Bonneville beach gravels (Qbg); Moraines (Qm)	Alluvial cones extend valleyward from the mouths of canyons feeding into American Fork Canyon. Deposits are angular, poorly stratified and often 10's of meters thick. Alluvium is a thin veneer of gravel, sand, silt and clay in gullies and as low cones and fans. Individual gravel are sub- angular and not well- sorted. Landslides of debris derived form Manning Shale are common in American Fork Canyon. Deposits include blocks and slump deposits, unsorted in an assortment of rock sizes in lobe- shaped bulges. Bonneville beach deposits are comprised of gravel, sand, silt and clay with some precipitates locally. Some are crossbedded, sorted sand and finer grained sediments of the deeper water facies. The glacial moraine deposits are composed of a jumbled assortment of rock sizes ranging from clay to boulder- sized particles in ridges and irregular shaped masses. Drapes of fine- grained glacial dust occur at high altitudes.	Low	Unconsolidated deposits could fail if water saturated and should be avoided for waste facilities and large structures, especially if slope is present.	Slump and sliding hazards, flash flood deposits	Packrat middens	May contain Native American artifacts and campsites	None	None	Gravel, sand, silt, clay deposits	Valley fill in area	Good for all uses unless slope is present to create unstable, unconsolidated surface	Bonneville beach deposits record levels of glacial Lake Bonneville in regionally correlative terraces
TERTIARY	Tibble Fork Formation (Tt)	Unit ranges in thickness between 0 and 762 m (0- 2500 ft). Comprised of fluvial pebble to boulder conglomerate. Larger boulders are well rounded and consist of gray to red andesite or latite. Smaller fragments are generally sedimentary rocks including quartz, limestone, brown- weathered rock and red sandstone. Some sandy to shaly greenish- gray to reddish- brown tuffaceous sediments occur locally as interbeds along with white algal limestone. Formation dips 20 to 40 degrees in TICA area.	Moderate to high	Should be suitable for most uses unless severely weathered, weathered volcanic beds may contain shrink- and- swell clays which will cause construction problems with roads and structures	Shaly layers may fail on slopes causing rockfall and landslide hazards, plucking of boulders from conglomeratic beds may cause rockfall hazard	Smooth ostracodes in limestone beds	None	None	Not enough carbonate rocks present to pose a karst problem	None documented	Plucked stones on cliff faces way provide bird nesting habitat	Good for all uses, climbing, and trails	Thick Tertiary deposits recording life after K- T extinction event
	Quartz monzonite of Little Cottonwood Stock (qm)	Part of the Little Cottonwood stock intrusive mass. Unit is quartz monzonite with phenocrysts of potassium feldspar in a medium- grained groundmass of plagioclase, quartz and orthoclase with some biotite and hornblende.	Moderate to high	Unit is exposed northeast of TICA and should be suitable for most development.	Rockfall hazard is high for this unit because of its proximity to the Deer Creek fault, rendering it highly fractured	None	None	Phenocrysts of potassium feldspar 7.6 cm (3 in) long	None	Rich in potassium and other alkali elements	None documented	Attractive for climbers	Rb/Sr date of 30.5 +/- 0.6 Ma (Oligocene in age), unit is component of Wasatch Igneous Belt
PERMIAN	Park City Formation (PNpc)	Only lowermost member is exposed and is 137 m (450 ft) thick in TICA area. Unit consists of thin- to medium- bedded fossiliferous limestone and some interbedded sandstone and a phosphatic shale.	Moderate	Unit is exposed northeast of TICA and should be suitable for most development except on phosphatic shale middle beds	Slumping and sliding hazards within shale beds, rockfall is possible for weathered and deformed beds in this unit	Permian age fossils abundant	None	Fossils	Karst potential exists for this unit	Phosphatic shale beds	Vugs on cliff could provide nesting habitat	Good for most uses except on shale beds	Permian in age, records life prior to mass extinction event

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Suitability for Development	Hazards	Paleontologic Resources	Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation	Global Significance
PENNSYLVANIAN	Oquirrh Group (Po); Bridal Veil Falls Limestone (Pob)	Unit is more than 1219 m (4000 ft) thick in TICA area, in Oquirrh Mountains it reaches a maximum thickness of 7900 m (26000 ft). Unit is composed of thin- to thick- bedded, fine- to medium- grained sandstone and quartzite. Unit is slightly calcareous and weathers to tan. Sandstones are interlayered with gray limestone, which lends a banded appearance to the unit. Sandstones are tabular crossbedded. Near the bottom of the unit is the medium- to dark- gray limestone called the Bridal Veil Falls Limestone. This member contains abundant fossils and chert beds and nodules.	Moderate	Unit is only exposed on the uppermost slopes of Mount Timpanogos and Box Elder Peak, however it should be competent for most forms of development unless highly fractured or weathered.	Rockfall hazard if rock is highly jointed or dissolved. Some shale layers may prove incompetent if highly weathered.	Early Pennsylvanian age fossils in conjunction with assorted fusulinids such as *Millerella* sp.	Chert nodules could have provided tool material	Fossils	Karst potential exists for this unit	None documented	Vugs on cliff could provide nesting habitat	Good for most uses, weathered surfaces could prove hazardous for rock climbing.	Unique, thick banded member prominent in region, Pennsylvanian age fossils
PENNSYLVANIAN - MISSISSIPPIAN	Manning Canyon Shale (PMmc)	Maximum thickness of unit in area is 488 m (1600 ft). Unit is poorly exposed in TICA area, composed of brown to black shale interbedded with fine- grained and gritty, commonly light- brown weathering, quartzitic sandstone and gray to black, generally shaly limestone. Some lenses of orange- brown- weathering sugary sandstone and grit occur locally.	Low	Rock weathers easily making it a poor foundation base for structures and most permanent development, especially if a slope is present	Slumping and sliding hazards exist for this unit on slopes and/or if water saturated	Brown shale contains fossil plants. Abundant marine fossils including: *Posidonia* cf. P. *wapanuckensis*, *Cravenoceras*, *Eumorphoceras* cf. E. *bisulcatum*, *Rayonnoceras* cf. R. *solidiforme Croneis*.	None	Fossils	Not enough carbonate rocks present to pose a karst problem	None documented	Burrowing material if highly weathered, forms gentle slopes in canyons for plant and animal habitat	Not stable	Contains boundary between Upper Mississippian and Pennsylvanian ages near middle of unit
MISSISSIPPIAN	Great Blue Limestone (Mgb)	Unit is 853 m (2800 ft) thick, informally divided into three parts: lower and upper limestone members, separated by carbonaceous shaly beds (Long Trail shale member). Unit is composed of nearly homogenous, calcitic, dark gray to black limestone and shaly limestone. Bedding is very regular and weathers to light- gray to pinkish- tan flaky, slabby rock. Some black chert nodules occur locally as well as some black shale and rusty weathering fine-grained quartzite.	Moderate	Suitable for most development unless significant dissolution or weathering has occurred. Weathered rock sloughs and flakes and is unstable for permanent structures. Dissolution can pose a problem with waste facilities	Rockfall hazard where unit is weathered and on a slope, can be unstable trail base if severely weathered or dissolved.	Late Mississippian age fossils	Chert nodules could have provided tool material	None	Karst potential exists for this unit	None documented	Vugs on cliff could provide nesting habitat	Good for most uses, weathered surfaces could prove hazardous for rock climbing.	Type locality in the Oquirrh Mountains
MISSISSIPPIAN	Humbug Formation (Mh)	Unit is more than 244 m (800 ft) thick in TICA area. Composed of interbanded dark to light- gray, fine- to coarse- grained dolomite with fine- to medium- grained limey sandstone. Unit appears banded with brown beds layered with gray beds.	Moderate	Good for all development unless highly fractured, which could pose a problem with waste facilities	Rockfall hazard on cliff faces	sparsely fossiliferous in limestone beds	None	None	Karst potential exists for this unit	Attractive building stone	Vugs and ledges on cliffs could provide nesting habitat	Rock climbing and Mountain biking. Good for all uses	Distinct banded unit

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Suitability for Development	Hazards	Paleontologic Resources	Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation	Global Significance
MISSISSIPPIAN	Deseret Limestone (Md)	The unit is more than 152 m (500 ft) thick. Unit is a massive to medium- bedded, cliff and cave- forming unit with dark- to light- blue- gray, fine- to coarse- grained dolomite with abundant lenticular, or lens- like, black chert deposits and some interbedded limestone. Timpanogos Cave is contained in this unit.	Moderate to high	Dissolution can create conduits which pose a problem for waste facilities and severe dissolution can make construction on this unit risky	Rockfall on cliff faces, and assorted cave-related hazards such as slippery trails, holes, and sharp speleothems	Late Mississippian age brachiopods and corals, crinoid stems, cup corals and colonial corals.	Native Americans may have used the caves for ceremonial and other purposes, chert masses may have been tool material	Speleothems, fossils	Karst exists in this unit, caves present	None documented	Caves provide animal lion and other mammal habitat	Caving, climbing	Cave and cave formations (speleothems)
MISSISSIPPIAN	Gardison Limestone (Mg)	Unit is more than 183 m (600 ft) thick in monument area. Lower beds are dark-gray, thin- bedded, coarse- grained limestone and dolomite. Middle beds contain thin- bedded, blue- gray limestone with silty partings. Upper beds are dark-gray, massive limestone and dolomite. Light- brown to black, and white chert abundant locally. Carbonaceous shale marks top of unit.	Moderate to high	Shaly partings can render the unit unstable for foundations and other permanent facilities	Shaly partings can pose rockfall hazards	Fossils of *Triplophyllites*, *Syringopora*, *Spirifer centronatus*, *Triplophyllites excavatum*, *Cliothyridina* and *Aviculipecten* of Mississippian age.	Many chert nodules useful for ancient tools	Fossils	Some karst potential in carbonate beds	Locally uraniferous and phosphatic layers	Vugs on cliff could provide nesting habitat	Good for all uses	Mississippian fossils of Kinderhookian age
MISSISSIPPIAN	Fitchville Dolomite (Mf)	In the TICA area the unit is more than 152 m (500 ft) thick, composed of coarse, light- gray to tan dolomite and dolomitic sandstone with some pebbly layers. Upper beds are very fine- grained dolomite.	Low to moderate	Dissolution can create water conduit problems and dangerous trail base, but otherwise okay for all uses	Jointed sandstone beds can pose rockfall hazards on cliffs, crystal lined vugs are hazardous hand and foot holds	Mississippian age fossils	None	Crystal lined vugs	Karst potential exists for this unit	Flaggy lower beds are attractive flagstone material	Many vugs present for bird and small creature habitat	Rock climbing and caving potential	Mississippian fossils, records profound unconformity
CAMBRIAN	Maxfield Limestone (Cm)	Unit ranges in thickness between 0 and 91 m (0- 300 ft). Unit contains thin- to thick-bedded, blue- gray, mottled or speckled magnesian limestone and dolomite. Some oolitic and pisolitic lower beds and white dolomite upper beds	Moderate	Dissolution can create hazardous trail base and conduits not suitable for waste facilities.	Rockfall hazard potential	Fossils of trilobites *Kootenia* sp., *Doliochometopsis* sp., *Spencia* sp.	None	Fossils, pisolite layers	Karst potential exists for this unit	None documented	Vugs on cliff could provide nesting habitat	Rock climbing potential	Cambrian fossils
CAMBRIAN	Ophir Formation (Co)	Near TICA unit is 91 m (300 ft) thick. Lower beds are olive- green micaceous shale. Middle beds are massive gray limestone and upper beds are brown, calcareous sandstone mixed with shale.	Low	Micaceous shale can be unstable for structure foundations	Unit can be a crumbly trail base	worm tracks, fucoid markings, brachiopods and trilobites. Fossils of *Olenellus*, *Micromitra*, *Obolus*	None	Fossils	Middle beds may have dissolution	None documented	Vugs on cliff could provide nesting habitat	Good for trails	Cambrian fossils
CAMBRIAN	Tintic Quartzite (Ct)	Unit is 396 m (1300 ft) thick in TICA region in prevalent exposures. Unit is nearly pure quartz. Weathers to brown, white and tan with thin to thick beds (irregular). It is medium- to coarse-grained, white to pinkish on fresh surfaces with conglomeratic lower beds. Some pebbles are up to 5 cm (2 in) in diameter. Random crossbedding and shale stringers locally.	High	Good for all development unless highly fractured, which could pose a problem with waste facilities	Rockfall hazard along cliffs is prevalent where unit is undercut along trails	None	Chert pebbles may have been used for tools	Glassy quartzite	No carbonate rocks present	Attractive building stone	None documented	Good for all uses unless undercut on steep slopes. Mountain biking	Pure quartzite

