2017 EarthScope National Meeting

Field Trip Guidebook

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

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Modified from original "EarthScope Alaska-Yukon Regional Workshop for Interpretive Professionals" Guidebook from April 2014.

Figure 1 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: Game McGimsey). Red arrows point to the McKinley Tower in both photos.

Introduction:

This 11-hour field trip, part of the EarthScope National Meeting, will review the impacts of the 1964 great Alaska earthquake and offer glimpses of the geology of south-central Alaska between Anchorage and Whittier. Initial field 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). The first stop will visit Sunset Park, the site of the Government Hill landslide that caused the collapse of the Government Hill Grade School, destroyed two houses and damaged a third, and wrecked railroad property along Ship Creek. The second stop involves a hike, from top to bottom, across the Turnagain Heights landslide and discussion of the Bootlegger Cove Clay alleged to have lost strength and failed during earthquake shaking.

Turnagain Arm, a shallow fjord that extends east from Cook Inlet, cuts through rocks accreted onto North America over the past 200 million years. Material presented at the Point Woronzof overlook and at two stops along the Seward Highway will show examples of two main rock units of the Chugach terrane that were accreted onto Alaska's southern margin as a consequence of convergence between the North America plate and an the Pacific plate to the south. Much of this material has been adapted from prior field trips sponsored by the Geological Society of America and the Alaska Geological Society (e.g., Bradley and Miller, 2006; Karl et al., 2011). Sites near Girdwood and the abandoned town of Portage will reveal the lasting effects of earthquake subsidence in 1964 that dropped Turnagain Arm by as much as 8 feet. The subsidence led to the relocation of Girdwood and the abandonment of Portage, dropped much of the railway and Seward Highway below high tide level, and killed swaths of spruce trees whose remains haunt the shoreline as forests of bleached snags.

Turnagain Arm is the scenic gateway to Whittier, Seward and other points of interest on the Kenai Peninsula. James Cook's 1778 expedition originally named the waterway Turn Again River out of frustration in their failed search for a Northwest Passage. Tides in Turnagain Arm range between 25 to 30 feet and produce currents in excess of 6 miles 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 15 miles per hour and reach a height of 6 feet. As we drive east along the Seward Highway, look for Dall sheep foraging or sunning themselves on the steep south-facing slopes of the Chugach Range.

The last stops of the day will take us to the port of Whittier at the western end of Passage Canal, and the Begich, Boggs Visitors Center on Portage Lake. The drive to Whittier passes through the second longest (2.5 miles) highway tunnel in North America, the Anton Anderson Memorial Tunnel. The Army Corps of Engineers built 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 (Kachadoorian, 1965). At Portage Lake we will discuss the dramatic historical retreat of the Portage glacier.

Sunset Park, Government Hill (map: https://goo.gl/maps/8A0wM)

Stop 1 — Sunset Park: 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 4 to 5 minutes and was felt 480 mile west as Dutch Harbor in the Aleutian Islands, and more than 1,200 miles southeast at Seattle, Washington, where the Space Needle swayed perceptibly (USGS Fact Sheet 2014–3018). 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 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 over 120 fatalities and an estimated $2.3 billion in property losses (in 2013 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) (USGS Fact Sheet 2004-3072). 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).

On our way to Stop 1 we will drive along Fourth Avenue and pass the head scarp of the Fourth Avenue landslide, now repaired (see photos on cover and inside cover of this guidebook). The slide involved 14 city blocks in the northern part of downtown Anchorage, impacting an area

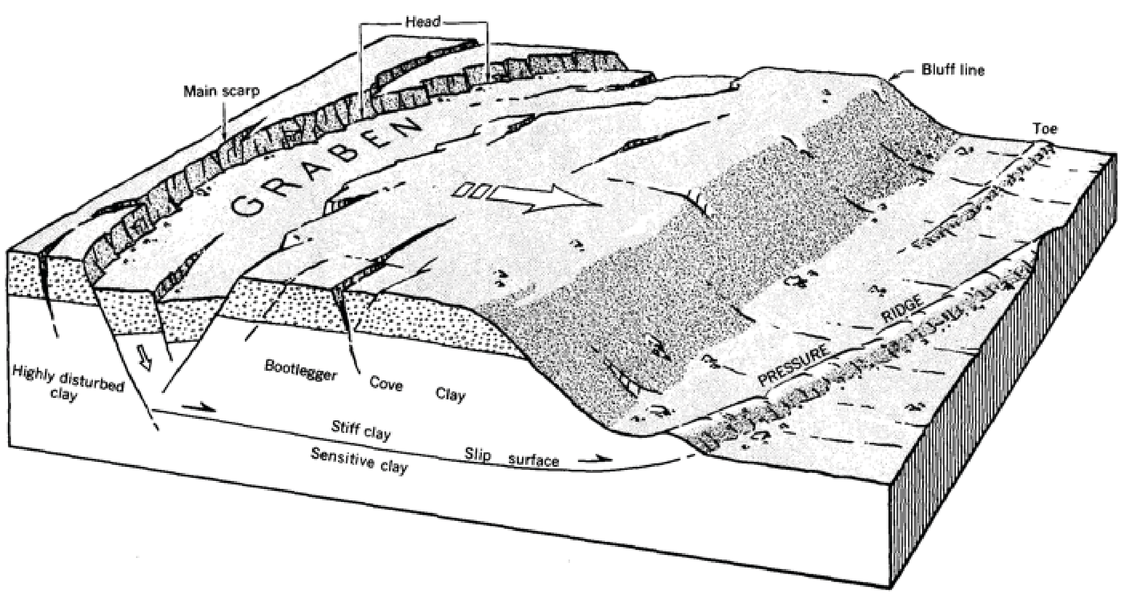


Figure 1.1. Block diagram of a translational landslide (from Hansen, 1966).

about 36 acres between Fourth and First Avenues and E Street and Barrow Street. The landslide was attributed to translational sliding on a failure plane at a depth of 60 feet due to the loss of strengh 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. Buttress Park, located between First and Fourth Avenues, has been re-graded and reinforced with a buried gravel buttress to stabilize the slope. The Port Access Bridge, over which we will drive on A Street, was constructed in 1975, seismically retrofitted in later years, and has been instrumented with seismometers to monitor bridge response to earthquakes and railroad vibrations.

At Sunset Park (Stop 1; Figure 1.2) we will discuss the geomorphology of the Government Hill landslide and its effects as documented by Hansen (1966). The 11-acre Government Hill landslide displaced 900,000 cubic yards of earth along a south-facing bluff on the north side of Ship Creek (Figure 1.3). The width of the slide extended 1,180 feet from west to east flank. The slide measured 600 feet from head to toe at its greatest length. The south wing of Government Hill school dropped 20-feet into a broad graben that formed 400 feet back from the original bluff edge, which sheared the building vertically and stopped electric clocks at 5:36 pm. Lateral displacements varied. Although the south wing of the school shifted 6–7 feet to the southwest, playground equipment and a house at the end of Birch Street moved as much as 35 feet. Sites involved in a lateral earthflow at the toe of the slide were displaced 150 feet causing damage to equipment in The Alaska Railroad yard. Geotechnical investigations determined the failure plane was located in a zone of low shear strength, high water content, and high sensitivity in the Bootlegger Cove Clay at a depth of 70–90 feet below the pre-earthquake bluff elevation (Figure 1.4).

On our way to Earthquake Park (Stop 2), we will detour along the base of Buttress Park and drive by the Native Hospital landslide. The headscarp of the Native Hospital landslide cuts across an older landslide scar, suggesting past large landslides have occurred in the Anchorage area and may have been triggered by ground motions that accompanied ancient earthquakes.

Earthquake Park via East Ship Creek Avenue (map: https://goo.gl/maps/6Ag4Q)

Figure 1.2. Top: View to the west showing the Government Hill School collapsed into a graben, or linear trough, formed by the Government Hill landslide in 1964. Bottom: Same view in 2013 (photo: Game McGimsey). The graben formed by the landslide is still expressed in the landscape in the lower photo.

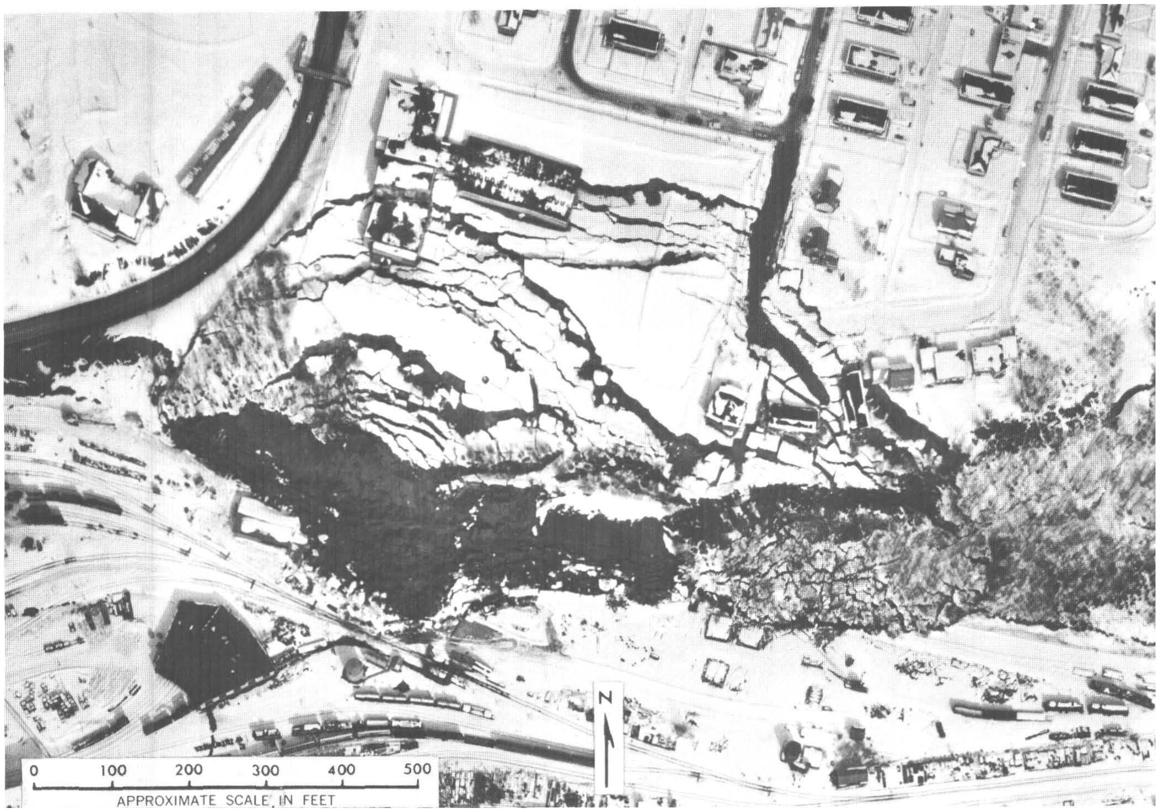


Figure 1.3. Aerial view of Government Hill landslide (from Hansen, 1966).

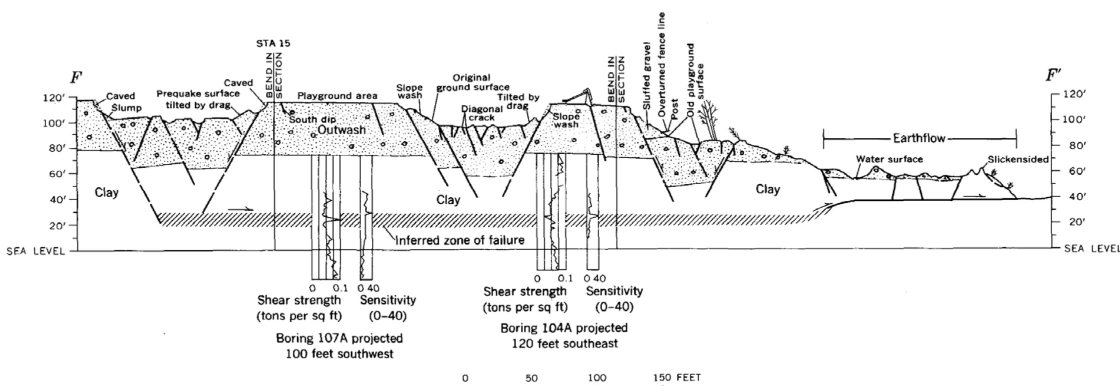


Figure 1.4. Geologic cross section through Government Hill landslide (from Hansen, 1966).

Stop 2 — Earthquake Park And the Turnagain Heights Landslide

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 account in the Anchorage Daily News, March 22, 2014).

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 east to west along the coastline. Early assessments by Hansen (1965) 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 at the bluff some two minutes after 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

