National Park Service
U.S. Department of the Interior

Geologic Resources Division
Denver, Colorado

Glacier National Park

Geologic Resource Evaluation Report

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Executive Summary

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

The story of Glacier National Park is the story of geology and ice: the natural ice of snowfall and glaciers and the rocks that form the basis for the entire ecosystem. The experience of Glacier National Park begins with the geological processes that established the groundwork from which the present- day environments and scenery arise. Understanding the geologic resources can directly impact resource management decisions pertaining to the Park, future scientific research projects, interpretive needs, and economic resources associated with Glacier National Park.

Geologic processes initiate complex responses that give rise to rock formations, mountains and valleys, waterfalls and lakes. The geology inspires wonder in visitors (some 1,864,822 in 2002) to Glacier National Park, and emphasis of geologic resources should be encouraged so as to enhance the visitor's experience.

As the name suggests, Glacier National Park hosts some of the most spectacular glacial geomorphology on earth. The interplay of geology, water, ice, tectonic forces, and climate created this architectural elegance on the landscape at Glacier. It is not surprising then that some of the principal geologic issues and concerns pertain to protecting these features. Humans have modified the landscape both in and surrounding Glacier and consequently have modified its geologic system. This system is dynamic and capable of noticeable change within a human life span (less than a century).

The following features, issues, and processes were identified as having the most geological importance and the highest level of management significance to the park:

- Slope failures and processes. Alpine environments are especially susceptible to slumping and landslide problems due to the lack of stabilizing plant growth combined with the substantial seasonal runoff and relatively frequent occurrence of intense seasonal rainstorms. This runoff can dramatically alter the landscape, creating new hazard areas in the process. Road and trail construction also impacts the stability of a slope. Mudstone- rich units are typically found in outcrop as slopes which are prone to fail when water saturated. In addition to this hazardous situation, the more resistant units in the park are exposed as cliffs. 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 hazard almost everywhere along the roads and trails of Glacier National Park.

- Glacial retreat. The park was created to preserve and protect some of the most spectacular glacial features in the world, including active glaciers. The glaciers at Glacier National Park have been retreating at a rapid rate, almost continuously since the mid 1800's – and in some models will be gone entirely by 2015. This retreat is intimately linked with regional to global climatic changes.

- Streamflow and channel morphology. In the climate of northwestern Montana, seasonal runoff and intense, short duration, seasonal rainstorms and subsequent flooding may impact channel morphology. These seasonal events also result in changes in the load and deposition of sediment in the valleys and along riverways. These changes affect aquatic and riparian ecosystems. Sediment loading can result in changes to channel morphology and overbank flooding frequency.

- Economic resources. Intimately tied with the story of Glacier is the record of man's quest to extract useful materials from the earth. Rocks in and near Glacier contain vast amounts of oil and gas as well as copper and other metallic ore deposits. Many of the Cretaceous age units underlying the park contain large amounts of coal. Management consideration must be given to these potential resources and their effect on the preservation of the pristine park environment.

- Avalanche threat. Glacier receives vast amounts of snowfall each winter. This, when combined with steep slopes and southern exposures creates severe snow avalanche hazards within and around the park. For this reason, monitoring climate and snow conditions is essential for predicting avalanche dangers in high risk areas, especially along the southern boundary along US Highway 2 and Going to the Sun Road. Avalanches or ice rafts from glaciers can form temporary dams across waterways, causing a severe flood hazard. These processes leave a substantial trace on the landscape. The park staff should be prepared to adjust accessibility when necessary to protect resources and public safety.

Other geologic parameters and issues such as the paleontological potential of the area, wind erosion and deposition, gravel and sand deposits, the process of glacier formation, wetlands, mining problems, seismicity, water issues, faulting and deformation processes, and cave resources, were also identified as critical management issues for Glacier National Park. These are listed in detail along with recommendations for inventories, monitoring, and research on pages 15- 20.

However, beyond just resource issues and concerns, the rocks of Glacier record the ancient beginnings of life on earth. The Precambrian Belt Supergroup strata range in age from about 1,325 million years ago (m.y.) to about 900 m.y. The Belt Supergroup was thrust over Cretaceous age shales in the Glacier Park area. The Precambrian strata are mostly reddish- brown and greenish- gray argillite and siltite with some quartzite and carbonate (Prichard, Grinnell and Snowslip Formations). They were deposited in near and far shore environments. The Empire Formation is a transitional unit as much as 1,170 ft (375 m) thick between the under lying Grinnell Formation and overlying Helena Formation. The Altyn, Helena, and Shepard Formations compose the Belt carbonate units. They reflect deeper water depositional settings with a carbonate saturated water chemistry. Stromatolites in these carbonate units record the only traces of Proterozoic life in the Belt basin. These unique features are formed by blue- green algae, primarily responsible for the oxygen rich atmosphere we breathe today.

Because of the nature of the landscape, several potential geological issues need to be considered with regard to land- use planning and visitor use in the Park. Along with a detailed geologic map and road log, a guidebook that would tie Glacier National Park to other Parks in the Pacific Northwest would enhance a visitor's appreciation of the geologic history and dynamic processes that not only created Glacier but also created the spectacular landscape of the entire region. Strategically placed wayside exhibits can help explain the geology to the visitor.

Introduction

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

Purpose of the Geologic Resource Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and an understanding of geologic resources yields important information needed for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. Ultimately, the inventory and monitoring of natural resources will become integral parts of park planning, operation and maintenance, visitor protection, and interpretation. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resource Division. The goal of the GRE Program is to provide each of the identified 274 "Natural Area" parks with a digital geologic map, a geologic resource evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and is designed to be user friendly to non- geoscientists.

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the specific geologic issues in the park. Park staff are afforded the opportunity to meet with the experts on the geology of their park. Scoping meetings are usually held at each park to expedite the process although some scoping meetings are multipark meetings for an entire Vital Signs Monitoring Network.

Bedrock and surficial geologic maps and information provide the foundation for studies of groundwater, geomorphology, soils, and environmental hazards. Geologic maps describe the underlying physical habitat of many natural systems and are an integral component of the physical inventories stipulated by the National Park Service (NPS) in its Natural Resources Inventory and Monitoring Guideline (NPS- 75) and the 1997 NPS Strategic Plan. The NPS Geologic Resources Evaluation (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 and Monitoring (I&M) Program of the Natural Resource Information Division, 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 with up- to- date contact information at the following website:
http://www.nature.nps.gov/grd

Geologic Setting

In December 1907, Montana Senator Thomas Carter first introduced legislation to authorize the land in northwest Montana as a national park over some objections of local residents. Fortunately for future generations, Montana Congressman Charles Pray, noted environmentalist George Bird Grinnell and James J. Hill of the Great Northern Railroad, fought to pass the legislation designating the park which was signed by President Howard Taft on May 11, 1910. By 1910, the controversy regarding potential mineral wealth had diminished in the face of hard economic reality. The rugged mountain wilderness with breathtaking scenery, rich in geologic wonders, was claimed by the federal government as a protected national park.

Glacier National Park encompasses about 1545 square miles (4100 square kilometers) of rugged, glaciated, mountainous terrain in northwestern Montana. It is located within the northeastern section of Belt Terrane, covering parts of Montana, Idaho, Washington, and southern Canada, and contains incredible exposures of Precambrian age Belt Supergroup sedimentary rocks, which in Tertiary time were displaced eastward onto Cretaceous age rocks by the Lewis thrust fault. These remarkable ancient rocks are relatively undeformed and unchanged by the forces of pressure and heat and remain among the finest examples of Precambrian sedimentary rocks in the world. They record an ancient Belt basin (sea) environment, opening and closing intermittently over many millions of years. The rocks record a quiescent northwestern margin to the North American craton similar to the modern day Atlantic Coast.

Paleozoic, Mesozoic, and Cenozoic rocks, deposited on top of the Belt rocks are missing at Glacier National Park. They were eroded long ago leaving the rocks we see in the present jagged peaks. This resulted in a unique as well as enigmatic geological setting. The Cretaceous rocks beneath the Lewis thrust sheet record the Cretaceous Inland Seaway, a vast inland sea that once stretched from the Arctic Ocean to the Caribbean Sea. This environment was rich in prehistoric flora and fauna.

The park is defined by sweeping U- shaped, glaciated valleys bounded by dramatic, shear rock faces topped by pinnacles of layered rock. The many streams and lakes, following the paths of previous glaciers descend outward from the continental divide, which runs up the middle of the Park. Over 700 miles of trails traverse the park giving backcountry access to thousands of visitors each year. The Going to the Sun Road crosses the park with stretches clinging to the steep walls of the glacial valleys.

Completed in 1932, the road is an engineering marvel and is listed as a National Historic Landmark.

Glacier National Park is in a southwesterly trending, structurally low area that is bounded on the north and south by southwest- trending structures or arches. The low, bowl- shaped depression of the basement rocks that influenced the present setting of the Glacier Park area was very likely established by the end of Cretaceous time, and it probably controlled, at least in part, the present northwest trending structural pattern in the area, a pattern resulting from the Laramide (early Tertiary) orogeny (Mudge 1977).

The Park is dominated by two linear mountain ranges trending northwest- southeast. On the west side of the Park, the Livingstone Range runs about 35 km (22 miles) from the Park boundary to Lake McDonald. To the east, the Lewis Range extends the full length of the Park, a distance of about 100 km (61 miles) from the International Park boundary on the north to Marias Pass on the south. The Continental Divide runs along the crest of the Lewis Range from Marias Pass to about 16 km (10 miles) south of the U.S. – Canada border; then it swings west to the crest of the Livingstone Range into Canada (Elias 1985).

Glacier National Park contains the eastern front of the Rocky Mountains of the United States (figure 1). It is also part of a series of northwest trending mountain ranges in Western Montana including the Whitefish Range (immediately west), the Flathead, Swan and Mission Ranges (to the southwest). The Sweetgrass Hills (part of the Sweetgrass Arch) bound the Park on the east. The Purcell Anticlorium, to the west of the Whitefish Range, contains the Purcell Mountains and the Salish Mountains in a region of broad folds that forms a large, elongate dome structure in far western Montana and eastern Idaho. The Bitterroot Mountains, which form the border between Montana and Idaho were mistaken by the Lewis and Clark survey team in 1805 as the continental divide. They followed the Bitterroots instead of the Anaconda Range north into Montana when surveying the boundary giving Idaho its "panhandle" and Montana some spectacular scenery.

Glacier National Park is considered part of the Cordilleran fold and thrust belt of the United States; continuous with that known in the southern Canadian Cordillera (McGimsey 1982). Price (1981) has interpreted the region to be a portion of the complex structures that resulted from intermittent collisional plate interactions beginning nearly 200 m.y. ago. Prominent regional structural features include: 1) the Lewis thrust fault system, 2) the disturbed Belt, a zone of closely spaced imbricate thrust faults to the east, 3) the Rocky Mountain Trench, a zone of closely spaced normal faults to the west, and 4) the Lewis and Clark line to the south, a major intraplate tectonic boundary in the region (figure 2). Deformation in the Cordilleran orogen was initiated during the late Jurassic and is believed to have terminated by late Eocene time (McGimsey 1982). This fold and thrust belt, however, has been undergoing extension since late Tertiary time along a series of major normal faults.

Glacial Setting

The name *Glacier* National Park is somewhat of a misnomer. Many visitors come to the park expecting to see enormous glaciers similar to those in Alaska. While those undoubtedly existed at one time in Glacier as evidenced by the U- shaped valleys, hanging valleys, cirques and other glacial features, today the warmer, drier climate could not support such ice masses. There are glaciers in the park still viewable by the public, but most have retreated back to their source cirques. What does remain of the past ice ages are the sculpted rocks and remnants left behind when these massive glaciers melted some 10,000 years ago.

Glaciers flowed ever so slowly down drainages that now contain narrow lakes. The numerous mountain valleys that wind their way between the high peaks are U-shaped, the typical product of glacial sculpting. The Park has been the setting for at least ten periods of widespread glaciation. It is difficult to determine just when the first advance took place, as evidence of early advances is often destroyed by later advances, but it may have been very early in the Pleistocene.

The Wisconsin Glaciation (the most recent of the 4 major Pleistocene Glaciations, from oldest to youngest: Nebraskan, Kansan, Illinoisan, and Wisconsin), is called the Pinedale Glaciation in the Rocky Mountain region (after terminal moraines near the town of Pinedale, Wyoming). The Pinedale Glaciation began after the last interglaciation, perhaps 110,000 years before present (B.P.), and included at least two major ice advances and retreats. Two ice sheets covered more than 16 million km^2 (6 million square miles) of North America, stretching from coast to coast. Glacier National Park was uniquely situated, hemmed in by the two great ice sheets (Elias 1996) (figure 3).

At the height of the Pinedale Glaciation, about 20,000 years ago, only the highest ridges and peaks in the Park were free of ice. These ice- free regions are called nunataks; today these appear as horns and arêtes. Mountain glaciers that formed on the western slope of the Continental Divide in the Livingstone Range flowed down the valley of the North Fork of the Flathead River. These glaciers joined with ice coming from the eastern slope of the Whitefish Range to the west, and the combined glaciers flowed south, overriding the lower Apgar Mountains, near West Glacier, and contributing ice to the Flathead Lobe of the much larger Cordilleran Ice Sheet. The Flathead Lobe gouged out a deep depression, and the terminal moraine left by this glacial lobe dammed the Flathead River about 20,000 years before present (B.P.), creating present day Flathead Lake (Elias 1996; Karlstrom 2000).

Glaciers that flowed from the western side of the Lewis Range south of Lake McDonald merged with ice from the southeastern flank of the Flathead Range to the south. This ice flow, combined with other mountain glaciers southeast of the Park, formed a large body of ice around the southwestern corner of the Park. This body pushed up and over the low divide at Marias Pass and ended up becoming part of the large piedmont glacier called Two Medicine Glacier.

This glacier was also fed by ice flowing from the southern end of the east slope of the Lewis Range. Two Medicine Glacier flowed out over the eastern plains for several kilometers, nearly intersecting with the massive continental ice sheet, or Laurentide Glacier, coming from the east. Farther north along the eastern slope of the Lewis range, mountain glaciers flowed out onto the plains to form the Cut Bank and St. Mary's glaciers. Ice from the northwestern flanks of the Lewis Range and the northeastern flank of the Livingstone Range flowed north in to Canada (Elias 1996; Osborn and Gerloff 1997; Karlstrom 2000).

During the Pinedale Glaciation, active volcanoes in the Cascade Range in Washington and Oregon erupted and deposited ash layers in the Glacier Park Region. These ash layers can be accurately identified, dated, and correlated in the large moraines left from Pinedale Glaciers. They provide useful dates about the timing of glacial recession in the area. Pinedale deglaciation was fairly rapid and by 11,200 years B.P. the ice had retreated to local mountain valleys in the Park, and by 11,300 and 10,000 ^{14}C years B.P. (using radiocarbon dates, tree- ring data, macrofossils, and the presence of the Mazama, Glacier Peak G and St. Helens J volcanic ash beds) it had withdrawn to the same high- mountain cirques and shaded niches where small glaciers persist today (Carrara and Wilcox 1984; Elias 1996; Osborn and Gerloff 1997).

The present day ice is probably not the remnants of Pinedale Glaciation. About 6,000 years ago all glacial ice probably disappeared from the mountains. After this there was a warm, dry climatic period during which it is probable that no glaciers were present (Carrara 1986). Then about 4,000 years ago the climate became wetter and cooler again, and small glaciers present today were formed (Dyson 1966).

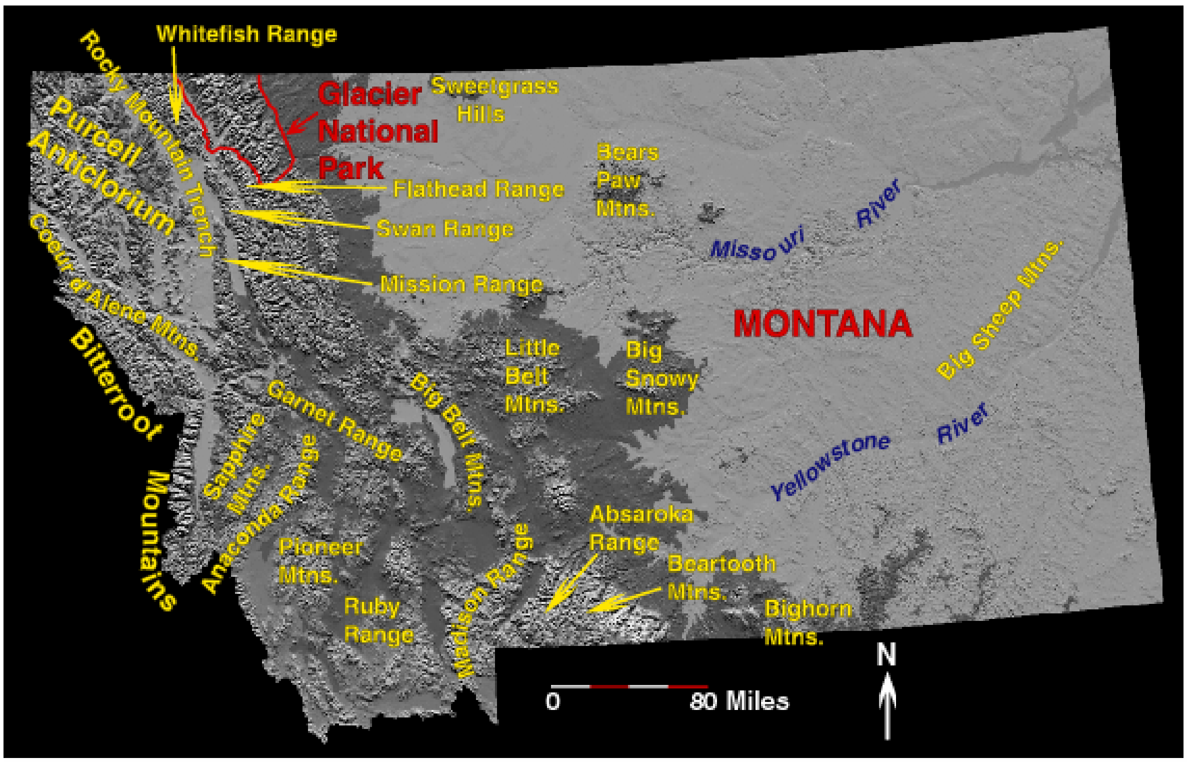

Figure 1: Map of Montana with physiographic features surrounding Glacier National Park. Modified version of map from Perry-Castañeda Library Map Collection.

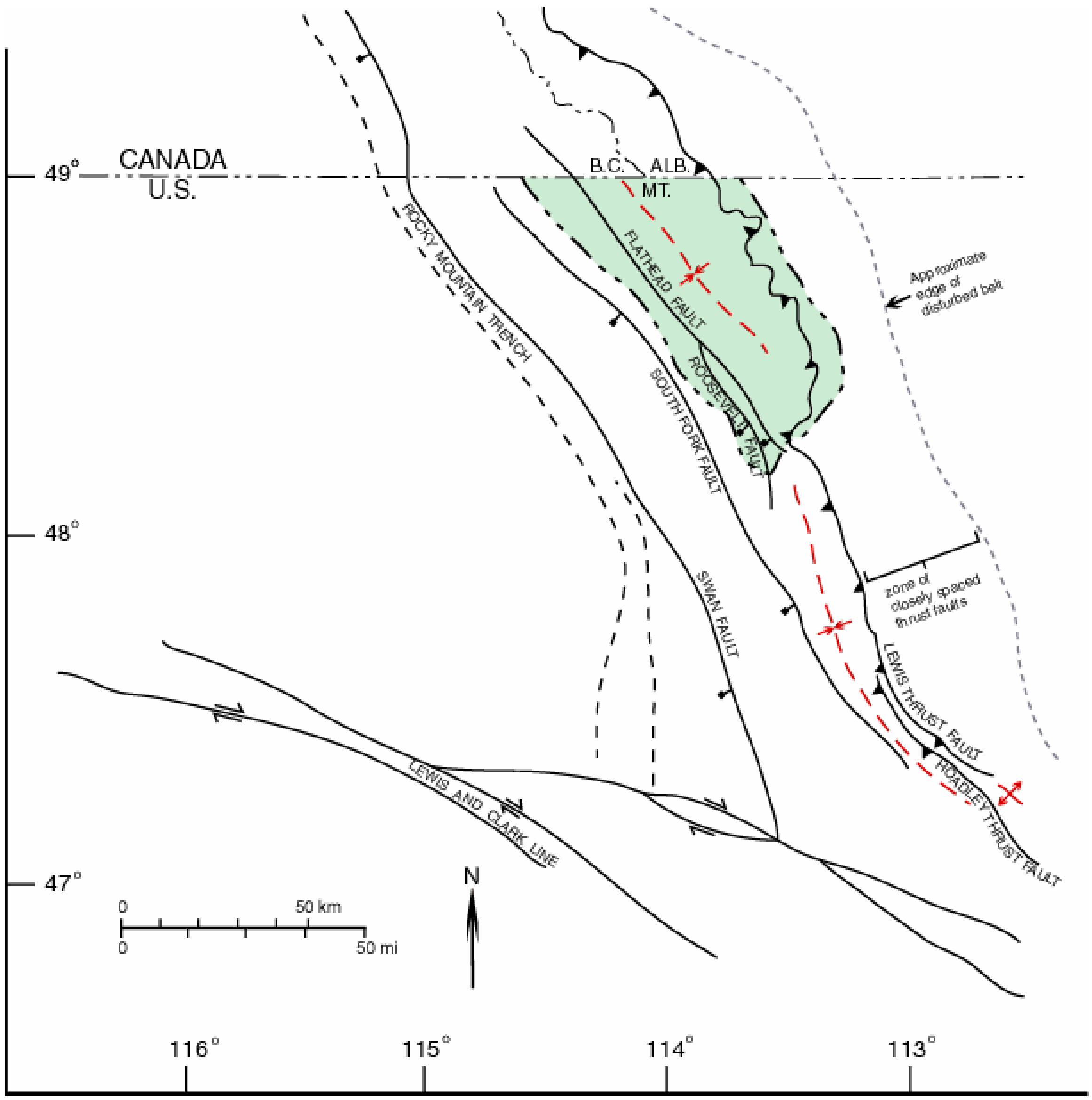

Figure 2: Map of structural features in Glacier National Park area, modified from McGimsey 1982.

