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FIELD TRIP GUIDE: THE 1964 GREAT ALASKA EARTHQUAKE AND ITS PREDECESSORS IN THE ANCHORAGE AND TURNAGAIN ARM AREAS

Edited by

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Field Trip Guide:

THE 1964 GREAT ALASKA EARTHQUAKE AND ITS PREDECESSORS IN THE ANCHORAGE AND TURNAGAIN ARM AREAS

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Coastal marsh and ghost forest near Girdwood, Alaska. Trees died as a result of ~2.4 m of subsidence (~1.5 m regional and ~0.9 m local compaction) during the 1964 great Alaska earthquake, resulting in subsequent flooding by seawater during high tides. The stratigraphy beneath the marsh records evidence of six similar previous events during the past ~4,000 yrs.

Most of the text and figures in this guidebook are excerpted from the following sources. See those sources for references cited therein. This informal guidebook should not be cited in published reports.

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INTRODUCTION

Tectonic setting

South-central Alaska's Pacific margin is underlain by two parallel composite terranes (Plafker *et al.*, 1994). On the inboard side is the Wrangellia–Peninsular composite terrane. The Peninsular terrane has been the site of episodic arc magmatism since the latest Triassic (Hacker *et al.*, 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 (fig. 1); 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.

The present-day tectonics of south-central Alaska are affected by the oblique collision of the Yakutat terrane into Alaska and subduction along the Aleutian megathrust of the Pacific plate beneath the Alaskan plate (Plafker and Berg, 1994). The Pacific plate moves northward at ~55 mm/yr. The Yakutat microplate, a fragment of the North American plate that is partially subducted beneath and partially accreted to the continental margin of North America, moves northwest at 40–50 mm/yr, 10–20^{o} counter-clockwise to the direction of the Pacific–Alaska convergence (Bruhn *et al.*, 2004; Fletcher and Freymueller, 1999).

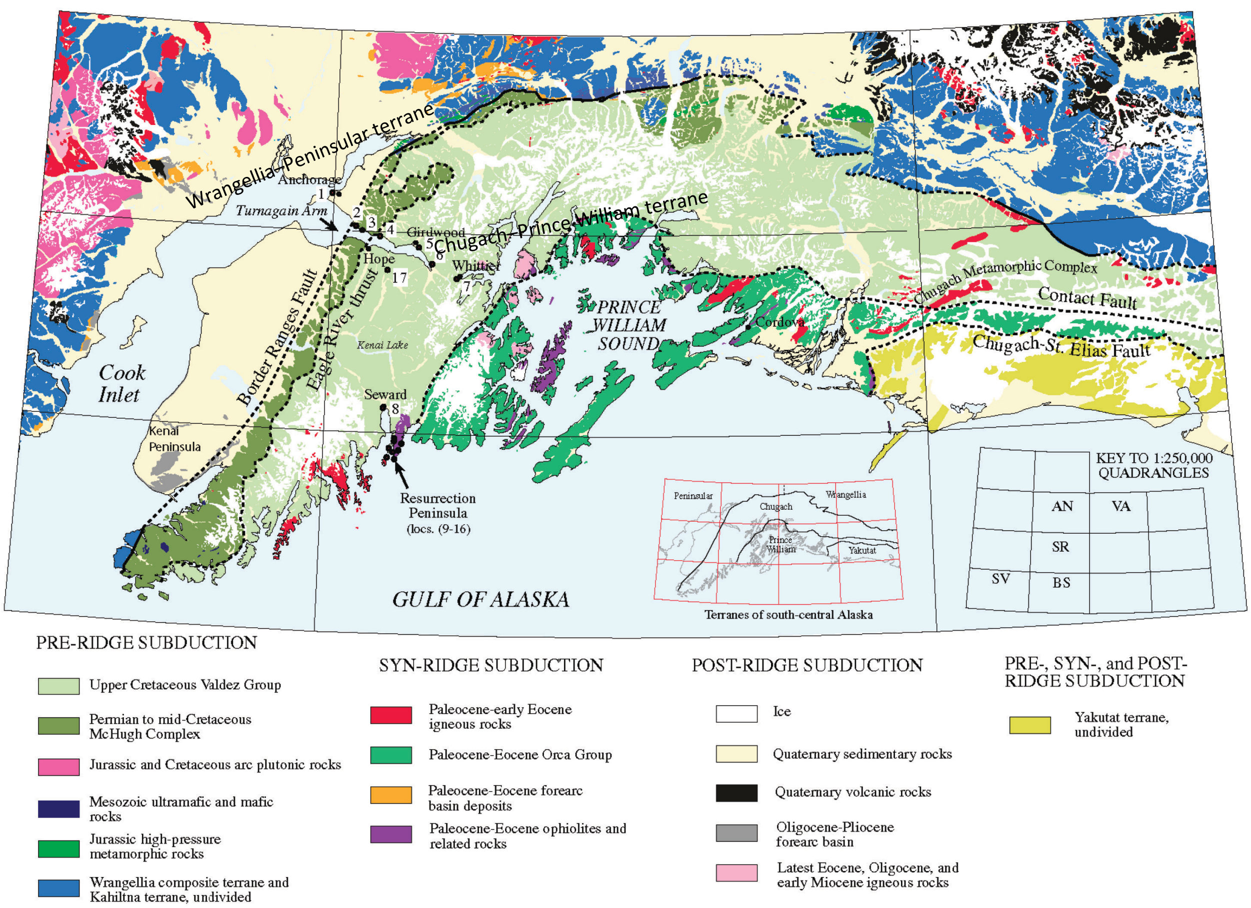


Figure 1. Generalized geologic map of south-central Alaska, from Bradley et al. (2003) and sources cited therein.

Sudden deformation of any part the active tectonic boundaries results in large-magnitude earthquakes. The largest historical earthquake in upper Cook Inlet (M_w 9.2) occurred on March 27, 1964, at 5:36 pm local time. A 600–800 km rupture of the eastern segment of the Aleutian megathrust produced surface deformation over 170,000–200,000 km^2 of south-central Alaska (Plafker, 1969) with upper Cook Inlet experiencing up to 6 ft (1.8 m) of tectonic subsidence and a zone of uplift seaward of the subsidence region through Prince William Sound and Copper River Delta (fig. 2). One hundred thirty-one people died (115 in Alaska and 16 in Oregon and California), primarily due to local and regional tsunami waves. Alaska also experiences intraplate earthquakes with ruptures along interior faults, including the AD 2002 M_w 7.9 Denali fault earthquake.

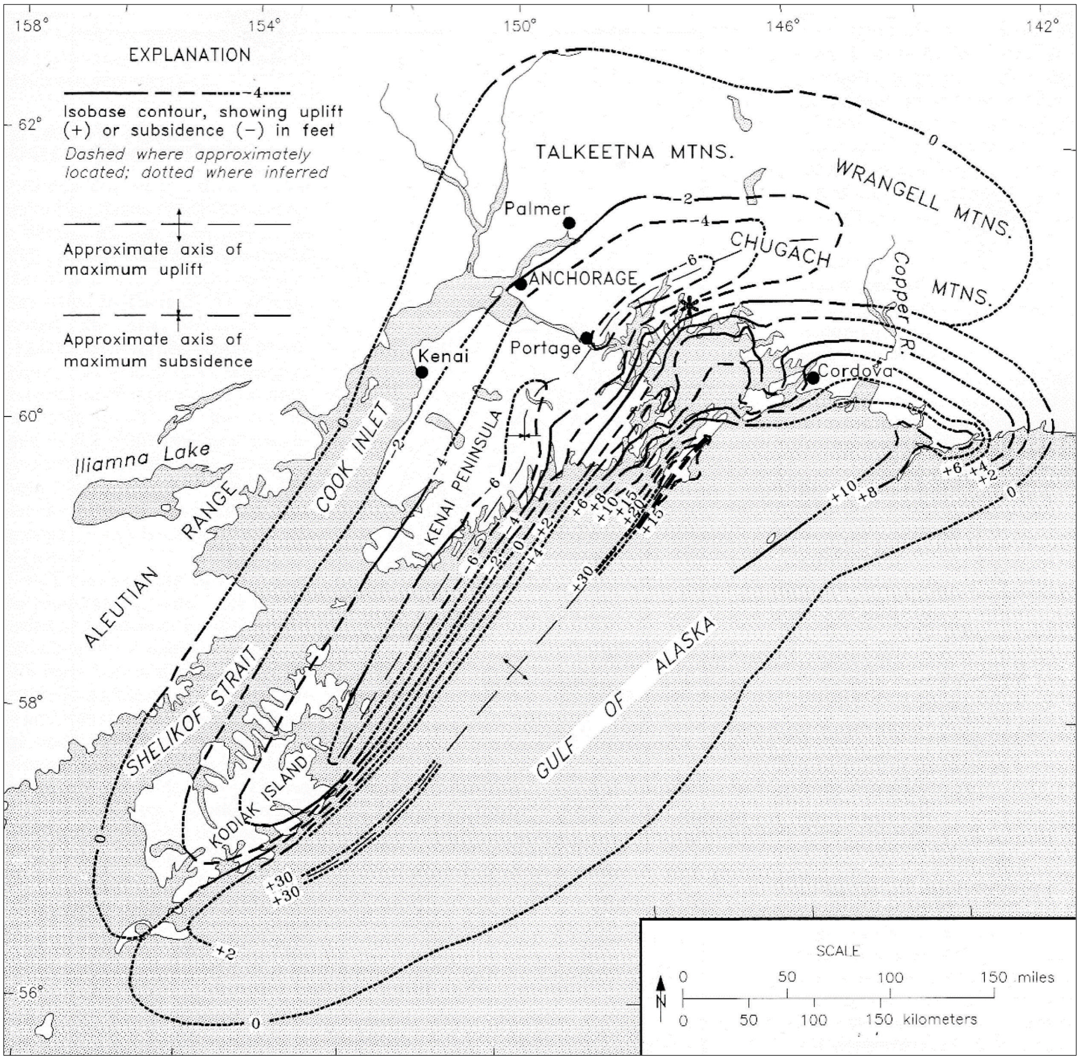


Figure 2. Regional vertical tectonic deformation, in feet, caused by the 1964 great Alaska earthquake (after Plafker, 1969).

Latest Pleistocene glacial history

In the Cook Inlet basin, the last major (Naptowne) glaciation peaked ~21,000 yrs ago. Thick glaciers estimated to be at least ~2,500 ft thick accumulated in the Turnagain Arm–Anchorage area, isostatically depressing the land. Following the glacier climax, ice thinning and recession allowed creation of an ice-walled, cold meltwater lake in the Anchorage lowland, where fine-grained lake sediments with numerous erratic dropstones accumulated as the lower Bootlegger Cove Formation. About 17,500 yrs ago, glacio-estuarine waters in lower Cook Inlet breached the ice barrier on the western Kenai Peninsula, entered the upper inlet basin, and the oldest known marine mollusk fossils were preserved in the upper third of the Bootlegger Cove Formation in the Anchorage area.