Age	Map Unit (Symbol)	Unit Description	Erosion Resistance	Suitability for Development	Hazards	Paleontologic Resources	Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation	Global Significance
PRECAMBRIAN	Mutual Formation (pCm)	The unit ranges in thickness from 0 to 396 m (0- 1300 ft) in TICA area. Composed of quartzite grit and conglomerate with minor amounts of shale. Quartzite is rusty to red- purple with tan to gray sandstones. Fragments consist of schist, gneiss, limestone and tillite. Fragments can be up to 1.5 m (5 ft) in diameter.	Moderate to high	Shaly layers should be avoided, but otherwise all is suitable.	Plucking of pebbles on cliff faces may pose rockfall hazard	None	Chert pebbles may have been used for tools	None	No carbonate rocks present	Attractive building stone	None documented	Good for all uses, rock climbing potential	None documented
PRECAMBRIAN	Mineral Fork Tillite (pCmf)	Unit is 0- 61 m (0- 200 ft) thick in TICA area and is composed of rounded pebbles, cobbles, and boulders in a silty and sandy matrix with glacial flour acting as cement. Fragments consist of quartzite, algal limestone, dolomite, schist, greenstone, gneiss, granite, and amphibolite. Unit appears as a dark gray to black massive conglomerate to sandstone.	Moderate	Glacial flour cement may degrade and cause the unit to be friable locally. Okay for all development.	Plucking of pebbles and boulders along steep slopes may pose a rockfall hazard	Some fossil algae boulders	Chert pebbles may have been used for tools	Unusual ancient glacial till	No carbonate rocks present	None documented	Plucked stones on cliff faces way provide bird nesting habitat	Good for all uses	Unique ancient glacial deposit formation
PRECAMBRIAN	Big Cottonwood Formation (pCbc)	Unit has maximum thickness in TICA area of 396 m (1300 ft). Composed of massive quartzite and gray to dull- purple shale. Weathers to rusty- buff color.	Moderate to high	Especially shaly layers may pose a problem to construction and highly fractured areas should be avoided for development, otherwise all is suitable.	Rockfall hazard if present on cliff face	None	None	None	No carbonate rocks present	Attractive building stone	None documented	Good for all uses, rock climbing potential on cliffs	23165 m (76000 ft) thick type section at Big Cottonwood Canyon

Geologic History

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

The rocks and geologic structures and features present in Timpanogos Cave National Monument record a vast span of Utah's geologic history from the time before plants or animals existed, through episodes of mountain building and extension of the earth's crust, to formation of the caves, and excavation of American Fork Canyon (figure 9).

The oldest rocks provide a rare glimpse into the tectonic setting of the Proterozoic Eon (figure 10). The earliest event preserved and recorded by rocks exposed in the Timpanogos Cave quadrangle was the deposition of the layers of sand and mud from nearby highlands. These deposits now form the uppermost part of the Big Cottonwood Formation. This deposition was interrupted by a prolonged period of glaciation during which massive tongues of ice extended into the area and deposited great bodies of poorly sorted glacial till (now tillite, the lithified equivalent of a jumbled assortment of rock sizes and types, Mineral Fork Tillite). This ancient glaciation was followed by local tectonic uplift and subsequent extreme erosion. These eroded surfaces were overlain by deposition of red sand, mud, and gravel, which now constitute the Mutual formation. This formation is the youngest unit of the Precambrian system at the monument and underlies American Fork Canyon today (figure 11) (Baker and Crittenden 1961).

Late Proterozoic rifting created a new continental margin along western North America. During the Late Precambrian through the Cambrian, thousands of feet of shallow- water, marine sediments accumulated along a passive plate- tectonic margin on the western side of the Transcontinental Arch, an upland that stretched from northern Minnesota southwestward across Nebraska, Colorado and northwestern New Mexico (Speed 1983; Sloss 1988; Graham et al. 2002). The area that is now Timpanogos Cave was approximately located along the shoreline in this paleoenvironment.

Throughout the Paleozoic Era, Europe, Africa, and South America were approaching North America as the two great landmasses, Laurasia and Gondwana, collided. The ancient continent of Gondwana included Australia, Antarctica, Africa, South America, and India south of the Ganges River, plus smaller islands. Laurasia, located in the northern hemisphere, contained the present northern continents (Graham et al. 2002).

In the early Cambrian Era, the region again underwent an uplift and erosional event. Following the uplift, the region subsided and an ancient sea advanced bringing with it the depositional environments necessary to capture vast amounts of sediments including the sand for the Tintic Quartzite, the mud for the Ophir Formation, and as the sea deepened, the limy ooze that lithified into the Maxfield Limestone.

This progression of units records the deepening of the sea during progradation in the area. During this time, prior to the evolution of land plants, loose sediment was continually reworked by wind and fluvial processes. Late Precambrian, shallow- water sediments thicken across Utah, from east to west, until they reach a thickness of 3,000- 6,000 m (10,000 to 20,000 ft) in western Utah (Hintze 1988; Graham et al. 2002).

In Utah, Cambrian strata are more widely distributed than deposits of any other time (Hintze 1988). Thinly laminated stromatolitic dolomites and mottled muddy limestones in the Middle and Upper Cambrian of Utah were deposited in very shallow marine waters that deepened westward. A wedge of Cambrian Period sediments thickened from eastern to western Utah approaching a total thickness of 3,700 m (12,000 ft) near the Utah/Nevada state line (Hintze 1988). The lateral and vertical distribution of marine fossils, primarily trilobites, paints a picture of the Utah area in Cambrian times with a shoreline slowly migrating eastward from Nevada to central Utah during the Early and Middle Cambrian. By Late Cambrian time, marine waters covered virtually the entire state. The Equator ran northward through Utah, and limy muds accumulated under these warm- water conditions in much the same way as they do in the broad lime- mud shoal- bank area in the Bahaman Islands today. The Ophir Formation and Maxfield Limestone are present in Timpanogos Cave National Monument as testament to these pervasive seas (Hintze 1988).

Whether similar deposition continued into the Ordovician, Silurian, and Devonian periods is not known because no sedimentary rocks representing any of those periods have been found in this part of the Wasatch Mountains. If any were deposited, they have since been removed, together with much of the Cambrian age rocks in some places, during the long erosion interval that is recorded in the profound unconformity at the base of the Mississippian age rocks (Baker and Crittenden 1961).

From elsewhere in Utah, rocks recording broad carbonate shelves evolving into open and restricted marine environments and later near- shore marine environments, fill in stratigraphic unknowns or gaps left in the Timpanogos area rock record.

In the Middle Devonian Period (about 401 Ma), the first compressive pulses of the Antler Orogeny in the west and the Acadian Orogeny in the east (part of the Appalachian Orogeny) began, as landmasses accreted onto both the western and eastern borders of North America.

To the west of Utah, a subduction zone formed and lithospheric plates collided against one another and their rocks were bent, buckled, folded, and faulted into a north- south trending pre- Rocky Mountains mountain range stretching from Nevada to Canada. The Roberts Mountains Thrust marks the easternmost thrust sheets generated by the Antler Orogeny.

During orogenic events, great sheets of rocks measuring tens to hundreds of kilometers in width and length are stacked on top of one another. The weight depresses the land in front of the thrust sheets, or *foreland*, and causes the foreland to subside into a *foreland basin*. As the highlands to the west were thrust above sea level at the beginning of the Mississippian, warm shallow marine water flooded the foreland basin and spread over eastern Utah giving rise to an extensive carbonate platform.

Found in the thick Mississippian marine limestones are fossils of animals that lived in normal marine salinity such as brachiopods, trilobites, corals, bryozoans, crinoids, fish, foraminifera, and conodonts (microscopic structures of an extinct animal that are excellent relative- age indicators). The sea became shallower during the regression that followed the Antler Orogeny, however, and habitats dwindled so that marine life became more restricted. Eastern Utah became a broad karst plain of shallow- marine sandstone and micrite (carbonate mudstone), and by the end of the Mississippian, the area was again exposed to subaerial erosion (Poole and Sandberg 1991; Graham et al. 2002).

During Early Mississippian and much of Late Mississippian time, layers of carbonates, intermittently alternating with sandy sediments, accumulated at roughly equal deposition rates north and south of the present day site of the Charleston Fault zone. These were to become the Fitchville, Gardison, Deseret, and Humbug Formations. Very late in the Mississippian period, and throughout Pennsylvanian and Permian time, more than 9,144 m (30,000 ft) of sediments accumulated in the basin to the south and west of the Charleston fault zone, whereas to the north and east less than 1,524 m (5,000 ft) of beds were laid down.

As the sea became shallower during the regression that followed the Antler Orogeny and the Kaskaskia Sequence came to an end, the shoreline again receded from the Transcontinental Arch and by early Pennsylvanian time, soils were beginning to form in low lands and the higher areas were being worn down by erosion. Much of the Oquirrh, Park City Formations, and possibly all of the Great Blue Limestone and Manning Canyon Shale may be missing to the north of the Timpanogos Cave quadrangle due to this erosion.

Coincident with Pennsylvanian tectonics (figure 12) was a global climate shift from the warm humid environment of the Late Mississippian to a much more arid environment in the region of Utah during the Early Pennsylvanian (Rueger 1996).

As the Ancestral Rocky Mountains formed, the Ouachita- Marathon thrustbelt, the Anadarko Basin, and other Permian basins developed to the southeast and the Oquirrh Basin subsided to the northwest (Jordon and Douglas 1980; Peterson 1980; Kluth 1986; Gregson 1992). Vertical relief in some of these basins relative to sea level (i.e., the Oquirrh and Central basins) was greater than the emergent mountains, and the Ancestral Rockies may have reached as much as 3,000 m (10,000 ft) of relief.

