

Draft Geology and Geologic Hazards Assessment

Tongass National Forest Plan Revision



Cover Photo: Calder Mountain on north Prince of Wales Island. Photo by Anna Harris.

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Introduction

This section will discuss the overall geology and important geologic types and features of the Tongass National Forest (Tongass or forest), and the geologic hazards known to cause negative effects to people, infrastructure, and property.

Resource Importance

The basic geologic makeup and history of the region is important for understanding effects of management. Geology affects the landforms, sometimes the vegetation, and the way ecosystems function. It also affects how humans interact with the landscape in terms of potential risks and where and how the Tongass is experienced. The overview of the general geology of this area and risks and trends associated with geology and geologic hazards focuses on geologic considerations that affect or can be affected by management of the Tongass National Forest.

Distinct and Variable Geology

The Tongass National Forest is dominated by steep, rugged terrain. This terrain was created by the convergence of the Pacific and North American Plate, making this region tectonically active and subject to earthquakes, volcanoes, and tsunamis. The landforms and rocks of Southeast Alaska are highly variable, resulting from the Pacific Plate being scraped off and welded to the North American Plate, which created what are called accreted terranes. These varying rock types are important because the type of rock can create different landforms and can influence vegetation types or vegetation growth potential. Figure 1 shows the major known faults in the region and the general layout of accreted terranes (Audubon Alaska 2016). Many other faults occur in the area, which are mostly part of the same Queen Charlotte-Fairweather fault system. The Queen Charlotte-Fairweather fault system is the boundary between the Pacific and North American Plates, which is a strike-slip fault with the west side (Pacific Plate) moving northward relative to the east side (North American Plate).



Figure 1. Simplified map showing the various accreted terranes in Southeast Alaska, and the fault lines in the area (Audubon Alaska, 2016, p. 12). Note: most of the karst landscapes on the forest are in the Alexander Terrane.

The converging plates created mountains along the Alaskan and Canada coastlines, and most of those mountains were subsequently carved by glaciers, creating deep valleys and steep-sided fjords on the mainland, many which are still filled with glaciers. Portions of the outer islands were not covered by glaciers during the last glacial maximum (when ice sheets were most recently at their greatest extent, between 20,000 and 26,000 years ago), and are therefore made up of rolling hills. Many faults are still active, continuing to shape this dynamic landscape. With earthquakes, volcanoes, and glaciers still active today, the land is dynamic and geologic hazards are prevalent (*USGS 2020, Audubon Alaska 2016, Nowacki et al 2001*). The steep terrain in these coastal mountains also contributes to active weather, including heavy rains, heavy snow, and wind as the moisture from the Gulf of Alaska is forced upward by the steep terrain, cooling it so it condenses and falls as rain, or snow in colder months.

Geology affects geologic hazards, development potential, and sometimes vegetation types. There are some geologic types that require distinct management considerations, which are called out in the current Forest Plan and remain important. The management implications of these geology types will be discussed in more detail below.

Geologic Hazards: Risk to Life, Property and Infrastructure

Steep and active geologic terranes create this landscape and its bountiful terrestrial and marine environment. When human development occurs in the same location as these terranes, where heavy rain, snow and wind occur, some of these natural processes become geologic hazards. Landslides, floods, earthquakes, tsunamis, snow avalanches, and sinkholes can all negatively impact human life and property.

Geologic hazards can affect many aspects of human life. They can block or damage roads and bridges important to access to homes, communities, subsistence, recreation, cultural sites, communication sites, mining, or other resource use. They can threaten private infrastructure, either on or off the Tongass National Forest, leading to loss of property or loss of life. They can affect communication infrastructure through damage to communication sites, power lines, or other facilities. They can also lead to threat to property or life to Forest Service developments such as visitor centers, roads, or campgrounds.

Ecological Drivers

The ecosystems on the Tongass National Forest formed with frequent disturbance as a natural phenomenon due to the dynamic landscape and weather, an important driver of ecological processes, sometimes hazardous to people. Disturbance is necessary for ecological integrity, since it creates diversity in soils, vegetation, and landforms, often resetting ecosystem to early seral states (Walker et al. 2009). Small scale diversity, or heterogeneity, is important in supporting natural variation in function and species. Landslide disturbance can be important for creating heterogeneity in soils and vegetation and landslides cause the largest area of disturbance of any natural phenomena on the Tongass National Forest.

Flooding can be important for maintaining species diversity, spreading nutrients and scouring channels, with both positive and negative ecological effects. It brings fresh water and nutrients into the marine environment and carries sediment into wetlands and floodplains. Continuation of natural flood processes is integral for maintaining stream and river aquatic and riparian ecosystems.

Karst landscapes are created when water dissolves carbonate rocks and creates subsurface drainage systems. These activities can create sinkholes, which can be hazardous. They also create unique and important features and ecosystems such as springs and caves which supports some of the highest productivity forests on the Tongass due to good water drainage. Caves support unique and endemic species and are also culturally important, having been used by humans for millennia (*Audubon Alaska 2016, Griffiths et al. 2002*).

Resource History and Current Management Direction

There are many geologic hazards in the area in and surrounding the Tongass National Forest. Those that can be affected by human activities, especially landslides, flooding, karst, and windthrow, are well documented, well monitored, and are largely addressed in current management on the Tongass.

The current plan has an entire appendix (Appendix H) dedicated to consideration and protection of karst landscapes. There are standards and guidelines for karst landscapes included in the management direction throughout the current Forest Plan.

The current Forest Plan also contains direction on avoiding specific activities in specific soils or geologic types (e.g. such as avoiding road building on collapsible schist or avoiding vegetation removal on slopes over 72%). These management directions have been reviewed to determine whether these specific avoidance measures remain appropriate, considering climate change, access needs, technology, and societal expectations. While monitoring has shown that existing direction and practices have minimized slope failures, further data could help improve understanding.

The current Forest Plan also refers to Region 10 Best Management Practices and Soil Quality Standards, and National Best Management Practices and Soil Quality Standards. These must continue to be referenced and met under any Forest Plan.

There have been some changed conditions and new information since 1997 that warrant a review of existing direction for geologic features and geologic hazards. Foremost are effects of climate change, which have become more evident and better understood. The Tongass, State agencies, and researchers have also completed 30 years of monitoring on landslide distribution, flooding, and culvert and bridge effects. There has been an increase in restoration activities on streams, with a greater emphasis on returning streams to natural conditions. Timber practices have also changed since 1997, mainly in reducing timber harvest, especially in old growth forests. These changed conditions and their effect to changing geologic hazards will be discussed in this assessment.

Scope and Scale of Assessment

The geologic hazards section describes the negative effects of geologic hazards to people, infrastructure and access. Considerations of effects of geologic processes as ecosystem drivers and stressors will be covered under the terrestrial and aquatic ecosystem assessment sections.

The geology and geologic hazards section will look at the entire landscape, both within and outside the boundaries of the Tongass National Forest. Geology and geologic hazards cross land management boundaries, and considering effect both from, and to, other lands is important for understanding implications.

The geologic characteristics discussed include those that require specific management consideration. They include:

- Karst and associated caves
- Glacial till and recently deglaciated areas
- Collapsible schist

-
- Ultramafics

The scope will include the major geologic hazards which can affect, or be affected by, Tongass National Forest management. These geologic hazards include:

- Flooding
- Landslides
- Earthquakes
- Tsunamis
- Volcanic activity
- Snow avalanches
- Karst collapse/sinkholes
- Acid rock drainage
- Windthrow

Status and Trends

Geologic Settings

Important geologic types cause distinct management considerations. This can be because they are especially prone to disturbance, they have specific ecological importance, specific laws, or cultural importance. A brief description of each important geologic type, along with management implications for those geologic types, is included here.

Karst and Associated Caves

General Description

Karst systems are unique for many reasons, one contributing factor is the transport rate of groundwater, which can flow rapidly and for long distances subsurface, making these ecosystems vulnerable to pollutants. This is correlated to the epikarst zone on the surface, which consists of cracks and fissures that connect to larger subsurface conduits, allowing for surface water to easily enter the groundwater system, re-emerging again as surface water at springs, which can be far away from the source. Karst landscapes promote better drainage than most other geologic types on the Tongass National Forest.

