

# Geologic Resources Inventory Scoping Summary Glacier Bay National Park and Preserve, Alaska

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The Geologic Resources Inventory (GRI) Program provides each of 270 identified natural area National Park System units with a geologic scoping meeting, a digital geologic map, and a geologic resources inventory report. Geologic scoping meetings generate an evaluation of the adequacy of existing geologic maps for resource management, provide an opportunity for discussion of park-specific geologic management issues and, if possible, include a site visit with local experts. The purpose of these meetings is to identify geologic mapping coverage and needs, distinctive geologic processes and features, resource management issues, and potential monitoring and research needs. Outcomes of this scoping process are a scoping summary (this report), a digital geologic map, and a geologic resources evaluation report.

The National Park Service held a GRI scoping meeting for Glacier Bay National Park and Preserve on June 18, 2009, at park headquarters near Bartlett Cove. Participants at the meeting included NPS staff from the park, Geologic Resources Division, and Alaska Regional Office; private consultants; and cooperators from the U.S. Geological Survey, Student Conservation Association (SCA), and Colorado State University (see table 5). Superintendent Cherry Payne welcomed the group and enthusiastically expressed her interest in seeing the results of the inventory. During the meeting, Tim Connors (Geologic Resources Division) facilitated the group's assessment of map coverage and needs, and Bruce Heise (Geologic Resources Division) led the discussion of geologic processes and features. Dave Brew (U.S. Geological Survey) presented the geologic "story" and setting of the region, and Greg Streveler (private consultant) presented the Quaternary geologic history of Glacier Bay. Robert Blodgett (private consultant) presented information about the paleontological resources of the park and preserve.

On June 19, 2009, park staff and cooperators participated in a field trip of the Glacier Bay environs (fig. 1). Participants traveled "upbay" on the scheduled Glacier Bay Lodge tour boat. Highlights included South Marble Island; a clear view of Mount Fairweather; the scarp at Tidal Inlet; numerous alluvial fans; the rocks of the Alexander terrane; the terminal moraine of the Carroll Glacier; the Rendu, Grand Pacific, Margerie, and Johns Hopkins glaciers; the delta at the river below Mount Abdallah; waterfall/meltwater stream emerging below Lamplugh Glacier; classic U-shaped valleys; Mounts Orville and Wilbur (layered gabbro); Reid Inlet; interglacial stumps south of Geikie Inlet; the twin roche moutonnée of Lemesurier Island; and Cooper's Notch—a break in the lateral moraine cut by a river about 210 years ago and abandoned about 180 years ago.

This scoping summary highlights the GRI scoping meeting for Glacier Bay National Park and Preserve and includes the geologic setting, the plan for providing a digital geologic map, descriptions of geologic features and processes and related resource management issues, and a record of meeting participants. This document and the completed digital geologic map (see Geologic Mapping for Glacier Bay National Park and Preserve) will be used to prepare the final GRI report.



Figure 1. Map of Glacier Bay. NPS graphic.

## Park and Geologic Setting

There is an intimacy about Glacier Bay National Park and Preserve that belies its vastness: Travelers arrive via chartered planes, generally chatting with the pilot and flying with people that they know. In the case of this scoping meeting, “guests” are met by friendly park staff who transport them to their lodgings. The “gateway city” of the park, Gustavus, is well, tiny, and the developed portion of the park is concentrated in a single area at Bartlett Cove. Yet, Glacier Bay National Park and Preserve is more than a million acres larger than Yellowstone National Park (Wyoming, Montana, and Idaho), and the difference in acreage between these two parks—430,365 ha (1,063,456 ac)—is greater than the size of Glacier National Park in Montana. Upon reflection, everything about Glacier Bay National Park and Preserve is larger than life: topography, tectonism, terranes, marine waters, and, of course, glaciers.

The extreme topography of the Glacier Bay region illustrates a landscape driven by immense energy. The Fairweather Range, which makes up the western part of the park, is the highest coastal mountain range in the world. Peaks even 1,000 meters (a few thousand feet) above sea level would be impressive in this scenery, but several peaks rise above 3,050 m (10,000 ft), and Mount Fairweather, which field-trip participants spied, soars 4,663 m (15,300 ft) above sea level.

The present landscape is in part a result of the area’s position astride an active plate boundary. For 180 million years, the Pacific Ocean basin and North America continent have been colliding, driving first the Farallon plate and now the Pacific plate beneath the North American plate. The active Queen Charlotte–Fairweather fault system marks the boundary between these plates. According to Horner (1990), the Pacific plate is moving north-northwest into the North American plate at a rate of 6 cm (2.4 in) per year. Compression has pushed some rocks up to form mountain chains while forcing other rocks down, creating magma in the process, which is then injected into the shattered landscape as plutons. When the molten rock cooled, it welded together one of the world’s most complex geological jigsaw puzzles with plates and terranes bounded by suture zones and faults. Terranes are geologic “pieces” such as island arcs, chunks of seafloor, and fragments of continents that have scraped off one of the colliding plates, shattered, and smeared along the leading edge of the North American plate. These terranes originated far from their present locations, moving northwards thousands of miles relative to North America. Two such terranes—the Chugach and Alexander—lie in a largely northwest-southeast direction across Glacier Bay National Park and Preserve. The Tarr Inlet suture zone welds together these two terranes in the vicinity of Glacier Bay. The Intermontane suture zone is situated to the east of the Alexander terrane.

Although Glacier Bay’s high coastal mountains, active tectonism, and exotic terranes are extraordinary, as its name attests, the national park is best known for its glaciers and bays: glaciers surging and advancing here and retreating there; ice fields and valley glaciers creating landscapes composed of outwash plains, drumlins, and eskers; and tidewater glaciers creating seascapes of deep fjords, accreting shoals, calving ice, and pits and gouges on the seafloor formed by passing icebergs.

Perhaps the most surprising glacial feature of the park is its “newness.” Students of geology need to sprint forward in time to keep up, while placing “classic” features expected from the Pleistocene into a present-day setting. And just as observers are intellectually catching up on the glacial front, in comes isostatic rebound and the succession of entire landscapes—rivers, lakes, plant communities,

and wildlife. Retreating glaciers, evolving landscapes, and recent changes in climate are superimposed on a long history of flux. Perhaps Justin Smith, the research vessel captain at Glacier Bay, put it best, “Things will probably change faster than you think.”

## Geologic Mapping for Glacier Bay National Park and Preserve

During the scoping meeting, Tim Connors showed some of the main features and uses of the GRI Program’s digital geologic maps, which reproduce all aspects of paper maps, including notes, legend, and cross sections, with the added benefit of being GIS compatible. The NPS GRI Geology-GIS Geodatabase Data Model incorporates the standards of digital map creation for the GRI Program and allows for rigorous quality control. Staff members digitize maps or convert digital data to the GRI digital geologic map model using ESRI ArcGIS software. Final digital geologic map products include data in geodatabase and shapefile format, layer files complete with feature symbology, Federal Geographic Data Committee (FGDC)–compliant metadata, a Windows HelpFile that captures ancillary map data, and a map document that displays the map and provides a tool to directly access the HelpFile. Final products are posted at <http://science.nature.nps.gov/nrdata/> (accessed November 30, 2009). The data model is available at <http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm> (accessed November 30, 2009).

When possible, the GRI Program provides large-scale (1:24,000) digital geologic map coverage for each unit’s area of interest, which generally is composed of the 7.5-minute quadrangles that contain NPS-managed lands. In Alaska, however, “large-scale mapping” has a different meaning than in the lower 48 states and Hawaii, and is usually defined as “one inch to the mile” or quadrangles produced at a scale of 1:63,360. The process of selecting maps for management begins with the identification of existing geologic maps in the vicinity of the National Park System unit. Scoping session participants then discuss mapping needs and select appropriate source maps for the digital geologic data (table 1) or, if necessary, develop a plan to obtain new mapping.

**Table 1. Existing Source Maps for Glacier Bay National Park and Preserve<sup>1</sup>**

| GMAP ID <sup>2</sup> | References                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 15335                | Gehrels, G. E., and H. C. Berg. 1992. <i>Geologic map of southeastern Alaska</i> . Miscellaneous Investigations Series Map I-1867. Scale 1:600,000. Reston, VA: U.S. Geological Survey. <a href="http://pubs.er.usgs.gov/usgspubs/i/i1867">http://pubs.er.usgs.gov/usgspubs/i/i1867</a> (accessed November 30, 2009).                                                                                                                                                                                                                                              |
| 74499                | Gehrels, G. E., and H. C. Berg (digital data). N. Shew, C. S. Peterson, N. Grabman, S. Mohadjer, D. Grunwald, F. H. Wilson, and C. K. Hults (digital files). 2006. <i>Preliminary integrated geologic map databases for the United States: Digital data for the geology of Southeast Alaska</i> . Open-File Report 2006-1290. Skagway-Juneau-Mount Fairweather sheets. Scale 1:500,000. Reston, VA: U.S. Geological Survey. <a href="http://pubs.usgs.gov/of/2006/1290/">http://pubs.usgs.gov/of/2006/1290/</a> (accessed November 30, 2009).                      |
| 7304                 | Richter, D. H., C. C. Preller, K. A. Labay, and N. B. Shew (geologic map). F. H. Wilson, K. A. Labay, N. B. Shew, C. C. Preller, and S. Mohadjer (digital files). 2005. <i>Preliminary integrated geologic map databases for the United States: Digital data for the geology of Wrangell-Saint Elias National Park and Preserve, Alaska</i> . Open-File Report 2005-1342. Yakutat sheet. Scale 1:250,000. Anchorage, AK: U.S. Geological Survey. <a href="http://pubs.usgs.gov/of/2005/1342/">http://pubs.usgs.gov/of/2005/1342/</a> (accessed November 30, 2009). |

<sup>1</sup>A map in preparation by Dave Brew (USGS) will supersede existing source maps.

