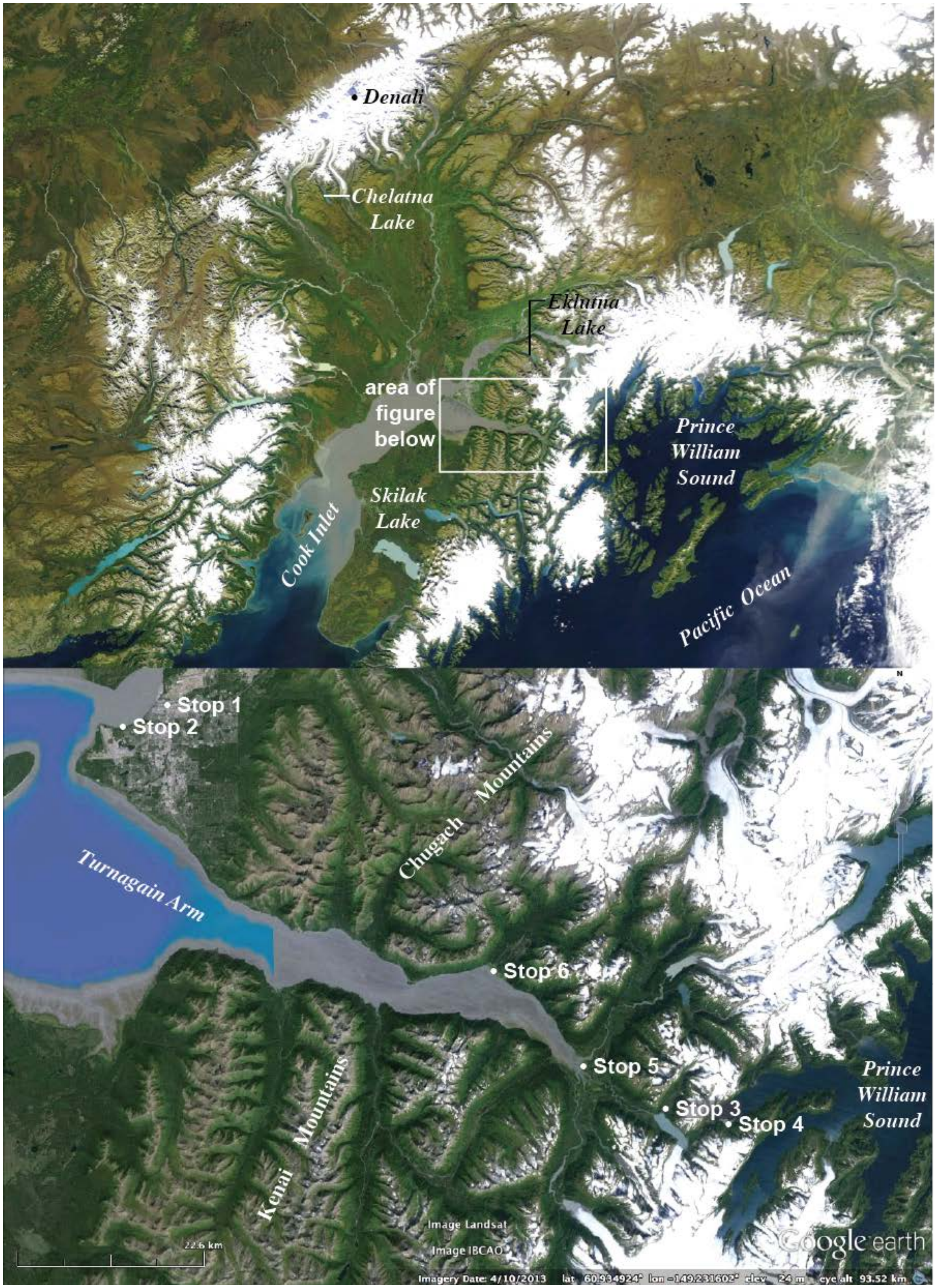
UJNR 2022

Field Trip Guidebook:

The 1964 Great Alaska Earthquake and Tsunami and the Geologic Consequences of Subduction: Anchorage to Whittier

Wednesday September 28th, 2022
Field trip leader:
Peter Haeussler, USGS Anchorage



Overview of field trip area. Upper – MODIS image. Lower – Google Earth image showing field trip stops.

Introduction:

This ~8 hour field trip will review the impacts of the 1964 great Alaska earthquake and offer glimpses of the geology of south-central Alaska – as well as the beautiful scenery - between Anchorage and Whittier. Initial stops will focus on some of the most costly effects of the 1964 earthquake in Anchorage. Among the many damaging effects of the earthquake, translational landslides triggered by earthquake ground motions caused the greatest devastation (Hansen, 1966). From the Hilton, we will first walk up to 4th Avenue and discuss the 1964 landsliding in downtown Anchorage, then drive to Earthquake Park and see the remnants of the most dramatic landslide that occurred in the earthquake. This second stop involves a 5-10 minute hike, from top to bottom, across the Turnagain Heights landslide and discussion of the Bootlegger Cove Formation alleged to have lost strength and failed during earthquake shaking. This is also a good location to discuss the regional tectonics, as you can see the Alaska Range in the distance.

From Earthquake Park, we will head to the community of Whittier, the western "Gateway to Prince William Sound". Along the way, we will travel along Turnagain Arm, a shallow fjord that extends east from Cook Inlet, and cuts through the Chugach accretionary complex. This subduction complex is the remnants of about 200 million years of subduction beneath the southern Alaska margin. We will just drive past these rocks, although we may have a few moments to see them later in the day. Captain James Cook's 1778 expedition originally named the waterway Turn Again River out of frustration in their failed search for a Northwest Passage. They had to "Turn Again" when heading up the arm, and went back to the deeper waters of what is now called Cook Inlet. Tides in Turnagain Arm average 11 m and produce currents up to 16 km per hour. Turnagain Arm is also one of only about 60 bodies in the world to host a tidal bore. A tidal bore is a wave that forms at the leading edge of the incoming tide, and on a high spring tide, the Turnagain bore may travel at speeds up to 24 km per hour and reach a height of 2 m. Occasionally, someone will surf this bore for several miles. As we drive east along the Seward Highway, look for white Dall sheep foraging or sunning themselves on the steep south-facing rocky slopes of the Chugach Mountains. Later in the summer, white Beluga whales are seen swimming in pods of a dozen or more along the shoreline.

The last part of the drive to Whittier requires that we drive through the second longest (2.5 miles; 4 km) highway tunnel in North America, the Anton Anderson Memorial Tunnel. This tunnel is one lane, and we need to travel thru the tunnel on the half hour (the return is at the top of the hour). The Army Corps of Engineers built the town of Whittier in 1942-43 to provide an all-weather port connected by railroad to Anchorage and Fairbanks for military purposes. Our visit to Whittier will focus on the devastating effects of tsunami waves generated by underwater landslides triggered by earthquake shaking in 1964 and we will discuss the recently discovered Barry Arm landslide and the tsunami hazard. On our way to or from Whittier, we will see Portage Lake, discuss the dramatic historical retreat of the Portage glacier, and use this lake as a backdrop to discuss recent lacustrine paleoseismology work in the region. On the way back to Anchorage, we will see the abandoned village of Portage and the Girdwood flats. These locations reveal the lasting effects of 1964 earthquake subsidence that dropped Turnagain Arm by as much as 2 m. The subsidence led to the relocation of Girdwood and the abandonment of Portage, and it dropped much of the railway and Seward Highway below high tide level. It also killed swaths of spruce trees whose remains haunt the shoreline as "ghost forests" of bleached snags.

There have been a number of excellent field guides to various aspects of south central Alaska. This one draws heavily on the one by Karl et al. (2011) and Bradley et al. (1997). Rob Witter and Emily Roland (USGS, Anchorage), adapted much of that material for this guide and inserted new material for an EarthScope workshop for interpretive professionals on April 29th, 2014. Peter Haeussler modified that guide for the 2014 SSA meeting in Anchorage and for this fieldtrip today.

Stop 1 — 4th Avenue Slide: Landslides triggered by the 1964 Alaska earthquake in Anchorage

The 1964 great Alaska earthquake
On Friday, March 27, 1964 the largest earthquake in U.S. history and the second largest recorded instrumentally worldwide struck south-central Alaska with a magnitude of 9.2. Shaking in the Anchorage area lasted for about 4.5 minutes. The earthquake was felt 790 miles (1,270 km) west as Dutch Harbor in the Aleutian Islands, and more than 1,300 miles (2150 km) southeast at Seattle, Washington, where the Space Needle swayed perceptibly. The 1964 great Alaska earthquake caused regional ground displacements, rockfalls and avalanches, damaging landslides, submarine slumps, liquefaction-related ground failures, and tsunamis. Seafloor displacement caused by slip on the megathrust fault generated a tsunami that propagated across the Pacific Ocean, which resulted in 17 fatalities in Oregon and northern California. Underwater landslides in Alaskan fjords generated local tsunamis that devastated coastal ports and communities in Prince William Sound. All told, the earthquake and tsunamis caused 131 fatalities and an estimated $2.8 billion in property losses (in 2023 dollars).

Translational landslides in Anchorage
The most devastating effects of the 1964 great Alaska earthquake in Anchorage were large translational landslides that caused extensive property losses (Hansen, 1966). Translational landslides involve mass movements that occur along planar failure surfaces with little rotation or backward tilting (Figure 1.1). Bootlegger Cove Clay that underlies much of Anchorage was deposited in a glacial-marine setting and consists of discontinuous layers of silty clay, sand and gravel. Post-earthquake geotechnical studies of the Bootlegger Cove Clay identified zones of low shear strength, high water content, and high sensitivity that lost strength under the dynamic stresses imposed by seismic shaking in 1964 (Hansen, 1966).

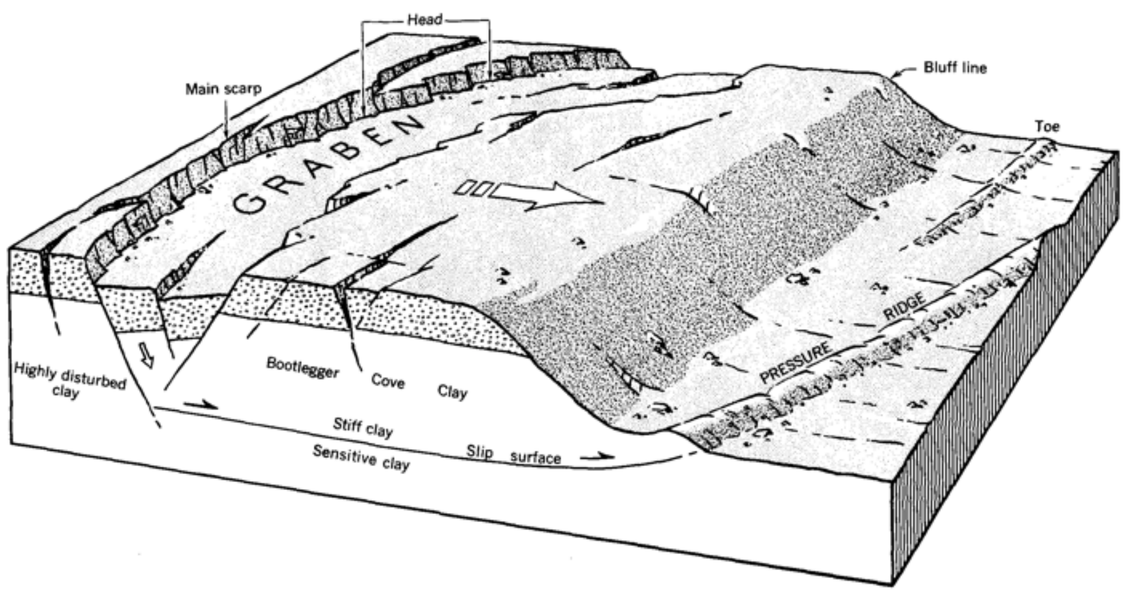


Figure 1.1. Block diagram of a translational landslide (from Hansen, 1966).

Stop 1 We are standing on, or next to, the repaired 4th Avenue slide (see photo on the cover of this guidebook). You will notice that buildings on the south side of the street look older than those on the north side. This is because those on the north side were all built after the 1964 earthquake and the slide area remediated. The slide contained perhaps 2 million cubic yards (1.5 million cubic meters) of earth, involved 14 city blocks in the northern part of downtown Anchorage, impacting an area about 36 acres (0.15 km^2) between Fourth and First Avenues. It was bounded headward on the south by 4th Avenue, on the west by E Street, on the north approximately by 1st Avenue, and on the east somewhat indefinitely by

Barrow Street. Its length north to south in the direction of slippage was about 1,050 feet (320 m); east to west it was about 1,800 feet (550 m) across. The landslide was attributed to translational sliding on a failure plane at a depth of 60 feet (18 m) due to the loss of strength of sandy layers in the Bootlegger Cove Clay attributed to liquefaction. The process of liquefaction causes saturated sandy sediment to lose strength during strong seismic shaking, which often leads to landsliding and other ground deformations. Eyewitnesses reported that sliding began about 2 minutes after the earthquake started and stopped about the same time as the earthquake (Hansen, 1965, p. A41). Buttress Park, located between First and Fourth Avenues, has been re-graded and reinforced with a buried gravel buttress to stabilize the slope. Drains were installed during remediation to help dewater the sediments and aid in drainage.

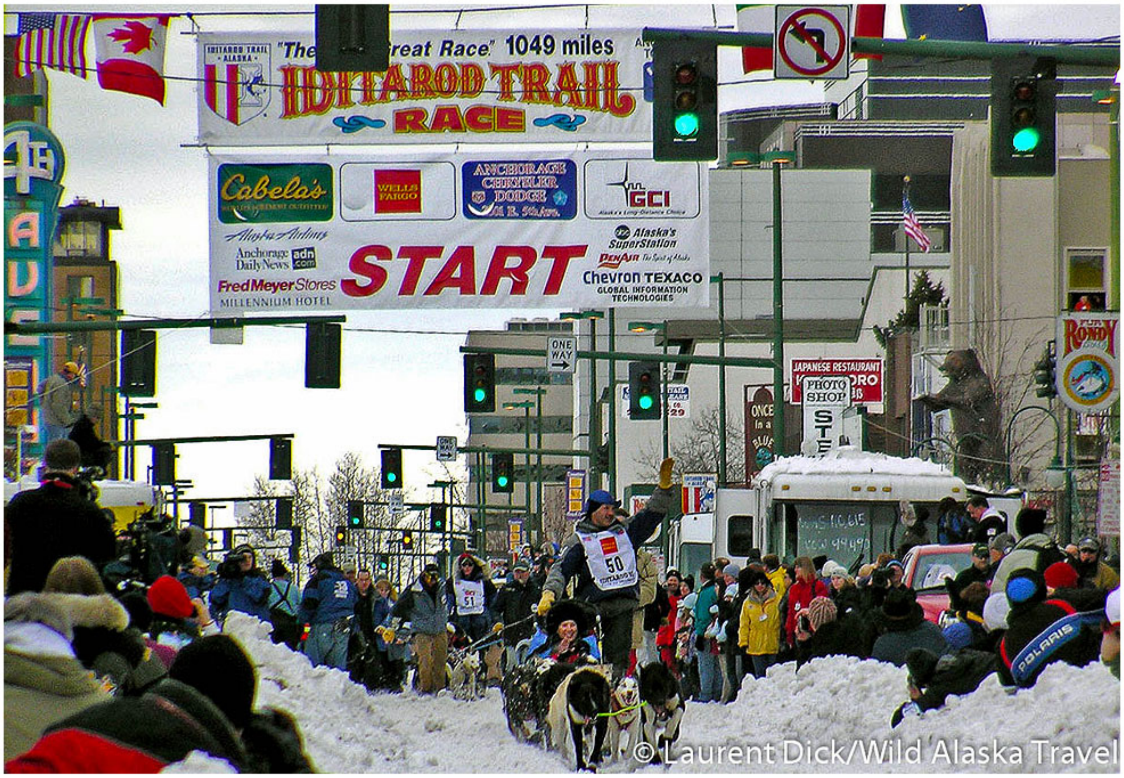


Figure 1.2. Iditarod race start on 4th Avenue.