Karst landscapes have been mapped on about 423,000 acres of the Tongass, spread mostly throughout the islands (Figures 2 and 3), with about 654,000 acres of mapped karst landscapes across all Southeast Alaska. The karst on the Tongass National Forest is mainly found in the Alexander Terrane, shown in Figure 1 (Baichtal and Swanston 1996). Karst applies to the unique topography, surface and subsurface drainage systems, and landforms that develop by the action of water on soluble carbonate rock (primarily limestone and marble). The dissolution of the rock results in the development of internal drainage, producing sinking streams (streams that sink into the stream bed or karst features), closed depressions, sinkholes, collapsed channels, micro relief karst features (e.g. karren), and caves. The Tongass National Forest contains the largest known concentration of solution caves in Alaska (Tongass National Forest 2013). Karst is especially prevalent in the northern part of Prince of Wales Island.

Laws require a process to review and manage cave and karst resources, rare ecologic resources inside caves, water quality, and archaeological and culturally important resources that are often found in caves.

The Federal Cave Resources Protection Act of 1988 requires protection of significant caves and resources within those caves, including plant and animal life and non-biological resources, and requires that significant caves are considered in preparation or implementation of any land management plan on Federal lands (Public law 100-691). The Cave and Karst Research Institute Act of 1998 established intent to research cave and karst systems with the goal of increasing knowledge of these resources and measures needed for the protection of cave and karst resources.

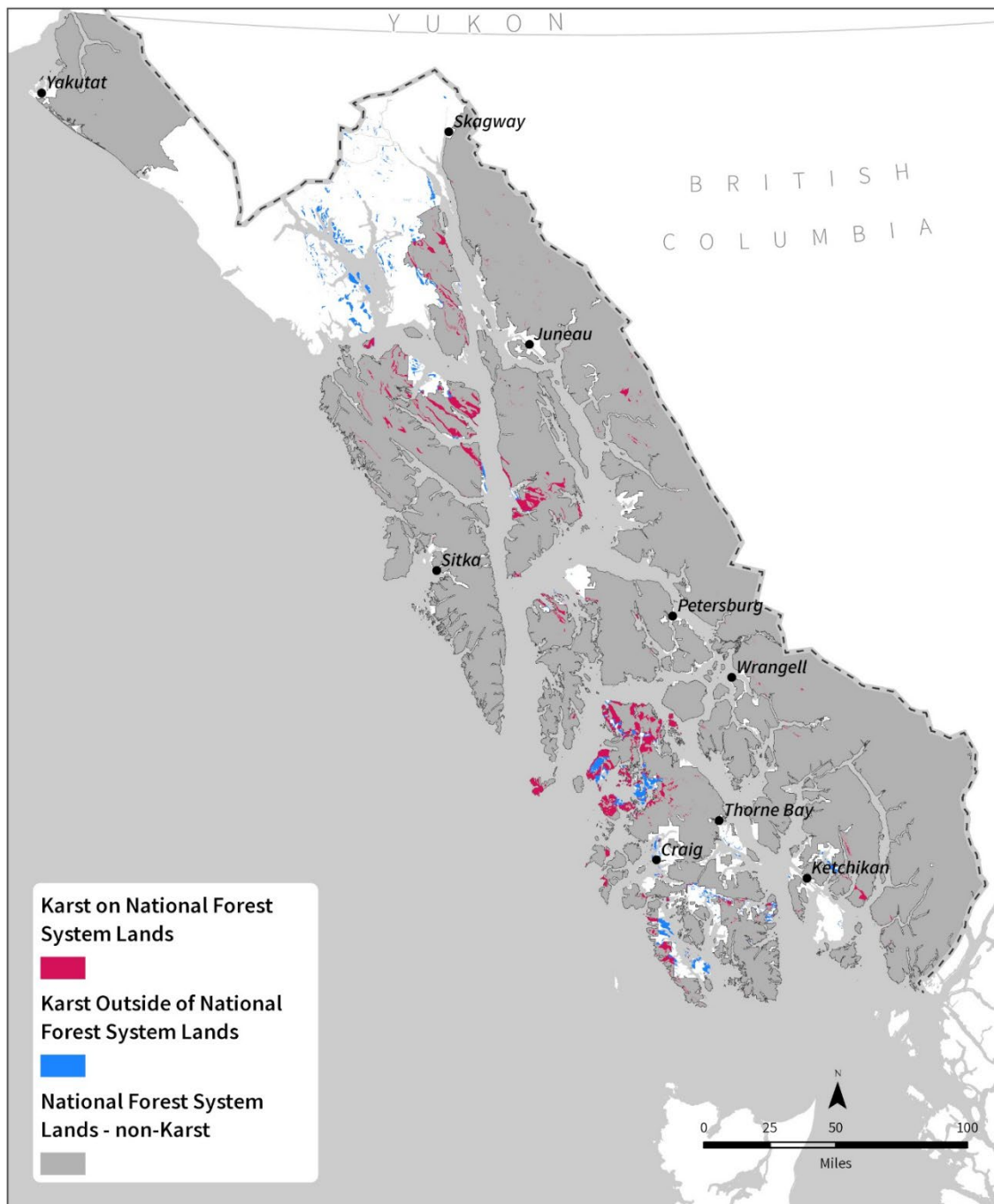


Figure 2. Mapped karst across the Tongass National Forest and in adjacent areas.

The current Forest Plan contains extensive direction to monitor and protect karst and cave resources. Forest-wide direction for management of karst and caves is included in Chapter 4 of the current Forest Plan. Where it differs from forest-wide direction, karst and cave direction for specific land use designations (LUDs), is included throughout Chapter 3. Appendix H describes the strategies for karst and cave systems, including vulnerability rating classifications and mapping. Overall, karst and cave resources are well represented in the current Forest Plan (Tongass National Forest, 2016).

Vulnerability mapping recognizes that some parts of a karst landscape are more sensitive than others. The key elements of the strategy focus on the openness of the karst system and its ability to transport water, nutrients, soil and debris, and pollutants into the underlying hydrologic systems. The strategy strives to maintain the capability of the karst landscape to regenerate a forest after harvest, to maintain the quality of the waters issuing from the karst hydrologic systems and protect the many resource values within the underlying cave systems as per the requirements of the Federal Cave Resources Protection Act. For example, timber harvest is not suitable in areas of high vulnerability karst.



Figure 3. Epikarst, which is the top layer in karst regions, and the point of contact between surface and subsurface water. This is in a sub-alpine area, and you can see where melting snow, or rain, can run into these deep cracks and feed aquifers below. If the karst is continuous, water from this site could directly feed springs or resurgent streams many miles away from this location and at lower elevations. Photo taken by Anna Harris, U.S. Forest Service.

Ecological Importance

A few characteristics of karst landscapes on the Tongass include mature, well-developed spruce and hemlock forests along valley floors and lower slopes, increased productivity for plant and animal communities, extremely productive aquatic communities, well-developed subsurface drainage, and the underlying unique cave resources (Baichtal and Swanston 1996, Wissmar et al. 1997, Bryant et al. 1998). The largest trees on the Tongass grow in these well-drained landscapes, and therefore, karst landscapes had disproportionate amounts of timber harvest in the past, compared to their overall area.

Cave systems provide habitat for many species. Some species are limited only to caves, such as cave-adapted invertebrates. Cave entrances are used by birds for nesting and feeding, and rookeries for sea birds (Baichtal and Swanston, 1996). They are used for shelter or den sites by mammals, and critical roosting and hibernating habitat for bats. The karst landscape influences fisheries in how it affects stream chemistry because water from karst systems has higher alkalinity (more basic, or less acidic). Karst-related aquatic systems are more productive than non-karst areas, with higher biodiversity, higher growth rates for smolts and resident fish, less variable water temperatures and flow regimes, and unique habitat features (Baichtal and Swanston, 1996).

Human importance

Caves have always been used for shelter and ceremony for Alaska Natives. Some caves on the Tongass National Forest are recreational and educational interpretive sites, such as El Capitan Cave on north Prince of Wales Island. Caves also preserve paleontological and archaeological resources, such as bone and organic materials, exceptionally well due to the cool, stable conditions.

Karst aquifers can store and transmit large amounts of water and are therefore a source of drinking water. While few municipal water supplies are sourced directly from a spring in a karst landscape, some are fed either partially or fully through karst systems, such as Port Protection. Because karst-related underground streams are directly connected to surface water, they do not get filtered out as most groundwater can be. Therefore, any water quality impacts higher in the karst system could impact drinking water quality at the resurgent end.