During the Skilak and Elmendorf stades of the late Naptowne glaciation, transgressing glacioestuarine waters followed retreating ice fronts as much as 60 mi into the isostatically depressed southern Susitna River lowland northwest of Anchorage and into Turnagain Arm east of Anchorage. Terminal moraines document Skilak stadial readvances from northern and eastern sources into glacioestuarine waters in the southern Anchorage lowland (fig. 3). The type Elmendorf terminal moraine was deposited just north of Anchorage by a southwest-flowing tidewater glacier from the Knik River valley, and proximal outwash spread across the Bootlegger Cove Formation in the northern Anchorage lowland. The level Bird Creek lateral moraine along the northern shore of Turnagain Arm documents a correlative westward Elmendorf readvance of the floating Turnagain Arm glacier to the vicinity of Hope. Following the climax of the Elmendorf readvance ~15,000 yrs ago, lowland glaciers receded into their mountain sources, and the Naptowne glaciation ended ~11,000 yrs ago.

Postglacial isostatic uplift has brought the upper part of the Bootlegger Cove Formation to ~100 ft above current sea level in the Anchorage area. Thick, sensitive clays of the Bootlegger underlie most of downtown and west Anchorage and were responsible for the major earthquake-induced landslides in 1964.

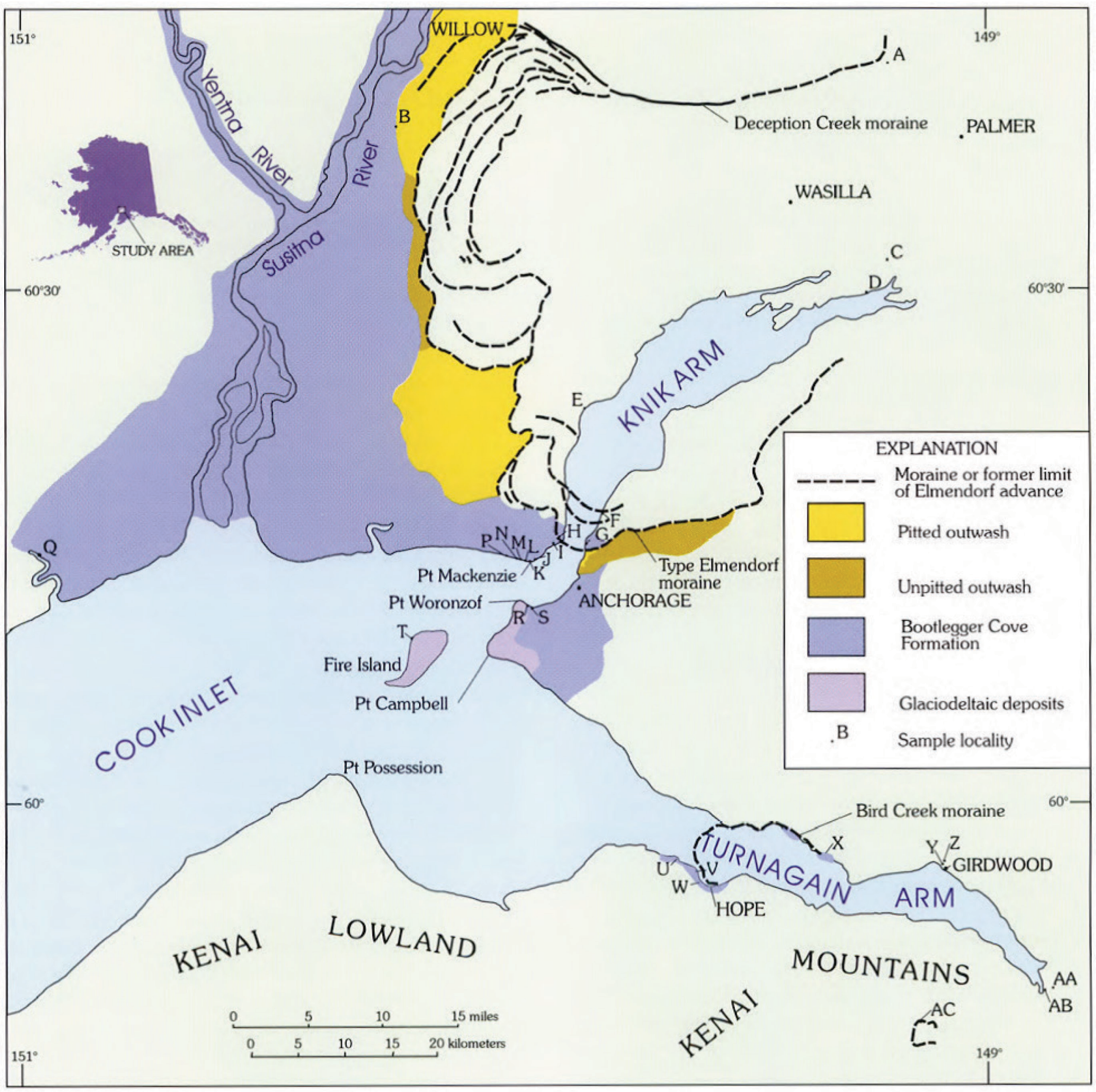


Figure 3. Map showing late-glacial geologic units and moraines in the upper Cook Inlet region (from Reger et al., 1995).

1964 EARTHQUAKE-INDUCED LANDSLIDES IN ANCHORAGE

compiled by Ed Garrett and Rod Combellick

Seismically triggered landslides caused the greatest damage to structures in the Anchorage area in 1964. The earthquake initiated large translational block landslides at Turnagain Heights, Fourth Avenue, Government Hill, L Street, and Native Hospital (fig. A1), devastating large areas of downtown and surrounding residential neighborhoods. The descriptions below are based on Hansen's comprehensive account (Hansen, 1965).

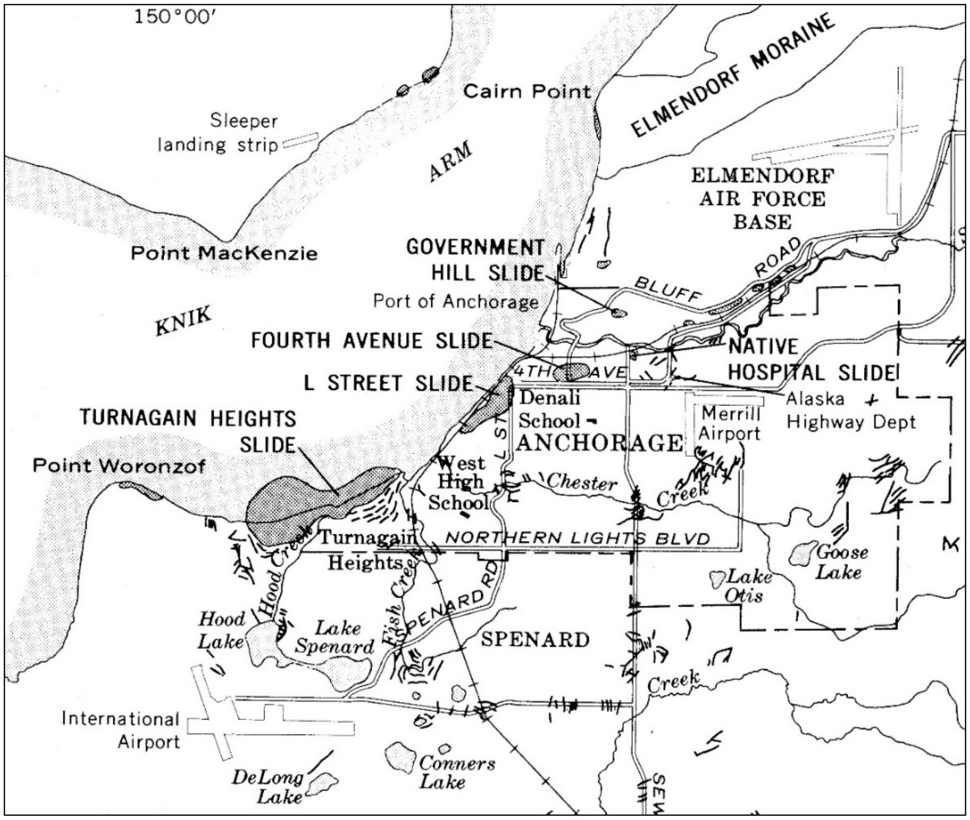


Figure A1. Major landslides and ground cracks in the downtown Anchorage area resulting from the 1964 M_w 9.2 earthquake (from Hansen, 1965, fig. 1).

The Turnagain Heights Landslide

The largest landslide occurred at Turnagain Heights, a residential area approximately 4 km southwest of downtown. There, two main lobes together extended for 2.6 km along the Knik Arm coastline. In the more developed eastern lobe, 75 houses were destroyed and four lives lost; the largely undeveloped western lobe is preserved as Earthquake Park (figs. A2a,b,c).

Mobilization of material at Turnagain Heights began approximately two minutes after shaking started and continued for one or two minutes after noticeable shaking ceased. The failure was retrogressive, progressing south from the 20–30-m-high coastal bluff. The maximum headward retrogression exceeded 350 m in the western lobe and 150 m in the eastern lobe, with a combined total of 12 million m^3 of material moved. Sub-horizontal basal shear surfaces caused blocks to rotate out from the bluff face, with the toe of the slide eventually extending more than 600 m offshore from the original bluff face. Subsequent erosion has restored the coastline of Bootlegger Cove to almost its pre-landslide position and subdued the chaotic topography of jagged rotated blocks and grabens in the area of Earthquake Park. Extensional fissures occurred more than 100 m behind the western lobe and 600 m behind the eastern lobe.

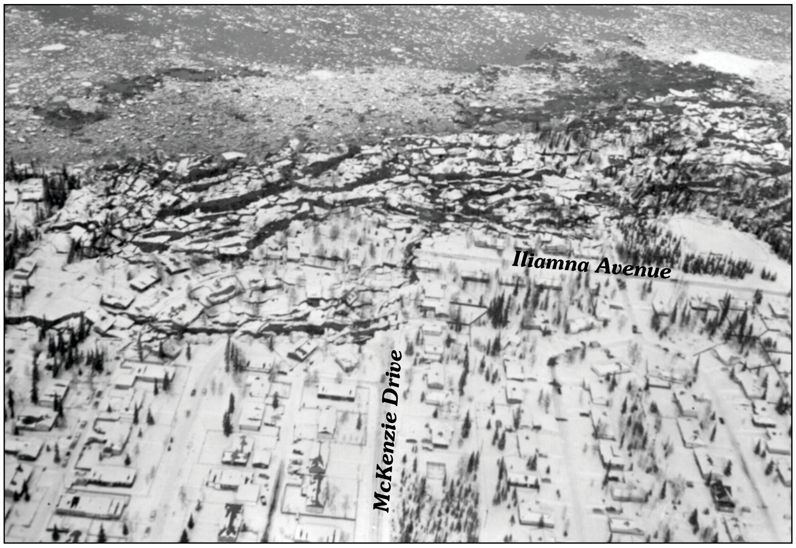


Figure A2a. Oblique aerial view of eastern portion of the Turnagain Heights landslide, looking north.