The thick sedimentary sequence of the Oquirrh Group in the Timpanogos Cave area represents the variety of shallow marine and arid near shore environments present in the Oquirrh basin area throughout the Pennsylvanian, including eolian dunes, marine shelf, open coastal area, intermittent fluvial systems/channels, and protected waters (Konopka 1982). The Oquirrh Basin along with all of these paleotectonic structures probably reflect a similar tectonic stress field controlled by Precambrian structural weaknesses and the compressional stress- field that evolved with the assembly of Pangaea (Tweto 1977; Kluth 1986; Ross and Ross 1986; Gregson 1992).

Continuing from the Pennsylvanian, during the middle part of the phase of the Park City Formation deposition, in Permian time, shallow stagnant seas persisted over most of the Timpanogos Cave region. These seas provided the arid/evaporitic conditions required for deposition of phosphate and other salts (Baker and Crittenden 1961). Across the globe, the Permian Period was a time of dramatic environmental change. The Permian equator was oriented southwest- northeast through Wyoming and eastern Utah. An arid climate prevailed in this western part of the supercontinent Pangaea and resulted in restricted marine evaporitic conditions over much of the cratonic shelf seaway (Peterson 1980; Graham et al. 2002). These shallow seas filled basins such as the Oquirrh and Paradox Basins, with incredible accumulations of sediments and salts.

From rock deposits around the globe, geologists have documented the third, and most severe, major mass extinction of geologic time at the close of the Permian. Geologists think a comet, about 6- 13 km (4 to 8 mi) in diameter, collided with the Earth (Becker et. al. 2001). The heat and shock waves generated from such an impact may have triggered vast volcanic eruptions that spread lava over an area two- thirds the size of the United States. Imagine, for example, basalt flows covering the area from San Francisco to St. Louis and Seattle to New Orleans. The amount of ejecta, volcanic ash, and toxic gases from such an event would have been devastating.

Powerful wind updrafts would have carried dust and grit swirling into the upper atmosphere. The particulate matter would have reflected back into space and scattered sunlight, resulting in years of global cooling with freezing temperatures even during summertime. A recent example of this type of global cooling occurred in 1816 "the year without a summer," following a volcanic explosion in Tambora, Indonesia. The sulfuric emissions from the volcanoes would have mixed with atmospheric water to produce downpours of corrosive acid rain. Thousands of species of insects, reptiles, and amphibians perished on land. In the oceans, coral formations vanished, as did snails, urchins, sea lilies, some fish, and the once- prolific trilobites. Five million years later, at the dawn of the Mesozoic Era, the oceans began to evolve into the chemistry of the modern oceans and on land, a new order arose, one that the world had never seen before and will never see again (Graham et al. 2002).

There are no Mesozoic age rocks present in the walls surrounding Timpanogos Cave. They were eroded from the uppermost reaches of the Wasatch Range upon uplift along the Wasatch fault. The absence of stratagraphic record makes determining the paleoenvironment of the Mesozoic at Timpanogos Cave National Monument and vicinity difficult. Geologists refer to surrounding areas to determine the history in a regional context.

The next major tectonic event to leave its mark on the Timpanogos Cave area was the North American plates switch from a passive margin to a convergent continental boundary, in Late Jurassic time. This compression, known as the Sevier- Laramide orogeny, resulted in the uplift of thousands of meters of sedimentary deposits that had lain buried in the basin that covered central Utah. During that time, great compressional forces pushed sheets of rock from west to east along thrust faults, first as thin slabs of sedimentary rocks, then as thick slabs with basement detachments. This formed overlapping columns of rock and eventually enough rock was uplifted to create the grandeur of today's Rocky Mountains and a thick pile of rocks in central Utah.

For about 35 million years during the Laramide Orogeny, from roughly 70 Ma to 35 Ma, the collision of the tectonic plates transformed the extensive basin of the Cretaceous Interior Seaway into smaller interior basins bordered by rugged mountains (Graham et al. 2002). The crustal unrest of the Late Cretaceous Laramide orogeny culminated in great dislocations along the Charleston Thrust. Present evidence, based on cross cutting relationships and contact metamorphism, indicates that the Charleston Thrust followed closely the intrusion of the Little Cottonwood igneous stock (Baker and Crittenden). Nearby, contemporaneous dikes, indicate the igneous activity was associated with a local extensional tectonic regime.

Following the extensive crustal thickening during the Laramide orogeny, melting of the lower crust occurred during decompression, giving rise to the material of the Wasatch Igneous Belt. The emplacement of this belt was facilitated by mantle upwelling and underplating of a hot lower crust during the regional, Basin and Range, crustal extension following decompression (Vogel et al. 1997). Near the end of the Laramide Orogeny, in early mid- Tertiary time, volcanic activity erupted across the southwest.

The laccoliths that formed the Sleeping Ute Mountain, La Plata Mountains, Henry Mountains, La Sal Mountains, and Abajo Mountains were emplaced during mid- Tertiary volcanism that also gave rise to the extensive San Juan volcanic field in southern Colorado (Baars 2000; Fillmore 2000). Laccoliths provide some of the spectacular topography seen from National Parks and Monuments in Utah (Graham et al. 2002).

This onset of volcanic activity signaled the ultimate end of the Laramide Orogeny. The area's deformational regime was to change once again from compressional to extensional. The San Andreas strike- slip fault system between the Pacific plate and the North American plate began to grow and as it lengthened, the southwestern margin of North America began to undergo extensional deformation. As the crust was extended, the surface began to be broken into the basin- and- range topography we see today in western Utah, Nevada, Arizona, and the Rio Grande Rift in New Mexico. The Basin and Range refers to a series of uplifted blocks bounded by downdropped valleys.

Where lithospheric plate collisions lead to violent volcanic eruptions, typical of those surrounding today's Pacific Rim, extensional tectonics generally produce less violent, basaltic lava flows. Thick flows of dark basaltic lava cap Grand and Battlement Mesas east and northeast of Colorado National Monument. Radiometric dating of basalt samples from these mesas indicates that the basalt flowed 9 to 10 Ma during the Miocene Epoch of the Tertiary Period (Lohman 1981; Graham et al. 2002). Often accompanying crustal extension are pervasive normal faults. The Wasatch Fault, uplifting the Wasatch Range, is a local result of crustal extension.

The Wasatch Range is located on the eastern edge of the Basin and Range structural province, and for much of its extent is defined by a zone of lesser faults and a well- marked fault scarp: the dramatically sharp Wasatch Front. The Wasatch Mountains are a narrow, fault- uplifted range trending north- south from southern Idaho (Malad City, ID) to central Utah (Gunnison, UT), some 370 km (230 mi) (Swan et al. 1980). The fault exhibits almost continuous geomorphic expression of late Quaternary uplift (Swan et al. 1980). Older faults and folds exposed within the range, mostly behind or east of the front, strike at various angles and are, in places, extremely complex, others are buried in the basin to the west (Baker and Crittenden 1961).

The normal faults that moved the Wasatch block upward are exposed in several places along the western base of the range and collectively make up the Wasatch Fault zone. Uplift along the Wasatch Fault system is still occurring today (figure 13). Though no significant seismic events have occurred in recorded history along the fault, geologists speculate from field evidence, measured tectonic stresses, and recurrence intervals that an earthquake is possible at any moment.

One of the largest of segments of the Wasatch Fault system, which extends south- southeastward from the mouth of American Fork Canyon, has a footwall of Great Blue limestone and a hanging wall of Manning Canyon shale. The top of the Great Blue limestone is displaced by this series of faults, from an altitude of approximately 2,743 m (9,000 ft), to a position below the valley floor, so that the total displacement must be more than 1,219 m (4,000 ft) (Baker and Crittenden 1961). Estimates of average total throw across the fault zone vary from 2.6 to 4 km (1.6 to 2.5 miles) (Bruhn et al. 1987).

Accompanying the uplift of the Wasatch Range and other ranges in the Basin and Range Province, fault-bounded valleys filled with a variety of sediments shed from the newly exposed highlands. In the Timpanogos Cave area, during and after a period of intense regional erosion that probably occupied much of the Eocene and early Oligocene, the conglomerates and reworked volcanics of the Tibble Fork Formation were deposited. This deposition was possibly contemporaneous with volcanic rocks being erupted in the Park City area to the northeast. Normal displacements along the Deer Creek normal fault then downdropped the Tibble Fork Formation several thousand feet in American Fork Canyon and east of Mount Timpanogos (Baker and Crittenden 1961).

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

The great glacial cirques that flank the summits of Box Elder Peak and Mount Timpanogos are impressive evidence of glaciers that melted and disappeared centuries ago. The glaciers left their mark in such alpine features as *arêtes* (knife- edge ridges), *horns* (pyramidal shaped summit), *cirques* (rounded depressions at the base of peaks – usually containing a lake), U- shaped valleys, and *moraines* (unsorted deposits of clay to boulder material left by a glacier when it retreats) (Graham et al. 2002).

American Fork Canyon, the deepest canyon in the Timpanogos Cave quadrangle, might have been occupied by some ice, at least above Tibble Fork, but instead of a characteristic glacial "U"- shaped valley, its jagged "V"-shaped lower canyon (so well seen from the trail to Timpanogos Cave) is a striking testimony to the erosive power of running water on a tectonically active landscape (Baker and Crittenden 1961).

During part of Quaternary time, 16,800 years ago, ancient Lake Bonneville covered the lowest ground in the west corner of the Timpanogos Cave National Monument (over 51,800 square km or 20,000 square miles) and was up to 305 m (1,000 ft) in depth. Its highest altitude shoreline, called the Bonneville shoreline, was about 1,565 m (5,135 ft) above sea- level over parts of Nevada, Utah, and Idaho. The Provo shoreline, at which the water level remained the longest, was a little over 1,463 m (4,800 ft) in elevation. Both are expressed by the marked contours, parallel to the valley floor, along the foot of the Wasatch Range (Baker and Crittenden 1961). Lake Bonneville left a lot of other evidence. In the foothills of the mountains in Utah and Salt Lake valley, there are benches of gravel and sand that were deposited by Lake Bonneville. At the mouth of American Fork canyon, there are two large hills (about 30.5 m or 100 feet high) made of gravel deposited as the ancient American Fork River reached Lake Bonneville and formed a river delta.

When Lake Bonneville crested over Red Rock pass near Downey, Idaho, it sent a torrent of water into the Snake River drainage. The water carved incredible deep valleys and left deposits of sand, gravel and even boulders as it rushed out. The Bonneville flood lasted less than a year and lowered lake level by 122 m (400 ft). As Utah's climate changed to become warmer and drier, Lake Bonneville slowly evaporated until the Great Salt Lake and Utah Lake were all that remained.

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

Geologically, the Wasatch Range has not changed much during the Holocene. The area as a whole has been subjected to repeated earthquakes and extensional uplift and downdrop of the blocks on either side of the Wasatch Fault, and streams have carved new landscapes since the end of the ice age, but 11,000 years is but a geological instant.

