



Fractures, Scarps, Faults, and Landslides Mapped Using LiDAR, Glacier Bay National Park and Preserve, Alaska

Natural Resource Report NPS/GLBA/NRR—2023/2605





ON THIS PAGE

Photograph of a rockslide scar near Sandy Cove that failed between November 15 2021 and January 31 2022 (NPS Photo)

ON THE COVER

Photograph of the south shore of Reid Inlet showing the abundant scarps running parallel with the ridge (NPS Photo).

Fractures, Scarps, Faults, and Landslides Mapped Using LiDAR, Glacier Bay National Park and Preserve, Alaska

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Abstract

This map of fractures, scarps, faults, and landslides was completed to identify areas in Glacier Bay National Park and Preserve that may present a landslide-generated tsunami hazard. To address the potential of landslide and tsunami hazards in the park, the National Park Service (NPS) and the U.S. Geological Survey (USGS) partnered to conduct a multi-year hazard assessment of Glacier Bay National Park and Preserve. To produce the map described in this report, we used the newly acquired (2019-2020) light detection and ranging (LiDAR) 0.5 to 1.0 m digital elevation models (DEMs) that cover all the coastal areas of the park and extend up to the ridgetops in places with steep slopes. A bare earth DEM was used to identify and map areas of incipient landslides (i.e., fractures and scarps), fault scarps, and areas where landslides have occurred in the past (i.e., areas where scars and deposits are clearly visible). This map provides a baseline data set that can be used to aid forecasts of where landslides are most likely to occur in the future.

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Introduction

Glacier Bay National Park and Preserve (referred to as “the park” herein) has a history of earthquake- and climate-induced rockslides and rock avalanches (Miller, 1960; Post, 1967; Evans and Clague, 1999; Geertsema, 2012; Bessette-Kirton and Coe, 2016; Coe et al., 2018; Bessette-Kirton et al., 2018). When these landslides rapidly enter the water, they can generate tsunamis with extraordinary destructive power. This phenomenon was demonstrated by both the 1958 Lituya Bay earthquake-triggered rockslide and tsunami (Miller, 1960) and the 2015 rock avalanche and tsunami in Taan Fiord in Wrangell-St. Elias National Park and Preserve (Higman et al., 2018). The park’s proximity to the active Fairweather and Icy Point–Lituya Bay faults at the boundary of the North American and Pacific tectonic plates (Figure 1) guarantees that large earthquakes could impact the park and trigger landslides in the future. However, in southern Alaska, the dominant triggering factor for landslides may be climate effects, rather than earthquakes (Coe et al., 2018, 2019; Bessette-Kirton and Coe, 2020). Climate change is causing permafrost degradation and deglaciation in Alaska (e.g., Hinzman et al., 2005; Jorgenson et al., 2006; Hock et al., 2019). Alpine permafrost degradation (i.e. melting of ice in fractures in rocks) reduces the cohesion and shear strength of rock (e.g., Svennevig et al., 2022), whereas glacier retreat and downwasting damages rock (e.g., Grämiger et al., 2017) and removes support from steep slopes (i.e., debutresses the slopes, e.g., Kos, et al., 2016; Dai et al., 2020), which may make them more susceptible to failure.

To address the potential of landslide-generated tsunami hazards in the park, the National Park Service (NPS) and the U.S. Geological Survey (USGS) partnered to conduct a multi-year hazard assessment of the park. The mapping project described in this report is part of the baseline studies needed for the hazard assessment which also includes mapping of submarine and subaerial-to-submarine landslides (Avdievitch et al., 2020), submarine landslide susceptibility mapping (Avdievitch and Coe, 2022), and Interferometric Synthetic Aperture Radar (InSAR) mapping of ground deformation (Kim et al., 2022). These mapping projects will be used to inform future fieldwork, hazard maps, and tsunami modeling.