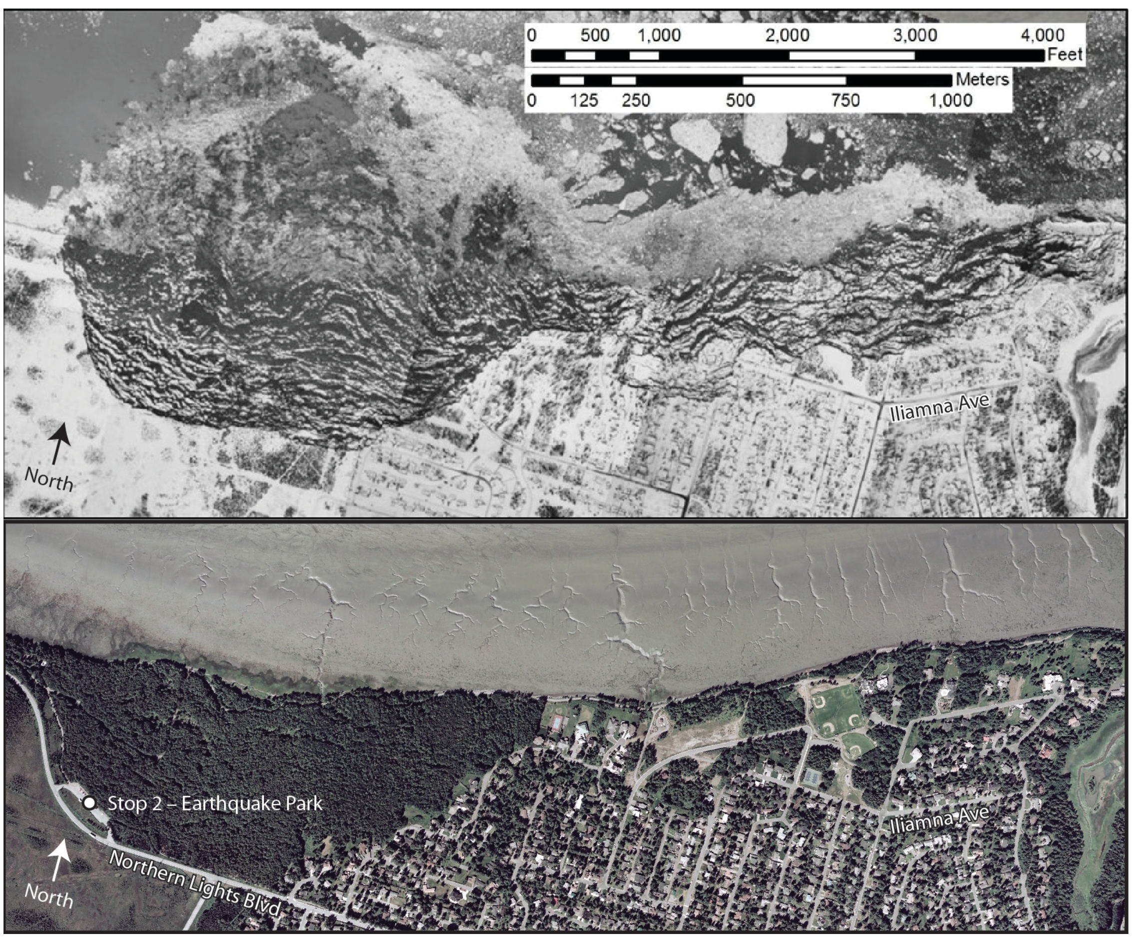
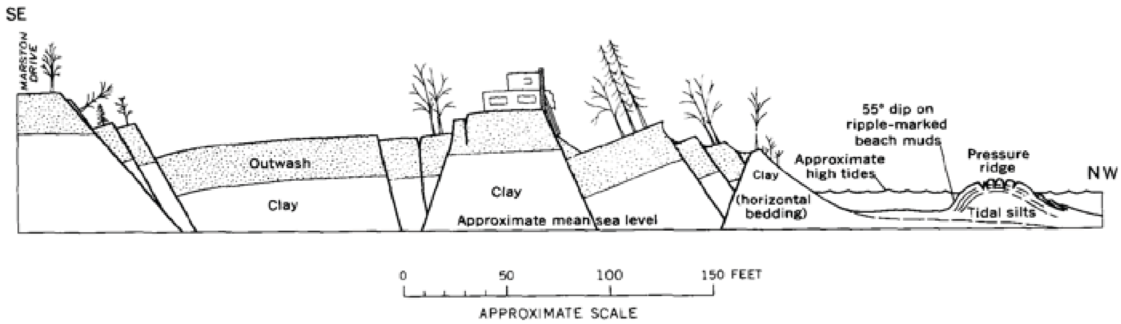


Figure 2.2. Top: Aerial view of the Turnagain Heights neighborhood and Earthquake Park area following the 1964 earthquake. Bottom: Modern day google map view of the same region. The location of Iliamna Ave, noted in the ADN article by Julia are labeled for reference. If you look closely, you'll see locations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

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.

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 (Karl et al., 2011). 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).

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. We will also (weather permitting) investigate exposed Bootlegger Cove Clay and talk about the mechanical properties of the deposits underlying landslide effected areas.

Point Woronzof overlook (map: https://goo.gl/maps/fhDSL)

Chugach Accretionary Complex exposed along Turnagain Arm

Terry L. Pavlis, Univ. Texas El Paso

The Kenai and Chugach Mountains contains one of the world's most spectacular exposures of an exhumed accretionary complex—rocks accreted in an ancient subduction zone, along the subduction interface. As such they are a marvelous record of subduction zone processes at depth, but their complexity has defied thorough understanding of these rocks for generations. Most geoscientists in North America are introduced to accretionary complex rocks via the Franciscan Complex in California, yet 99% of the Franciscan is very poorly-exposed with deep soil development, forest and grass cover, etc. Young uplift and glacial erosion, however, have produced thousands of square km of rock exposure in southern Alaska, yet there are hundreds of times more pages written about the Franciscan than these rocks. Today you'll see a cross-section across this assemblage as we drive along Turnagain arm, and hopefully have time for stops to look at the rocks.

A Little History on Geologic Studies of the Chugach accretionary complex:

Like the stop at Girdwood, George Plafker played a huge role in our understanding of the Chugach rocks by making one of the first clear plate tectonic interpretations of the assemblage (Plafker et al., 1977, 1994). However, Casey Moore was probably the researcher that first emphasized the plate tectonic affinity of these rocks from work to the southwest on Kodiak Island and the Shumagin Islands(Moore, 1973a, 1973b). In the Anchorage area, however, the Chugach rocks were first described by Clark (1973) from reconnaissance geologic studies in what is now Chugach State Park including the area we will see along Turnagain arm. Clark coined the term "McHugh Complex" for exposures along McHugh Creek, which we pass on this field trip. Interestingly, Clark clearly stated in her studies that the McHugh was comprised of two distinct lithologic types, but it took 40 years and technology advances to allow the recognition of what we now know, that these lithologic divisions comprise two subdivisions of the assemblage that are very different in age and provenance.

A key development in our understanding of the Chugach rocks came with the advent of detrital zircons. Detrital zircons have revolutionized many areas of geology, but perhaps nowhere more strongly than in accretionary complex rocks. Before detrital zircon dating the only information we had on ages of these rocks was a tiny collection of fossil ages, most of which came from radiolarian cherts. It is hard to imagine a more difficult chronometer to work with than a fossil age from cherts because these rocks could have been deposited thousands of km from a trench and accreted 10's of millions of years after deposition. Thus, they give a depositional age, but are confusing when you try to use them to constrain the timing of accretion. In the area we will look at today, for example, chert fossil ages scattered between Permian and mid-Cretaceous, which isn't particularly informative in light of what we know now. Detrital zircons were critical because we could obtain maximum depositional ages from metagreywackes, which represent trench fill deposits. Thus, their depositional age is nearly indistinguishable from their accretion age and if we have an active arc at the time of deposition, the maximum depositional age from zircons typically is close to the actual depositional age. Amato and Pavlis (2010) rationalized this approach, and although we got criticized for it in detail, it provided major insights into this accretionary system.

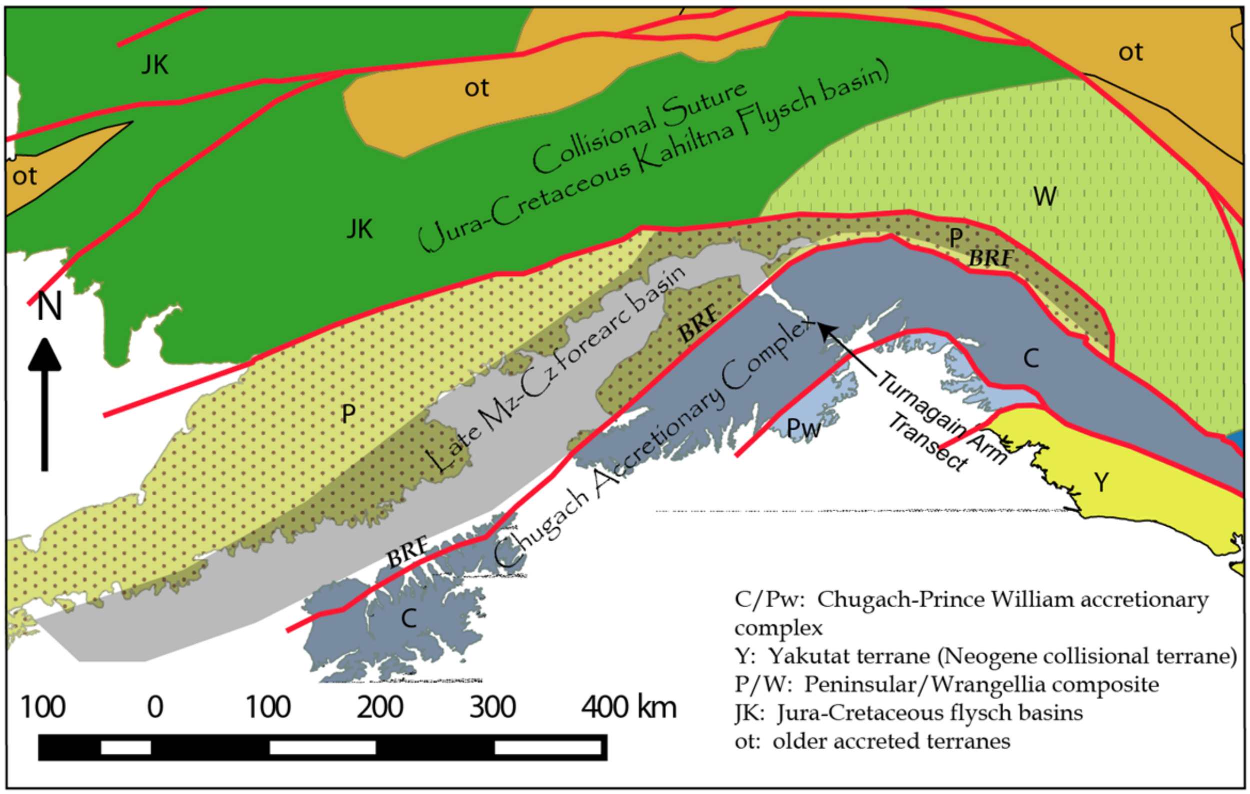


Fig. 1. Regional tectonics of southern Alaska showing the Chugach accretionary complex relative to major regional tectonic elements and terranes. Figure made from Colpron and Nelson's (2011) GIS files of northern Cordilleran terranes.

Regional Geology of the Turnagain Arm transect

Southern Alaska carries a signature of subduction with the same polarity as today extending to at least 200 million years ago (late Triassic). This record is carried in a classic tripartite assemblage diagnostic of a convergent margin with coeval magmatic arcs, forearc basins, and accretionary complex rocks exposed across strike (Fig. 1, 2 and 3). From Anchorage we can look across the inlet at the active arc to the west (Mount Spurr and Illiamna), the deep forearc basin occupied by Cook Inlet and the Cook Inlet lowlands, and the accretionary complex assemblages exposed in the Kenai and Chugach Mountains continuing out to the modern trench. In detail these rocks record a complex history of subduction with cycles of accretion and tectonic erosion within the accretionary complex, a record of rise and fall of the forearc basin in association with changes in plate interactions (including ridge subduction events), and 3D complications of strike-slip systems, particularly in the Early Cenozoic.

For the purposes of this trip, however, we can simplify the history by concentrating on the story told by the accretionary complex rocks exposed along the road that is revealed by their structure, their lithology, and their associated detrital zircon record. Like the grand canyon, we can trade space for time in this transect to deduce a history (Fig. 3), but unlike the grand canyon where the observations are clear in a simple stratigraphic sequence, here we deduce the history from rocks shredded by the subduction process with complex connections to regional geology. We have the structural equivalent of sedimentary deposition (subduction accretion) and unconformity (subduction erosion) with the added complication that we can shuffle the deck here by out-of-sequence faulting.

Two fundamental tectonic boundaries are present in southern Alaska and these structures are important to the history we see along Turnagain arm (Fig. 1):

1) Across Cook Inlet to the west, and continuing through central Alaska into the northern Talkeetna Mountains north of us is a major Cretaceous suture that records the closure of an ocean basin between a Mesozoic oceanic arc (aka, the Talkeetna arc and its big brother, the Wrangellia composite terrane) and the Mesozoic North American convergent margin. This suture is recognizable from Washington State to SW Alaska as a broad band of mid-Cretaceous (~85-110Ma) deformation representing one of the biggest orogenic periods in the Cordillera. This history played a major role in the rocks we will see on this field trip through the erosional products of that the orogen shed to a coeval forearc system that developed along the trailing edge of the collision.

2) Neogene uplift of the northern margin of the Pacific Coastal Ranges from Kodiak Island to southeast Alaska have variably exposed a fundamental tectonic contact between older crystalline basement of the Mesozoic arc and rocks accreted by subduction zone processes (Fig. 1). Regionally this arc-forearc boundary is called the Border Ranges fault (MacKevett and Plafker, 1974) and this structure carries a long and complex history of reactivation (Pavlis and Roeske, 2007). Outboard (toward the trench) of the Border Ranges Fault all of the rock assemblages have been accreted by subduction zone processes.

The Border Ranges fault is not exposed along Turnagain arm, but is visible from our first stop in Anchorage looking northeast toward Eklutna where upper mantle ultramafic rock lie in fault contact with the accretionary complex, although at that locality, the fault contact is actually Cenozoic.

The focus of this part of the field trip are exposures of the accretionary complex which lies just below (to the east) of the Border Ranges fault. In terrain terminology, the rocks we'll see all below the Border Ranges fault are the Chugach terrane which represents the Mesozoic part of the accretionary complex. Just to the east and south the accretionary complex continues as a vast latest Cretaceous to Paleogene assemblage, the Prince William terrane, but we will not see these rocks on this trip.

Early in studies of the Alaska margin Plafker et al. (1977) emphasized that the "Chugach terrane" was easily divided into two "subterranes": a mélange subterrane and a "flysch" subterrane. These subdivisions were recognized both on the basis of structural style (mélange vs coherently bedded, but highly deformed "flysch") and lithology (pelagic to hemi-pelagic rocks in the mélange and turbidites in the "flysch"). In the Anchorage area these subdivisions correspond to Clark's (1973) McHugh Complex (mélange subterrane) and the Valdez Group (flysch); both of which we'll see on this field trip.

The Valdez group was long established as a major flood of clastics to the Pacific Ocean basin as trench-fill turbidites, submarine fans, or both (e.g. Moore, 1973a, 1973b) with sediments derived from northern Cordilleran orogenesis that began in middle Cretaceous and culminated in Late Cretaceous to Paleogene time. This was well established from a variety of relatively simple observations: the thick, turbidite facies assemblage implying very rapid deposition; sandstone petrology that reflected a source consistent with what is now the Canadian Cordillera; and fossil ages (not cherts) spanning a narrow age range (65-75Ma) in the latest Cretaceous. Detrital zircon dating (Fig, 4c) provided strong support for this hypothesis with a age signature that was a virtual copy of the igneous history of the Coast Plutonic complex in western Canada and SE Alaska (Kochelek et al., 2011; Amato et al., 2013).

The greatest insight from detrital zircon dating came from the "mélange subterrane"/McHugh complex. Figure 4 shows the main results of this work from Turnagain arm with three key observations:

1) Detrital zircons showed that Clark's (1973) lithologic divisions for the anchorage area—her greywacke vs mélange assemblage—are actually two units of very different age that easily mapped (Fig. 2). The mélange contains zircons no younger than about 145-150Ma but the greywackes are dominated by much younger zircons clustering around 100Ma (Fig. 4). Amato et al (2013) suggested new names for these rocks: Potter Creek assemblage for the older mélange and McHugh Creek assemblage for the younger greywacke dominant rocks.