Karst systems include sinkholes, where karst collapses or dissolves over time. Sinkholes can be a threat to human property if they form near infrastructure such as a road or buildings. Although sinkholes exist throughout karst systems, sinkhole collapse has not been identified as a major hazard in this region.

Management considerations

Karst ecosystems are productive but fragile. Development on them can lead to sinkhole collapse, desertification, flooding, water quality degradation, or rapid contaminant transport. The main stressors of concern that can affect karst systems are hazardous spills, timber harvest, road building, or other land disturbing activities.

Timber harvest can affect hydrology and sediment delivery if it causes direct disturbance of karst openings or creates erosion that leads to higher levels of sediment washed into cracks, tunnels, or sinkholes. These changes could affect caves far away from the harvest if sediment was transported through the underground tunnels, or flows were altered in tunnels, caves or springs. Soils tend to be shallow in karst landscapes, and therefore more susceptible to relatively large soil loss through heavy equipment use. In the 1990s, during larger-scale timber harvest with fewer protections, observers found evidence of increase surface runoff after timber harvest, and additional runoff from road surfaces diverted into karst features. There was also evidence of cave flooding after timber harvest, thought to be beyond natural levels (Baichtal 1993). In addition to hydrologic or water quality effects, logging slash can block cave or sinkhole entrances, which could affect wildlife use or divert flows.

Timber harvest practices have changed drastically since the 1997 Tongass Forest Plan, when many restrictions were put in place, including the karst and cave management direction (Tongass National Forest 1997). Recent monitoring has not found karst and cave impacts with recent harvest practices, indicating that protections are sufficient. However, some uncertainty remains due to limited monitoring and incomplete understanding of the connections between specific surface areas and specific downstream caves or springs (Tongass National Forest 2019, 2013).

Other activities which disturb ground could affect karst resources. Understanding karst vulnerability and where source water can enter the karst systems is important when looking at management of all activities in carbonate rocks on the Tongass.

Glacial till and Recently Deglaciated Areas

General Description

Glacial till is the sediment deposited directly by a glacier, without being reworked by water. It has a distinctive composition because glaciers pluck large rock chunks and grind rocks into very fine pieces. Therefore, glacial till is composed of large rocks surrounded by sand, silt and glacial flour. It can range from very shallow, to almost 100 feet deep. It is often compacted and has low permeability. With recent glacial retreat, there is extensive glacial till in active glacial terrains, which can be unstable where very recently exposed.

Many of the upland slopes on the Tongass are underlain by glacial till, since most of it was covered by glaciers just 15,000 to 25,000 years ago.

Ecological Importance

Glacial till can either be loose or very compacted and dense. Compacted glacial till is the focus of this assessment, due to its influence on landslides. The dense surface of compacted till concentrates water and can create a weak plane where the water concentrates, which is a natural failure surface for landslides. Nutrient levels depend on parent material of the till, with till from carbonate parent material having higher nutrient levels. These high nutrient levels are a reason that Prince of Wales Island has such high productive forests, since much of the till is from carbonate parent material eroded from carbonate bedrock on the island. Soils can develop in non-compacted till within 300 years of exposure (Portes et al. 2024). Where it is compacted and has low permeability, it contributes to the poorly drained landscape over much of the Tongass National Forest. In areas where relatively shallow till overlies karst ecosystems, areas are better drained and therefore support large and more productive forests. Although impermeable, till generally supports less productive forests, but can still support specific important species, such as red and yellow cedar, which do not compete as well on productive sites (Audubon 2016).

Very recently deglaciated areas are ecologically important because they begin plant succession and create ecosystem heterogeneity across the landscape and can support uncommon plant species. These recently exposed areas grow vegetation quickly in Southeast Alaska, with a generally predictable succession of bare rock or till, followed after a year or two by lichen and moss. Nitrogen fixing vegetation begins growing in these areas, bringing nutrients into the glacial till and building organic soil. Larger deciduous shrubs and trees such as alder and cottonwood begin to grow (which can also be nitrogen fixers), with spruce and hemlock eventually recolonizing the deglaciated areas (Chapin et al. 1994).

Human importance

One of the major management considerations for compacted glacial till is that on steep slopes, it is often a sliding surface for landslides. When over bedrock, areas with till over bedrock are some of the most

susceptible to landslides, due to two surfaces blocking water, creating a weak plan, and allowing sliding when wet.

Recently deglaciaded areas are often covered in till on very steep slopes of u-shaped valleys or fjords. These areas can also be highly susceptible to landslides or rockfall once the ice is no longer holding steep unconsolidated till in place.

Management considerations

Steep areas with compact glacial till are at higher risk for landslides. On compact glacial till, lower slope thresholds, and slope stability investigations may be needed when any ground-disturbing or vegetation removal occurs. Compact glacial till is already managed as a high-risk substrate under the existing land management plan. The existing Forest Plan does not specifically identify glacial till as having higher landslide risk, but refers to the Region 10 soil handbook, which does. The existing plan requires minimization of mass failure by identifying and avoiding areas with higher risk, mitigating impacts in high-risk areas, and completing a checklist for slope stability when completing projects on steep slopes. The Forest Plan also requires limiting activities on steep slopes, and the risk analysis requires review of slopes and substrate when considering risk and planning activities accordingly.

Compact glacial till is also susceptible to erosion from cut and fill slopes, and therefore road building on deep, compacted glacial tills requires special control of excavation and sidecast materials (USDA Forest Service Handbook 2409.22, p. 77-78).

Volcanic Ash Soils

General Description

Layers of recent volcanic ash are found in discrete areas of the Tongass National Forest, specifically on Kruzof Island near Sitka and related to the Mt. Edgecumbe volcanic field. Ash falls can form impermeable layers on top of the glacial till of various permeabilities, created a layer cake of compacted and more permeable layers.

Ecological Importance

Ash layers can have low permeability, affecting water runoff and increasing landslide potential. Ash can have a greater water holding capacity, though that is not a major ecological driver for ash soils in Southeast Alaska. The more important effect is that it can often act as an impermeable layer, where water runs along the surface. Ash soils can have limited regrowth after disturbance, due to low organic matter and sometimes high acidity, and sometimes high aluminum or other chemistry that affects vegetation growth.

Human importance

Areas with relatively recent ash falls are at higher risk for landslides. They can act as a consolidated layer, creating multiple water paths and multiple weak layers, which can cause soil collapse and as a sliding surface with high rain, increasing risk of landslides. Landslides can initiate at lower slope angles on ash soils than on other soils, due to their inherent weakness.

Management considerations

On layered ash soils, lower slope thresholds, and slope stability investigations, may be needed when any ground-disturbing or vegetation removal occurs. Ashy soils on Kruzof island have been a timber and road management concern since the 1960s. The muddy ash remaining after road construction and other disturbance was very difficult to re-seed and therefore any disturbance should consider the greater potential impacts and less on the potential for successful restoration.

Collapsible schist and other brittle rocks

Collapsible schist is a bedrock type that is important because it can shear or split into layers if disturbed. Therefore, roads will be unstable and road construction on the Tongass National Forest is avoided on collapsible schist whenever possible. Knowing where collapsible schist occurs is important when planning ground-disturbing activities. Schist is found throughout the Tongass National Forest, but is not always brittle, so site-specific investigations are, and will continue to be, important for determining road placement and design.

Beyond collapsible schist, there are other rock types that are brittle and must be considered when planning ground-disturbing activities, or when using them for road fill or other construction materials. Examples of brittle rocks include metasedimentary and conglomerates, shale, and schist, which decompose easily. Roads built using these rocks for fill can fail or be very difficult to maintain, and therefore, potential rock sources should be well vetted before use.

Ultramafics

General Description

Ultramafic rocks contain a high proportion of Magnesium and Iron, and little Silica. Ultramafic rocks are common in the earth's mantle, but at subduction zones (where the oceanic plate is pushing underneath the land) these normally deep rocks can be scraped off and thrust on top of the continental plate. Therefore, they are most common in subduction zones, or former subduction zones like Southeast Alaska.

Ecological Importance

The Tongass is known to have ultramafic-derived soils with toxic tendencies, limiting plant growth, and because of these soils, the forest-alpine transition zones occur at lower elevations compared to other bedrock (Nowacki 2001). Globally, and on the Tongass, ultramafics are known to support endemic plant communities (Whittaker 1954). Ultramafics typically support less productive vegetation and unique plant communities because ultramafic soils are deficient in plant nutrients, have cation imbalances (low calcium) and high concentrations of chromium, nickel and magnesium. One of the Tongass sensitive species, the fern *Polystichum kruckbergii* (Kruckeberg's holly fern) is known from only two locations on ultramafic geology on the Cleveland Peninsula and on east Baranof Island. Ultramafic plant communities across the Tongass are not well studied. Some of these areas with ultramafic geology and rare plants have been proposed in past studies to become special interest areas, as discussed in the Designated Areas assessment section.