Figure 9 summarizes the geologic history from the Proterozoic to the present at Timpanogos.

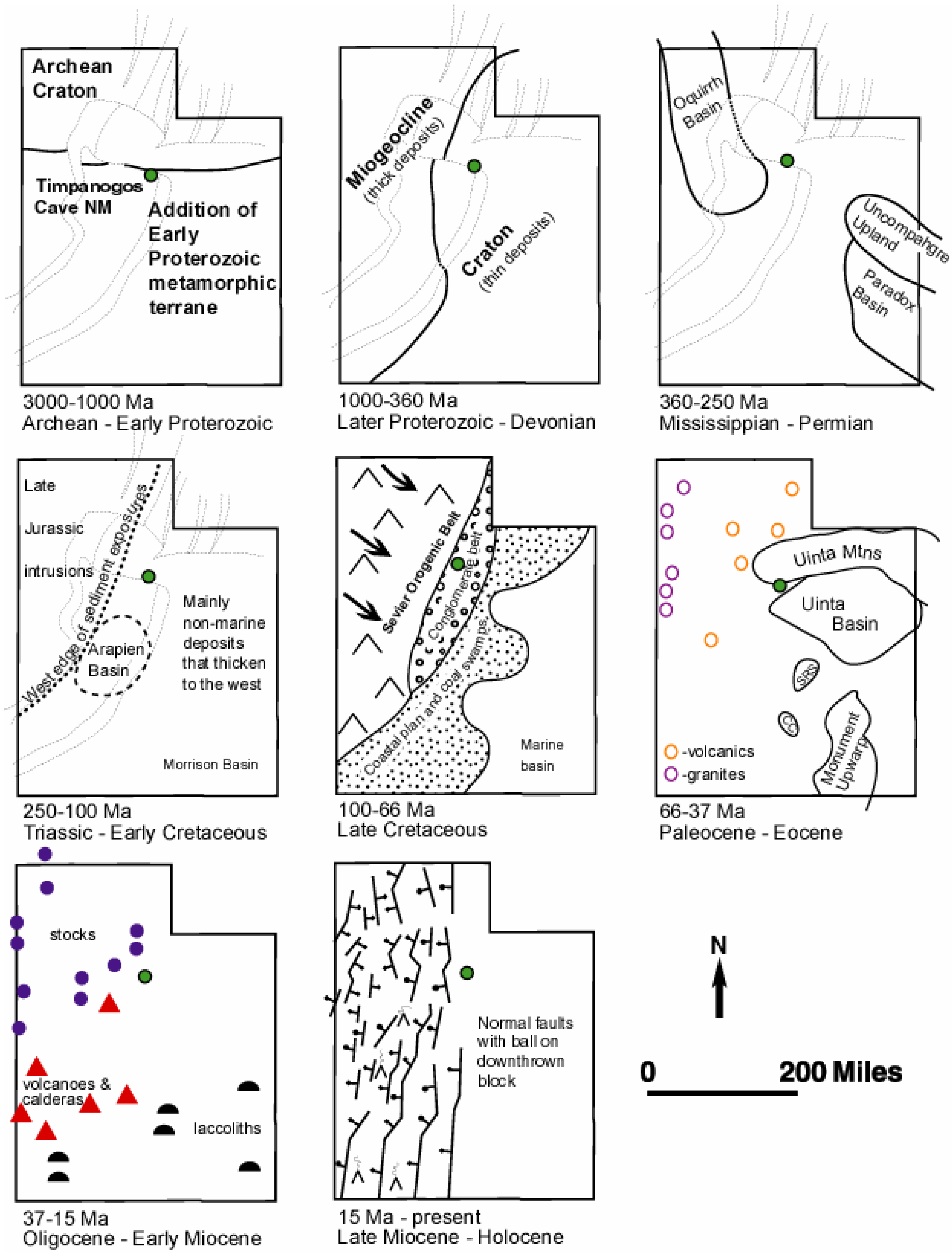


Figure 9. Generalized graphic overview of geologic evolution of Utah from the Archean Eon to the Holocene Epoch (adapted from Hintze 1988).

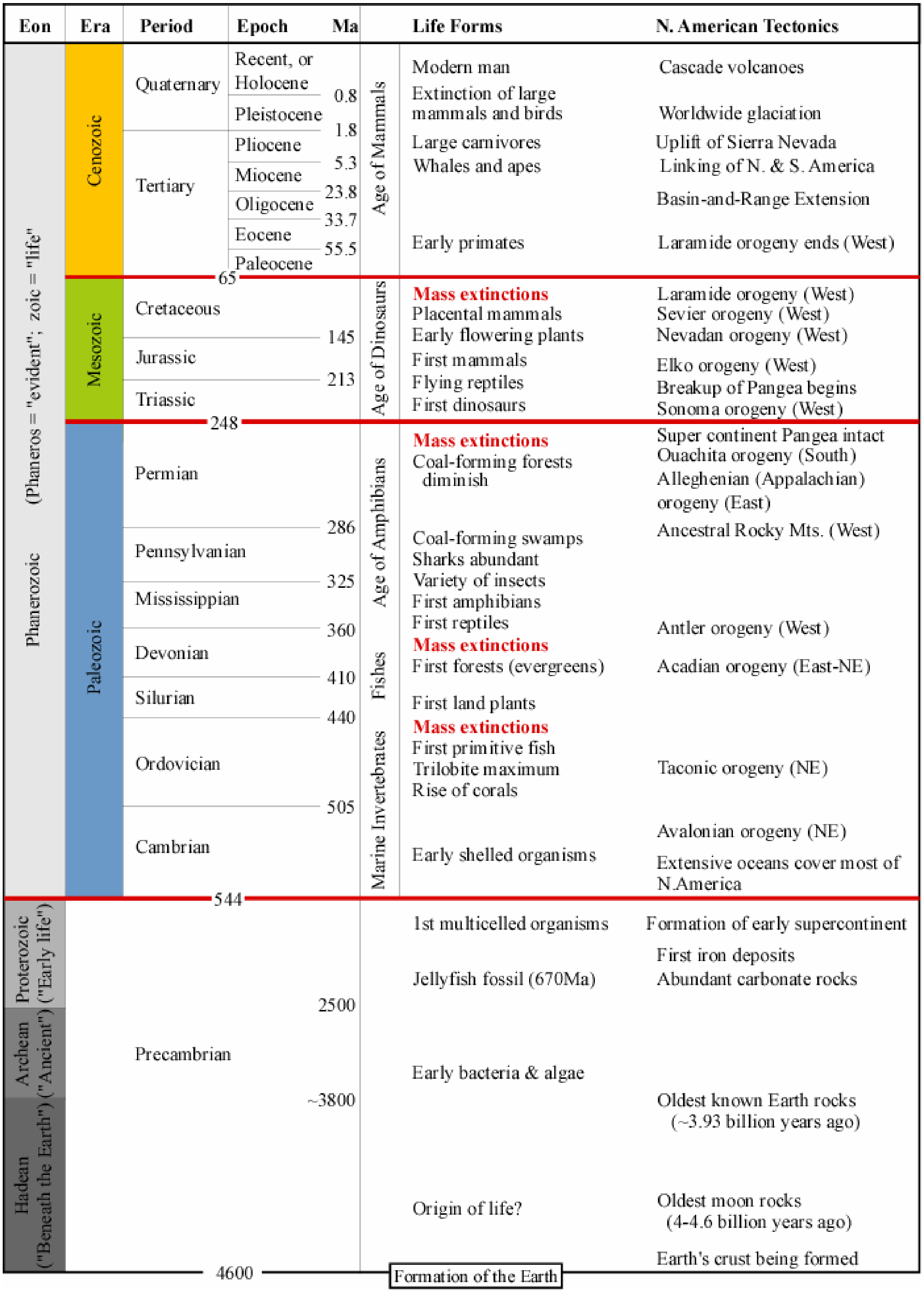


Figure 10. Geologic time scale; adapted from the U.S. Geological Survey. Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring on the North American continent. Absolute ages shown are in millions of years.

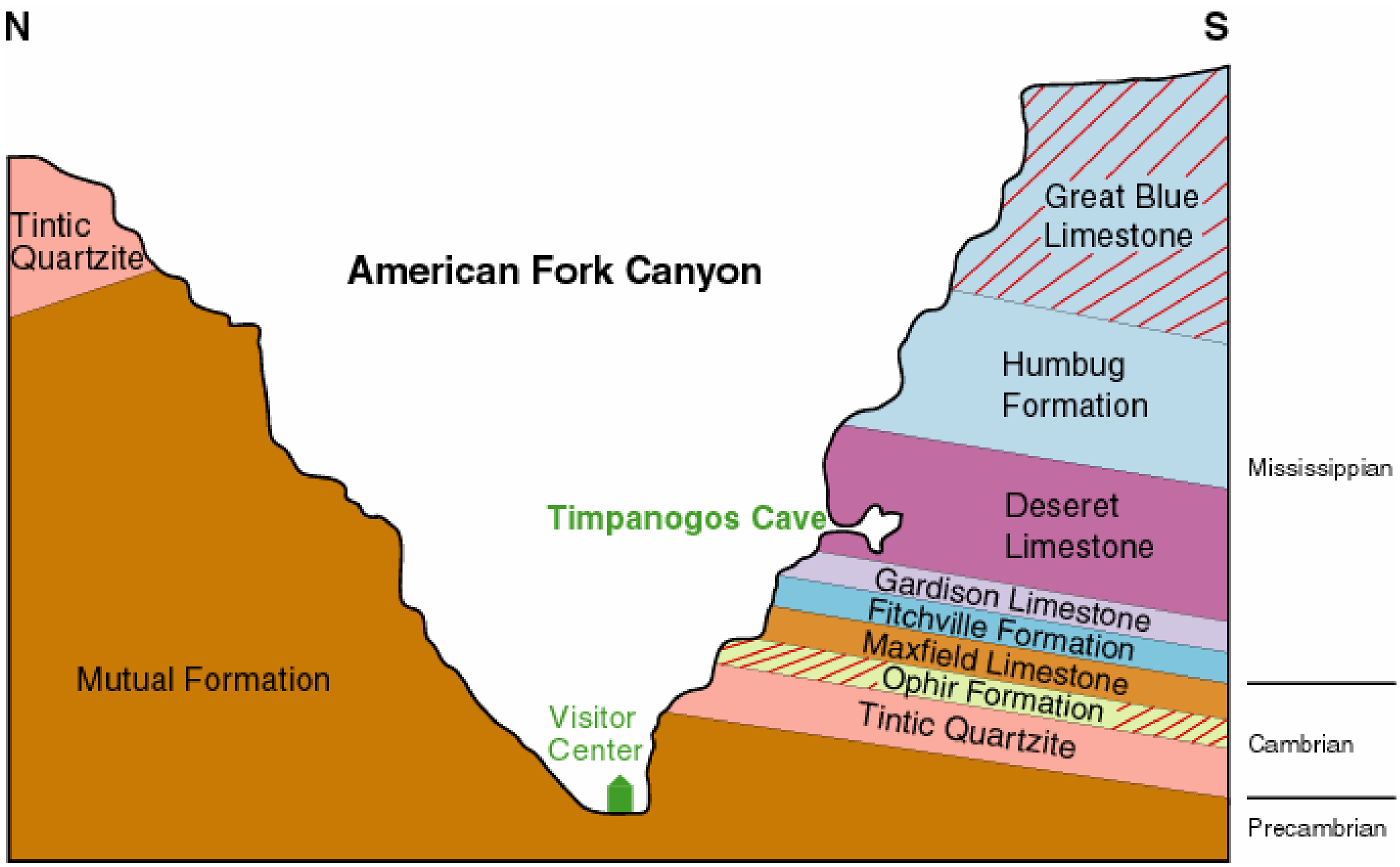


Figure 11. Generalized cross section of American Fork Canyon including Timpanogos Cave system (adapted from NPS graphic, http://www.nps.gov/tica).