2) Beyond these simple divisions, there is a grossly different source indicated for these rocks. In the older mélange rocks (Potter Creek) the zircons show a source exclusively from the adjacent Talkeetna arc with a dominance of Jurassic plutonic sources and no

ages older than middle Paleozoic aside from two questionable outliers (Fig. 4). In contrast, the greywacke assemblage (McHugh Creek) not only contains younger zircons with a dominant peak younger than any of the mélange rocks (~100Ma), but they also contain older zircons (including abundant Precambrian zircons) consistent with a North American source. Our interpretation of this observation is that the data from the mélange assemblage support other observations (e.g. the lithology) that these rocks were accreted when the Wrangellia composite terrane was an offshore, oceanic arc with no connection to North America. The greywacke assemblage records the first arrival of clastics shed from the mid Cretaceous northern Cordilleran orogen, during closure of the suture. Note, this source is present at the same time that the suture to the north was still a wide open ocean basin (see extensive work by Ken Ridgway, Jeff Trop and their students). Thus, the forearc rocks have either been displaced laterally from their source, sediments were transported down the trench, or both. The preferred interpretation supports an old model by Pavlis (1982, 1989) that this suture closed zipper-like, from south to north, during the middle Cretaceous and this orogen provided part of the source to McHugh Creek assemblage.

3) Finally, the detrital record indicates that this arc-trench system has a record consistent with modern Circum-Pacific arc terranes with cycles of tectonic accretion and tectonic erosion. The gap in maximum depositional ages between the greywacke assemblage and the mélange suggests a period of tectonic erosion which we interpret as a consequence of an Early Cretaceous ridge-trench interactions that generated forearc plutons north and east of Anchorage (Amato et al., 2013; Labrado et al., 2016).

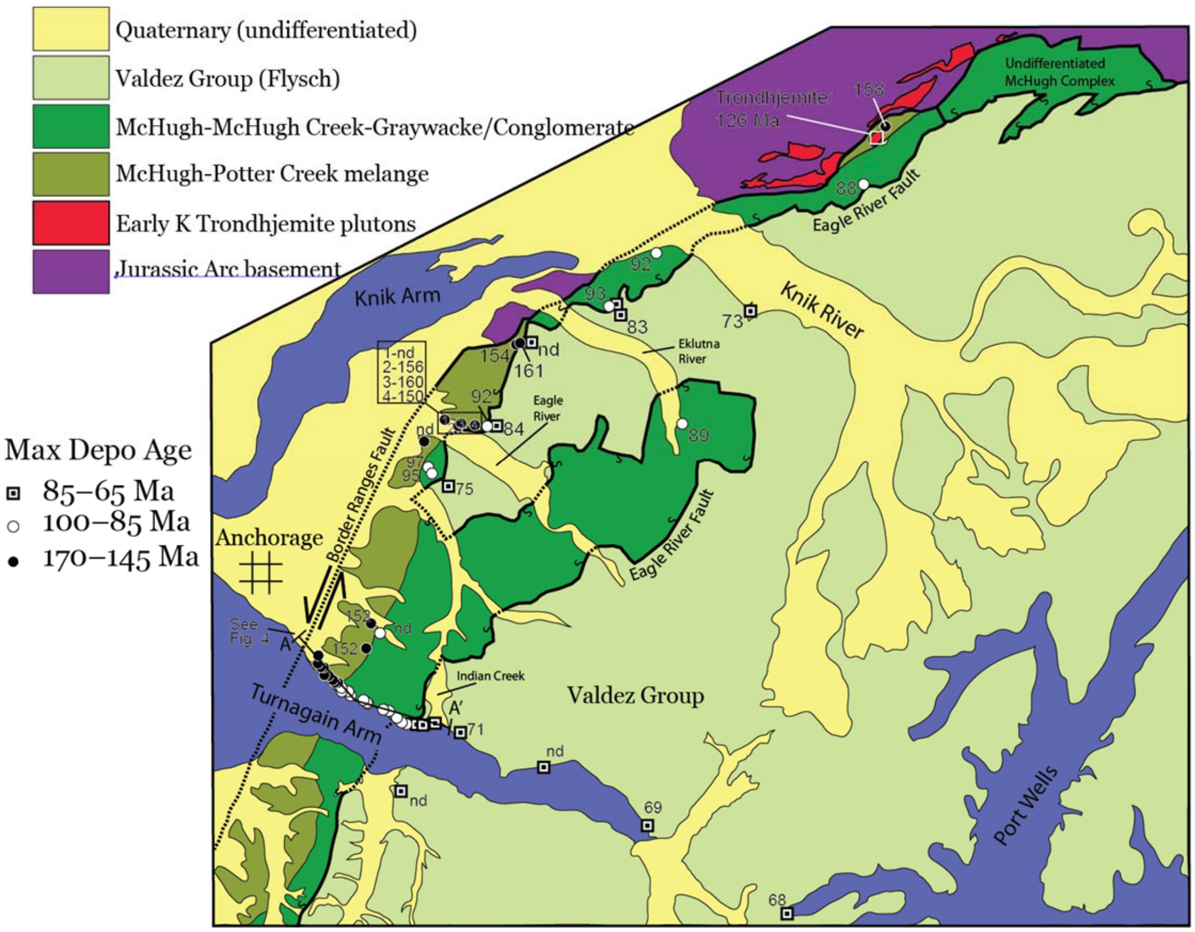


Fig. 2. Simplified geologic map of the Anchorage area showing maximum depositional age distributions and rocks units we will see during the field trip. Figure is color version of Fig. 2 in Amato et al. (2013)

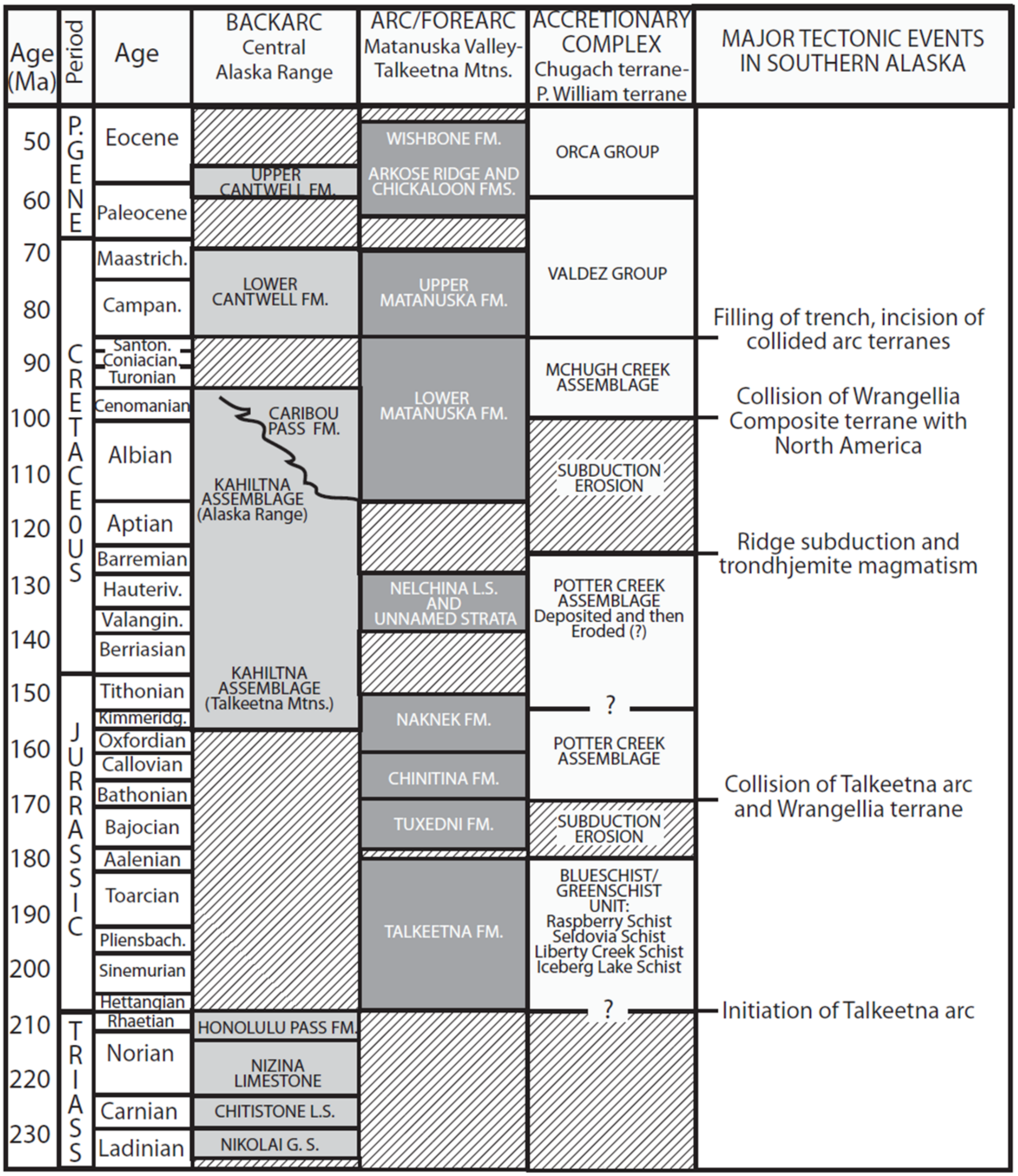
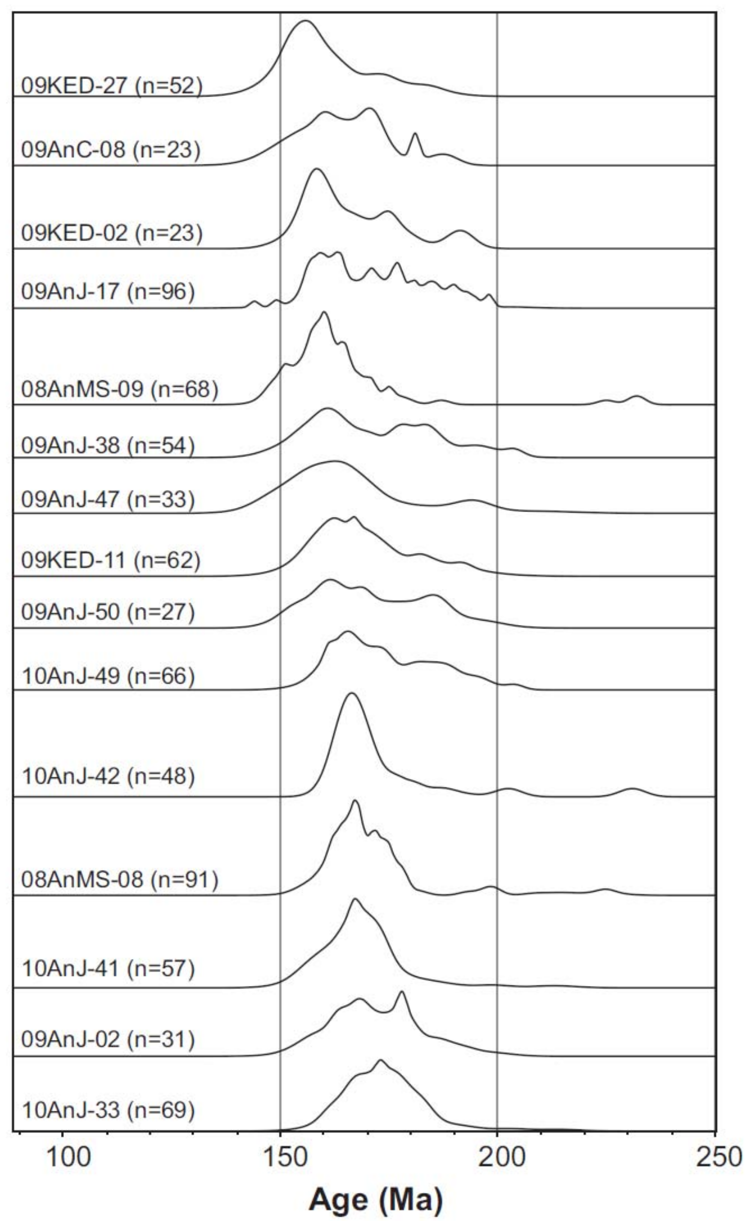


Fig. 3. Age diagram showing regional stratigraphic assemblages associated with the Chugach terrane forearc assemblage from the suture zone (backarc) to forearc basin and accretionary complex rocks we'll see on this field trip. Also note major tectonic events shown on the right. Figure is from Amato et al. (2013)

Fig. 4 (next three pages)—Detrital zircon data obtained for the Chugach terrane in the Anchorage area. Figures are probability distribution diagrams. Note the significant variation between the Potter Creek, McHugh Creek and Valdez Group rocks. Figures are from Amato et al. (2013, p. 1898, 1899, 1900) wih original captions included for clarification.

Figure 5. Relative probability distribution diagrams for the Potter Creek assemblage. Samples with n < 25 are not plotted. Samples are ordered from oldest maximum depositional age at the bottom to the youngest at the top. See Table 1 for a summary of all ages and Table DR1 (see footnote 1) for all data.