<sup>2</sup>GMAP numbers are identification codes for the GRI Program’s database.

Glacier Bay National Park and Preserve has 40 “inch-to-the-mile” quadrangles of interest (fig. 2). From northeast to southwest, these are Skagway B-4, Skagway B-8, Yakutat B-1, Yakutat B-2, Skagway A-2, Skagway A-3, Skagway A-4, Skagway A-5, Skagway A-6, Skagway A-7, Skagway A-8, Yakutat A-1, Yakutat A-2, Juneau D-5, Juneau D-6, Mt Fairweather D-1, Mt Fairweather D-2,

Mt Fairweather D-3, Mt Fairweather D-4, Mt Fairweather D-5, Mt Fairweather D-6, Mt Fairweather D-7, Juneau C-4, Juneau C-5, Juneau C-6, Mt Fairweather C-1, Mt Fairweather C-2, Mt Fairweather C-3, Mt Fairweather C-4, Mt Fairweather C-5, Mt Fairweather C-6, Juneau B-4, Juneau B-5, Juneau B-6, Mt Fairweather B-1, Mt Fairweather B-2, Mt Fairweather B-3, Mt Fairweather B-4, Mt Fairweather A-2, and Mt Fairweather A-3. Other areas of interest to park staff for resource management and interpretation are the park's viewshed and the Glacier Bay watershed. The viewshed encompasses some lands in British Columbia, including views near the Ferris, upper Carroll, and Grand Pacific glaciers. To the east (on USDA Forest Service lands), Endicott Gap also is part of the park's viewshed. Bill Eichenlaub (GIS data manager, Glacier Bay National Park and Preserve) can supply a file that shows the extent of the watershed. The British Columbia Geological Survey has given the U.S. Geological Survey in Anchorage geologic data that cover the Glacier Bay watershed, which will be incorporated into this mapping project (Dave Brew, U.S. Geological Survey, written communication, October 14, 2009).

During scoping, Dave Brew told the group that he is working on a new and improved version of a compiled geologic map for Glacier Bay National Park and Preserve that will supersede any existing USGS iterations of mapping in the area. Ric Wilson (U.S. Geological Survey) is responsible for USGS mapping projects in Alaska and concurred that this mapping will supersede any existing mapping of the area and will become available in a digital GIS format. The map could be published as either an open-file report, which would facilitate review and completion, or a scientific investigations map.

After scoping, Dave Brew relayed the following information about the completion of the map:

The estimated date for completion of the map as a USGS product is still fuzzy. If I were to guess, I would say sometime about a year from now. We are still dealing with obtaining and integrating both the topographic base and the geology from the "areas of interest" that were requested to be added to the map. I expect to have that part completed within a few weeks, but the topo base for the British Columbia part is still iffy. Then come two USGS internal peer reviews. I have the reviewers identified, but I can't predict how quickly they will complete their task. Then comes a series of approvals: One from the USGS Office Chief in Anchorage; then one from the USGS Alaska Science Center Director in Anchorage; then finally one from the USGS Director's agent in Menlo Park (Dave Brew, U.S. Geological Survey, e-mail to Tim Connors, Geologic Resources Division, August 18, 2009).

Dave Brew's map primarily shows bedrock geology. Greg Streveler and Richard Becker (Glacier Bay National Park and Preserve) are interested in compiling existing surficial data of unconsolidated Quaternary deposits in the park to complement the bedrock geology map. During scoping, they discussed submitting a proposal to the GRI Program to accomplish this work. Additionally, the Southeast Alaska Network is interested in producing a landform map for Glacier Bay National Park and Preserve; this would supersede the existing landform map (i.e., Brew 2008). These two products could serve as the surficial geologic map for Glacier Bay National Park and Preserve.

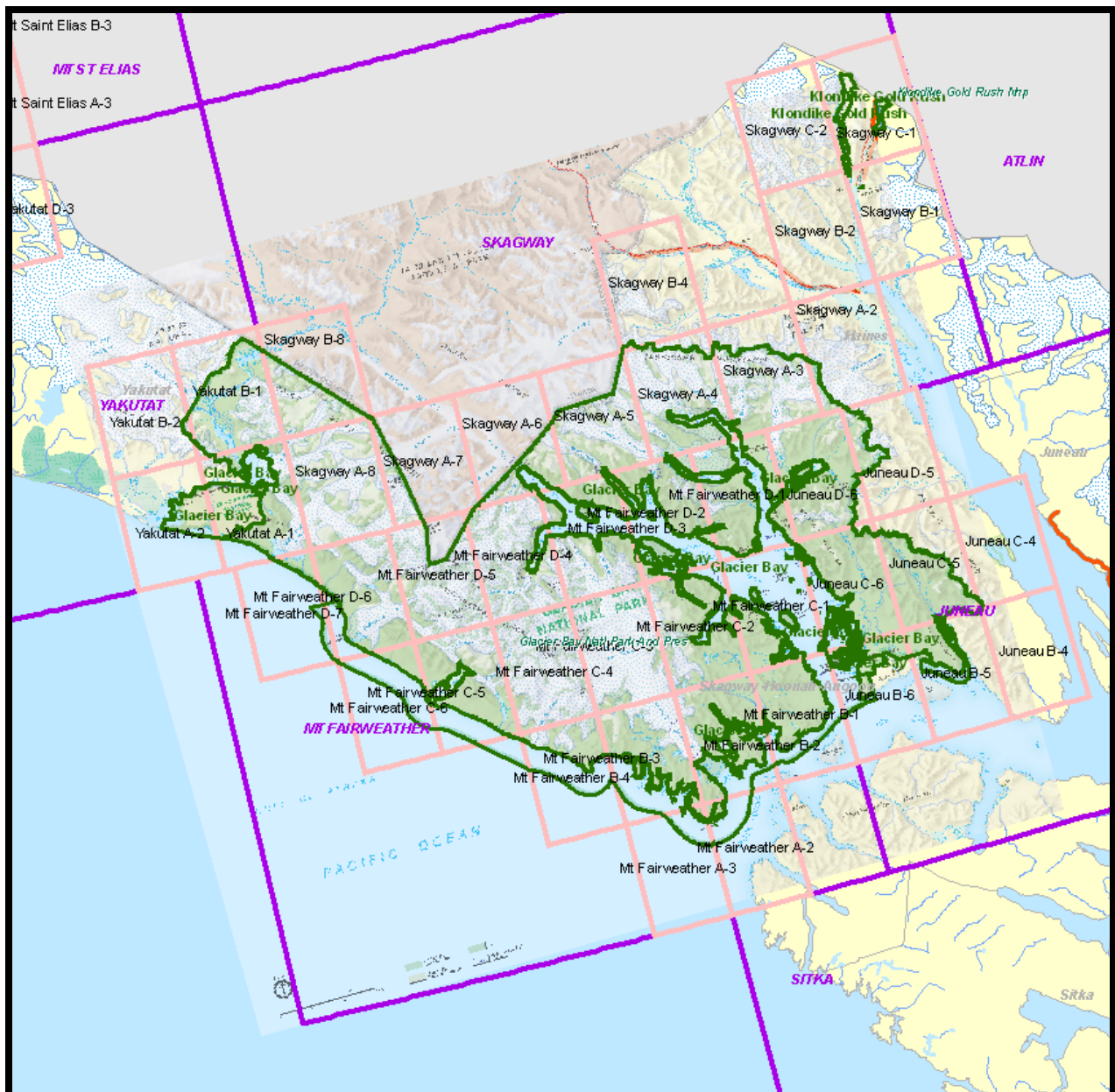


Figure 2. Area of Interest for Glacier Bay National Park and Preserve. Park and preserve boundaries are shown in green. The “inch-to-the-mile” (scale 1:63,360) quadrangles are outlined in pink and labeled in black. The purple outlines and labels indicate 1°×3° sheets (scale 1:250,000).