The ceremonial start line of the famous Iditarod Sled Dog Race also lies above the 4th Avenue landslide and is in view to the east. This race is run every year in early March and is about 1,100 miles (1,800 km) long. The current race record is 8 days and 11 hours. Racers start with 16 dogs and at least 6 must make it to the finish. To do the start in downtown Anchorage, snow is piled onto the streets. This ceremonial start ends about 10 miles across town, and the time for this does not count. The following day is the "Restart," which is the real start of the race, and that takes place in Willow, which is about 35 miles north at Willow.

Figure 1.3 Top: View to the east in downtown Anchorage, Alaska showing buildings damaged at the head of the Fourth Avenue landslide in 1964 (photo: USGS). Bottom: The same view in 2013 (photo: USGS, Game McGimsey). Red arrows point to the McKinley Tower in both photos. From Thoms et al. (2014).

On our way to Earthquake Park (Stop 2), we will pass three features of interest in quick succession.

Figure 1.4. Nesbitt Courthouse. Note eccentric bracing in windows.

(1) The Nesbitt Courthouse—Along the north, or right, side of 4th Avenue, west of the Hilton, you can see the Nesbitt Courthouse, which was built on land expected to fail in future seismic shaking. The remarkable decision making process leading to construction was the subject of a PhD in urban planning, which concluded everyone wanted to look the other way with respect to the hazard, and no one wanted to take final responsibility (Selkregg, 1994). The Nesbitt Courthouse is a 6-story building designed according to the 1991 Uniform Building Code and constructed in the mid-1990s. The site lies within Anchorage's Seismic Hazard Zone 4, which means it has a "high" potential for earthquake-induced ground failure. The building *was designed to fail* in a controlled way in order to accommodate ground displacements, caused by landslides, predicted to be 4 feet horizontally and almost 3 feet vertically. The main structural support for the building is on steel beams, girders, and columns bearing on a continuous and massive 3-foot thick reinforced concrete slab foundation. Wind and seismic forces (that is, lateral loads on the building) are resisted by a dual system of eccentric braced frames and special moment frames. These lateral loads are transmitted to the slab foundation through huge concrete shear walls in the basement. The predicted lateral and vertical displacements during a major earthquake-induced landslide were designed to be taken up by rotation and deflection within unbraced sections of the building frame, or “flexible bays,” in order to avoid complete collapse (from Thoms et al., 2014).

(2) Bend in L Street—The main scarp of the 1964 L Street Slide cut across L Street between 7th and 8th Avenues. Because the slide mass west and north of the scarp in the foreground moved seaward while the ground headward of the scarp in the background remained in place, the centerline of L Street now bends about 12 feet (3.7 m) to the east, just south of 7th Avenue (from Thoms et al., 2014).

Figure 1.5. View looking south down L Street from a just south of 6th Avenue, Anchorage, Alaska. The two subtle but distinct kinks in the centerline, as it is traced from lower left toward the upper right, represent the re-alignment of L Street where it crossed the main scarp at the head of the L Street Slide (from Thoms et al. (2014).

(3) Inlet Tower—This is along the north, or left side, of L Street, just before a distinctive downhill section of road. The Inlet Tower was moderately damaged from the 1964 earthquake because of ground shaking (Figure 1.6) (Hansen, 1966, p. A26). The damage appears to just have been patched over. This is now a hotel.

Figure 1.6. Comparison photographs of the Inlet Tower taken from the same location on 13th Avenue. (Left photograph [1964] from U.S. Geological Survey Photographic Library, ID aeq00019; right photograph [2013] taken by R.G. McGimsey, U. S. Geological Survey). From Thoms et al. (2014).

Stop 2 — Earthquake Park, the Turnagain Heights Landslide, and Regional Tectonics

The Turnagain Heights landslide was the most extensive of the five major landslides in Anchorage triggered by the 1964 earthquake (also including Government Hill, Native Hospital, 4th Avenue, L Street). This slide occurred within a residential area built on a flat-topped bluff that is almost 70 feet (~21 m) above sea level and overlooks Knik Arm. The bluff consists of coarse-grained glacial outwash overlying thick clay deposits of the Bootlegger Cove Formation. In the eastern, developed part of the slide, about 75 homes were destroyed and four people were killed (Figure 2.1); the western lobe of the slide was undeveloped and is preserved as Earthquake Park. During the earthquake and landslide, surviving residents from the Turnagain Heights neighborhood told harrowing accounts of houses cars and people sliding into Cook Inlet during failure of the bluff and cracks opening up in the ground beneath their feet (e.g., read Julia O'Malley's story in the Anchorage Daily News, March 22, 2014, reproduced at the end of this section).

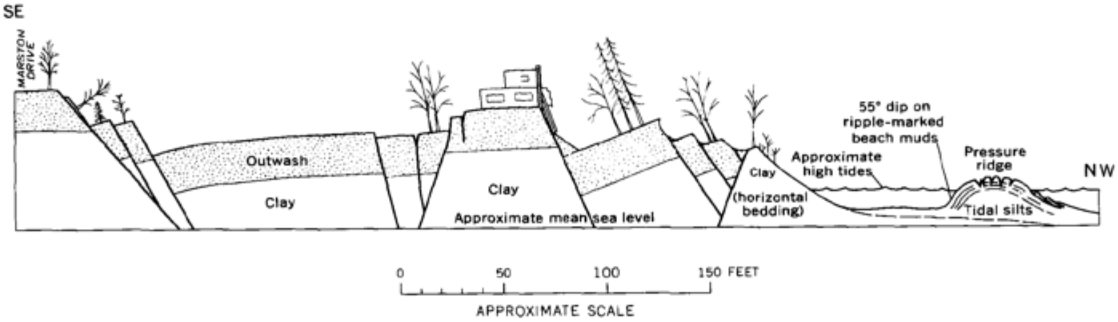
Figure 2.1. Top: About 75 homes were destroyed in the Turnagain Heights landslide (from USGS Circular 491). Bottom: From Anchorage Daily News Article by Julia O'Malley: The Mead home, right, slid away from Chilligan Drive and out of Turnagain towards Cook Inlet and was buried, along with two children, in the 1964 Good Friday earthquake. The neighboring Thomas home, left, was also carried north, but not as far. Mossy Mead has a mylar overlay and several aerial photos taken before and after the earthquake to show the scope of the disaster.
ERIK HILL — Anchorage Daily News

The slide extended about 8,600 feet (2,600 m) east to west along the coastline. The maximum retrogression from the former bluff line was 1,200 feet (370 m). The maximum lateral slippage was in excess of 2,000 feet (610 m) Early assessments by Hansen (1966) indicated that, "a total area of about 130 acres (0.5 km^2) was completely devastated by displacements that broke the ground into countless deranged blocks, collapsed and tilted at all odd angles." The portion of the slide that extended into Knik Arm/Cook Inlet has eroded away (Figure 2.2). Shaking in the Anchorage area during the 1964 earthquake lasted approximately 4.5 minutes. Movement of the Turnagain Heights slide began about two minutes after the onset of shaking. The slip surface was in the upper part of a sensitive-clay and silt layer in the Bootlegger Cove Formation, at or slightly above mean sea level, about 20 m below the original ground surface, and sloped gently northward toward the shoreline (Figure 2.3; Hansen, 1966).

The slide broke the ground up into a chaotic jumble of rotated blocks and grabens; sliding continued one or two more minutes after noticeable shaking stopped. Hundreds of tension cracks extended landward, causing structural damage to homes, disrupting underground utilities, and damaging streets.

Early reports (e.g., Shannon and Wilson, 1964) attributed the slide to liquefaction of noncohesive silts and sands, others (e.g., Hansen, 1966) invoked sensitive-clay failure as the primary mechanism. This and other slides in Anchorage sparked several decades of research on both phenomena. Cone-penetration tests in undisturbed deposits headward of the slide confirmed that the landslide was likely due to fabric collapse of sensitive silty clays (Updike, 1984); sand liquefaction was secondary.

Figure 2.2. Top: Aerial view of the Turnagain Heights neighborhood and Earthquake Park area following the 1964 earthquake. Bottom: Modern day google map view of the same region. The location of Iliamna Ave, noted in the ADN article by Julia are labeled for reference. If you look closely, you'll see locations that have been redeveloped since 1964.



Figures 2.3. Top: Sketch section through eastern part of Turnagain Heights slide. Note pressure ridge, upright blocks at center and to left of pressure ridge, and tilted collapsed blocks between (from Hansen, 1966). Bottom: Photo taken from within Turnagain Heights slide. Sharp-crested clay ridge, with collapsed blocks tilted toward ridge on both flanks. Note horizontal stratification in ridge.

In an interesting post-earthquake development, the City of Anchorage granted land parcels in safer areas of the city to many landowners whose homes were destroyed in Turnagain Heights. However, the city did not void the titles to their Turnagain Heights parcels. In recent years, some of these landowners or their families have reclaimed their original properties and have begun building new homes on the landslide deposit (Figure 2.2). Some geotechnical studies, now required by ordinance in areas designated as having highest susceptibility of earthquake-induced landslides, have concluded that the areas being developed are stable and unlikely to slide again in another earthquake. However, published maps of areas that have potential for seismically induced ground-failure assign high seismic landslide susceptibility to the Earthquake Park and Turnagain Heights areas (Harding-Lawson Associates et al., 1997; Jibson and Michael, 2009).

Also, beneath the tidal flats, about 50 m offshore of the trail, lies a jet fuel pipeline between the Port of Anchorage and the Anchorage International Airport. The airport had proposed an alternative overland route. However, that route would have been challenging and expensive to build as it would cross a lot of private property, roads, and utilities. Moreover, the Municipality's Geotechnical Advisory Commission was not satisified that the route would avoid landslide hazards. Eventually, the Airport sought and received permission from the Army Corps of Engineers (the regulatory authority for the tidal flats) to bury the pipeline beneath the tidal flat, thus avoiding the issues of the overland route.

At this stop we will discuss the structure of the Turnagain Heights slide, and explore slide debris morphology still apparent in the land surrounding Earthquake Park. Near the parking area, you can see a cliff in the trees, which is the headscarp of the landslide. As we walk to the shoreline, you will be able to see the linear ridges and valleys of the landslide blocks. Most of the blocks are back-tilted toward the headscarp. In some places, you may be able to see the peat that developed on the pre-1964 surface, which is now tilted. All trees growing on the landslide material are vertical, indicating that there are no trees that predate 1964.

March 27, 1964: The day the earth fell to pieces for one Anchorage family

By JULIA O'MALLEY, From Anchorage Daily News, March 22, 2014

Pam, Penny, Paul Mead in Ralph Alley's Buick, June 1964. Photo courtesy of Mossy Meade.

When the ground stopped moving, 8-year-old Penny Mead and her little brother, Paul, were sitting on the hood of an old light green Plymouth station wagon out on the Cook Inlet mud flats. The earthquake had been so loud. Now it was quiet. Not far away, water lapped the shore.

When they had climbed on that car, minutes earlier, it was parked outside their house on Chilligan Drive in Anchorage's Turnagain neighborhood. Now it was lodged in a bizarre new landscape next to the ruins of their garage. Broken chunks of snowy ground, rafts of mud, and upended trees stretched all around them. Behind them, across 150 feet of debris, a newly formed cliff rose three stories. Near the top of it, torn pipes stuck out of the earth, dripping. Sandy soil trickled down the bluff.

There had been four Mead children in the house when it started -- Penny and her three brothers, Perry, 12, Paul, 4, and Merrell, 2. There had been a yard. There had been a driveway. Now there were just two of them. The house was crushed. The driveway was gone. Paul was crying. He had no shoes.

Penny heard a voice, and saw Tay Thomas, a neighbor, across the mess. Thomas and her two kids were climbing a tree, trying to get to the top of the bluff. Penny slid off the station wagon and coaxed Paul to follow her back toward the cliff.

You can still find Chilligan Drive on the western edge of the Turnagain neighborhood, but it doesn't look the way it did before the Great Alaska Earthquake.

In the spring of 1964, Chilligan was a curved street that headed north off Clay Products Drive and then turned east, running parallel to the shore of Cook Inlet. The Mead house sat off the curve on a bluff above the water with views Mount Susitna, Fire Island, and on clear days, Mount McKinley.

Now Chilligan dead-ends at a steep drop. The curve and part of the street that paralleled the inlet were shorn off by a massive landslide during the earthquake. Part of the street was rebuilt and given the name Kissee Court.

Much of the Turnagain neighborhood sits on a layer of sandy clay that can turn to liquid in strong shaking. It is still classified among the places in Anchorage with the highest risk of ground failure during a quake. Seventy-five houses in the neighborhood were destroyed as the land under them collapsed in 1964. In aerial photos taken afterward, a huge crater bites into the land there and extends out into the inlet. The slide zone was estimated to cover 130 acres.

The 1964 earthquake was the second largest ever recorded. It registered 9.2 and lasted as long as five minutes. The death toll is still subject to dispute. The latest number is 139. Nine people died in Anchorage. Four of those deaths occurred in Turnagain. Two of those were on Chilligan Drive.

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The Mead family earthquake story begins like a lot of Anchorage earthquake stories. It was dinnertime on Good Friday. At 5:36 p.m. four Mead children sat around a table, eating. The oldest daughter, Pam, who was 11, was at a friend's house a block away. On the TV: "Fireball XL5," a children's sci-fi puppet program.

Maybe 15 minutes before, their mother, Wanda Mead, left for a quick errand. Wanda is 84 years old now. She has since remarried and goes by Wanda Wright. I reached her last week at her home in Maine. The family had planned to go to Independence Mine at Hatcher Pass that day, she told me. The car was packed for the trip, but her husband, Perry, who was a neurosurgeon, left that morning to make rounds at the hospital and was delayed all day. He still wasn't home when she left the house.

It has been 50 years, but I could hear in Wanda's voice the anguished desire to rewind that day. She wished they would have driven the car out of town. Then the house would have been empty. And everything might have been different.

"(Independence Mine) was one of those wonderful places like the Homer Spit where you could take your kids and turn 'em loose," she told me. "And nothing bad would happen."

Her errand took her to Bert's Drug Store on Fourth Avenue between G Street and H Street, she said. She had special-ordered Easter presents for her boys. They were cars that went on rails. She got to the store and parked. She remembers that she walked in and picked up the cars. She remembers that she paid.

"I was on my way out of the store when it hit," she said.

She huddled behind a counter as the store rocked. A block or two away, a fissure split the street. Entire buildings dropped 10 feet. Nearby, on Fifth Avenue, the side of the JC Penney store collapsed, killing two people. Wanda doesn't remember any of that destruction. All she remembers is that when the quake stopped, she got in her car and wound through the streets until she found a way out of downtown. Then she headed west, toward Turnagain.

"I had to be home. That was the only thing in my mind: I need to be home. I need to be home," she said.

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First, the children felt house began to rattle. The rattling grew violent. Penny, the 8-year-old, lives in Fairbanks now. Most people know her as "Mossy," a nickname she's had since college.

She sent me a written account of what happened next a few weeks ago. She didn't talk about the earthquake for 20 years, she said. Then it came up in therapy. And then she started to bring it up with family and friends. Even now it's easiest for her to write about it.

Penny ran outside the house when it was clear the earthquake wasn't going to stop, she wrote. As she watched, cracks snaked through the hard-packed snow. She tried to avoid them and took refuge near an old car parked near the driveway. Her ears filled with noise.

"There are loud rumbling, groaning and screeching sounds," Mead wrote. "I say over and over to myself, 'Stay calm! Stay Calm!' "

The shaking slowed, but then something deep beneath the ground gave way. The driveway, the house, the car, all of it, lurched, sinking toward the inlet. Mead's brain tried to keep up with what her eyes were taking in, she wrote. The only explanation that made sense in her child's mind was that the world was coming to an end.

"God help us!" she remembers yelling.

The house was breaking up and her brothers were still inside.

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The Meads shared a driveway with the neighbors, Tay and Lowell Thomas Jr., who had two children, Anne, 8, and David, who was 6.

Tay is now 86. She was home with the children that late afternoon, she told me recently when I visited her in Anchorage. She said she heard a noise she thought was guns coming from Fort Richardson. Soon she realized it was an earthquake. She gathered Ann and David and hurried out the door.

"We got about 10 feet beyond the steps into the snow," she said. "A very, very strong shake of the ground knocked us all off our feet."

She turned back toward her house, looking for the family dog.

"At that moment, there was a big crack (sound)," she said.

Her house split in two. Part of it began moving down the bluff toward the inlet. They were moving, too. She grabbed her children and held one under each arm.

"We just lay on this piece of frozen ground and started floating down," she said.

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Next door, the Mead yard was breaking up like pieces of a puzzle. Penny stood next to the car. Perry herded his two younger brothers down a short flight of stairs, out the door, into the driveway.