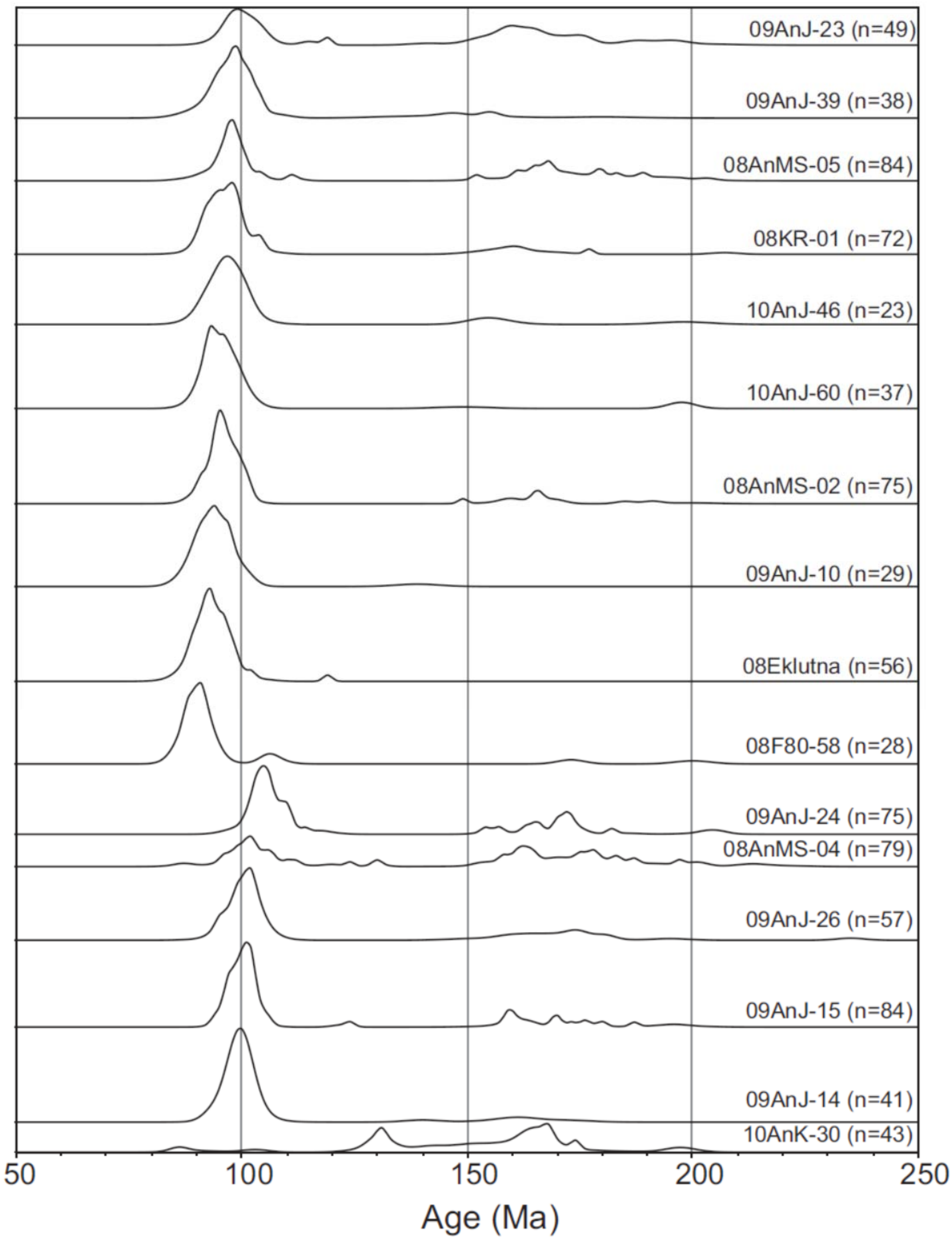


Figure 6. Relative probability distribution diagrams for the McHugh Creek assemblage. Samples with n < 25 are not plotted. Samples are ordered from oldest maximum depositional age at the bottom to the youngest at the top. See Table 1 for a summary of all ages and Table DR1 (see footnote 1) for data.

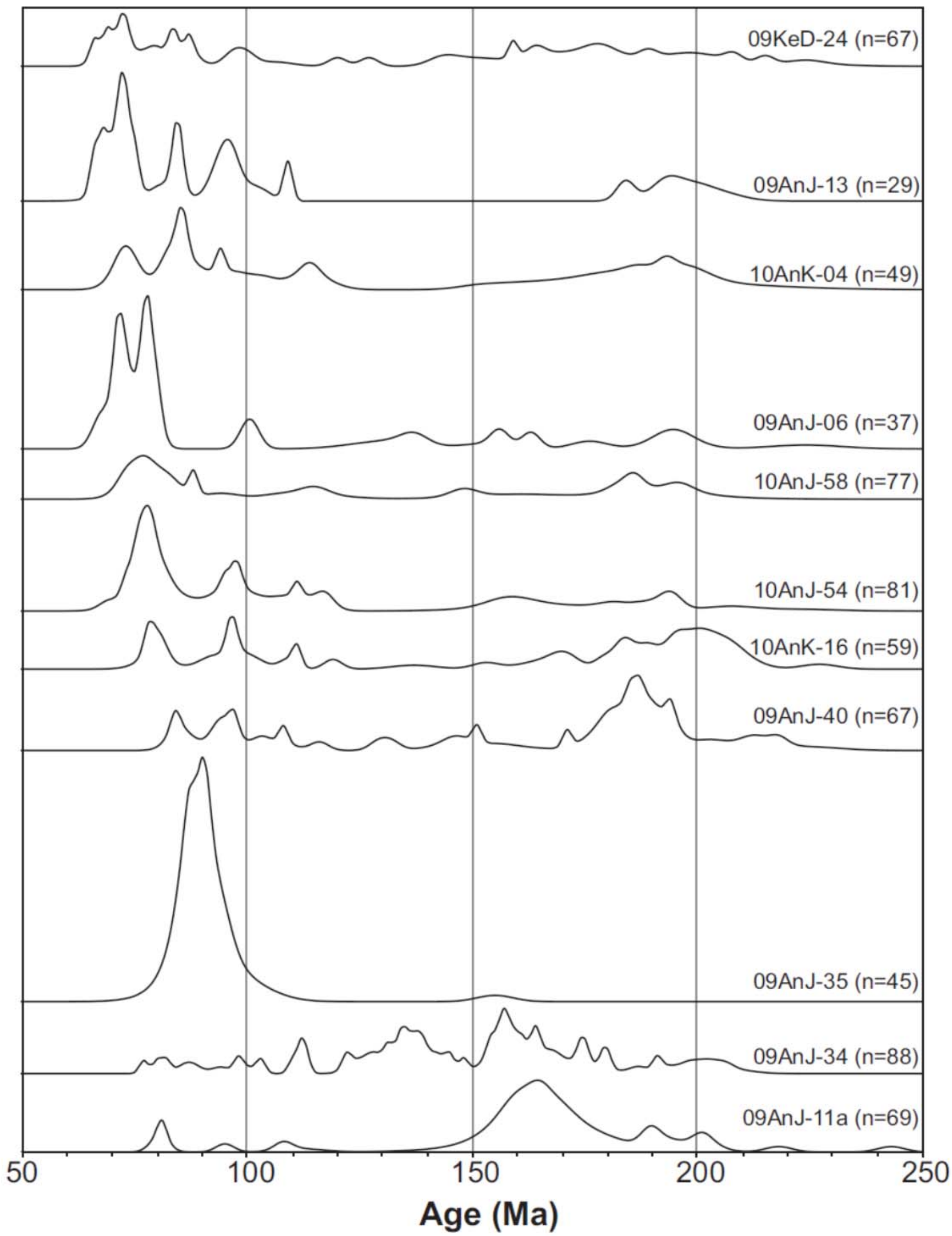


Figure 7. Relative probability distribution diagrams for the Valdez Group flysch. Samples with n < 25 are not plotted. Samples are ordered from oldest maximum depositional age at the bottom to the youngest at the top. See Table 1 for a summary of all ages and Table DR1 (see footnote 1) for data.

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One Pager description of the road trip and stop(s)

<u>View from area Earthquake Park—active faults and exposed mantle rocks</u>

As we leave the area of our first two stops, look toward the northeast (assuming it is not foggy!). In the far distance you will see a linear mountain front which marks the trace of the Castle Mountain fault. The Castle Mountain fault is an active oblique-slip fault that crosses the Cook Inlet Basin north of Anchorage, passing just south of Mt. Susitna to our northwest (often called the sleeping lady by locals). South of this linear mountain front is the Matanuska Valley and Knik Arm of Cook Inlet which extends to our northeast as we look back toward downtown Anchorage. Looking up Knik Arm, you will see the relatively linear Chugach Mountain front trending southward from the deep valley (Matanuska and Knik river valleys) toward Anchorage. Just south of the Matanuska-Knik Valley you may be able to see the reddish colored top of Mt Ekultna and higher peaks of the Chugach behind. The reddish rocks at Mt. Eklutna are ultramafic rocks lying in the hanging wall (west) of the Border Ranges fault juxtaposed against the McHugh complex—rocks we'll see extensively on the field trip. The ultramafic rocks are the upper mantle rocks formed at depths of ~30km beneath the Talkeetna arc at about 190Ma. These rocks were brought up along the Border Ranges fault and to the east of here form one of the world's most well exposed crustal sections of an oceanic arc—you can literally walk across the moho north of Valdez.

<u>Approaching the Chugach Mountain Front</u>

As we proceed down the new Seward Highway you should spot Turnagain Arm as we near the Chugach Mountain front. As the road reaches the coast we drive along Potter Creek marsh and somewhere near the turnoff to Potter Creek road we cross the buried trace of the Border Ranges fault system. If time permits, we will stop at the Potter Creek weight station to look at the Potter Creek assemblage—the older mélange assemblage of the Chugach accretionary complex.

<u>Stop 3: Potter Creek weigh station</u>.

The best outcrops in this stop are across the road, on the shoreline. However, because it is dangerous for 50+ people to cross the road, and we will be here near high tide, we will limit our stop to outcrops along the road near the weigh station. Spend a few minutes here looking at these rocks which show classic mélange fabrics—stratally disrupted rocks with the characteristic circum-pacific mélange rock assemblage of grey to red chert; green tuffaceous rock and black argillite. If you look around you can find blocks of bedded radiolarian chert, pillow lavas, and limestone in this area. A detrital zircons sample from this locality (10AnJ41) yielded a maximum depositional age of 167Ma but the Potter Creek assemblage as a whole has MDA's as young as 146Ma, which is Early Cretaceous (Amato et al., 2013). Interestingly, just east of this locality Nelson et al., 1987 and Gladstein et al., 2005 collected cherts that yielded radiolarian fossils with ages between 146-130Ma. The overlap between these chert ages and the zircon ages, together with the lithofacies of the Potter Creek assemblage led us to suggest that much of the zircon in these rocks may have come from air fall tuffs that found their way to trench either directly or via sedimentary recycling. This also has paleogeographic implications for wind directions—e.g. were these rocks at tropical latitudes, as commonly suggested by paleomagnetic derived estimates? We can discuss this topic at the outcrop.

For the earthquake seismologists and geodesists in the group we will plan on a discussion of how these rocks came to be. In particular, these rocks form along the subduction megathrust interface but geologists have debated for decades on the relative role of tectonics (mega fault-rocks) vs submarine landslide vs mud diapiric origins for these types of rocks.

Driving from Stop 3 to Stop 4

As we proceed up Turnagain arm you will see nearly continuous exposures of the Potter Creek mélange. You may spot some large blocks of chert, greenstones (metabasalt—many of them pillow basalts), or both in the mélange.

About 3km from stop 3, we pass a small gully that hides the fault contact between the Potter Creek mélange and the massive, but strally disrupted, greywacke/conglomerate of the McHugh Creek assemblage. As we pass the McHugh Creek recreational area we are fully within the McHugh Creek assemblage (hence, the name)

Stop 4: Beluga Point

If time permits we will make this stop to look at the greywacke/conglomerate assemblage (McHugh Creek assemblage) here where the rocks are not only metasandstones, but also contain conglomerates with clasts up to boulder size. Here the best outcrops are across the road but again, crossing this road with a large group could be too dangerous. Thus, we will probably cross the railroad tracks and look at exposures there and also get a great view up and down the inlet.

Some key data from this outcrop are: 1) the detrital zircon signature for sandstone from this site are indistinguishable from adjacent parts of the McHugh Creek assemblage (Fig. 4); and 2) We (Amato et al., 2013) not only dated detrital zircons in sandstone, but also dated some of the igneous clasts and detrital zircons in sandstone boulders contained within the conglomerates. The plutonic clasts are compositionally similar to Talkeetna arc basement rocks exposed above the Border Ranges fault and yielded SHRIMP ages between 179 and 199Ma, which is consistent with that conclusion. Curiously, sandstone clasts yielded detrital zircon signatures indistinguishable from host sandstones, suggesting local recycling of sediments with sandstone rip-up clasts analogous to abundant mud rip-up clasts in these rocks.

We will discuss the significance of these rocks at the outcrop. Our interpretation is that these rocks were accreted following a prolong period of subduction erosion along the margin and they record a reversal of that pattern toward an increasingly accretionary margin with time. That is, just to east of this locality we cross the "Eagle River Fault" which separates the McHugh Creek assemblage from the Valdez Group, which begins the vast sea of coherent, but highly deformed, turbidites that comprise most of the Chugach terrane. Our detrital zircon work showed that there is a narrow transition zone between McHugh Creek rocks and typical Valdez where the rocks young rapidly to the east, into a sea of homogeneous age rocks that comprise the coherent flysch. Based on the sedimentary facies and detrital zircon signatures we inferred that these rocks record the transition from a steep, slope developed above an erosional forearc with an emergent forearc high that developed following a ridge subduction event—the forearc high feeding coarse, locally derived clastics into the trench together with material shed from an emergent mid-Cretaceous orogen to the east/south (to produce the 100Ma sources) and beginning a new accretion cycle. As this system evolved, continued uplift in the mid-Cretaceous orogen shed vast quantities of clastics to this trench, overwhelming the trench and converting it to an accretionary prism not unlike modern Cascadia; a history that continued for nearly 50 million years into the Eocene.

Drive from Beluga Point to Girdwood

As we leave Beluga Point headed east along the inlet we continue initially past large exposures of the McHugh Creek metagraywacke/conglomerate. About 8km down the road we pass some poor outcrops below a small valley (Fall Creek) and cross over the Eagle River fault—not exposed in the roadcuts, but visible in the cliffs above as a slope break. Note, this is not the Franciscan where the mélange is the cliff former! Here, like many places where the Eagle River fault preserves the primary subduction boundary, rocks that are lithologically Valdez Group turbidites are stratally disrupted for almost a km below the Eagle River fault contact and we can see these as we pass. This mélange zone shows an interesting age progression in detrital zircon maximum depositional ages from ~90Ma at the contact to ~80Ma by Indian Creek where the rocks become coherent. From Indian creek eastward, the rocks show nearly identical detrital zircon signature with max depo ages of ~75-80Ma, consistent with latest Cretaceous fossil ages for the Valdez Group. The Valdez Group rocks show spectacular fold structures and cleavages associated with early Cenozoic metamorphism during ridge subduction events.

Stop 3 — Large-Scale Tectonics of Southern Alaska: Overview at Point Woronzof

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 (crashing into one another!) at a rate of about 2.3 inches/year (~5.8 cm/year), and this convergence directly or indirectly causes many of the most prominent geological features in this region. The Alaska-Aleutian subduction zone, at the plate boundary, is responsible for most of the earthquake activity in south-central Alaska – including the 1964 Earthquake. Because of its higher relative density, as it collides into North America, the Pacific plate descends (subducts) beneath the North American plate. The broad interface where the two plates come into contact (shown in pink in Figure 3.1) is a giant thrust fault called the eastern Aleutian megathrust. The megathrust projects to the seafloor at the Aleutian trench, which is greater than 3 miles (>5000 meters) deep in the Gulf of Alaska. As the two plates converge, the megathrust undergoes "stick-slip" motion: Friction causes the plates to stick and accumulate elastic strain, which slowly bends and buckles the plates as they continue to move. An earthquake happens when the megathrust fault slips, causing the plates to rebound elastically like springs, relieving the stress and resulting in widespread vertical and horizontal changes of the surface topography. The 1964 great Alaska earthquake was an example of slip on the eastern Aleutian megathrust over an area ~580 miles long by ~150 miles wide (pink area shown in figure 3.1).