## Geologic Features, Processes, and Issues

The scoping session for Glacier Bay National Park and Preserve provided the opportunity to develop a list of geologic features and processes occurring at the park and preserve, which will be further explained in the final GRI report. Past investigations have compiled bibliographies of research and exploration in the Glacier Bay region (e.g., Howe et al. 1996), which will be useful sources of information for completing the final GRI report. Many of the features and processes have associated issues of resource management concern. Scoping participants did not prioritize the issues discussed during scoping, and the features and processes are listed in alphabetical order here.

## Cave and Karst Features and Processes

Before summer 2000, nearly nothing was known about the cave and karst resources of Glacier Bay National Park and Preserve. However, discovery of an extensive alpine karst area on White Cap Mountain revealed what appears to be a far-reaching hydrologic system underlying the immense alpine and subalpine topography (see fig. 1). Park managers would like to have a data layer of cave and karst resources as part of the GIS dataset; Wayne Howell (archeologist, Glacier Bay National Park and Preserve) has shapefiles of cave/karst features. In summer 2001, six explorers participated in an eight-day expedition and became the first to survey and document cave and karst resources at the park (Allison 2001). The expedition concentrated on the southern portion of White Cap Mountain called “Little White Cap.” Explorers estimated that the alpine karst in the combined White Cap–Little White Cap area covers nearly 8 km<sup>2</sup> (3 mi<sup>2</sup>) (Allred 2001). Thousands of hollow depressions called dolines mark the surface of the rock. Some of these hollows are cylindrical while others resemble glacial crevasses up to 40 m (230 ft) long. Karst features include channels or furrows formed by solution such as heelprint karren, grikes, wall karren, some solution pans, and rare rillenkarren (Allred 2001). Explorers also observed numerous patches of thin, white deposits below organic-rich silt, mosses, lichens, and low plants, which they interpreted as residual calcite left at the surface as a result of a week-long period of dry weather (Allred 2001).

During the expedition, explorers discovered and then surveyed 21 caves, totaling a length of 613.2 m (2,011.7 ft) and a depth of 420.4 m (1,379.3 ft). The deepest cave was #6 (informally called “Ai Chihuahua Cave”) at 74.6 m (244.9 ft). The longest cave was #21 (“Ice Scream Cave”) at 85.6 m (281.0 ft). Perhaps the most beautiful cave was #11 (“Clueless Cave”), which formed in gray-and-white banded marble. All the caves ended in shattered rubble or narrow cracks too small for human entry. Breakdown and snow commonly inhibited further exploration. Some of the caves had drafts of air, which indicates cave passage beyond. In one cave, #14 (“Bad Joke Cave”), explorers could hear running water below the rubble-choked pit. Entrances often resembled sinkholes, but some (e.g., #16 [“Y Cave”]) had the appearance of crevasses splitting the rock.

Most of the caves did not host speleothems, though on the last day of the expedition, #21 offered up popcorn and flowstone. The explorers found “past life” (i.e., marmot remains) in a few of the caves (i.e., #6, #15 [“Marmot Jerkey Pit”], and #20 [“Tidy Bowl Cave”]), but these are not likely paleontologically significant finds. Some caves were connected to marmot burrows; this is the only known use of the caves by mammals (Allison 2001).

The explorers concluded that the White Cap Mountain area is “a world-class karst area warranting further study and investigation.” They surmised that the park contains many other alpine karst areas. Scoping participants thought that these areas would occur in Willoughby Limestone and the Pyramid Peak Formation. During the scoping field trip, participants discussed caves on the east side of Marble Mountain and the south side of Reid Inlet. The caves explored thus far do not appear to contain sensitive archaeological or paleontological resources, thereby rendering them “off limits” to the general public; however, at the time of scoping, park managers did not feel prepared to support recreational caving activities or potential cave rescue operations. Because of the extreme remoteness and difficulties involved in transporting in the necessary gear to explore these cold, wet, vertical caves, Allison (2001) recommended the following: (1) only experienced cavers be permitted to explore the caves; (2) park managers pursue a partnership with experienced speleologists to further identify, inventory, and study the park’s cave resources; and (3) park managers develop a cave

management plan to guide future inventory, research, and access to the caves in Glacier Bay National Park and Preserve.

## **Climate Change**

As one scoping participant stated, “This park is about climate change.” Climate-related changes in Glacier Bay National Park and Preserve include isostatic rebound, glacial retreat, and landscape succession. Isostatic rebound was a repeated topic of conversation during scoping in the Southeast Alaska Network. Dave Brew mentioned a study by Christopher F. Larsen and others that addressed isostatic rebound in Southeast Alaska (i.e., Larsen et al. 2005). According to this study, this part of Alaska hosts “the world’s fastest present-day glacio-isostatic uplift yet documented.” Larsen et al. (2005) used global positioning system (GPS) geodesy combined with raised shorelines to determine the rates of uplift, which are as much as 32 mm (1.6 in) per year in parts of Southeast Alaska. Peak uplift is occurring at the Yakutat Icefield, situated in the Tongass National Forest northwest of Glacier Bay National Park and Preserve. At 30 mm (1.2 in) per year, Glacier Bay has the second greatest area of uplift. According to scoping participants, the Glacier Bay area is about halfway through its isostatic uplift; that is, about 3.7 m (12 ft) since deglaciation with about 7.6 m (25 ft) total expected. Rebound should be complete in another 400 years. Investigators attribute the majority of uplift to viscoelastic rebound following the post–Little Ice Age deglaciation, with extreme uplift beginning about 1770 AD (Larsen et al. 2005). Other contributors to uplift are current ice thinning, tectonic forcing, and global glacial isostatic adjustment (Larsen et al. 2005).

The Intergovernmental Panel on Climate Change determined that over the past 120 years, global relative sea-level rise has been 1.8 mm (0.07 in) per year (Intergovernmental Panel on Climate Change 2001). The volume of ice lost in Glacier Bay alone since the end of the Little Ice Age is equivalent to a global rise in sea level of 8 mm (0.3 in). Comparing the rate of sea-level rise to the rate of uplift determined by Larsen et al. (2005), rising sea level is not a threat to national parks in Southeast Alaska.

Investigators have attributed increased erosion and sedimentation to isostatic rebound (Hallett et al. 1996; Jaeger et al. 2001). This, combined with the meltwater of retreating glaciers, has resulted in high rates of sediment deposition and shoal building in park waters, which is an issue for vessel navigation. Glacial retreat has caused infilling of some inlets; for example, in the last 100 years the upper Queen Inlet has filled with more than 100 m (328 ft) of sediment (Molnia et al. 2007).

Another effect of climate change is glacial retreat. Since Dave Brew first began mapping Glacier Bay National Park and Preserve in the 1970s, when it was still a national monument, glacial retreat has exposed 425 km<sup>2</sup> (164 mi<sup>2</sup>) of ground surface (bedrock and surficial deposits). By comparing the GIS data of Dave Brew’s original mapping with ice extent in the year 2000, Bill Eichenlaub found that 344 km<sup>2</sup> (129 mi<sup>2</sup>) of bedrock and 91 km<sup>2</sup> (35 mi<sup>2</sup>) of surficial deposits are now ice free in what was the national monument. The difference between the monument boundary and the park and preserve boundary is 2,178 km<sup>2</sup> (841 mi<sup>2</sup>) (Bill Eichenlaub, Glacier Bay National Park and Preserve, e-mail, November 27, 2009); the estimate of now-exposed bedrock does not cover this area. The data for the Muir Inlet area is particularly telling: glacial retreat has exposed 106 km<sup>2</sup> (41 mi<sup>2</sup>) of ground (bedrock and surficial deposits) in the last 30 years (fig. 3). During scoping, participants discussed whether glacial retreat has revealed any geologic “surprises,” but the original interpretations seem sound.