Human Importance

Ultramafic rocks in Alaska have some economic importance because they contain high levels of valuable metals, including chromium, platinum, iron, nickel, and copper (Himmelberg and Loney, 1994). Duke Island in the Tongass National Forest has numerous mining claims within this rock type, some with recently active exploration. These rocks can also contain so much iron that they alter aircraft and ship compasses, as noted in the Mount Barnett and Golden Mountain on Cleveland Peninsula near Ketchikan (Nowacki 2001).

Management Considerations

Ultramafic rocks are noteworthy mainly because they can support rare plants. Ultramafic rocks are mapped throughout the Tongass National Forest, usually with small bodies scattered throughout other rock types (Himmelberg and Looney, 1994). When management occurs on ultramafic rocks, it is important to consider impacts to rare plant species.

Geologic Hazards

Southeast Alaska is a dynamic landscape with many overlapping and related geologic hazards, at the boundary of the Pacific and North American Plates. These plates smashing into each other, causing uplift, followed by glaciation created a steep landscape that remains tectonically active. Due to its location along the coastline at mid-latitude, it also receives very heavy precipitation, making the steep slopes susceptible to avalanches and landslides. Glaciation has carved the landscape into steep fjords and mountains, and glacial retreat can leave loose material poised to collapse down mountainsides. Earthquakes can trigger landslides or avalanches, and when they occur in water, both earthquakes and landslides can lead to tsunamis. There are still active volcanoes in the region, which are yet another geologic hazard related to the Pacific/North American Plate boundary. Volcanoes are their own geologic hazard, and potentially can create volcanic ash deposits which are yet another area of high landslide risk. All of these hazards, coupled with communities built almost entirely along the coastline at the foot of steep mountains, means that Southeast Alaskans must live with any number of geologic hazards.

Snow Avalanches and Risks

History and Background

Snow avalanches occur throughout Southeast Alaska wherever steep slopes receive sufficient snowfall. Due to the steep nature of most of this region, coupled with locations of communities and roads on slope toes, many communities and infrastructure are vulnerable to avalanches. The City of Juneau is especially vulnerable, due to the location of downtown and other subdivisions directly below Mt. Juneau avalanche paths. Avalanches are the deadliest natural hazard in the State of Alaska (Climate Adaptation Science Centers 2024). The risks to Tongass users can include injury or death for those skiing, hiking, hunting, driving, or otherwise using the Tongass National Forest. In Southeast Alaska, avalanches tend to occur more often in fall and spring, which have less stable snowpacks, but can occur in any month with sufficient snowpack (White et al., 2024 and Peitzsch et al. 2023).



Figure 4. Mt. Juneau Avalanche Paths, as shown on the City and Borough of Juneau avalanche information website (<https://juneau.org/emergency/avalanche-resources>).

While dangerous to humans, avalanches can also kill large numbers of ungulates, such as mountain goats (White et al., 2024). Like all natural hazards, avalanches are also ecologically important. They create winter foraging, remove trees to create heterogeneity, and act foot travel corridors for animals and humans.

Trends

Climate change will alter avalanche timing and prevalence, though the effect in each location is unknown. One study found that large avalanche occurrence near Juneau between 1920 and 2020 had no overall trend as temperatures have warmed, but did find that there were fewer avalanches in warm winters (Peitzsch et al. 2023). Other studies predict more avalanches at higher elevations with more rain-on-snow events and more extreme storms, and fewer avalanches at lower elevations due to less overall snow (Eckert et al., 2024). The Climate Change Vulnerability Assessment (CCVA) predicts snowpack losses over 30% throughout low elevations of the Tongass National Forest in the next few decades, with less reduction at higher elevations, relative to 1970-1999 time period (Halofsky et al. DRAFT). However, there are expected to be more, and more intense, atmospheric rivers. Atmospheric rivers are warm and wet air masses flowing from the subtropical Pacific to the Gulf of Alaska, which can bring especially high-magnitude precipitation. When atmospheric rivers occur in winter, they can bring high amounts of snow during a short period of time, creating conditions ripe for high avalanche potential.

Opportunities for mitigation and adaptation

Most of the management actions that the Forest Service can use to mitigate or adapt to avalanches include working with partners. Cities and Boroughs and Avalanche Centers, such as the Coastal Alaska Avalanche Center based in Juneau, post avalanche hazards and observations, and lists mitigations completed by them and other road maintenance entities, such as setting off controlled avalanches above roads to reduce overall risk.

Forest management activities can affect avalanches, though the influence seems to be minor on the Tongass National Forest. Generally, areas of large trees have far fewer snow avalanches, since trees hold snow in place and prevent it from sliding. If those trees are removed through clear cutting, snow avalanches can occur where they were unlikely before. Studies in Quebec showed that increased avalanche risk persisted only for four years after logging (Germain et al, 2005). While the increase in avalanches initiating in clear-cuts is well-documented in British Columbia (Stitzinger & McClung, 2002), documentation of clear-cut related avalanches could not be found for Southeast Alaska, but are known to be a risk in higher elevation areas. Current harvest practices avoid clear cuts uphill of communities, and therefore there are unlikely to be increased hazards related to current harvest practices in the Tongass National Forest.

Landslides and Other Mass Wasting

Background and History

Landslides are a major geologic hazard in much of Southeast Alaska, due to high rainfall and steep slopes. Fatal and damaging landslides occurred in or near Sitka, Ketchikan, Wrangell, and Haines in the past decade. The landslides in Sitka and Wrangell initiated on Tongass National Forest lands, but none of the recent fatal or destructive landslides initiated on areas that were harvested in the past few decades. Over 12,000 landslides have been mapped across the Tongass National Forest, using air photos and field surveys. For those mapped slides, there was an average number of about 100 landslides per year in the 50-year period from 1948-1997, covering an average area of 242 acres annually (Landwehr & Richter, 2021).

There are many different types of landslides, with debris flows, debris slides, and debris avalanches and rockfall being the most prevalent in Southeast Alaska. Landslides are a natural occurrence throughout the entire area and are a part of the landscape dynamics by which heterogeneity is created, nutrients are mixed, and large woody debris is carried to streams to improve in-stream habitat. However, they also denude vegetation in an area, can dam a stream or negatively affect water quality in areas where such effects can be natural, can negatively affect human uses, and can cause long-term productivity loss or even change the vegetation potential of an area permanently. When they occur adjacent to communities and infrastructure, they can be catastrophic.



Figure 5. A small landslide that deposited debris on a gravel road, showing an example of an impact of geologic hazards to infrastructure.

The Region 10 Soil and Water Resources handbook requires that management will minimize mass failures (BMP 13.5). The current Forest Plan includes restrictions on harvest and road building activities to minimize mass failures.

Debris Flows, and Debris Avalanches

Debris flows, debris avalanches, debris torrents and debris slides are types of landslides that occur when unconsolidated material becomes saturated with water and fluidized. Soil, rock and entrained materials suddenly flow down the slope. Different definitions are used, with debris flows usually referring to flows that begin in incised areas, or v-notches, and flow within a stream channel. Debris avalanches, or debris flows, usually refer to flows that begin on open slopes, usually at a topographic low. However, these names are not exclusive and are used inconsistently between publications (Swanston and Marion 1991, Swanston 1969, Cruden and Varnes, 1996). They are all shallow-seated landslides which are triggered by

heavy rain or snowmelt. These types of landslides are particularly dangerous because they often occur with little warning, move quickly, and destroy objects in their path. These are the most common landslides in Southeast Alaska (Swantson and Marion 1991) and the focus of most research and monitoring on the Tongass National Forest. Examples of some of the more notable landslides of this type are those fatal landslides in Ketchikan in 2024, Wrangell in 2023, Sitka in 2015, and the 2013 landslide at Redoubt Lake that destroyed the USFS recreation cabin.



Figure 6. Large landslide on a steep mountainside on the Tongass National Forest. This landslide is in an area with no roads or other development.