Figure 3.1 Perspective view of the Pacific Plate being subducted beneath the North American plate at the Alaska-Aleutian Subduction zone. The pink highlighted region shows the part of the megathrust fault (plate boundary) that slipped in 1964 during the Great Alaskan Earthquake. White arrows show relative plate motion. Red and black bold lines show important faults of the South Central Alaska region.

Mountains of the Aleutian Volcanic Arc and the Alaska Range

Various mountain ranges, visible from the Anchorage area on a clear day are, formed as the result of the plate tectonics of this area. Similar to the largest earthquakes in this region, the Aleutian volcanic arc that extends more than 2,500 miles from south-central Alaska to the far western Aleutian Islands is formed as a result of subduction zone processes. As the Pacific plate descends beneath the North American plate, increasing temperatures and the presence of water in the subducting plate causes melting, which eventually leads to the formation of hot buoyant magma that escapes to the surface of the Earth at volcanoes like currently active volcanoes visible from Anchorage (Figure 3.2). Mt. Redoubt, for example, 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. This event led to the formation of the Alaska Volcano Observatory.

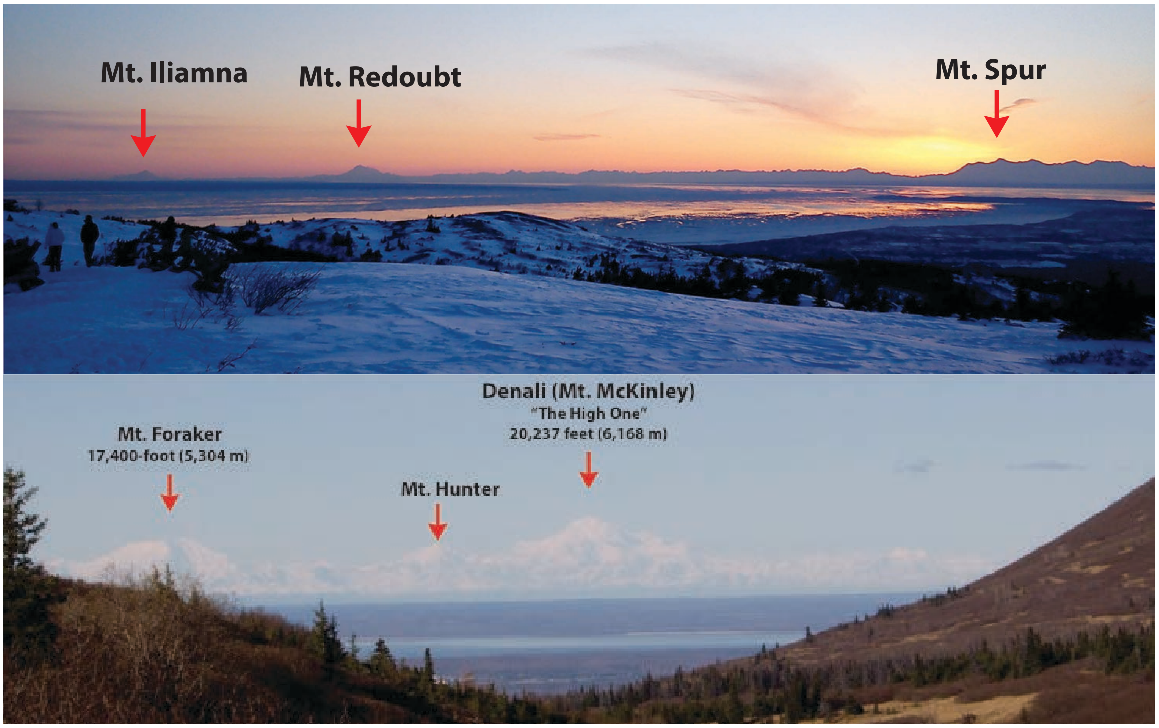


Figure 3.2. Top: View of active, ice-covered stratavolcanos visible from Anchorage. Mt. Spur and Redoubt have had several eruptions in the last 100 years. Bottom: View to the north of three of the tallest peaks of the Alaska Range that result from compressional tectonics in central Alaska..

Although not directly caused by subduction, the Alaska Range, home of North America's highest peak, Denali (or Mt. McKinley) is also a result of active tectonic processes in the state. The Alaska Range, visible to the north of Anchorage on clear days (Figure 3.2) formed as a result of movement on the Denali Fault, a major "inter-plate" fault which extends throughout central Alaska and into the western Yukon. Uplift of the mountain range helps to accommodate compressional forces within central Alaska. A compressional bend along the western portion of the strike-slip Denali fault leads to the uplifted Alaska Range (Haeussler, 2008). Though not a plate boundary itself, 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.

Beluga Point (map: https://goo.gl/maps/l7eH3)

Stop 4 — Beluga Point: McHugh accretionary complex

Geology Exposed along Turnagain Arm

Convergence between an oceanic plate and the North American Plate has been shaping the geology of south-central Alaska since Jurassic time, spanning more than 200 million years. It may not be surprising that there are signs of modern subduction processes in south-central Alaska, as well as evidence of processes associated with ancient subduction.

The southern margin of Alaska is composed of belts of rocks, called terranes. The Border Ranges fault marks the boundary between two terranes and also (no coincidently!) coincides with the northwest front of the Chugach Mountains in the Anchorage area (Figure 4.1). Northwest of the Border Ranges fault, rocks of the Wrangellia terrane reveal a history of episodic magmatism (processes related to magma, molten rock) probably caused by plate convergence in the early Jurassic. Although in the Turnagain Arm area, Wrangellia rocks are covered by basin sediment and not visible at the surface, they make up the Talkeetna Mountains to the north of Palmer (e.g., Hatcher Pass). Southeast of the Border Ranges fault, the Chugach-Prince William terrane consists of rocks that formed originally in a marine setting around the same time, landward of an ancient Alaskan trench. Rocks that make up the older part of this composite Chugach terrane crop out along the Seward Highway on Turnagain Arm. The Chugach rocks were scraped off an oceanic

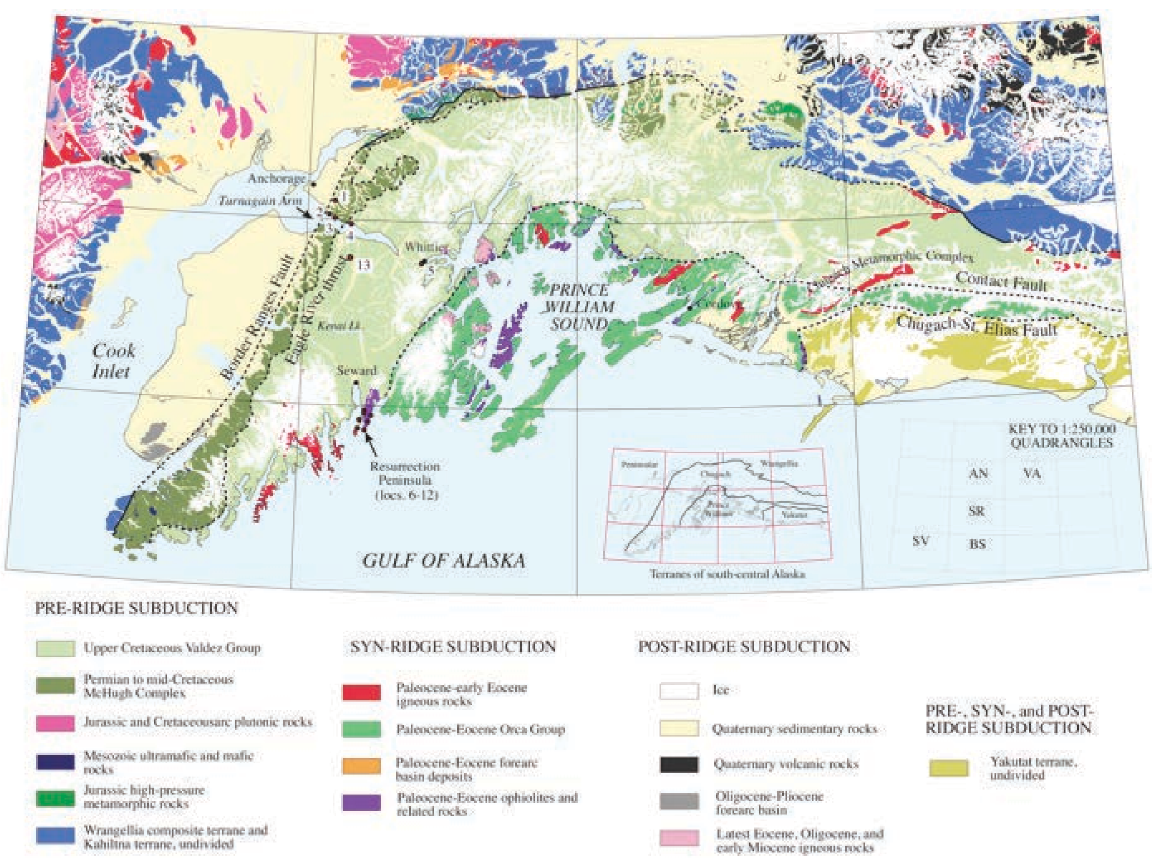


Figure 4.1 Geologic map of South-central Alaska. Clearly, there are many lithologic formations in this area that makes for a complicated geologic picture. Tow prominent terrains that we will see today are the Valdez Group (light green) and McHugh Complex (dark olive green).

plate and attached (accreted) to North America in the Mesozoic (Figure 4.2). The Chugach terrane is thus a jumbled assemblage of rocks known as an accretionary complex that has been divided into two groups based on age, composition and degree of deformation: the McHugh Complex and the Valdez Group. We will examine rocks from both groups at Stops 4 and 5.

Currently, as the Pacific plate is being subducted beneath the North American plate, a wedge of material is collecting just landward of the trench, south of mainland Alaska called an accretionary prism. This wedge forms as marine sediments are scraped off of the Pacific plate, as it subducts, and continental sediments, eroding from higher terrestrial topography, are transported down hill and deposited below the continental slope. Over time, this wedge-like section of accumulating sediment may be subjected to great temperatures and pressures as it is compressed and buried: as younger sediments continue to accumulate at the trench to the south or older material is thrust over it to accommodate compression from the north (for a visual, see the lower figure 4.4).

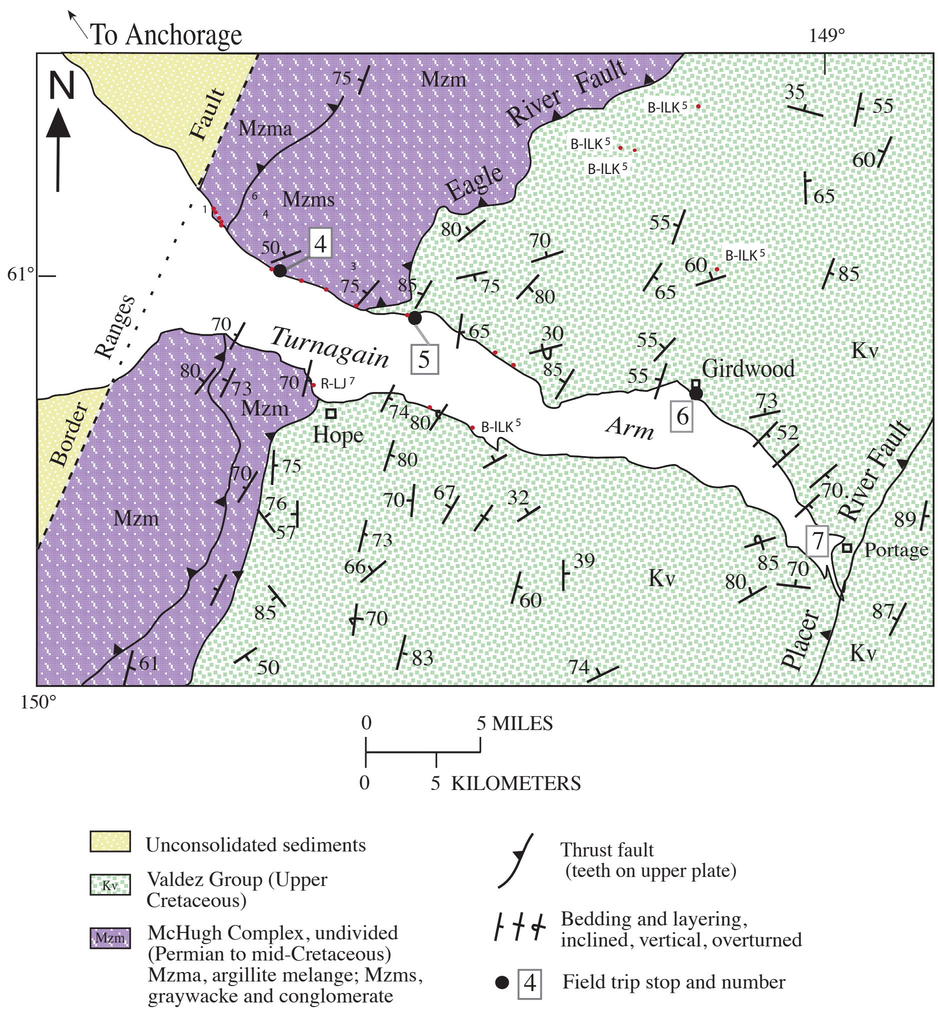


Figure 4.2 Borrowed from 2012 AGS Field Guide (Karl and others), a generalized geologic map of the Turnagain Arm area, with fieldtrip stops labeled.

Figure 4.3 Left: McHugh Complex near the weight station on the Seward Highway, rotated block of sheared accretionary mélange. Right: Early Jurassic red and green chert.

The McHugh complex represents an ancient version of an accretionary prism that has been worked and reworked in this manner throughout the past 200 million years (Permian to mid-Cretaceous). This formation has undergone significant faulting and folding, and as such, many kinds of rocks may be seen juxtaposed in the McHugh complex (Figure 4.3). This kind of heavily faulted and deformed combination of rocks is often called a mélange, or mixture of different rock types. The sections of the McHugh complex that we will see on Turnagain Arm at Stop 3 are composed of rocks associated with the marine continental slope environment, such as greywacke (poorly sorted sandstones in a mud matrix), pebble and coble conglomerates, an few examples of limestones, and interbedded chert.

At this stop CAREFULLY cross the road and get a closer view of the rock outcrop of McHugh complex. Look for evidence of deformation – do you see small faults or folds? Discuss the different rock types, and take a close look at how compositions change in rocks juxtaposed in the accretionary mélange. Can you visualize how these rocks were formed in the subduction zone accretionary wedge and how they were altered as they were deformed, barried, and exhumed or faulted back to the surface?