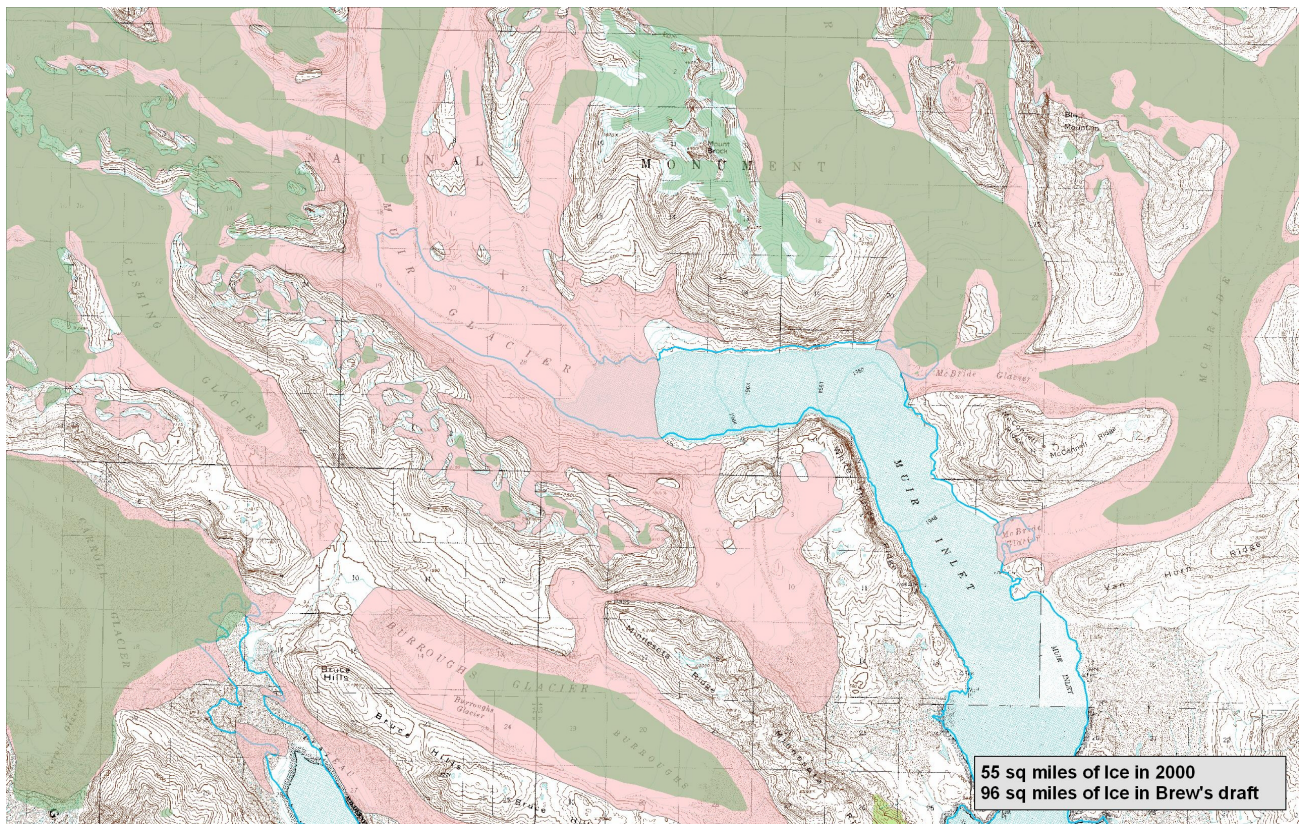


**Figure 3. Ice Extent in the Muir Inlet Area.** Since Dave Brew (USGS) first began mapping in the 1970s, 106 km<sup>2</sup> (41 mi<sup>2</sup>) of land has been exposed by glacial retreat around Muir Inlet. The pink shaded areas show the ice extent at the time of 1970s mapping; the green outline represents ice extent in 2000. NPS graphic by Bill Eichenlaub (Glacier Bay National Park and Preserve).

Lichens colonize, soils develop, and plants grow on exposed bedrock. Although plant succession takes place in all environments, it is much easier to see and study on surfaces devoid of organic matter—from the bedrock up, so to speak. Hence, many investigators have studied plant succession in Glacier Bay National Park and Preserve. William S. Cooper began studying plant succession in 1916. In 1941, Donald Lawrence continued these studies. More recently, Chapin et al. (1994) and Fastie (1995) made contributions to this research.

Many factors influence succession (e.g., type of bedrock, nature of the substrate, geographic location, and proximity to mature vegetation), but in general, ecosystems become younger “upbay,” following the retreat (location and rate) of glaciers. Insects, herbivores, and carnivores follow (and influence) plant succession. Scoping participants noted the appearance of moose as an outcome of plant succession. Rare occurrences of moose began upbay nearly 40 years ago, and they have become “common” in portions of Glacier Bay and certainly on the Gustavus forelands in the past 15 years (Lewis Sharman, Glacier Bay National Park and Preserve, written communication, November 11, 2009).

### **Coastal and Marine Features and Processes**

Glacier Bay National Park and Preserve is the largest marine area managed by the National Park Service. The Park Service has jurisdiction over more than 242,820 ha (600,000 ac) of marine waters, including 21,449 ha (53,000 ac) of designated wilderness in the park and preserve. The

approximately 1,900 km (1,180 mi) of coastline in Glacier Bay National Park and Preserve represent nearly 30% of the total marine coastline in the National Park System, nearly three times more than the next largest coastline park (Moynahan and Johnson 2008).

Because of limited expertise in coastal geology on staff, park employees often consult Dan Mann (University of Alaska Fairbanks) on coastal issues. Features and processes in need of investigation include marine terraces, particularly their association with isostatic rebound; an inventory of coastal archaeological sites; and sea-level rise.

In 2003 the U.S. Geological Survey published bathymetric habitat maps of lower Glacier Bay, which provided “an unprecedented new baseline for resource and habitat assessment, as well as geological and oceanographic research” (Carlson et al. 2003). This study revealed Glacier Bay as the deepest silled fjord in Alaska, with depths greater than 450 m (1,476 ft). In addition, investigators discovered a series of iceberg drag marks on the seafloor of the lower bay; strong tides formed these impressions as they pulled icebergs “through the muck” of the bay floor (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009). Also, park employees have created a GIS database that classifies coastlines and identifies coastal features ([http://www.nps.gov/glba/naturescience/coastal\\_mapping.htm](http://www.nps.gov/glba/naturescience/coastal_mapping.htm); accessed November 30, 2009). In fall 2009, the National Oceanographic and Atmospheric Administration (NOAA) surveyed the benthic habitats of upper Glacier Bay. This effort will provide new, high-resolution data for updating the Glacier Bay nautical chart. In addition park staff will archive the data, which will be available for use in generating highly detailed benthic mapping products (Lewis Sharman, Glacier Bay National Park, written communication, November 11, 2009).

Morainal banks are a combined glacial-marine feature in lower Glacier Bay, where world-class examples occur. These are the underwater equivalent of recessional moraines (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009). Unlike moraines on land, this submerged moraine material has been sorted and stratified by tidal and wave activity. Morainal banks record stillstands in the retreat of glaciers; a noteworthy locale is off Muir Point at the entrance to the East Arm of Glacier Bay.

An interesting feature on the park’s exposed outer coast is the abrupt change from “drowned rocky” shoreline south of Icy Point to “accreting sandy” beaches north of this point. Accreted beaches are popular camping sites. The Fairweather fault moves offshore at Icy Point and presumably causes this sudden geomorphic change. In addition, stumps and peat in the intertidal zone have been instrumental in deciphering the story of deglaciation in the park (see Paleontological Resources). Other coastal and marine features of interest are sea arches along the outer coast, high rates of sedimentation and resultant turbidity flows, mudflats and tidal flats (and their association with fluvial and glacial processes), submerged ancient terminal moraines (e.g., near Johns Hopkins Glacier)—a classic glacial feature that in other parts of the world would be above water (and much easier to study), and barrier islands. The barrier islands at the mouth of the Alsek River are the only barrier islands in the park and preserve; scoping participants suspected that the variety of coastlines inhibits the establishment of a long barrier-island chain.

## **Disturbed Lands**

Disturbed lands are those parklands where the natural conditions and processes have been directly impacted by mining, oil and gas production, development (e.g., facilities, roads, dams, abandoned campgrounds, and trails), agricultural practices (e.g., farming, grazing, timber harvest, and abandoned irrigation ditches), overuse, or inappropriate use. The NPS Disturbed Lands Restoration Program, administered by the Geologic Resources Division, usually does not consider lands disturbed by natural phenomena (e.g., landslides, earthquakes, floods, hurricanes, tornadoes, and fires) for restoration unless the areas are influenced by human activities.

Scoping participants identified some disturbed areas at Glacier Bay National Park and Preserve, namely current clean-up and rehabilitation of a fuel storage leak near the Public Use Dock at Bartlett Cove. Over several decades, underground storage tanks leaked approximately 114,000 L (30,000 gal) of fuel into the soils beneath today's parking lot; remediation began in the early 2000s. The facility, referred to as the "BarCo fuel farm," provided gasoline and fuel for NPS and concessionaires' "rolling" and "floating" vehicles. Concessionaires also sold fuel to the public. Additionally, the fuel farm provided diesel for the park's generators, creating electricity for the water-treatment and wastewater-treatment facilities, lighting, heating, and all other electric needs (Lewis Sharman, Glacier Bay National Park and Preserve, e-mail, August 6, 2009). Remediation is in progress under the supervision of the park's maintenance division. The new fuel farm is located across the road from the former site.

In addition, scoping participants mentioned three mining-related sites: (1) the Brady Glacier prospect, (2) the abandoned LeRoy Mine, and (3) an adit at Sandy Cove. MacKevett et al. (1971) and Brew et al. (1978) discussed these and other mineral resources at Glacier Bay National Park and Preserve. Before retiring, Phil Cloues (Geologic Resources Division) prepared documents about the Brady Glacier prospect and LeRoy Mine; these documents remain in GRD files.