Rockfall and Other Landslide Types

While rockfall does not cause as many deaths or as much damage as debris flows, it can be dangerous particularly in alpine areas or other areas of very steep slopes with little vegetation. Rockfall is particularly of concern with melting ice and permafrost in alpine areas, and in some areas has been found to becoming more frequent with alpine warming (Stoffel et al. 2024, Alaska Geological and Geophysical Surveys 2024). Hazardous rockfall can be as small as one rock, or huge rockfall such as the 2016 Cowee Creek rockfall on the Tongass National Forest, which was estimated at about half a million cubic meters (Karasözen and West 2023).

Other landslides in the region have included huge landslides in steep-sided fjords, such as the Taan Fjord landslide in 2015 in nearby Wrangell St. Elias National Park. An estimated 180 million tons of rock collapsed onto a glacier and into the Taan Fjord. The landslide type was a gradual slumping and cracking of a very steep slope of glacial till, where glacial retreat had left over steepened loose sediment with a glacier no longer holding it back. The slump suddenly released on October 17, 2015, likely triggered by a combination of above average rainfall and a distant earthquake, causing a huge tsunami in Taan Fjord, that luckily caused no damage because there were no humans present nearby (Higman et al. 2018).

A major hazard from large landslides on fjord walls, or into lakes, is the resulting tsunami that occurs with no warning. While rockfall and other slump types of landslides can occur with heavy rainfall, they can also be initiated by melting ice or earthquakes. With more open water where glaciers filled just a few

decades ago, these landslide-induced tsunamis are becoming more common in Alaska and around the world (Higman et al. 2018, Coe et al 2018).

These types of large landslides on fjord walls are not a major concern on the Tongass National Forest and tend to have greater impacts and greater potential in areas north of the forest.

When Landslides Happen

It is clear that debris flow-type landslides occur when there is heavy rain. Hundreds can occur during one storm. For example, a storm in October 1993 on north Prince of Wales Island caused at least 140 landslides in the Thorne Bay Ranger District alone. This storm produced almost 7 inches of rain in two days, and over 8 inches in a 10-day period. Similarly, in August 2015, over 60 debris flows occurred during an atmospheric river near Sitka. The area received 2.5 to 3.25 inches within a 6-hour period. Such large clusters of landslides occur irregularly, not every year. Many debris flow landslides occur during atmospheric rivers. Atmospheric rivers contribute up to 90% of extreme precipitation in mountain terrain near the coast of Southeast Alaska and have the greatest influence in September through December. Rainfall occurs year-round in Southeast Alaska, but August to November are the wettest months (Patton et al. 2023).

There is not one predictive model for the rainfall intensity that causes debris flows. It can vary across different slopes and substrate types, as even wind intensity. One model used in Sitka found that 3-hour rainfall intensity was the best predictor of debris flows and determined that 1.34 inches of rain over a 3-hour period is a threshold for a high landslide risk warning, and 0.84 inches for a moderate risk warning (Patton et al. 2023). Sitka is the only community in Southeast Alaska with a community-specific landslide warning systems in place, though efforts are underway to develop more. For the major slides near Wrangell in November 2023, over 4 inches of rain fell in the 24 hours before the slides initiated (Nicolazzo et al. 2024). For the major slide near Haines in December 2020, the record-breaking effects of an atmospheric river dumping more than 6 inches of rain in one day, on top of snow, led to landslides in an area not previously identified as a great risk (Darrow et al. 2022).

High winds can also increase risk of landslide initiation, by felling trees and disturbing soil, or causing downward force from blowing trees. The relationship to wind is weaker than topography or rainfall (Buma and Johnson 2015). Landslide types other than debris flows can be triggered by earthquakes or melting ice which releases perched sediment that is very steep or otherwise primed to collapse.

Specific characteristics – slope, soil type, bedrock type, aspect, windthrow, receding glaciers.

Landslides occur in different geologic types, slopes, and aspects. However, certain characteristics increase risk.

Landslides in Southeast Alaska have occurred on slopes as low as 30 percent. However, they are more common on slopes over 55 percent, and the mean slope has been found to be somewhere between 70 and 77 percent (Landwehr and Richter 2021, Schroeder and Swanston 1987).

Specific substrate types with heightened landslide risk include compact glacial till, till over bedrock, collapsible schist, ortstein and placic soil horizons (impermeable organo-metallic layers) and in some areas, volcanic tephra and ash deposits overlying consolidated glacial till (Landwehr and Richer 2021). Areas underlain by karst tend to have low landslide potential, often due to very shallow till or soil overlying the karst, or good drainage that reduces soil saturation. In some areas on the Tongass National Forest, slope stability analysis is completed on any slopes greater than 55%, and timber harvest or road building can be restricted on those slopes if topography and other conditions suggest landslide susceptibility. If there are many breaks in slope, there will likely be a lower risk of a landslide running

great distances, since it may stop at the slope break. In cases where there are no slope breaks, and there is a continuous steep slope, risk of a large landslide increases. Therefore, short sections of steep slopes do not have the same risk as long continuous steep slopes. For example, the 2023 landslide in Wrangell was on a consistently steep slope, and continued over minor slope breaks, to run out for about ¾ of a mile before it entered water.

Aspect has also been found to affect landslide risk. In this region, there is higher landslide risk on southwest and south aspects, with a lower likelihood on north and northeast slopes. This is thought to be related to the general northwest to southeast trend of the mountains, and prevailing wind direction from the south (Landwehr and Richter 2021, Swanston and Marion 1991).

How they respond to management (risks and mitigations)

Road risks

Roads, particularly where they concentrate water flows, can cause or exacerbate landslides. Landwehr and Richter (2021) reported 295 known road-related landslides on the Tongass National Forest, mostly along roads constructed before 1997. They estimated an average of 5 landslides per year associated with almost 5,000 miles of road (constructed from the 1940s through 2021), with the average size of one acre. Between 1997 and 2021, about 338 miles of road were constructed. On those roads, 6 landslides occurred that were associated with the road. That is a rate of one landslide per 56 miles of road. From 1949-1997, 2,540 miles of road were constructed, with a total of 286 landslides attributed to the roads. That is a rate one landslide for every 16 miles of road constructed, which is a higher rate than more recent road construction (Landwehr and Richter, 2021). While there are many confounding factors, this suggests that road building and maintenance practices have been generally successful under the current forest plan.

The 1997 Forest Plan included standards and guidelines that require on-site analysis of proposed timber harvest on slopes over 72 percent gradient and geotechnical analysis for road construction proposed on slopes over 67 percent gradient. In addition, the Region 10 Soil and Water Handbook requires avoiding locating roads, trails, and other transportation corridors in landslide prone areas and soils with low strength. It adds that, “ash and glacial fluvial deposits” are some soil types with low strength. Landwehr (2018) reported, “Since the early 1990s, most road construction and timber harvest activities proposed on slopes over 50 percent gradient have received slope stability investigations prior to construction. The 1997 Forest Plan direction has effectively limited timber harvest and road construction on steep slopes”. Tongass staff reported that they generally avoid both temporary and permanent road construction on deep glacial till over 55%, because investigations generally show that those are landslide prone areas. These investigations show that on undulating terrain, the risk is higher because water is concentrated in v-notches that flow during heavy storms and can destabilize cut and fill slopes, leading to landslides. Temporary roads are often constructed with less design work, and therefore can be a higher risk soon after construction. Culverts are pulled once the roads are no longer in use, which reduces the longer-term risk of clogged culverts and subsequent erosion and mass soil movement or landslides. If culverts are not pulled after the road is closed, then landslide risk can remain.

Effects from roads can continue for decades after construction, due to plugged culverts and other features concentrating runoff.

Vegetation removal risk

Timber harvest is well known to increase landslide risk. However, the degree of influence, particularly with partial cut, is not well defined. There have been varying estimates of the time after harvest with increased landslide density. Miller (2021) reported that landslide risk decreases since time from harvest, with the return to unharvested landslide density taking 50-60 years.