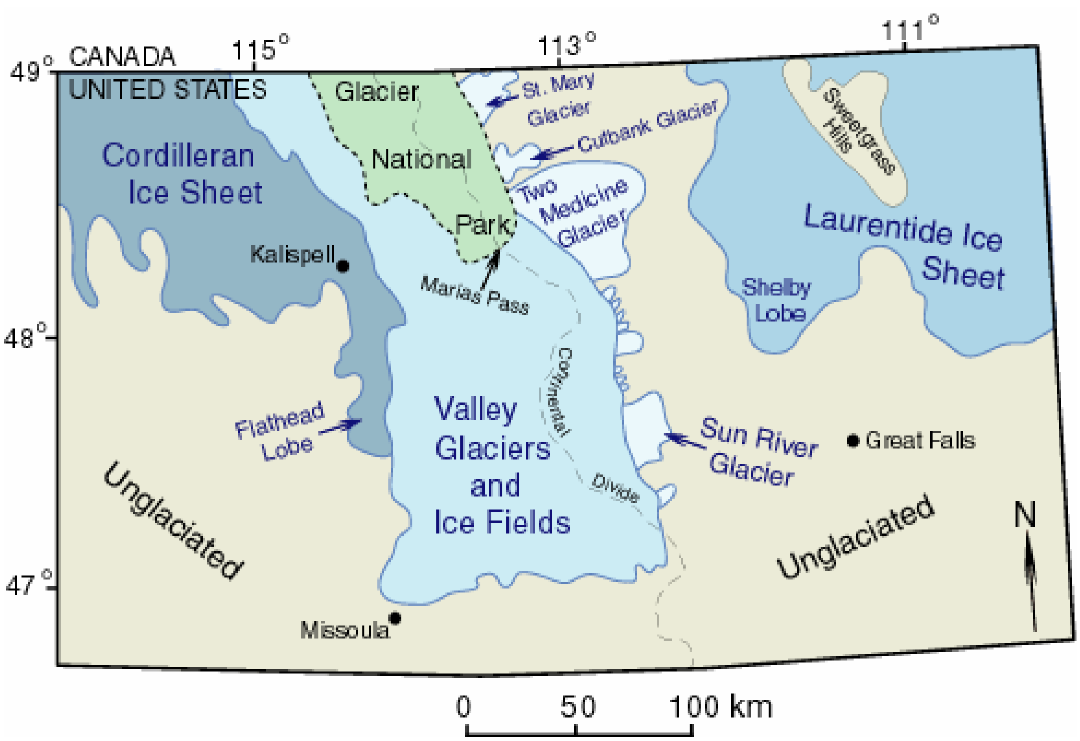

Figure 3: Map showing location of Glacier National Park in relation to glacier and ice sheets present during the Pinedale Glaciation's maximum extent. Modified from Carrara 1986.

Geologic Issues

A Geologic Resource Evaluation (GRE) workshop and Geoindicators scoping meeting were held at Glacier National Park on August 20- 22, 2002, to discuss the geologic resources, and to assess resource management issues and needs. The following pages synthesize the results of these meetings to address economic resources, potential geological issues, future scientific research projects, and interpretive needs for Glacier National Park.

Economic Resources

In the Glacier National Park area, many of the Cretaceous age rocks contain beds of coal. Coal is also present in the Tertiary age Kishenehn Formation. These beds are thin and discontinuous making economic extraction difficult. See Unit Properties and Limitations section for more information about specific units.

The structural features present at Glacier National Park including faults and folds are natural fossil fuel traps. Exploration for oil and gas in the area began as early as 1892. This exploration led to the formal report of the Canadian Geological Survey on the subject of the numerous oil seeps in the region. While the bulk of exploration for oil and gas takes place in Canada, the region has been continuously scrutinized for its potential fossil fuel abundance. Before the formation of the park, drilling along the western slope in the North Fork of the Flathead River Valley, near oil seeps, failed to achieve significant production in 1901 (Boberg 1984). The first oil well drilled in what is now the park was located at the east end of Lake Kintla, begun in October 1901.

The primary structure in the Park area, the Lewis thrust system, is largely responsible for the capture of oil and gas. The thrust sheet covers Paleozoic, Mesozoic and Cenozoic age rocks, rich in organic materials. Upon burial, fossil fuels matured and flowed upwards through cracks and joints to produce the telltale seeps in the area. The oil in the seeps is high API gravity (low specific gravity), generally light in color, very volatile with little residue. The seeps are often coincident with water springs and are ephemeral as opposed to perennial (Boberg 1984). Seeps are located in the Park area at Kishenehn Creek, Sage Creek Headwaters, Bowman Lake, Kintla Lake, Christensen Ranch, and Mount Hefty among others.

Pleistocene glaciation may also have played a role in the formation of some oil and gas interest in the Glacier National Park area. Organic debris trapped in glacial sediments such as till can be sufficiently sealed so that when it decays, it produces methane gas that can be trapped in place until released by drilling or erosion. This release can be mistaken for an oil seep.

The lakes and marshes characteristic of the glacial landscape in the Park can also lead to organic matter decay and release of methane gas (swamp gas) from sediments underwater (Boberg 1984).

The Waterton Lakes area and areas of British Columbia north of Glacier National Park produce oil and gas from the Lewis thrust sheet at the present time. There has been continual interest in the Glacier National Park area for pervasive exploration and drilling. Balancing the pristine nature of the Park and economic interests is essential to Park management.

While not permissible within the park, development of coal, oil, and gas surrounding the Glacier area pose a threat to the park's viewshed and ecosystem. The influx of drill rigs and extraction equipment necessary for oil and gas production creates new road construction, water pollution, noise pollution and a localized population increase.

Inventory, Monitoring, and/or Research Needs

- Park staff should remain aware of the potential encroachment of oil and gas exploration in the area of the park.

- Acquire plugging records of oil and gas wells potentially connected to park groundwater systems.

Mining Issues

The initial interest in the Glacier National Park area was fueled by potential mineral wealth. After the Civil War, the region, like much of the American West, embodied the ideals of untamed capitalism, and was seen as a sea of endless possibilities for settlement, mining, and later, fossil fuel extraction. The various dikes, sills and other igneous intrusions led to the formation of the ore deposits in the Belt Supergroup rocks.

When an early explorer, Dutch Lui's, illegal prospecting efforts indicated the presence of copper ore east of the continental divide, word spread and soon other squatters were disregarding the Blackfeet Reservation laws. The Blackfeet, desperate and pressured, sold the "ceded strip" (area of Glacier Park east of the continental divide) for $1.5 million in 1896; an Act of Congress officially changed the land on April 15, 1898.

The area of the ceded strip was nearly half the area of the present day Park. Hundreds of anxious miners staked claims hoping to strike it rich, perhaps finding gold or silver as well. By 1902, the ceded strip, so alluring to impatient prospectors, was largely abandoned because no economically viable deposits of ore were uncovered. The prospectors all moved to the next "hill" in search of instant riches and the ceded strip was largely abandoned.

Metallic mineral deposits were rare and few discoveries were made. Although copper is often associated with gold and silver, no economic deposits of base or precious metals were found in Glacier National Park. Mining in the area was abandoned prior to 1910. All that remains in the park are abandoned mine openings and deteriorating equipment.

Abandoned mines pose a serious potential threat to the ecosystem from acid mine drainage and heavy metal concentrations in both surface and groundwater. Heavy metals may also contaminate the surrounding soil, adversely impacting plant and animal life.

Inventory, Monitoring, and/or Research Needs

- Periodic water (surface and groundwater) and soil sampling and testing should be conducted to detect heavy metals in those resources. Drinking water is especially important to monitor.
- Research needs include a thorough investigation of ore bearing beds throughout the park including descriptions, ore content tests, and locations, i.e. where the beds crop out and are accessible to the public, flora and fauna.
- Complete inventory of the ore content in the recent unconsolidated deposits and soils as well as the ore bearing stratigraphic units.

Avalanche Hazards

Glacier receives substantial snowfall each winter. This combined with the extreme slopes and exposures creates severe snow avalanche hazards within and around the park. Monitoring climate and snow conditions allows for some predictability of avalanche dangers in high risk areas such as the southern boundary along US Highway 2 and Going to the Sun Road.

Avalanches or ice rafts from glaciers can form temporary dams across waterways. One dramatic example of this was the damming of the Middle Fork of the Flathead River by an avalanche, destroying a bridge, in 1979. When the dam inevitably melted, the rush of water and debris destroyed many structures along U.S. Highway 2, and it created a long detour for motorists and a large mess for clean- up crews and residents below the slide. During the winter of 2002- 2003, an avalanche destroyed some of the railroad and blocked the highway along the Park's southern boundary.

These processes leave a large mark on the landscape and the Park should be prepared to adjust accessibility when necessary to protect the resources and public safety.

Inventory, Monitoring, and/or Research Needs

- Perform an exhaustive mapping study of where specific snow accumulation areas are located on the slopes above Glacier's valleys to allow for more precise hazard assessment.
- Using repeat aerial photography to document the change in snow avalanche paths over time and document the effects of slope processes can predict hazard areas in the park.
- Update surficial geologic map including snow avalanche paths, landslide areas, and lake deposits.
- Snow avalanche studies including the frequency, cycles, and locations of avalanche sites are possible using historic records, satellite imagery, tree rings. From this information, comparing east and west side (of continental divide) cycles of snow avalanches would give an overall view of the climatic differences in the park.
- Use climate information and topographic information in a GIS to map areas unsuitable for recreational development due to avalanche danger.

Wetlands

The dynamic nature of wetland environments makes them an indicator of the overall status of the ecosystem. Many sites have yet to be identified. The first step toward an inventory would be to validate the classification of the Fish and Wildlife Service and refine is delineation according to their guidelines. Once sites are identified and compared with past photographs and records, monitoring trends becomes possible. Parameters could include water chemistry, sediment influx and vascular plants.

Inventory, Monitoring, and/or Research Needs

- Study the effects of fire on wetlands and slope stability.

Cave Resource Issues

Several units including the Helena Formation and the Snowslip Formation contain enough carbonate layers to support cave systems. The Park does not have a current inventory of caves or their contents.

Inventory, Monitoring, and/or Research Needs

Conduct a survey which would consist of identifying cave locations. The project will include the cartographic survey, inventory, and legal land description of know cave resources.

Conduct the cave inventory project of the park's known cave systems by developing and implementing an action plan for the inventory of all known caves.

This project will include mapping and assessment of the natural and cultural resources as follows:

Priority 1: Conduct cartographic surveys of all known caves within +/- 2% error of closure. Data should be delivered on computer disk, compatible with a Geographic Information System, and as finished plan and profile Class 1 maps. Cave locations will be recorded on aerial photographs of each park and on USGS topographic maps (UTMs will be required for each cave entrance marked on the maps). Brass survey markers at least one inch in diameter will be obtained for marking cave entrances and tying into surface and cave surveys.

Priority 2: In conjunction with the cartographic survey base line resource inventories will be conducted. Initial data collection will include the following information: geology, mineralogy, archeology (including all cultural associations), paleontology, hydrology, and biology (flora and fauna). This data collection process will be accomplished through contracts, MOUs, and/or park personnel.

Seismicity

Earthquakes are common, but mostly too small to feel in the northwest Montana area. Tremors in conjunction with wet, unstable slopes could pose a serious threat to the parks resources, roads and visitors.

Inventory, Monitoring, and/or Research Needs

- Perform a comprehensive study of the faulting and seismic processes active at Glacier National Park, taking into account rock formations, slope aspects, location and likelihood of instability.
- The cliffs above the Going to the Sun Road are prone to slumping and sliding (see Formation Properties table). The slopes of this area would likely fail in a moderate to large seismic event. Care must be taken when planning trails and other visitor access along steep walls beneath obvious rockfall prone areas.
- Monitor seismic activity in the Glacier area by cooperating with local agencies including the USGS and Montana Geological Survey.
- Perform exhaustive study of seismic/active faults in close proximity to the Glacier area including the mapping of small scale faults and shear fractures.

Slope Processes

The topographic relief in Glacier is extreme. In areas such as Going to the Sun Road and Many Glacier Road, the likelihood of landslides increases with precipitation and undercutting. Using a topographic map and a geologic map in conjunction with rainfall information could provide some warning for areas especially at risk.

The intense erosion of the steep slopes is responsible for the stunning vistas at Glacier National Park. However, these erosional processes are also the cause of the most important geological resource management issue: mass wasting and rockfalls.

The walls of many of the broad valleys at Glacier have extreme slopes. This renders them highly dangerous because of the likelihood of rock falls, landslides, slumps, and slope creep. This issue is a major concern in the weaker rock units such as shales and siltstones. Stronger rock units such as the Helena and Grinnell Formations are highly fractured 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 incredible large volume of runoff can scour alpine slopes lacking stabilizing plant and tree roots. The rock and soil, suddenly saturated with water, slip down the slope causing a huge slump, mudslide, or flow.

Many trails in the park trail lead visitors through spectacular alpine and forest scenery, however, these trails are at extreme risk for rockfall and landslides. In less visited areas of the park slope processes are also creating an impact.

Inventory, Monitoring, and/or Research Needs

- Perform a comprehensive study of the erosion/weathering processes active at Glacier National Park, taking into account the different rock formations versus slope aspects, location and likelihood of instability.
- Create a rockfall susceptibility map using rock unit versus slope aspect in a GIS; use the map in determining future developments and current resource management including trails, buildings, and recreational use areas.
- Inventory and monitor debris flow potential near picnic areas, relate to slope and loose rock deposits.
- Inventory runoff flood susceptible areas, relate to climate and confluence areas
- Perform trail stability studies and determine which trails are most at risk and in need of further stabilization.
- Siting facilities is also a major issue because of the fractures and potential for sloughing; these areas should be monitored for growth and potential danger.
- Further research the causes of landsliding and slumping to help predict future events.

- The potential for landslides and rockfalls exists along all roads and trails at Glacier National Park. The risk of such occurrences is greatest during the spring runoff season when high levels of snowmelt saturate the thin alpine surficial deposits.

Glacier Formation

Glaciers form when the average snowfall exceeds the rate of average melting. When this happens, snow begins to accumulate from year to year in what is called an *accumulation zone*. The snow turns to ice, and as it thickens, the ice undergoes plastic deformation (a permanent change in shape of a solid that does not involve failure by rupture) and begins to creep downslope under the force of gravity. No other erosional process on earth is as effective as glacial erosion. As glaciers move downslope, they pluck underlying rocks from the hillside and carry them along in the glacial ice. The boulders act as abrasives to gouge, scour, and polish the floor and walls of the valley down which the glacier flows.

During the mid- 19th century, more than 150 glaciers in Glacier National Park advanced to their furthest extent since the Pinedale glacial event. Glacier National Park is the only park in the conterminous U.S. Rocky Mountain region with a climate suitable for maintaining substantial glaciers since the end of the Pinedale glacial maximum some 10,000 years ago. This climate exists there for two reasons. One is that the Park is situated far enough north and its mountains are high enough to keep relatively cool in the short summers. The other reason is that the mountains in the Park are high enough to capture significant precipitation from moist Pacific air moving inland.

The impressive glaciers that existed in northwestern Montana at the turn of the twentieth century, along with the incredible mountain scenery and wildlife, led to the creation of the Park. When the park was established in 1910, the glaciers were already retreating from their interglacial maximum around 1850, when they were larger than they had been in the last 10,000 years (Elias 1996). Since the Little Ice Age (16th – 18th centuries), many of the remaining glaciers have shrunk to the point of becoming snowfields, no longer capable of downslope movement.

Inventory, Monitoring, and/or Research Needs

- Monitor and inventory human signatures in the park on glaciers.
- Study the role of enlarging fractures around glaciers due to freeze- thaw cycles.
- Study how different lithologies respond to glacial movement.
- To comprehensively study and monitor the atmospheric conditions and snow accumulation in the park

Paleontologic Potential

The alpine landscape at Glacier contains more than just a collection of glacial features, it contains a record of prolific ancient life. Fossils at the park record the first forms of life and include several types of Precambrian age algae (stromatolites) and later Cretaceous oysters, brachiopods and dinosaurs. These preserved specimens should be protected and catalogued for scientific study, future generations, and increased visitor appreciation of the entire park.

Inventory, Monitoring, and/or Research Needs

- Study the Cretaceous rocks to determine if dinosaur and other fossils are present in the backcountry.
- Perform a comprehensive study of the paleontologic resources at Glacier National Park.
- Compile an inventory of all paleontologic specimens present in the park.
- Ongoing discussion of the lifeforms present during the Precambrian age demands more detailed, microscopic study of the preserved sedimentary Belt rocks of Glacier.
- Attempt to determine the locations of paleontologic specimens removed from the park as part of private collections to obtain an accurate inventory.
- Draw visitor attention to the fossil resources at Glacier with graphics, brochures and exhibits.
- The susceptibility to erosion difference between Conophyton and Baicalia stromatolites

Faulting and Deformation Processes

The rock units present at Glacier have undergone multiple phases of deformation resulting in folds, faults, joints and other fractures. These features compromise the strength of any rock unit. These weaknesses have many effects on the features present at Glacier. For instance, a fault or fracture can serve to focus surface runoff, eventually widening into a stream gulley such as Sunrift Gorge.

Deformation is still occurring at Glacier. Rocks are responding to pressures within the earth and recent small scale fractures and joints attest to this. Understanding the nature of these features allows predictions of where weathering and erosion are likely to be concentrated making this knowledge indispensable to resource management.

Inventory, Monitoring, and/or Research Needs

- Study the role of jointing versus faulting (including strike- slip, normal, and thrust faulting).
- Determine extent of Cretaceous deformation below the Lewis thrust to the south and east.
- Conduct an inventory of any recent fault scarps in the area. These are commonly present in Quaternary surficial deposits.

Glacial Retreat

Glacial retreat is of major interest to resource managers at Glacier as well as to climate researchers worldwide. The glacial response to climate change is immediate and striking. The overall trend of glacial retreat at Glacier National Park indicates the local climate is getting warmer, possibly evidence of a global greenhouse effect. From six glaciers mapped from 1993 aerial photos, and two mapped through 1979, retreat from ca. 1850 maxima ranged from 818- 1440 m and averaged 1244 m. Overall retreat rates varied between 6- 17 m/yr. Those glaciers were reduced in area by 62- 80%, for an average shrinkage to 27% of the estimated area in 1850. Climate models suggest that all the glaciers in the park will be gone by 2025.

Inventory, Monitoring, and/or Research Needs

- Research of how observed glacier changes might affect streams and surface characteristics across a mountain landscape is of interest to ecosystem modeling and climate change research. Further work in the Glacier National Park area is needed to complete regional assessment of glacial recession, and address climatological and ecological implications.
- Study rates of edge retreat and migration, erosion, retreat of leading edge, rates of downcutting of streams on the glacier's surface, and accumulation of fill (glacial till) at bottom.

Water Issues

Water is ubiquitous in the park and preserving its pristine state is crucial. The potential for pollution from human waste facilities, campgrounds, watercraft, and vehicular use requires intense regulation of the human impact in the Park. Groundwater, either from precipitation or snow melt moves quickly through the fractured bedrock and down steep hydraulic gradients in the Park. Because of the dynamic nature of the interaction between water and geologic processes at Glacier National Park the role of hydrogeology must be taken into consideration when making management decisions.

The interaction between water and geology is especially obvious in a mountainous environment like Glacier which receives significant snowfall each year. The glacial features described above lend a unique aspect into the situation. The moraines left by glaciers commonly act as dams to the drainages in front of the glaciers. These can be found in any scale in Glacier from Lake McDonald, to a small alpine tarn (lake). If these dams should fail, the potential flash flood would have a tremendous impact on the valley below the lake.

Water continues to play a critical role in sculpting the present landscape of Glacier National Park. During intense seasonal thunderstorms, rain acts like a sledgehammer on unprotected soil, knocking apart individual soil particles and washing unconsolidated sediment into the valleys. The steep slopes of Glacier's valley walls are susceptible to intense erosion and rock fall during these storms.

Fire activity only increases the likelihood of rock fall and landslides by removing the stabilizing plant material from the slopes. Water freezing and thawing also plays a large role in changing the landscape. The expansion upon freezing pries rocks apart, crack by crack.

The thin, poorly sorted, glacially- derived alpine soils of glacier are susceptible to slumping and sliding especially when water- saturated. This can be a hazardous situation for roadways and trails which are situated on or near steep slopes and planners must be prepared to predict when the potential hazard is high and adjust accessibility to those areas accordingly. Slide Lake for instance, formed when a recent landslide blocked Sherburne Creek, diverting forever the trail that once was along the lakeshore.

The North Fork Valley is largely underlain by the Tertiary age Kishenehn Formation. This formation contains clays derived from volcanic sediments including bentonite. Bentonite is a clay mineral which greatly expands when wet causing the rocks around it to crack and move. This type of shrink- and- swell clay poses an obstacle to road and trail builders. The presence of bentonite and its hydrogeologic properties in the North Fork Valley should be noted in the planning of future roads, facilities, and/or trails.

Inventory, Monitoring, and/or Research Needs

- Determine the nature of the park's watershed by compiling baseline watershed, and surface to subsurface hydrogeologic data.
- Monitor water quality on a multiple sample location basis within the park, drinking water sources are especially important. .
- Conduct a thorough inventory of lakes in the park.
- Create a "lake ice model" to determine climate change patterns and help the management of wildlife such as migrating waterfowl.
- Install further wells for testing and drinking water access.

- The impacts of nearby mining are unknown (see above mining issues discussion)

- Identify and study potential sources for groundwater quality impacts at the park.

- Install transducers and dataloggers in wells.

- Investigate additional methods to characterize groundwater recharge areas and flow directions.

Streamflow, Channel Morphology and Sediment Load

Surface water is drained from Glacier National Park by many rivers flowing down slopes on either side of the continental divide. In the high alpine climate of northwestern Montana, intense, short duration, seasonal rainstorms and subsequent floods in addition to seasonal runoff from snow melt profoundly impact channel morphology. These intense events may also result in periodic deposits of deep sediments.

Sediment loads and distribution affect aquatic and riparian ecosystems, and because sediment loading can result in changes to channel morphology and overbank flooding frequency.

Inventory, Monitoring, and/or Research Needs

- Monitor seasonal spring and stream locations with regards to their location, water quality, and maximum flow.

- Perform channel morphology studies, with regards to intense seasonal runoff. Consult professional geomorphologists with regards to erosional processes.

- Measuring sediment load and erosion rates would give a detailed view of problem areas in the park.

- Changes in streamflow record basin dynamics, climate and land use.

- Study the sediment influx for small alpine lakes in the park

- Inventory current channel morphological characteristics.

- Monitor changes in channel morphology.

- 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.

Wind Erosion and Deposition

In addition to water, wind is a major force that can redistribute snow, soil, and other materials (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind is important at Glacier National Park 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 park. Because park management practices limit or prohibit off- road travel, human impacts within the park primarily are associated with off- trail hiking in high- use areas.

Inventory, Monitoring, and/or Research Needs

- 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 Geology

The Precambrian Era (4600 – 570 Ma) is notoriously difficult to decipher. Much of the rock record necessary for tectonic correlation with other areas is missing or buried beneath younger rocks. For this reason study of the Belt Supergroup rocks at Glacier National Park is crucial for understanding at least one setting from the Precambrian, but the rock record gap leaves a heavy reliance on the study of adjacent areas to determine the tectonic setting between the Precambrian and the Tertiary.