To produce the map of fractures, faults, scarps, and landslides (Plate 1; <https://irma.nps.gov/DataStore/Reference/Profile/2299382>) that we describe in this report, we used the newly acquired (2019-2020) light detection and ranging (LiDAR) 0.5 to 1.0 m resolution digital elevation models (DEMs) that cover all the coastal areas of the park and extend up to the ridgetops in places with steep slopes (Figure 2). LiDAR acquisition was planned and funded by NPS, the City of Gustavus, and the USGS (3DEP, <https://www.usgs.gov/3d-elevation-program>). The LiDAR coverage area (a land area of 5100 km², Fig. 1 and Plate 1) provides a detailed DEM of landslide prone areas along the coast. Areas along the Fairweather fault on the western coast of the park were funded by USGS 3DEP and the USGS Earthquake Hazards program in support of on-going research on the Fairweather fault (Witter et al., 2017; Lease et al., 2021; Witter et al., 2021).

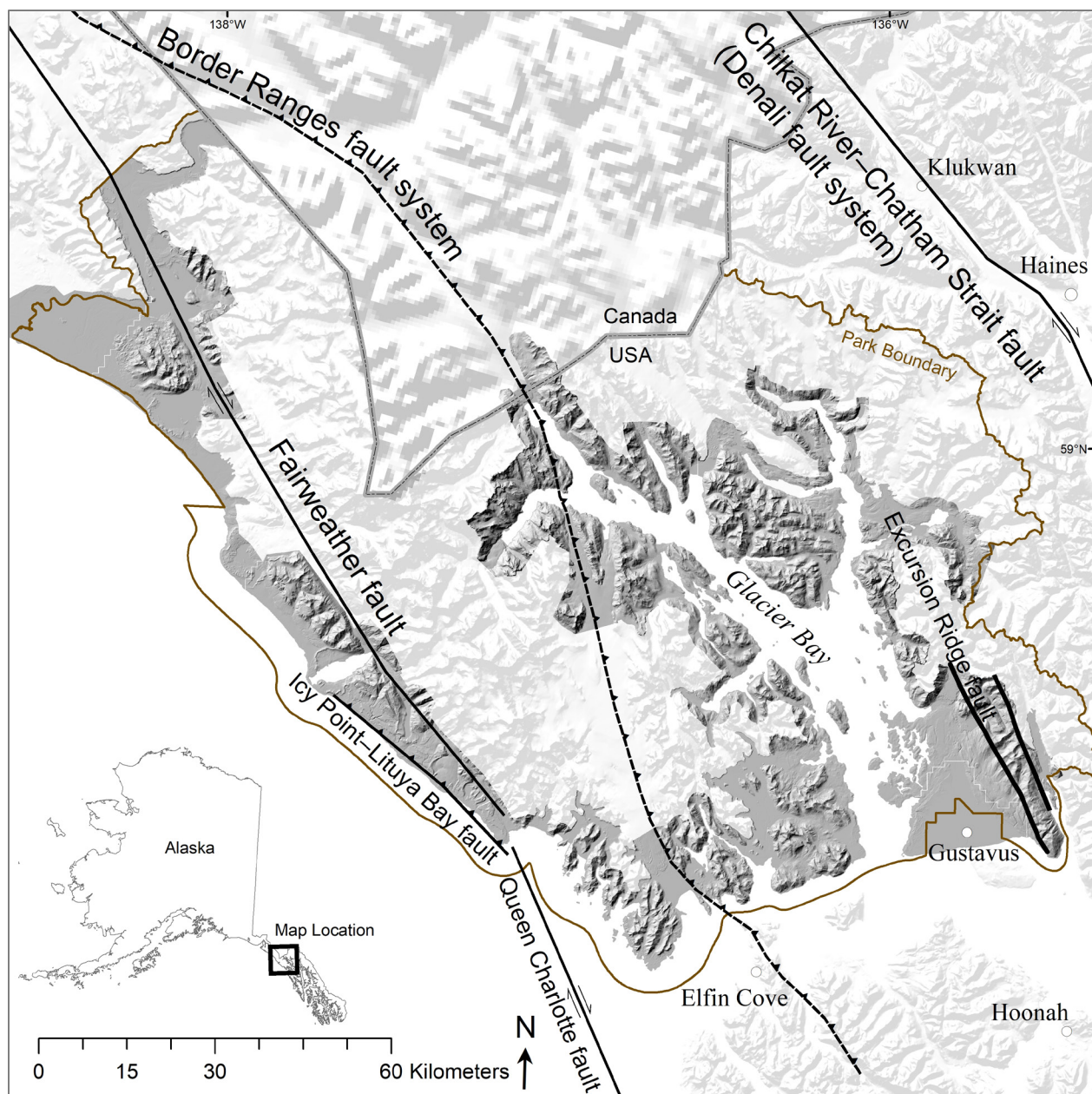