"I remember (Perry) giving me a shove and that's really the last I remember of him," Paul, who was 4 at the time, told me when I reached him at home in Colorado.

Penny saw Perry come out of the house, she wrote. He towed a little brother in each hand.

"When he sees the devastation from the earthquake and how the property is dropping downward towards the sea, he panics," she wrote.

Perry let go. He ran away from the house as if he were trying to escape to Chilligan Drive, but a cliff was rising at the end of the driveway.

"The huge cracks splitting open everywhere snatch him from my sight in a split second," she wrote.

Mossy said she felt calm then; it's a feeling she still gets in emergencies. The two little boys, Paul and Merrell, stood by the house, crying**.** The ground was still moving. She stayed by the car and called to them.

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Time slowed down for Tay Thomas as she and her children rode down with the landslide.

"I remember seeing the children's swing move by us on a piece of frozen ground," she said. "I thought, that's odd, because that was in the backyard, but it was ahead of us now."

She heard the shattering of glass. They passed her greenhouse.

"I couldn't believe what I was seeing. I couldn't believe what I was experiencing," she said.

Then she noticed that the water lay ahead. They were still moving down.

"I wondered," she said, "if we were going in."

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The little Mead boys, Paul and Merrell, worked across the driveway to their sister. Soon they were right next to her, standing on a chunk of earth.

Penny lifted Paul onto the car. He scrambled up. Safe. She turned around to lift Merrell.

"In that split second," she told me. "Merrell was just gone."

"A crevasse opened up and took him, sand peeling from its sides," she wrote. Then it closed up again, swallowing him "like an earthen monster."

She doesn't remember climbing up on top of the car with Paul or if she understood they were moving down toward the water with the wreckage of their house. Paul didn't see his brothers go into the cracks, he told me. He just remembers the trees whipping back and forth.

"I was just focused on what was in front me," he said. "What used to be a solid world had just suddenly fallen to pieces."

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Next door, Tay Thomas became sure that she and the children were going to die, she told me.

"I remembered hearing somewhere or other that God would be with us at the end of the world. I looked up in the sky and I didn't see anything," she said. "Just clouds."

And then a feeling of peace came over her, she told me.

"I just accepted what was happening at that moment," she said.

And then the shaking stopped.

"What I've never forgotten is the shatteringly loud silence when the earthquake finally stopped," Tay's daughter, Anne, wrote in an email. "It had been so incredibly loud."

Tay Thomas noticed what she recognized as a piece of the Mead house. It had slid closer to the water than she had. Later that night, when the tide came up, the house would be totally submerged.

Thomas saw the car that used to sit near the Mead's driveway. Two children sat on the hood.

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Wanda made it back to Turnagain no more than 50 minutes after she left the neighborhood to go downtown, she told me. She took a right on Chilligan and drove to where the road used to turn along the bluff.

"It was gone. The trees were gone. The houses were gone. Thomas' house. Our house. It was gone," she said.

She looked down from the top of the cliff where her house used to be and saw Thomas below.

"I yelled at her and asked if she'd seen any of my kids and she said yes, on the car," she said.

Then she saw her two children near the station wagon. Penny was gripping Paul.

What happened after that gets tangled up, refracted through all the emotion of the moment and the years that have passed. A neighbor made his way out to the kids. They were carried back up to the top of the cliff.

Wanda asked her daughter what happened. Penny said that her older brother "jumped in a hole" and her younger brother was swallowed up.

"She said, 'Mama, I tried, I tried to get Merrell,' " Wanda recalled. "It just broke my heart. Because I knew she would live with that until she died."

Paul remembers his mother holding him and taking him to the home of a neighbor. Penny remembers her father, Perry Mead, getting home around the time her mother did.

"My dad asked me, 'Where is Perry and Merrell?' I told him they were gone. ... He just kind of freaked and grabbed a shovel and ran down there."

Wanda went down to the debris pile with a neighbor, she said. The house was crushed, its parts strewn over a distance. There was no sign of the boys. She doesn't remember her husband going down. Soon they were told that a tsunami was headed for the city and they all had to move to higher ground.

The tsunami never arrived, but the tide came up and covered what was left of the Mead house. The family spent the night with a friend of a friend out of the neighborhood.

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Over the days that followed, volunteer searchers went through the muddy wreckage. They found the Mead's kitchen table and hauled out a convertible that had been in the garage. There was no sign of the boys' remains.

"I guess because I was so small people assumed I wouldn't have known anything but I knew a lot," Penny said. "I always wondered if someone had approached me, you know in an appropriate manner because I was just small, they might have been able to search and find the bodies."

It might have given everyone more closure, she said.

A memorial service for Merrell and Perry was held at First Presbyterian Church. Mourners packed the service. A singer sang Psalm 131. Penny and her brother were kept home.

"I did not introduce the subject (of the boys' deaths)" Wright said. "If the subject came up, I tried very hard to be straight and honest and not overload them with information."

Penny "Mossy" Mead remembers that her parents stayed mostly quiet about what happened. There were immediate needs to tend to. They had to find a temporary place to live, and later they built a new house in South Anchorage.

"I think that's partly that generation to a degree," Mossy said. "It seems like a lot of people in that era, you didn't talk about things."

The Meads divorced several years after the earthquake.

Shortly after the quake, a story emerged, published in news reports. It said Perry died after he ran back into the house to rescue Merrell. No one in the Mead family spoke directly to a reporter.

"Maybe because he died, they needed to do something to bring condolences to the family for his loss, and making him the hero probably made it easier to bear," Mossy said.

Wright donated their lot to the city to become parkland. Her only stipulation was that the ground remain undisturbed. It's now at the eastern edge of Earthquake Park. The Thomas lot next door was redeveloped. Many lots that slid in the quake have been rebuilt with expensive new homes, their yards rolling downhill to border the Coastal Trail. Building codes have changed. Houses may still end up sliding, but they are supposed to be designed not to break apart.

Mossy's sister Pam was killed in a car accident in Homer in 1981. Her father, Perry, died of cancer in 1995. Both of their ashes are spread on the mud flats. The ruins of the house, visible for years, were slowly buried in silt until they disappeared. In the 1980s, Mossy had a memorial stone for her siblings placed at a cemetery in Wasilla. But to her, Earthquake Park will always feel like her family's real burial site, she said. When she wants to remember all the people she has lost, she walks out along the Coastal Trail to mile marker 1.5 and looks at the water and the trees

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Julia O'Malley writes a regular column. Reach her by phone at 257-4591, email her at jomalley@adn.com

Read more here: http://www.adn.com/2014/03/22/3388654/march-27-1964-the-day-the-world.html#storylink=cpy

Tectonics and Neotectonics of Southern Alaska: Overview in Earthquake Park

The Anchorage area is poised on the edge of a very active plate boundary between the North America and Pacific plates (Figure 3.1). These two plates are converging at a rate of about 5.5 cm/year (2.1 in/yr), and this convergence directly or indirectly causes many of the most prominent geological features in this region. The Benioff zone is at a depth of about 50 km beneath Anchorage, and 120 km to the west, the Aleutian arc volcanoes mark where the slab is at a depth of about 100 km (Figure 3.1). Here you can see, or if the weather is bad—envision, the three major components of a convergent margin: the active arc, the accretionary complex, and the forearc basin (Figure 3.2).

Spurr Volcano is the northeastern most active volcano of the Aleutian arc, and it last erupted in 1992, when it blanketed Anchorage with a dusting of ash (Figure 3.3). Redoubt Volcano, the next volcano to the west, erupted in 1902, 1922, 1966, 1989 and 2009. The eruption in 1989 spewed volcanic ash to a height of 45,000 ft (14,000 m) and caught KLM Flight 867, a Boeing 747 aircraft, in its plume. It caused $80 million in damage to a $120 million dollar aircraft (in 1989 dollars). The modern arc is built on the Peninsular-Wrangellia composite terrane (Plafker et al., 1994). The Peninsular terrane has been the site of episodic arc magmatism since the latest Triassic (Hacker and others, 2008; 2011). Farther outboard and paired with it is the Chugach-Prince William composite terrane, an accretionary complex that formed in the same time interval. These terranes were juxtaposed before they approached the North American margin in latest Jurassic to Cretaceous time (e.g., Trop et al., 2002; Pavlis and Roeske, 2007). The Border Ranges Fault forms the boundary between the Wrangellia-Peninsular and Chugach terranes; it began as a subduction thrust but has been reactivated in various places as strike-slip or normal faults (e.g., Little and Naeser, 1989; Pavlis and Roeske, 2007). The Mesozoic part of the accretionary wedge is referred to as the Chugach terrane, the Cenozoic part as the Prince William terrane. The distinction between Chugach and Prince William terranes appears artificial (Dumoulin, 1987; 1988) but the names are entrenched and are retained for now. Moreover, the 'terrane' nomenclature doesn't really seem appropriate for a subduction complex, which intrinsically has no stratigraphy, so this author prefers not to call them terranes.

The ~200 million year history of the accretionary prism shows a complex and sporadic history of accretion (see Figure 3.2). The McHugh Complex is the oldest and most landward part of the subduction complex. The McHugh is dominantly mélange, and recent detrital zircon work indicates that sediment in it has 2-3 main ages, with the youngest sediment being about 90 Ma (see Karl et al., 2011 for more details). The point here is that this rock unit contains about 110 million years of subduction history, but it is roughly 20 km in width. The prevalence of normal motion fault fabrics, and the narrow width of the unit have led some to argue for there being significant subduction erosion during the time encompassed by this unit.

The next youngest rock unit in the accretionary complex is the Valdez Group and the Orca Group. As both of these rock units consist dominantly of slate and greywacke turbidites, the distinction between the two is almost artificial. Regardless, fossil and detrital zircon studies indicate these rocks were deposited between 80 or 75 Ma and 55 Ma, and that the time encompassed by these two units is 15-20 million years (see summary in Karl et al., 2011). Given their width of about 120 km on the regional geologic map, it seems likely that a lot of sediment was entering the trench at this time, and thus the accretionary complex built outward.

Anchorage is at the edge of the Cook Inlet forearc basin, which lies between the arc and the subduction complex. The Cook Inlet basin also has a history stretching back to early Mesozoic time. The geologic and geophysical framework for the basin is shown in Figure 3.1. The basin fill is nearly 8 km thick in upper Cook Inlet, which is also where there are some active fault-cored folds in the basin (Figure 3.1A). Magnetic, gravity, and electrical data are consistent with there being a strongly serpentinized mantle wedge (Fig. 3.1). This composition likely leads to low viscosity mantle, and corner flow in the wedge may dynamically drive subsidence in the basin and cause the negative isostatic residual gravity anomaly (Haeussler and Saltus, 2011).

The nature of the subducting slab likely has a huge impact on the geology of southcentral Alaska. Southwest of Anchorage, there is typical oceanic crust subducting beneath the continental margin. Northeast of Anchorage (YSE on Figure 3.1), is the Yakutat microplate slab. The Yakutat microplate, or terrane, began its life off the coast of British Columbia. It is a composite terrane. The eastern part, a relatively small part, consists of subduction complex rocks. The western part, which is most of the terrane, consists of Eocene volcanic rocks, which have the velocity structure of an oceanic plateau (Christeson et al., 2010). Sometime after 50 Ma, after relative plate motions turned northwesterly, the transform margin stepped inboard, and then the terrane started moving northward, similar to the way Baja California was plucked from the Central American margin. The Yakutat slab was first imaged geophysically in this region by Ferris et al. (2003) and then mapped out in 3D by Eberhart-Phillips et al. (2006). A somewhat-too-small version of the Eberhart-Phillips et al. (2006) map is shown in Figure 3.1B. The Yakutat slab has likely been subducting beneath southern Alaska for 25 million years (Haeussler, 2008). The thicker, more buoyant nature of the Yakutat slab results in a very shallow angle of dip of the subduction zone in the region northeast of the Yakutat slab, and the distance between the trench and the arc widens drastically, such that for Spurr Volcano the distance is about 450 km – one of the largest in the world. Eberhart-Phillips et al. (2006) argued that this shallow subduction angle may have been the cause of greater coupling beneath Prince William Sound, which resulted in a large slip patch in the 1964 earthquake. The Yakutat slab also correlates with the region where there are no active arc volcanoes along the Alaska-Aleutian subduction zone. Either the low subduction angle or the nature of the subducting crust is likely the reason for no magmatism above the slab.

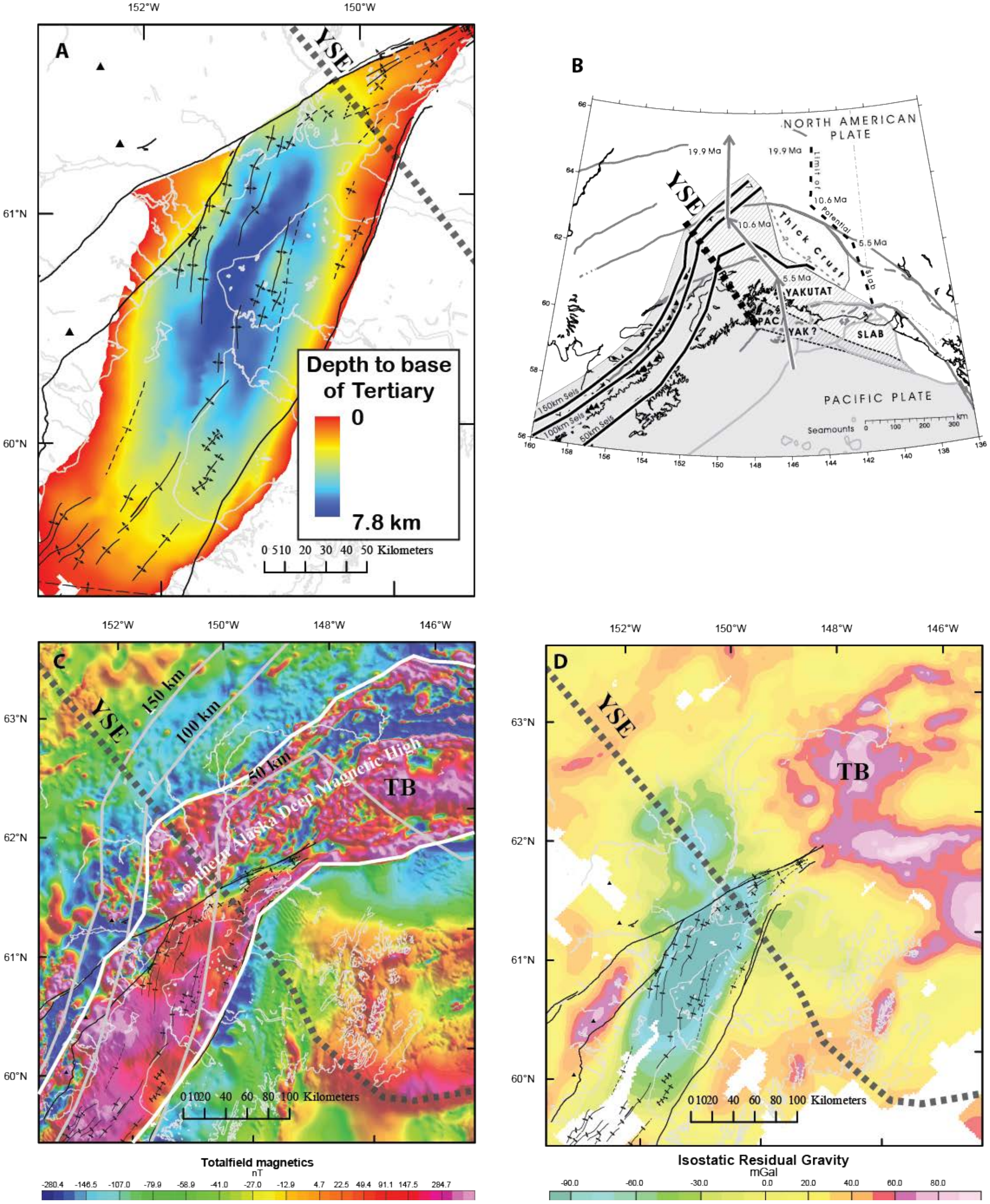


Figure 3.1 Maps showing the relationship of the Cook Inlet Basin to the subducted Yakutat terrane slab, Alaska, from Figure 5 of Haeussler and Saltus (2011). Dashed gray line is the Yakutat Slab Edge (YSE), from Eberhart-Phillips and others (2006). A, map of depth to Tertiary basement in the Cook Inlet Basin from Shellenbaum and others (2010). B, Map showing the location of the subducting Yakutat slab from the tomography of Eberhart-

Phillips and others (2006). C, Merged total field magnetic intensity map. Grey contours to Benioff zone seismicity from Eberhart-Phillips and others (2006). Outline of southern Alaska Deep Magnetic High (Saltus and others, 1999) shown with white lines. TB, Talkeetna batholith. D, Isostatic residual gravity map.. TB, Talkeetna batholith.