An understanding of the geological processes and resources at Glacier is fundamental to management decision making. This report hopes to further this long term goal at Glacier with further suggestions and baseline information, including the digital geologic map of the park to be incorporated into a natural resources GIS for help in management decision making. However, for the scientific community and the general public, the geology of Glacier National Park offers vast opportunities to further the knowledge of alpine erosional processes, geologic and earth history.

Inventory, Monitoring, and/or Research Needs

- Perform rock color studies.

- Identify unconformity- bounded stratigraphic packages in order to better define the depositional systems present in the past.

- The continuing 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.

- Contact for geologic training sessions: UGS Geologic Extension Services.

- .The Belt Supergroup records rare Precambrian age environments, yet a detailed correlation of the rocks present in the Park and those found to the south, north and west has not been completed.

- Continued study of why the northern Rocky Mountains exist so far inland from a continental margin. How compressional stresses were translated so far inland remains a geologic enigma.

- Further research is needed to determine if the Belt basin was a open marine environment, or a restricted lacustrine (lake) environment.

Geologic Features and Processes

Glacial Features

The rugged landscape of Glacier National Park was formed by glacial processes. A glacier is a powerful agent of erosion, capable of profoundly altering the landscape over which is passes. Glaciers erode primarily by two distinct processes, plucking and abrasion (Dyson 1966). In plucking, the glacier actually quarries out distinct masses of rock, incorporates them within the ice and carries them along. As the glacier moves forward these blocks of rock are dragged or carried along with it (Dyson 1966).

Bergshrunds

Usually a large crevasse, the bergschrund, develops in the ice at the head of a glacier as a result of gravitational stresses pulling the glacier away from the headwall. The bergschrund of most active glaciers in Glacier National Park consists of an opening, usually 10 to 20 feet wide at the top and as much as 50 feet deep, between the head of the glacier and the mountain wall. It is at this site that plucking is most active and dominant because water enters by day and freezes in the rock crevices at night.

Cirques

By quarrying headward and downward the glacier finally carves the formation of a steep- sided, bowl- shaped basin called a cirque or glacial amphitheatre. The cirque is the first place that ice forms and the place from which it disappears last, thus it is subjected to intense glacial erosion longer than any other part of the glacial valley. A body of water known as a cirque lake may form in the depression after the glacier melts (Dyson 1966). Iceberg Lake, for example, lies in one of the most magnificent cirques in the park.

Glacial Stairways

Rock fragments of various sizes frozen into the bottom and sides of the glacier form a huge file or rasp which abrades or wears away the bottom and sides of the valley course down which the glacier flows. The valley thus attains a characteristic U- shaped cross section, with steep sides and a broad bottom. Practically all the valleys of the Park, especially the major ones, possess this distinct U- shaped cross section. Splendid examples are the Swiftcurrent Valley, St. Mary Valley, and the Belly River Valley. The floors of many of the Park's major U-shaped valleys are marked by several steep drops or "steps", between which the valley floor has a comparatively gentle slope. Such a valley floor is called a glacial stairway (Dyson 1966). These features result from the differences of erosional resistance between different rock types of the of the underlying formations.

A glacier will scour more deeply into a weaker rock forming a "tread" in contrast to the cliffs or "risers" formed by the erosion of stronger rocks. Resistant layers in the lower portion of the Altyn Formation, the upper part of the Appekunny Formation, and the upper part of the Grinnell Formation normally create risers in Glacier National Park.

Hanging Valleys

The "tributaries" of glacial valleys, filled with smaller glaciers which feed into the larger ones, are known as hanging valleys. They form as a result of differences in erosional power between the smaller glacier and the valley glacier. The thicker a stream of ice, the more erosion it is capable of; consequently, the main valley becomes greatly deepened, whereas the smaller glacier in the tributary valley does not cut down so rapidly, leaving its valley hanging high above the floor of the major valley once all the ice melts (figure 4) (Dyson 1966). The valleys of Virginia and Florence Creeks, tributaries to St. Mary Valley are excellent examples of hanging valleys.

Arêtes

Conspicuous throughout the park are the long, sharp ridges which form most of the backbone of the Lewis and Livingston Ranges. These features, of which the Garden Wall is one of the most renowned, are known as arêtes and also owe their origin to glacial processes. As the long valley glaciers enlarged their cirques by cutting farther in toward the axis of the mountain range, the latter finally was reduced to a very narrow steep- sided ridge, the arête. In certain places glaciers on opposite sides of the arête essentially cut through the ridge creating a low place known as a col, usually called a pass (Dyson 1966). Gunsight, Logan, and Red Eagle passes are a few examples. At locations where three or more glaciers plucked their way back toward a common point, they left at their heads a sharp- pointed peak known as a horn. Reynolds, Bearhat and Clements Mountains are excellent examples of horns.

Waterfalls and Lakes

Other features of the park which can be attributed to glaciation, at least in part, are the spectacular waterfalls. There are two principal types of falls at Glacier. One occurs in the bottom of the main valleys, the other at the mouth of the hanging tributary valleys (Dyson 1966). The former exemplified by Trick Falls of the Two Medicine River, is located where the stream drops over the risers of the glacial stairway (see description above). Examples of the hanging tributary type of fall, are Bird Woman and Grinnell Falls.

Most lakes throughout the Park also owe their existence directly or indirectly to glaciers. They may be divided into five main types, depending on their origin: 1) cirque lakes, 2) other rock- basin lakes, 3) lakes held in by outwash, 4) lakes held by alluvial fans, and 5) moraine lakes (Dyson 1966).

Cirque lakes fill the depression plucked out of solid rock by a glacier at its source. Other rock- basin lakes fill depressions created where glaciers moved over areas of comparatively weak rock. In all cases of cirque or rock-basin lakes, the water is contained by a bedrock dam. A typical example of this type of feature is Swiftcurrent Lake.

Lakes held in by glacial outwash are dammed by stratified gravel which was washed out from former glaciers when they extended down into the lower parts of the valleys. Lake McDonald exemplifies this type of lake. Lakes held by alluvial fans differ from the previous lake type in that they may have started as rock- basin lakes, but at a relatively recent date streams entering the lake valley have completely blocked the valley with deposits of gravel; thus creating a lake or raising the level of the one already present. St. Mary and Lower St. Mary lakes probably were joined originally, but the alluvial fan of Divide Creek, entering the basin from the south created a dam which cut the original lake body into two separate bodies. Finally, moraine lakes are formed when a moraine deposit blocks a stream outlet. Josephine Lake is a prominent example of a moraine lake. Another type of unique moraine lake has a glacier for part of its shoreline. In Glacier National Park, there are two of these lakes at Sperry Glacier and one at Grinnell Glacier.

Glacial Deposits

As the glacial ice moves it continually breaks rock fragments lose. Some of these are ground into a type of powder as they move against each other and against the bedrock under the glacier. Most types of rock, especially the limestones and shales on which the glaciers rest in Glacier National Park, yield a gray powder when finely ground. All melt- water streams issuing from present-day glaciers are cloudy or milky from their load of this finely ground “rock flour”. Much of this silt is deposited in lakes giving them a milky, turquoise color.

Although the former large glaciers of the Ice Age transported huge amounts of rock debris down the valleys of the Park, the moraines which they deposited are, as a rule, not conspicuous features of the landscape. They are susceptible to intense erosion immediately following deposition as well as the obscuring effects of a vegetative cover of over 10,000 years The Going- to-the- Sun Road transverses a number of moraines along the shore of Lake McDonald. Because of the large proportions of rock flour (clay) in these accumulations, the material continually slumps, sometimes sliding onto the road surface. Knowledge of the location of such deposits is critical for maintenance of the road.

Glacial Retreat

In the late 1800’s, all 150 glaciers began to shrink in response to a slight change in climate, probably involving both a temperature rise and a decrease in annual precipitation. From about 1900 to 1945 glacial retreat was very rapid (Dyson 1966). Over a period of several years such shrinkage is apparent to the eye of an observer and is manifested by a lowering of the glacier’s surface elevation and a reduction of surface area. When the yearly snow accumulation decreases, the ice front of the glacier seems to retreat or move back, whereas the mass of the glacier is merely decreasing by melting on top and along the edges, analogous to an ice cube melting on a kitchen counter.

Six glaciers mapped from 1993 aerial photos, and two others mapped through 1979, retreat from 1850 maxima ranged from 818- 1440 m and averaged 1244 m. Overall retreat rates varied between 6- 17 m/yr. Those glaciers were reduced in area by 62- 80%, for an average shrinkage to 27% of the estimated area in 1850. Retreat rates were never constant over time on any single glacier, but roughly correlative with warmer climate trends. Pulses of recession occurred during the 1920’s through the mid- 1940’s, and seem to be recurring now, as evidenced by dramatic change in glacier size since 1979. This inconsistency also means there have been periodic glacial advances throughout recorded history in Glacier National Park. Between 1966 and 1979, several of the larger glaciers in the Mount Jackson area advanced as much as 100 m (Key *et al.* 1996). This means that glacial response to climatic trends is very rapid, and could be relevant to the recent worries about the greenhouse effect and global warming.

Recent moraines of two different age groups have been identified fronting the present- day glaciers and snowfields in Glacier National Park, ranging in size from a few m to more than 60 m (200 feet) (Dyson 1966; Carrara 1987). The subdued, vegetated moraines (sparse willows and other forms of dwarf vegetation) of the older group have been found at 25 sites, mainly in the central part of the Lewis Range.

These older moraines are in places overlain by volcanic ash from the eruption of Mount Mazama (now Crater Lake) in Oregon and therefore must predate the 6,800 year old B.P. event (Carrara and Wilcox 1984; Carrara 1986; Osborn and Gerloff 1997).

The younger set of moraines, which has accumulated during the last several hundred years, consists of fresh bouldery rubble on which only small pioneer plants and lichens have begun to establish themselves. They are common throughout Glacier Park (Dyson 1966; Carrara 1986). Tree- ring analyses indicate that some of these younger moraines were deposited by advances that culminated during the mid- 19th century (Carrara and Wilcox 1984; Carrara 1986). The moraines are particularly striking at Grinnell, Sperry, Blackfoot, Agassiz and Sexton Glaciers. Because of recent glacial retreat most, if not all, of the glaciers are no longer in contact with these newer moraines. In some cases a quarter of a mile or bare rock surface intervenes between the moraine and the glacier terminus (figure 5) (Dyson 1966).

A few glaciers have disappeared within recent years, but their distinctive moraines remain as evidence of former glacier activity. One of the most notable examples is the former Clements Glacier, a small body of ice which existed until about 1938 in the shadow of Clements Mountain at Logan Pass. The trail to Hidden Lake skirts the outside edge of the moraine. Between the mountain and moraine lies an obvious, bare expanse of rock where the Clements Glacier once existed (Dyson 1966).

Glaciers

Some 37 named glaciers (50- 60 total) currently exist in various cirque, niche, ice apron, group and remnant forms in Glacier National Park (Key *et al.* 1996). Only two have surface areas of nearly one- half square mile, and not more than seven others exceed one- fourth square mile in area (Dyson 1966) (figure 6).

All the present- day bodies of ice in Glacier National Park lie at the heads of valleys with high steep headwalls, on the east and north sides of high ridges at elevations between 6,000 and 9,000 feet, in all cases well below the snowline (the elevation above which more snow falls in winter than can be melted or evaporated during the summer, about 10,000 feet in Glacier). Consequently, these glaciers owe their origin and existence almost entirely to wind- drifted snow (Dyson 1966; Allen *et al.* 1995). Ice within these glaciers moves slowly. The average rate in the smallest ones may be as low as 6 to 8 feet a year, and in the largest glaciers probably 25 to 30 feet a year.

There is no time of year when the glaciers are motionless, although movement is somewhat slower in winter than in summer. Despite its slow speed, over a period of years, the glacial ice transports large quantities of rock material ultimately to the glacier's end where it is piled up in the form of a moraine. The largest glacier in the Park is Grinnell Glacier. In 1960 it had a surface area of 315 acres. Sperry Glacier is the second largest glacier in the Park. Its surface in 1960 was 287 acres (figure 7). Both Grinnell and Sperry Glaciers probably have maximum thicknesses of 400 to 500 feet (Dryson 1966; Key *et al.* 1996). Retreat has continued since 1960 and the glaciers are all much smaller now.

Other important Park glaciers, although much smaller than the first two mentioned, are Harrison, Chaney, Sexton, Jackson, Blackfoot, Siyeh, and Ahern Glaciers. Several others approach some of these in size, but because of isolated locations they are seldom measured. There are people who visit Glacier National Park without seeing a single glacier, while others, although they actually see glaciers, leave the park without realizing they have seen them. This is because the roadways afford only distant views of the glaciers, which from a distance appear as mere accumulations of snow.

Short-lived Glacial Features

There is a myriad of interesting, short- lived surface features which can be seen at times on any glacier. These include crevasses, moulins (glacier wells), debris cones, and glacier tables (figure 8). Crevasses are cracks which occur in the ice of all glaciers due to tensions caused by differences in ice velocity throughout the body of the glacier. They can be hidden by skiffs of snow or debris and thus can pose an access problem to visitors. Debris cones result from the insulating effect of rock debris, usually deposited by a stream running over the glacier's surface, which protects the ice underneath from the sun's rays. As the surface of the glacier is lowered by melting, cones or mounds form beneath the rock- insulated area and grow gradually higher until the debris slides from them. They are seldom higher than 3 or 4 feet, but can pose a hazard to hikers on the glacier. A glacier table is a mound of ice which is capped and insulated by a large boulder. Its history is similar to that of the debris cone or mound (Dyson 1966). Snow which fills crevasses and wells during the winter often melts out from below leaving thin snowbridges over the cracks in the early part of the summer. These pose a very real danger to those traveling on a glacier because of their inherent weakness and instability.

The Belt Supergroup

Glacier National Park contains the best exposed and most complete sections of the Belt Supergroup rocks. A partial section of the Belt Supergroup is about 2900 m (9514 ft) thick in the central and northeastern margin of the Park, with the base being in fault contact with underlying Cretaceous strata and the top having been removed by erosion. Neither the base nor the top of the Belt Supergroup is present anywhere in Glacier National Park. Although these strata were subjected to lowermost greenschist- facies metamorphism (~300°C and 2 Kbar), details of sedimentary structures and fine sedimentary laminae are extremely well preserved, and for the purposes of sedimentary study are considered to be essentially unmetamorphosed (Horodyski 1983).

Because they were deposited before the evolution of complex plants and animals, the Belt Supergroup provides a unique context to study ancient sediments undisturbed by the bioturbation ubiquitous with younger rocks. The only organisms present to leave their mark on Belt rocks are stunningly variable stromatolites or algal mats present in many rock formations of Glacier National Park (figure 9).

The Belt Supergroup is generally regarded to be of Middle Proterozoic age (~1100 – 1850 Ma), but its exact span within the Middle Proterozoic is poorly constrained. It was deposited in either (1) a large intracratonic rift basin, like the East African Rift Zone, or (2) a passive margin, such as that along the present day eastern United States (McGimsey 1985; Moe *et al.* 1996). There has been considerable discussion about whether the Belt Supergroup rocks were deposited in a basin that was marine (open ocean) or lacustrine (constrained, fresh water). Evidence points to either possibility in the Belt basin (figure 10). Winston (1986) proposed a lacustrine intracratonic basin for the deposition of the Belt Supergroup, however, Hoffman (1988) suggested an episutural basin (a basin which persists between two converging land masses) underlain by oceanic crust trapped in the North America continent. Whether marine or lacustrine, what all researchers agree upon is that the Belt Supergroup was deposited in a largely shallow basin with a variety of nearshore and subaerially exposed deposition environments recorded in the rocks of Glacier National Park.

In either hypothesized depositional environment, the Belt Supergroup was deposited in water, with a variety of near and far shore environments recorded in Glacier's rock formations. The carbonate units record deeper water environments as do fine- grained clay rich rocks. Sandstones and desiccated mudstones record beach and other near shore subaerially exposed deposition sites. The ancient Belt basin was a dynamic system intimately tied to the surrounding tectonic setting.

Faults at Glacier

The Proterozoic rocks at Glacier are now exposed at the surface because of the movement associated with the Sevier- Laramide orogeny along the Lewis thrust fault. In Glacier, the Lewis thrust fault not only underlies the entire park, but is responsible in part for the rugged alpine scenery. The fault initiated intermittent deformation and movement some 200 million years ago and ceased some 15 million years ago.

The Lewis thrust fault, discovered and named by Willis in 1902, juxtaposes mid- Proterozoic Belt Supergroup rocks (~1600 million years old) in its upper plate with the late Cretaceous age Marias River Shale (~90 million years old) in its lower plate. The surface of the fault is usually covered by talus and other slope debris which makes it difficult to measure the surface directly.

Ross (1959) described the average strike, or compass direction of a horizontal line of intersection of a plane with Earth's surface, of the thrust fault in this area as N30°W and the dip of the gently folded fault surface as generally less than 10° SW. From a point 225 km (140 mi) north of the International boundary, the fault extends southward for 452 km (281 mi) (McGimsey 1982). Maximum translation, or horizontal distance the fault has moved, of the Lewis thrust is approximately 65 km (40 mi), this measurement was inferred from a location along the southern edge of the Glacier. The fault is located at an elevation of about 1829 m (6000 ft) along the eastern edge of Glacier National Park, and dips down to less than 1372 m (4500 ft) in elevation in western areas of the Park (Yin 1988).

The Lewis thrust has long been considered the "classic" example of an overthrust. The architecture of the Lewis thrust is extremely complex. It consists of symmetric and asymmetric concentric folds, high- angle and low- angle contractional and extensional faults, zones of complex structures, and imbricate thrust systems (Yin1988). The fault overlies the Cretaceous age rocks of the disturbed belt; a narrow north- south trending strip of land to the east of Glacier National Park (figure 11). Individual faults within the disturbed belt are difficult to distinguish given the extreme, pervasive deformation. East of the disturbed belt lies the Sweetgrass Arch and associated Kevin Sunburst Dome. These features are likely the results of flexural folding of the crust in response to the weight of the thick rock column to the west (Lewis thrust sheet). The Lewis thrust sheet (column of rock above the fault surface) is several kilometers thick, and is characterized by broad open folds in relatively undeformed rocks.

The Lewis thrust sheet is offset by the Flathead- Blacktail normal fault zone in the North Kootenay Pass and Marias Pass areas (Yin 1988). This indicates that after the Lewis thrust ceased movement around 15 Ma, the younger normal faults became dominant. The Flathead fault is a family of major listric normal faults (Flathead, Blacktail and Roosevelt faults) with an average high angle (40° or greater westward dip), but seismic data indicates the fault flattens with depth and may either sole into or just offset the Lewis thrust at depth. Displacement along the Flathead fault is estimated to be at least 13 km (8 mi) (McGimsey 1982; Yin 1988).

Running along the western edge of Glacier National Park is the Kishenehn Basin. This basin formed on the down-dropped side of the Flathead- Blacktail normal fault system. As the Roosevelt (to the west) and Flathead-Blacktail normal fault systems sole into and locally offset structures in the Lewis thrust sheet, the Roosevelt and Flathead- Blacktail fault postdate the Lewis thrust fault. Thus, the Tertiary age of the Kishenehn basin presumably provides an upper limit for the movement along the Lewis thrust (Yin 1988). The basin is very deep, more than 600 m (1969 ft).

These faults are among a number of roughly parallel faults west of Glacier National Park which sole into the Lewis Thrust fault. They record the extensional tectonic regime which followed the orogenic compressional events in the Rocky Mountains.

Akamina Syncline

The prominent syncline, the Akamina Syncline, running up the axis of the park is a broad open structure which lies totally within the upper plate of the Lewis thrust (figure 12). The trend of the syncline is roughly parallel to the strike of the thrust and numerous local normal faults in the Glacier National Park area (McGimsey 1982). The Akamina syncline is a doubly plunging structure (a fold that reverses its direction of plunge within an area, resembles the surface of a upturned bread loaf) that occupies the entire Lewis salient (portion of the thrust sheet which projects further than surrounding areas) from North Kootenay Pass to Marias Pass. It records the structural low, bowl shaped depression, in which the Park lies. Regionally, the Akamina syncline is bounded by the Lewis thrust to the east, and the Flathead-Blacktail normal fault system to the west. Within Glacier National Park, the hinge or axis of the syncline follows the continental divide and ends at the south- central edge of the Park (Yin 1988).