Figure 1. Map showing the extent of the LiDAR coverage and locations of the major faults in the park. Quaternary faults include the Icy Point–Lituya Bay, Fairweather, and Excursion Ridge (new) faults (Plafker et al., 1994; Witter et al., 2021; this study). To the east of the park, the Chilkat River–Chatham Strait fault is considered the southern-most extension of the Denali fault zone, with possible movement on this segment in the Quaternary (Plafker et al., 1994). Also, shown as a dashed line, is the pre-Quaternary Border Ranges fault system (Wilson et al., 2015), which forms a major divide between contrasting rock units in the park and forms a topographic trough.

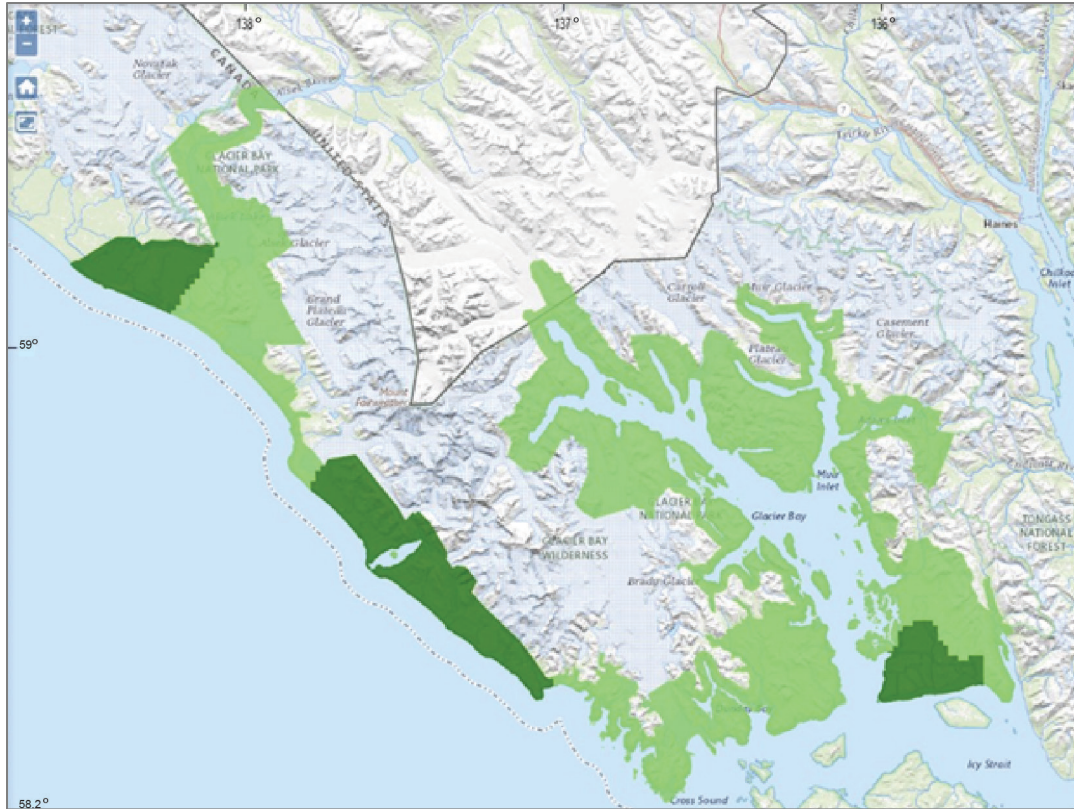


Figure 2. Map area and LiDAR coverage as shown on the USGS 3DEP LiDAR Explorer. Light green areas are QL2 resolution data (1 m DEM) and dark green colors are QL1 resolution data (0.5 m DEM). (<https://apps.nationalmap.gov/lidar-explorer/#/>; accessed January 2023).