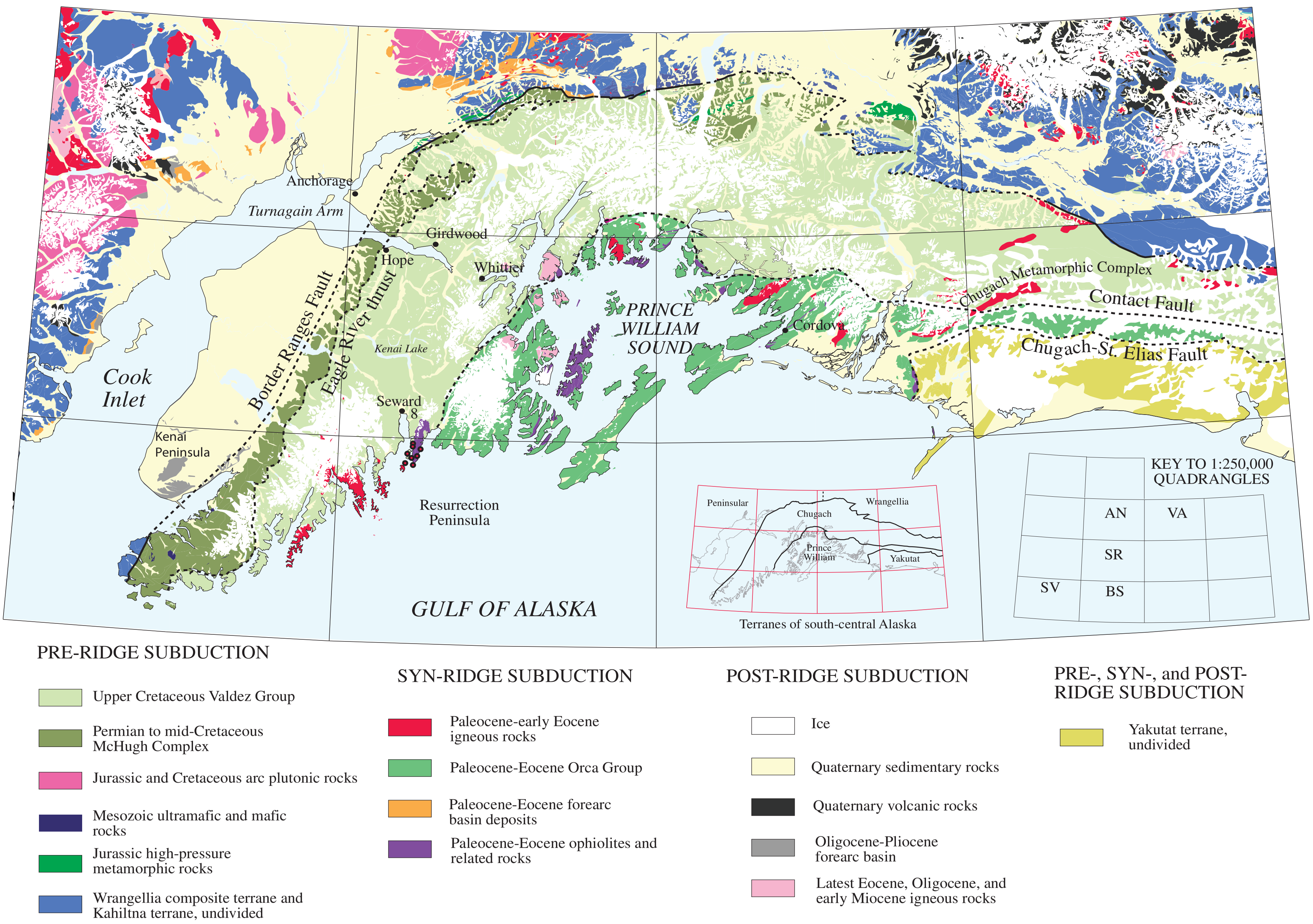


Figure 3.2. Generalized geologic map of south-central Alaska, from Bradley et al. (2003) and sources cited therein. Abbreviations for 1:250,000-scale quadrangels: AN, Anchorage; BS, Blying Sound; SR, Seard; SV, Seldovia; VA, Valdez.

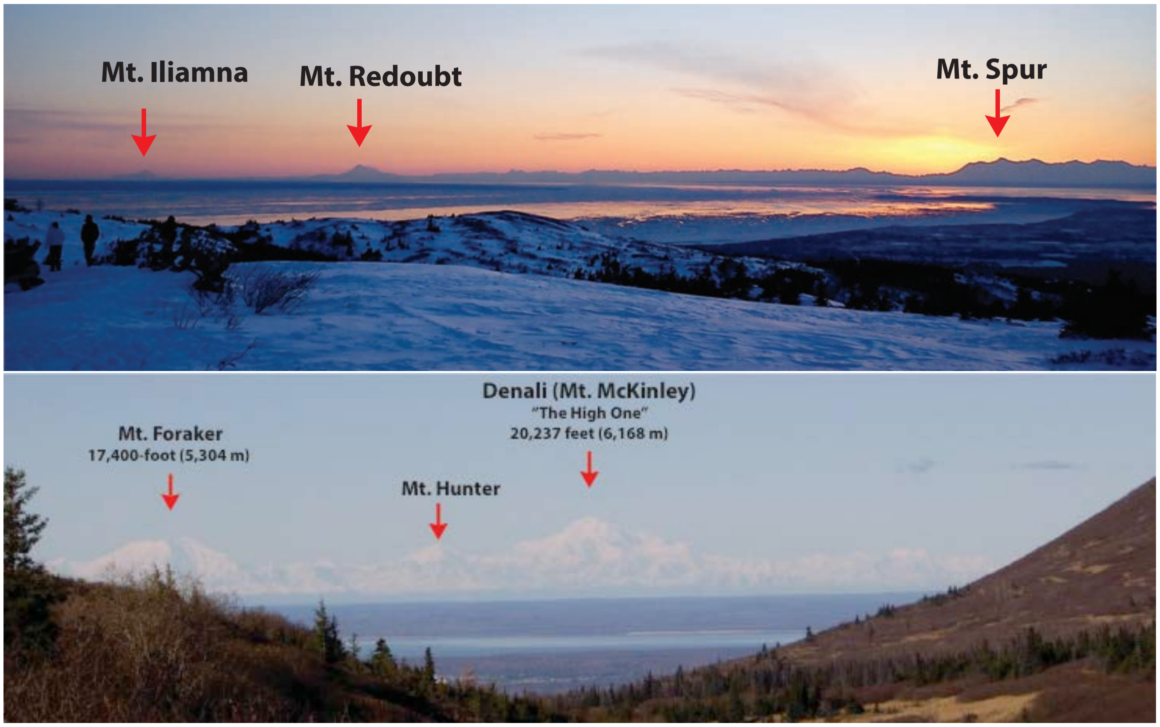


Figure 3.3. Top: View of active, ice-covered stratavolcanos visible from Anchorage. Spur Volcano and Redoubt Volcano have had several eruptions in the last 100 years. Bottom: View to the north of three of the tallest peaks of the Alaska Range that result from active tectonics in central Alaska..

The Alaska Range, home of North America's highest peak, Denali (or Mt. McKinley) is also a product of the Yakutat collision. The Alaska Range, visible to the north of Anchorage on clear days (Figure 3.3) formed as a result of movement along the Denali Fault system. The Denali fault is the principal intracontinental fault accommodating the far field effects of the Yakutat collision in central Alaska. The Tordrillo Mountains, which are the highest part of the western Alaska Range, which includes Mt. Spurr, began rapid exhumation around ~23 Ma (Haeussler et al., 2008), and then experienced additional exhumation at 6 Ma. Denali also began rapid exhumation around 6 Ma (Fitzgerald et al., 1995). Presumably these far-field effects of the Yakutat collision occurred as a result of the insertion of the Yakutat slab beneath the margin, and the involvement of the orogenic wedge in deformation (Haeussler, 2008). The Denali fault has also hosted large earthquakes, most recently in 2002 when a M7.9 earthquake on the Denali fault shook much of Southern Alaska.

Drive toward Whittier. Drive 58 mi (77 min) to Anton Anderson Memorial Tunnel. **Stop 3 -** As time allows, we will pull over next to Portage Lake either before or after our visit to Whittier.

Stop 3 — Portage Lake, Portage Glacier retreat, lacustrine paleoseismology

Figure 4.1 Photo of Portage Glacier and Portage Lake in 1957

The Portage Glacier used to be easily viewed from the U.S. Forest Service Begich, Boggs Visitor Center when it was first open to the public in 1986. During the past century, the terminus of the glacier has retreated nearly 5 kilometers to its present location, where it can hardly be seen. At this location near Placer Creek, it is easier to see today. Like other glaciers that terminate in water, such as Columbia Glacier near Valdez, Portage Glacier experienced accelerated retreat in recent decades that likely were initially triggered by climate change beginning at the end of the Little Ice Age in the late-1800s. Photographic records of the terminus covering 1914 until present day track the patterns of retreat. These data, coupled with USGS climate information collected from the southern end of the ice field, provide insight to the patterns of retreat that might be observed in the future (Kennedy et al, 2006).

During the late 1800s and early 1900s, Portage Glacier terminated on land and at the rock wall at the north end of Portage Lake (Figure 4.2 - 1914). Since the early 1900s, the glacier has receded, leaving ice-filled Portage Lake in the scoured basin. As the glacier receded, its land-based terminus retreated into proglacial Portage Lake and changed from its relatively stable land-based environment to an unstable calving environment. The most rapid recession rate of some 140 to 160 meters per year occurred between 1939 (Figure 4.2 -1939) and 1950, when water depth at the terminus was at its maximum—roughly 200 meters. Recession continued through the 1970s and 1980s (Figure 4.2 -1972, 1984) until by late 1999, Portage Glacier had receded almost 5 kilometers, to a more stable position at the eastern end of Portage Lake (Figure 4.2 - 1999). The retreat was driven primarily by calving of unstable ice at the glacier terminus into Portage Lake. Ice loss resulting from increased melting of the glacier surface was a less important factor in the last century than the warming climate (Kennedy et al, 2006).

The Above is taken from Kennedy et al. (2006).

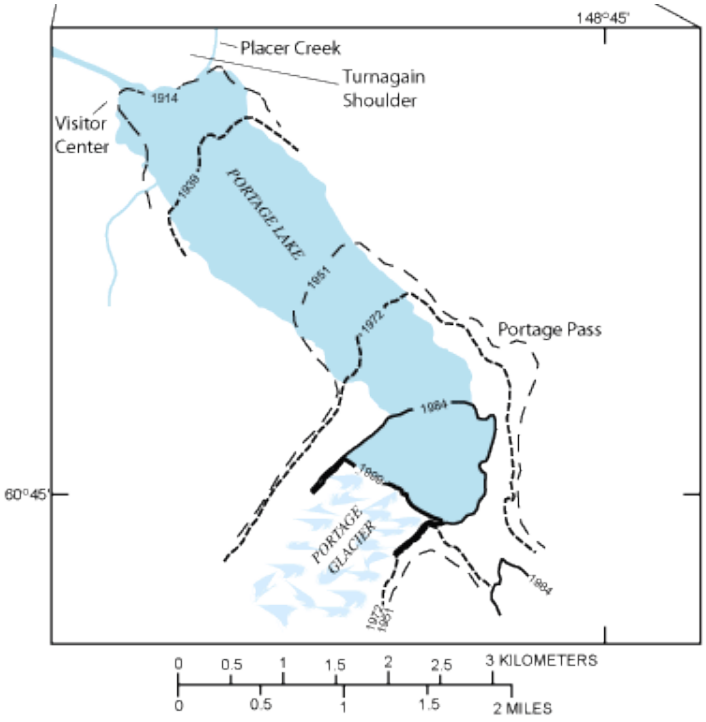


Figure 4.2 Approximate terminus positions of Portage Glacier 1914–1999 (Modified from Mayo et al., 1977 with additional USGS imagery). The 2006 location is very similar to the marked 1999 location. U.S. Forest Service Begich, Boggs Visitor Center location is marked. Portage Glacier is located in south-central Alaska.

The future of the Portage Glacier

Early scientific theories proposed that calving glaciers cycle between advance and retreat patterns; with rapid retreats, followed by stable retracted positions, slow advances, and then stable extended positions that are not directly related to climate change. This would suggest that the glacier would advance again in the future as part of this cycle. However, current research in Alaska and elsewhere does not support this theory – thus far showing no evidence for this cycle with lake terminating glaciers and favoring the possibility that Portage glacier will continue to retreat (*E. Burgess, personal communication*). It is possible however that Portage glacier retreat will stabilize somewhat once the terminus reaches shore, and the glacier no longer terminates in the lake.