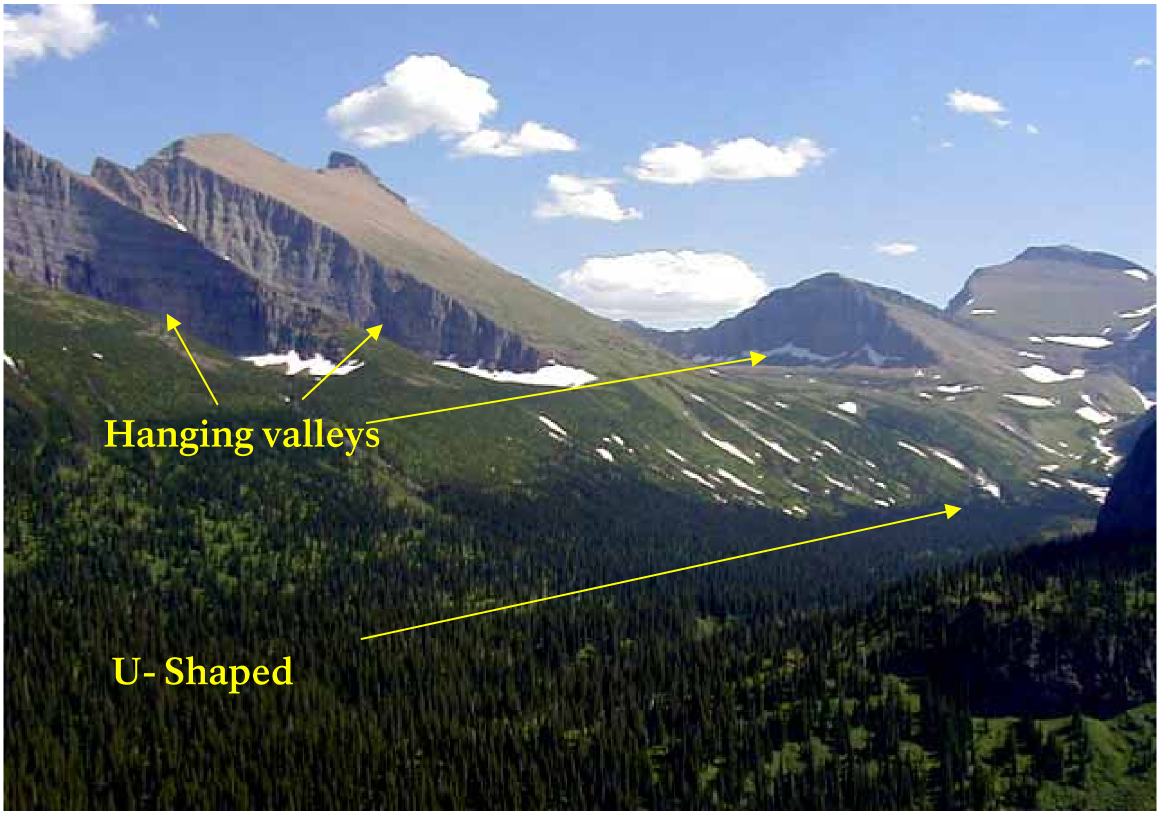

Figure 4: Three hanging valleys left as remnants of former glaciers flowing into the larger that once occupied the U-shaped valley running up the axis of the image. Modified from photo by Dawes and Dawes 2001. For more information see: http://wvcweb.ctc.edu/rdawes/VirtualFieldSites/GrinnellGlacier/VFSGrinnell.html

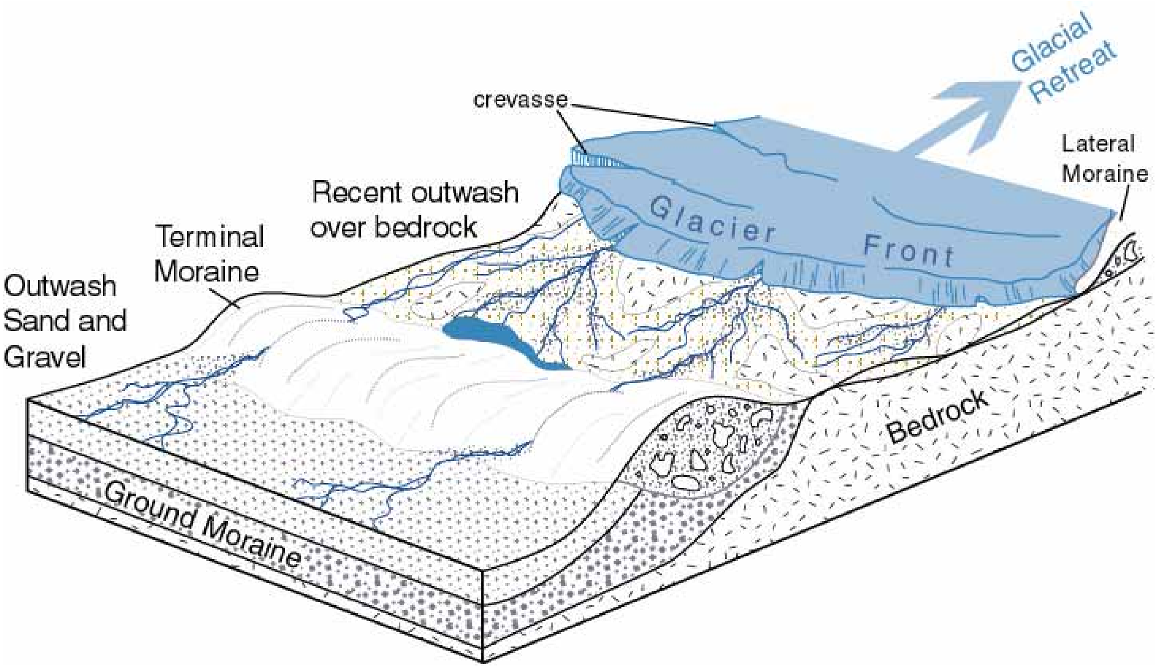

Figure 5: Diagrammatic view of a retreating glacier with a recent terminal moraine and a broad space between the moraine and the glacier front. Note the variety of deposits associated with glacial melt.

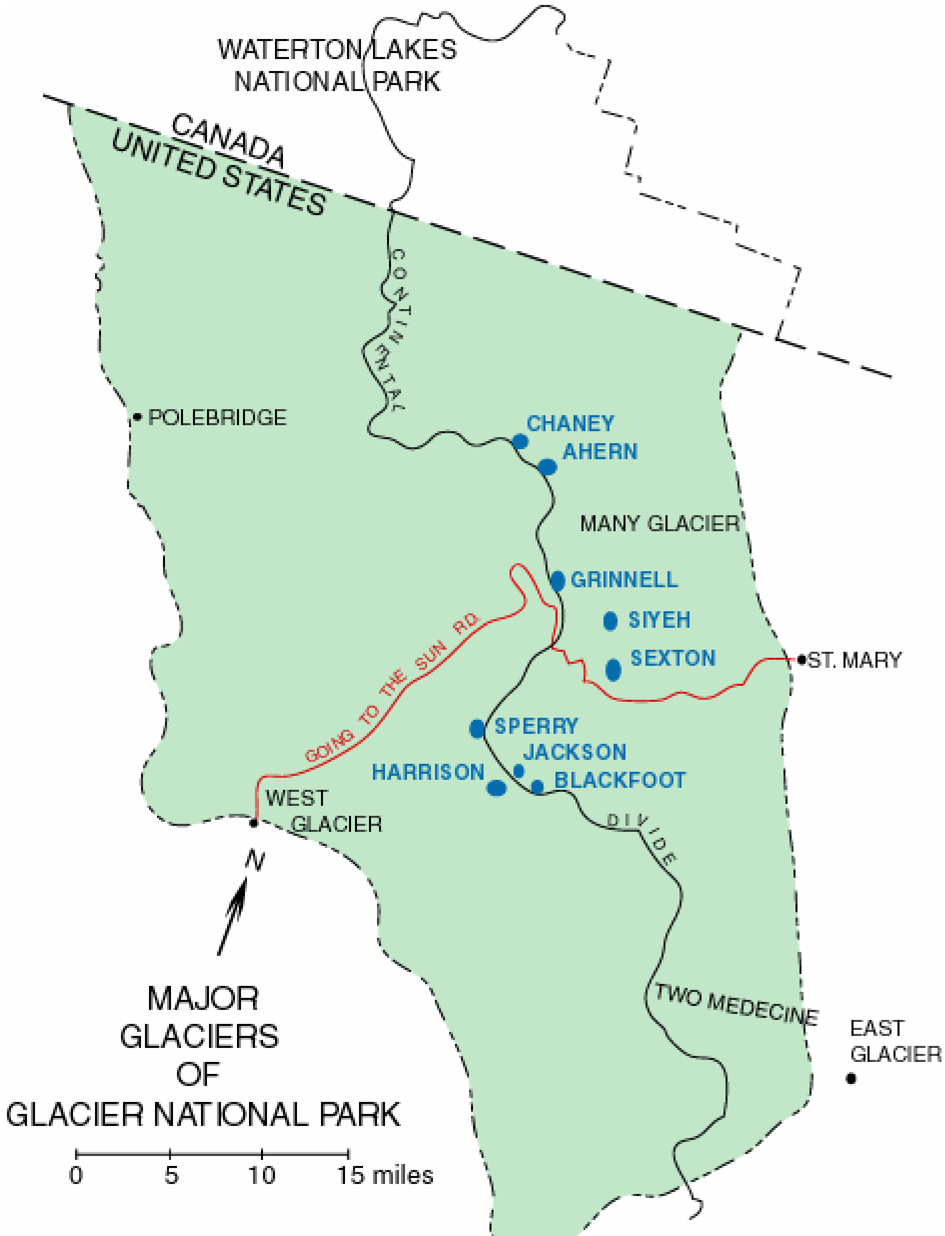

Figure 6: Map of Glacier National Park showing locations of the largest glaciers present today. Modified from Dyson 1966.

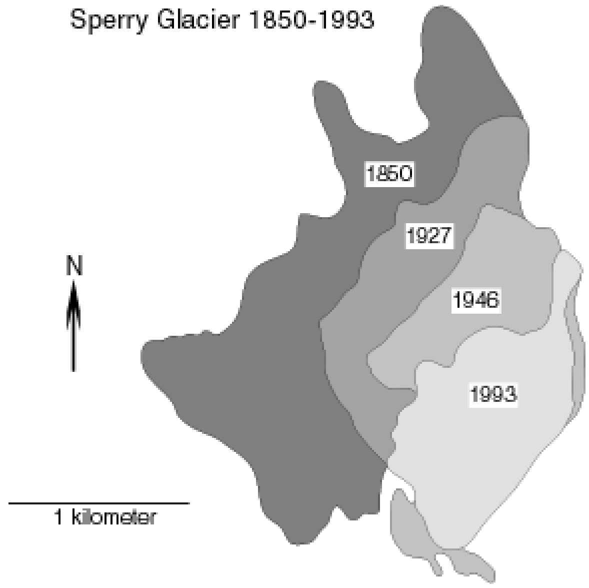

Figure 7: The aerial extent of Sperry Glacier reflecting steady glacial retreat from 1850-1993. Modified from Key *et al.* 1996

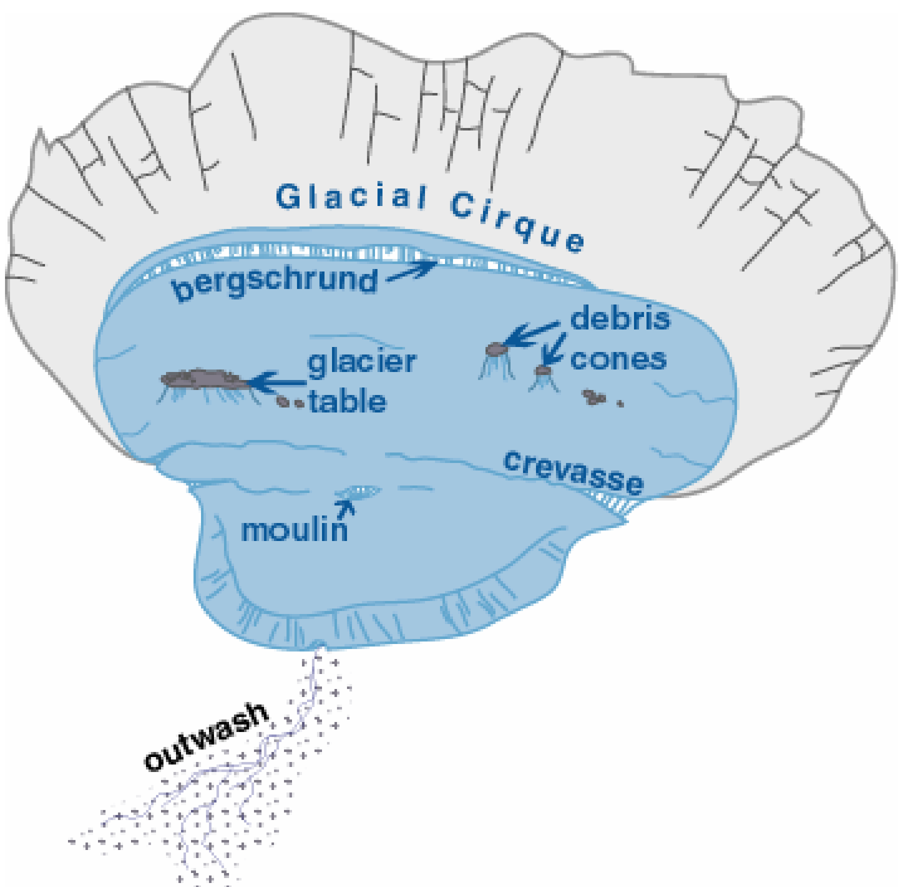

Figure 8: Short-lived surface features on glaciers.

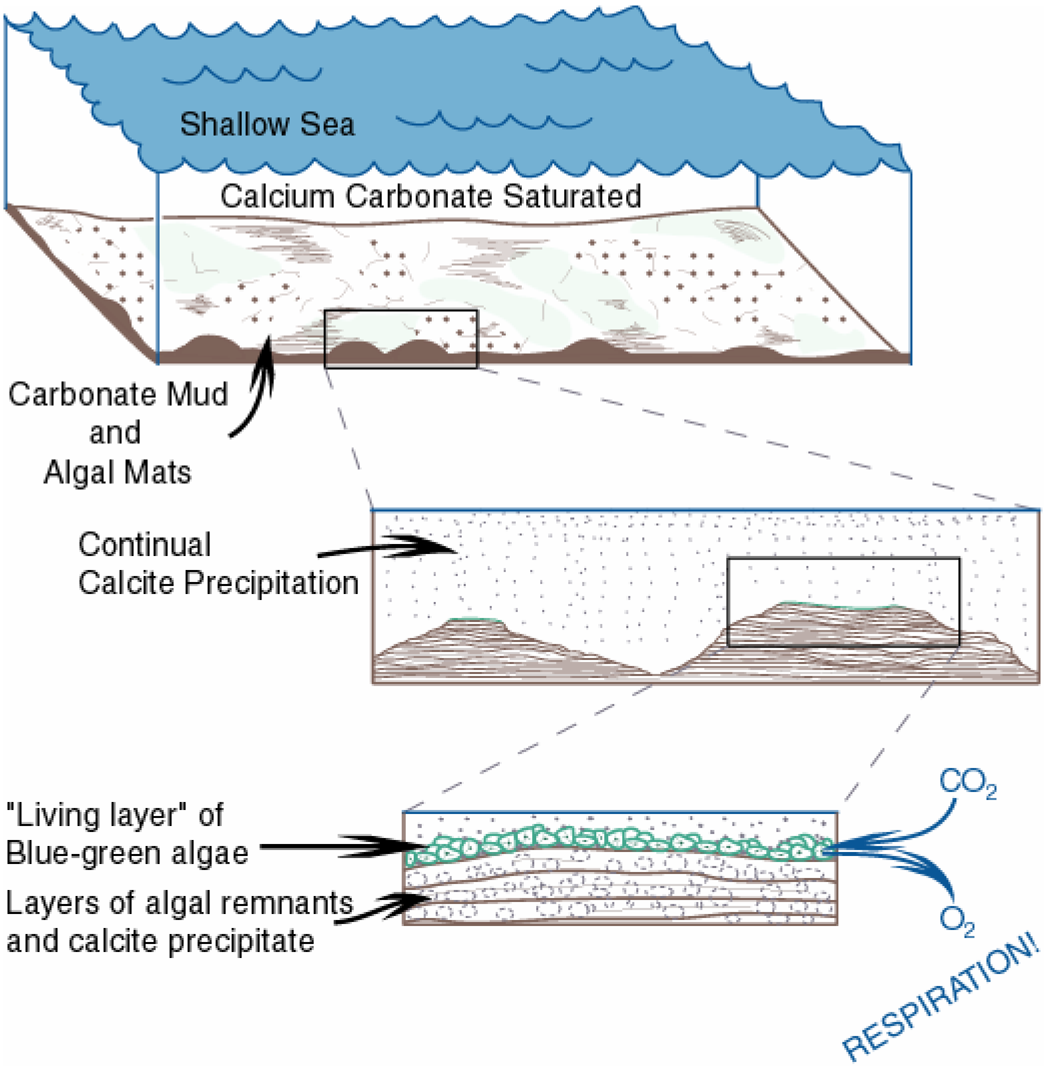

Figure 9: Formation of stromatolites from a combination of precipitation of calcium carbonate from seawater and layers of blue green algae.

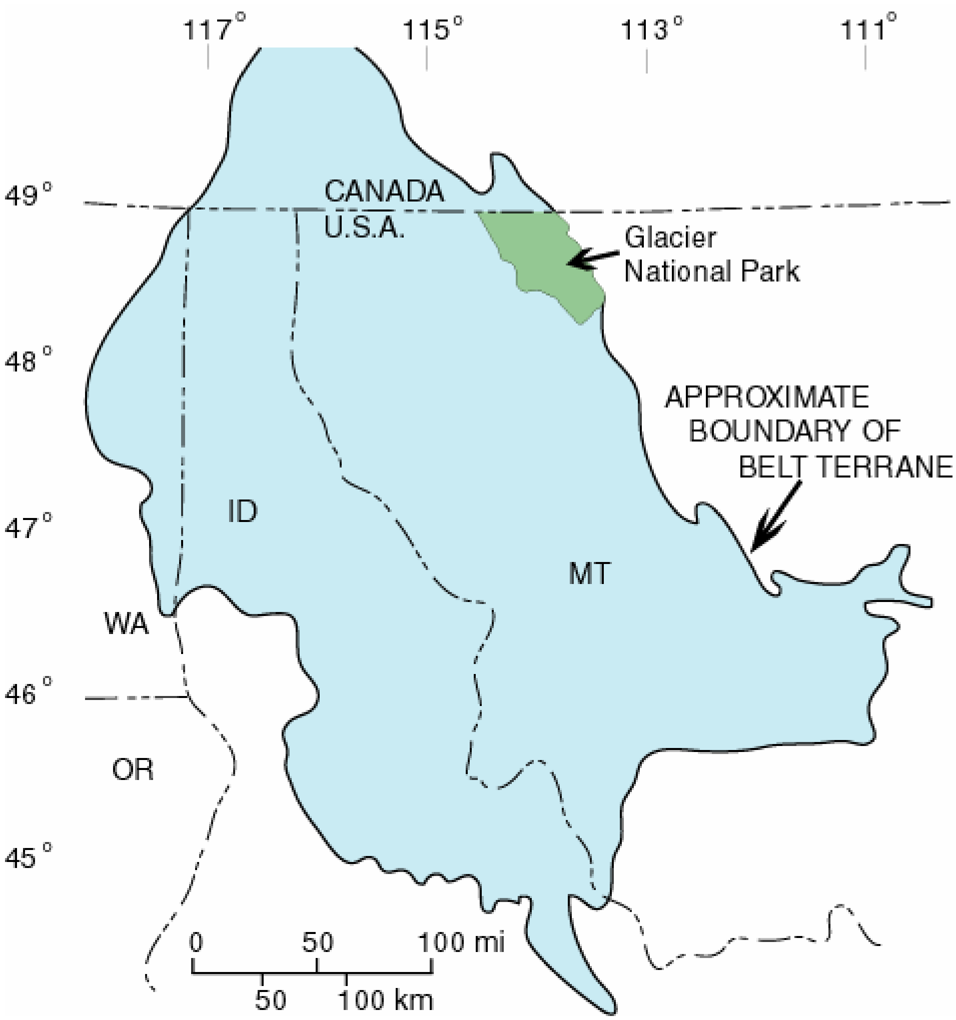

Figure 10: Location of Glacier National Park relative to the entire Belt Terrane (basin).

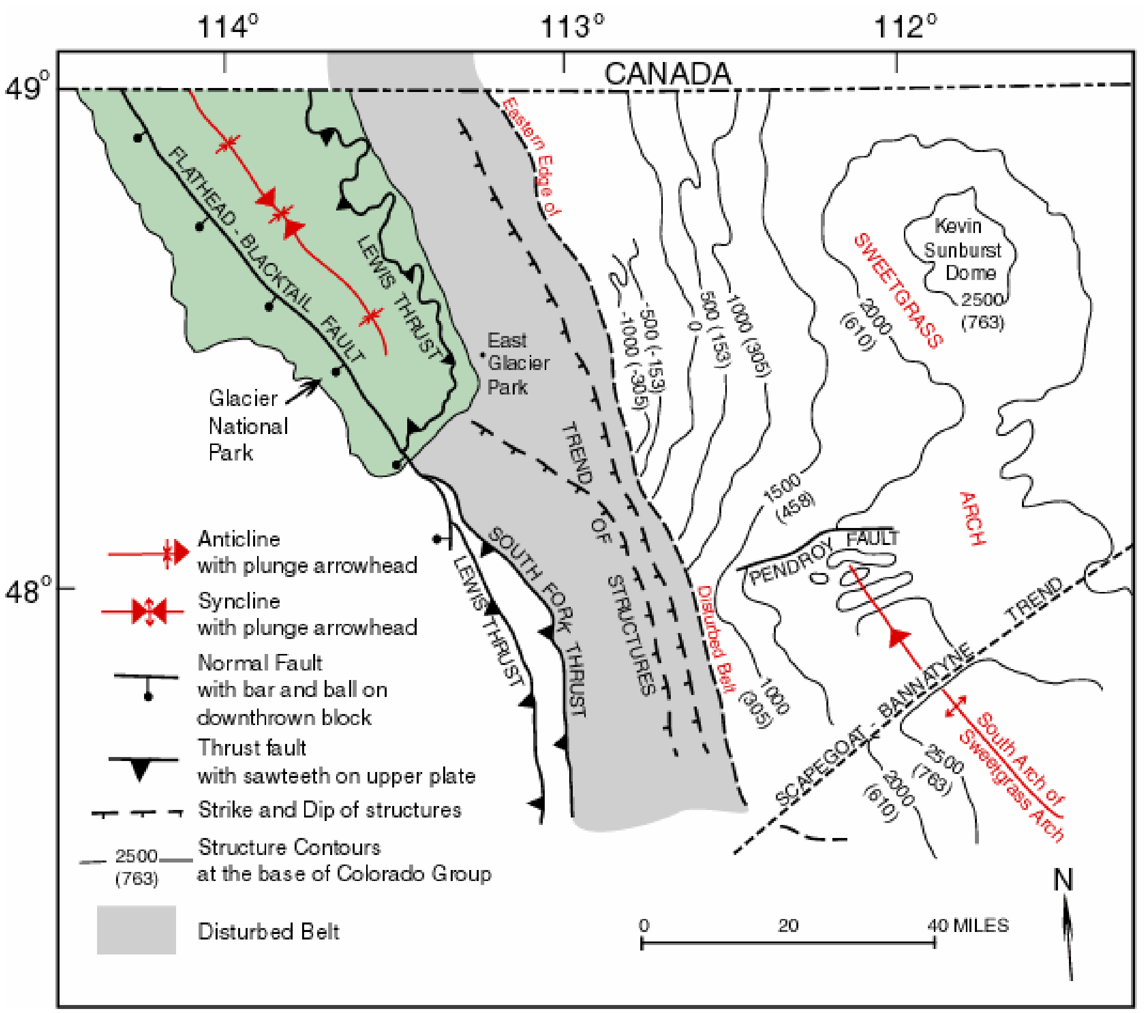

Figure 11: Structural features east of Glacier National Park. Note the structure contour lines recording the elevation below the surface of the top of the Cretaceous age Colorado Group rocks. The contours record the subsurface depression the Park is situated in.