Figure A2b. Landslide damage to homes in the Turnagain Heights subdivision.

Figure A2c. Tilted slide blocks and grabens in the western Turnagain Heights landslide area, now Earthquake Park.

L Street Landslide

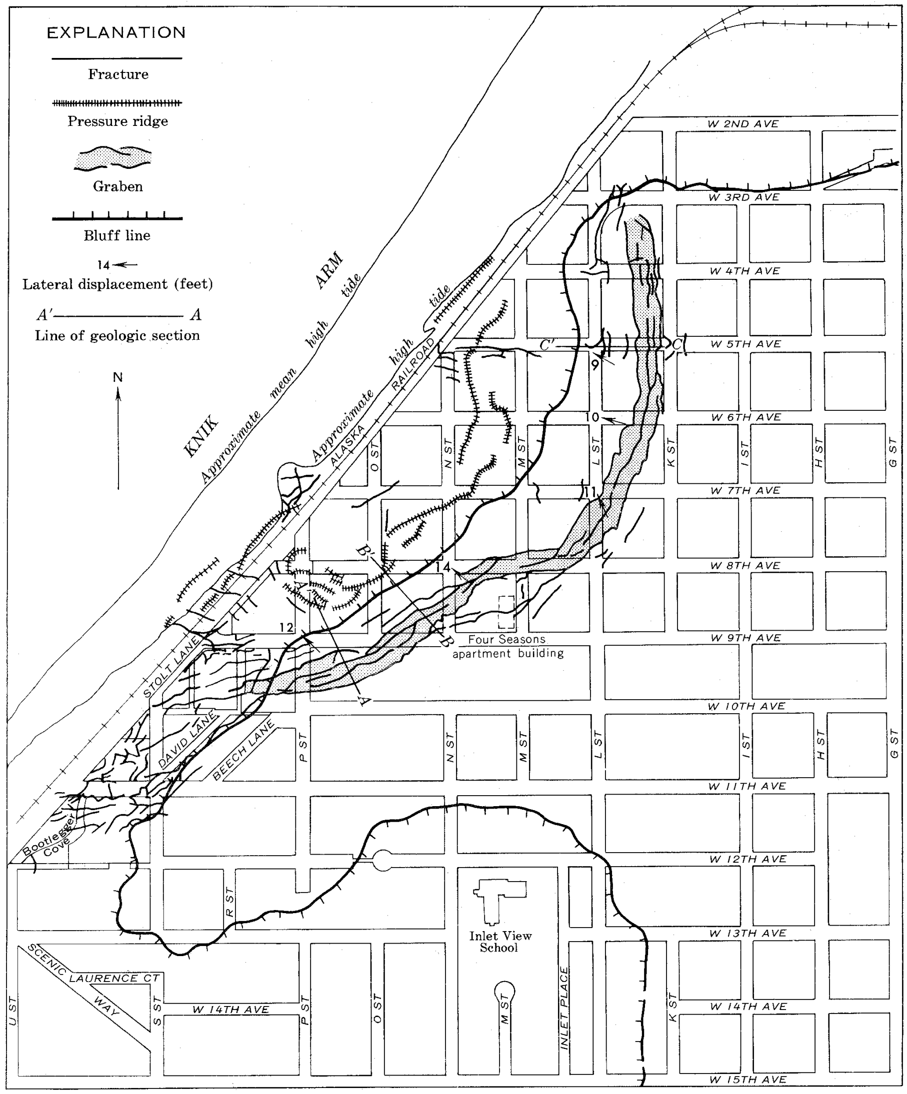


Figure A3. L Street slide, graben, and pressure ridges (from Hansen, 1965).

The L Street slide involved all or parts of about 30 city blocks in the northwest part of Anchorage adjacent to Knik Arm (fig. A3). It extended northeast about 4,800 ft along the bluff and had a maximum breadth northwest across the bluff of about 1,200 ft, parallel to the direction of slippage. It reached about a block and a half back from the bluff line into thickly settled residential and commercial neighbor-hoods of Anchorage. In all, about 72 acres were included between the graben at the head of the slide and the outermost pressure ridges at the toe. Much of the 72-acre area, however, was little, if at all, damaged despite lateral shifting of as much as 14 ft. Most of the damage was con-centrated along the graben, which with marginal fractures covered about 14 acres, and along the pressure ridges at the toe. There was very little fracturing much beyond the bounding fractures of the graben, and there was not much fracturing within the slide mass itself except for the graben area. Eyewitness reports indicate that slippage began during the latter part of the earthquake.

Total collapse of the newly completed but unoccupied Four Seasons apartment building at 9th Avenue and M Street (figs. A4a,b) was originally attributed strictly to ground shaking, but upon later evaluation it appears likely that ground fracturing and differential subsidence of ~2 ft along the southeast margin of the L Street graben initiated the failure (Hansen, 1965). Although eyewitnesses observed the building shaking violently during the earthquake, it was not until the graben began opening near the end of shaking that the building started to collapse. The fact that the two poured-concrete towers within the building, one for the stairway and one for the elevator, both tilted northward toward the graben as the building began to collapse from the northeast corner, supports this conclusion.

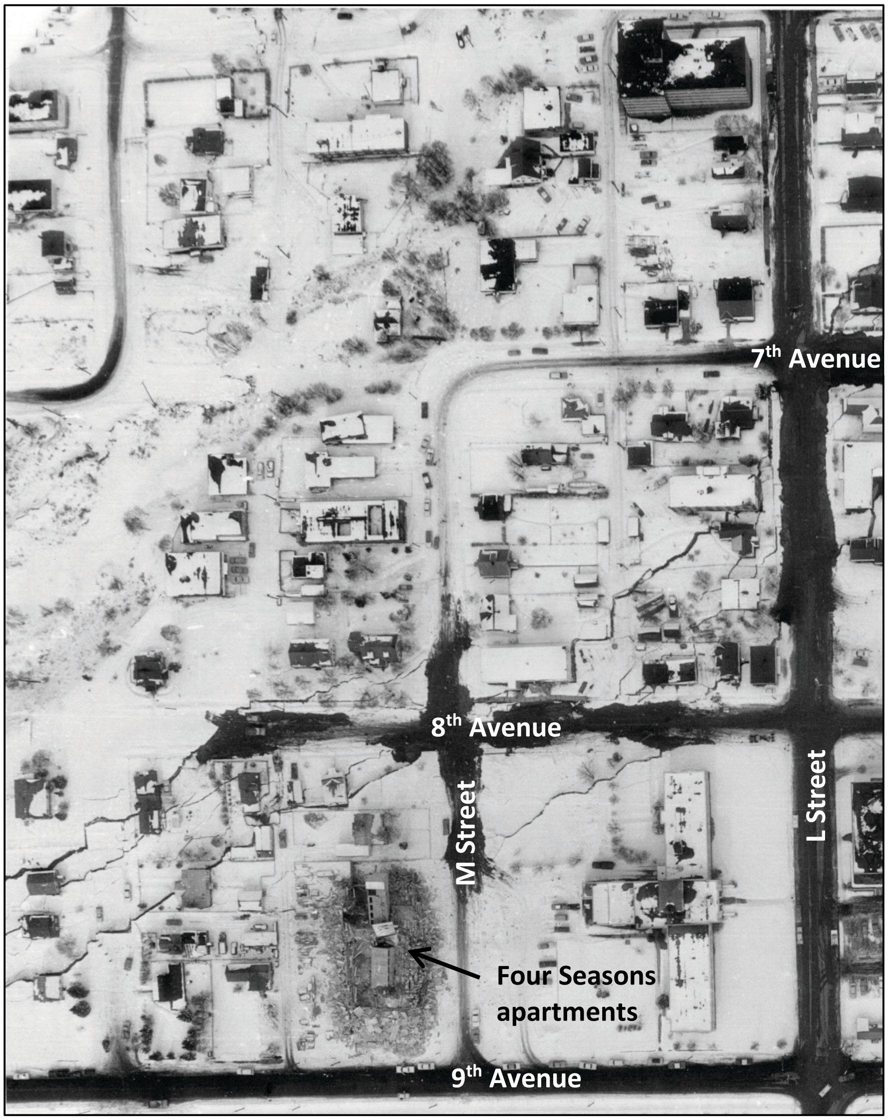


Figure A4a. Aerial view of the southern portion of the L Street slide and graben.

Figure A4b. Collapsed Four Seasons apartment building at 9th Avenue and M Street

The Fourth Avenue Landslide

The Fourth Avenue landslide involved 14 city blocks on the north side of downtown Anchorage, immediately east the Hilton Hotel (fig. A5). Incorporating a volume of more than 1.5 million m^3 of material, the Fourth Avenue slide devastated the area north of Fourth Avenue between E Street and Barrow Street (fig. A6). The landslide moved as a single large block, sliding on a subhorizontal basal shear surface. The north side of Fourth Avenue descended into the graben, which subsided 3 m in response to 5 m of horizontal movement. The translational sliding mechanism created zones of extensional ground cracking landward of the scarp, with fissures occurring up to 150 m to the south. The movement also created pressure ridges around Second Avenue at the toe of the slide.