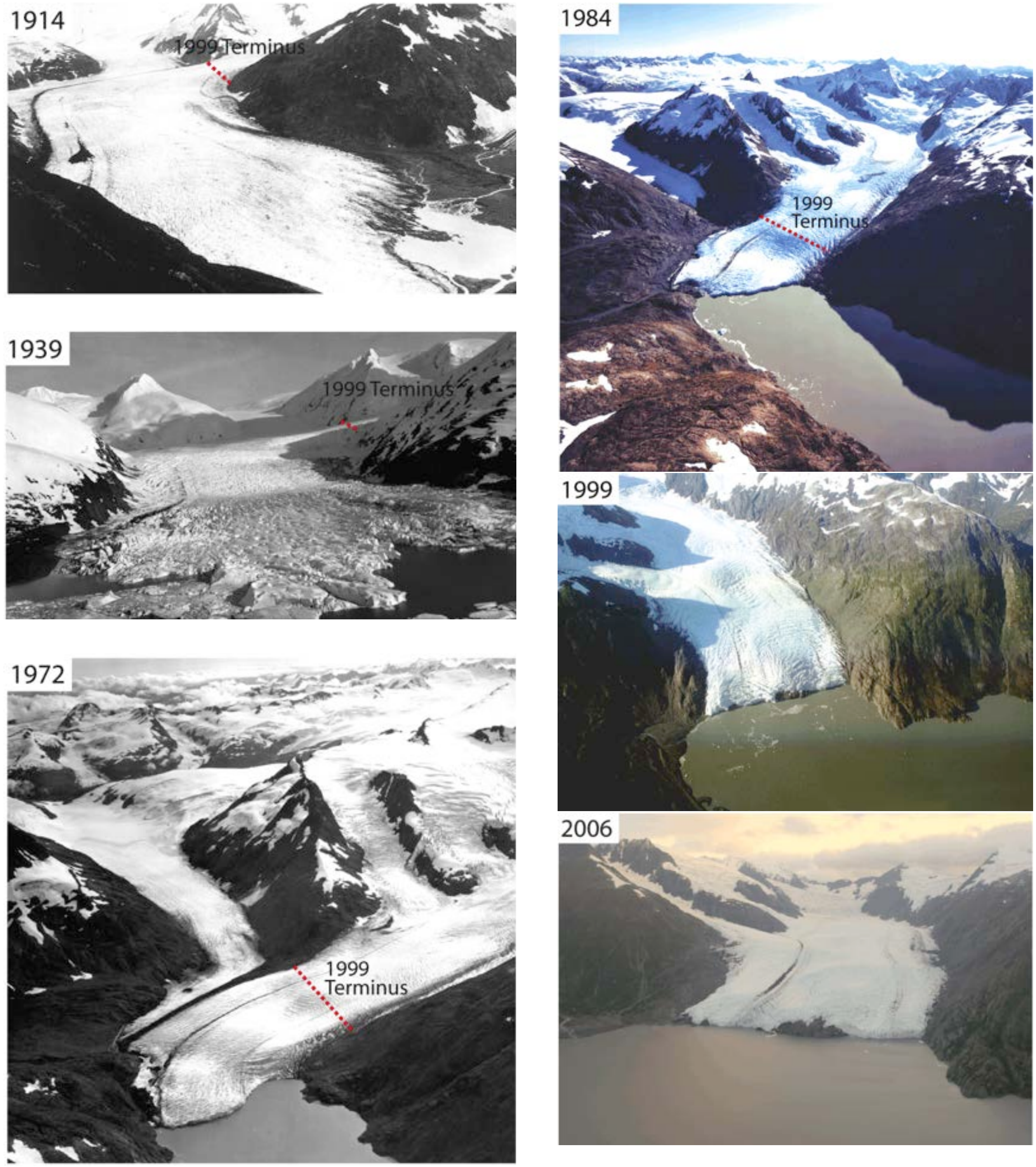


Figure 4.3. Photo record of Portage Glacier retreat from 1914-2006

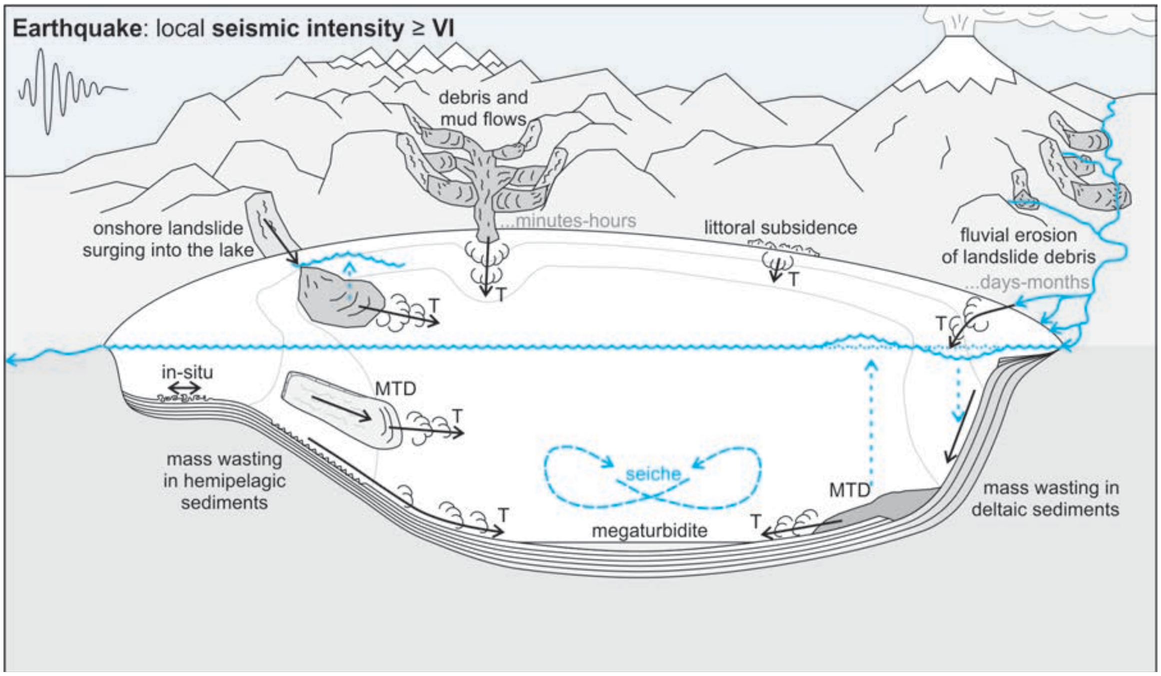


Figure 4.4. Sources of sediment in lake basins as a result of earthquake shaking. From Van Daele et al. (2015). Mass wasting of hemipelagic sediments on slopes is the most common.

Lacustrine Paleoseismology in Southcentral Alaska

Lacustrine (lake) paleoseismology aims to use lake bottom sediments as recorders of earthquakes. During strong ground shaking from an earthquake, surficial sediments on slopes and deltas can get mobilized and deposited into lake basins at MMI intensities of greater than ~V½ (Figure 4.4). These earthquake-generated turbidites and mass transfer deposits can be seen in cores and imaged using pinger and chirp subbottom profling methods (Fig. 4.5). Lacustrine paleoseismic records can have near-annual resolution, as sediments in many Alaskan lakes are varved, meaning they have annual laminations with a winter clay cap and a summer silt or sand deposit. They are analogous to tree rings. Lacustrine paleoseismic records are agnostic of the shaking source. They can record, megathrust, intraslab, and crustal earthquakes, depending on where the lake is located, and they appear to be the only environment capable of recording intraslab earthquakes.

Portage Lake shares some characteristics of lakes that have been successfully used for paleoseismology studies in southcentral Alaska. It lies in a deep glacially carved valley, there are glaciers in the headwaters of the catchment, sediments on the lake bottom are varved, and the lake surface freezes in the wintertime., Portage Lake differs from lakes we have studied in that it has a sedimentary record that only extends about 110 years, during that time there was a calving front within the lake, and most other lakes have runs of salmon.

Recent lacustrine paleoseismology research in southcentral Alaska shows that lakes are rich repositories of earthquake histories. In particular, we have studied Eklutna Lake (near Anchorage), Skilak Lake (on the Kenai Peninsula), Kenai Lake (on the Kenai Peninsula), Tustumena Lake (on the Kenai Peninsula), and Chelatna Lake (along the south flank of the Alaska Range). We find clear evidence of the 1964 great Alaska earthquake in all lakes we have studied, and subbottom profiles and cores show there were numerous sublacustrine landslides and turbidites generated (for example Figure 4.5 at Skilak Lake, Praet et al., 2016). On Figure 4.5, note there are landslides originating from both sides of the basin. This meets the "synchronicity" criterion for establishing that a sublacustrine landslide was generated by earthquake shaking. Long cores (up to 17 m) were collected using a Uwitec platform with a hammer corer and re-entry cone on Eklutna and Skilak Lakes. These long cores show approximately 2300 years of history and show numerous earthquake and flood turbidites. Distinguishing these two types of deposits is relatively straightforward in that earthquake turbidites are brown in color and show typical Bouma sequence grading. Flood "turbidites" are often dark in color from organic matter, and show gradual onset and decline of current related to the rise and fall of precipitation in the catchment. At Eklutna Lake, Praet et al. (2020) found the average recurrence of earthquake turbidites was every 93 years (Figure 4.6). Van Daele et al. (2019) documented evidence of a turbidite deposited in Eklutna Lake as a result of the 2018 M7.1 Anchorage earthquake. Moreover, they showed that the thickness of the 2018 turbidite increased in the direction toward the epicenter of the earthquake, relative to the thickness of the 1964 turbidite. With the success of these and other recent lacustrine paleoseismology studies in southcentral Alaska, our principle paleoseismology focus in Alaska is now on obtaining lake records.

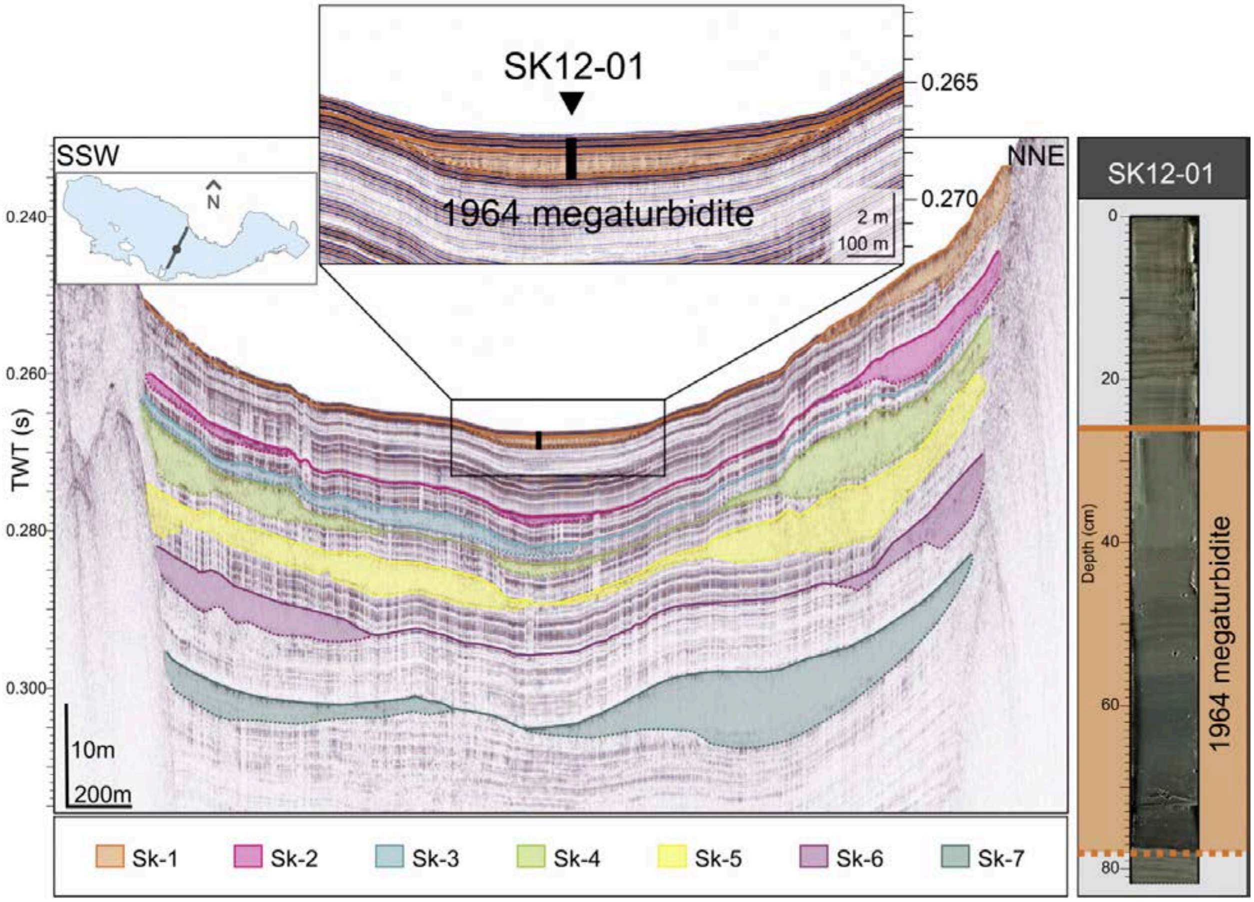


Figure 4.5. Pinger profile (SSW-NNE) in Skilak Lake showing landslide deposits, megaturbidites and seismic event horizons (solid line) from Praet et al. (2016, Figure 7). The base of the landslide deposits and megaturbidites represents an unconformity, which is indicated by a dashed line. Seven events can be identified, where Event Sk-1 represents the historic 1964 megathrust earthquake. A transparent facies with ponding geometry is indicative of megaturbidites. The megaturbidite related to the 1964 earthquake is a graded deposit with coarse-grained base (~50 cm) in core SK12-01. The in situ core length of SK12-01 is decreased by compaction of the sediments, during and after coring. Therefore the length of the core appears longer on the seismic data.

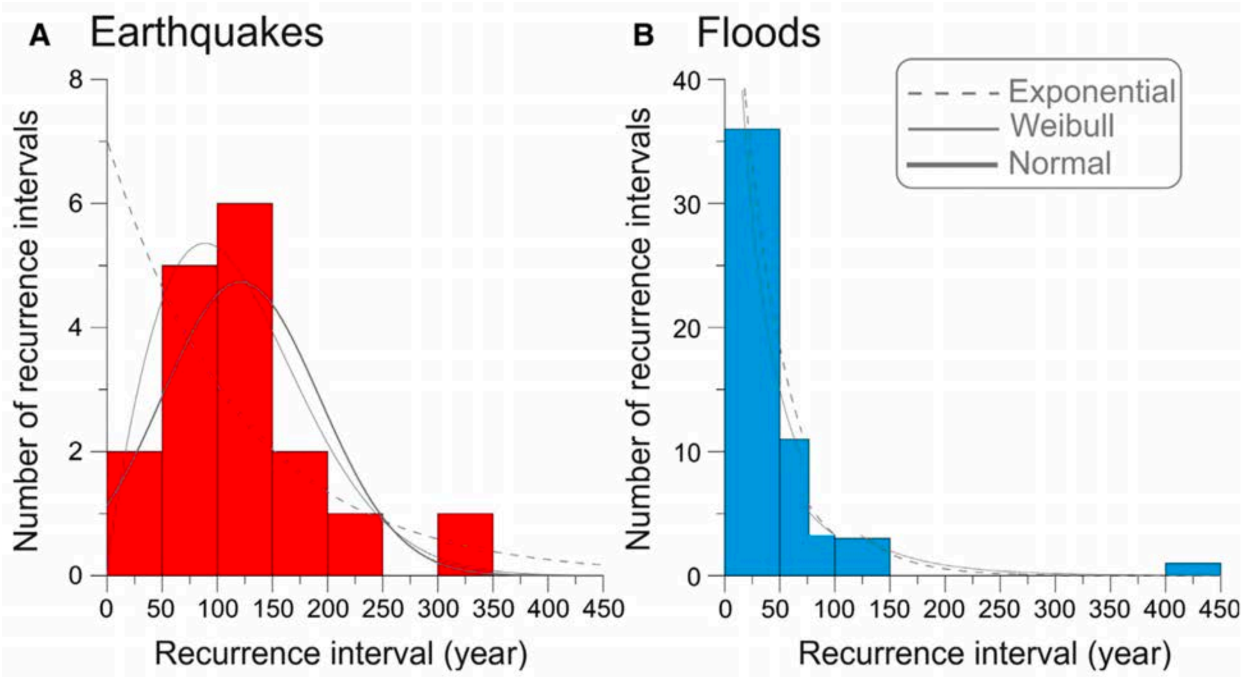


Figure 4.6. Histograms with recurrence intervals of prehistoric earthquake (A) and flood (B) events in location 4 of Eklutna Lake, based on the median ages inferred from the age model, provided in Fortin et al. (2019). An exponential, Weibull and normal distribution are displayed for each histogram. Earthquake recurrence (in red) fits a Weibull distribution, while flood recurrence intervals (in blue) correspond best with an exponential distribution. Figure from Praet et al. (2020, Figure 11).

Drive thru tunnel to Whittier, approximately 2.8 miles (7 minutes). Go to harbor front or Inn at Whittier.

Stop 4 — Whittier, 1964 tsunami and the Barry Arm landslide and potential tsunami

On our way to Whittier, Alaska, we will pass thru the 4.1 km long Anton Anderson Memorial Tunnel. This is an unusual tunnel in that it is one lane and dual use for road and rail (no human powered use!), and has some interesting features. The tunnel was initially built in World War II between 1941 and 1943 as a railroad tunnel. After the 1964 earthquake, no major problems were reported with the tunnel. Between 1999 and 2000 the tunnel was re-engineered for its current dual use format. Both tunnel entrances are built with an A-frame design to withstand potential large snow avalanches loads. Inside the tunnel, you will note some sections of the walls are covered with shotcrete, to cover slatey sections of bedrock, which were more likely to produce rockfall. There are also several “safe houses” inside the tunnel that people could take refuge in, should they become trapped inside the tunnel.

Discussion of effects of 1964 tsunamis at Whittier and recent studies. Indoors if weather is bad; outdoors if its not raining. Could walk 0.4 miles (7 minutes) to covered pavilion overlooking harbor if time allows.

The beautiful topography of southern Alaska is an ideal environment for producing submarine landslides, which can generate local tsunamis. Glaciers and streams erode the mountains depositing sediment at the margins of the fjords. And it is very wet. Whittier, for example, has an average of 198 inches (502 cm) of rain per year and 248 inches (630 cm) of snow per year. Moreover, the entire region lies above the megathrust, which can be a trigger for submarine landslides. Of the 122 fatalities in Alaska after the 1964 earthquake, 106 (87%) were the result of tsunami impacts. Of the 106 deaths in Alaska caused by tsunamis, 85 of those (80%) were related to submarine-landslide generated tsunamis.

The effects of the 1964 tsunamis in Whittier were similar to those in other coastal communities in Alaska, including Seward, Valdez, and the village of Chenega, which lost a third of its population (Plafker et al., 1969). In Whittier, three waves were observed (Kachadoorian, 1965). The first wave arrived about 1-minute after the earthquake began and water rose to an elevation of 8 m. The second tsunami was a muddy, breaking wave that arrived 1 to 1.5 minutes later and reached an elevation of 12.5 m. Forty-five seconds later, a third smaller wave arrived. Flooding by the tsunami waves was exacerbated by 5.3 feet (1.6 m) of earthquake-related subsidence, although the earthquake occurred near low tide (Kachadoorian, 1965).