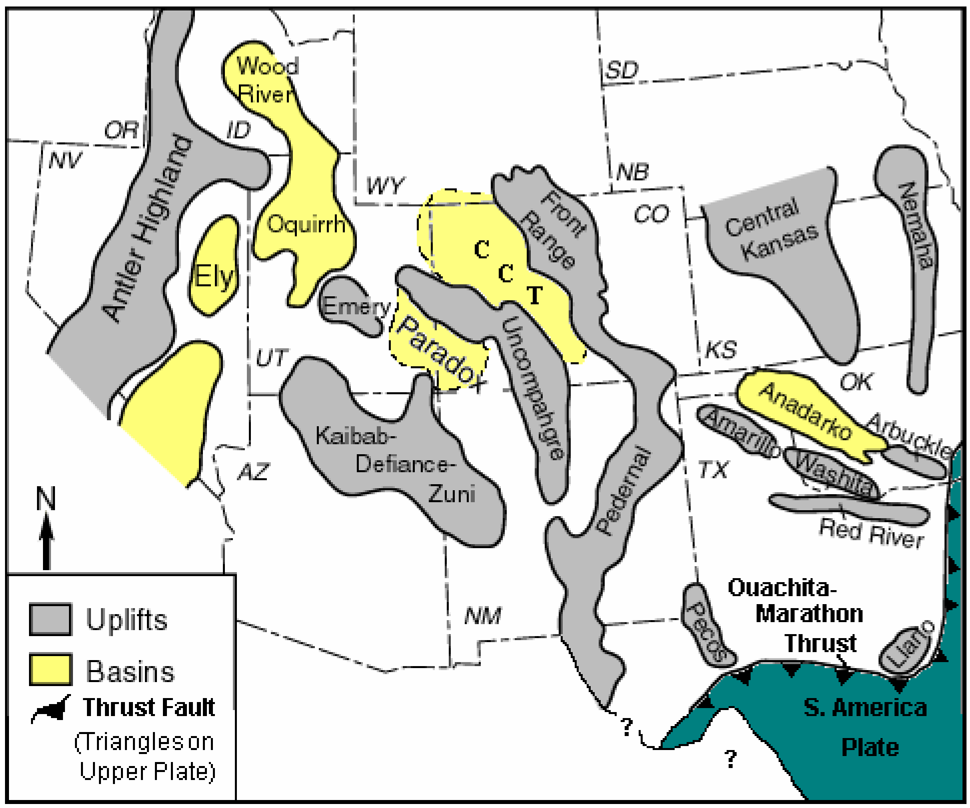


Figure 12. Major uplifts and basins present during the Pennsylvanian age in the southwestern United States. Sediment eroded from the uplifts was deposited in the adjacent basins. Modified from Rigby, (1977).

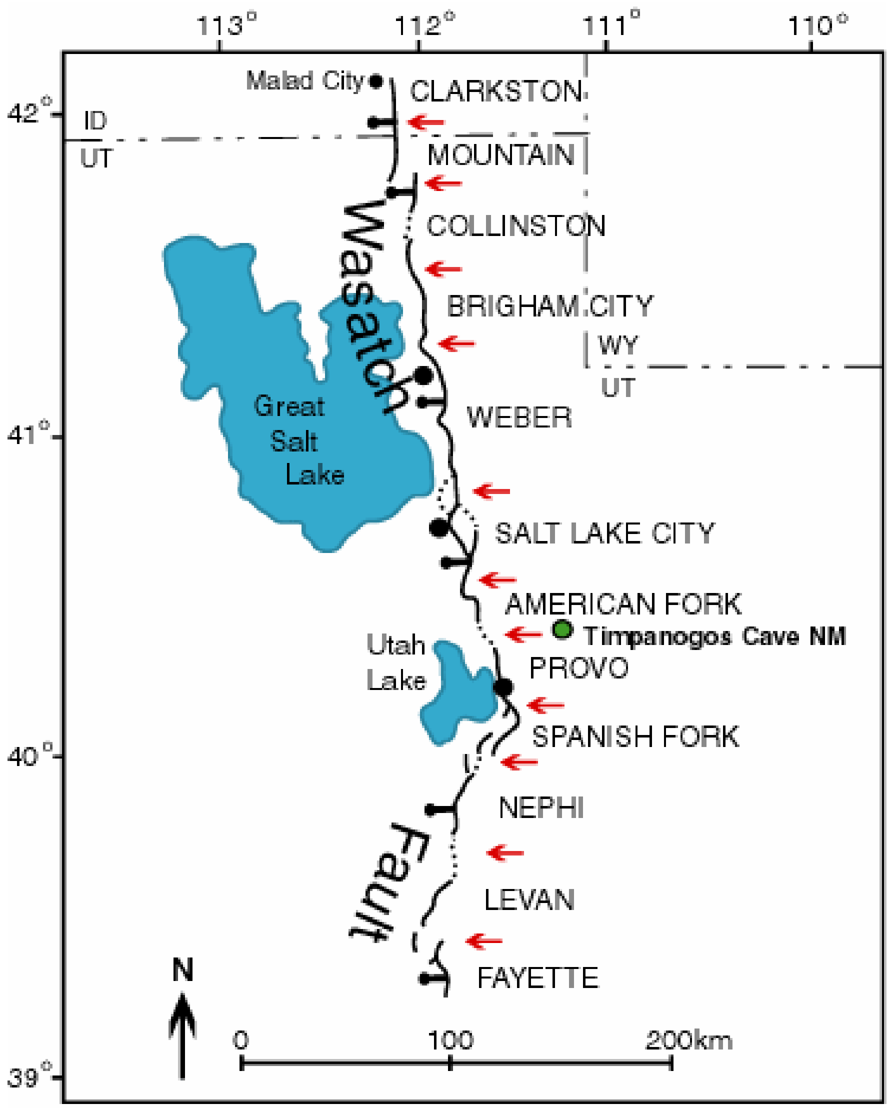


Figure 13. Segments of the Wasatch Fault as identified by Machette (1987). Boundaries are placed at offsets of discontinuities in the trend of the fault and are marked by red arrows. Balls indicate downdropped block relative to the fault surface. Note the location of the American Fork segment (adapted from Hintze 1988).

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://wrgis.wr.usgs.gov/docs/parks/misc/glossarya.html.

active margin. A continental margin where significant volcanic and earthquake activity occurs; commonly a convergent plate margin.

alluvial fan. A fan- shaped deposit of sediment that accumulates where a high gradient stream flows out of a mountain front into an area of lesser gradient such as a valley.

alluvium. Stream- deposited sediment that is generally rounded, sorted, and stratified.

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

angular unconformity. An unconformity where the strata above and below are oriented differently; generally caused by structural deformation and erosion prior to deposition of the upper bed.

aquifer. Rock or sediment that are sufficiently porous, permeable, and saturated to be useful as a source of water.

baseflow. Stream flow supported by groundwater flow from adjacent rock, sediment, or soil.

baselevel. 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.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie the rocks of interest.

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

bedding. Depositional layering or stratification of sediments.

bedrock geology. The geology of underlying solid rock as it would appear with the sediment, soil, and vegetative cover stripped away.

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

braided stream. A stream, clogged with sediment that forms multiple channels that divide and rejoin.

calcareous. A rock or sediment containing calcium carbonate.

carbonaceous. A rock or sediment with considerable carbon, esp. organics, hydrocarbons, or coal.

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. The dissolution or chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances.

conglomerate. A coarse- grained sedimentary rock with clasts larger than 2 mm in a fine- grained matrix.

continental drift. The concept that continents have shifted in position over Earth (see and use 'plate tectonics').

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

cross-bedding. Uniform to highly- varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in an oriented vertical plane.

crust. The outermost compositional shell of Earth, 10- 40 km (6- 25 mi) thick, consisting predominantly of relatively low- density silicate minerals (also see oceanic crust and continental crust).

debris flow. A rapid and often sudden flow or slide of rock and soil material involving a wide range of types and sizes.

deformation. A general term for the process of faulting, folding, shearing, extension, or compression of rocks as a result of various Earth forces.

delta. A sediment wedge deposited at a stream's mouth where it flows into a lake or sea.

dike. A tabular, discordant igneous intrusion.

dip. The angle between a structural surface and a horizontal reference plane measured normal to their line of intersection.

disconformity. An unconformity at which the bedding of the strata above and below are parallel.

discordant. Having contacts that cut across or are set an angle to the orientation of adjacent rocks.

divergent boundary. A tectonic plate boundary where the plates are moving apart (e.g., a spreading ridge or continental rift zone).

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

eolian. Formed, eroded, or deposited by or related to the action of the wind.

ephemeral stream. A stream that flows only in direct response to precipitation.

evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute- rich water under restricted conditions.

exfoliation. The breakup, spalling, peeling, flaking, etc. of layers or concentric sheets from an exposed rock mass due to differential stresses resulting from thermal changes or pressure unloading.

extrusive. Of or pertaining to the eruption of igneous material onto the surface of Earth.

fault. A subplanar break in rock along which relative movement occurs between the two sides.

formation. Fundamental rock- stratigraphic unit that is mappable and 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, fault)

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

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

graben. A down- dropped structural block bounded by steeply- dipping, normal faults (also see horst).

horst. An uplifted structural block bounded by high-angle normal faults.

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

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

joint. A semi- planar 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.

laccolith. A tack head- to arcuate- shaped, concordant pluton that domed or up- arched the overlying country rocks.

landslide. Any process or landform resulting from rapid mass movement under relatively dry conditions.

lithification. The conversion of sediment into solid rock.

lithology. The description of a rock or rock unit, especially the texture, composition, and structure of sedimentary rocks.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 mi) thick, that encompasses the crust and uppermost mantle.

loess. Silt- sized sediment deposited by wind, generally of glacial origin.

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

matrix. The fine- grained interstitial material between coarse grains in porphyritic igneous rocks and poorly sorted clastic sediments or rocks.

meanders. Sinuous lateral curves or bends in a stream's channel.

mechanical weathering. The physical breakup of rocks without change in composition (syn: physical weathering).

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

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

nonconformity. An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks.

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

orogeny. A mountain- building event, particularly a well-recognized event in the geological past (e.g. the Laramide orogeny).