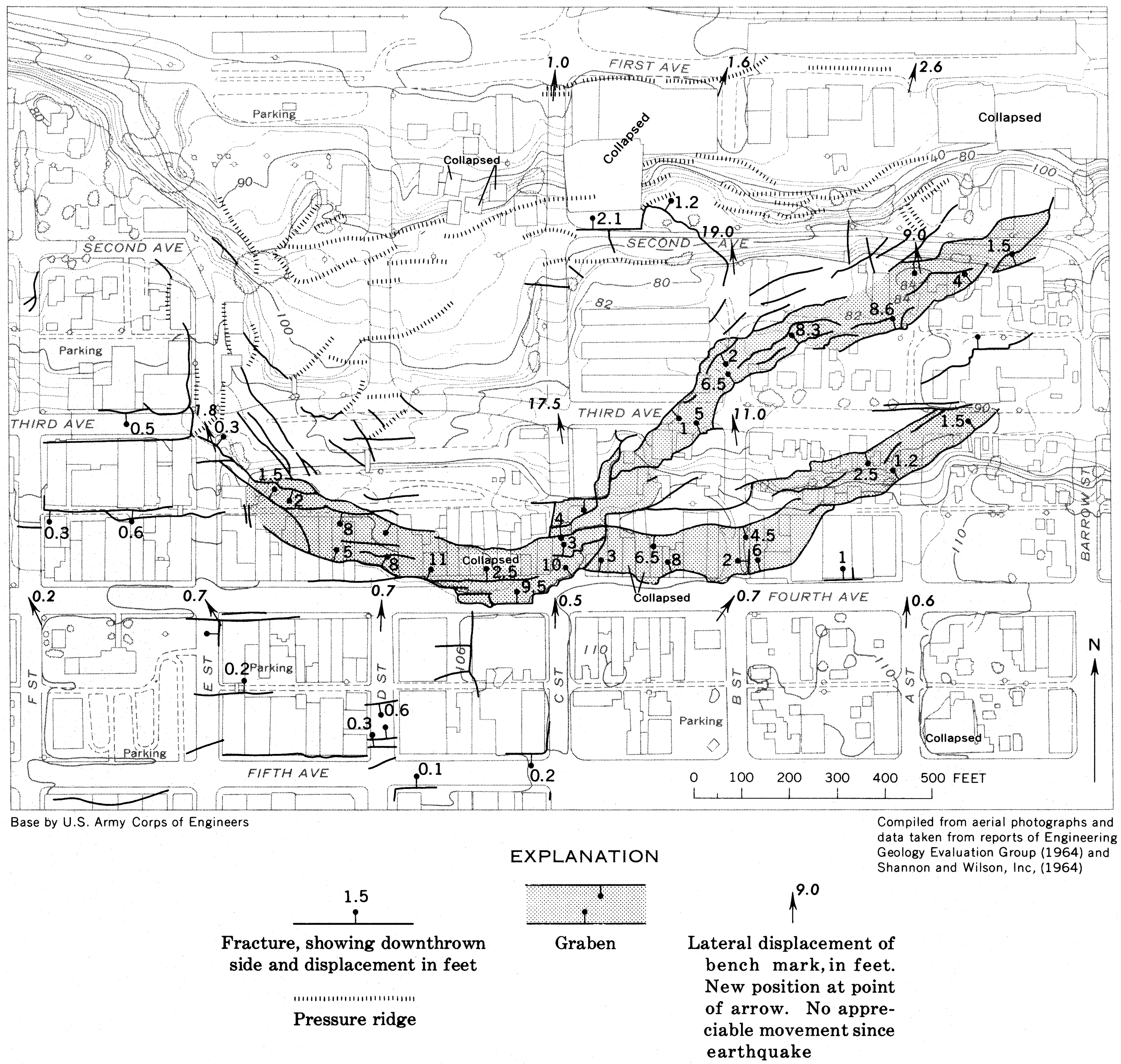


Figure A5. Fourth Avenue landslide.

Figure A6. Two views of the headwall scarp of the 4th Avenue landslide, looking east between C and D Streets.

Failure Mechanism

A layer of glacioestuarine sediments, the Bootlegger Cove Formation, underlies the center and west of Anchorage. Debate in the years following 1964 revolved around whether landsliding could be attributed to liquefaction of noncohesive sands and silts (e.g. Shannon and Wilson, Inc., 1964; Seed and Wilson, 1967) or sensitive clay failure within the Bootlegger Cove Formation (e.g. Hansen, 1965). This debate was not resolved until the 1980s, with the publication of comprehensive geotechnical investigations by Updike *et al.* (1988) supporting the latter hypothesis. The formation, incorporating silty clay and clayey sit, with thin beds of sand, diamicton, and occasional pebbles and cobbles, consists of three layers: stiff upper and lower facies, separated by sensitive intervening units. Sensitivity is a measure of the reduction in shear strength of a clay when remolded; samples from the middle unit of the Bootlegger Cove Formation exhibit very low strengths and high sensitivity ratios. During long-duration shaking, the flocculated sedimentary fabric collapsed, allowing platy clay particles to reorient, releasing pore fluid and enabling failure (Updike *et al.*, 1988). With the shear resistance of the sensitive clays reduced by shaking during the earthquake, gravity provided the propelling mechanism and the landslides continued until resistance from the toe or shear resistance of the clay exceeded the gravitational component on the shear surface (fig. A7).

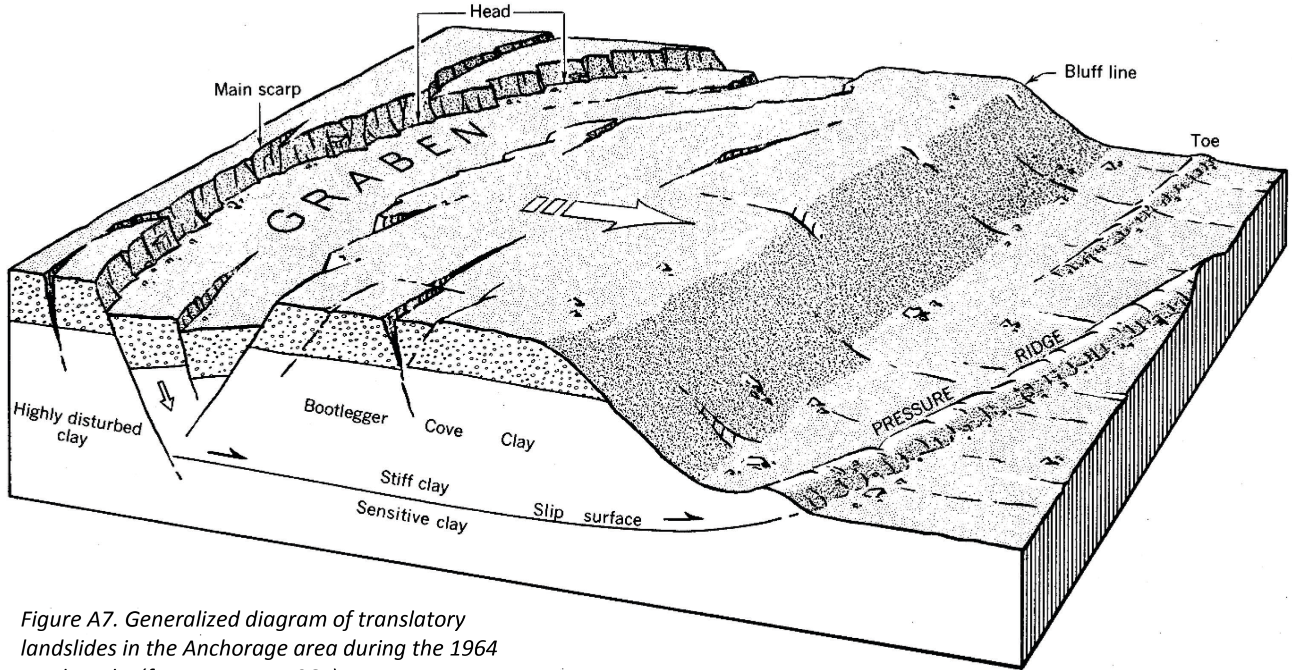


Figure A7. Generalized diagram of translatory landslides in the Anchorage area during the 1964 earthquake (from Hansen, 1965).

The Bootlegger Cove Formation is 40–65 m thick beneath Anchorage, with the upper part dated at 15,870 cal yr BP (Schmoll *et al.*, 1972; Reger *et al.*, 1995). The high sensitivity ratios may derive in part from the leaching of salts following the postglacial uplift of clays deposited in marine settings (Kerr and Drew, 1968).

Stability and Future Landslide Susceptibility

The landslides at Turnagain Heights, Fourth Avenue, Government Hill, L Street, and Native Hospital demonstrated that seismically-triggered landslides are a major geohazard in the Anchorage area. Quantifying and mapping the potential for further large translational landslides is consequently of strategic importance for planning, zoning, and emergency response preparation. Such activities rely on hazard maps produced by Harding-Lawson Associates (1979), recently updated by Jibson and Michael (2009).

The failure mechanism responsible for the larger Anchorage-area landslides requires long-duration shaking, implying that large translational block slides generally occur only during large subduction earthquakes. Shallow crustal earthquakes, such as those generated along the Castle Mountain and Border Ranges faults, are unlikely to trigger failures of this kind (Jibson and Michael, 2009). Barnhardt and Kayen (2000), however, suggest the substantial drop in shear resistance resulting from straining during megathrust earthquakes persists for decades to centuries, leaving soils vulnerable to further failures.

GIRDWOOD MARSH PALEOSEISMOLOGY

Analysis of sediment sequences beneath the tidal marsh at Girdwood, Alaska (see cover photo), shows seven great earthquakes recorded in the past 4,000 yrs, including the M_w 9.2 earthquake of March 27, 1964. The key theme that arises from studies of crustal deformation for the southcentral Alaska earthquake zone over timescales of the last few millennia is one of temporal and spatial variability. Quantitative data show both temporal and spatial similarities and differences for different earthquake cycles. There is not a fixed recurrence interval. The shortest interval is between ~180 and 720 yrs. The longest interval is 790–920 yrs, which is between the penultimate and the 1964 earthquakes. Estimates of subsidence at Girdwood for each earthquake show values similar to or less than that recorded in 1964. Similarities between each earthquake cycle leads to a model for the Girdwood area with coseismic subsidence followed by rapid postseismic uplift in the decades after the earthquake. This merges into centuries of slower interseismic uplift before a period of pre-seismic subsidence. Correlations with sites beyond Girdwood (fig. G1) reveal regional-scale temporal variability and spatial heterogeneity in the crustal deformation processes.

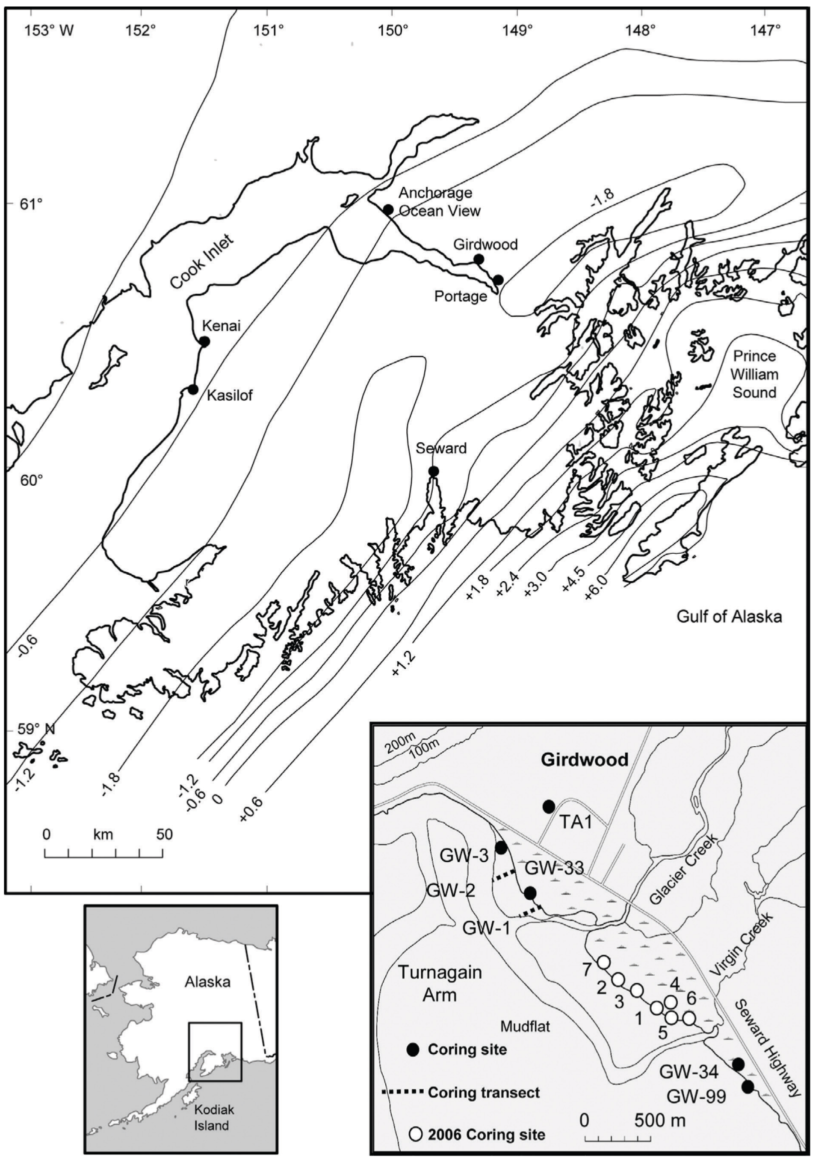


Figure G1. Locations of sample sites around Cook Inlet, detail of Girdwood sampling sites, and regional setting. Contours (m) show vertical deformation caused by the A.D. 1964 earthquake (after Plafker, 1969). Contours hide many local-scale variations, including local subsidence caused by sediment compaction.