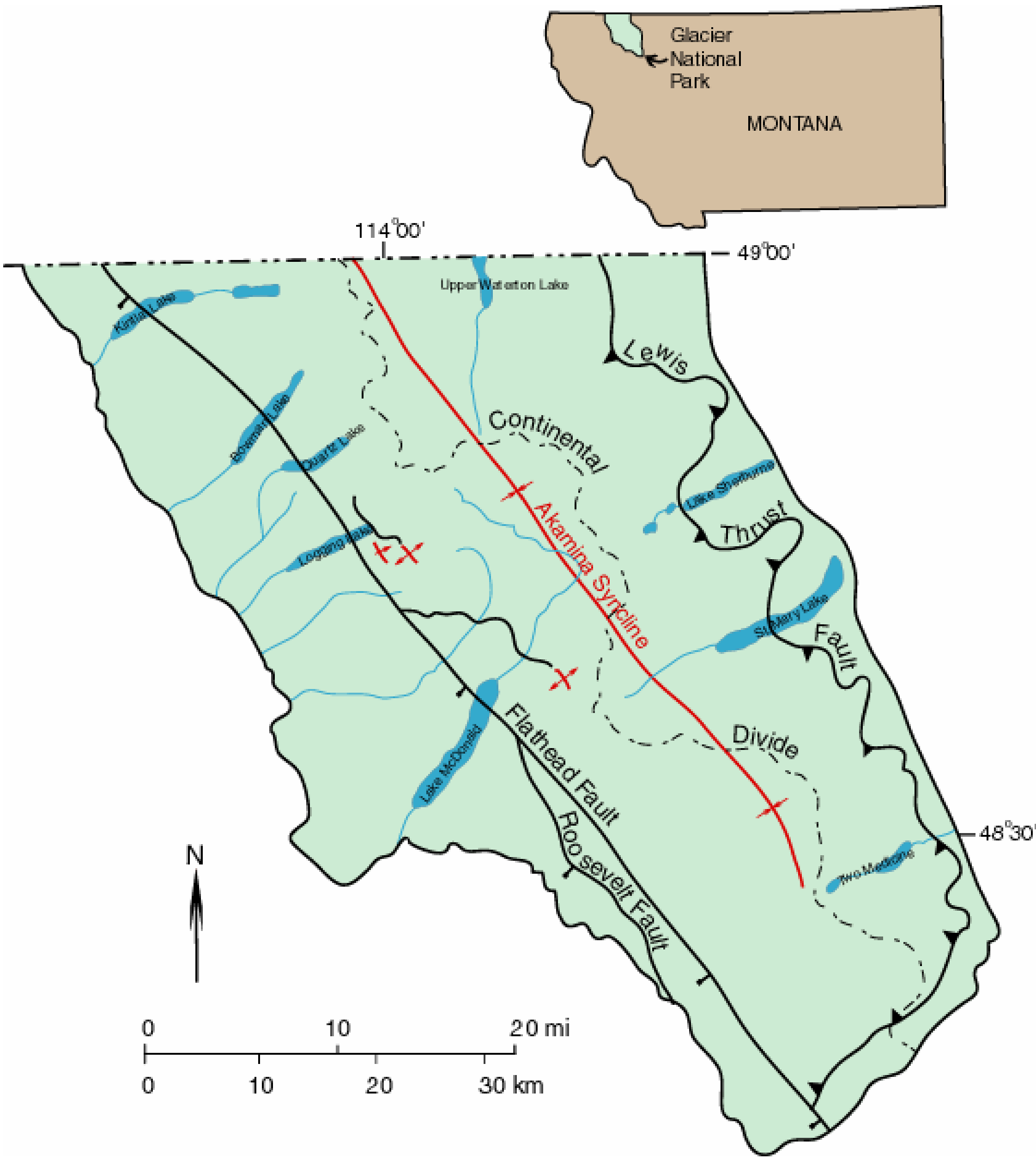

Figure 12: Prominent structural features inside Glacier National Park, including Akamina syncline. Modified from McGimsey 1982

Formation Properties

This section serves as a critical link between resource managers and the digital geologic map of the park. Formation Tables are highly generalized and are provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in these tables. More detailed unit descriptions can be found in the help files accompanying the digital geologic map or by contacting the Geologic Resources Division.

Glacier National Park is underlain almost entirely by Proterozoic age rocks. Beneath the Lewis thrust fault and filling valleys are Cenozoic age rocks. Because of the intense regional erosion these rocks are on striking display, indicative of the history of the area.

The oldest rocks of the area, composing the Ravalli Group, the Middle Belt Carbonate and the Missoula Group are Late Proterozoic in age. These were deposited in an ancient Belt sea basin. In the early Cretaceous Era, the sediments deposited include the sands, silts and muds for the Kootenai, Willow Creek, St. Mary River, Telegraph Creek, Two Medicine, and Blackleaf Formations, the mud for the Marias River and Bearpaw Shales, and the sand for the Virgelle and Horsethief Sandstones.

The late Cretaceous to early Tertiary compressional Sevier–Laramide orogenic events caused huge blocks of buried rock to slide over younger rock in an easterly direction. These episodes caused the dramatic juxtaposition of rock ages found today at Glacier. The Tertiary age Kishehnehn Formation is the result of the local basins filling with sediments when extension along normal faults followed mountain building. Pleistocene glaciation and other geomorphological agents such as streams and landslides have all left recent, Quaternary age deposits on the landscape of Glacier National Park.

Formation Properties Table

The following three pages present a table view of the stratigraphic column and an itemized list of features per rock unit. This table 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.

Formation Properties Table

Age (West)	Age (East)	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
QUATERNARY	QUATERNARY	Glacial and Alluvial Sediments (Qal, Qc, Qls, Qg, Qt1, Qor, Qac, Qrg, Qta, Qso, Qtr, Qt2, Qtg, Qes, Qt3, Qat, Qtdi)	Unconsolidated surface deposits 0 - 50 m (0- 164 ft) thick; includes alluvium, alluvial fill, colluvium, landslide deposits, terrace gravel, glacial till and outwash deposits; till is jumbled assortment of subrounded to subangular bouldery rubble combined with sand, silt and clay; landslides are large slumps, block slides and earth flows; colluvium is comprised of unsorted, angular gravel- size clasts in a sand- silt- clay rich matrix with small pockets of till, talus, rock-avalanche and debris flow deposits; alluvium consists of sand and gravel deposits as well as channel and overbank deposits of silt and sand	Very low	Unconsolidated material underlies most valleys of the park where buildings already exist and may heave with frost or extreme moisture	Slump and slide potential high	None	Possible camp sites preserved and other Native American artifacts	None	None	Sand, gravel, clay	Valley fill	Good for trails and campgrounds	None documented	None
TERTIARY		Kishenehn Formation (Tku, Tkp, Tkcc)	Unit is more than 610 m (2000 ft) thick; contains layered gravel, sand, mud, volcanic ash, limestone, and coal; appears pale gray and tan in outcrop, with poor cementation; interlayered sandstone, mudstone and conglomerate; most pebbles are from Belt Supergroup rocks, some up to 2.5 m (8.2 ft) in diameter; oil shale, coal, marlstone, litharenite, lignite and tuff beds are locally present	Low	Altered volcanic clays and poorly cemented rock layers render this unit rather unstable for development, especially for roads and structure foundations	Slump, slide and rockfall potential high if slope is present	Abundant petrified wood (Dawn redwood), fossil gastropods, mammals and palynomorphs, fish, insects and mollusks; leaves of *Macginitea augustiloba*	Possible camp sites preserved	Zircon in tuff beds	None	Several hundred feet of oil shale and some seeps; coal; sand and gravel	None documented	Good for trails and campgrounds	Thick, Tertiary- aged deposits; type section in North Fork of the Flathead River Valley	None
MP	MID PROTEROZOIC (MP)	McNamara Formation (Ym)	Exposed locally at GLAC, unit is 61 m (200 ft) thick near Mt. Shields; contains grayish- green siltstone and argillite with fining upward sequences common; some local beds of calcareous siltstone and arenite	Moderate	Locally exposed in park; suitable for all development unless highly fractured	Rockfall potential in steeper terrain	None	None	Mud breccias	None	None documented	None documented	Good for all uses	Precambrian sedimentary rock	Only locally exposed
MP	MID PROTEROZOIC (MP)	Bonner Quartzite (Ybo)	Exposed locally at GLAC, unit is 244 m (800 ft) thick near Mt. Shields; consists of pinkish- gray to pale red, very fine- to medium- grained feldspathic arenite, some channel deposit sand some siltstone and argillite in fining upward sequences; ripple marks are common	High	Locally exposed in park; suitable for all development unless highly fractured	Rockfall potential in steeper terrain	None	Possible tool material	None	None	Attractive flagstone potential	None documented	Good for rock climbing and other uses	Extensive Precambrian sedimentary rock	None
MP	MP	Mt. Shields Formation (Yms)	Unit 777 m (2550 ft) thick in GLAC; maroon to pale purple argillite, siltstone and arenite, some greenish- gray siltstone and arenite, some unique cream colored limestone beds present locally (contain stromatolites), and black argillite at the top of the unit; fining upward sequences are common, as well as wavy and parallel bedding and salt casts.	Moderate	Good for most uses unless thin bedding is present, providing planes of weakness in the rock column. Mostly exposed at higher elevations	Rockfall potential in steeper terrain	Stromatolites in unique limestone layers	None	Salt casts	If severe dissolution is present, karst may be an issue	None documented	Vugs on cliffs may provide bird nest habitat	Good for all uses	Type section at Mt. Shields; Precambrian sedimentary rock with stromatolites in conspicuous limestone layer	None
MP	MP	Shepard Formation (Ysh)	Ranges from 472- 168 m (1550- 550 ft) thick in GLAC; yellowish, greenish- gray dolomite and pyritic siltstone and argillite, with beds of coarse- grained calcarenite, sandstone, limestone and dolomite locally as well as stromatolites and "molar tooth" calcite	Moderate	Good for most uses unless pervasive dissolution is present	Usually exposed on cliffs; rockfall potential high	Stromatolites are common in this unit	None	"Molar tooth" calcite crystals, and pyrite	If severe dissolution is present, karst may be an issue	Pyrite present locally	Vugs on cliffs may provide bird nest habitat	Good for all uses	Type section near Shepard Glacier; Precambrian sedimentary rock with stromatolites	Usually exposed at high elevation
MP	MP	Purcell Lava (Ypb)	Sequence of mafic lava flows forms a marker bed 77- 15 m (253- 50 ft) thick; fine- grained, vesicular bluish- gray to greenish- gray altered basalt; subaqueous pillow structures and vent facies alternate with surface (pahoehoe) flows	Moderate	Exposure limited; if altered volcanic clay is present, may be unstable for construction	Rough surface; locally could pose walking hazard	None	None	Chlorite vesicular filling	None	None documented	None documented	Rough surface for trails; good for all uses	Precambrian lava flows and sedimentary rock; type section locality at Mt. Snowslip	Only locally exposed
MP	MP	Snowslip Formation (Ysn)	Ranges from 357.2 m to 489.5 m (1171- 1606 ft) thick; contains terrigenous green and red argillite, dolomitic argillite and muddy sandstone; some calcareous siltstone and arenite locally; mud breccia occurs in some lower beds; some beds contain calcite and dolomite cements; stromatolite beds common; beds are thin to thick, with prevalent fining upward sequences; contains the Purcell Lava	Moderate	Only in layers where calcite or dolomite cement is present; if dissolved out, rock is friable and weak	Potential rockfall hazards in cirques and cliffs	Stromatolites common in some beds	None	None	Not enough carbonate present					

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
West	East														
MP	MP	Helena Formation (Yh, Ycs)	750- 1030 m (2460- 3380 ft) thick dolomite, limestone and minor quartz arenite in conspicuous gray cliffs; stromatolites make up entire beds, some ripples, mostly parallel bedding; diorite sill 39.6 m (130 ft) thick forms obvious band on many outcrops; many "molar tooth" calcite beds, oolitic limestone and stromatolite beds present; *Baicalia-Conophyton* cyclic stromatolite marker beds stand in relief; contains the most fossil algae of all Belt rocks in park; marker bed ranges from 24 to 32 m (79- 105 ft) thick	Moderate to high	Good for most uses unless pervasive dissolution is present	Some rockfall potential where unit is present as cliff face	Unique *Conophyton-Bacalia* stromatolite cycles documented	Occasional chert may have provided tool material	"Molar tooth" calcite crystals	Caves are present in the Helena Formation in GLAC; others likely undiscovered	Limestone and dolomite for building	Vugs on cliffs may provide bird nest habitat	Good for all uses, considerable; caving interest	Unique stromatolites including important marker bed, Precambrian sedimentary rock	Only if karst is present
MP	MP	Empire Formation (Ye)	In GLAC, the unit is 122- 158 m (400- 518 ft) thick; green argillite, subordinate maroon argillite, buff and green siltstone and quartz sandstone; locally dolomitic with "molar tooth calcite" present; unit contains carbonate cement in upper beds and quartz sandstone in lower beds. Iron sulfide ooids in lowermost beds; thin to thick bedded.	Moderate	Good foundation, except in upper layers where carbonate cement may weather easily making the rock friable	Where rock is friable in upper layers, rockfalls on slopes	None	None	"Molar tooth" calcite crystals	Not enough carbonate present	None documented	None documented	Good for all uses	Precambrian sedimentary rock, "molar tooth" calcite specimens	None
MP	MP	Grinnell Formation (Ygl)	530- 790 m (1740- 2590 ft) thick; brilliant, conspicuous beds of maroon argillite and sandstone with beds of green, white, purple, and brown colored crossbedded layers locally present; generally coarse- grained and prominent in outcrop; unit is terrigenous with argillite, sandy argillite, muddy sandstone, sandstone, and quartz arenite; mud cracks, mud breccias and oolites common; east to west unit gets finer grained, less intensely colored, quartz sand; iron oxide rich beds locally present	Moderate to high	Good foundation for all uses	Rockfall potential where highly fractured and along cliffs	Some mound shaped dolomitic stromatolites	None	Mud breccias are attractive to collectors	Not enough carbonate present	None documented	None documented	Good for all uses	Precambrian sedimentary rock, some stromatolites; fine red- bed sequence, type section at Mt. Grinnell	None
MP	MP	Appekunny Formation (Yap, Yapa, Yapp)	671 m (2200 ft) thick; green, fine- grained argillite; interbeds of pale-maroon siltstone and arenite are commonly parallel to nonparallel with some cross stratification and ripple marks; shrinkage cracks present along with associated mud breccias, load structures, and calcite clots; some beds have iron sulfide; upper beds mud- rich	Low to moderate	Strong bedding with contrasting rock types in sharp contact may present structural weakness; competent enough for most uses	Rock fall and slide potential where upper part exposed	None	None	None	None	None documented	None documented	Fine for trails	Precambrian sedimentary rock; type section locality near Many Glacier	None
MP		Prichard Formation (Yapp)	About 1219 m (4000 ft) thick, thin, parallel laminae of rusty-weathered, blackish gray argillite and light- gray siltstone; carbonate, limestone, breccia, and quartz arenite occur locally; some small scale crossbedding; iron sulfide bearing beds sparsely present; some lenticular beds and limestone breccia deposits as well as occasional stromatolites dot the unit	Low to moderate	Probably okay as a foundation layer, but not if slope is present	Rock slides and slumps parallel to bedding on exposed slopes	None	None	None	Not enough carbonate present	Some pyrite and pyrrhotite locally	Exposed in lower valleys	OK for trail base	Precambrian sedimentary rock	None
	MP	Altyn and Waterton Formations (Ya, Yapa, Ywt, Yae)	238 to 256 m (780- 840 ft) thick; thin to thick beds of buff weathered dolomite, limestone, and arenite; fine- to coarse- grained; stromatolites common in cyclic units as well as desiccation cracks and herringbone lamination	Moderate	Where highly fractured & exposed (east edge of park) new construction should be avoided	Rockfall potential where exposed on slopes	Stromatolites common in lower beds	None	None	None documented; carbonate content suggests possibility	Attractive flagstone potential	Vugs on cliffs may provide bird nest habitat	OK for trails	Precambrian sedimentary rock, and stromatolites	None
		LEWIS THRUST FAULT													
CRETACEOUS (K)	UPPER K	Willow Creek Formation (Ku)	Composed of 244 m (800 ft) of variegated clayey rocks, mudstone, and sandstone with occasional limestone nodules; outcrop is reddish in color	Low to moderate	Clay rich layers might prove unstable for construction	Slump and slide potential	Fresh water mollusks and an occasional dinosaur bones	None	None	None	None documented	None documented	OK trail base	Contains the top of the Cretaceous stratigraphic column	Only locally exposed
	UPPER K	St. Mary River Formation (Ku)	Unit is 305 m (1000 ft) thick and is composed of greenish- gray mudstone interlayered with lenticular beds of fine- to medium-grained crossbedded sandstone, some red mudstone locally and thin coal beds	Low to moderate	Shaly layers may prove incompetent as foundation material for construction	Slump and slide potential	Fossils of nonmarine bivalves, such as *Fusconaia*? *stantoni*, and locally, fossil leaves; incomplete skeleton of *Montanaceratops*	None	None	None	Coal beds	None documented	OK trail base	Fossil rich	None
	UPPER K	Horsethief Sandstone (Ku)	About 27 m (90 ft) thick; composed of a massive, light- gray, fine- to coarse- grained sandstone which is commonly crossbedded and contains calcareous concretions	High	None documented	Rock fall potential where highly fractured	Brackish water bivalves *Crassostrea wyomingensis* and *Veloritina occidentalis*, the gastropod *Melania wyomingensis*, and a shallow- water marine bivalve, *Tancredia*?	Concretions may have been used for tools	None	None	Titanium bearing magnetite	None documented	Good for all uses, esp. rock climbing	None documented	None

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Potential Paleontologic Resources	Potential Cultural Resources	Mineral Specimens	Karst Issues	Mineral Resources	Habitat	Recreation Potential	Global Significance	Limits on restoration
West	East														
CRETACEOUS (K)	UPPER K	Bearpaw Shale (Ku)	Unit is 72- 122 m (235- 400 ft) thick, dark- gray marine shale interbedded with sandstone, siltstone and bentonite; sandstones are very fine- to fine- grained and thin bedded; fossil rich	Low	Swelling clays make unit poor for most development; friable shale layers are also unstable	Slump and slide potential high	Fossils of *Baculites compressus, B. coneatus*, and *B. reesidei*; ammonites *Hoploscaphites* and *Placenticeras*, and bivalves *Nucula, Nuculana, Inoceramus, Oxytoma, Cymella* and *Nymphalucina*	None	None	None	None documented	None documented	Unstable for most uses	Fossil rich	None
	UPPER K	Two Medicine Formation (Ku)	About 610 m (2000 ft) thick in GLAC area; silty, calcareous mudstone; weathers to pale greenish- gray; some calcareous concretions present locally as well as interbeds of sandstone, conglomerate and coal; conglomerate contains clasts of limestone, dolomite, quartzite, hornfels, welded volcanic tuffs and other igneous rocks	Moderate to high	Where calcareous shaly layers have weathered, slopes can be unstable for construction, if altered volcanic clays are present, unit is unstable	Slump and slide potential	Fauna include the dinosaur *Barchyceratops montanesis*, scales of ganoid fishes, ostracodes and fresh- water mollusks	Concretions may have been used for tools	None	Not enough carbonate present	Some coal beds present	Vugs on cliffs may provide bird nest habitat	OK for trails	Igneous pebbles are useful for tectonic correlation	None
	UPPER K	Virgelle Sandstone (Ku)	The unit is 49 m (160 ft) thick and consists of light- gray to white, fine- to medium- grained, partly calcareous arkosic sandstone; some cross- beds and sandstone concretions present locally	High	None documented	Rock fall potential where highly fractured	Fossils of ammonites *Desmoscaphites bassleri* and *Inoceramus lundbreckensis*	None	Some concretions	None	Titanium bearing magnetite	None documented	Good for all uses, rock climbing	Magnetite deposits useful for tectonic correlation	None
	UPPER K	Telegraph Creek Formation (Ku)	Unit is 36- 52 m (120- 170 ft) thick consisting of interbedded shale and sandstone of gray to buff color; most of the unit is very fine- grained with abundant ripple marks and some burrows	Moderate	None documented, though shale layers may be less stable	Rock fall potential where exposed	Scant mollusk fossils; Inoceramids and oysters; some wood	None	None	None	Some carbonized wood suggests coal present	None documented	Okay trail base	Some fossils present	Only exposed locally
	UPPER K	Marias River Shale (Km)	Unit is 366- 396 m (1200- 1300 ft) thick and contains dark- gray shale, with sandy, silty, pebbly, and calcareous beds and some calcareous and ferruginous concretions; marlstone, bentonite and limestone locally present	Low to moderate	Some bentonite layers present make development risky; other layers contain shale partings which are somewhat unstable	Slump and slide potential	Fossils include: *Inoceramus (Mytiloides) labiatus, Ostrea, Watinoceras reesidei, Scaphites nigricollensis, Inoceramus deofmis, Baculites mariasnsis*, and *Scaphites preventricosus*	Chert and concretions are tool material	Large calcite crystals in some concretions	Not enough carbonate present	Some coal beds present	None documented	Rather unstable unit, unsuitable for most uses	Fossils and concretions	Only locally exposed
	LOWER K	Blackleaf Formation (Kb, Kbk)	Unit is 229- 244m (750- 800 ft) thick, composed of dark- gray fissile shale and sandstone with alternating beds of light colored clastics and conglomerates; some mudstone beds are locally bentonitic and carbonaceous	Low	Swelling clays make unit poor for most development; friable shale layers are also unstable	Slump and slide potential high	Arenicolites present, some fossil plants, large logs locally	None	None	Not enough carbonate present	Coal beds and other fossil rich layers	None documented	Unstable unit, not suitable for most uses	Fossils present	Only locally exposed
	LOWER K	Kootenai Formation (Kk, Kbk)	Unit thickness is around 305 m (1000 ft); composed of variegated mudstone, siltstone and sandstone; unit is typically grayish- green in color, some pebble conglomerate locally, as well as fossiliferous limestone beds	Low to moderate	Rather friable for foundation purposes, scantly exposed	Slumping possible in clay rich beds	Bivalves *Protelliptio douglassi, P. reesidei, Lampsilis farri*; gastropods *Stantonogyra silberlingi* and questionably *Reesidella montanaensis*	Chert cobbles and pebbles are tool material	None	Not enough carbonate present	Potential reservoir rock for hydrocarbons	Vugs on cliffs may provide bird nest habitat	Good for all uses unless highly fractured	Nonmarine fossil rich coquina beds	Only locally exposed

Geologic History

The story at Glacier begins in the Proterozoic Eon (see Figure 21). Little is known about this period of earth's history. Most rocks on earth of Precambrian age are incredibly deformed and metamorphosed, losing most, if not all traces of their original structures. Glacier, however, hosts one of the most pristine Precambrian sedimentary records on earth. It is by examination of this rock record that the tectonic history of the region is revealed.

The Proterozoic rocks at Glacier are part of the Belt Supergroup. This name refers to a stack of rocks formed in the ancient Belt basin that covered large parts of Montana, Idaho, Alberta, and Washington. The Belt basin formed in response to high angle faulting and subsidence of large continental basement rock blocks, veneered by a discontinuous blanket of quartz sand. Dark quartzite, argillite, and carbonate of lower Belt formations including the Prichard, Altyn and Appekunny mark the first and most extensive spread of the great Belt lake over basement crystalline rocks (Winston 1989b).