While numerous landslide frequency analyses have been completed in recent years, they cannot conclusively state that changes in harvest practices since the 1997 Forest Plan reduced landslide risk related to timber harvest. It has been difficult due to confounding factors, such as one major storm causing hundreds of landslides, or different data collection or analysis methods and varying methods for estimating effects. Landwehr and Richter (2021) found that landslide frequency was 30% higher for young-growth harvested between 1997 and 2007 than in previously harvested young-growth. However, due to variation in air photo coverage and methods for collecting landslide data, and recent changes in climate, no real conclusion can be made about the relationship between changes in harvest practices and landslide rates. A comparison of four different landslide frequency inventories between 1964 and 1998 all showed that the rate of landslides increased between harvested and unharvested areas. The increase was anywhere from 3.5 times to 9 times greater in harvested areas than unharvested. Miller (2021) found that young growth stands had a 15-20 times higher density of landslides on Prince of Wales Island. A 2021 analysis by the Forest Service found that the number of landslides per acre of young growth actually increased by 1.15 times in the time period between 1997 and 2021. However, the landslide rate in unharvested old growth increased by 1.9 times during the same time period. All of these estimates are confounded by different imagery quality over time, varying methods, differing levels of ground-truthing, and possibly different storm intensity and frequency in different locations. However, all found an increase in the number, but smaller size, of landslides in harvested areas when compared to unharvested areas.

Because so little harvest has occurred since 1997, recent landslide frequency studies have been unable to accurately tease out how much the 1997 Forest Plan changes actually reduced landslide frequency across the entire Tongass National Forest, though the assumption, based on monitoring, is that it did.

On the Tongass National Forest, timber harvest is restricted on sustained slopes 72% gradient or greater, and any exception requires a case specific on-site analysis and assessment. These slope limits pertain only to timber harvest within the Tongass National Forest. Timber harvest on land managed by other entities does not have the same slope limits.

On glacial till and other types with high landslide risk, Tongass staff completes a slope stability analysis to develop site-specific harvest restrictions. Local knowledge suggests that aerial harvest over 55% or even 65% gradient slopes on glacial till haven't increased landslide risk. While not a strict requirement, mechanical harvest is usually avoided on slopes with sustained slope over 35% gradient on the Tongass National Forest.

Analysis of landslides in young growth areas was completed for this assessment, to better understand slope at initiation points, using data for landslides occurring between 1948 and the present (Figure 5). The median landslide initiation angle in harvested areas is 62 percent gradient. This number is nearly identical for both debris torrents and debris avalanches. The analysis also showed 25% of young growth landslides initiated below 50 percent gradient. Landslides in the lower quartile are rare on a per acre basis. Slopes below 50 percent gradient represent 25% of the total, because they were preferentially harvested. 68% of young growth slides occurred under 72 percent gradient. When adjusted for area, young growth landslides start becoming more common somewhere around 50 percent gradient.

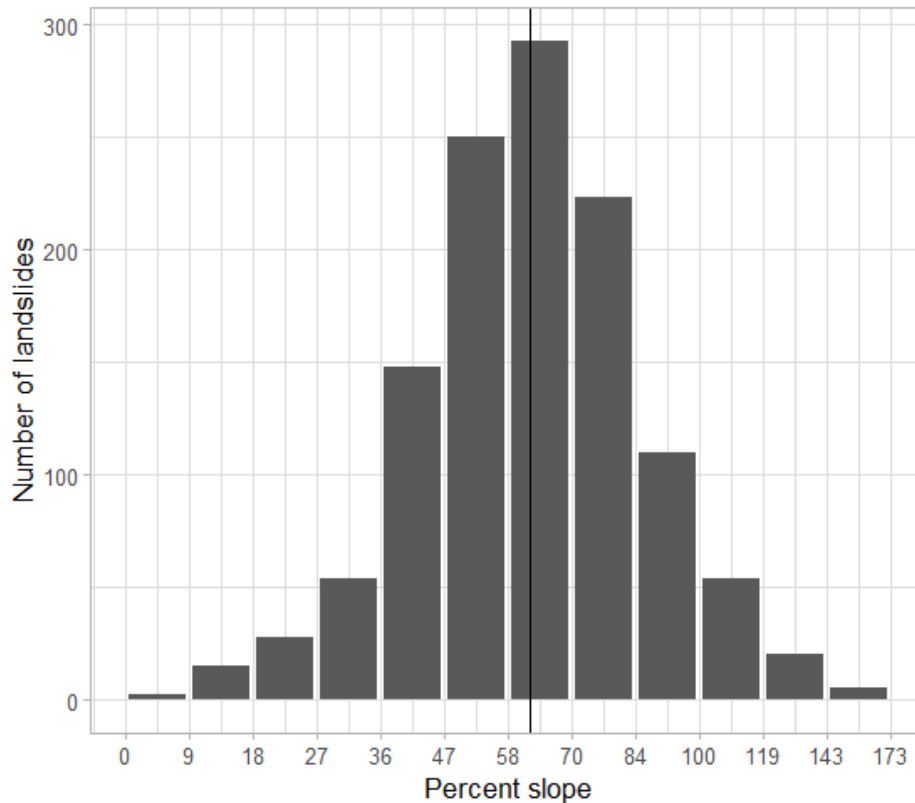


Figure 7. Number of landslides in young growth forest by percent gradient slope. Vertical black line shows median value (62% slope).

Trends

Whether on or off National Forest lands, it is assumed that landslides have become more frequent with climate change, and that the risk will continue to increase in the coming decades, both due to climate change and possibly due to increased human development that may occur on or below slopes. This is expected for both the debris flow and rockfall type. While no statistical analysis of natural landslide increase is known for Southeast Alaska, there is data showing that rainfall has gotten more intense, and atmospheric rivers are becoming more frequent (citation CCVA, Nash et al. 2024). Because debris flows are closely associated with heavy rainfall and atmospheric rivers, it follows that there has been a trend toward more landslides.

Beyond increased rainfall, glacial retreat is already increasing rockfall and landslides in alpine areas and along steep fjord walls. This hazard is compounded by the fact that in areas of glacial retreat, there are often lakes or open water fjords that were filled with ice only a decade or two ago. Therefore, when large landslides collapse into lakes or fjords, it can lead to mega-tsunamis that can be catastrophic if they occur near habitation or at the same time a boat occupies the waterbody. Only areas with actively melting glaciers are subject to this phenomenon.

Specific considerations for locations near communities and infrastructure

Landslides are catastrophic when they occur uphill of communities and infrastructure. Landslides can be very destructive and deadly, and are a major hazard in many communities near the Tongass National Forest. Communities throughout Southeast Alaska are built on the only flat areas available, which are

often on former meadows, wetlands, or alluvial fans between steep mountains and the ocean. These are also often runout zones for landslides.

The Tongass National Forest considers communities and infrastructure when planning management activities on slopes, and completes a slope stability assessment for projects on steep slopes. This requirement is not included in the current Forest Plan, but is a best management practice to meet the Region 10 Soil and Water Handbook.

Opportunities for mitigation and adaptation

Existing restrictions on road building and timber harvest on steep and unstable slopes were put in place in the previous Forest Plan, or are already integrated into project planning, as described above. Further monitoring in multiple young-growth entries may be helpful for adjusting harvest and temporary road building in areas where young-growth will be re-harvested in coming decades. As climate change likely increases landslide risk, the Forest may need to consider adapting road maintenance strategies and storage methods to minimize risk of landslides related to roads.

The Tongass National Forest staff works with other agencies to understand and mitigate landslides. Because landslides must be considered in all land use decisions, it has been important to work with agencies that build and maintain roads and other infrastructure to understand and mitigate threats on or adjacent to National Forest land. Collaboration with adjacent landowners can improve understanding of hazards that may cross land ownership boundaries and develop mitigation that serve all landowners and land managers. Continuation of such collaboration in the future will maximize learning and developing mitigation and adaptation strategies.

Consideration of climate change in future management will be essential to adaptation to minimize landslide hazard and loss of productive land beyond that of the natural range of variation. It is anticipated that this region will receive more intense rain and increasing number of atmospheric rivers, and also more rain on snow events. These will likely lead to more landslides. Designing adaptive strategies for activities such as infrastructure placement, construction activity timing, or harvest and road design will be important to ensure uncertain climate impacts are incorporated as they become better understood or change over time.

Landslide rehabilitation can include seeding with fast-growing plants, such as grasses, to help stabilize the landslide. It is best done within 4 years of the landslide, but even when seeding occurs, it does not always successfully grow or improve slide vegetation regrowth. Seeding and planting shrubs or trees can speed tree growth and slope stability. Landslide restoration could also include removing landslide debris when it is damming streams that could overflow and affect infrastructure or key salmon runs. While stream damming is a natural consequence of landslides, effects to human infrastructure or natural resources could warrant human intervention. Because landslides that affect communities often cross land ownership boundaries, any restoration usually needs to be coordinated across agencies and may be a good fit for the Resource Advisory Councils (RACs) in the affected communities (Becki Reynolds, personal communication, 2024). The Interagency Working Group for landslides (also known as Káadi), of which the Tongass National Forest is an active member is working to increase understanding of, and integrated response to, landslide risk.