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.

overbank deposits. Alluvium deposited outside a stream channel during flooding.

overthrust. A nondescript and not recommended term for a large- scale, low- angle, thrust fault.

paleogeography. The study, description, and reconstruction of the physical geography from past geologic periods.

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

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic Periods (also see Laurasia and Gondwana).

parent (rock). The original rock from which a metamorphic rock or soil was formed.

passive margin. A tectonically quiet continental margin indicated by little volcanic or seismic activity.

pebble. Generally, small, rounded, rock particles from 4 to 64 mm in diameter.

permeability. A measure of the ease or rate that fluids move through rocks or sediments.

plateau. A broad, flat- topped topographic high of great extent and elevation above the surrounding plains, canyons, or valleys (both land and marine landforms).

plate tectonics. The theory that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid aesthenosphere.

porosity. The proportion of void space (cracks, interstices) in a volume of a rock or sediment.

prodelta. The part of a delta below the level of wave erosion.

progradation. The seaward building of land area due to sedimentary deposition.

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age in years determined from radioisotopes and their decay products.

recharge. Infiltration processes that replenish groundwater.

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

relative dating. Determining the chronological placement of rocks, events, fossils, etc. from geological evidence.

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

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

ripple marks. The undulating, subparallel, usually small-scale, ridge pattern formed on sediment by the flow of wind or water.

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

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

seafloor spreading. The process in which tectonic plates diverge and new lithosphere is created at oceanic ridges.

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

sedimentary rock. A consolidated and lithified rock consisting of detrital and/or chemical sediment(s).

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

slickenside. A smoothly polished and often striated surface representing deformation of a fault plane.

slope. The inclined surface of any geomorphic feature or rational measurement thereof (syn: 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 rock from which it formed.

spring. A site where water flows out at the surface due to the water table intersecting the ground surface.

strata. Tabular or sheetlike masses or distinct layers (e.g., of rock).

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

stream. Any body of water moving under gravity flow and confined within a channel.

strike. The compass direction of the line of intersection that an inclined surface makes with a horizontal plane.

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

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.

suture. The linear zone where two continental landmasses become joined due to obduction.

system (stratigraphy). The group of rocks formed during a period of geologic time.

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

tectonics. The geological study of the broad structural architecture and deformational processes of the lithosphere and aesthenosphere (also see structural geology).

terraces (stream). 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).

terrane. A 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 (<45°) where the hanging wall moves up and over relative to the footwall.

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

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

trace fossils. Sedimentary structures, such as tracks, trails, burrows, etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transgression. Landward migration of the sea due to 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 (also see tufa).

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

unconformity. A surface within sedimentary strata that marks a prolonged period of nondeposition or erosion.

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

volcanic. Related to volcanoes; describes igneous rock crystallized at or near Earth's surface (e.g., lava).

water table. The upper surface of the saturated (phreatic) zone.

weathering. The set of physical, chemical, and biological processes by which rock is broken down in place.

References

This section provides a listing of references cited in this report. It also contains general references that may be of use to resource managers. A more complete geologic bibliography is available and can be obtained through the NPS Geologic Resources Division.

Anderson, L.W. 1979. Weathering rinds as a relative age indicator and late glacial chronology of Mt. Timpanogos, Wasatch Range, Utah. *Abstracts with Programs – Geological Society of America* 11 (6): 265-266.

Anderson, L.W., D.S. Anderson. 1981. Weathering rinds on quartzarenite clasts as a relative- age indicator and the glacial chronology of Mount Timpanogos, Wasatch Range, Utah. *Arctic and Alpine Research* 13 (1): 25- 31.

Baars, D. L. 2000. *The Colorado Plateau*. Albuquerque, NM: University of New Mexico press.

Baker, A.A. 1964. *Geologic Map and sections of the Orem Quadrangle, Utah*. U.S. Geological Survey, Report: GQ- 0241.

Baker, A.A., M.D. Crittenden, Jr. 1961. *Geology of the Timpanogos Cave Quadrangle, Utah*. U.S. Geological Survey, Report: GQ- 0132.

Baker, A. A., J.W. Huddle, D.M. Kinney. 1949. Paleozoic geology of the north and west sides of the Uinta Basin, Utah. *American Association of Petroleum Geologists Bulletin* 33: 1161- 1197.

Baker, A. A. 1947. *Stratigraphy of the Wasatch Mountains in the vicinity of Provo, Utah*. U. S. Geological Survey Oil and Gas Preliminary, Chart 30.

Becker, L., R.J. Poreda, A.G. Hunt, T.E. Bunch, M. Rampino. 2001. Impact event at the Permian- Triassic boundary, Evidence from extraterrestrial noble gases in fullerenes. *Science*, February 23: 1530- 1533.

Bruhn, R.L., P.R. Gibler, W.T. Parry. 1987. Rupture characteristics of normal faults: An example from the Wasatch fault zone, Utah. *Journal of the Geological Society of London* 28: 337- 353.

Bullock, K.C. 1944. Origin of the Timpanogos caves [Utah] [abs]. *Proceedings of the Utah Academy of Sciences, Arts and Letters* 19- 20: 18- 19.

Bullock, K.C. 1942. *A study of the geology of the Timpanogos caves*. Master's thesis, Brigham Young University, Provo, Utah.

CCC. 2006. *American Fork Canyon Home Rivers Project*. Cooperative Conservation Case (CCC) study. http://www.cooperativeconservationamerica.org/viewproject.asp?pid=508 (accessed April 19 2006).

Constenius, K.N. 1998. *Extensional tectonics of the Cordilleran foreland fold and thrust belt and the Jurassic- Cretaceous great valley forearc basin*. Dissertation, University of Arizona, Tucson, AZ.

Corporate Author. 1987. *Timpanogos Cave National Monument Utah*. U.S. National Park Service, American Fork, UT, GPO: 1987- 181- 441/60006.

Dickinson, W. R. 1979. Cenozoic plate tectonic setting of the Cordilleran region in the United States. In *Cenozoic Paleogeography of the Western United States*, eds. Armentrout, J.M., M. R. Cole, H. Terbest, Jr., 1- 13. Society of Economic Paleontologists and Mineralogists, Pacific Section.

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

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

Dott, R.J., Jr., C.W. Byers, G.W. Fielder, S.R. Stenzel, K.E. Winfree. 1986. Aeolian to marine transition in Cambro- Ordovician cratonic sheet sandstones of the northern Mississippi Valley, U.S.A. *Sedimentology* 33: 345- 367.

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

Dubiel, R.F., J.E. HuntoonS.M. Condon, J.D. Stanesco. 1996. Permian deposystems, paleogeography, and paleoclimate of the Paradox Basin and vicinity. In *Paleozoic Systems of the Rocky Mountain Region*, eds. Longman, M.W., M.D. Sonnenfeld, 427- 444. Rocky Mountain Section, SEPM (Society for Sedimentary Geology).

Evans, S.H., W.T. Parry, R.L. Bruhn. 1985. *Thermal, mechanical, and chemical history of the Wasatch fault cataclastic and phyllonite, Traverse Mountains area, Salt Lake City, Utah – age and uplift rates from K/Ar and fission tract measurements*. U.S. Geological Survey Open- File Report: 86- 31.

Fillmore, R. 2000. *The Geology of the Parks, Monuments and Wildlands of Southern Utah*. The University of Utah Press.

Graham, J. P.,T.L. Thornberry, T.L., S.A. O'Meara. 2002. *Geologic Resources Inventory for Mesa Verde National Park*. Fort Collins, CO: unpublished.

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

Gregson, J.D., D.J. Chure. 2000. Geology and paleontology of Dinosaur National Monument, Utah-Colorado. In *Geology of Utah's Parks and Monuments*, eds. Sprinkel, D.A., T.C. Chidsey, Jr., P.B. Anderson, 61- 83. Utah Geological Association Publication 28.

Griffitts, M. O. 1990. *Guide to the Geology of Mesa Verde National Park*. Mesa Verde National Park, CO: Mesa Verde Museum Association, Inc.

Hanson, W.R. 1975. *The Geologic Story of the Uinta Mountains*. U.S. Geological Survey Bulletin 1291.

Herbert, L.R., C.B. Burden, B.K. Thomas. 1992. *Seepage study of the Timpanogos, Wasatch, Sagebrush, and Spring Creek, Upper Charleston, and Lower Charleston canals, Wasatch County, Utah, 1989*. State of Utah, Department of Natural Resources Technical Publication Report: 104.

Herron, D.C. 1997. *Origin and geologic history of the Timpanogos Cave system, Timpanogos Cave National Monument, Utah County, Utah*. Master's thesis, Brigham Young University, Provo, UT.

Hintze, L.F. 1993. *Geologic history of Utah*. Brigham Young University Geologic Studies, Special Publications 7.

Hoffman, P.F. 1989. Precambrian geology and tectonic history of North America. In the Geology of North America: An Overview, eds. Bally, A.W., A.R. Palmer, 447- 512. Geological Society of America, The Geology of North America, v. A.

Horrocks, R.D. 1995. Artificial fill removal project; Timpanogos Cave System, Timpanogos Cave National Monument. *NSS News* 53 (4): 102- 107.

Horrocks, R.D., M.J. Tranel. 1994. Timpanogos Cave research project 1991- 1992. *National Speleological Society News* 52 (1): 15- 21.

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

Jordan, T. E., R.C. Douglass. 1980. Paleogeography and structural development of the late Paleozoic to early Permian Oquirrh Basin, northwestern Utah. In Paleozoic Paleogeography of the West- Central United States, eds. Fouch, T.D., E. R. Magathan, 217- 238. SEPM (Society for Sedimentary Geology).

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

Kluth, C. F. 1986. Plate tectonics of the ancestral Rocky Mountains. In Paleotectonics and Sedimentation in the Rocky Mountain Region, ed. Peterson, J.A., 353-369. American Association of Petroleum Geologists Memoir 41.

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

Konopka, E.H. 1981. *Stratigraphy and sedimentology of the Butterfield Peaks Formation (Middle Pennsylvanian), Oquirrh Group, at Mt. Timpanogos, Utah*. Master's thesis, University of Wisconsin- Madison, Madison, WI.

Konopka, E.H., R.H. Dott, Jr. 1982. Stratigraphy and sedimentology, lower part of the Butterfield Peaks Formation (Middle Pennsylvanian), Oquirrh Group, at Mt. Timpanogos Utah. *Utah Geological Association Publication* 10: 215- 234.

Lageson, D.R., D.R. Spearing. 1988. *Roadside Geology of Wyoming*. Missoula MT: Mountain Press Publishing Company.

Lohman, S. W. 1981. *The geologic story of Colorado National Monument*. U.S. Geological Survey Bulletin 1508.

Machette, M.N., W.R. Lund. 1987. Late Quaternary history of the American Fork segment o the Wasatch fault zone, Utah. *Geological Society of America – Abstracts with programs* 19: 317.

Madison, J.P.; Lonn, J.D.; Marvin, R.K.; Metesh, J.J.; Wintergerst, R., 1998, Abandoned- inactive mines program, Deer Lodge National Forest; Volume IV, Upper Clark Fork River drainage. MBMG Open- File Report, 151 p.