The Brady Glacier Nickel Claim is the only valid mining claim within Glacier Bay National Park and Preserve. It is a low-grade, nickel-copper deposit situated 120 m (400 ft) to 180 m (600 ft) beneath the west flank of the Brady Glacier. This deposit is exposed on two small nunataks that rise above the glacier's surface (MacKevett et al. 1971). In 1996, Phil Cloues prepared a technical review of an appraisal of the deposit. The engineering challenges of mining a deposit buried beneath hundreds of feet of glacial ice are substantial, to say the least, but the disposal of tailings and the location of the concentration mill and other support structures, including marine transfer, are equally complicated issues. In addition, economic roadblocks such as the high cost of transporting ore and operating under adverse weather, topographic, and geographic conditions are formidable impediments.

The abandoned LeRoy Mine between Reid Inlet and Lamplugh Glacier produced \$250,000 worth of gold before closing in 1996. In 1994, an evaluation of the mine's condition noted rotten timbers throughout both adits and unstable rock in both the west and east portals (Phil Cloues, Geologic Resources Division, written note, GRD files, March 17, 1994). GRD records contain no information about the Sandy Cove adit, but this site may have been recorded under a different name (Pasha Enzi, Geologic Resources Division, e-mail, October 30, 2009). Further inquiry will be conducted for the final GRI report.

## **Eolian Features and Processes**

Eolian features and processes are not a primary resource at Glacier Bay National Park and Preserve; however, windblown deposits occur at the mouth of the Alsek River on beaches and as active sand dunes, as vegetated dunes in the vicinity of Gustavus, and as consolidated dunes within forests. Outwash plains (e.g., at Taylor Bay) and other recently deglaciated areas are sources of fine-grained sand and silt to be reworked by the winds.

## **Fluvial Features and Processes**

According to Moynahan and Johnson (2008), more than 300 streams are present in Glacier Bay National Park and Preserve, 100 of which are newly formed since glaciers have receded. On the western side of the park, rivers fringe the glaciers, which dominate the landscape and serve as fluvial source areas. For example, the Brady Icefield is a major source area for streams such as the Crillon River, Kaknau Creek, Dundas River, and Dixon River. Because glaciers are so ubiquitous in this area, rivers flow only short distances from glacial snouts to bays and harbors (e.g., Lituya Bay, Palma Bay, Dixon Harbor, Graves Harbor, Taylor Bay, and Dundas Bay). Tidewater glaciers flank much of Glacier Bay, limiting fluvial activity around the bay itself.

Scoping participants pointed out that the most noteworthy fluvial system in the park is the Alsek River. The river crosses an international boundary and is one of the only breaks in the Coast Range. Its headwaters are in Canada, and the river flows south for 386 km (240 mi) to the Gulf of Alaska at Dry Bay. It is a world-class destination for “pristine experiences” of river recreation and supports an active fishery. The river’s drainage area is huge: it collects water from the Alsek Range via the Tatshenshini River in British Columbia, enters the United States as it flows through the St. Elias Mountains, serves as the inflow and outflow of Alsek Lake, and then before emptying into Dry Bay, forms a portion of the northwest boundary of the park and preserve. To the east of Glacier Bay, the Excursion, Beartrack, and Bartlett rivers are the only other “major” rivers in the park and preserve. The Excursion River is the longest of these at approximately 22 km (14 miles) and its watershed forms the southeast corner of the national park and preserve, just east of Gustavus (Eckert et al. 2006).

Milner (1987) characterized the streams in Glacier Bay National Park and Preserve as follows: meltwater (glacially fed) streams, which are laden with sediment; clearwater streams (with and without lakes); brownwater streams (draining wetlands); and karst-influenced streams. Milner’s work also highlighted Glacier Bay National Park and Preserve as having world-class examples of stream evolution. For example, under the influence of glacial meltwater, isostatic rebound, and sedimentation, the Adams Inlet is changing from a glacial, to a marine, to a terrestrial system. Such evolution dramatically affects salmon fisheries. Moreover, the rivers that drain into the Adams Inlet are world-class examples of low-gradient, braided rivers. Braided rivers also run from the snouts of glaciers into bays, for instance from the Brady Glacier into Taylor Bay and from the Carroll Glacier into Queen Inlet. These systems are dominated by the transport and deposition of sediment; however, the erosional power of streams is also displayed in the park. For example, the glacial valley above Russell Fan is becoming stream dominated in sections, with a distinctive V-shape (fluvial) superimposed on the larger U-shape (glacial) valley.

## Geothermal Features and Processes

Geothermal features such as warm springs and mud occur at Icy Point. The area is relatively small (0.4–0.8 ha [1–2 ac]) and not developed. Geothermal activity results in noticeable changes in vegetation type in this area. Geothermal activity probably is related to the Fairweather fault, which runs directly through Icy Point.

## Glacial Features and Processes

According to scoping participants, “You name it, we’ve got it” when it comes to glacial features and processes at Glacier Bay National Park and Preserve. Both erosional and depositional features abound, as do the various types of glaciers. Scoping participants, in particular Richard Becker, provided examples that are listed in the following tables. These examples will be used when preparing the final GRI report. In addition to the geomorphic interest and interpretive value, these features document rapid glacial retreat and diverse responses to climate change.

Glacier Bay National Park and Preserve contains the fourth largest concentration of glacial ice on Earth (Moynahan and Johnson 2008). It hosts one icefield (Brady Icefield) and more than 200 valley, cirque, or smaller glaciers (Eckert et al. 2006). The longest glacier that flows (partially) in the park is the Grand Pacific Glacier: it begins in British Columbia but terminates at the head of Tarr Inlet. According to scoping participants, Casement Glacier, which flows entirely within the park’s boundaries, is another very long glacier. The summer 2009 edition of *The Fairweather* listed eight glaciers in the park as having lengths greater than 15 km (9 mi): Grand Pacific (55.5 km [34.5 mi]), Margerie (34 km [21 mi]), Lamplugh (26 km [16 mi]), Riggs (23 km [14.5 mi]), Johns Hopkins (20 km [12.5 mi]), Muir (20 km [12.5 mi]), McBride (19 km [12 mi]), and Reid (15 km [9.5 mi]) (see fig. 1).

Tidewater glaciers are a distinctive type of glacier. Rather than being defined by size, this type of glacier is defined by location. By definition, tidewater glaciers terminate into the sea, but Glacier Bay National Park and Preserve also has glaciers that terminate into large freshwater lakes near sea level (e.g., Alsek Glacier). The park contains 12 tidewater glaciers, including La Perouse, Margerie, Grand Pacific, Johns Hopkins, Gilman, Lamplugh, and McBride. La Perouse Glacier, on the park’s outer coast, actually terminates into the open Pacific Ocean, the only tidewater glacier in the park to do so. Tidewater glaciers are known for their spectacular calving. During the field trip, scoping participants were entertained by the displays at Margerie and Johns Hopkins glaciers. The park also hosts piedmont glaciers (e.g., north of Alsek Lake, flowing west off the Fairweathers), which are the snowy/icy equivalent of alluvial fans. Some of the park’s glaciers periodically surge (e.g., Carroll and Rendu glaciers). Glaciers themselves also possess distinctive features such as bergschrund, crevasses, and foliation. Margerie Glacier (and probably others) is known for its ogives (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009).

During the 2003 and 2004 field seasons, investigators revisited nearly 100 unique locations of historic photographs taken between the late 1890s and mid-1900s. Investigators, including Ron Karpilo (Colorado State University) who participated in scoping, compared the modern and historical images in order to better understand rates, timing, and mechanisms of landscape change. They placed particular emphasis on understanding the response of specific glaciers to changing climate and environment (Molnia et al. 2007). Hal Pranger (Geologic Resources Division) presented the following results at the 2005 George Wright Society Biennial Conference:

- During the last century, the majority of glaciers in Glacier Bay have retreated rapidly (generally kilometers to tens of kilometers) (e.g., Muir, Hugh Miller, and Geikie glaciers).
- A few glaciers have remained stable, slightly advanced (generally only hundreds of meters), or slightly advanced and retreated (e.g., John Hopkins, Lamplugh, and Rendu glaciers).
- Tidewater glaciers have widely varying behaviors, which are inconsistent with observed global climate trends.
- Unique and sometimes opposite trends have occurred (some in very close proximity). For example, the following “pairs” of glaciers are in close proximity but have displayed differing behaviors over the last century: Grand Pacific (advanced) and Muir (retreated), and Reid (retreated) and Lamplugh (advanced). Moreover, the Rendu and Carroll glaciers are an interesting pair. They occupy adjacent valleys, and both have experienced periods of surges and retreat but at different times during the past 100+ years (Ron Karpilo, Colorado State University, e-mail, August 13, 2009).
- Since about 1800, more than 2,500 km<sup>3</sup> (600 mi<sup>3</sup>)—90% of the total volume—of ice was lost from Glacier Bay by the 1940s. Catastrophic retreat occurred when tidewater glaciers reached their threshold depths. That is, when a tidewater glacier recedes off of the “grounding point” of its moraine shoal, the glacier terminus is undercut by tidal ocean water, causing increased calving and resulting in the rapid retreat of the glacier (if accumulation of ice cannot keep pace with the ice loss due to calving). This explains the rapid but asynchronous retreat in Glacier Bay: the West Arm was free of ice 50 years before the East Arm due to differences in inlet geometry. Generally speaking, the West Arm is wider and deeper. As a result, when the “west side” glacier terminus backed off its protective shoal, its tidewater snout was subject to significantly greater tidal effects than the more protected terminus in the narrower and shallower East Arm.