Perhaps the most striking tectonic event during lower Belt deposition was block faulting along the Perry line, which uplifted the Dillon crustal block of the Archean Wyoming province to the south and downdropped crustal rocks to the north, forming the southern margin of the basin (figure 13). The resulting eastern indentation is called the Helena embayment and comprises an arm of the Belt basin. The Prichard, Altyn and Appekunny Formations filled the main part of the basin that extended across western Montana, northern Idaho, and into eastern Washington (Winston 1989b).

The western side of Glacier National Park has the dark gray to nearly black quartzite and argillite as well as graded arenite beds of the Prichard Formation (Winston 1989; Winston 1989b). Most of the Prichard formation is composed of subaqueous, sub- wave base, pelagic and turbidite deposits that pass to the deltaic facies in the west, reflecting sediment influx from the west of the Belt basin (Winston 1989). Interlayered carbon- poor and carbon- rich sediments indicate alternating oxygenated and anoxic, stagnant bottom conditions for the Belt basin. Paleocurrent data from western Prichard exposures indicate that the basin deepened eastward to the vicinity of the Purcell anticlorium, west of Glacier National Park, near Libby, Montana, where currents were deflected northwestward (Winston 1989b).

Simultaneously, sediments entering the eastern, more tectonically stable side of the basin, appear to be limited to coarse quartz sand, most likely reworked from the Neihart sediments. The coarse sand was mixed with carbonate mud forming the micritic limestone - sandstone mixture of the Altyn Formation, now present along the eastern side of Glacier National Park (figure 14) (Winston 1989; Winston 1989b). Micrite deposition along the eastern and northeastern margin of the basin probably reflects tectonic stability of the Archean craton to the east and south.

The Altyn is overlain by black, green and red argillite and coarse- grained arenite of the Appekunny Formation. Deposition of the siliciclastic Appekunny Formation over the Altyn Formation may reflect the filling of the Purcell trough (with sediments of the Prichard Formation) and the spreading of suspended mud from the west across the eastern part of the basin (Winston 1989).

From the relatively quiet, subaqueous, evenly layered deposits of the lower Belt formations, the upward transition into the ripplemarked, mudcracked redbeds of the Ravalli Group indicate progradation of playas and alluvial aprons from the west across the Belt basin (Winston 1989b). In other words, the advance of continental environments, as opposed to marine, broadly across the basin (figure 15). The dominantly redbed Ravalli Group is represented in Glacier National Park by the Grinnell Formation, and the green argillite unit, the Empire Formation.

The well- exposed Grinnell Formation records the intermittent emergence of subaerial shoreline in the Belt basin. The lowermost units of the Grinnell record subaqueous accumulation of sediments settling from suspension, and being partly reworked by wave oscillation. Upsection, desiccated mud, indicates exposure on extensive flats. Thin, rare beds of medium- to coarse- grained sand record ephemeral flooding across these exposed mud flats (Kuhn 1987). Periodic floods ripped up mudcracked polygons and moved them as mudchips to be deposited as unique thin conglomeratic beds. Laterally continuous silt beds, indicate sheetlike deposition over broad, flat surfaces, with occasional microlaminated beds recording submergence. The increasing amounts of coarser grained sand upsection signal the return to a prograding sandflat (Kuhn 1987). Westward thinning of the sand layers within the Grinnell indicates an eastern source terrain for medium- to coarse- grained sand in the Ravalli Group (Winston 1989).

The Empire Formation is dominated by shallow water rippled and mudcracked rocks (Winston and Lyons 1993). With deeper water facies increasing gradually upsection. The green argillite of the Empire Formation on the eastern side of the Belt basin becomes calcareous and tan weathering upsection. The upsection change from redbeds of the Grinnell Formation into greenbeds at the base of the Empire Formation signals submergence and the onset of the Middle Belt carbonate progression across the Belt basin (Winston 1989b).

The first change recorded in the Empire is water deepening and a shift from oxidizing to reducing conditions. The second dramatic change recorded in the Empire is the decline of the supply of terrigenous clastic material, from both the eastern and southwestern sources. This clastic supply was replaced by carbonate mud (Link 1993).

The Helena Formation, consisting of a thick sequence of interlayered siliciclastic and carbonate cycles, represents the eastern facies of the Middle Belt carbonate. The Helena contains deeper water sediments than the underlying Empire Formation, recording an overall transgression of the sea onto the shoreline. The sediments fine and thin eastward. This is interpreted to record periodic turbidite underflows and interflows from the west that spread out above the sub wave base floor of the Belt basin (Winston 1989) (figure 16). The sediment may have come mostly from floods that drained the western side of the basin. Along the eastern side of the basin, authigenic carbonate mud precipitation overwhelmed siliciclastic influx forming the carbonate mud sediments there. The occasional siliciclastic beds in the Helena Formation record the episodic expansion of the Belt "sea" across subjacent exposed surfaces in response to wetter climatic conditions. Erosion scoured the carbonate flats exposed as the shoreline further regressed seaward, shifting the carbonate deposition westward.

The outcrop extent of the Helena Formation is immense. Today is extends from eastern Washington to Glacier National Park, which shows that, during its maximum spread, the Belt sea had a fetch of more than 300 km, and this is not including the western edge of the basin, now lost as described earlier. This inferred basin is comparable in scale to the northern part of the modern Caspian Sea (Winston and Lyons 1993).

Above the Helena Formation is a thick sequence dominated by red argillite, pink arenite and green argillite, containing some carbonate and black argillite intervals. These rocks comprise the formations of the Missoula Group, which are from bottom to top: the Snowslip Formation, the Shepard Formation, the Mount Shields Formation, the Bonner Quartzite, and the McNamara Formation and several others not exposed at Glacier National Park (the Garnet Range Formation, and the Pilcher Formation). Major transgression and regression of the Belt sea during Missoula Group deposition resulted in four progradational sequences separated by transgressive (highstand) sequences (figure 17). The Snowslip and Mount Shields (lower beds) Formations, the Bonner Quartzite and upper McNamara Formation comprise the major progradational sequences whereas the remaining rocks comprise the transgressive (deeper water) sequences. The progradational deposits probably reflect periods of tectonic uplift in the Belt source area and a corresponding downdrop of the basin (Ackman 1988) (figure 18).

The red argillite of the Snowslip that characterizes the base of the Missoula Group passes progressively westward to green argillite, thus the westward correlative of the Snowslip becomes green and black argillite, overlain by black argillite and carbonate of the Shepard Formation correlative unit (Winston 1989). This indicates deeper water environments progressively westward in the Belt basin at the time of the initial Missoula Group deposition. The red argillite also records the regressional environment that signaled the end of Helena Formation deposition as the mudflats were exposed. Alluvial aprons of great areal extent bordered the uplifted continent southwest of the Belt basin and sloped gently into the Belt sea.

Missoula Group rocks record the changing of sea level along this alluvial apron. During lowstand conditions, the variety of shoreline environments including: 1) braided flood channels filled with cross bedded sand, 2) shallow sheetflood tracks, 3) shallow ponds with mud layers and small- scale ripplemarks, 4) exposed, desiccated mudflats, vulnerable to rip- ups during occasional floods, 5) broad sandflats, and 6) beaches, all moved progressively basinward whereas in transgressive situations, these environments retreated from the basin towards the craton.

The Snowslip Formation is representative in its record of the variety of environments present during Missoula Group Formation. From deposition on distal sandflats, exposed mudflats and submerged mudflats during shoreline transgression, to basinward progradation of the alluvial aprons (Ackman 1988; Winston 1989). Some beds contain laminated sand, sheetflood deposits, desiccation cracks and abundant mudchips, ripped up during occasional floods over the increasingly exposed apron (Ackman 1988). The Purcell Lava, which is a basalt flow (1,075 m.y.) in the Snowslip, as well as gabbroic sills and some dikes of similar age provide isotopic dating opportunities. Pillow basalts of the Purcell Lava poured out into the waters of the Belt sea and were succeeded by a regressive sequence of red microlaminated beds capped by lenses of coarse sand and larger clasts and stromatolites (figure 19) (Winston 1989).

The base of the Shepard Formation is marked by thin beds of coarse sand and larger clast sediments and stromatolites. These deposits were overlain by dark carbonaceous beds, signaling deeper water and a transgression of the great Belt sea (Winston 1989). The middle and upper parts of the Shepard are composed of calcareous varieties of sediments. During Missoula Group deposition, when terrigenous sediment was not included in carbonate deposits, this is interpreted to indicate quiet, protected environments of the Belt sea at this time, not necessarily deeper water conditions (Ackman 1988).

Carbonate mud in the northwestern part of the basin was succeeded by widespread development of microlaminated, fine- grained sediment record expansion, transgression and freshening of the Belt sea high in the Mount Shields Formation. The pink crossbedded, coarse- grained sand of the Bonner Quartzite records yet another progradational advance of the alluvial apron complex from the southwest across Montana, north into Canada. The argillite of the overlying McNamara Formation records another transgressive drowning of the alluvial aprons and advance of playa flats. A wedge of sand sediment high in the McNamara marks progradation of a final alluvial apron complex in the southern part of the basin from that direction (Winston 1989).

Rocks of Mesozoic age are not present at Glacier National Park. They were eroded from the uppermost reaches of the Belt Supergroup rocks upon uplift along the Lewis thrust fault. This missing rock record makes determining the paleoenvironment of the Mesozoic at Glacier very difficult. Geologists refer to surrounding areas to determine the history in a regional context. This report is focusing on the map units (rocks) present at Glacier National Park today. Reference texts on the history of the Rocky Mountain Region should be consulted for further information.

The Cretaceous age rocks, present in limited exposure beneath the Lewis thrust sheet and east of the fault in Glacier record a myriad of marine environments present during the intermittent progradations and regressions of the Cretaceous Interior Seaway. These units include the Kootenai, Blackleaf, Telegraph Creek, Two Medicine, St. Mary, and Willow Creek Formations, the Marias River and Bearpaw Shales, and the Horsethief and Virgelle Sandstones. The fossils contained in these rocks indicate incredible biodiversity during this time and should be protected.

During the Cretaceous- age Sevier Orogeny (about 105 to 75 Ma), great sheets of sedimentary rocks that covered miles of terrain were thrust westward from what is now western Nevada into central Utah, a distance of roughly 500 km (300 mi). The emplacement of these thrust sheets can be seen today in the mountains of Arizona, Utah, Wyoming, Montana, and Idaho. The Sevier Orogeny showed an example of *thin- skinned* thrust faulting wherein just the upper sedimentary strata of Earth's crust were transported on laterally extensive thrust planes that dip at a low angle, generally 10- 15 degrees, from the horizontal surface of Earth. In contrast, thrust faults associated with the Late Cretaceous- Early Tertiary Laramide Orogeny are *thick- skinned*, that is, they are faults with nearly vertical fault planes at the surface of Earth that flatten and sole out in Precambrian basement crystalline rock at depths up to 9,000 m (30,000 ft) below sea level (Gries, 1983; Erslev, 1993).

During the Laramide Orogeny, tectonic forces folded and faulted the entire geologic column, from Precambrian to Cretaceous age rocks, into the north-south trending Rocky Mountains and adjoining basins (Graham *et al.* 2002).

At one time, the Proterozoic Belt Supergroup and overlying rocks were buried beneath thick deposits of Cretaceous strata. Then the Laramide orogeny started. The Lewis thrust fault, though having moved intermittently for some 200 m.y., became the primary plane of movement for the massive rock column containing the Belt Terrane. This column moved eastward some 10's of miles. This changed the Glacier area, once underwater during the tenure of the interior seaway into a mountainous highland. The Laramide event transformed the extensive basin of the Cretaceous Interior Seaway into smaller interior basins bordered by high arches (anticlines and synclines on the scale of miles) (Ehrlich 1999). The Laramide Orogeny (active from about 75 to 35 Ma) is one of the more perplexing episodes in the structural history of the Rocky Mountains. The orogeny affected rocks hundreds of miles inland from the continental margin where the so-called Farallon plate was subducting beneath North America. Modern geologists have struggled with models to predict these results (Graham *et al.* 2002).

By 20 Ma, only remnants of the Farallon plate remained. 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 around 15 Ma, 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. In summary, from the Late Cretaceous to the Late Tertiary, the tectonic regime on the western margin of the North American continent changed from a steeply- dipping subduction zone to flat- plate subduction to extension caused by a growing transform fault system (Graham *et al.* 2002).

This extensional tectonic setting in Tertiary time is recorded in the array of normal faults in Glacier National Park. These include the Roosevelt, Flathead and Blacktail faults as well as many parallel faults west of the park. When one block of rock falls relative to another, the resulting graben valley forms a substantial sediment sink. Such was the case for the North Fork valley and the resulting sedimentary fill, the Tertiary Kishenehn Formation (figure 20). The Kishenehn is characterized by its variety of sediments ranging from sandstone, mudstone, limestone, and coal to volcanic ash deposits. This assortment indicates the tectono- climatic variations during the Tertiary. The volcanic ash records volcanic activity along the western margin of North America, mostly in the Cascade Mountains of Oregon and Washington.

The limestone and coal seams imply the presence intermittent ponds and restricted lakes that formed in the graben. These occur in isolated patches probably indicating a relatively dry climate. However, the abundant petrified wood specimens in the Kishenehn Formation indicate that the climate was not desert like, but wet enough to support abundant plant life.

The Quaternary Period is subdivided into two epochs: 1) the Pleistocene, which ranges 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. Huge volumes of water were stored in the glaciers during glacial periods so that sea level dropped as much as 300 feet (Fillmore, 2000). When sea level lowered, land bridges emerged such as the Bering Land Bridge that linked North America and the Eurasian continents. During interglacial periods, Earth warmed and the glaciers retreated toward the polar regions. Sea level rose and the great land masses were once again isolated (Graham *et al.* 2002).

Glaciers played a huge role in forming the landscape now present in Glacier National Park. This role is manifested in the glacial features and deposits now omnipresent in the Park. These deposits include huge terminal and lateral moraines which record the greatest glacial extent. Many of these deposits dam glacial valleys resulting in the narrow lakes so characteristic of the Park. Jumbled glacial till, esker, and outwash deposits are strewn along every valley traversed by a glacier in the Park. These impacts are described in detail in a following section.

Quaternary age rocks in Glacier are represented by the glacial deposits from the Pleistocene and Holocene and recent alluvial gravel deposits, present along Glacier's myriad of streams and rivers. Landslide and slope deposits are also prevalent in recent sediments due to the spectacular relief of the Park.

The Holocene, of course, 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 and the Great Lakes region), 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). Climate change is readily observable in the retreat of the Park's remaining glaciers. The response time of a glacier to climate change is rapid and the recent melting rate serves to substantiate the greenhouse effect hypothesis.

The Glacier Park area is experiencing significant growth in population. The Park boundaries are being inundated with the effects of development. Man- made bridges, roads and dams, such as the Hungry Horse Dam in Hungry Horse, Montana change the course of rivers and sediment deposition. Questions constantly arise about how to balance man's use of nature with its preservation.

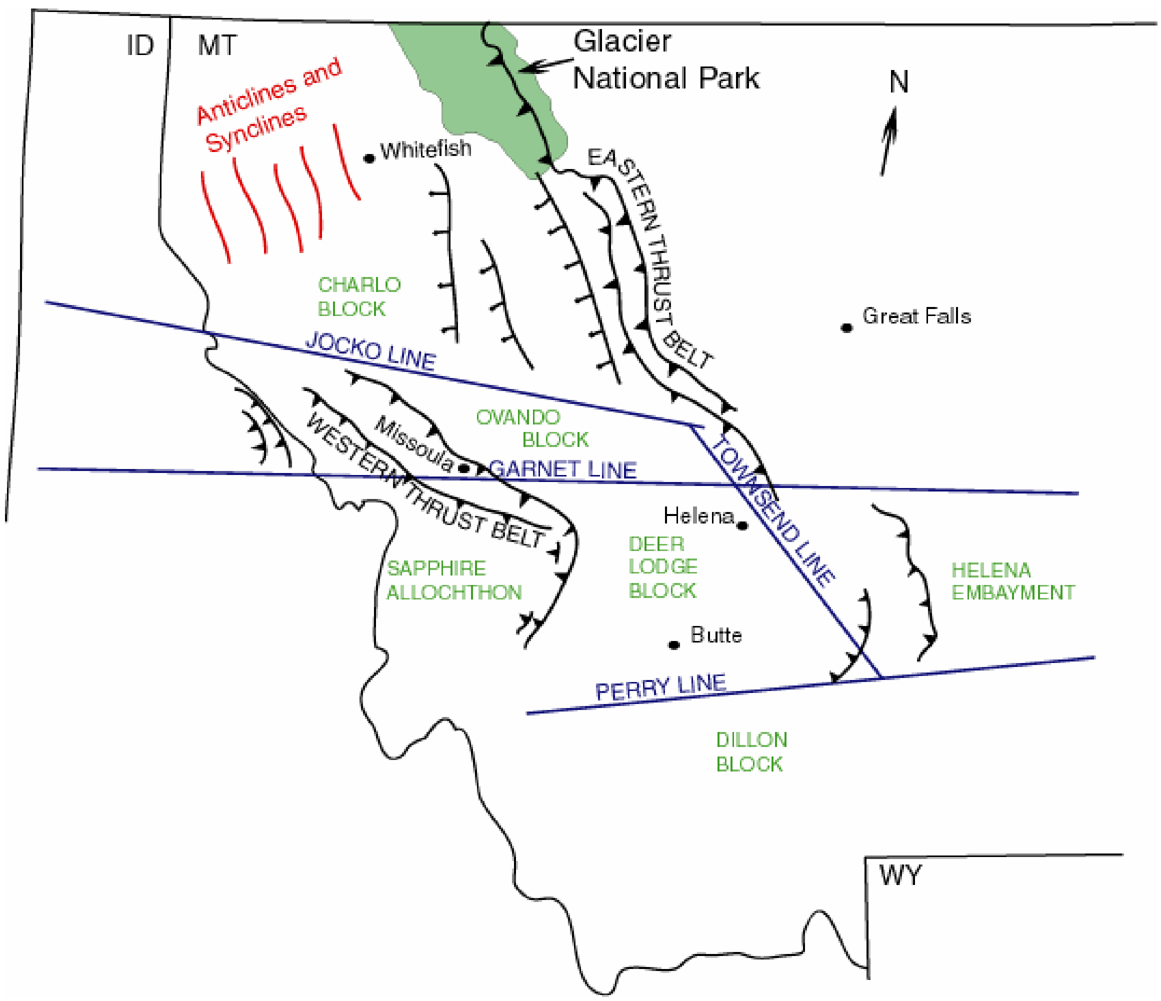

Figure 13: Map of present day structural features in the Glacier National Park area superimposed on Mid-Proterozoic fault lines (blue) with cratonic blocks labeled in green. Red lines indicate fold axes, black lines with teeth indicate thrust faults with teeth on overriding plate, black lines with bar and ball show normal faults with the symbol on the downthrown block. Adapted from Winston 1989.

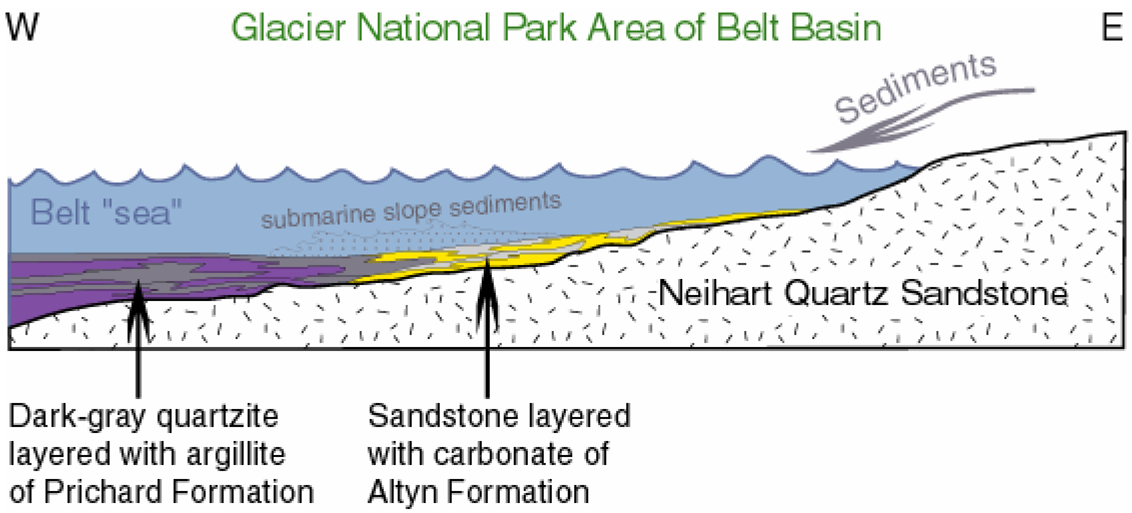

Figure 14: Depositional environment of the Prichard-Altyn Formation atop the Neihart Quartzite which acts as a sediment source.

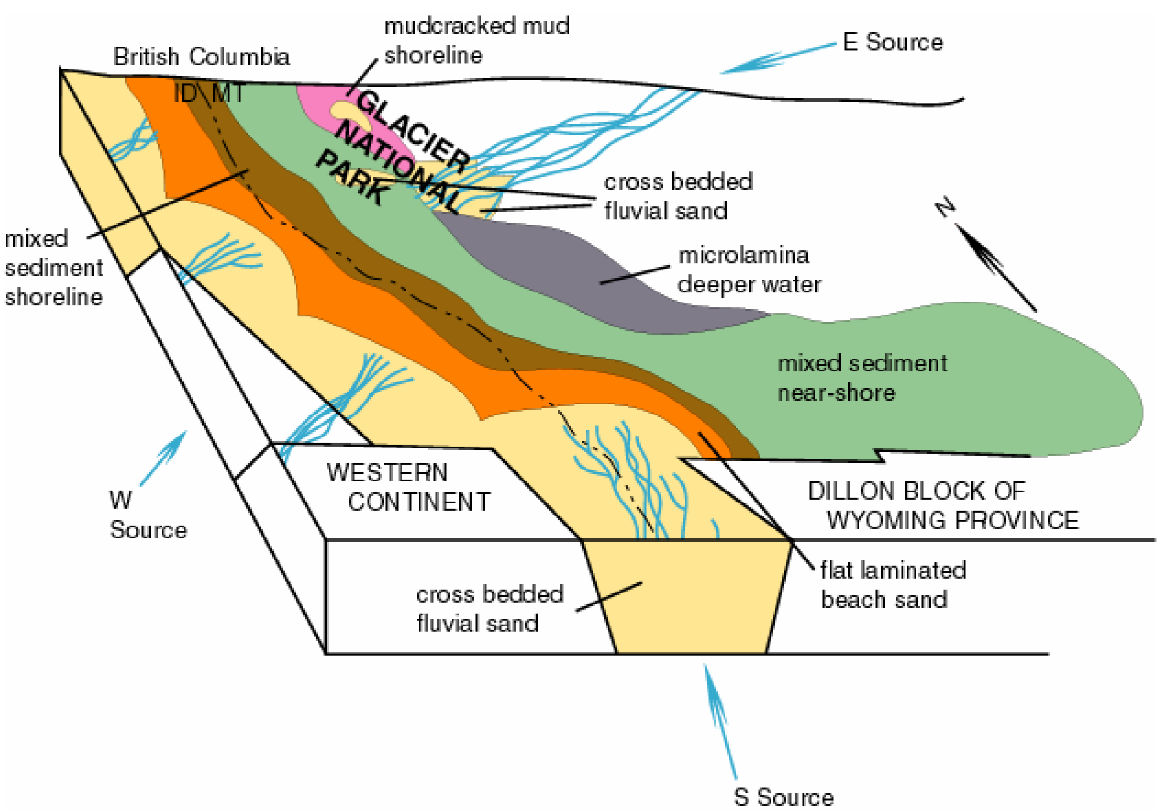

Figure 15: Conceptual depositional environment of the Ravalli Group, showing basinward progression from the western continent to the near shore and deeper water settings. Adapted from Winston 1989.