Figure 5.1. Alaska Earthquake March 27, 1964. The dock area, a tank farm, and railroad facilities at Whittier were severely damaged by surge-waves developed by underwater landslides in Passage Canal. The waves inundated the area of darkened ground, where the snow was soiled or removed by the waves (USGS).

Whittier suffered massive damage from the earthquake and tsunami amounting to $10 million (~$74 million in 2012 dollars) and 13 of the city's 70 inhabitants died (Kachadoorian, 1965). Twelve of the fatalities were at a lumber mill located at the present site of The Inn At Whittier. Much of Whittier's harbor, railroad and sawmill facilities were completely wrecked, particularly buildings constructed on artificial fill or unconsolidated sediment.

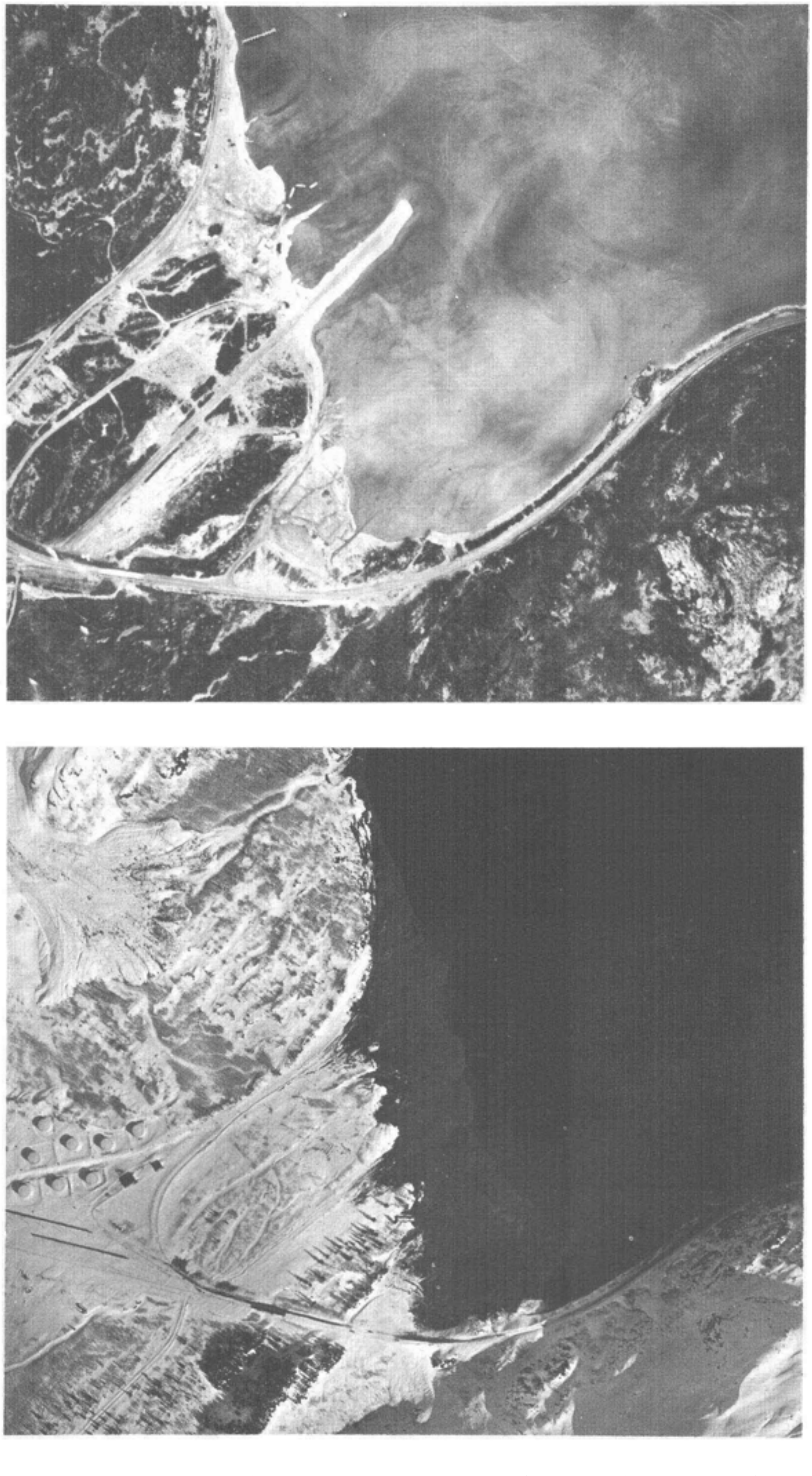


Figure 5.2. Aerial photographs of the head of Passage Canal, Alaska, before and after the 1964 earthquake (Kachadoorian, 1965). Top: Before the 1964 earthquake. Composite photograph by BLM , 23 September 1963. Bottom: After the earthquake. Photograph by U.S. Army, 28 March 1964.

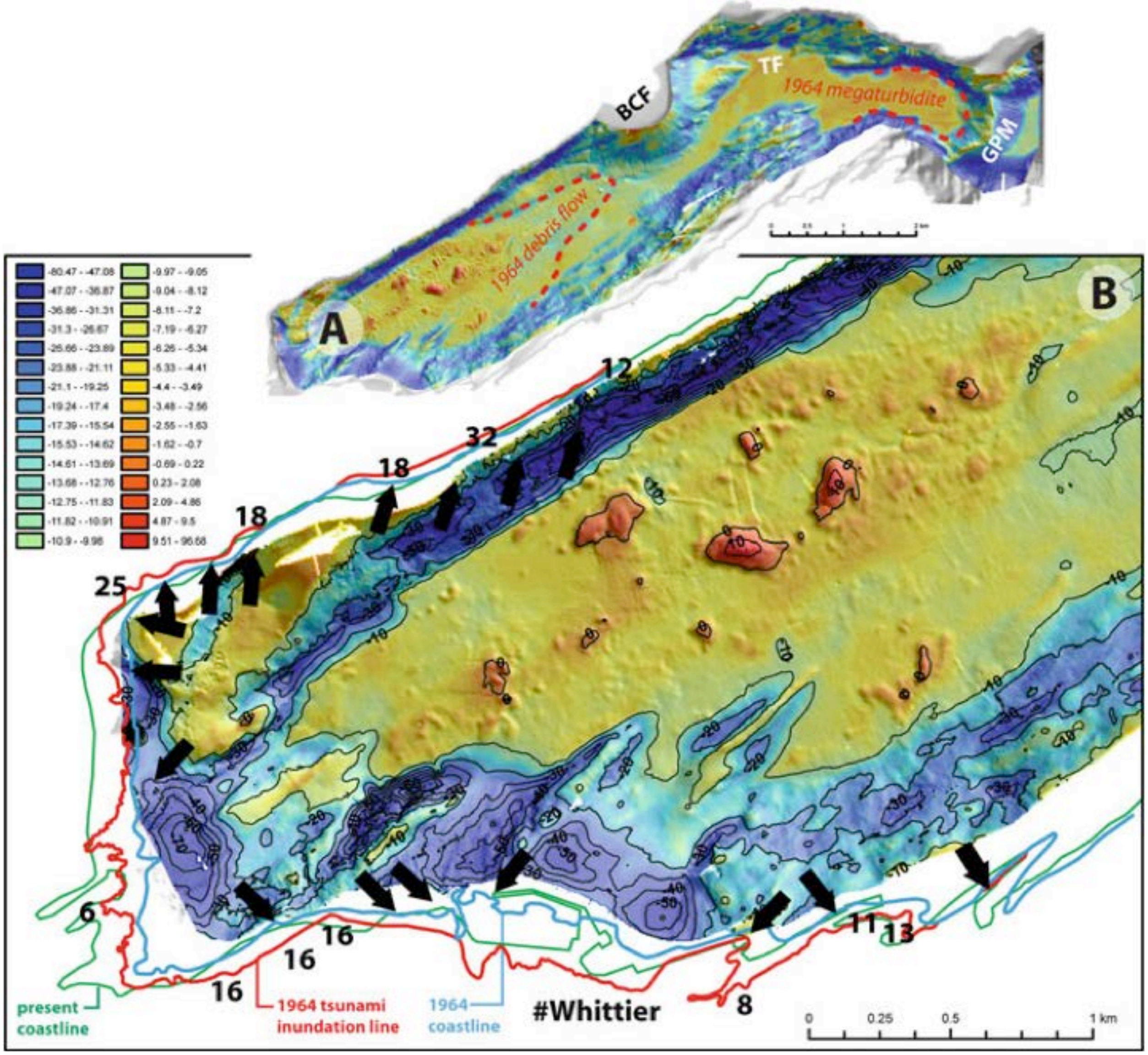


Figure 5.3. Haeussler et al. (2014) investigated changes in bathymetry in Passage Canal by comparing a 1948 bathymetric survey to multibeam survey data acquired in 2011. The inset map (A) covers the entire multibeam survey area and shows the Billings Creek fan (BCF), Trinity Flats (TF) and the Gradual Point moraine (GPM). The detailed map of the western end of Passage Canal (B) shows the coastline in 1964 and present, the tsunami inundation line and wave runup direction and height, in meters (runup data from Kachadoorian, 1965; maps from Haeussler et al., 2014).

Only slight damage occurred to buildings constructed on bedrock. Fire destroyed the fuel oil tanks along the waterfront (Figure 5.1). The tsunami was attributed to the collapse of delta sediment at the west end of Passage Canal (Figure 5.2).

Recent studies of the 1964 earthquake and tsunami in Whittier have explored the details of submarine landsliding and the tsunami it triggered. A study of bathymetric changes before and after the

earthquake show evidence of collapse of the fjord head and Whittier Creek deltas, resulting in the mass displacement of 54.9 million yd^3 (42 million m^3) of landslide material (Figure 5.3; Haeussler et al., 2014). This volume is equivalent to the combined capacity of 132 supertankers. Individual landslide blocks within the deposit measured as much as 475 feet long by 82 feet tall (145 m by 25 m), or about one and a half football fields long and as tall as an 8-story building. Material continued down fjord as a debris flow deposit with an average thickness of ~18 feet (5.4 m). A plume of sediment, identified as a megaturbidite, continued to flow down the fjord for a distance of 6 miles (10 km). The study by Haeussler et al. (2014) showed that the landslides that generated tsunamis in Alaska's fjords eroded the seafloor and involved large blocks that controlled the maximum tsunami runup. They concluded that the abundant glacial sediment produced by Little Ice Age glaciers loaded fjord-head deltas, which were highly susceptible to seismic shaking in 1964. The unusually long (~900 years) interval between the 1964 earthquake and its predecessor (e.g. Shennan et al., 2008) may have resulted in the high number and large volume of submarine landslides.

Figure 5.4. Two views of Barry Arm and the Barry Glacier from 1937 (left) and 2020 (right). Barry Glacier had about 3.5 km of retreat in this interval. A careful look shows the development of the landslide headscarp, thickening of the toe of the landslide and thinning of the head of the slide.

Discussion of Barry Arm Landslide and Tsunami Hazard

The Barry Arm landslide was first identified in 2019 as a large and slow-moving mass that had a volume of about 500 million m^3 (Dai et al., 2020). Initial work showed the slide was identifiable on imagery dating back to the 1920s (see also Figure 5.4), but the slide did not move much until rapid retreat of the tidewater Barry Glacier between 2010 and 2017, when the slide mass moved about 120 m, based on satellite data. During that interval, the movement of the slide directly correlated with the retreat of the calving front of the Barry Glacier (Fig. 5.5). Prior to 2010, failure of the landslide would have resulted in runout onto the glacier surface. Thus, the progression of the Barry Arm landslide is directly related to the removal of glacial ice, which "debutressed" the valley walls enabling subsequent failures. In this way, there is a cascade of events from global warming, to glacial thinning and retreat, to landslides and tsunami. Dai et al. (2020) modelled the Barry Arm landslide and tsunami and found a maximum wave height at Whittier of 10 m that would arrive about 20 minutes after a slide occurred. This work resulted in considerable concern for the town of Whittier, which depends on its waterfront for all its economy. The summer of 2020 was the first of the coronavirus pandemic, and in general, Alaskans were in the wilderness in record numbers, except for out of Whittier, where people were concerned about the hazard and risk of tsunami.

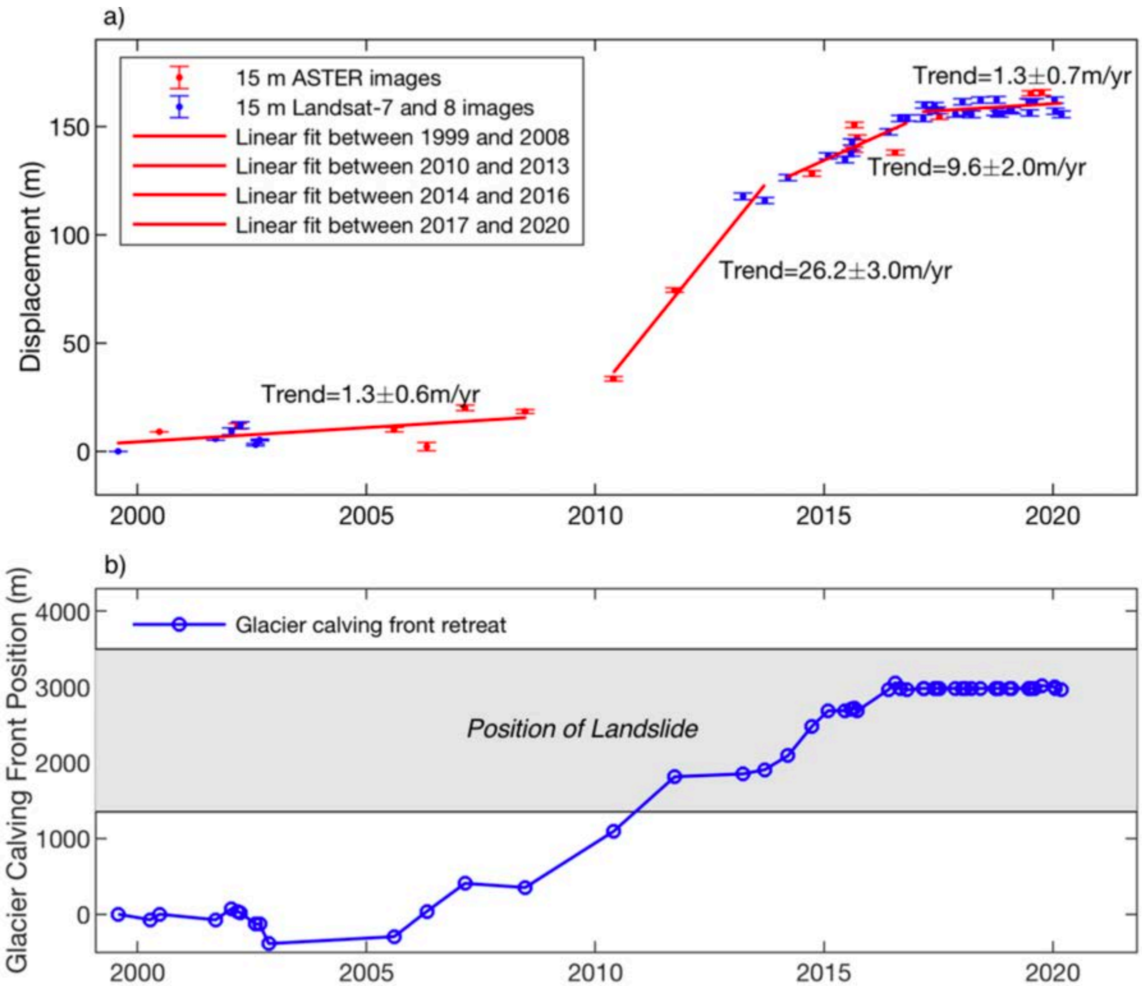


Figure 3.5. Horizontal displacement of the Barry Arm landslide and its correlation with the retreat of the Barry Glacier calving front, from Dai et al. (2020, figure 4). A) The cumulative magnitude of horizontal displacement between 1999 and 2020. Red and blue error bars denote the time series of horizontal displacement in meters relative to the first observation, acquired on 31 July 1999. The estimated uncertainties of the displacements are about 1.3 m, which seems to be slightly underestimated because the fluctuations of the displacments are larger than the uncertainties. Red lines show linear fit to the displacements during four periods. B) The Barry Glacier calving front position time series. Blue circles show the glacier front positions relative to the first acquisition on 31 July 1999. The grey shading shows the landslide position along the glacier centerline.