LiDAR data were processed to remove vegetation and produce high-resolution topography of the bare earth (i.e., a bare earth DEM, e.g., Haugerud et al., 2003). As a result, these LiDAR data can be used for mapping landslide scarps and deposits, as well as fractures and other features that may indicate ongoing slope deformation. In addition, this bare earth DEM can be used to efficiently identify and map areas of incipient landslides (i.e., cracks and scarps), and areas where landslides have occurred in the past (i.e., areas where scarps and deposits are clearly visible). Our map of these features ([Plate 1](#)) provides a baseline data set that can be used to aid forecasts where landslides are most likely to occur in the future. LiDAR also provides a means to characterize the structural fabric of rock that contributes to the overall stability of bedrock.

Rock fabric describes discontinuities (fractures, joints, and bedding planes) in a rock mass and is often quantitatively assessed using rock-mass-quality ranking schemes that account for the orientations, density, and characteristics of discontinuities (e.g., Coe et al., 2005; Marinos et al., 2005; Basahel and Mitri, 2017). Rock-slope stability is often determined more by the rock fabric than by inherent, intact rock strength (Basahel and Mitri, 2017). That is, rock slides, falls, and topples usually move along existing zones of weakness and discontinuities. Our LiDAR-based map ([Plate 1](#)) includes rock fabric and can be used to prioritize areas where field work is needed to better define and map differences in rock-mass-quality.

LiDAR

LiDAR data covering all the coastal areas and up to the ridgelines in steep areas (Figure 2) were collected and processed by Quantum Spatial (acquired by NV5 GeoSpatial Inc. Hollywood FL) in 2019 and 2020. Areas along the Fairweather fault, around Dry Bay, and around Gustavus were flown at higher resolution QL1 specifications (Heidemann, 2018), producing a DEM with a 0.5 m resolution. The rest of the park was flown at lower resolution QL2 specifications (Heidemann, 2018), producing a 1.0 m resolution DEM (see Heidemann, 2018, and the USGS 3DEP website (www.usgs.gov/3d-elevation-program) for details about the QL1 and QL2 specifications). LiDAR point cloud data were processed by Quantum Spatial to produce the bare-earth DEMs used in this mapping project. For optimal shadowing and highlighting of features of interest, we produced hillshades in two directions with illumination from the NE and NW. These two hillshades assured that differently oriented features were highlighted or shadowed for best visibility.

Where InSAR work by Kim et al. (2022) detected ground deformation outside of the area covered by LiDAR, we used high-resolution (0.50 m) Maxar satellite imagery available through the ArcGIS World Imagery Basemap service (https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer/4; accessed January 2023) to map landslide features local to the InSAR ground deformation area ([Plate 1](#)).

Previous Mapping

Previous mapping of geology, bedrock fabric, and landslides in the park was either highly localized, or highly generalized. Bedrock geology maps for the park were compiled for a statewide map by Wilson et al. (2015). The primary sources compiled for the park were Brew and Ford (1985) and Brew (1997); however, portions of the Rossman (1963) map for the central portion of Glacier Bay were also included in the compilation with some minor changes. The Wilson et al. (2015) compilation does not distinguish younger faults from older faults, but does show abundant faults throughout the park, and provides names of the main fault systems. Numerous past surficial mapping projects have focused on lowland glacier deposits, which are not relevant to this bedrock landslide-focused mapping effort.

The neotectonic map of Alaska by Plafker et al. (1994) includes many faults from previous geologic maps of the park but shows most of them as pre-Neogene faults. The only Neogene faults that Plafker et al. (1994) show in the park are the Fairweather and Icy Point–Lituya Bay faults (Figure 1). The Excursion Ridge fault shown in Figure 1 was mapped by Brew and Ford (1985) and is shown as a pre-Neogene map in Plafker (1994); but is shown herein as a newly named Quaternary fault (its expression in the LiDAR described below). Witter et al. (2021) also mapped numerous active fault strands and landslide scarps using a previous LiDAR collection along the faults, and we also mapped numerous fault strands and associated landslide features along these faults ([Plate 1](#)).