Numerous earthquake deformation cycle models exist (e.g., Thatcher, 1984; Nelson *et al.*, 1996; Shennan *et al.*, 1999). These describe periods of crustal deformation associated with great plate boundary earthquakes and intervening periods (fig. G2). Crustal deformation, through land surface elevation change, can be recorded as relative sea level change in marsh and tidal flat sediments. For a site in south-central Alaska undergoing coseismic subsidence (sudden relative sea-level rise), the models propose rapid postseismic rebound (relative sea-level fall) in the decades after the earthquake, followed by centuries of slower interseismic uplift (relative sea-level fall). For upper Cook Inlet specifically, Shennan *et al.* (1999) propose a fourth-stage, relative sea-level rise for a short period before a great earthquake (Bourgeois, 2006).

Girdwood is probably the classic site in Alaska for recording multiple cycles of coseismic subsidence. Karlstrom (1964) provides one of the earliest descriptions and radiocarbon dates of the upper part of the sequence, but this was written before the 1964 earthquake during which there was ~1.5 m regional subsidence and up to ~0.9 m additional local subsidence of unconsolidated sediment (Plafker *et al.*, 1969). Combellick (1991) provided much of the impetus for later research, including a key analogue used by Atwater (1987) in his seminal paper on the seismic hazard to the northwest coast of the Lower 48. Combellick (1993) provided radiocarbon dates from tree stumps rooted in peat ~1 m below the 1964 peat–silt contact at the east end of the Girdwood marsh, establishing the ~900 yr BP age for the penultimate event (fig. G3).

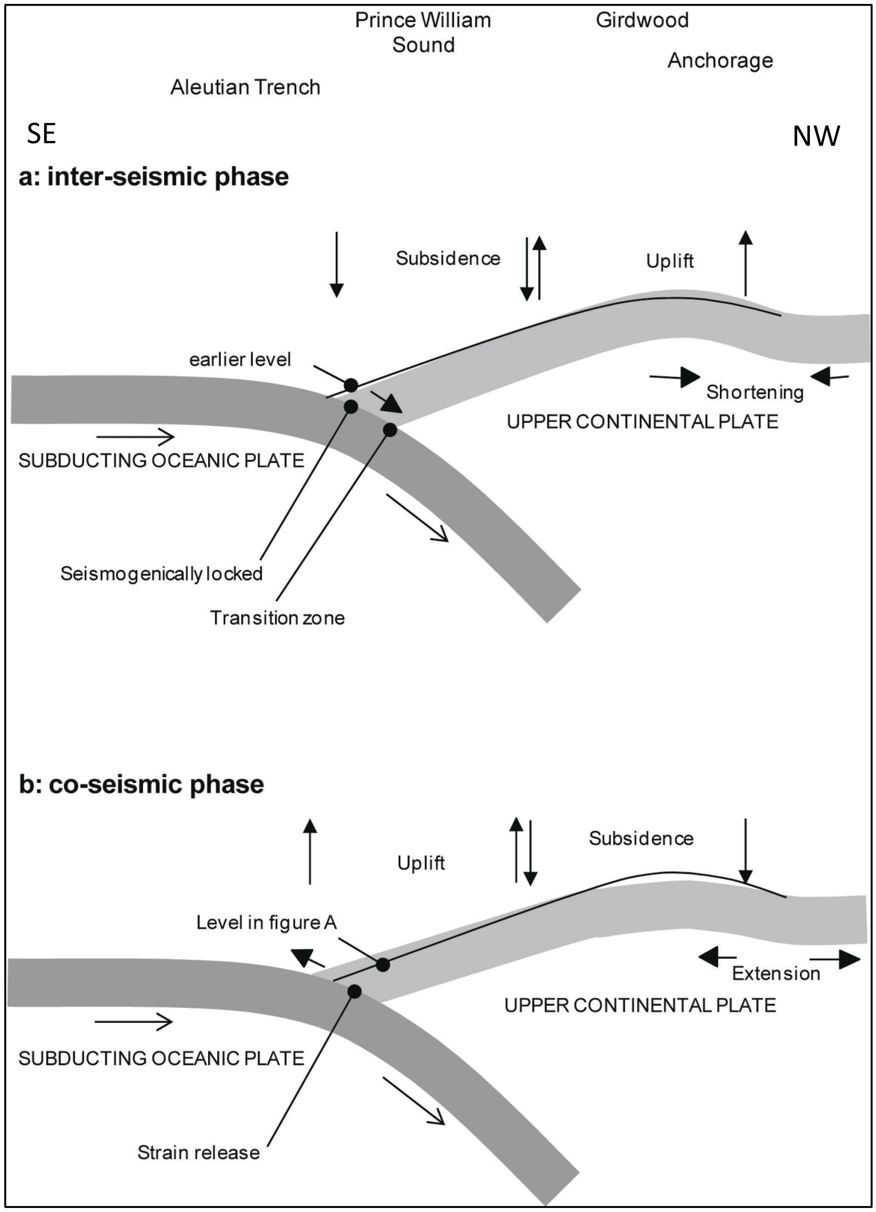


Figure G2. Schematic diagrams showing the pattern of (a) interseismic and (b) coseismic deformation associated with a subduction zone earthquake during an earthquake deformation cycle. Adapted from Nelson et al. *(1996) to reflect the spatial pattern of coseismic deformation during the A.D. 1964 earthquake in Alaska along a section from Anchorage to the Aleutian Trench.*

Figure G3. One of many tree stumps rooted in peat ~1 m beneath the 1964 peat-silt contact.

Late Holocene diatom stratigraphy at Girdwood

Sediment sequences beneath the present tidal marsh contain a record of potential earthquake cycles (fig. G4), with up to ten peat-mud couplets. Diatom analyses indicate no elevation change associated with couplets Z, B and C, and we do not attribute these to be the result of coseismic subsidence. For all couplets, the upper stratigraphic boundary of each peat is sharp, usually < 2 mm.

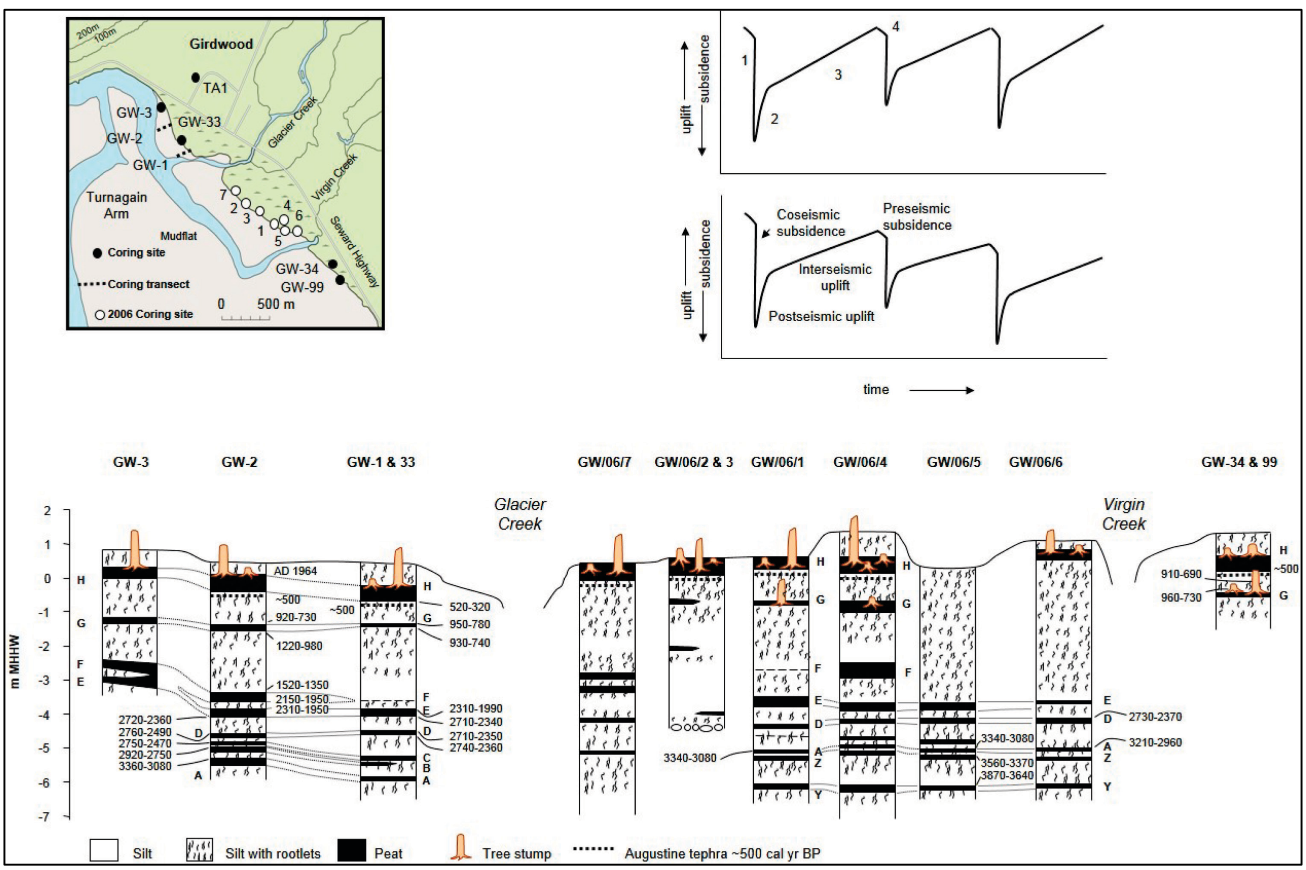


Figure G4. Coring sites on the Girdwood marsh (top left), earthquake deformation cycle (top right), and core stratigraphy with 95% probability age ranges (bottom).

Accumulation of peat G, ~1,100 cal yr BP, reflects interseismic strain accumulation at the plate boundary, causing gradual relative land uplift. In the upper 3 cm of peat G, diatom assemblages show land subsidence. The boundary between peat G and overlying silt represents coseismic subsidence during the penultimate great earthquake. Evidence of rapid marsh submergence following subsidence includes a buried peat layer with a sharp upper boundary that can be traced widely across the marsh and intertidal diatoms dominant in the overlying silt.