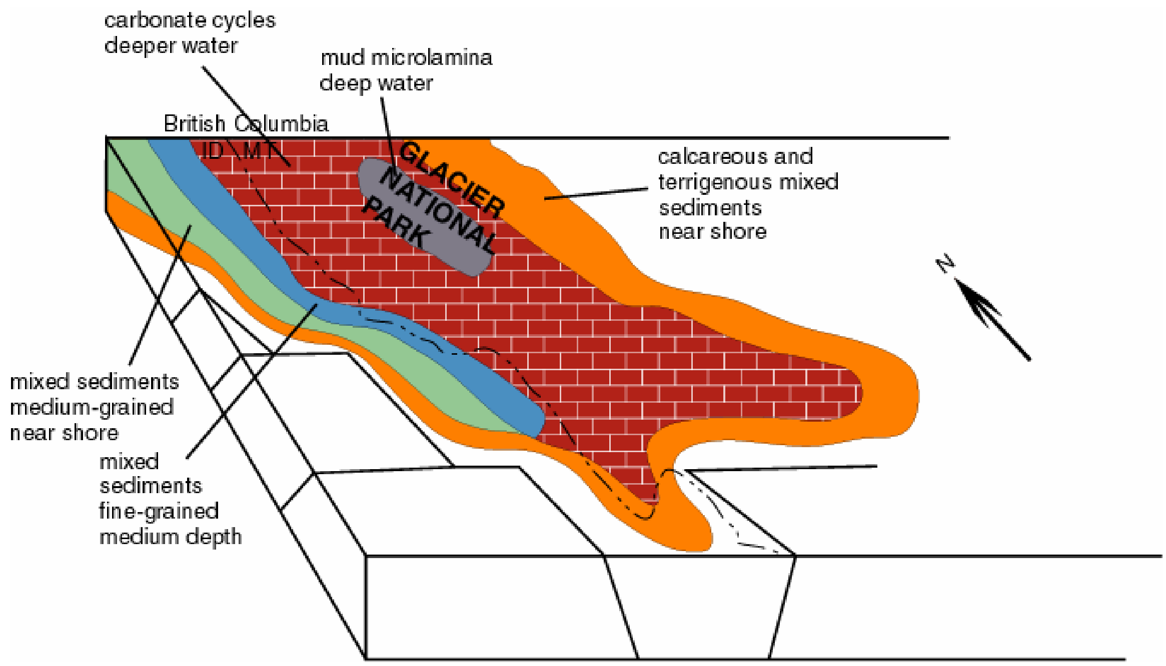

Figure 16: Middle Belt Carbonate depositional facies. Modified from Winston 1989.

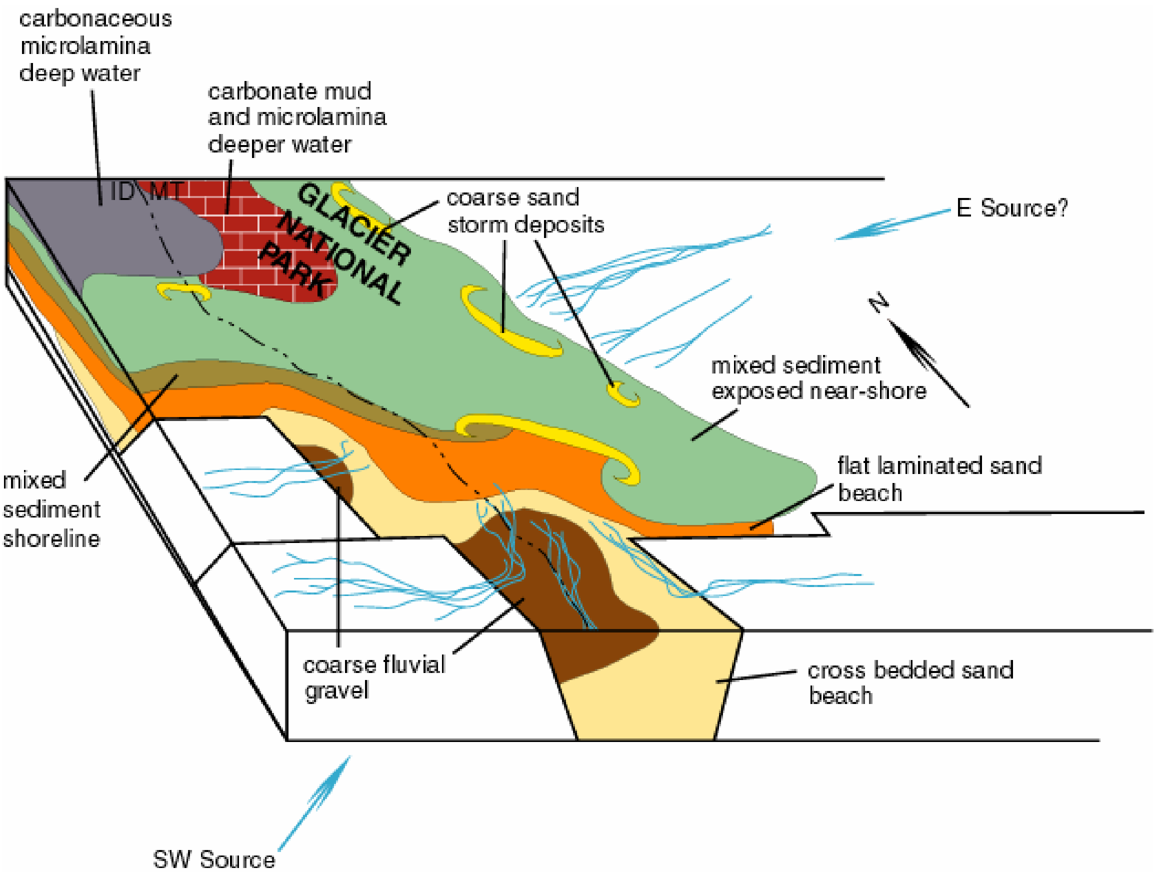

Figure 17: Conceptual depositional environment of the Missoula Group up to the Garnet Range. Deeper water facies to the northwest. Adapted from Winston 1989.

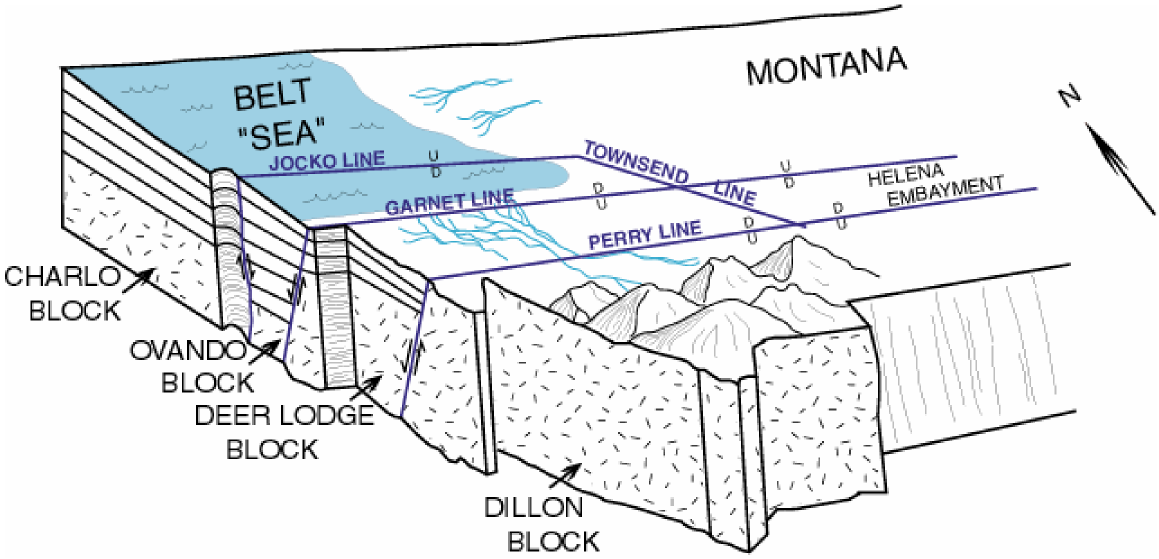

Figure 18: Showing inferred Proterozoic structure of the Belt basin during Missoula Group deposition. Note numerous faults providing means for uplift south of the basin (sediment source area). "U" indicates the uplifted side of the fault, "D", the downdropped side. Modified from Ackman 1988.

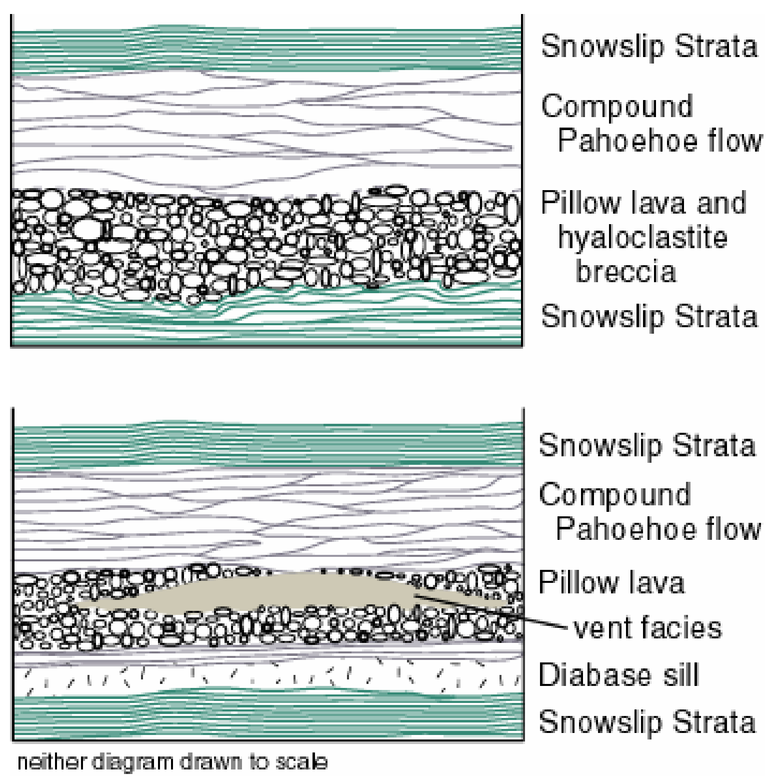

Figure 19: Subaqueous (pillow layers) and subaerial (flows) phases of Purcell Lava enclosed by Snowslip Formation strata in Glacier National Park. The lower diagram depicts the vent facies found within the Purcell Lava locally. Modified from Raup *et al.* (1997).

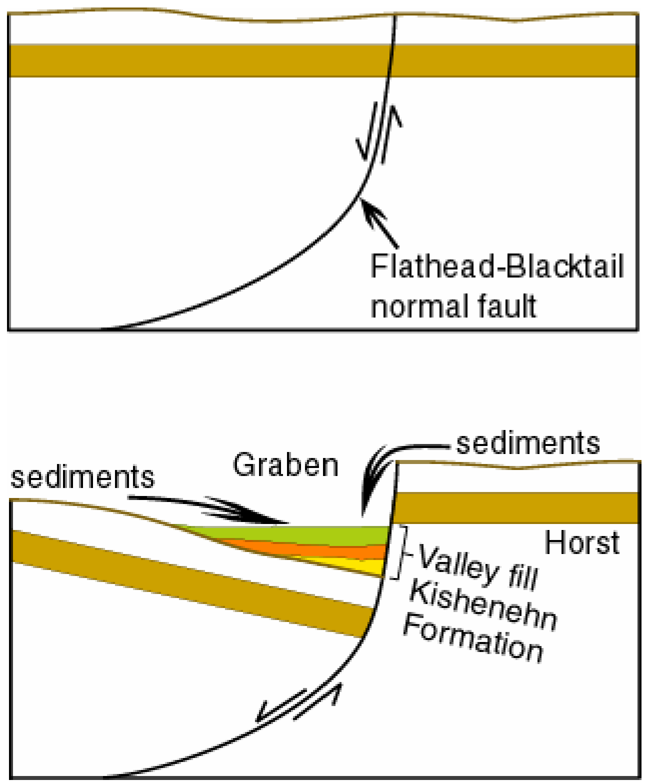

Figure 20: Deposition of the Kishenehn Formation as sediments continuously filled the graben valley of the North Fork of the Flathead River.

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

Figure 21: Geologic Time Scale; Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring North American continent. Absolute ages shown are in millions of years and are from the United States Geological Survey (USGS) time scale found at: http://geology.wr.usgs.gov/docs/usgsnps/gtime/timescale.html.

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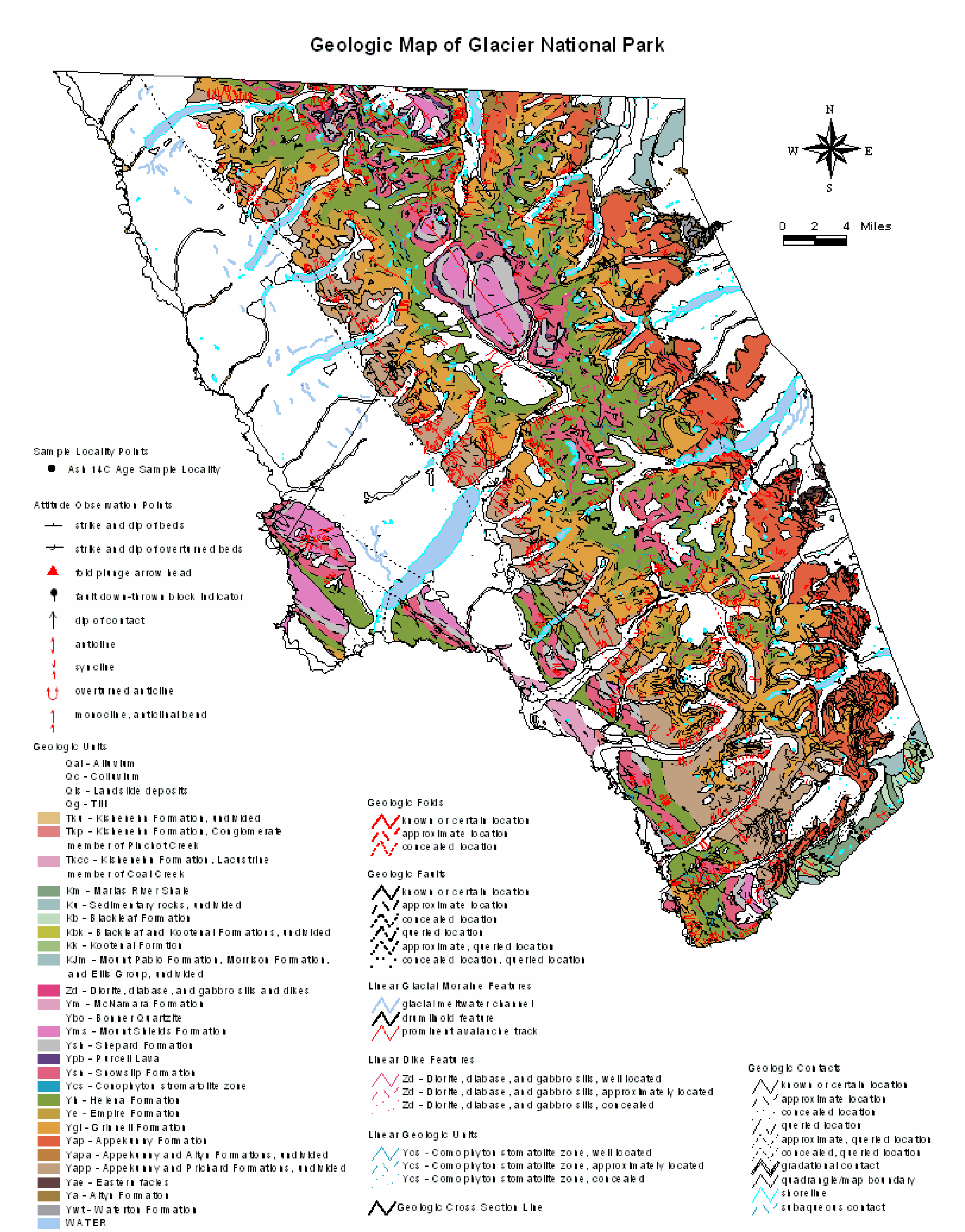
Appendix A: Geologic Map Graphic

Bedrock geologic units shown for graphic clarity, surficial geologic units and contacts are included on CD. For a detailed digital geologic map with all available coverages and cross sections produced by the GRE of the parks see included CD.



The original maps digitized by NPS staff to create this product were: Carrara, P.E., 1990, Surficial geologic map of Glacier National Park, Montana, U.S. Geological Survey, I-1508-D, 1:100000 scale, and Whipple, James W., 1992, Geologic map of Glacier National Park, Montana, U.S. Geological Survey, I-1508-F, 1:100000 scale. For a detailed digital geologic map and cross sections, see included CD.

Appendix B: Scoping Summary

The following excerpts are from the GRE Workshop Summary for Glacier National Park. This summary is included as a historical document and as such contact information and web addresses referred to herein may be outdated.

Executive Summary

A geologic resources inventory workshop was held for Glacier NP (GLAC) on August 20- 22, 2002 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), NPS Glacier NP, the Montana Bureau of Mines and Technology, the Canadian Geological Survey, Parks Canada and other academics were present for the workshop.

This involved a field trip to view the geology of the Glacier NP area and a scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the Geologic Resources Division, and the on- going Geologic Resources Evaluation (GRE). Round table discussions involving geologic issues for Glacier NP included interpretation, the status of geologic mapping efforts, sources of available data, and action items generated from this meeting.

Currently, some of the biggest geologic issues the park faces are retreat of its glaciers (it's estimated that they will all be melted by 2030) and landslides and geologic hazards along Going to the Sun Road.

Overview of Geologic Resources Evaluation

The NPS GRE has the following goals:

- to assemble a bibliography of associated geological resources for NPS units with significant natural resources ("GRBIB") to compile and evaluate a list of existing geologic maps for each unit,
- to conduct a scoping session for each park,
- to develop digital geologic map products, and
- to complete a geological report that synthesizes much of the existing geologic knowledge about each park.

It is stressed that the emphasis of the inventory is *not* to routinely initiate new geologic mapping projects, but to aggregate existing "baseline" information and identify where serious geologic data needs and issues exist in the National Park System. In cases where map coverage is nearly complete (ex. 4 of 5 quadrangles for Park "X") or maps simply do not exist, then funding may be available for geologic mapping.

After introductions by the participants, Tim Connors and Bruce Heise (both NPS- GRD) presented overviews of the Geologic Resources Division, the NPS I&M Program, the status of the natural resource inventories, and the GRE in particular.

They also presented a demonstration of some of the main features of the GRE digital geologic database. This has become the prototype for the NPS digital geologic map model as it reproduces all aspects of a paper map (i.e. it incorporates the map notes, cross sections, legend etc.) with the added benefit of being geospatially referenced. It is displayed in ESRI ArcView shape files and features a built- in Microsoft Windows help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the paper "analog" map. Geologic cross section lines (ex. A- A') are subsequently digitized as a line coverage and are hyperlinks to the scanned images.

Tim further demonstrated the developing NPS Theme Manager for adding GIS coverage's into projects "on- the- fly". With this functional browser, numerous NPS themes can be added to an ArcView project with relative ease. Such themes might include geology, paleontology, hypsography (topographic contours), vegetation, soils, etc.

At the scoping session, individual Microsoft Word Documents of Geologic Bibliographies for GLAC were distributed.

The sources for this compiled information are as follows:

- AGI (American Geological Institute) GeoRef
- USGS GeoIndex
- ProCite information taken from specific park libraries

These bibliographic compilations were validated by GRE staff to eliminate duplicate citations and typographical errors, as well as to check for applicability to the specific park. After validation, they become part of a Microsoft Access database parsed into columns based on park, author, year of publication, title, publisher, publication number, and a miscellaneous column for notes.

From the Access database, they are exported as Microsoft Word Documents for easier readability, and eventually turned into PDF documents.

Geologic Mapping

After the bibliographies were assembled, a separate search was made for any existing surficial and bedrock geologic maps for GLAC. The bounding coordinates for each map were noted and entered into a GIS to assemble an index geologic map. Separate coverage's were developed based on scales (*1:24,000, 1:100,000*, etc.) available for the specific park. Numerous geologic maps at varying scales and vintages cover the area. Index maps were distributed to each workshop participant during the scoping session.

At present, the USGS has produced numerous publications on the Geology of Glacier NP. Their I- 1508 map series has both bedrock (Whipple, J.W., 1992, Geologic map of Glacier National Park, Montana, US Geological Survey, I- 1508- F, 1:100000 scale) and surficial (Carrara, P.E., 1990, Surficial geologic map of Glacier National Park, Montana, US Geological Survey, I- 1508- D, 1:100000 scale) geologic paper maps covering the current park boundary.

The general consensus of those cooperators at the meeting was that these existing maps were quite adequate for resource management purposes.

Suggested improvements included upgrading a layer showing geologic hazards and landslides, as well as further refinement of a few surficial units.

Digital Geologic Map coverage

The GLAC GIS staff has obtained completed digital geologic coverages for the two maps mentioned above along with FGDC compliant metadata. Tim Connors previewed this data to the group and Richard Menicke also showed an image of the geology draped over a shaded relief map to illustrate the bedrock control on the topography.Apparently, these maps were digitized out of North Carolina State University. They captured geologic polygons on both maps, but excluded other coverages from the bedrock map such as folds, faults, contact line types, cross sections, etc. It will be likely that GRE staff will have to re- digitize these maps to capture this other necessary attribute data, but we will try to work with the existing linework and match it up to the original attributes on paper as best as possible.