**Table 2. Erosional Glacial Features in Glacier Bay National Park and Preserve**

| Feature        | Location                                                                                                                                                                      | Comments                                                                                                                                                                                                                                                                                       |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Arête          | Throughout the Fairweather Mountains                                                                                                                                          | Many textbook examples; too many to list                                                                                                                                                                                                                                                       |
| Chattermarks   | Rocky point on the northwest side of Johns Hopkins Inlet about 2.4 km (1.5 mi) from the terminus                                                                              | Only location that I've seen chattermarks, but I'm sure that there are many others where bedrock is exposed (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009).                                                                                  |
| Cirque         | Located at a variety of locations and elevations throughout the park                                                                                                          | In terms of form, the cirque on the north side of Beartrack Peak is particularly shapely, but it's remote (I've never seen it in person; I've only looked at it on maps and in Google Earth [Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009]). |
| Fjord          | The entire bay but Johns Hopkins Inlet and upper Muir Inlet are particularly stunning                                                                                         | Park employees have described Johns Hopkins Inlet as “nature's equivalent of the Sistine Chapel.”                                                                                                                                                                                              |
| Grooves        | Many places, but three particularly outstanding locations: Gloomy Knob, Jaw Point, and the rocky promontory just east of the terminus of Lamplugh Glacier                     | They are often called “striations” to passengers on ships, but really what we can see from that distance would be termed “grooves” (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009).                                                           |
| Hanging valley | Many around the park, but outstanding ones above “Russell Cut” (valley north of Russell Island) and along Johns Hopkins Inlet                                                 | The Russell Cut one is the best, at least of the ones that can be seen from ships (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009).                                                                                                            |
| Horn           | A number from around the park, probably the best are located in the Fairweathers                                                                                              |                                                                                                                                                                                                                                                                                                |
| Polish         | Around the park, but the rocks of Johns Hopkins Inlet probably have the best (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009) |                                                                                                                                                                                                                                                                                                |

|                        |                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                              |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Roche moutonnée        | Lemesurier Island in Icy Strait (just outside the park)                                                                                                                                                                                                                               | Twin roche moutonnée                                                                                                                                                                                                                                                         |
| Rock flour             | Upper West Arm                                                                                                                                                                                                                                                                        | LOTS slowly settling out in the water of the upper West Arm; Gustavus is built on rock flour deposited a few hundred years ago that has since been lifted out of the ocean by isostatic rebound.                                                                             |
| Scour marks            | Submarine in the lower main bay                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                              |
| Striations             | Many locations, but four particularly outstanding locations: Gloomy Knob, Jaw Point, the rocky promontory just east of the terminus of Lamplugh Glacier, and a rocky point on the northwest side of Johns Hopkins Inlet about 2.4 km (1.5 mi) from the glacier's terminus "Seal Camp" | World-class striations aren't that uncommon in the park; most temperate glaciers probably leave them behind, but they are as nice in Johns Hopkins Inlet as I've ever seen (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009). |
| Tarn                   | Many in the deglaciated mountain valleys                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                              |
| U-shaped valley/trough | Nearly everywhere, in some shape or form, with the exception of the lower bay where there has been lots of deposition                                                                                                                                                                 |                                                                                                                                                                                                                                                                              |
| Whaleback              | Francis Island                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                              |

**Table 3. Depositional Glacial Features in Glacier Bay National Park and Preserve**

| Feature            | Location                                                                                                                                                                                                                                              | Comments                                                                                                                                                                                                                                                             |
|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Drumlin            | One definite location and another possible: definite = east of Hutchins Bay in the Beardslees; possible = low-lying area of land between Wachusett Inlet and lower Muir Inlet                                                                         | The drumlins east of Hutchins Bay look stunning in Google Earth; I've never seen them personally nor do I know of anyone who has; they appear erosional in genesis (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009). |
| Erratic            | Nearly everywhere                                                                                                                                                                                                                                     | None famous in particular                                                                                                                                                                                                                                            |
| Kettle/kettle pond | Along the moraines of the lower bay and a few places in the East Arm; definitely Adams Inlet (I've seen photos of kettles flooded by the sea there [Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009]). | The most famous kettle pond in the park would be Blackwater Pond on the Forest Loop Trail (one-mile nature hike at Bartlett Cove).                                                                                                                                   |
| <i>Moraines</i>    |                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                      |
| End/terminal       | Along the shorelines of the lower bay                                                                                                                                                                                                                 | The NPS facilities in Bartlett Cove are built at the base of an end moraine (the terminal moraine of the Little Ice Age); the road from town passes right over it; an analogous moraine on the west side of Sitakaday Narrows partners with it.                      |
| Ground/fluted      | Fluted ground moraine on the hillslopes around the Burroughs Glacier                                                                                                                                                                                  | I'm sure that there are many other examples as well, probably in the area of the drumlins surrounding Hutchins Bay (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009).                                                 |
| Lateral            | Many places, but a great example about halfway up Marble Mountain                                                                                                                                                                                     | Best seen with a bit of snow cover to accentuate the flatter sections                                                                                                                                                                                                |
| Medial             | Many                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                      |
| Recessional        | Probably some, but none in particular on land                                                                                                                                                                                                         | See Coastal and Marine Features and Processes                                                                                                                                                                                                                        |
| Outwash            | The Gustavus forelands, the area south of the Brady Glacier, the area in front of the Carroll Glacier, the northeast corner of the Grand Pacific Glacier/Ferris Glacier terminus, many places extending into Adams Inlet                              | Adams Inlet is visibly in the process of being converted from an inlet to a valley                                                                                                                                                                                   |

**Table 4. Fluvioglacial Features in Glacier Bay National Park and Preserve**

| Feature              | Location                                                                                                                                                                                                                                                                                                            | Comments |
|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| Eskers               | Some in the Bartlett Cove area, but difficult to see with all the trees. There are a number up around the Burroughs Glacier. I'm sure that there are others, probably mainly in the flat areas around Adams Inlet (Richard Becker, Glacier Bay National Park and Preserve, written communication, August 13, 2009). |          |
| Kame                 | Some in the area deglaciated by the Burroughs Glacier, possibly some in the forests of Bartlett Cove / the mainland east of the Beardslees                                                                                                                                                                          |          |
| Subglacial waterfall | Lamplugh Glacier                                                                                                                                                                                                                                                                                                    |          |

## Glacial Outburst Floods

Glacial outburst floods combine glacial, fluvial, and lacustrine features and processes. Also known by their Icelandic term “jökulhlaup,” investigators began studying these floods in the 1950s. In 1971 the U.S. Geological Survey published work that focused on Alaska (i.e., Post and Mayo 1971). However, predicting these floods is still a “mystery,” and scoping participants identified understanding ice-dam cycles as a research need in the park. Two potential triggers of glacial outburst floods are climate change and seismicity (Grover 2003).

Abyss Lake periodically has outburst floods, for example, during the summers of 1994, 1997, 1998, 2000, 2001, and 2005

(<http://home.nps.gov/applications/digest/printheadline.cfm?type=Announcements&id=4700>; accessed November 30, 2009). Aerial photographs reveal earlier floods after 1979 when “the valley was subjected to a large flow event, which created sandbars, reclaimed old overflow channels, and removed many acres of mature forest near the channel” (Grover 2003, p. 13). Outburst floods at Abyss Lake affect the Oscar River valley and Dundas Bay (see fig. 1). An ice dam at the west end of the lake periodically fails, initially causing subglacial flow under the Brady Glacier, which surfaces in the Oscar River drainage and results in a flood of water, temperature spikes, sediment input, and thousands of trees deposited in Dundas Bay. Other lakes in the park appear to be likely candidates for similar flooding. Scoping participants identified potential sites for outburst floods along the southern and western extent of the Brady Icefield and Glacier, which would affect Palma Bay, Dixon Harbor, Taylor Bay, and Dundas Bay.

In recent years the surging Tweedsmuir Glacier in British Columbia threatened to block the Alsek River and cause a glacial outburst flood. According to a July 30, 2008, NPS briefing statement, “such an event could result in a catastrophic outburst flood that could threaten the safety of Alsek and Tatshenshini River rafters, commercial fishermen, visitors and concessioners in Dry Bay as well as park staff. In addition there is potential for damage to park and private property.” Chris Larsen (University of Alaska Fairbanks) is studying this surging glacier. As of May 2009, this surging episode appeared to have ended ([http://aprfc.arh.noaa.gov/general/tweedsmuir\\_status.php](http://aprfc.arh.noaa.gov/general/tweedsmuir_status.php); accessed November 30, 2009).