The Plafker et al. (1994) map also shows a suspected Neogene fault near Fossil Peak, west of Geikie Inlet (see location of Fossil Peak in [Plate 1](#)), which was described by Seitz (1959) as an active fault. However, we interpret these features as landslide related fractures and scarps. InSAR work by Kim et al. (2022) detected ground deformation in a couple areas near Fossil Peak. The area was not covered by LiDAR, so we reviewed Maxar satellite images and identified numerous landslides, scarps, and linear fractures ([Plate 1](#)). We suspect that what appeared as a fault to Seitz, was likely a developing scarp of a sackung (sagging and ridge spreading, see definition below), because sackungen (features formed by sackung) can often be mistaken for faults (e.g. Varnes et al., 1989). The Fossil Peak area is notable because it contains a dense cluster of three large landslides and numerous scarps.

A wealth of previous work has also shown landslides to be ubiquitous in the region, though this report represents the first comprehensive map of landslides in the park. Miller (1960) mapped landslides and fractures on the hillsides at the head of Lituya Bay after the 1958 landslide-generated tsunami. Wieczorek et al. (2007) mapped the scarps of the Tidal Inlet landslide. Mapping of submarine scarps and subaerial-to-submarine landslides, debris-flow fans, and glacial-outwash deltas was completed by Coe et al. (2019), Avdievitch et al. (2020), and Avdievitch and Coe (2022) using bathymetry of various resolutions and the statewide interferometrically derived 5 m resolution DEMs for subaerial areas. Bessette-Kirton and Coe (2016) mapped large ($> 0.5 \text{ km}^2$ in area) rock avalanches that were visible on glaciers from 1984 to 2016 using Landsat satellite imagery. Bessette-Kirton et al. (2018) mapped a large, 2016 rock avalanche that traveled onto the Lamplugh glacier. Becker et al. (2012) created a surficial geologic map of the park using air-photos and a Shuttle Radar Topography Mission (SRTM) DEM. The U.S. Forest Service mapped landslides in the Tongass National Forest

adjacent to the park boundary on the east side (USFS, 2020). The USFS landslide compilation shows a cluster of landslides adjacent to the Mein Valley area where there is a dense cluster of fractures and faults ([Plate 1](#)).

The glacial history of the area is important to understanding both the age of exposure of the features mapped for this study, and the age of exposure and evolution of the landscape in general. Glacier deflation and debulking of slopes adjacent to deflating and retreating glaciers may be important factors that influence landslide susceptibility (e.g., Dai et al., 2020). Although we do not specifically address these factors in this map report, a history of glacial thinning or thickening (such as reported in Loso et al., 2014) or retreating glacial terminus positions (such as reported in Powell, 1980 and Avdievitch and Coe, 2022) may likely be important factors to consider for future landslide susceptibility mapping.

An understanding of post-glaciation isostatic rebound in the park (e.g., Larsen et al., 2005) is also important to understanding the stability of the landscape. For example, tectonic uplift has been shown to increase landslide frequency (Roering, 2012). In the park, isostatic rebound has been significant (> 200 m since the last glacial maximum; see Larsen et al., 2005; Baichtal et al. 2021). This large amount of rebound in a relatively short period has likely influenced the stability of the landscape.

Mapping Explanation

We examined the LiDAR data to map fractures, scarps, faults, and landslides. These features are indicators of bedrock displacement due to tectonic or gravitational stress that exceeds the local bedrock shear or tensile strength. We mapped fractures where cracks were apparent, but the sense of displacement could not be determined. We mapped scarps where fractures had visible dip-slip shear displacement. Landslide headscarps were mapped at scarps at the heads of landslides where significant downslope displacement of landslide blocks had occurred. In most cases, mapped scarps were due to landslide displacement, with most of these scarps being from deep-seated landslide movement resulting from slow gravity ridge-spreading, forming sackungen. In a few cases, where scarps were linear, laterally extensive, and not clearly related to landslide movement, they were mapped as faults. Landslide deposits were mapped where material was significantly displaced from its source and deposited by landslide movement. More detailed descriptions of these features are provided in the sections below.

During mapping, a constant scale was not always maintained, but features were typically mapped at a scale of about 1:5,000, with some areas mapped at scales up to 1:10,000. In some areas, the LiDAR DEM-derived hillshade covered by QL2 quality (1 m resolution) often has features resolvable down to the 1:3000 scale, but in other areas, features are not as clear at that scale. Because of the variability in feature resolution and the large size of the map area ($>5,000 \text{ km}^2$), the general intent of the mapping was to capture landslide features at a regional 1:10,000 scale. Where a mapped feature was visible, but its type was uncertain, dashed lines were used to represent uncertainty.