Interseismic recovery followed, with relative land uplift allowing development of peat H ~450 BP. Within peat H, which was submerged following the 1964 great earthquake, a temporary increase in silt between 82 and 91 cm coincides with a temporary decrease in salt-intolerant diatoms and an increase in intertidal diatoms. A similar oscillation in diatom stratigraphy at Kenai indicates a regional rather than local-scale process. We suggest this is probably Little Ice Age expansion of ice fields, causing glacioisostatic loading and deformation of the Earth's crust. Diatom assemblages indicate relative land subsidence in the upper few centimeters of peat H followed by rapid subsidence in AD 1964. The diatom estimate is close to that observed (Plafker *et al.*, 1969).

Evidence for preseismic sea-level change

Almost all the peat-mud couplets that record great earthquakes at Girwood have a precursor: Diatom or pollen evidence of preseismic land subsidence in contrast to relative sea-level fall through the preceding interseismic period of each earthquake cycle. Of 24 couplets analyzed, from Girdwood, Ocean View, Kenai and Kasilof only four appear to be influenced by mixing of sediment and diatoms from overlying silt into the peat. Many couplets show preseismic elevation change smaller than the error term but the evidence suggests that changes are not random. Trends indicating subsidence appear in lithostratigraphy, and in biostratigraphy and all the quantitative estimates are negative (indicating land subsidence), rather than a mixture of positive and negative values.

Independent observations of relative land-level changes before 1964 offer limited support for preseismic subsidence. Storm tides that first flooded the marsh surface at Girdwood after AD 1953 deposited thin surface layers of silt that became progressively thicker each year thereafter (Karlstrom, 1964). This date agrees with ^{137}Cs profiles and the start of the preseismic subsidence identified from the microfossil data at both Girdwood and Kenai.

PORTAGE AND THE AREA OF MAXIMUM COSEISMIC SUBMERGENCE

by Ian Shennan and Rod Combellick

Portage lies along the axis of maximum coseismic subsidence in 1964. Following ~2.5 m subsidence (1.5 m tectonic subsidence and ~1.0 m due to ground shaking and consolidation of unconsolidated sediments), tidal flooding (fig. P1) and high sediment input rapidly buried and preserved the 1964 marsh surface, with much of the accommodation space infilled in the next 10 yrs (Atwater *et al.*, 2001; Ovenshine *et al.*, 1976). Rapid sedimentation over longer timescales, more than 90 m during the Holocene (Bartsch-Winkler *et al.*, 1983), means that records longer than a few hundred years require cores through thick, unconsolidated sediment sequences. As a result, studies of multiple earthquake cycles at Portage are limited to cores collected with motorized drilling rigs (Combellick, 1991, 1993; Combellick and Reger, 1994). Despite the early interest, it proved difficult to reliably correlate the Holocene paleoseismic record from Portage with those from other locations.

Figure P1. Aerial view of Portage during high tide following the 1964 earthquake.

Late Holocene earthquake record at Portage

In 1985, hollow-stem auger drilling at two sites in Turnagain Arm, one at Girdwood and one at Portage, confirmed the presence of multiple organic layers interbedded with tidal clastic deposits below the 1964 soil horizon (Combellick, 1991). The split-spoon samples were not continuous and the radiocarbon ages of the abrupt contacts correlated poorly with those from other sites in the region (Bartsch-Winkler and Schmoll, 1987). A second core at Portage, and another one at Girdwood, were commissioned in 1988, using a motorized drill rig capable of recovering a more continuous sequence (Combellick, 1991). These cores had excellent recovery and provided more than 16 m of undisturbed sediment at Portage. Fine laminations in many of the clastic horizons were very well preserved, suggesting intertidal sedimentation, and supported the original hypothesis of multiple cycles of coseismic subsidence and gradual interseismic recovery, superimposed upon glacio-isostatic relative sea-level change. But the radiocarbon chronologies from the 1988 cores at Girdwood and Portage failed to resolve the discrepancies between the sites, with no clear correlation of events or the number of events indicating coseismic submergence (Combellick, 1991, 1993; Combellick and Reger, 1994).

It was thought that the 1988 Portage core had been lost or destroyed, but it was found in 2008, repackaged, and transferred to the Alaska Division of Geological & Geophysical Surveys' Geologic Materials Center for archiving. Initial analyses revealed the samples to be in good condition, and we undertook sampling for diatom and AMS radiocarbon dating. To preserve these important cores for future research we limited the number of samples and volume of sediment taken to address the key hypotheses relating to the identification of coseismic subsidence and the chronology of events (Shennan *et al.*, in press). This approach leaves the whole of the 16 m core available for future analyses.

We recorded six distinct organic layers in the archive core (fig. P2), each with a clear, abrupt, upper contact and directly comparable to those originally described. We could not identify a layer of disseminated fine organic material recorded in the original core at almost 16 m depth and saw only one, rather than two layers of sedge leaf and stem fragments in the upper 3 m.

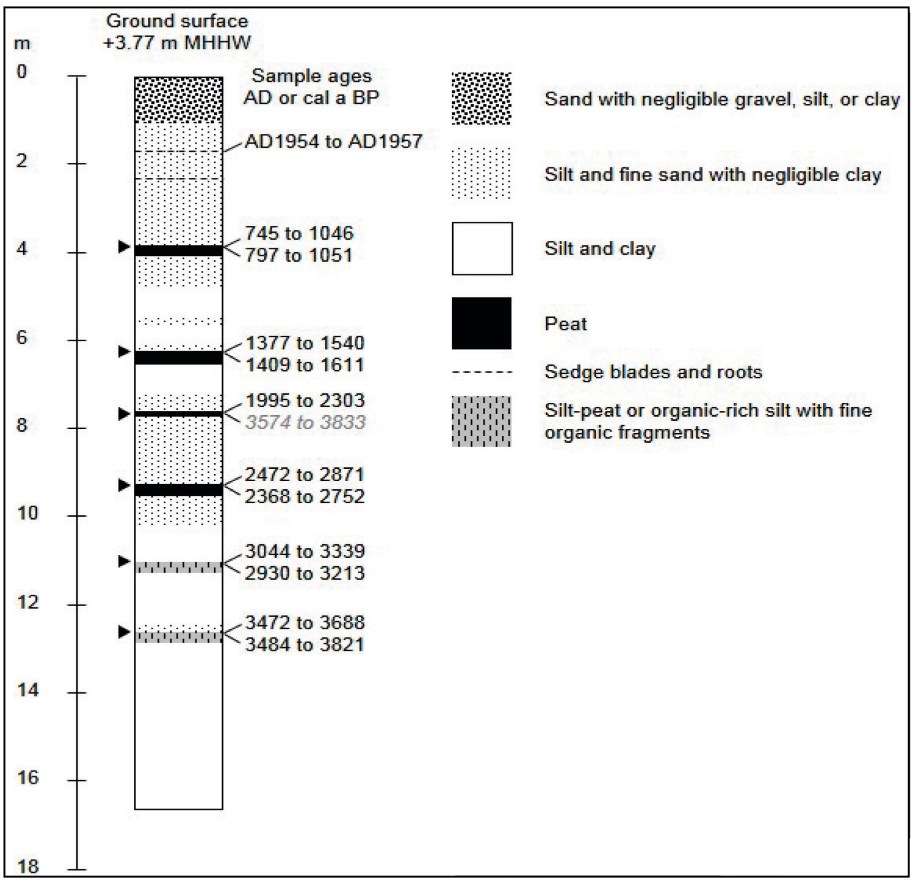


Figure P2. Submergence of the marshes in 1964 is indicated in the Portage core by interlayered brown-gray silt and silty fine sand with disseminated fine organic material, probably sedge blades and roots. A sample of these gave a modern radiocarbon age, calibrated as AD 1954 to 1957. Other locations at Portage, including intertidal outcrops, record the submerged 1964 marsh surface as a 1–2 cm organic mud, with rooted plant remains (Atwater et al.*, 2001; Combellick, 1991), rather than a thick peat horizon as seen at Girdwood, Bird Point, and Anchorage. Four of the six couplets show strong evidence of sudden submergence, with sharp peat-silt contacts, and estimates of vertical change in the range of 1.9 to 2.2 ±0.9 m (95 percent limits) which together are consistent with rapid subsidence of high marsh or freshwater marsh to intertidal flat (see fig. P3 for an example from 924 cm). The lowest two couplets suggest slightly less submergence (Shennan et al., in press).*

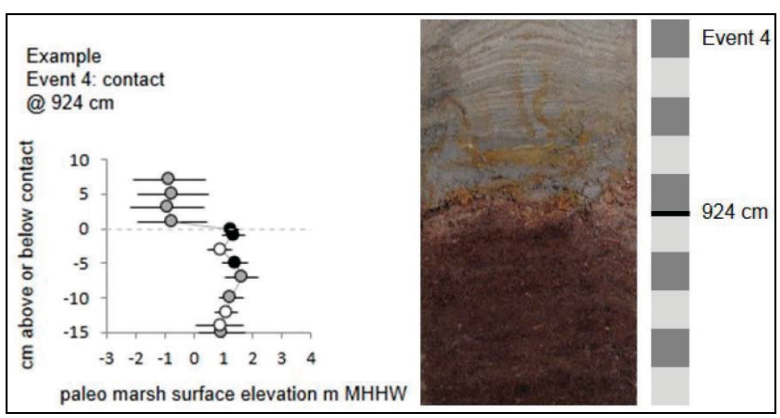
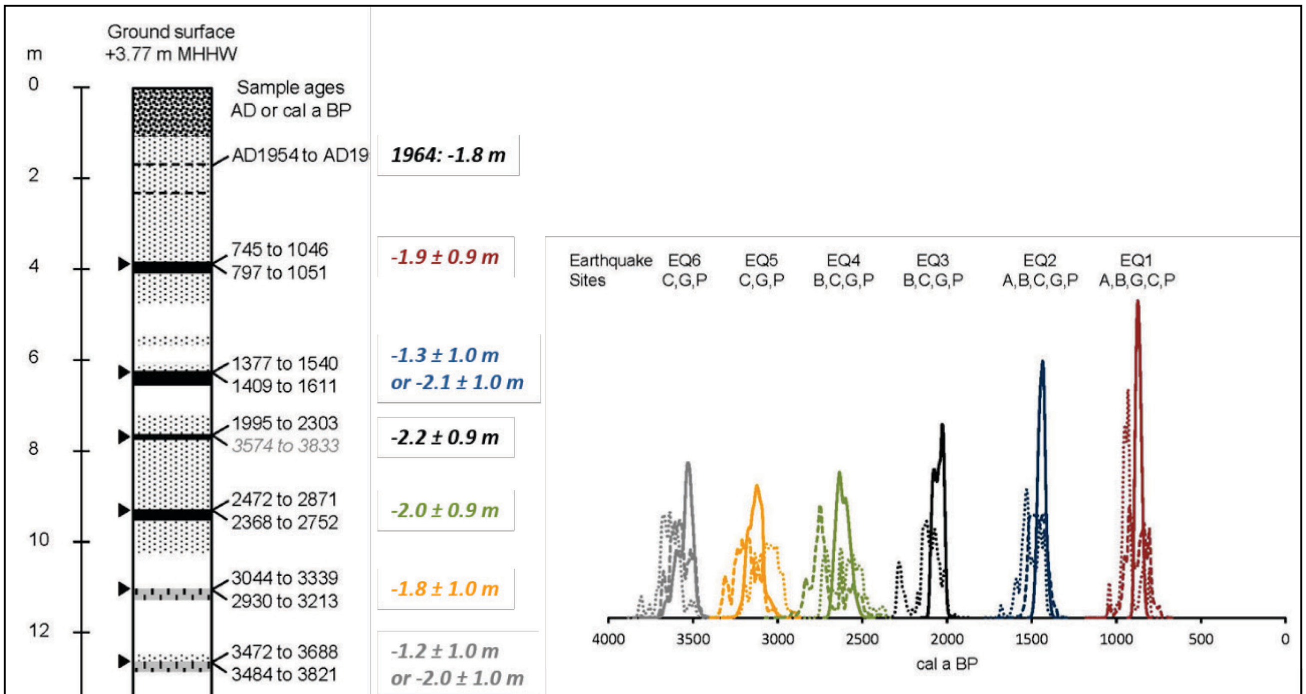


Figure P3. Example of a sharp peat–silt contact at 924 cm in the Portage core (see fig. P2) and associated diatom evidence of sudden submergence.