The concerns about the Barry Arm landslide and tsunami hazard were brought to the Alaska congressional delegation. On January 4, 2021, congress provided the USGS landslide hazards program $4 Million dollars above the fiscal year 2020 enacted level (which was $4 Million dollars) to address concerns about the potential for a major landslide and subsequent tsunami in Prince William Sound. The USGS was directed to conduct data collection and analysis to develop a site-specific landslide hazard assessment, and-provide

recommendations to support a long-term monitoring strategy. Moreover, the USGS was directed to work with area stakeholders, the Department of Homeland Security, the National Oceanic and Atmospheric Administration, the Forest Service, and other relevant Federal, State, and local agencies to develop an emergency early warning system to alert of an impending or actual landslide that could result in a tsunami. Of the initial $4M, $2.15M was directed to the State of Alaska Division of Geological & Geophysical Surveys (DGGS) to develop an Alaska Landslide Hazards Program. The remainder of the FY21 budget was used to create a long-term project focusing on landslides in Prince William Sound. Funding continued at FY21 levels and is expected to remain the same in FY23 and beyond.

The objectives of the collaboration between the State of Alaska and the USGS in Prince William Sound are to a) identify potentially tsunamigenic landslides in the region, b) determine geologic and meteorologic controls on landslide movement, c) surveil potentially hazardous landslides to detect elevated rates of landslide motion that may presage failure, d) produce coupled landslide and displacement wave hazard and risk assessments in Prince William Sound, and e) provide input needed to develop early warning capabilities and increase situational awareness of potential hazards in the surrounding communities.

Notable findings and achievements from this project include:

1. **Refinement of wave-height estimates for a catastrophic failure of the Barry Arm landslide, in the splash zone and near-field, and at nearby communities such as Whittier (Barnhart et al., 2021). The refined wave-height estimates are lower than the initial study of Dai et al. (2020) in part because of new bathymetry data collected by NOAA for the region where the Barry Glacier retreated. Depths of this area strongly control the height of the produced tsunami.**

2. **Installation of a diversity of monitoring equipment in Barry Arm, including a ground-based synthetic aperture radar, meteorological stations, seismometers, and infrasound array, GPS receivers, and telemetry to receive the data in real time.**
3. **Partnership with the National Tsunami Warning Center to develop a tsunami early-warning system for detecting and alerting of a catastrophic failure of the Barry Arm landslide and potential tsunami. This is unprecedented for NOAA's Tsunami Warning Centers to undertake a site-specific tsunami warning from a subaerial-to-subaqueous landslide generated tsunami.**
4. **There are weekly updates at:** https://dggs.alaska.gov/hazards/barry-arm-landslide.html

This is remarkable progress on understanding this hazard within two years. Nonetheless, a principal question remains – what is the failure mode of the landslide? Will there be a catastrophic failure of the entire slide mass? Or part of it? Or will it unravel slowly such that no large failure occurs? What might trigger a failure? We note the slide went through the 1964 M9.2 earthquake, which ruptured beneath the slide. The slide also went through the 2018 M7.1 Anchorage earthquake, which occurred during a wet period in the fall. Since monitoring has ramped up, the slide has not moved much. It has had small rockfall events, some which can be correlated to seismicity and infrasound events. However, within the last month, the southern part of the slide, referred to as "the kite" seems to be moving as a large piece, again raising concerns that parts of the slide might fail catastrophically.

Drive back to tunnel. After tunnel opening on the hour, proceed 12 miles (23 minutes) to Portage train depot area for view of abandoned village of Portage.

Stop 5 — Portage townsite

The abandoned townsite of Portage marks the location of the main route through the mountains to Prince William Sound used by native Alaskans and developed by miners in 1902 (Karl et al., 2011). The buildings west of the highway (Figure 6.1) were flooded by high spring tides following subsidence during the 1964 earthquake. The buildings were then partially buried by tidal silt deposition that covered more than 18 km^2 (7 mi^2) at the head of Turnagain Arm over the next two decades. Liquefaction and resulting lateral spreading were responsible for major damage to the highway, railroad, and bridges in the Portage area during the earthquake. Hundreds of fissures up to 4 feet (1.2 m) wide developed, from which water and sand reportedly ejected as much as 25-30 feet (7.6-9.1 m) high for about 2 minutes (Plafker, 1969).

At this location, near the axis of maximum subsidence in 1964 (Figure 6.2), the Placer River Silt is up to 6 feet (~2 m) thick. Numerous abandoned buildings in the vicinity are filled with silt and, as at Girdwood, most of the trees on Portage flats were killed by saltwater flooding during the next high tides about two weeks after the earthquake. The pre-1964 ground surface, associated peat layer, and numerous artifacts such as milled wood, cables, and pallets are visible in the bank exposures downstream from the bridge. The infilling of tidal sediment and rapid remaking of the pre-1964 landscape near Portage gives such soils the potential of recording recurrence intervals of great earthquakes that are quite short, on the order of decades (Figure 4.3; Atwater et al., 2001).

Get a good view of what remains of the Portage townsight as we head toward Girdwood. The vegetation tells a story. You will see the dead gray trees that comprise the “ghost forest” that was killed in 1964. You may also see birch, willow, alder, and shrubs growing on this surface. All these trees are completely intolerant to saltwater. No saltwater gets to these plants anymore. This is a combination of post seismic rebound and infilling with silt. If you were to go stand in any of the buildings, you would find your head near the ceiling. It is clear there has been a lot (perhaps ¾ of a meter) of sedimentation since 1964.

Drive to Girdwood flats. Drive 10 miles (11 minutes) to Girdwood railroad terminal area (turnaround at Toadstool Dr.) for hike to Girdwood flats and ghost forest. This is where you need rubber boots.

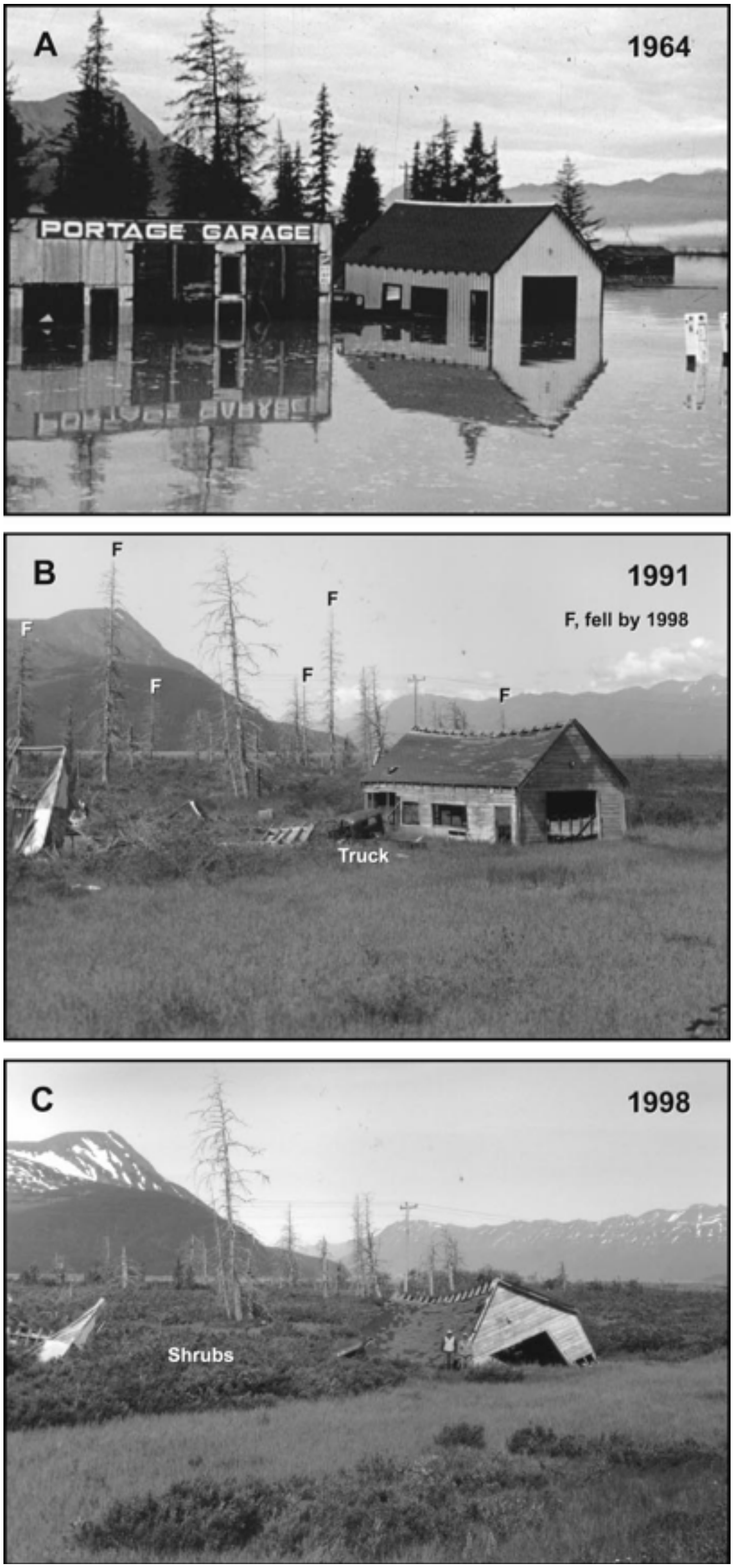


Figure 6.1 From Atwater et al. (2001). Photos documenting post-earthquake subsidence followed by relatively rapid (10 yrs) redeposition and gradual uplift of the Portage town site following the 1964 Earthquake.

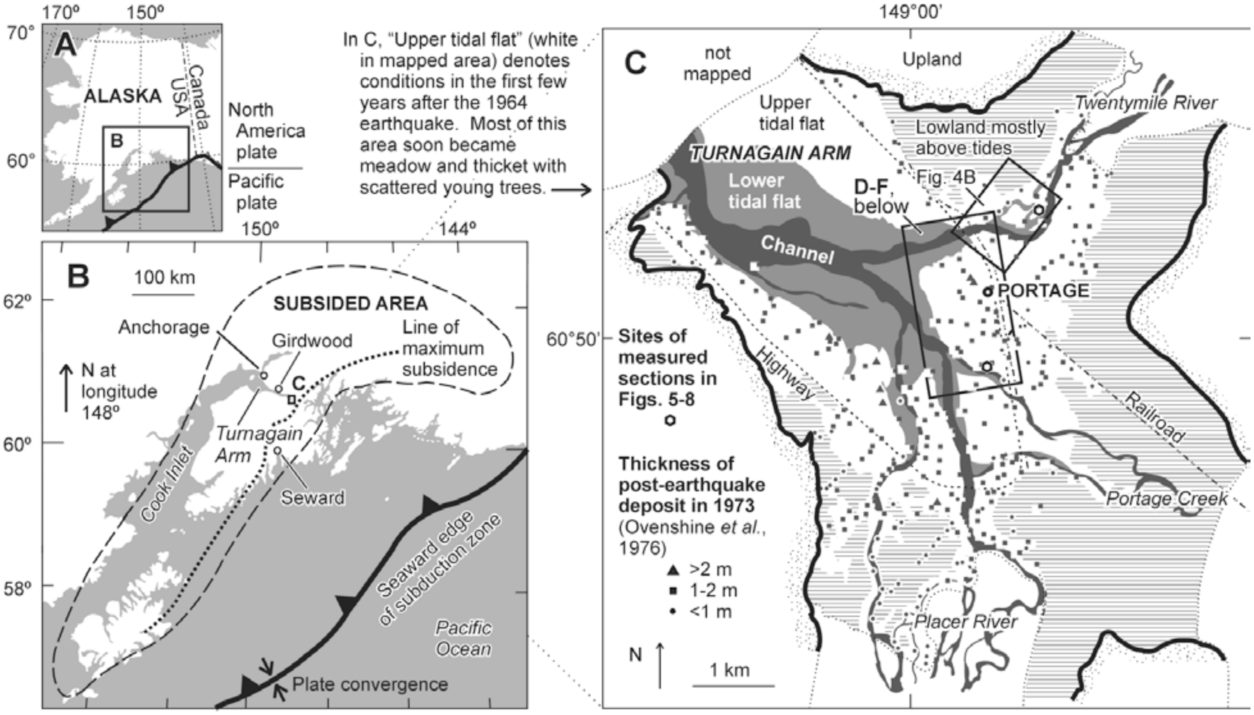


Figure 6.2 From Atwater et al. (2001). Location of the Portage Town site near the line of maximum subsidence during the 1964 earthquake.

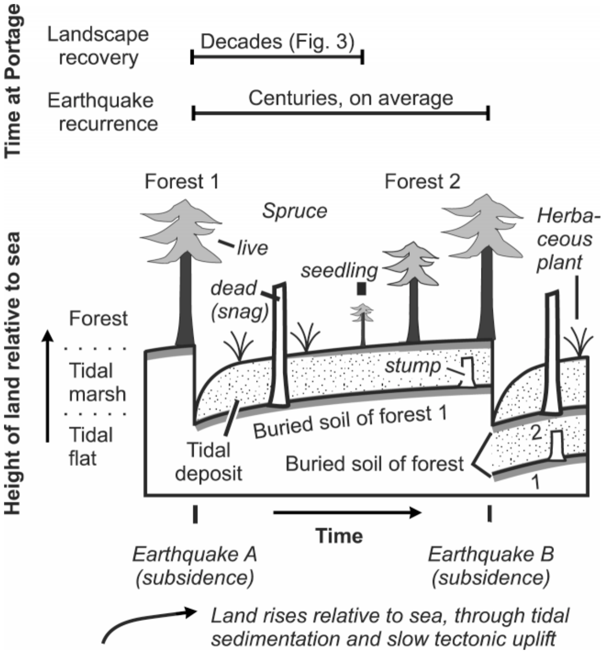


Figure 6.3 From Atwater et al. (2001). Earthquake-induced cycle of forest death and renewal at an estuary. Forest 1 dies from tidal submergence due to earthquake A (Figs. 12A and 4A). Tidal sediment buries the floor of the dead forest and builds land on which forest 2 grows. This next forest eventually dies from effects of earthquake.

Stop 5 — Paleoseismology at Girdwood Marsh

The tidal marsh at Girdwood, Alaska, records 7 great earthquakes on the eastern Aleutian megathrust in the past ~3,900 years (Shennan et al., 2008). Predecessors of the 1964 earthquake occurred every ~600 years on average. However, some earthquakes were separated by longer or shorter intervals than 600 years and the amount of land-level change that accompanied some events differed from the ~1.5 m of subsidence in the Girdwood area during the 1964 earthquake.

The Girdwood marsh records vertical changes in land level related to the earthquake deformation cycle (Figure 6.1). The cycle involves the accrual of strain above a locked megathrust between earthquakes, which leads to slow, gradual uplift of Girdwood and Turnagain Arm. When stresses on the megathrust exceed the strength of the locked interface, the megathrust breaks (slips) and the land rebounds elastically in the opposite direction. Sudden slip on the megathrust during the 1964 earthquake resulted in a regional pattern of deformation: a wide belt of uplift raised coastal areas in Prince William Sound and a parallel trough of subsidence dropped areas along Turnagain Arm and Cook Inlet (Figure 6.2). Girdwood lies in the area that dropped by ~1.5 m. As a consequence, spruce forests along the shoreline subsided below tide level and were killed by encroaching seawater. The landscape was quickly buried by silt deposited by tides in the decade after the earthquake (Atwater et al., 2001).

Like a bar code, peaty soils buried by silt beneath the Girdwood marsh record seven episodes of sudden earthquake subsidence, including the 1964 soil in which Girdwood's ghost forest is rooted (Figure 6.3). Three-to-six feet (1–2 m) of silt buries the 1964 soil and today, marsh plants and young trees indicate that the landscape has been restored to conditions similar to the 1964 landscape. Repeating layers of peaty soil buried by silt at the Girdwood marsh indicate that large earthquakes have dropped Turnagain Arm repeatedly in the past (Figure 6.4). Radiocarbon ages from samples near the top of each soil show some variability in the time between earthquakes, the earthquake recurrence interval. Some earthquakes were separated by only a few centuries, the time between 1964 earthquake and its predecessor may have been as long as 900 years. Fossil diatoms above and below the top of the soils indicate past earthquakes subsided Girdwood by 0.7 to 1.5 m (Shennan et al., 2008).

At this stop, as a group we'll hike out to the exposed edge of Girdwood Marsh, and explore the paleoseismic record. Stratigraphy here has recorded the pattern of subsidence and uplift associated with ancient megathrust earthquakes in south-central Alaska. Don't be afraid to get dirty!