A note on the Border Ranges Fault:

The McHugh Complex constitutes the older, inboard part of the Chugach terrane in south-central Alaska. To the northwest, the Chugach terrane is bound by the Border Ranges Fault (Figures 4.1 and 4.2). This fault is thought to have originated as the primary subduction zone thrust separating the Wrangellia terrane from the Chugach accretionary complex. Since that time, the Border Ranges Fault has been reactivated several times – and is currently coincident with an active deformation zone called the Knik Fault (Karl et al., 2011).

Bird Point (map: https://goo.gl/maps/tSAEg)

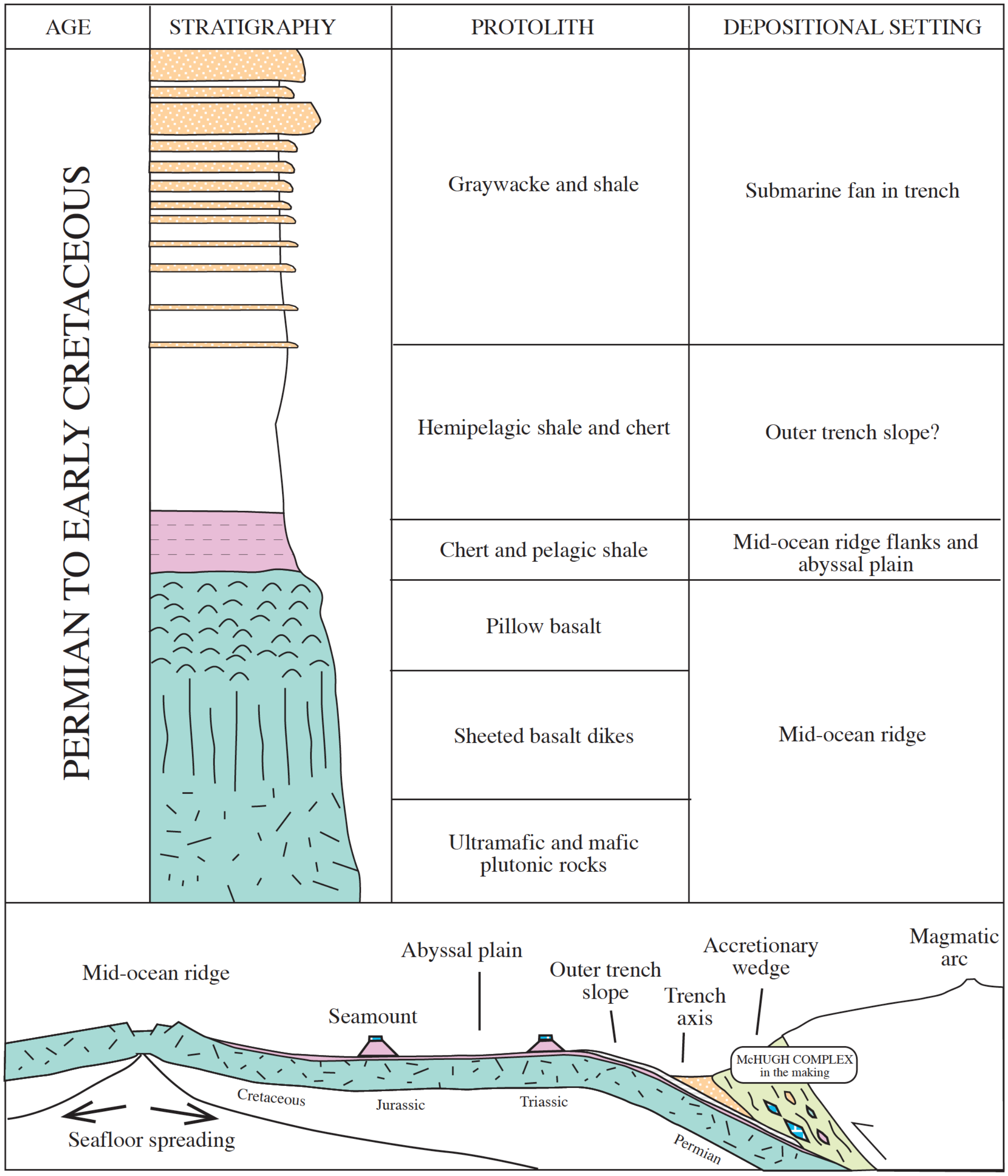


Figure 4.4 Modified from Connely (1978). Cartoon of several rock types we would expect in the vicinity of a subduction zone prism. The sections of the McHugh and Valdez formations that we will see today are similar to the top half of the rocks depicted here – including greywacky, shale, and chert - characteristic of the trench axis (Valdez Group) and accretionary wedge (McHugh). The bottom diagram shows a cartoon of a subduction zone. The Chugach terranes are thought to be representative of an ancient accretionary wedge where younger material has been accreted onto the seaward end and extruded to the surface by compressional thrusting.

Stop 5 — Valdez Group rocks (Bird Point) arrive 12:00 PM for lunch

Rocks on the seaward part of the Chugach terrane have been mapped as the Late Cretaceous age Valdez Group. The age of the rocks were determined by the presence of fossil clams (inoceramid bivalves) around 65 to 75 million years old. Rocks in the Valdez Group include gray, moderately well-sorted sandstone with some volcanic rock fragments, black quartz-rich sandstone and rarer pebble to cobble conglomerates (Figure 5.1). The well-bedded, gray sandstones have been interpreted as marine turbidites, or rocks formed from the deposits of turbidity currents in a deep-sea trench. Turbidity currents occur from undersea slope failures on the continental slope, sometimes triggered by earthquake shaking. This would represent a depositional environment similar to the McHugh complex, but slightly closer to the trench (see orange wedge in the lower part of Figure 4.4). Valdez Group rocks have been uplifted, folded and faulted on a regional scale as a result of plate convergence. At Bird Point, layers of sedimentary rock, originally deposited horizontally on the seafloor, have been deformed to a near vertical orientation.

Figure 5.1 Left: McHugh Complex conglomerate along Turnagain Arm. Clasts include intermediate plutonic rocks, sandstone, argillite, limestone, and greenstone (from Bradley and Miller, 2006). Right: Valdez Group turbidites from along Turnagain Arm. Coherent bedding is common in the Valdez Group but rare in the McHugh Complex (from Bradley and Miller, 2006).

At this stop take a similar look at the outcrop of Valdez complex – get up close and look for turbidites where the grainsize of the sandstones go from course-grained to fine-grained. How does this formation differ from the McHugh complex? Enjoy Lunch and enjoy the view!

Girdwood Marsh (map: https://goo.gl/maps/dA8ug)

Stop 6 — 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, (weather permitting) as a group we'll hike out to the exposed edge of Girdwood Marsh, and explore the paleoseismic record. Stratigrphy 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!

West entrance to Whittier Tunnel (map: https://goo.gl/maps/snkjt)

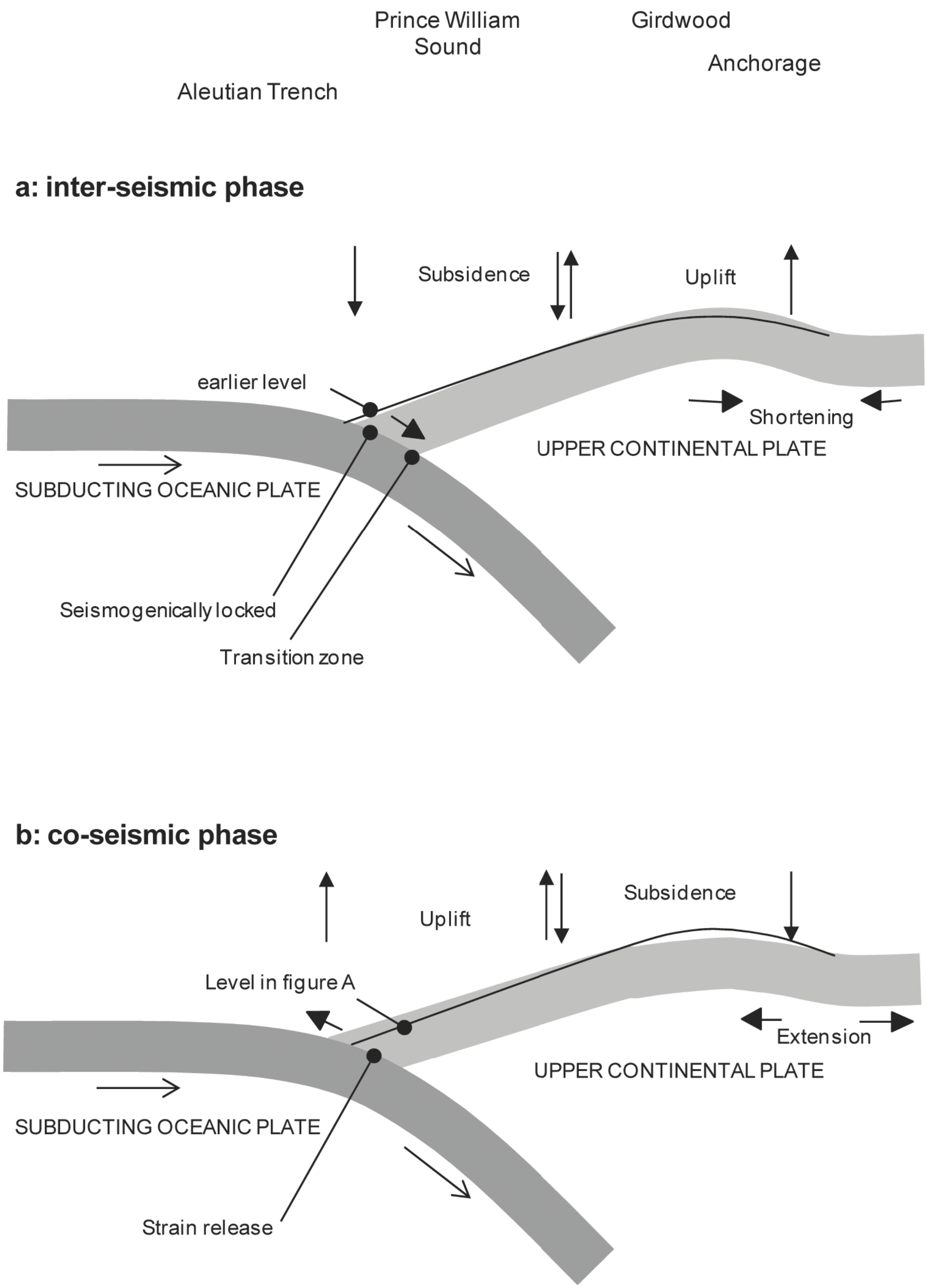


Figure 6.1. Schematic profiles of the deformation of tectonic plates that occurs (a) between earthquakes (interseismic) and (b) during an earthquake (coseismic). The profiles reflect two components of the earthquake deformation cycle at eastern Aleutian subduction zone along a section from the Aleutian trench to Anchorage (from Shennan et al., 2008).

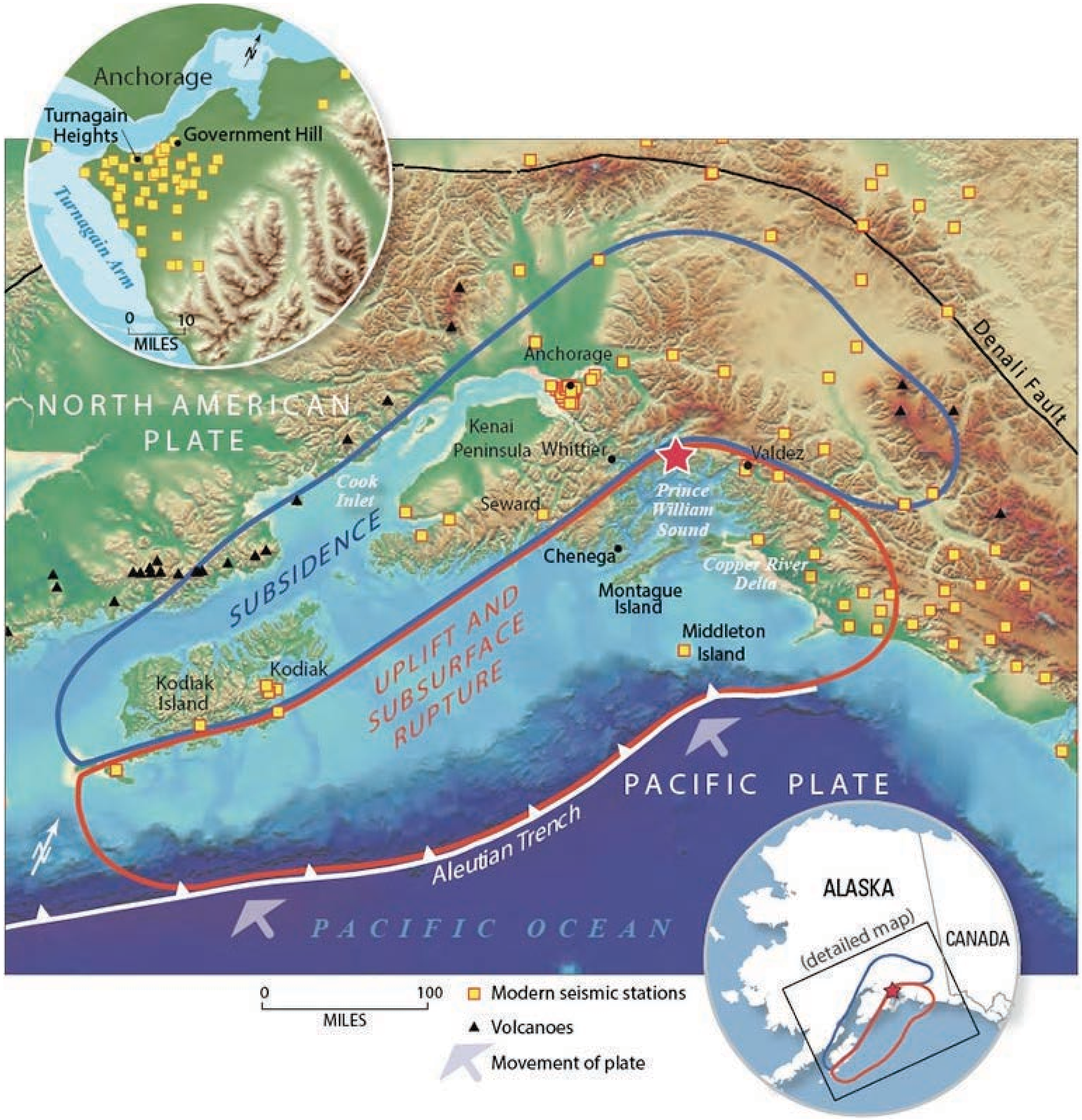
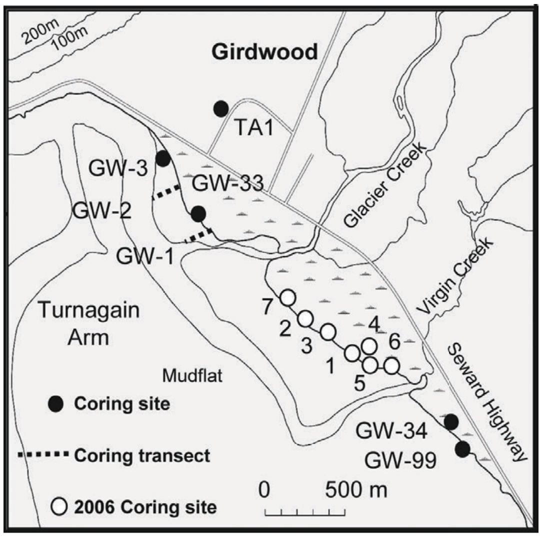


Figure 6.2. Map of southern Alaska showing the epicenter of the 1964 Great Alaska Earthquake (red star), caused when the Pacific Plate lurched northward underneath the North American Plate. There was extensive damage to coastal towns and infrastructure throughout the region, particularly in Anchorage, 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).