Advancing glaciers, particularly surging ones, block lateral valleys causing glacially dammed lakes to form. This is the process damming Abyss Lake. However, glaciers also can dam lakes on their surfaces (supraglacial), at their beds (subglacial), and, though more common in Klondike Gold Rush National Historical Park than in Glacier Bay, recessional moraines can dam lakes in front of a receding glacier (proglacial).

Because of the extremely abrupt releases of water that can issue from even very small glacially dammed lakes, such lakes produce serious local hazards. As described by Grover (1997), “the flowing water melts the constricting ice, which allows more water to flow. This increased flow, in turn, melts additional ice and flows increase accordingly. This process continues until the glacial lake is drained” (p. 2–3). Wide floodplains are inundated to unusual depths, and the high discharge rates can produce rapid erosion, deposition, and changes in the stream channel (Post and Mayo 1971). As noted by scoping participants, such floods are likely to affect salmon fisheries.

## Hillslope Features and Processes

Glacial outburst floods can cause massive landslides, and rain-on-snow and intense-rain events can lubricate landslides, causing them to move with or without seismic triggers (Greco 2008).

Moreover, rapid glacial retreat can result in destabilization of moraine material and loss of lateral support to valley walls, resulting in debris flows, rockfall, and other types of mass wasting (Deanna Greco, Geologic Resources Division, personal communication, July 23, 2009). However, “the most important mass-wasting events in the Glacier Bay region are directly linked to large magnitude (M) earthquakes. The best known of these is the rockfall in Lituya Bay associated with the M=7.9 earthquake on the Fairweather fault in 1958” (Brew et al. 1995, p. 8).

Mass wasting in some areas is constant, for example, the continuous rockfall (and ice fall) into Alsek Lake. Calving of glacial ice and associated rocks also occurs regularly at John Hopkins Glacier. This debris can cause substantial wave activity.

Mass-wasting events also can be concentrated into a specific period of time (e.g., the week-long landslide on Mount Crillon in June 2004). This series of small, persistent slope failures coincided with a period of warmer than usual air temperatures ([http://www.avo.alaska.edu/activity/print\\_report.php?output=screen&id=72&type=update](http://www.avo.alaska.edu/activity/print_report.php?output=screen&id=72&type=update); accessed November 30, 2009). It produced so much dust and for such an extended period that pilots flying over the park thought it was a volcanic eruption. The park’s archives contain photos of this event.

In 2008, the Geologic Resources Division responded to a technical assistance request from park staff to evaluate the potential hazard of a giant wave in the event of a catastrophic failure of the landslide in Tidal Inlet. The slide is moving at an average rate of 3–4 cm (1.2–1.6 in) annually (Wieczorek et al. 2007). Catastrophic failure would be of particular concern to park visitors in the immediate area, as well as those in the impact area of a giant wave (i.e., low elevations on land, as well as tourist boats, private vessels, and cruise ships) (Greco 2008). The landslide is on the north slope of the inlet and contains fresh scarps, rotational blocks, and localized secondary slope failures (Greco 2008). Investigators found that the maximum-volume slide would generate very high waves (tens of meters in amplitude with possible greater-than-100-m [328-ft] wave run-up on the opposite shore) near the source within Tidal Inlet. Outside the inlet, waves of significant amplitude (>10 m [33 ft]) would occur in shallow-water regions, especially near the mouth of Tidal Inlet. Wave amplitude would be greatest within approximately 40 minutes of the landslide entering the water, with the potential for significant wave activity continuing for several hours (Wieczorek et al. 2007).

In addition, Greco (2008) identified Blue Mouse Cove as a particular area of concern in the event of catastrophic failure of the Tidal Inlet landslide. Blue Mouse Cove is situated 10 km (6 mi) directly across the bay from Tidal Inlet (see fig. 1). The cove housed a floating ranger station and floating fuel barge, the *Petrel*, with an 11,356-L (3,000-gal) capacity. The “ranger raft” typically remained moored in place year-round, but every fall park staff towed the fuel barge to Bartlett Cove, where it was tied safely to the dock for the winter. Come spring, it was refilled and towed back to Blue Mouse Cove for another summer season. In response to scientific findings and the hazard assessment, the National Park Service relocated this floating ranger station and fuel barge to South Sandy Cove in August 2009. According to Lewis Sharman, “As we came to better understand the threat of a catastrophic failure of the Tidal Inlet slump and subsequent giant wave (quite low probability but potentially high consequence), and the potential propagation of the wave across the

West Arm and into Blue Mouse Cove (it was modeled), park management deemed it prudent to relocate both the ranger raft (employee safety) and the *Petrel* (potential for resource damage from fuel spill)” (Lewis Sharman, Glacier Bay National Park and Preserve, e-mail, August 7, 2009).

### **Lacustrine Features and Processes**

According to scoping participants, the quality of freshwater at the national park is “pristine.” Freshwater lakes and ponds are typical features of recently deglaciated landscapes and, as a result, are abundant in Glacier Bay National Park and Preserve (Eckert et al. 2006). Small lakes are particularly numerous in the area between the Dundas River and the southwestern shore of Glacier Bay and in the region between Gustavus and the Beartrack River. Small subglacial lakes probably occur under the Brady Icefield. According to scoping participants, hundreds of thousands of small ponds occur in areas of muskeg, which forms in areas of very recent deglaciation; these ponds are important nesting sites for migratory birds. Moreover, hundreds of tarns (lakes in glacially scoured bedrock basins) dot the environs of the West Arm of Glacier Bay. Vivid Lake, a tarn near Gloomy Knob, is of particular interest to park visitors; the rocks at this easily accessible locale display glacial striations and fossils.

The park also includes large lakes. Boaters often consider Alsek Lake as “marine waters” because of its size. Ten-kilometer- (6-mi-) long Alsek Lake is proglacial (in location and genesis), and icebergs calve into it. In addition to Alsek Lake, large lakes in the park include the unnamed lakes at the termini of the Grand Plateau and the Fairweather glaciers, Crillon Lake, and two “stacked” lakes that drain into Palma Bay. All of these lakes are west of the Brady Glacier.

Scoping participants mentioned Dan Engstrom (University of Minnesota) as having conducted notable research on the lakes in the park, in particular understanding the physical evolution following deglaciation (e.g., Engstrom and Fritz 1988; Fritz and Engstrom 1993; Engstrom et al. 2000; Fritz et al. 2004). Engstrom and others completed a study of 33 lakes ranging in age from 10 years to 13,000 years, demonstrating that lacustrine successional development is closely tied to the ecological development of the land in the surrounding watershed.

Though seemingly odd to classify as “lacustrine,” collapsed forests are a notable feature in the park. Where forest soils and associated trees overlie glacial ice and the ice melts, forests collapse, producing large ponds. One scoping contributor noted that this might be thought of as “plant regression” amongst so much succession in the park. Melted glacial ice has produced an ephemeral pond on a remnant of the Fairweather Glacier. The pond formed in an area where ice underlying the forest melted, and remaining ice and debris collapsed. As the stagnant portion of the Fairweather Glacier continues to melt away, this pond will likely disappear (Eckert et al. 2006).

### **Paleontological Resources**

During scoping, Bob Blodgett (private consultant) gave a presentation on the paleontological resources of Glacier Bay National Park and Preserve, focusing on the Paleozoic Era, in particular Silurian fossils of the Alexander terrane. Between 400 and 430 million years ago, the Alexander terrane was connected to Siberia and the Ural Mountains. Hence, the Paleozoic fossils in Glacier Bay have a distinct Russian-like character. According to Soja (1994), the strong similarities in Silurian marine fossils in southeastern Alaska, the Urals, and Siberia indicate that all these areas must have shared a contiguous seaway in the Northern Hemisphere that allowed generation upon

generation of organisms to transmigrate, intermingle, and undergo genetic exchange. More recently, Blodgett and Boucot (2009) contend that the Alexander terrane is more properly interpreted as a rift fragment of eastern Siberia that was formerly adjacent to the region of the Omulevsk Mountains of northeast Siberia.

Silurian fossils at Glacier Bay National Park and Preserve include bivalves, gastropods, brachiopods, sponges, corals, and calcareous green algae (stromatolites). The primary host rocks are the Willoughby Limestone, Heceta Limestone, and Tidal Formation. Studied first by Edwin Kirk in 1917, the Willoughby Limestone is the “most published” of these formations. Kirk suggested that the bivalve he discovered in the Willoughby Limestone was “the largest known genus of Paleozoic bivalve,” which he called *Pycnodesma giganteum* (not surprisingly). Notable paleontological locales in the park include Drake Island and Willoughby Island. Scoping participants thought that Marble Mountain may also host a diversity of paleontological resources. Some of the park’s Paleozoic fossils are younger than Silurian (e.g., Devonian calcareous green algae, gastropods, and brachiopods from the Black Cap Formation and Permian brachiopods from the Pybus Formation). Devonian fossils in the park are equivalent to those of the Farewell terrane in southwestern Alaska. Bob Blodgett provided an annotated bibliography of paleontological resources (see Annotated Bibliography of Paleontological Resources).