Since 1997, remote sensing techniques, such as LiDAR, have provided more accurate information about topography. This allows a much more efficient view of a larger area of the landscape, so landslide-prone areas are now better able to be identified. This improved knowledge will be important to use for future project design to minimize mass failure potential.

Flooding

Background and History

Flooding is another natural phenomenon that is an important part of ecosystem function. Floods spread nutrients, scour channels, build floodplains, and are important for species diversity. However, like landslides, they become hazards and can be catastrophic where they occur near communities or infrastructure.

Flooding over the past two decades in Juneau, Yakutat, and in many coastal areas has led to structural damage and sometimes secondary erosion that has destroyed homes and other infrastructure. Floods in Southeast Alaska can result from coastal storm surge, heavy rainfall, rain on snow, glacial outburst flooding, or rapid thawing of snow and ice.

River and stream floods are common. River and stream floods can occur due to heavy rainfall, usually with steady rain for multiple days or weeks. These floods can result in streams or rivers overtopping their banks, and infrastructures such as roads, homes, trails and campsites being damaged. An example is the January 2014 floods in Yakutat, due to above average rainfall for over a month, combined with a warm atmospheric river. Like landslides, many rain and rain-on-snow floods are associated with atmospheric rivers (Nash et al. 2024).

Glacial lake outburst floods (also called Jökulhlaup) have received much attention in recent years due to major flooding and erosion along the Mendenhall River in Juneau. These floods occur when water dammed by a glacier, or a moraine, is suddenly released through failure of the ice or moraine. They occur rapidly and with little warning, since they are the result of a breaking dam, though they can be predicted with some certainty if the lakes are monitored. The Mendenhall River glacial outbursts floods are now an annual event, but did not occur in history before 2011. Before then, the Suicide Glacier, tributary to the larger Mendenhall Glacier, joined the Mendenhall Glacier year-round. Over the last century, the Suicide Glacier has retreated, and now a lake, with the Mendenhall Glacier as a dam, fills the Suicide Glacier Basin during the summer (Figure 6). The lake fills throughout the warm season and the outburst flood occurs when the ice dam fails and lake water is suddenly released and flows downstream. This has occurred in July or August in most years since 2011. Before 2023, there were multiple partial releases with smaller and less damaging floods. In 2023 and 2024, the flooding occurred all at once. The flooding in 2024 was the highest ever recorded, and flooded streets and homes in northern Juneau. In 2023, in addition to flooding parts of Juneau, extreme bank erosion occurred, with 20 to 150 feet of bank being eroded in just a few days.

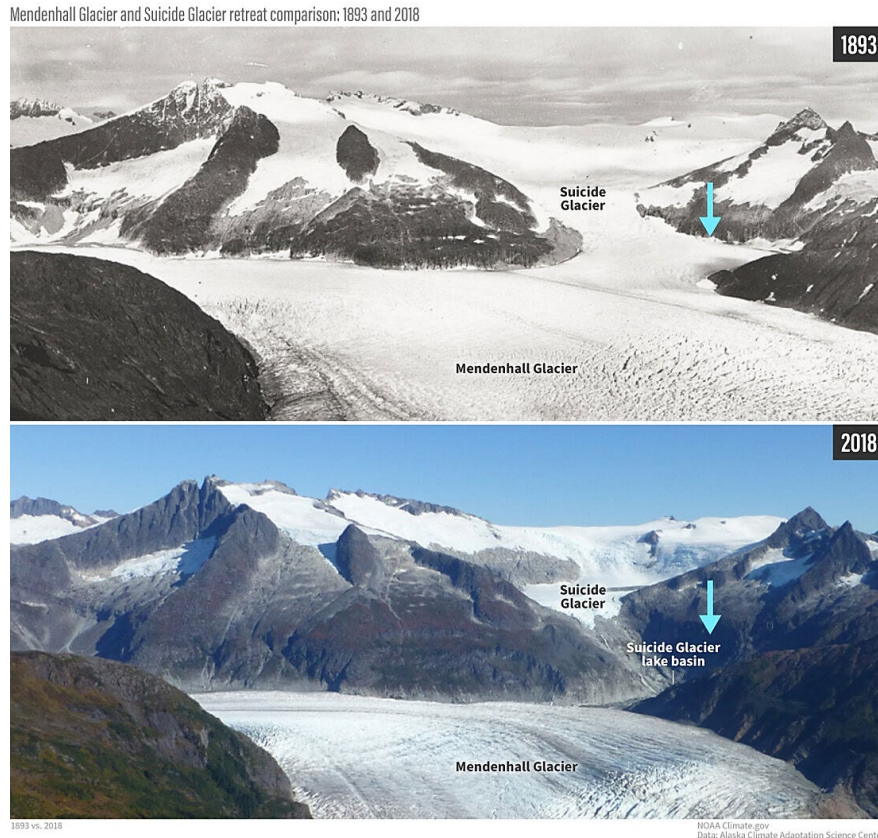


Figure 8. Two photos showing the retreat of the Mendenhall and Suicide Glaciers between 1893 (top) and 2018 (bottom). Suicide Glacier has retreated up onto a ridge. A meltwater lake now fills the lower basin, dammed by the Mendenhall Glacier. Photos from the [Alaska Climate Adaptation Science Center](#).

Glacial lake outburst floods can occur anywhere with glaciers and may become more common throughout the glaciated portions of the Tongass. This phenomenon is also known from the community of Hyder, where the Salmon River has been recorded as receiving damaging glacial lake outburst floods related to Summit Lake since 1961. These floods have caused road damage and washouts, temporarily cutting off access to the community and nearby mining and tourism sites important to the economic viability of Hyder (U.S. Army Corps of Engineers 2008).

Floods can affect human life and property and can also affect natural resources. Roads, campgrounds, and other infrastructure near rivers and streams can be damaged by natural flooding. Roads often cross streams or rivers, either over culverts or bridges. If culverts or bridges are undersized or not maintained, they can plug and flooding can back up behind them. This can cause road erosion, or culvert or bridge failure. If roads are poorly maintained, heavy rain and flooding can travel down the road, eroding the road and possibly concentrating water that can erode adjacent land. Well maintained roads, culverts, and bridges can mitigate these hazards. The Tongass National Forest has been implementing culvert replacement projects to create larger culverts to benefit fish passage. This also has the effect of allowing a more natural flood pattern.

National Forest land is often uphill from the private, State, or Alaskan Native Corporation land. Therefore, activities on Forest Service land have more likelihood of effect on landowners than vice versa. However, anything that downstream landowners do in-stream, relative to flooding or infrastructure in the floodplain, could affect anadromous fish passage upstream into spawning areas. Therefore, consideration

of entire stream or river channels, and the balance between human uses and aquatic ecosystem needs from the headwaters to the ocean is necessary for true flood and stream habitat management.

Trends

As flooding patterns change with the climate, there will likely be larger floods, possibly intermixed with drought periods, which would lead to higher floods and lower base flows. In some rivers, such as the Mendenhall River, entirely new flood risks may emerge with climate change, melting ice, and then change again with a decrease in overall snow over time. Glacial outburst floods are a result of climate change and glacial retreat. While not all areas have the potential for this type of flooding, it may increase in the future as more glaciers recede. Over decades, it may change again as the glaciers retreat further.

As the climate warms and more precipitation falls as rain, it is expected that there will be more rain-on-snow flooding events. Further, with less snowfall, the region is already seeing a shift to higher peak flows and floods in the fall, with atmospheric rivers, rather than spring high flows due to snowmelt. An example of this is the Taiya River flooding in fall 2022, where peak flows were some of the highest seen in history, though peak flows were historically in spring under a snowmelt hydrologic regime (CCVA, Hydrology chapter).

Opportunities for mitigation and adaptation

Consideration of changing flood dynamics with climate change will be necessary to ensure hazards are mitigated as much as possible, and there are opportunities for adaptation. Considering future flood potential will be important when designing or maintaining infrastructure such as bridges or culverts, or campgrounds. When infrastructure needs replacing, modeling of future floods could help it last longer and be more resilient to future changes. Working with other agencies to design infrastructure adapted to climate change will also be important when on or adjacent to National Forest land.