Leave Girdwood flats, head back to Anchorage. Drive 38 miles to Anchorage Hilton (50 minutes).

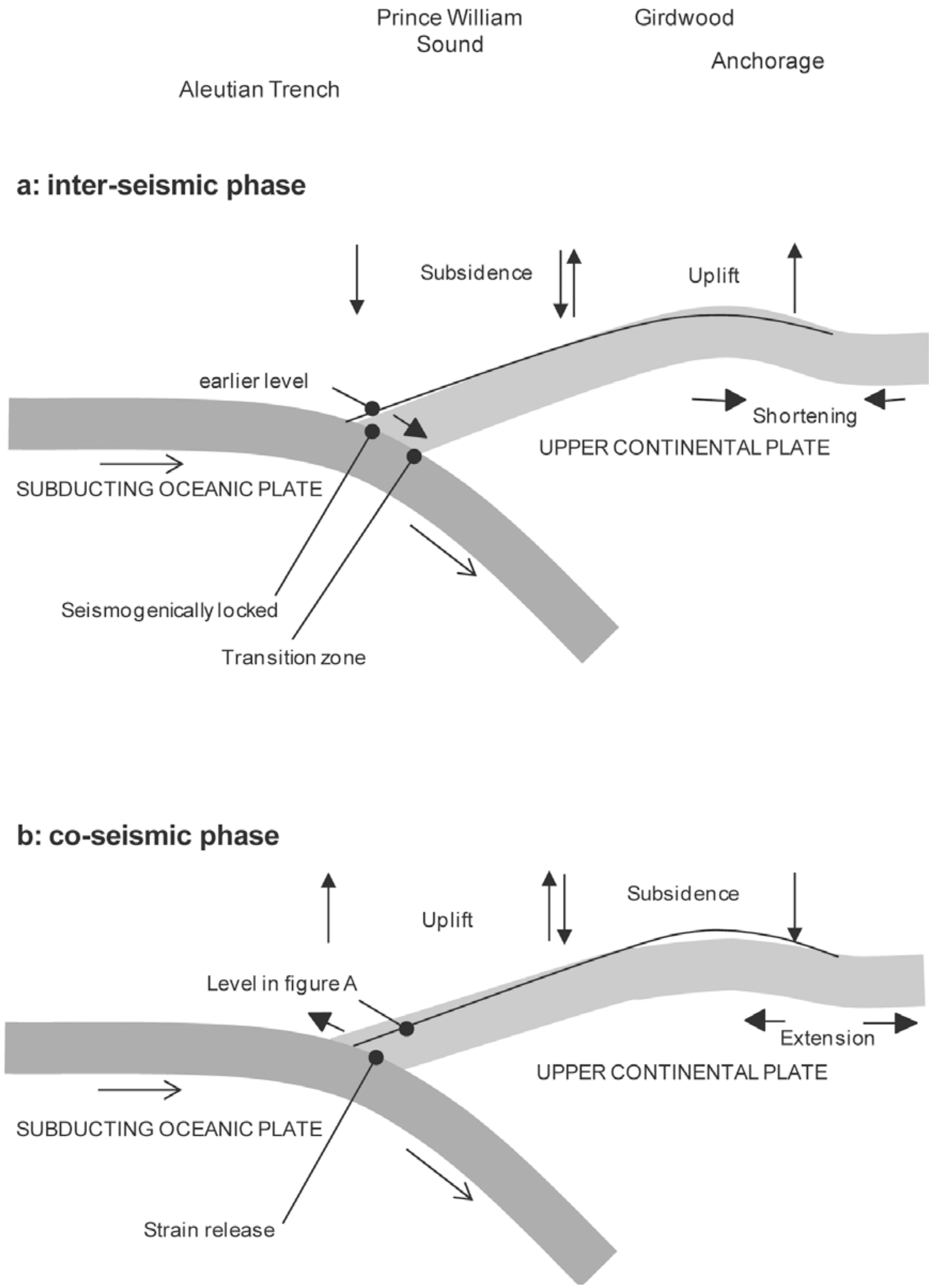


Figure 7.1. Schematic profiles of the deformation of tectonic plates that occurs (a) between earthquakes (interseismic) and (b) during an earthquake (coseismic). The profiles reflect two components of the earthquake deformation cycle at eastern Aleutian subduction zone along a section from the Aleutian trench to Anchorage (from Shennan et al., 2008).

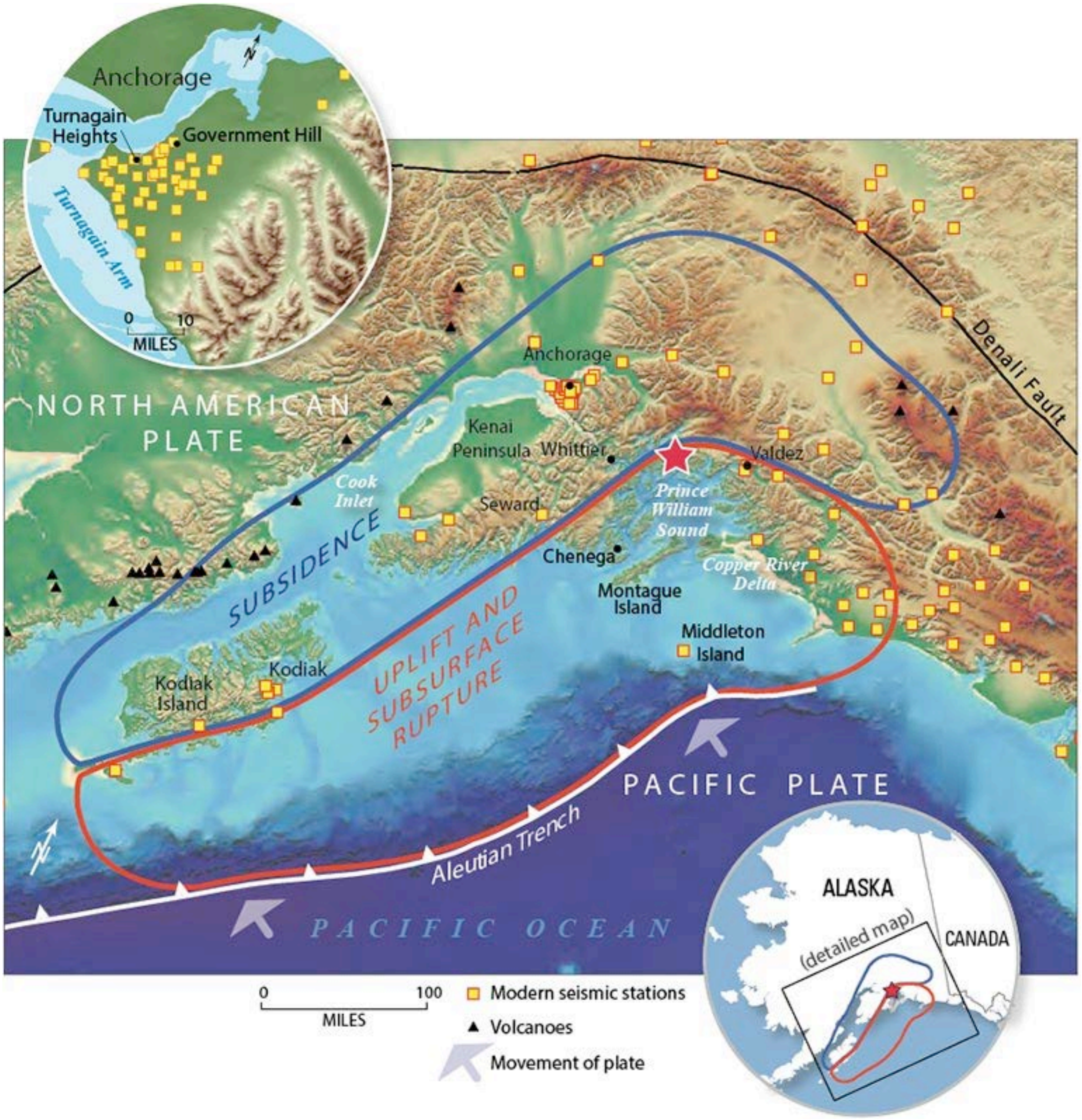


Figure 7.2. Map of southern Alaska showing the epicenter of the 1964 Great Alaska Earthquake (red star), caused when the Pacific Plate lurched northward underneath the North American Plate. There was extensive damage to coastal towns and infrastructure throughout the region, particularly in Anchorage, Seward, Whittier, and Valdez. Widespread uplift occurred seaward of Kodiak Island and the Kenai Peninsula, while subsidence occurred inland as a result of the magnitude 9.2 earthquake. In 1964, there were no instruments in Alaska capable of recording the earthquake, but now there is an extensive network of stations (yellow squares) that monitor the seismically active plate boundary along the Aleutian Trench (USGS Fact Sheet 2014-3018).

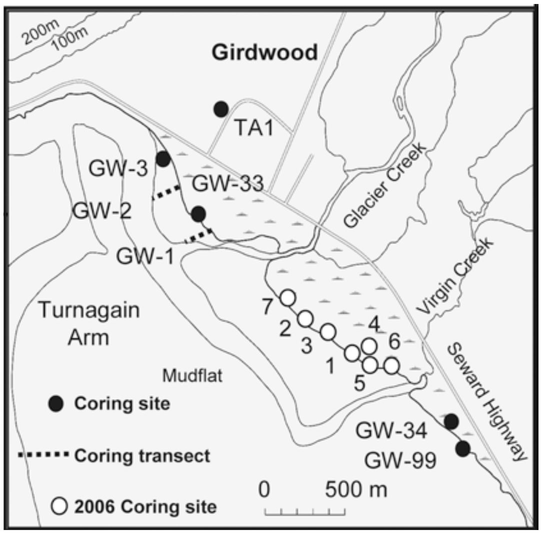
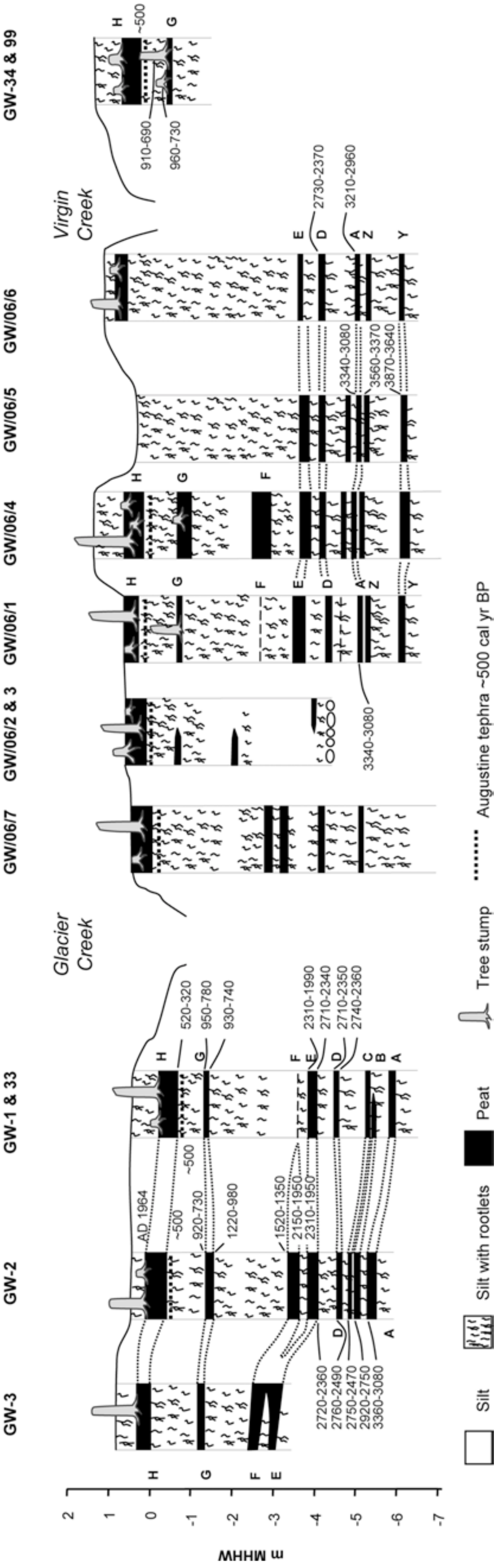


Figure 7.3. Left: Girdwood marsh site. Right: Stratigraphy at Girdwood marsh consisting of interbedded peat and silt. Radiocarbon age estimates shown on right (Shennan et al., 2008). Below: Peat subsided by earthquakes and buried by intertidal mud at Girdwood, Alaska.



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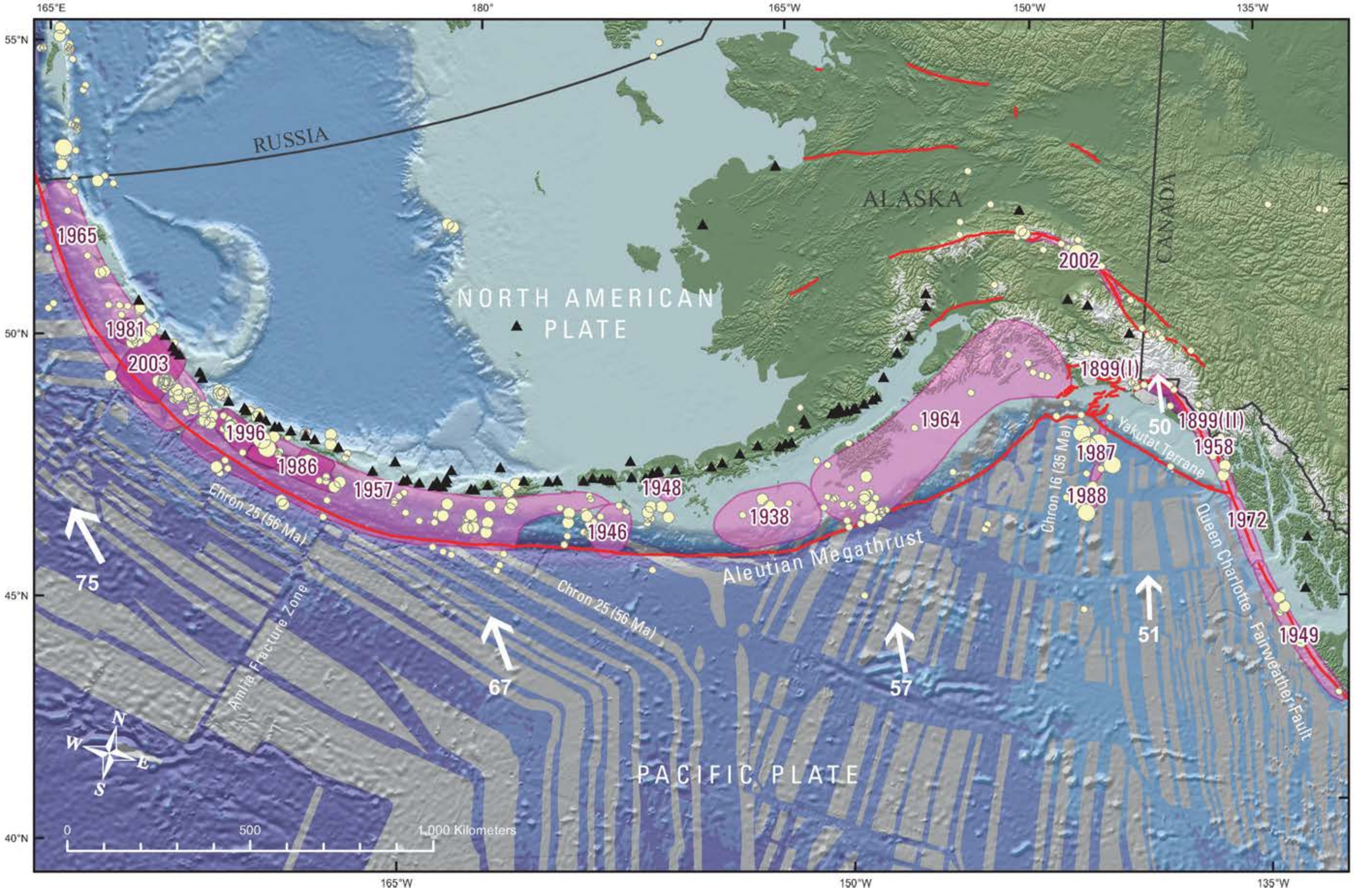
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