Distinguishing fractures and scarps from sedimentary rock bedding was sometimes difficult. Limestone, sandstone, silt, and shale units are abundant in the map area, and bedding was apparent in the LiDAR where these units cropped out. Where bedding was dominant and was clearly not associated with any fractures, we did not map any features. However, there are locations where bedded units are intersected by fractures that locally run parallel with bedding (e.g.: Lituya Bay and Excursion Ridge). In these areas, mapped fractures, scarps, and faults may instead be bedding where they have similar attitudes and topographic expression. Another challenge was mapping fractures, scarps, and faults in steep (often high altitude) areas because of the abundance of jagged and blocky terrain underlain by bedrock.

Fractures

A fracture line feature was mapped when a break in the rock or surficial materials was visible and generally linear and did not have visible shear displacement. Some mapped fractures could be strands of faults, or linear fault scarps, but if we were not sure about their origin, we simply mapped them as fractures. Fractures, faults, and scarps are often found in clusters, which may indicate that they have a common origin.

Scarps

Scarps were mapped where arcuate and linear fractures had visible dip- or oblique-slip shear displacement. To be consistent with our mapping of fractures and faults, which we delineated at the locations of existing weaknesses (cracks), we mapped scarps in the troughs at the base of the scarps

rather than at the top edge (crest) of a scarp. However, in a few places where large landslide headscarps are visible above concavities where material had moved, we mapped the scarp at the crest in order to delineate the outermost extent of landslide areas.

Many of the scarps mapped were found near ridge tops and were uphill facing, which are indicative of sackungen scarp geometries (e.g. Varnes et al., 1989). Sackungen scarps are formed by gravity sliding near ridge top either by slow sagging and spreading of fractured rock or during seismic shaking. Sackungen are common along ridges and in the hills surrounding tectonic faults.

Mapped scarps represent landslide scarps, and sackungen, but may also locally be tectonic fault scarps, especially along the Fairweather, Icy Point–Lituya Bay, and Excursion Ridge faults ([Plate 1](#)). Wide (> 1km) damage zones were evident along these faults, so delineation between fault scarps and landslide scarps was sometimes challenging. The hills adjacent to the Fairweather fault have lateral moraines that are coincident with landslide scarps. In these areas, differentiating uphill facing scarps from lateral moraines can be challenging. So, it is possible that some lateral moraines were incorrectly interpreted as scarps. In a few locations where scarps were parallel with the strike of bedding, we may have incorrectly mapped steps in sedimentary beds as scarps.

Faults

We mapped scarps as faults when we could identify laterally extensive scarps or linear chain of scarps and fractures that continued over multiple ridges and valleys. In places where fractures or scarps ran parallel and adjacent to the mapped faults, we also mapped them as faults because they appeared to be closely related to the main fault.

Where we observed faults offsetting glacial or post-glaciation deposits, those segments were mapped as Holocene faults (Fault Holocene in [Plate 1](#)). As an example, we observed numerous offsets of alluvial and glacier materials along the Icy Point–Lituya Bay and Fairweather faults (Figure 1; also see Witter et al, 2021).

We suggest there is a third possible Quaternary fault system, which we call the Excursion Ridge fault system (Figure 1). Along the informally named Excursion Ridge, there are two trends of linear fractures and scarps that appear to have formed post-glaciation and are on trend with topographic troughs that extend for a distance of about 30 km. One of these lineaments was mapped by Brew and Ford (1985) as a fault, but they did not assign an age to the fault. Although we did not observe Holocene sediments offset by the faults, the relatively sharp-edged fractures and scarps along the glaciated hills and valleys suggest that the fault has been active in the Quaternary, which could be determined by future study.

Landslides

Landslides were mapped using three different types of polygons:

Landslide—displaced blocks on steep slopes bounded by scarps,

Landslide debris—hummocky lobes of material at valley bottoms that could be identified as blocks or debris that were transported by landslide displacement,

Landslide undifferentiated or incipient—general areas with abundant scarps that appear to indicate unstable slopes but without clearly identifiable landslide boundaries.

Talus, scree, fans, and other colluvium deposits were not mapped as landslides because the focus of the greater landslide study is to identify deep-seated landslides with potential to generate a tsunami.

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