Acid rock drainage

Background and History

Acid rock drainage occurs when rock types containing iron sulfide minerals are exposed to water and air, and sulfuric acid is released. The sulfuric acid dissolves the rock, and releases metals. The acid and dissolved metals can enter lakes, wetlands, or streams, and can cause threats to aquatic life, and affect drinking water quality. While potential acid generating rock is natural, and stable when not exposed to oxygen, it can become a serious environmental hazard when blasting, digging, or other activities expose the rock to the elements (Byl et al. 2023). Activities that can cause acid rock drainage include expanding quarries, road building, mining, and any construction that requires blasting of potential acid generating rock. Landslides could also expose these rocks.

Active mining activities are a well-known potential source of acid rock drainage. Plans of operation at Greens Creek and Kensington Mine incorporate mitigations, such as avoiding disturbance in areas with potential to generate acid rock drainage, covering tailings piles or mixing tailings rock types to neutralize acid (Hecla 2019). Monitoring programs at these mines track water quality and metal levels in fish tissue. While levels fluctuate and are sometimes elevated, they mostly fall within standards (Lundgren and King 2022). Acid rock drainage from mines in Canada along transboundary rivers are of concern and outside of the direct control of the Tongass National Forest. If severe, acid rock drainage related to mining along the Taku or other Canadian Rivers could affect ecosystems on the Tongass National Forest.

Road building and quarry expansion are the higher risk activities with less regulatory oversight than mining. These activities break up relatively stable rock into small pieces, exposing many surfaces to water and air. An example of an acid rock drainage issue was on Coffman Cove Road (Forest Service Road

3030) on Prince of Wales Island. Rock used for the road fill was placed up to 20 feet below the surface, to ensure a stable road surface. The rock used to fill in sections re-constructed in 2005 through 2007 was acid generating rock, though it was not known at the time. In 2007, it was noticed that culverts were corroding after being in place for less than a year. Water quality testing found that waters were very acidic (pH 2.3), a violation of Alaska water quality standards. Acid rock drainage, copper and iron, was also leaching into the muskeg as well as streams (Howard et al. 2008). Fish left affected streams and macroinvertebrates were killed, adversely affecting the aquatic ecosystem. For remediation, the rock was removed, and water quality levels have since greatly improved and approached cleanup goals (Carlson 2011).

Opportunities for mitigation and adaptation

The Tongass National Forest now tests rock in areas of road building, quarries, or other construction if there is potential for acid generating rock types. Because mitigation can be very difficult and expensive, avoiding disturbance of potential acid generating rock types is the most effective mitigation measure. It is possible that warming will increase potential for acid rock drainage because warmer temperatures increase chemical reactions. Quarries are abandoned when they are found to contain acid generating rock, because the negative consequences of exposing this rock.

Coordination with other governments, agencies, landowners, and construction companies can help fully address prevention and mitigation of acid rock drainage, since upstream acid rock drainage can affect ecosystems and human health within the Tongass National Forest, just as acid rock drainage sourced on the Tongass National Forest can affect ecosystems and human health downstream.

Earthquakes

Southeast Alaska is tectonically active, with numerous earthquake faults across the entire Region. The larger fault locations are shown in Figure 1. The major fault system in and adjacent to the Tongass National Forest is the Fairweather/Queen Charlotte Fault system. It is strike slip fault, with the west side (Pacific Plate) moving north relative to east side (North American Plate). The Pacific Plate is moving north at roughly 2 inches per year, and subducts under the Pacific Plate at the Aleutian Peninsula and along southern Alaska where the plate boundary bends east-west. This combination of strike slip and subduction creates a very tectonically active area. The larger and greater number of earthquakes usually occur outside of this region, in Southcentral and Southwest Alaska at the subduction's zones. Large earthquakes are related to these faults systems and can affect people throughout all of Southeast Alaska. Smaller earthquakes can be caused by volcanic activity.

Earthquakes threaten life and property, including secondary effects from earthquake-induced tsunamis or liquefaction in areas with wet soils in coastal areas. Earthquakes cannot be predicted. The Tongass National Forest can prepare through awareness of hazards and consider them in construction or other development, and in safety and evacuation procedures.

Tsunamis

Tsunamis occur when there is any large movement of land near or in an ocean or lake. In Alaska, tsunamis can be caused by earthquakes, landslides or volcanic eruptions. The source of the waves can be very nearby or can be caused by earthquakes or volcanic eruptions across the Pacific Ocean. Tsunamis with an origin nearby, such as a landslide collapse into a fjord, may occur only minutes after the event. If their source is farther away, there will likely be hours of warning.

As described above, the largest tsunamis in Alaska, as defined by the highest water runup onto land, have been caused by huge landslides collapsing into fjords. Examples are the 1948 Lituya Bay and 2015 Taan

Fjord Landslides and Tsunamis. Both tsunamis reached a wave height well over 1,000 feet, ripped out forests, and altered the landscape. These landslide-induced tsunamis are the most likely types of tsunamis to have major effects to Southeast Alaskan communities not exposed to open ocean. The communities on the west side of the outermost islands are most susceptible to tsunamis from a far source, or from offshore earthquakes along the Alaskan faults.

As with earthquakes, preparation and understanding the risk is key to locating and designing facilities, and warning users, to best prevent loss of life and property.

Volcanic activity

There is only one active volcano within the Tongass National Forest, Mt. Edgecumbe, which is about 15 miles west of Sitka on southern Kruzof Island. It has not erupted in over 1,000 years, but since 2018, there have been increased small-magnitude earthquake swarms and ground deformation with less than a foot of uplift. This indicates that magma could be rising far under the volcano, but there is no indication of impending eruption. Because of its proximity to Sitka, and potential for major effects if it does erupt, Mt. Edgecumbe is being closely monitored by the Alaska Volcano Observatory, which updates risk levels on their website continuously (Alaska Volcano Observatory website 2024).

As mentioned in the landslide section, the ash layers from Mt. Sitka related to the Mt. Edgecumbe volcanic field are some of the high landslide risk substrates. The compacted ash layers on top of, or layered with, glacial till create sliding surfaces that facilitate landslides.

Key Takeaways

- Geologic hazards are prevalent throughout this geologically active area of Southeast Alaska. They can lead to loss of life and property, and management decisions depend on knowing risk factors.
- Many geologic hazards, such as earthquakes, tsunamis, volcanic activity, cannot be affected by management. However, knowing where they occur, and their consequences, can help the Tongass manage to minimize exposure to hazards.
- Climate change will alter avalanche risk. Increased rain on snow events will likely increase avalanche risk at mid-elevations, but due to less snow overall, avalanche risk could decrease at lower elevations. Climate change is expected to increase the number and severity of floods and landslides, due to more intense heavy rainfall, and may alter locations or types of these hazards.
- While avalanches, floods and landslides occur naturally across the Tongass National Forest, they can all be affected by management activities.
- Vegetation harvest can exacerbate landslide potential. While the precise effect related to landslide increase is unknown, it is well understood that removing trees from steep slopes does increase landslide risk.
- Roads can increase landslide potential. Roads can increase landslide risk any time they increase instability, by concentrating water flow or collapse of cut and fill. This can occur if culverts get plugged or are undersized, if roads are built on steep slopes or unstable rock/substrate, or if they are constructed on unstable slopes.
- The current Forest Plan, Region 10 best management practices, and general practice includes direction for reducing potential for mass wasting, including road construction and vegetation harvest restrictions on specific slopes or specific soil types, and requires slope stability analysis on steep slopes. These restrictions have mostly been successful and minimized hazards.

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- Evaluation of future flooding potential will be important for properly designing stream-related infrastructure, such as culverts and bridges, and other development such as recreation sites, trails and roads. Allowance for adaptive management will be necessary to ensure the ability to adjust to new information on climate change effects, as well as future changes.
 - Management actions, especially timber harvest and road construction or maintenance will need to be adaptive in the revised plan, to ensure that changing risks can be addressed. This may require alteration of existing slope limits or more rigorous investigation of slope stability, especially uphill of communities.
 - Landslides, avalanches, and other geologic hazards can cut communities off from road access. There is often a need to act quickly along with various agencies and municipalities to work across boundaries to restore access and mitigate hazards.
 - The Interagency Working Group for landslides, of which the Tongass National Forest is an active member, and the findings coming out of that group, can help inform plan revision and adaptation in the revised plan.

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