Mayo, A.L., D.L. Loucks. 1995. Solute and isotopic geochemistry and ground water flow in the central Wasatch Range, Utah. *Journal of Hydrology* 172: 31- 59.

Mayo, A.L., D. Herron, S.T. Nelson, D. Tingey, M.J. Tranel. 2000. Geology and hydrogeology of Timpanogos Cave National Monument, Utah. *Utah Geological Association Publication* 28: 263- 276.

McNeil, B.E., J.D. Jasper, D.A. Luchsinger, M.V. Ransmeier. 2002. Implementation and application of GIS at Timpanogos Cave National Monument, Utah. *Journal of Cave and Karst Studies* 64 (1): 34- 37.

Moore, J.N., W.W. Woessner. 2000. *Geologic, Soil Water and Groundwater Report – 2000*. Grant- Kohrs Ranch National Historic Site, National Park Service.

NPS. 1999. *Park Paleontology*, Winter 1999, Volume 5, Number 1. http://www2.nature.nps.gov/geology/paleontology/paleo_5_1/index.htm (accessed June 9 2006).

NPS and USFS. 2004. *Timpanogos Reflections: Visitor Guide – Fall/Winter 2004*. National Park Service, U.S. Forest Service publication.

Palmer, A.N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin* 103: 1- 21.

Paulsen, T., S. Marshak. 1998. Charleston transverse zone, Wasatch Mountains, Utah – Structure of the Provo salient's northern margin, Sevier fold- thrust belt. *Geological Society of America Bulletin* 110 (4): 512- 522.

Peterson, J. A. 1980. Permian paleogeography and sedimentary provinces, west central United States. In *Paleozoic Paleogeography of the West- Central United States*, eds. Fouch, Thomas D. Esther R. Magathan, 271- 292. Rocky Mountain Section, SEPM (Society for Sedimentary Geology).

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

Prothero, Donald R., Fred Schwab. 2006. *Sedimentary Geology, an Introduction to Sedimentary Rocks and Stratigraphy*. New York: W.H. Freeman and Company.

Rigby, J. K. 1977. *Southern Colorado Plateau*. Dubuque, IA: Kendall/Hunt Publishing Company.

Ross, C.A., J.R.P. Ross. 1986. Paleozoic paleotectonics and sedimentation in Arizona and New Mexico. In Paleotectonics and Sedimentation in the Rocky Mountain Region, ed. Peterson, J.A., 653- 668. American Association of Petroleum Geologists Memoir 41.

Rueger, B. F. 1996. *Palynology and its relationship to climatically induced depositional cycles in the Middle Pennsylvanian (Desmoinesian) Paradox Formation of Southeastern Utah*. U.S. Geological Survey Bulletin 2000- K, 4 plates.

Santucci, V. 2000. A Survey of the Paleontological Resources from the National Parks and Monuments in Utah. In *Geology of Utah's Parks and Monuments*, eds. Sprinkel, D.A., T.C. Chidsey, Jr., P.B. Anderson, 535- 556. Utah Geological Association Publication 28.

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

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

St. Clair, L.L., S.R. Rushforth. 1976. The diatoms of Timpanogos Cave National Monument, Utah. *American Journal of Botany* 63 (1): 49- 59.

Summerfield. M.A. 1991. *Global Geomorphology*. New York: John Wiley and Sons, Inc.

Swan, F.H., III, D.P. Schwartz, L.S. Cluff. 1980. Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah. *Bulletin Seismological Society of America* 70: 1431- 1432.

Timpanogos Cave National Monument. 2006. Timpanogos Cave National Monument Science & Resource Management. http://www.nps.gov/tica/RMweb/ (accessed April 20 2006).

Tranel, M., A.L. Mayo, T.M Jensen. 1991. Preliminary investigation of the hydrology and hydrogeochemistry at Timpanogos Cave National Monument, Utah, and its implications for cave management. In *Proceedings of the National cave management symposium*, American Cave Conservation Association, Horse Cave, KY.

Trexler, B.D.Jr., D.A. Ralston, D.A. Reece, R.E. Williams. 1975. *Sources and causes of acid mine drainage*. Idaho Bureau of Mines and Geology, Pamphlet 165.

Tuttle, E.R. 1957. *The heart of Timpanogos*. Salt Lake City.

Tweto, O. 1977. *Nomenclature of Precambrian rocks in Colorado*. U.S. Geological Survey Bulletin 1422- D.

United States, Congress, Senate, Committee on Energy and Natural Resources. 2002,.*Timpanogos Interagency Land Exchange Act of 2001*. 107th Congress, Senate, Report: 107- 108.

United States Department of the Interior, National Park Service. 1986. *Timpanogos Cave National Monument: statement for management*.

United States Department of the Interior, National Park Service. 1989.*Timpanogos cave: official map and guide*. Timpanogos Cave National Monument, Utah, 1 sheet.

United States, National Park Service, Rocky Mountain Regional Office. 1993. *Environmental impact statement, general management plan, development concept plan*. Timpanogos Cave National Monument.

Vogel, T.A., F.W. Cambray, L. Feher, K.N. Constenius. 1997. Petrochemistry and emplacement history of the Wasatch igneous belt, central Wasatch Mountains, Utah. *Geological Society of America – Abstracts with Programs* 29 (6): A- 282.

White, W.B., J.J. Van Gundy. 1971. Geological reconnaissance of Timpanogos Cave, Utah. *The NSS Bulletin* 33 (4): 147- 148.

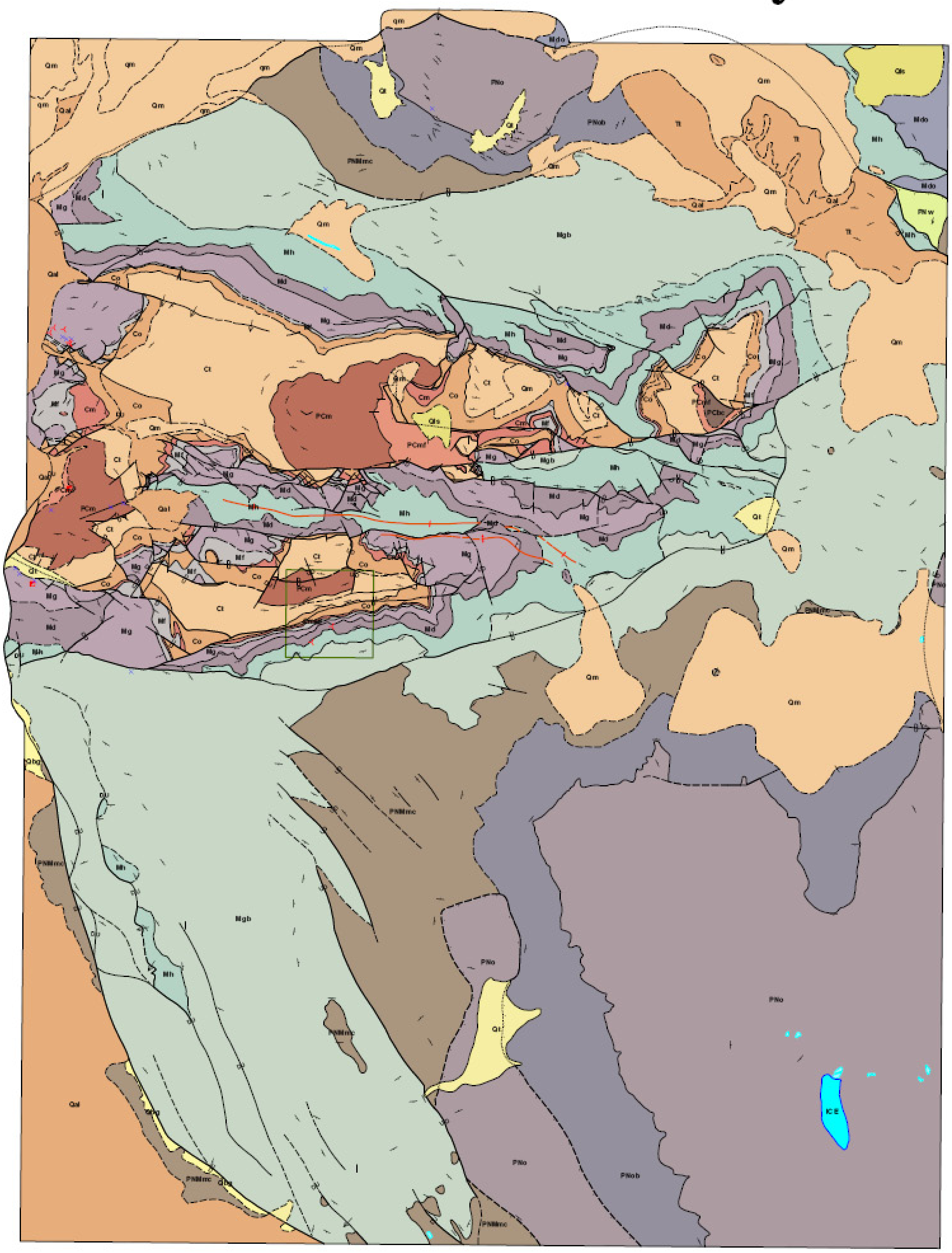
White, W.B., J.J. Van Gundy. 1974. Reconnaissance geology of Timpanogos Cave, Wasatch County, Utah. *National Speleological Society Bulletin* 30 (1): 5- 17.

Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Timpanogos Cave National Monument. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

National Park Service
U.S. Department of the Interior

Geologic Map of Timpanogos Cave National Monument and Vicinity



Timpanogos Cave NM

Geologic Attitude Observations
- strike and dip of beds
- strike and dip of overturned beds
- strike of vertical beds
- dip of fault plane
- upthrown side of fault
- downthrown side of fault
- anticline
- syncline

Mine Point Features
- prospect pit
- adit
- shaft

Folds
- syncline, known or certain
- syncline, approximate
- anticline, known or certain
- anticline, approximate

Faults
- fault of unknown offset, known or certain
- fault of unknown offset, approximate
- fault of unknown offset, concealed
- normal fault, known or certain
- normal fault, approximate
- normal fault, concealed
- thrust fault, known or certain
- thrust fault, approximate
- thrust fault, concealed

Geologic Contacts
- known or certain
- approximate
- concealed
- quadrangle/map boundary
- shoreline
- ice, approximate

Geologic Units
- Qal - stream gravel, valley fill and alluvial cones
- Qt - talus and high angle alluvial cones
- Qls - landslide deposits
- Qbg - Bonneville beach deposits
- Qm - moraines
- Tt - Tibble Formation
- qm - quartz monzonite of Little Cottonwood stock
- Ppc - Park City Formation
- PNo - Oquirrh Formation
- PNob - Oquirrh Formation, Bridal Veil limestone
- PNw - Weber quartzite
- PNMmc - Manning Canyon shale
- Mdo - Doughnut formation
- Mgb - Great Blue limestone
- Mh - Humbug formation
- Md - Deseret formation
- Mg - Gardison limestone
- Mf - Fitchville formation
- Cm - Maxfield formation
- Co - Ophir formation
- Ct - Tintic quartzite
- PCm - Mutual formation
- PCmf - Mineral Fork Tillite
- PCbc - Big Cottonwood formation
- GLACIAL ICE
- WATER

0 0.5 1 2 Miles

0 1 2 4 Kilometers

N

The original map digitized by NPS staff to create this product was:

Baker, Arthur A., Crittenden, Max D., 1961, Geology of the Timpanogos Cave Quadrangle Utah: U.S. Geological Survey, Geologic Quadrangle Maps, GQ-132 scale 1:24,000.