The chronology of great earthquakes across multiple sites

We can compare the new dates from Portage with a chronology derived from the analysis of all sites across the region (Shennan *et al.*, 2014) using a Bayesian modeling approach (Lienkaemper and Bronk Ramsey, 2009) of all radiocarbon ages that provide minimum or maximum ages to constrain events that may indicate coseismic subsidence or uplift. The probability density functions of the modeled ages reflect the better constraints on the more recent earthquakes (fig. P4).

The oldest three events are recorded only at Copper River Delta (Carver and Plafker, 2008), with the younger ones dated at a minimum of two locations, one site indicating uplift and at least one indicating subsidence. When we overlay the ages obtained from the Portage core, which are not included in the regional model and therefore independent for this analysis, we see that they all fit within the joint probability ranges for earth-quakes recorded elsewhere.

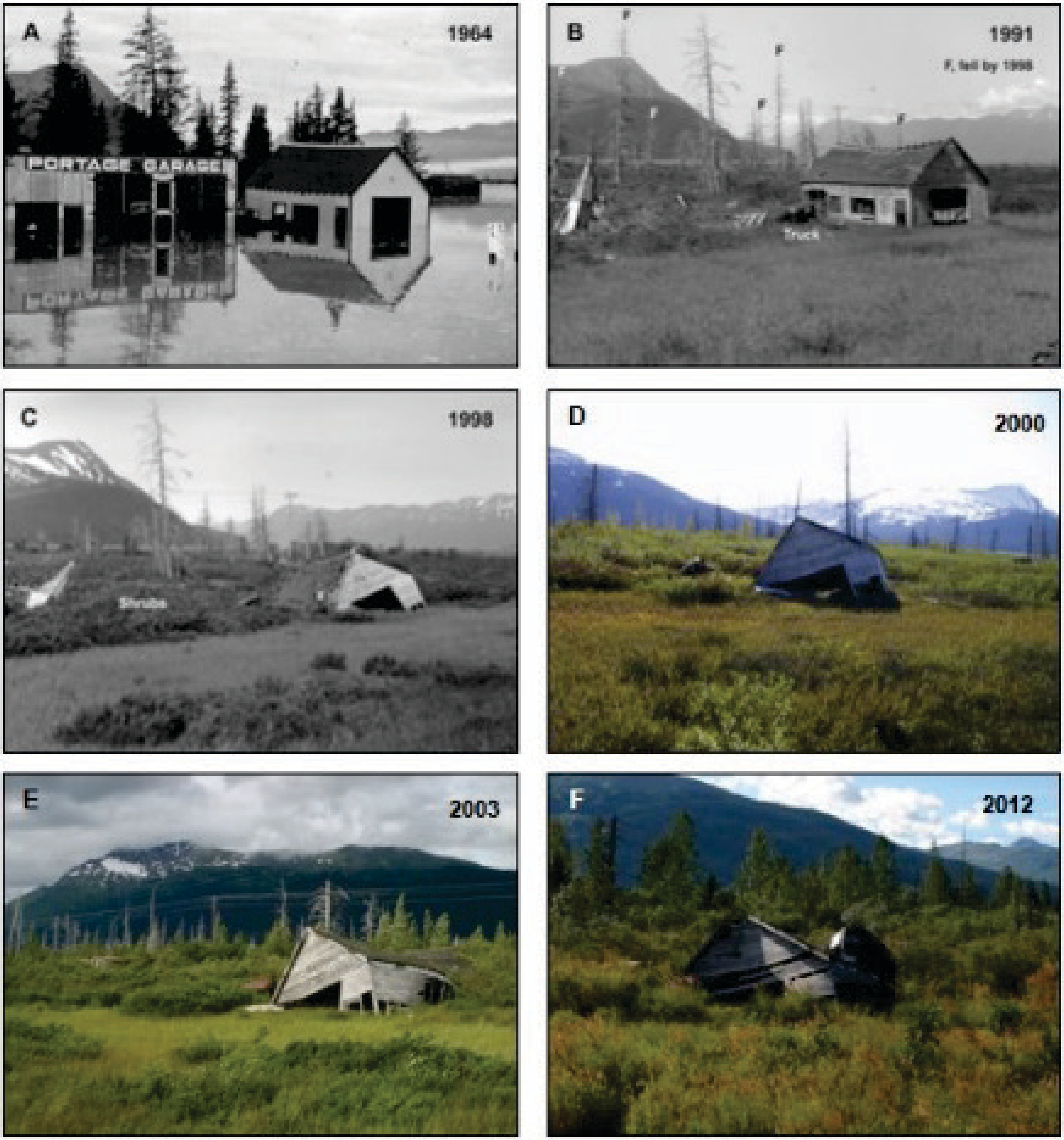


	EQ9	EQ8	EQ7	EQ6	EQ5	EQ4	EQ3	EQ2	EQ1	1964
Copper River Delta	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Portage				☑	☑	☑	☑	☑	☑	☑
Girdwood				☑	☑	☑	☑	☑	☑	☑
Bird Point						☑	☑	☑	☑	☑
Anchorage								☑	☑	☑

Figure P4. Portage core log showing estimated subsidence and regional correlation with other evidence of great earthquakes in the 1964 rupture zone, including coseismic uplift (Copper River Delta) and coseismic subsidence (all others). Site codes: A=Anchorage; B=Bird Point; C=Copper River Delta; G=Girdwood; P=Portage. In the correlation, Portage samples are dashed.

Portage garage

The dilapidated garage at Portage is an iconic reminder of the 1964 earthquake and the rapid post-seismic changes in a dynamic marsh environment. Observations post 1964 indicate ~0.3 m land uplift by 1975 (Brown *et al.*, 1977) and 0.7 m by 1995–2000 (Freymueller *et al.*, 2008). The photo mosaic (fig. P5) summarizes the recolonization of the tidal flat by freshwater vegetation.



Portage area liquefaction

(The following paragraph is excerpted and modified from Kachadoorian, Reuben, 1968, Effects of the earthquake of March 27, 1964, on the Alaska highway system: U.S. Geological Survey Professional Paper 545-C, 66 p.)

The Portage area was also the site of spectacular damage to the highway and railroad systems from lateral spreading and fracturing caused by earthquake-induced liquefaction. The extent and nature of the fractures depended upon the type and thickness of the sediments and the depth to the water table. Fractures were conspicuous in swamp deposits and in thick accumulations of silt and sand, especially if the water table was within 6 ft of the ground surface. In general, the closer the water table was to the ground surface, the more extensive and varied were the fracture patterns. Near Portage, the Seward Highway passes over silt and sand, and the water table is within 2 ft of the ground surface. The fractures there were very extensive (fig. P6).

Figure P6. Longitudinal centerline fracture in the Seward Highway near Portage

Three decades after the 1964 earthquake, Walsh *et al.* (1995) observed 150 clastic dikes and sills in channel banks along the lower Portage Creek and Twentymile River that they attributed to liquefaction during the earthquake. This area is on the axis of maximum coseismic subsidence, which resulted in deposition of as much as 2 m of intertidal silt on the pre-earthquake ground surface. Lateral migration of the stream channels has exhumed many clastic dikes, most of which intersect the pre-earthquake surface through breaks in the 1964 soil, confirming their association with that event. The dikes probably intruded ground cracks mapped soon after the event. They ranged in width from 0.5 cm to 1.9 m and consisted predominantly of medium to coarse sand, although 27 dikes contained appreciable pebble-size gravel. Sand boils up to 6 cm thick rest on 1–2 cm of silt overlying the 1964 soil (fig. P7).

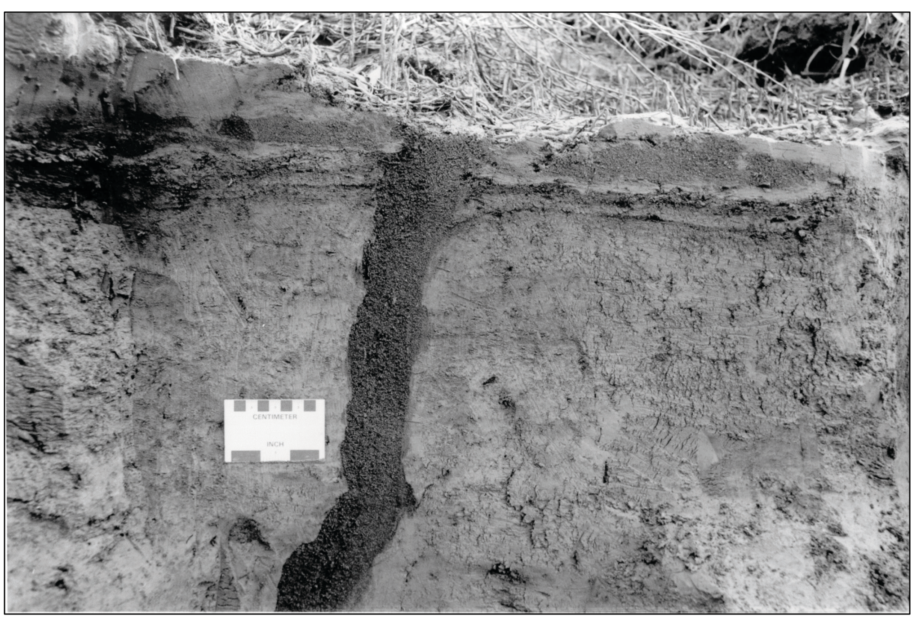


Figure P7. Clastic dike and sand boil along the south channel of Portage Creek.