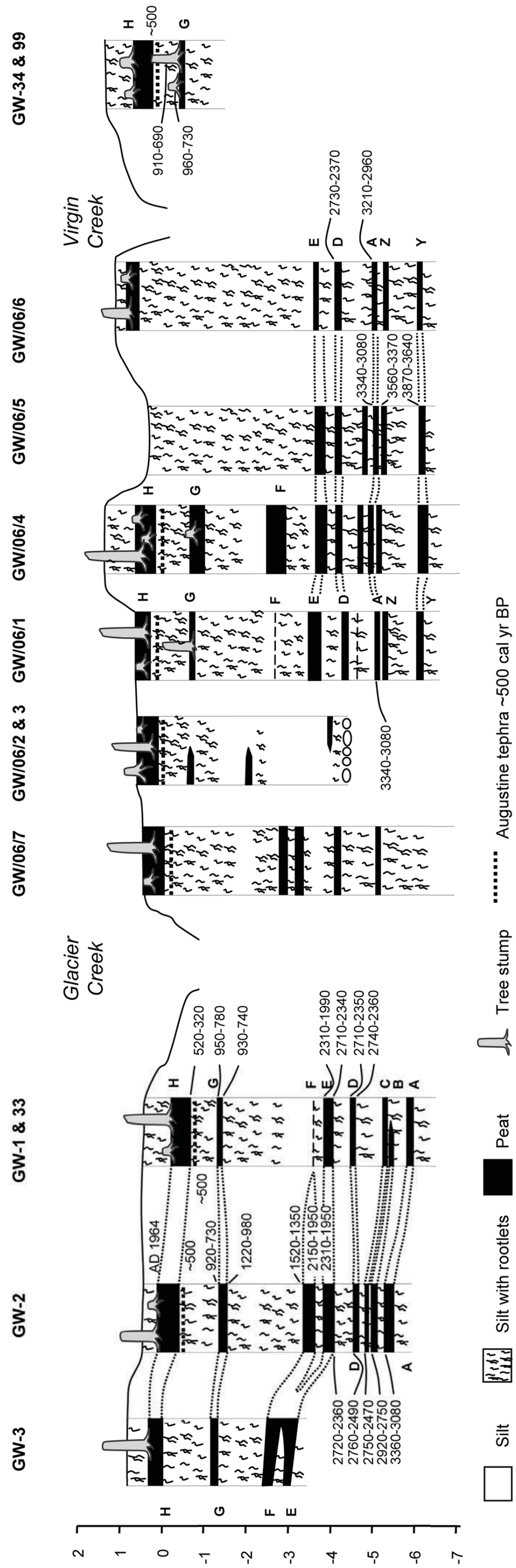


Figure 6.3. Left: Girdwood marsh site. Right: Stratigraphy at Girdwood marsh consisting of interbedded peat and silt. Radiocarbon age estimates shown on right (Shennan et al., 2008). Below: Peat subsided by earthquakes and buried by intertidal mud at Girdwood, Alaska.

Stop 7 — 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 7.1) were flooded by high tides following subsidence during the 1964 earthquake and 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 wide developed, from which water and sand reportedly ejected as much as 25-30 feet high for about 2 minutes (Plafker et al., 1969).

At this location, near the axis of maximum subsidence in 1964 (Figure 7.2), 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 (remarkably fast!) 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 7.3; Atwater et al., 2001).

Get a good view of what remains of the Portage townsight as we head toward the Wittier tunnel. Also observe the prominent "Ghost Forest" caused by subsidence associated with the earthquake in this area.

Drive through Whittier Tunnel, 4.6 mi (12 min) to Whittier (map: https://goo.gl/maps/sLvw5)

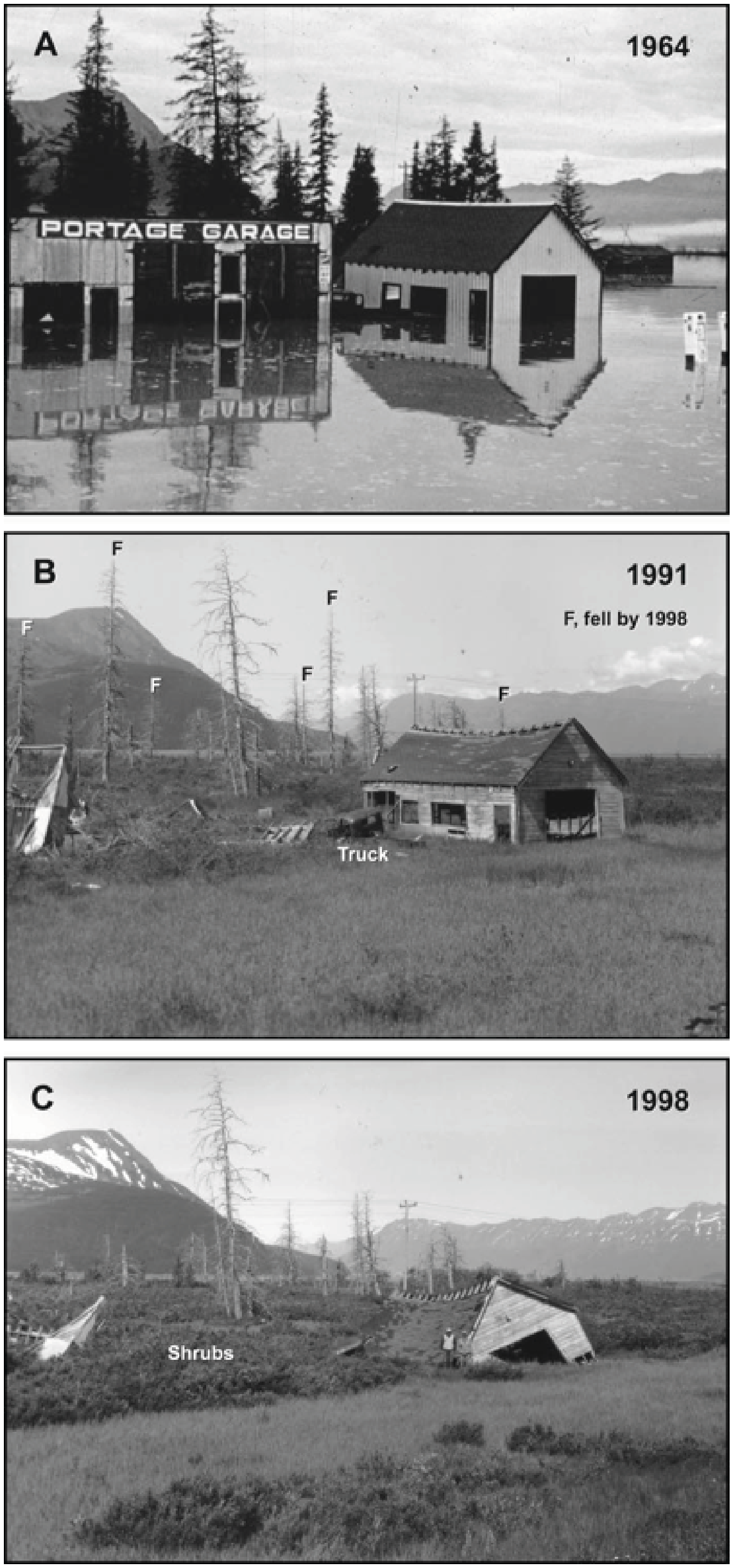


Figure 7.1 From Atwater et al. (2001). Photos documenting post-earthquake subsidence followed by relatively rapid (10 yrs) redeposition and gradual uplift of the Portage town site following the 1964 Earthquake.

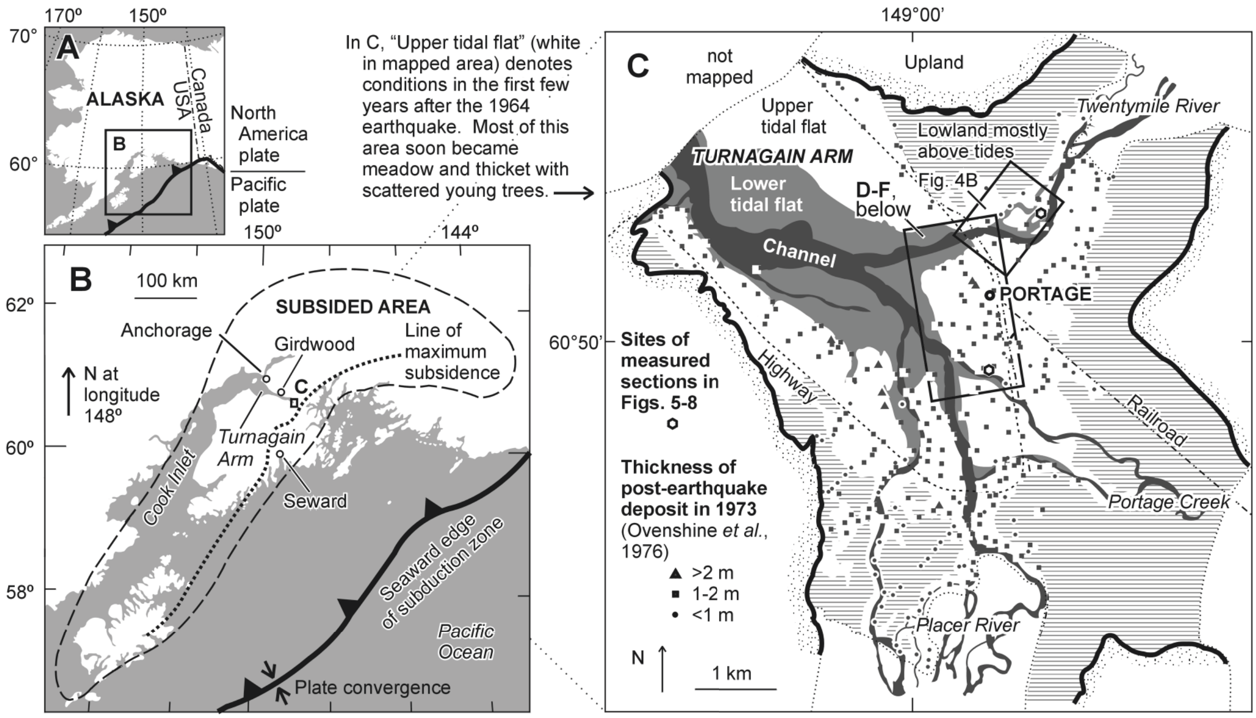


Figure 7.2 From Atwater et al. (2001). Location of the Portage Town site near the line of maximum subsidence during the 1964 earthquake.

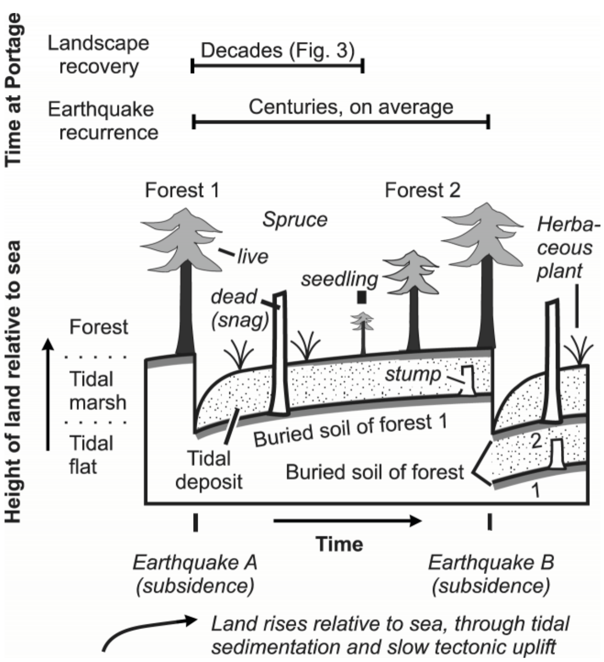


Figure 7.3 From Atwater et al. (2001). Earthquake-induced cycle of forest death and renewal at an estuary. Forest 1 dies from tidal submergence due to earthquake A (Figs. 12A and 4A). Tidal sediment buries the floor of the dead forest and builds land on which forest 2 grows. This next forest eventually dies from effects of earthquake.

Stop 8 — Whittier, 1964 tsunami (Rob)

Processes at work in Alaska's fjords create the dangerous potential for underwater landslides triggered by earthquakes, which can generate local tsunamis that may hit nearby shorelines before seismic shaking stops. 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 tsunamis generated by submarine landslides. In Alaska's fjords, sediment transported to the sea by glacial-fed rivers form large deltas of unconsolidated materials that are highly susceptible to slumping during seismic shaking.

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 hit 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 of earthquake-related subsidence (Kachadoorian, 1965).

After the 1964 earthquake and tsunami, Whittier suffered massive damage amounting to $10 million (~$74 million in 2012 dollars) and 13 of the city's 70 inhabitants died (Kachadoorian, 1965). Much of Whittier's harbor, railroad and sawmill facilities were completely wrecked, particularly buildings constructed on artificial fill or unconsolidated sediment. Only slight damage occurred to buildings constructed on bedrock. Fire destroyed the fuel oil tanks along the waterfront (Figure 8.1). The tsunami was attributed to the collapse of delta sediment at the west end of Passage Canal (Figure 8.2).

Studies since the devastating 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 8.3; 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 may have resulted in the high number and large volume of submarine landslides.

Begich, Boggs Visitor Center on Portage Lake (map: https://goo.gl/maps/uCMx0)

Figure 8.1. 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).