Digital geologic data and cross sections for Timpanogos Cave National Monument, and all other digital geologic data prepared as part of the Geologic Resources Divisions Geologic Resource Evaluation Program, are available online: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

Produced by Geologic Resources Division

June 2006

Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Timpanogos Cave National Monument. The scoping meeting occurred on May 10- 11, 1999; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

An inventory workshop was held at Timpanogos Cave National Monument on May 10- 11, 1999 to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Timpanogos Cave NM (interpretation, resource management and superintendent), Utah Geological Survey, and local academic researchers were present for the two- day workshop.

Day one involved a two- part field trip first led by University of Arizona Geologist Kurt Constenius, who has done extensive research on the regional tectonics and geologic structure, followed by a tour through the Timpanogos Cave system led by National Park Service (NPS) Geologic Resources Division (GRD) Cave Specialist Ron Kerbo.

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

Overview of the Geologic Resources Inventory

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

Tim Connors (NPS- GRD) followed with a presentation summary of the up- to- date results of the Colorado GRI program. The status of each park area for geologic mapping inventories, digitizing maps, assembling bibliographies, preparing reports and defining deliverable dates for the NPS units in Colorado was discussed, as the Utah parks will follow a similar process.

Interpretation

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

During the walk up to the cave, the topic of how to improve the trailside exhibits was discussed in depth with Suzanne Flory. Many suggestions involved creating stratigraphic column signs with the theme of "you are here" in the geologic column and also giving geologic ages.

It was also noted that in the near future, there will be a joint NPS- US Forest Service (USFS) visitor center at the mouth of American Fork Canyon. It was suggested that a 3- dimensional model of the cave would be a nice feature of such a visitor center. It was suggested that interpreters from both agencies try to work together to promote the regional geologic story using the latest technologies as American Fork Canyon and Mount Timpanogos are major features of the Salt Lake City skyline. Being within such a short driving distance of such a large metropolitan area has turned TICA into an "urban" park.
Because of this, Kit Mullen sees TICA as having the best opportunity to combine with the State of Utah for interpretation, education, and protection of resources.

Lee Allison (UGS) mentioned that the UGS has targeted the NPS as a major partner for the next decade. They are currently assisting the NPS with their geologic mapping program and geologic extension services to facilitate information transfer to the public. Sandy Eldredge is available to conduct workshops with park personnel (including seasonals) and to work with Suzanne Flury regarding the interpretive trail signs. Specific programs that they can relay to park staff involve general geology, the geology of Utah, and the specific geology of NPS parks. They also have a brochure on the Geologic History of Utah that has been used by other parks such as Zion. They like to coordinate with other government agencies (BLM, USFS etc.) to minimize training sessions and redundancy. They think of it as "training the trainers."

Lee also mentioned that the UGS has a paleoecology team (headed by Dave Madsen) working in the western Utah desert studying both the human and paleoclimate history in caves. They may be able to help in studying age relations in the Timpanogos Cave System. This is further discussed in "Future Research Topics."

Paleontological Resources

After the meeting, Vince Santucci (NPS- GRD Paleontologist) was consulted for insight into the paleontological resources of the area. He mentions a series of fossiliferous units in American Fork Canyon in the following geologic units:

- The Cambrian Ophir Formation has marine invertebrates including an assemblage of trilobites.
- The Mississippian Deseret Limestone, the cave forming unit at TICA, has a variety of marine invertebrates.
- Precambrian trace fossils have been reported from the American Fork Canyon area.
- There are other units that have not yet been surveyed and are potentially fossiliferous.

He also reports receiving a copy of a TICA RMP (resource management plan) Project Statement from past Superintendent Cordell Roy in 1997. This project statement proposed the excavation of paleontological resources from various cave fill sites at the monument. Rod Horrocks was very interested in initiating this project. A Paleontology Intern, Christian George, was recruited from Franklin and Marshall University, PA, to assist in the project.

Packrat middens and cave fill samples were obtained in 1998. One collection was made from a midden in the Organ Pipe Room of Hansen Cave. Small collections were made in Hidden Mine Cave and Boneyard Cave. There is a small collection of bones made during 1939 from Grotto Cave.
Carbon- 14 dating for a few of the samples is being funded through GRD. Christian George has analyzed the faunal material under the supervision of paleontologists at the Academy of Natural Sciences in Philadelphia and his undergraduate advisor. The results of Christian's analysis are being published in the 4th NPS Paleo Research Volume.

The monument currently has 59 cataloged paleontology specimens and will more than double with the curation of the cave fill material collected in 1998.

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

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

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

Status of Geologic Mapping Efforts for Timpanogos Cave National Monument

Currently, the UGS is mapping in Utah at three different scales:

- 1:24,000 for high priority areas (i.e. National and State parks)
- 1:100,000 for the rest of the state
- 1:500,000 for a compiled state geologic map

The UGS plans to complete mapping for the entire state of Utah within 10- 15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from "special interest" areas (i.e. areas such as Zion and growing metropolitan St. George). The UGS simply does not have enough manpower and resources to do more areas at this scale. UGS mapping goals are coincident with those of the National Geologic Mapping Program of the USGS. Kurt Constenius showed the group a compilation of the four major 1:24,000 scale quadrangles that encompass the Timpanogos Cave region (See Appendix C, Timpanogos Cave NM Index of Geologic Maps, 1:24,000 Scale, and Appendix D, Timpanogos Cave NM Index of Geologic Maps, 1:48,000 Scale):

- Dromedary
- Brighton
- Timpanogos Cave
- Aspen Grove

He noted that the map edges match quite well on all four quadrangles and that there is a summary of the geology, stratigraphy, and geologic history for the area that accompanies the maps.

All four quadrangles are published, but are not believed to be in digital format. The main author on these maps was Arthur Alan Baker and most were published in the 1960s prior to digital compilations. The NPS only requires digitization of the Timpanogos Cave quadrangle (GQ- 132), but welcomes digitization of the surrounding area by other agencies, if possible. Grant Willis needs to be consulted to find out the possibility of the UGS digitizing this quadrangle.

Constenius noted that he is currently working with the UGS and Jim Coogan (Denver, CO) to compile the Provo 30x60 quadrangle at 1:100,000. This project encompasses some minor changes to the existing Baker quadrangles incorporating modern thought into the stress field systems and thrust belts using some aerial reconnaissance. Work will begin in July 1999 and will be a high priority for completion, but is expected to be a 3-year project.

The NPS feels digitization of the Timpanogos Cave quadrangle can begin immediately, and that any refinements to the area by Constenius and Coogan could be incorporated at a later time.

Other Sources of Natural Resource Data

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

- NRID has compiled a geologic bibliography for numerous parks and monuments, including Timpanogos Cave.
- It was mentioned that Rod Horrocks worked on a map of the area at ~1:100,000 scale that is hand- drawn and should probably be digitized.

Geologic Hazards

There are numerous issues related to geologic hazards in and around Timpanogos Cave NM. Below is a brief list of some mentioned during the scoping session:

- Rockfalls in American Fork Canyon have caused human fatalities and have damaged trails
- Debris flows in picnic areas have buried gates and posed threats to the public
- Slip/fall hazards are present on many trails within the canyon, especially during cooler weather
- Flash floods and snow avalanches occasionally occur within American Fork Canyon
- Low ceiling heights in the caves pose both a potential danger to visitors who may hit their head, and to speleothems that are hit by those heads
- Significant earthquake potential exists along the Wasatch Fault of the mountain front just west of American Fork Canyon
- There is a potential for Radon in the caves; TICA has study with official report
- Drop- offs (> 1 meter) and narrow passages within the cave exist and pose safety hazards

Unique Geologic Features

The Timpanogos Cave area has some spectacular geologic features; a few are listed below:

- Timpanogos Cave system with three distinct cave areas/names: Hansen Cave, Middle Cave, Timpanogos Cave.
- Walls of the American Fork Canyon and the path leading up to the cave
- Speleothems: flowstone, Helictites, stalactites, stalagmites
- Speleogens: features related to genesis of caves that was created as cave was formed
- Fracture flow ground- water river system
- Paleoclimate record in minerals and sediments (especially cobbles); pack rat middens in cave;
- human signatures in the cave
- Paleo river system and paleohydrology (sediments in cave cobbles, etc.)
- Fault and fracture system on cave control
- Box Elder Peak anticline is major crustal scale anticline
- Tibble Fork half- graben
- Wasatch Fault that marks the beginning of the American Fork Canyon

Potential Research Topics

A list of potential research topics and future needs includes the following:

- A detailed 3- dimensional cartographic survey of the cave interior including features (speleothems and speleogens) that follows standards and guidelines
- Determination of the age, origin, and geologic history of the cave system and American Fork Canyon
- Use Uranium series dating (or C- 14 if young enough) or U- Pb (if old enough) to determine when active speleological deposition began while extracting paleomagnetic data if possible; determine number of depositional episodes
- Study palynology and stratigraphy of sediments and cores. It was mentioned that 13' of flowstone was cored; try to locate this core and where it was taken from within the cave.
- Determine age of canyon cutting using apatite fission tracks for peaks and surface exposure ages for minimum age of canyon from the exposed flatirons
- Date small vugs in other stratigraphic units for timing of deposition; use isotopic composition of CO_3 minerals to determine source (hydrothermal or other)
- Collect current drip waters to determine potential for precipitation (deposition) or dissolution (erosion) by current chemical composition parameters (pH)
- Determine air flow directions in the cave for use in interpreting the direction of deposition of speleothems
- Use resistivity to locate cavities in other stratigraphic units
- Conduct a detailed study of fractures, faults and bedding within the area
- Conduct a minerals inventory within the cave (aragonite, calcite, etc.)
- Review catalog of different types of speleothems catalogued so far for accuracy for IM purposes
- Use pressure transducer to study storms moving in and out of cave system to determine pneumatic permeability and the exchange of air within American Fork Canyon
- Study CO_2 concentration within the cave

Timpanogos Cave National Monument

Geologic Resource Evaluation Report

Natural Resource Report NPS/NRPC/GRD/NRR—2006/013
NPS D-30, July 2006

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup

Natural Resource Program Center

The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring and Evaluation, and the Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross-cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the national park system.

Geologic Resources Division

Chief • David B. Shaver
Planning Evaluation and Permits Branch Chief • Carol McCoy

Credits

Author • Trista Thornberry-Ehrlich
Editing • Jon Jasper, Ron Kerbo, and Melanie Ransmeier
Digital Map Production • Stephanie O'Meara, Sara Kane, Eileen Ernenwein, and Trista Thornberry-Ehrlich
Map Layout Design • Melanie Ransmeier

National Park Service
U.S. Department of the Interior

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, CO 80225

http://www.nature.nps.gov/geology/inventory/
(303) 969-2090