Although Bob Blodgett’s presentation did not highlight Cenozoic fossils, he manages the “Alaska Paleontological Database,” which contains records of more than 14,406 entries from an estimated 24,000 fossil localities, including many younger (Cenozoic) localities (<http://www.alaskafossil.org>; accessed November 30, 2009). Furthermore, Blodgett suggested Louie Marinovich (California Academy of Sciences; [lmarinovich@calacademy.org](mailto:lmarinovich@calacademy.org)) as a potential resource, particularly for mollusks from this time period. Marinovich is “the expert” for Miocene mollusk fossils of the Topsy Formation in the Lituya Bay area, which is a notable paleontological locale and identified in the park’s Government Performance Results Act (GPRA) goal for paleontological resources (Lewis Sharman, Glacier Bay National Park and Preserve, written communication, November 12, 2009). The bibliography in Marinovich (1980) contains the majority of published information about the fossils in the Lituya Bay area (Bob Blodgett, e-mail, July 29, 2009).

In addition, investigators completed an inventory of the paleontological resources for the Southeast Alaska Network in 2008, which lists Cenozoic fossils from the Oligocene, Miocene, Pliocene, Pleistocene, and Holocene epochs as occurring within the park and preserve (Santucci and Kenworthy 2008). Fossils include plants, bivalves, gastropods, fish vertebra, echinoids (sand dollars), gastropods, ostracods, foraminifera, and worm burrows. Of particular interest to John Muir—and seemingly Santucci and Kenworthy (2008), which provided more than a page of John Muir’s quotations on the subject—was “fossil wood.” According to Lawson and Wiles (2008), “these interstadial forests were extensive and their preservation, although discontinuous and fragmented, is remarkable” (p. 3). Many stumps are still rooted in growth position, and logs held within outwash sediments remain from forests that existed at various times between glaciations over approximately the last 10,000 years (Lawson and Wiles 2008). Lawson and Wiles (2008) used interstadial wood to reconstruct the Quaternary landscape history of Glacier Bay.

## **Permafrost Features and Processes**

Scoping participants thought that perhaps some permafrost existed on the shoulder of Mount Wright. Follow-up inquiries with NPS soil scientist Pete Biggam (Geologic Resources Division) who contacted scientists from the Natural Resource Conservation Service (NRCS) in Palmer, Alaska, confirmed that although permafrost is not widespread in the vicinity of Glacier Bay because of the maritime climate, it could definitely be present in small isolated areas of loamy soils at high elevation or north-facing slopes and concave areas that have near-continuous shade (Joe Moore, NRCS, e-mail to Pete Biggam, August 7, 2009).

In addition, post-scoping conversation with GRD staff who have conducted work in the park suggested that thermokarst (ground subsidence resulting from melting permafrost) may occur south of La Perouse Glacier and in the Alsek River valley. However, these suspected areas are probably forest-covered “dead ice” / collapsed forests (see Lacustrine Features and Processes). According to soil scientists Mark Clark and Joe Moore (Natural Resource Conservation Service), established forests on moraine-covered glacial ice are fairly common phenomena in terminal moraines in southeastern and south-central Alaska. The ice and forests may remain stable for decades, but when disturbed by river erosion or warming air temperature, the ice begins to melt, forming pits similar to thermokarst (but on outwash plains). The only difference is that the origin of the ice is glacial and not from permafrost formation (Mark Clark and Joe Moore, Natural Resource Conservation Service, e-mails to Pete Biggam, Geologic Resources Division, August 7 and 10, 2009).

## **Seismic Features and Processes**

The Fairweather fault runs northwest-southeast through Glacier Bay National Park and Preserve, 8–16 km (5–10 mi) inland from the park’s western boundary. The fault plunges under the Pacific Ocean at Icy Point where it joins the Queen Charlotte fault. Regionally, seismic activity is concentrated along this fault system and occurs almost exclusively in large earthquakes (Brew et al. 1991). Locally, most earthquakes occur away from this fault system in a cluster that straddles the Alaska–British Columbia border in the northern part of the park and preserve (Horner 1990). According to the Alaska Earthquake Information Center, four major earthquakes have been linked to the Queen Charlotte–Fairweather fault system in the last century: In 1927 a magnitude (M)=7.1 earthquake occurred north (offshore) of Chichagof Island. In 1949 a M=8.1 earthquake occurred along the Queen Charlotte fault near the Queen Charlotte Islands. In 1958 movement along the Fairweather fault near Lituya Bay created a M=7.9 earthquake. In 1972 a M=7.4 earthquake occurred offshore near Sitka.

As a result of the 1958 Fairweather earthquake, observable displacement occurred from Palma Bay to Nunatak Cove in Glacier Bay National Park and Preserve. Investigators measured the greatest displacement near Crillon Lake: the southwest side of the fault moved 6.5 m (21 ft) to the northwest and 1 m (3.3 ft) upward relative to the northeast side (Tocher 1960). In addition, the earthquake triggered a large rockslide with a volume of about 30 million m<sup>3</sup> (1,059 million ft<sup>3</sup>) at the head of Lituya Bay. The avalanche of rock generated the so-called “world’s largest tsunami wave,” though technically it was not a tsunami (Dave Brew, U.S. Geological Survey, written communication, October 14, 2009). The water surged down the bay, denuding both shorelines to an elevation of about 60 m (197 ft). On the shore opposite of the slide, the wave run-up reached an elevation of 530 m (1,739 ft). Near the mouth of the bay, 11 km (6.8 mi) away, two fishing boats sank, resulting in two deaths (Miller 1960). Scoping participants pointed out that recreationists in low-elevation areas

(e.g., camping on beaches) and any water activities—from kayaks to cruise ships—would be at risk during a similar event in the future. Miller (1960) demonstrated that similar events had occurred prehistorically.

The 1958 earthquake also triggered a submarine slide in Beartrack Cove (Miller 1960) and caused the Alsek River to dam as a result of accelerated ice calving from the Alsek Glacier. When the ice dam gave way a few hours later, flooding occurred (Horner 1990). Finally, scoping participants noted the potential for liquefaction because of ground shaking in areas of the park and throughout Gustavus; of particular concern are structures built on fill.

During scoping, participants facetiously discussed whether park staff members needed to brace themselves for another “large” quake. Based on the probabilistic estimates of Horner (1990), the recurrence interval for an average earthquake nearby is 69 years; this study also estimated the recurrence interval of 120 years for a  $M=7.9$  or larger earthquake on the Fairweather–Queen Charlotte fault system. However, the recurrence interval for the Fairweather fault alone is 67–85 years (Lisowski et al. 1987). Earthquakes of  $M=6.0$  or greater can be expected every five years (Horner 1990).

### **Unique Geologic Features**

Often “unique geologic features” are mentioned in a park’s enabling legislation; these features are of widespread geologic importance and may be of interest to visitors and worthy of interpretation. Moreover, type localities and isotopic age dates are unique geologic resources, and are, therefore, of interest to a park’s geologic inventory. During his presentation, Bob Blodgett mentioned that the type section for the Willoughby Limestone is Willoughby Island. Dave Brew is in the process of preparing a manuscript that contains 30 isotopic dates from plutonic rocks in Glacier Bay National Park and Preserve. In 1978, Bruce Johnson collected geochemical data specific to Glacier Bay (Johnson 1978). In addition, Greg Streveler has compiled hundreds of carbon-14 dates from interstadial wood and peat within the park. Finally, in the early 1990s, the U.S. Geological Survey created an archive of geochemical data for Alaska that contained 330,000 samples.

### **Volcanic Features and Processes**

Volcanic rocks and processes are not prevalent in Glacier Bay National Park and Preserve. However, one notable ash layer exists—an 11,250-year-old, 15-cm- (6-in-) thick bed of volcanic ash from Mount Edgecumbe, near Sitka National Historical Park. Good exposures of this ash occur in Adams Inlet. This layer documents the largest late Pleistocene eruption from Mount Edgecumbe (Begét and Motyka 1998). In addition to Glacier Bay (McKenzie 1970), investigators have recognized this ash layer in Sitka (Yehle 1974) and Juneau (Heusser 1960). Because ash contains minerals with datable elements such as potassium and argon, ash layers are useful tools (i.e., tephrochronologic marker horizons) for putting recent geologic events in sequence on a regional scale.

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## **Annotated Bibliography of Paleontological Resources**

*Compiled by Bob Blodgett, July 28, 2009*

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**Table 5. Scoping Meeting Participants and Post-Meeting Cooperators**

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