These coverages are currently downloadable from: http://www.nps.gov/gis/available_data

Other desired GIS data

Soils maps are also of interest to GLAC staff. Tim Connors will check with Pete Biggam (NPS- Soil Scientist) on the status of soils mapping for the area; will require more follow- up.

Miscellaneous

Another bibliography was distributed by David Butler to some meeting attendees; needs to be compared and synthesized into our GRBIB

List of Scoping Meeting attendees with contact information

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Appendix C: Geoindicators Scoping Report

The following are excerpts of the Geoindicators Scoping Report for Glaciers National Park, compiled by Katie KellerLynn, 2002. This summary is included as a historical document and as such contact information and web addresses referred to herein may be outdated.

Introduction

The National Park Service, Parks Canada, U.S. Geological Survey, and International Union of Geological Sciences sponsored a geoindicators scoping meeting in Waterton- Glacier International Peace Park in West Glacier, Montana on August 20- 22, 2002.

Purpose of meeting

The purpose of the meeting was threefold: (1) to identify significant geological processes and features that are part of the park's ecosystem, (2) to evaluate human influences on those processes and features, and (3) to provide recommendations for studies to support resource management decisions, geologic inventory and monitoring projects, and research to fill data gaps. The scoping meeting was designed to use the participants' expertise and institutional knowledge and build on the synergy of the participants through field observations, group discussion, and the exchange of ideas.

Government Performance and Results Act (GRPA) Goal Ib4

This meeting satisfies the requirements of the GPRA Goal Ib4, which is a knowledge- based goal that states, "Geological processes in 53 parks [20% of 265 parks] are inventoried and human influences that affect those processes are identified." The goal was designed to improve park managers' capabilities to make informed, science- based decisions with regards to geologic resources. It is the intention of the goal to be the first step in a process that will eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features, or cause critical imbalance in the ecosystem.

Because GPRA Goal Ib4 inventories only a sampling of parks, information gathered at Waterton- Glacier International Peace Park may be used to represent other parks with similar resources or human influences on those resources, especially when findings are evaluated for Servicewide implications.

Geoindicators background information

A Working Group of the International Union of Geological Sciences developed geoindicators as an approach for identifying rapid changes in the natural environment.

The National Park Service uses geoindicators during scoping meetings as a tool to fulfill GPRA Goal Ib4. Geoindicators are measurable, quantifiable tools for assessing rapid changes in earth system processes.

Geoindicators evaluate 27 earth system processes and phenomena that may undergo significant change in magnitude, frequency, trend, or rates over periods of 100 years or less and may be affected by human actions. Geoindicators are used as a framework to guide the discussion and field observations during scoping meetings. The geoindicators scoping process for the National Park Service was developed to help determine the studies necessary to answer management questions about what is happening to the environment, why it is happening, and whether it is significant.

The health and stability of an ecosystem is evaluated during the geoindicators scoping process. The geologic resources of a park—soils, caves, streams, springs, beaches, volcanoes, etc.—provide the physical foundation required to sustain the biological system. Geological processes create topographic highs and lows; affect water and soil chemistries; influence soil fertility, hillslope stability, and the flow styles of surface water and groundwater. These factors, in turn, determine where and when biological processes occur, such as the timing of species reproduction, the distribution of habitats, the productivity and type of vegetation, and the response of ecosystems to human impacts.

Park Selection

The idea to hold a geoindicators scoping meeting in Waterton- Glacier International Peace Park developed at the "International Workshop on Geoindicators for Ecosystem Monitoring in Parks and Protected Areas" in Gros Morne National Park, Newfoundland, Canada on September 10- 14, 2001. The desire for continued collaboration between the National Park Service and Parks Canada, in particular, made hosting a meeting in the Peace Park an ideal location. In addition the park was selected for is its unique geologic resources, park setting, and human use.

It is important to note that 95% of Glacier National Park is proposed wilderness, and over 80% of Waterton Lakes National Park has been recommended for wilderness declaration.

The remaining small percentage of land—that is, the developed corridors along the Going- to- the- Sun Road, all roads and part of Blakiston Fan in Waterton Lakes, and established townsites—is where park staff focuses much of their energy and resources on managing the effects of human activities.

Summary of Results

During the scoping meeting, geoindicators appropriate to Waterton- Glacier International Peace Park were addressed. Of the 27 geoindicators, 21 were recognized as on- going processes in the park. The issues surrounding each geoindicator were identified, and participants rated the geoindicator with respect to the importance to the ecosystem and human influence (Geoindicator table). The park staff rated the significance for park management. A compilation of the notes taken during the scoping session and field trip are included with the report. These notes highlight additional information regarding geoindicators that may be useful to park managers.

Significant geoindicators

The following is a summary of the results for the 11 geoindicators that rated the highest in all three categories, as well as the recommendations for these geoindicators that were proposed during the meeting.

Snow Avalanches

Snow avalanches are ubiquitous throughout the park; they are a major landscape disturbance that shapes the park's ecosystem. Snow- avalanche tracks have great importance to the ecosystem; they are: productive environments, key habitat that serve as migration paths for grizzly and mountain goats, fuel breaks for fire, conduits for carbon and sediment from higher to lower elevations, including streams.

Human impacts
Snow avalanches are a public safety issue, particularly for winter backcountry users. Park staff spends a considerable amount of time forecasting snow avalanches. Snow- avalanche hazards are a factor in determining the opening date of the Going- to- the- Sun Road and may influence the clearing of Akamina Parkway through the winter months. Snow avalanches are also significant to management as creators of wildlife habitat, particularly grizzly bear, a threatened species in the United States.

Soil and sediment erosion

Soil erosion is part of the natural system in Waterton- Glacier International Peace Park. Concerns arise for ecosystem health when effects of soil and sediment erosion are human- caused and detrimental, such as soil erosion resulting from poor design and construction of facilities and infrastructure. Estimates of soil erosion are essential to issues of land and water management and to ecosystem health and function.

Human impacts
Management issues include construction projects that result in pulses of sediment carried downstream. For example, sediment resulting from the construction of the Going- to- the- Sun Road can be seen in the sediment column in McDonald Creek and in Lake McDonald. Reclamation of soils degraded by human actions is of high management significance.

Soil quality

Concerns regarding soil quality in the park include: breakdown of soil structure, loss of function, harm to soil biota, regional acid deposition, nitrate deposition (from urban pollution and fertilizers), and airborne-mercury deposition from power plant emissions.

Human Impacts
Park managers spend time and resources dealing with soil quality and restoration issues, particularly because of the human impacts in developed areas, such as social trails and trail maintenance; borrow pits (historically became garbage pits, which attracted bears); horse use (primarily a legacy issue); popular lakes with multiple entry points; locating and constructing park facilities, e.g., Logan Pass Visitor Center; depletion of soils along roadsides, which causes greater amount of noxious weeds; plowing which causes soil compaction and depletion along roadsides; and salt and petrochemical runoff from roads.

Streamflow

Streamflow affects riparian zones and wetlands in the park. Streamflow directly reflects climatic variation. Stream systems play a key role in the regulation and maintenance of biodiversity. Changes in streams and streamflow are indicators of changes in basin dynamics and land use.

Human impacts
The potential for human impact to stream sediment erosion, storage, and load is great. These impacts include building parking lots and structures in or near channels, building structures (e.g., culverts and bridges) in floodplains, grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Wetlands extent, structure, and hydrology

Waterton- Glacier International Peace Park has many different kinds of wetlands, including fens, bogs, nutrified lakes, and swamps. Glacial retreat has influenced wetlands. Wetlands in the park are extremely dynamic, and nearly all species of wildlife rely on wetlands in one way or another.

Human impacts
In the United States, law mandates that land managers always consider wetlands in management decisions. In Canada, it is not legally mandated, but managers recognize the significance of wetlands and the potential impact of human uses on them.

Surface water quality

In addition to being a public health issue, surface water quality is an essential component of ecosystem health. All forms of life depend on clean water. Waterton- Glacier International Peace Park sits at the headwaters of the Waterton and Belly rivers. Since water quality exceeds standards, the surface water quality geoindicator is a good indicator of change, and minor changes are easily detectable.

Human impacts
Human practices that affect surface water quality include herbicide and pesticide applications, e.g., for eradicating knapweed. Locations of campgrounds, lodges, roads, and other facilities and infrastructure in sensitive floodplain and stream delta areas have produced runoff that impacts fragile invertebrate communities in streams. Localized situations, such as boating on St. Mary Lake and Upper and Middle Waterton Lake, have resulted in diesel fuel spills. For instance, during a high wind event, a barge capsized on St. Mary Lake spilling 50 gallons of diesel fuel.

Wetlands extent, structure, and hydrology

Wetlands are important ecosystems because they stabilize streambanks, act as filters to improve water quality, attenuate floodwaters, enhance biodiversity (important habitat for amphibians, reptiles, birds, and Threatened and Endangered Species), are highly productive in terms of biomass and nutrient productivity, and are valuable water sources for wildlife and recreationists.

Human impacts
The potential for human impacts on wetlands is great. These impacts include building parking lots and structures in or near channels, building structures (e.g., culverts and bridges) in floodplains, grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion. In addition, agricultural activities and past extirpation of beaver have affected wetlands.

Groundwater quality

Management concerns revolve around human influences on groundwater quality, such as the effects of sewage treatment, inholders' septic systems, salt application to roads (in Waterton Lakes National Park only), road runoff, pesticides, gasoline leaks from underground storage tanks (e.g., in Apgar), and service stations in the park.

Slope failure

Slumping along Many Glacier Road is a continuing maintenance issue. Not only does the road undercut the slope, but water from adjacent Lake Sherburne saturates and weakens the slope. Slumping along Blakiston Creek is a concern along parts of the Red Rock Parkway. Also, a pending question with respect to climate change and slope failure is whether increased rainfall events will cause more landslides.

Sediment sequence and composition

One geoindicator in particular was singled out and warrants mention. Unlike the other geoindicators, sediment sequence and composition is not a geological process, but rather a tool with great significance for enhancing the information base of the park's ecosystem, identifying human influences on the ecosystem, and providing data for resource management decisions and planning. It provides the necessary background information and a past context of both natural processes and human activities. The chemical, physical, and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguished from human inputs.

Soil and sediment erosion and deposition by water

During the discussion of this geoindicator, participants chose to focus on water transport and deposition, therefore the words, "and deposition by water" were added to this geoindicator. Transport and/or loss of soil may result in degradation of soil quality (see Soil quality geoindicator).

Summary of Recommendations

The following summary of recommendations lists ideas that were discussed during the August 20- 22, 2002 scoping meeting held in Waterton- Glacier International Peace Park. The summary includes recommendations for inventory and monitoring, as well as research. Recommendations are not listed in any order of priority.

Inventory and monitor wetlands

There are many different kinds of wetlands in the park: fens, bogs, nutrified lakes, swamps, etc. Park managers need more accurate and consistent descriptions of these wetlands. The first step toward an inventory would be to validate the classification of the Fish and Wildlife Service and refine its delineation. Once sites have been identified, historical aerial photographs (in sequence) followed by ground- truthing could be used to verify and characterize the sites. The inventory could be supplemented by remote sensing, although remote sensing can be expensive and the tree canopy may hide some wetlands.

Monitoring is needed to determine future changes in wetlands. If significant changes are detected, then research will be required to determine the cause(s). Monitoring of wetlands could be multi- faceted, including vascular plants and water chemistry. Wetland studies suggest opportunities for integrated research and collaboration. Paleoecological methods can be used to date peat and/or sediments to determine the hydrological succession of wetlands.

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Provide groundwater data to Montana Bureau of Mines and Geology

The Montana Bureau of Mines and Geology has a statewide groundwater program. Park staff is welcome to share/submit data to Montana Bureau of Mines and Geology for entry into the Bureau's Ground- Water Information Center (GWIC) database. Information in the database is available via the Bureau's GWIC Web site at http://mbmggwic.mtech.edu/. High mountain areas, such as those in the park, typically do not have many wells, so information for these areas is limited.

Contact
Tom Patton, Manager, Ground Water Assessment Program, 406- 496- 4153, tpatton@mtech.edu or directly access the database

Verify soil survey

Both Waterton Lakes National Park and Glacier National Park have soil surveys but need a consistent interpretation of soil classification, derivative products, and sampling to characterize locales (e.g., along road corridors).

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Monitor change in soil carbon storage

Participants recommend that park managers monitor changes in carbon storage once every 5 to 10 years, by measuring the organic carbon in surface soil layer(s) through sampling and then resampling at the same locations. The use of Douglas fir, which is very sensitive to CO_2, can be used as an indicator species and as an early warning of detrimental changes in the ecosystem. See Appendix I for corresponding proposal.

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References

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White, J.D., Running, S.W., Thornton, P.E., Keane, R.E., Ryan, K.C., Fagre, D.B., and Key, C.H., 1998, Assessing simulated ecosystem processes for climate variability at Glacier National Park, USA: Ecological Applications, v. 8, no. 3, p. 805- 823.

White, J.D. and Running, S.W., 1994, Testing scale- dependent assumptions in regional ecosystem simulations: Journal of Vegetation Science, v. 5, no. 5, p. 687- 702.

Sources of information on the Web
http://www.forestry.umt.edu/ntsg/
Web site of work done by Steve Running on carbon and climate change

Monitor streamflow and seek secure funding

The park needs basic monitoring of streamflow in the interior of park. Secure funding is needed. Participants recommend that park managers pursue a partnership with U.S. Geological Survey. The NPS Water Resources Division can assist with defining needs including monitoring locations, number of monitoring stations needed, and cost. Redwood National and State Park has an established partnership with U.S. Geological Survey for monitoring gauging stations and could serve as a model.

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Repeat survey of lakes

A survey of baseline water quality data for lakes needs to be repeated.

Contact
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Use aerial photography to document changes and features in the landscape

Use repeat aerial photography to document the change in snow- avalanche paths (extent, location) over time and document features caused by slope failure. Scan past aerial photographs, contained in park archives, to use for analysis and interpretation of future slope failure in a digital format.

Add seismic station(s) within park boundary

A seismic monitoring program run by Montana Bureau of Mines and Geology (MBMG) currently has 34 stations, mostly in the western part of Montana. Additionally, they receive data from stations in bordering areas, including a station in Waterton Lakes National Park. The latter, in conjunction with other stations that they operate, allows MBMG to locate earthquakes in the vicinity of the park, but resolution is poor and the smaller earthquakes go undetected. Much better detection and resolution could be obtained with 1 or 2 additional stations inside the park. MBMG data feed into the national U.S. Geological Survey system in Colorado. Detected quakes are automatically analyzed and information is posted on MBMG's Web site within minutes: http://mbmgquake.mtech.edu/. Each station costs $15,000- $25,000 plus nominal upkeep of the station.

Contact
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Monitor dust storms as part of air quality monitoring

Dust storms may be a factor in the decline of air quality and visibility in Waterton- Glacier International Peace Park. If air quality declines, an analysis of particles (size and composition) would help determine source area(s). It would assist in answering the question, What impact are western Washington's agricultural practices having on the park? This type of data collection is being conducted in Olympic National Park.

Inventory cave resources

Park managers in Glacier National Park have basic information, e.g., number and location, about the significant caves within its boundaries, but do not have information on cave resources or whether conditions within the caves are changing. Local cavers could be used to perform an inventory, specifically there is a "grotto" (cavers group of the National Speleological Society) in Missoula. Such groups have the necessary expertise to perform such an inventory and have been known to provide this service for free.

Contact
Ron Kerbo, Cave Specialist, NPS Geologic Resources Division, 303- 969- 2097, ron_kerbo@nps.gov

Study wind erosion on an ecosystem-wide scale

How significant overall is the wind as an erosion- causing agent? What ecosystem- wide impact does wind erosion have? In order to answer these questions, wind erosion would need to be identified and separated from impacts caused by other forms of erosion, including human-caused erosion. Once these impacts are identified, site-specific inventories could be performed using repeat photography and Global Positioning System (GPS) surveys.

Inventory stream channels

Natural Resources Conservation Service (NRCS) in Montana is photographing stream reaches using digital video camcorder (with GPS and Red Hen software systems). The effort was initiated for fisheries and riparian management, but information could be extrapolated and used for stream channel morphology and stream sediment storage and load.

Contact
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Monitor mass balance of glaciers

Knowledge of seasonal mass balances (e.g., summer and winter) would shed light on glacier fluctuations in Waterton- Glacier International Peace Park. For example, it would help answer questions such as: Is glacier contraction caused primarily by less nourishment in winter or by more melt in summer? Monitoring of mass balance would also assist in the interpretation of streamflow records.

Having a glacier mass balance site at the longitude of Waterton- Glacier International Peace Park would make an excellent contribution to the Global Terrestrial Network- Glacier (GTN- G) of World Meteorological Organization's (WMO) Global Climate Observing Network (GCOS). A site this far south may provide a good analog for what could be expected further north in the Canadian Rocky Mountains over the next century with respect to global climate change. In addition, Waterton- Glacier International Peace Park could be part of the Global Terrestrial Observing Systems (GTOS), Terrestrial Monitoring System (TEMS).

Contact
Michael N. Demuth, 613- 996- 0235, mdemuth@nrcan.gc.ca

Create "lake ice model"

Information about lake ice (annual first thaw and first freeze) would provide data regarding climate change and serve as an early- warning indicator of change. It is also significant for the arrival of migrating waterfowl. Creating a "lake ice model" could be done using existing meteorological data and information from past issues of the Hungry Horse newspaper, which records years that the large lakes in the area have frozen over.

Contact
Dan Fagre, 406- 888- 7922, dan_fagre@usgs.gov

Determine whether small lakes are being filled in with sediment

Radiometric dating techniques could be used to address the question of whether the small lakes in the park are being filled in with sediment.

Contact

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Update surficial geologic map

The surficial geologic map of Glacier National Park needs to be updated. The current map does not show all of the locations of snow- avalanche paths, all the areas of landsliding, or all the lake deposits. A coordinated mapping effort between Glacier National Park and Waterton Lakes National Park is recommended for consistency across the Canadian- United States boundary.

Once this map is updated, a derivative map that shows landslide- hazard areas could be produced that would provide needed information to park managers.

Reference

Carrara, P.E., 1990, Surficial geologic map of Glacier National Park, Montana: U.S. Geological Survey Miscellaneous Investigation Series, No. I- 1508- D, 1:100,000.

Conduct snow-avalanche studies

The significance of snow avalanches on the park's ecosystem and for park management was discussed previously. Having more information regarding the frequency, cycles, and locations of snow avalanches would be useful to park managers. Park managers are encouraged to seek funding through the NPS Geoscientist- in- the- Parks program. Possible projects include:

Develop frequency of event analysis and historical record (e.g., from Waterton townsite record). Some attempt as this has been made using tree rings.

Compare east and west side cycles of snow avalanches.

Establish landscape- level disturbance agent and look at drivers. Check against Pacific Decadal Oscillation climatic variations and see if it is tied to the response of snow avalanches.

Answer questions such as, Does snowfall level influence frequency? How much woody debris do snow avalanches deliver to the Highway 2 corridor? What is the relative amount of woody debris vs. rock material in snow avalanches?

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Answer research questions regarding slope failure

What is the relative importance of mass movement vs. stream transport? Will an increase in rain events cause more landslides?

Reference

Rapp, A., 1960, Recent development of mountain slopes in Karkevagge and surrounding northern Scandinavia: Geografisk Annaler, v. 42, p. 73- 200.

Answer research questions regarding wetlands

What is the effect of fire on wetlands? Where and to what extent do wetlands exist from year to year? What are past impacts of glacier fluctuations on wetlands?

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Hansen, H.P., 1948, Postglacial forests of the Glacier National Park region: Ecology, v. 29, p. 146- 152.

Elias, S.A., 1988, Climatic significance of Late Pleistocene insect fossils from Marias Pass, Montana: Canadian Journal of Earth Sciences, v. 25, p. 922- 926.

Carrara, P.E., 1995, A 12,000 year radiocarbon date of deglaciation from the Continental Divide of northwestern Montana: Canadian Journal of Earth Sciences, v. 32, p. 1203- 1307.

Carrara, P.E., 1989, Late Quaternary glacial and vegetative history of the Glacier National Park region, Montana: U. S. Geological Survey Bulletin 1902, 64 p.

Other recommendations

Recommend that the Vital Signs Network hire a soil scientist. Many of the natural resources staff members in Glacier National Park have strong backgrounds in plant ecology and work with the Natural Resource Conservation Service (NRCS). However, there is a need for expertise in soil science. Hiring a soil scientist would be extremely difficult at the park- level because of budgetary constraints, so the participants suggest that park staff encourage the Rocky Mountain Vital Signs Network to hire a soil scientist that could be shared with the other parks in the network.

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Geoindicator table for Glacier National Park.

GEOINDICATOR	Importance to park ecosystem	Human influence on geology	Significance for natural resource management
AEOLIAN			
Dust storm magnitude, duration, and frequency	2	1	1
Wind erosion (transport and deposition)	3	3	4
GLACIAL & PERIGLACIAL			
Frozen ground activity	2	1	1
Glacier fluctuations	4	N/A	2
GROUNDWATER			
Groundwater chemistry in the unsaturated zone	1	1 (3 locally)	3
Groundwater quality	4	1 (5 locally)	3
Groundwater level	4	1	2
SURFACE WATER			
Lake levels and salinity (including lake ice)	2	1	3
Stream channel morphology	4	2 (4 locally)	4
Stream sediment storage and load	4	2 (4 locally)	4
Streamflow	5	1	3
Surface water quality	5	1 (5 locally)	3
Wetlands extent, structure, hydrology	5	2 (4 locally)	5
SOILS			
Soil quality	5	2 (4 locally)	5
Soil and sediment erosion	5	2 (4 locally)	5
TECTONICS & GRAVITY			
Seismicity	1	N/A	1
Slope failure	4	1	5
Snow avalanches	5	1	5
OTHER			
Karst activity	1	U	2
*Sediment sequence and composition	5*	5*	5*
Subsurface temperature regime	U	U	U
N/A - Not Applicable 1 - LOW or no substantial influence on, or utility for 3 - MODERATELY influenced by, or has some utility for 5 - HIGHLY influenced by, or with important utility for U - Unknown; may require study to determine applicability	*Sediment sequences and composition is a tool with great significance for enhancing the information base of the park's ecosystem, identifying human influences on the ecosystem, and providing data for management decisions and planning.		

Glacier National Park

Geologic Resource Evaluation Report
NPS D450, August 2004

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The Geologic Resources Division, in partnership with parks and others, works to protect, preserve, and understand the geologic resources of the National Park System and to protect park resources from the adverse affects of mineral development in and adjacent to parks. One of the functions of the Division, carried out in the Planning Evaluation and Permits Branch is the Geologic Resource Evaluation Program. This program develops digitized geologic maps, reports, and bibliographies for parks.

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The *Geologic Resource Evaluation Report for Glacier National Park* is published electronically on the World Wide Web, please see www2.nature.nps.gov/geology/inventory/reports. For a printed copy write to:

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