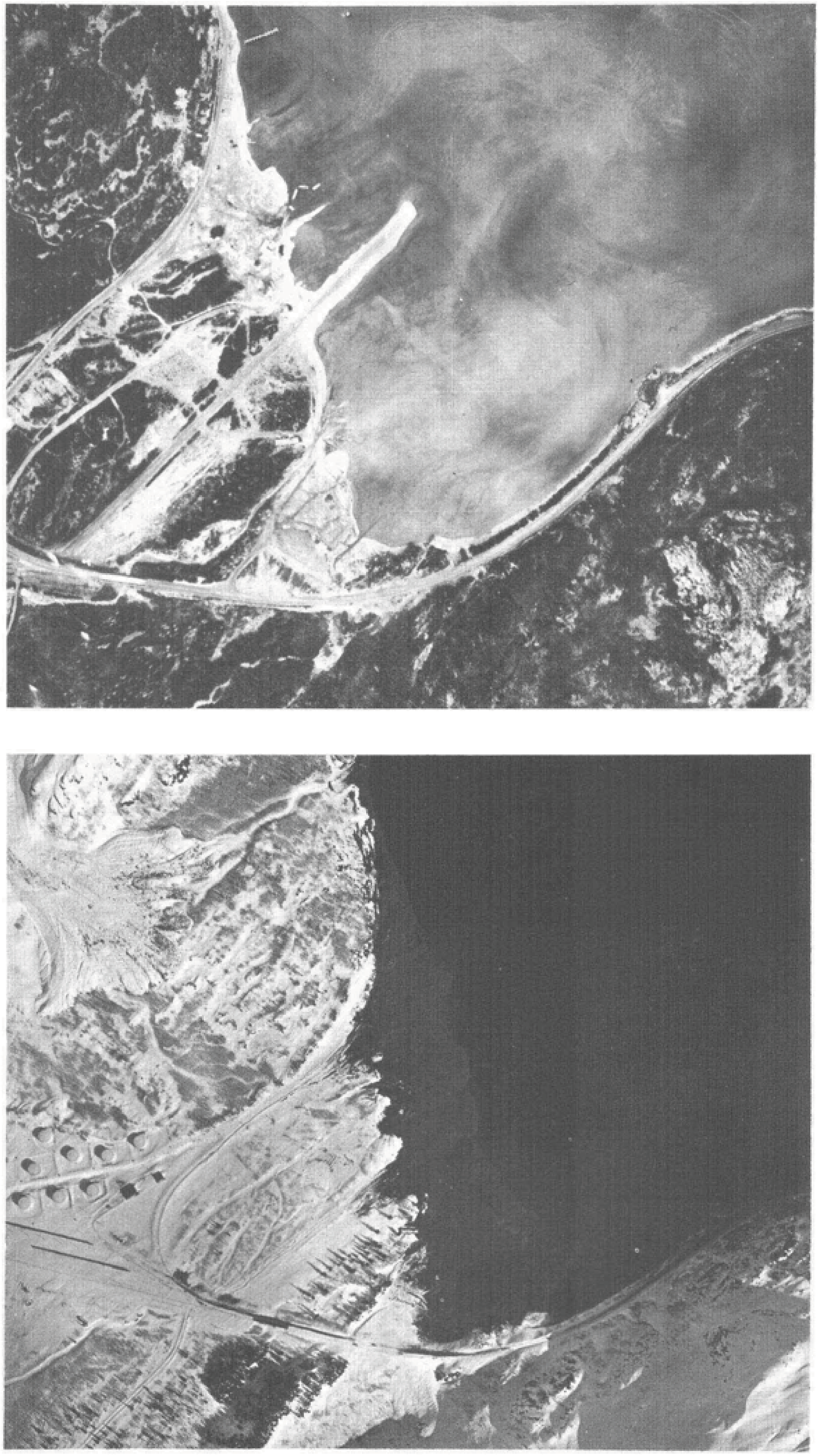


Figure 8.2. Aerial photographs of Whittier, Alaska, before and after the 1964 earthquake (Kachadoorian, 1965). Top: Whittier before the 1964 earthquake. Composite photograph by BLM , 23 September 1963. Bottom: Whittier after the earthquake. Photograph by U.S. Army, 28 March 1964.

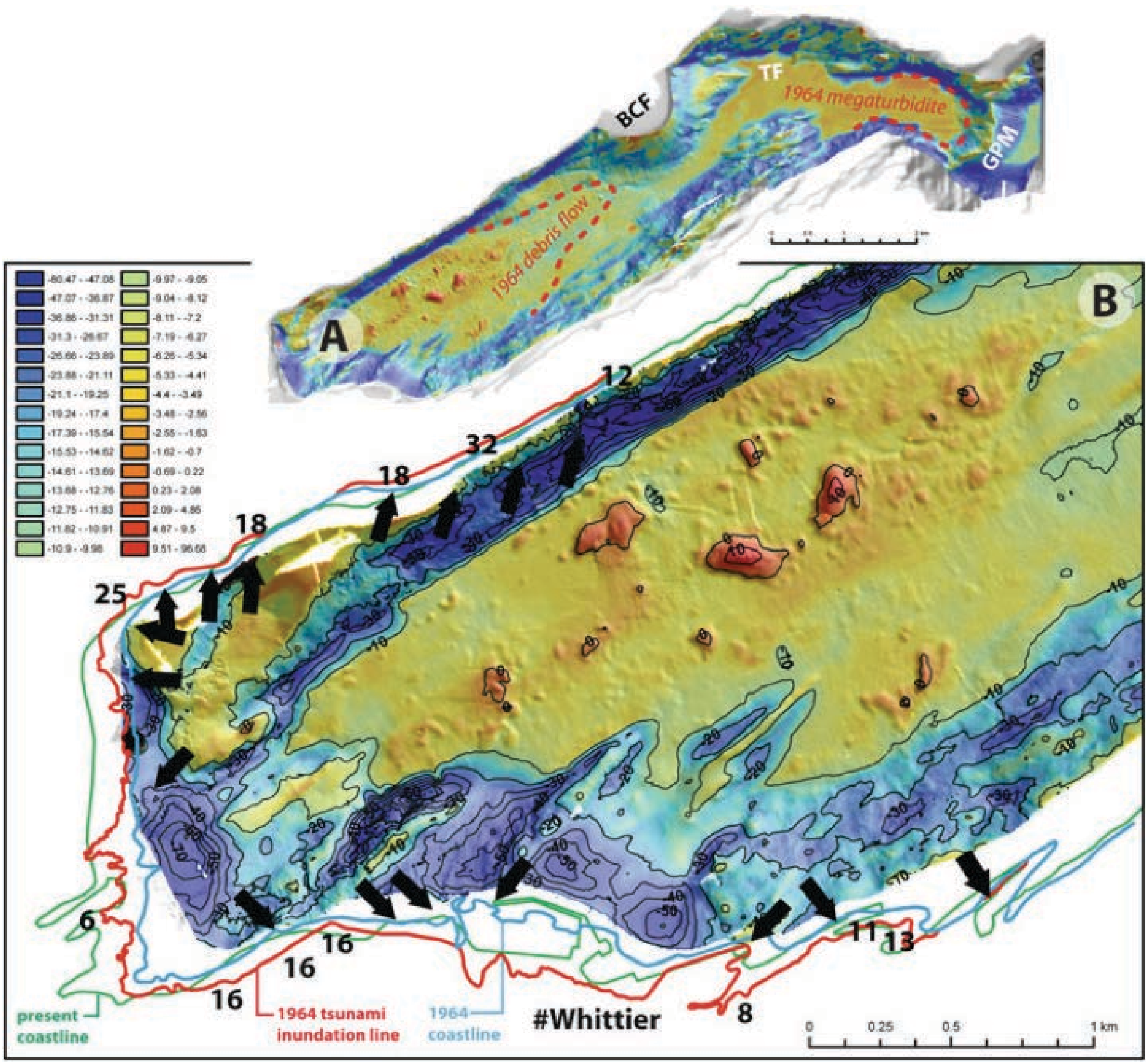


Figure 8.3. Haeussler et al. (2014) investigated changes in bathymetry in Passage Canal by comparing a 1948 bathymetric survey to multibeam survey data acquired in 2011. The inset map (A) covers the entire multibeam survey area and shows the Billings Creek fan (BCF), Trinity Flats (TF) and the Gradual 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).

Stop 9 — Portage Lake, Portage Glacier retreat

Figure 9.1 Photo of Portage Glacier and Portage Lake in 1957

The Portage Glacier could be viewed easily 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. Like other glaciers that terminate in water, such as Columbia Glacier near Valdez or Mendenhall Glacier near Juneau, Portage Glacier has experienced accelerated retreats in recent decades that likely were initially triggered by climate change beginning at the end of the Little Ice Age in the mid-1800s and subsequently controlled in recent history primarily by calving of the glacier terminus. 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 at the western end of Portage Lake, filling Portage Lake with ice (Figure 9.2 - 1914). Since the early 1900s, the glacier has receded, leaving 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 of some 140 to 160 meters per year occurred between 1939 (Figure 9.2 -1939) and 1950, when water depth at the terminus was at its maximum—roughly 200 meters. Recession continued through the 1970s and 1980s (Figure 9.2 -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 9.2 - 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 during the past century-long general warming trend contributed to glacier retreat, but to a lesser extent (Kennedy et al, 2006).

The Above is taken from USGS Open File ***2006-3141 and references therein.***

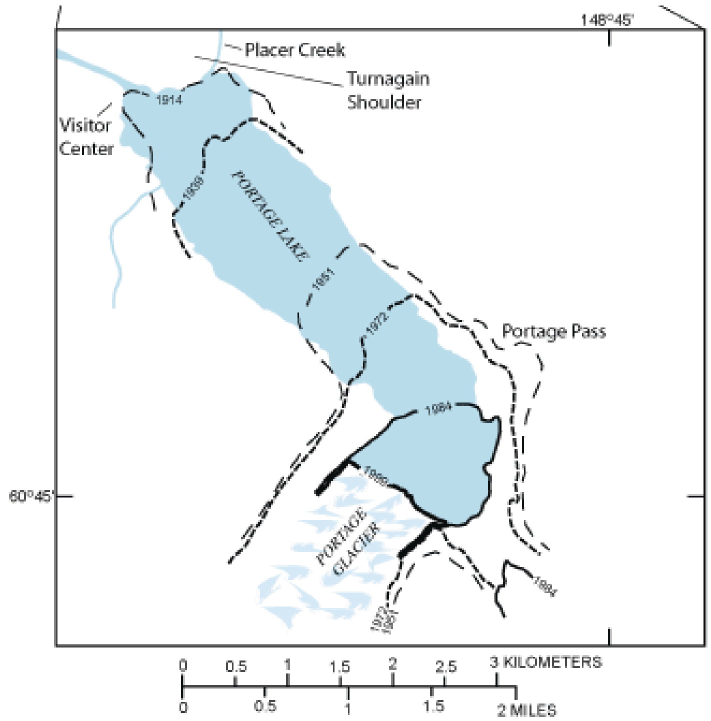


Figure 9.2 Approximate terminus positions of Portage Glacier 1914–1999 (Modified from Mayo et al., 1977 with additional USGS imagery). The 2006 location is very similar to the marked 1999 location. U.S. Forest Service Begich, Boggs Visitor Center location is marked. Portage Glacier is located in south-central 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.

Girdwood (map: https://goo.gl/maps/ky0gL)

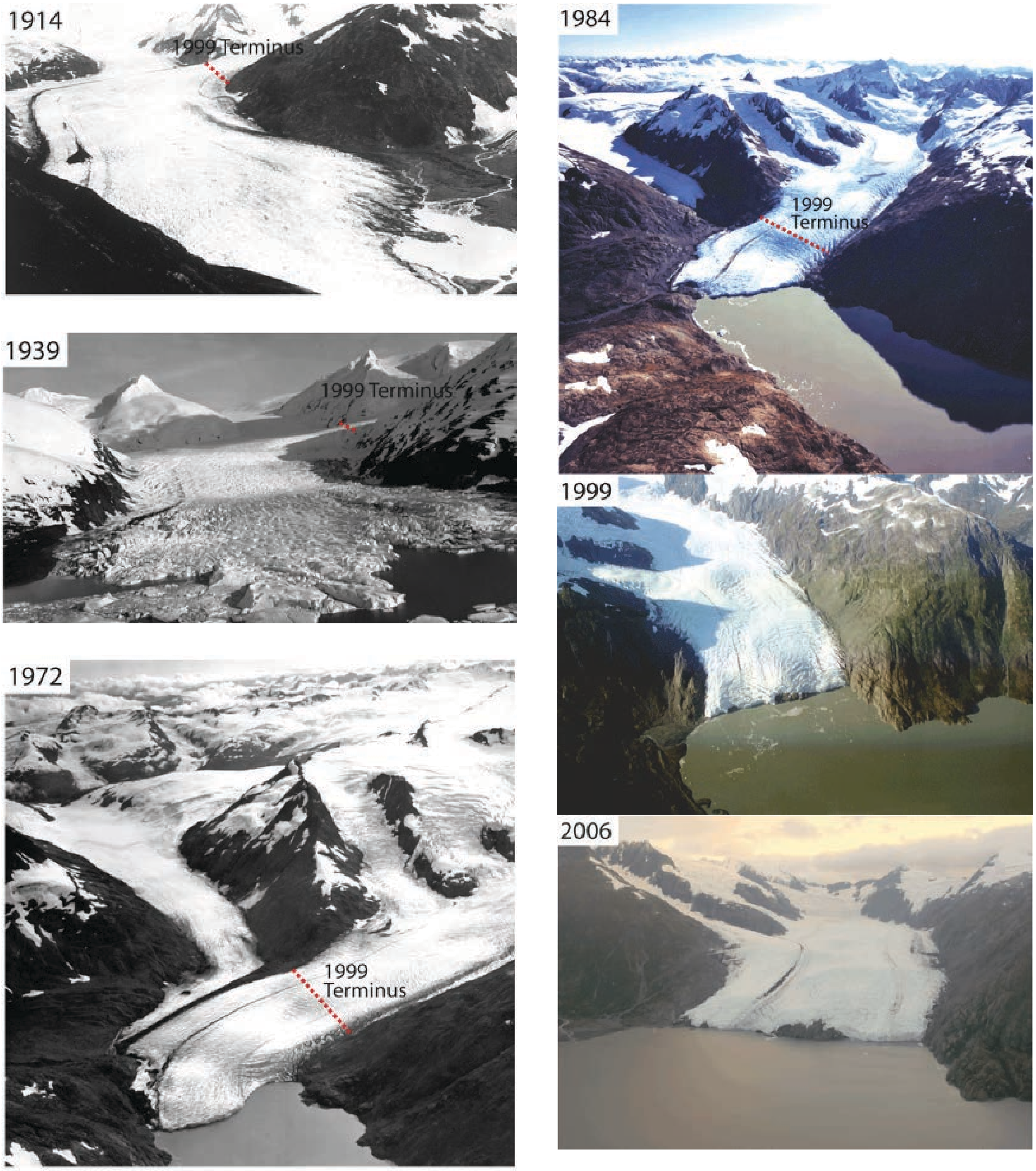


Figure 9.3. Photo record of Portage Glacier retreat from 1914-2006

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