EARTHQUAKE AND TSUNAMI HAZARDS IN WHITTIER

The port of Whittier was constructed under the supervision of the Corps of Engineers in 1942-43 to provide an all-weather terminal for the Alaska Railroad. During World War II, Whittier and Seward served as the two all-weather railroad ports that safeguarded the flow of military supplies, equipment, and personnel from tide-water to Anchorage and Fairbanks. The town of Whittier was owned and operated by the U.S. Government, specifically by the Alaska Railroad of the Department of the Interior and by the U.S. Army of the Department of Defense. Some of the land had been leased to private enterprise. The City of Whittier was incorporated in 1969. Today, fewer than 300 people reside in the town, which supports the Alaska State Ferry, the Alaska Railroad, freight barge, commercial fishing, the Whittier Harbor, recreation, and tourism with an annual visiting population of more than 700,000. Many of the buildings are now under private ownership.

Whittier was hard hit by the earthquake and tsunami of March 27, 1964 (fig. W1). Tragically, 13 persons were lost during the earthquake. At the time, only 70 people were living at Whittier. The official 1960 census lists a population of 800; however, this figure included military personnel who were subsequently transferred when the Army closed its Whittier operation. Only one body was recovered; the remaining 12 persons were presumed dead. In addition, the earthquake destroyed or made inoperable a major part of the port facilities. Total damage to the Federal and privately owned facilities at Whittier was in excess of $5 million.

Figure W1. Tsunami damage in Whittier.

The loss of the Whittier port facilities, coupled with destruction of those at both Seward and Valdez, left Alaska without any all-weather port for unloading supplies for movement either by rail or highway to the metropolitan areas of Anchorage and Fairbanks.

Seismic motion lasted only 2½–3 minutes, but when it stopped the Whittier waterfront was in shambles and the port facilities were inoperable. Damage was caused by (1) a 5.3-ft subsidence of the landmass, sufficient to put some of the developed land under water during high tides, (2) seismic shock, (3) fracturing of fill and unconsolidated sediments, (4) compaction of fill and unconsolidated deposits, (5) submarine landslides that generated waves that destroyed part of the Alaska Railroad road bed and other property, (6) at least two, but probably three, waves generated by landslides, which completely wrecked the buildings of two lumber companies, the stub pier, the small-boat harbor, the car-barge slip dock, and several homes, and (7) fire that destroyed the fuel-storage tanks at the Whittier waterfront. Many buildings and other facilities were totally wrecked, others were damaged to lesser degrees. For example, the 14-story reinforced concrete Hodge Building, which rests upon at least 44 ft of sandy gravel, was moderately damaged by seismic shock, but the six-story reinforced-concrete Buckner Building, which rests on bedrock, was only slightly damaged.

Seismic damage

In the downtown area of Whittier away from the waterfront, most of the damage was caused by seismic shock. In the area inundated by waves, seismic shock severely damaged one of the slip towers of the car-barge slip dock, part of the marginal wharf, one of the storage tanks at the U.S. Army tank farm, and the highway and railroad bridges crossing Whittier Creek. Beyond the inundated zone there was moderate damage to the Hodge Building, the composite shop, and part of the station storage warehouse**.** The Buckner Building, gymnasium, fire station, telephone building, ACS (Alaska Communication System) building, powerhouse, and the railroad bridge near the airstrip were slightly damaged.

The Hodge Building (now Begich Towers), a reinforced-concrete 14-story structure 265 ft long and 50 and 110 ft wide (fig. W2)**,** rests on at least 44 ft of unconsolidated sand and gravel. The building was constructed as three structural monolithic units connected by 8-inch expansion joints. In the corridors, metal jumper plates span the 8-inch joints; on the exterior, the joints were secured by a weather seal. The long dimension of the building was parallel to the predominant east–west direction of the seismic motion; the expansion joints were perpendicular to the motion. During the earthquake the individual units banged against each other, the weather seals popped out, and the jumper plates were curled. Damage to the structural connections (weather seals and jumper plates) was progressively more intense upward in the structure owing to the larger horizontal component of movement. Jumpers on the top floor were shortened 4 inches by curling, whereas on the third floor they curled only a quarter of an inch. The interior partition walls of the Hodge Building were constructed of concrete blocks. Damage to the walls was also greater in the upper floors. The walls on the 13th and 14th floors either collapsed or were cracked. On the fourth floor the blocks were loosened, except near the expansion joints where some of the blocks were dislodged. The exterior of the building was not substantially damaged, even where the units banged against each other.

Figure W2. Fourteen-story Begich Towers (formerly Hodge Building) in Whittier.

The largest building in Whittier, probably the largest in Alaska at the time of the earthquake, is the long-abandoned Buckner Building (fig. W3). It is a six-story reinforced-concrete structure about 500 ft long and 50–150 ft wide. The long dimension of the structure runs northeast-southwest, oblique to the seismic motion of the earthquake. The building rests on bedrock and did not receive any significant structural damage. The steam powerhouse near the Alaska Railroad depot also rests on bedrock and was not damaged by seismic motion.

Figure W3. Buckner building in Whittier.

Landslide-generated waves

At least three waves were observed during the earthquake or immediately after it. A minute after the shaking began, a glassy wave, containing no debris, apparently no suspended sediment, and traces of turbulence, rose to 7.6 m (25 ft) above sea level, which at that time was 0.3 m (1 ft) above the mean lower low water (MLLW) level. The wave rose rapidly and immediately receded. Then, a minute to a minute and one-half later, a muddy 12.2-m (40-ft)-high breaking wave inundated the port facilities and ran up to an elevation of 10.7 m (35 ft), approximately 2.7 m (9 ft) above the ground level at the Alaska Railroad depot. The third wave hit the town approximately 45 seconds after the second one, and was a breaking wave and similar in nature to the second wave, except its amplitude was smaller, reaching an elevation of 9.2 m (30 ft) near the depot. There are no eyewitnesses to waves that struck the shore at other locations along Passage Canal. However, the inundation line was clearly evident from scattered debris and marks on fresh snow. The highest location that was inundated by waves was 31.7 m (104 ft) above mean sea level (MSL), along the northern shore of Passage Canal. Near the airstrip, the wave topped 6.1 m (20 ft) altitude, while one-quarter mile north the inundation line was at 25 m (82 ft) elevation. In Whittier, the maximum altitude reached by the wave was 13.1 m (43 ft) at the small boat harbor northeast of the Alaska Railroad depot. On the waterfront area waves reached a height of 7.9 m (26 ft).

Unlike residents of Valdez, Cordova, and Seward, who observed high waves late in the evening, Whittier residents noticed no 'strange' waves in Passage Canal other than the three that struck during and immediately after the earthquake. The tectonic tsunami, which should have arrived in Whittier no later than one hour after the earthquake, was probably not observed and its damage to the port of Whittier remains unknown.

Although it is difficult to determine the source of the first observed ‘glassy’ wave, there is general agreement that the second and third waves were landslide generated. The landslides occurred in delta sediments at the head of Passage Canal, in delta sediments and fill at the Whittier waterfront, and possibly in a submarine lateral moraine along the northern shore of Passage Canal (fig. W4). It is highly probable that these landslides did not occur simultaneously, but rather at two or three different times during the earthquake.

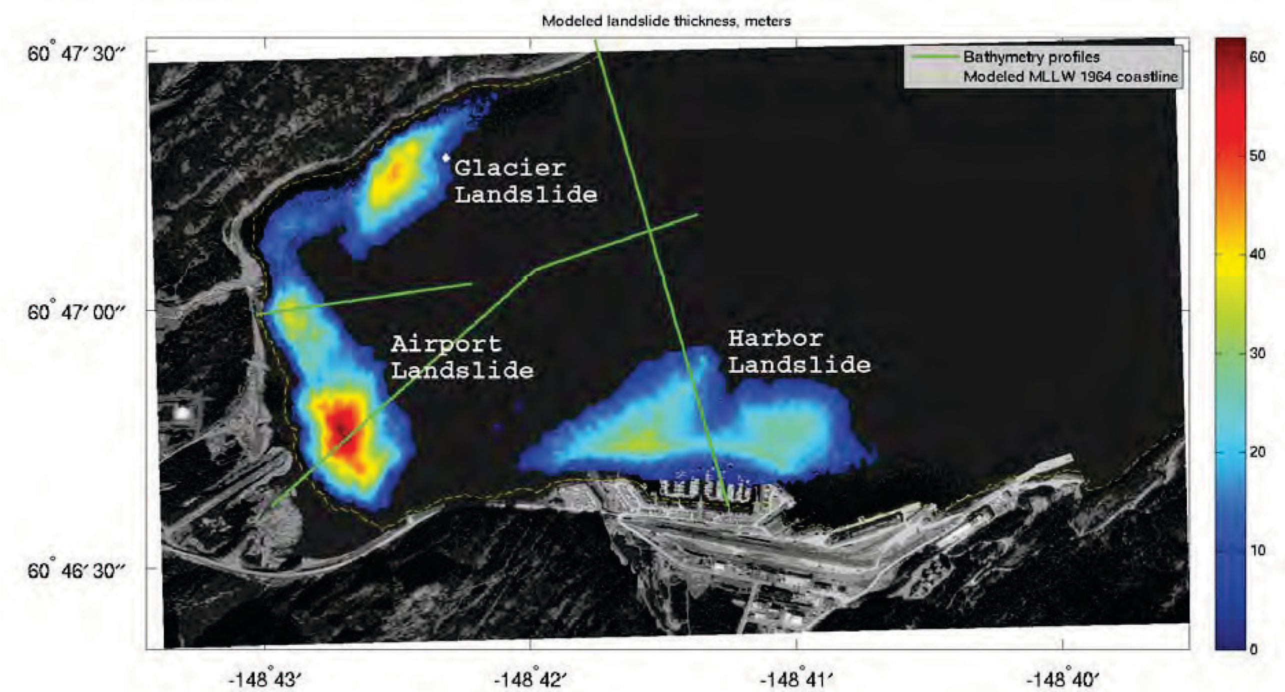


Figure W4. Three submarine slide complexes in upper Passage Canal that were the major contributors to the locally generated waves that inundated the city of Whittier.

Tsunami inundation modeling for Whittier

To estimate future tsunami hazard in Whittier, Nicolsky *et al.* (2011) numerically modeled the run-up extent and depth of inundation due to tsunami waves generated from earthquake and landslide sources. Tsunami scenarios included a repeat of the tsunami triggered by the 1964 Great Alaska Earthquake, as well as tsunami waves generated by a hypothetically extended 1964 rupture, a hypothetical Cascadia megathrust earthquake, hypothetical earthquakes in Prince William Sound, and Kodiak asperities of the 1964 rupture. They also modeled multiple scenarios involving underwater landslides in Passage Canal, occurring both separately and simultaneously. A total of 13 scenarios were modeled. All scenarios assume the tsunamis are generated at mean higher high water (MHHW) and take into account the 5.3 ft (1.8 m) of subsidence that occurred in 1964 as well as the modern digital elevation model and configuration of major structures.

Figure W5 shows the maximum estimated composite potential inundation extent due to tectonic and landslide-generated waves for all scenarios, the maximum composite flow depths over dry land, and the inundation extent in 1964.

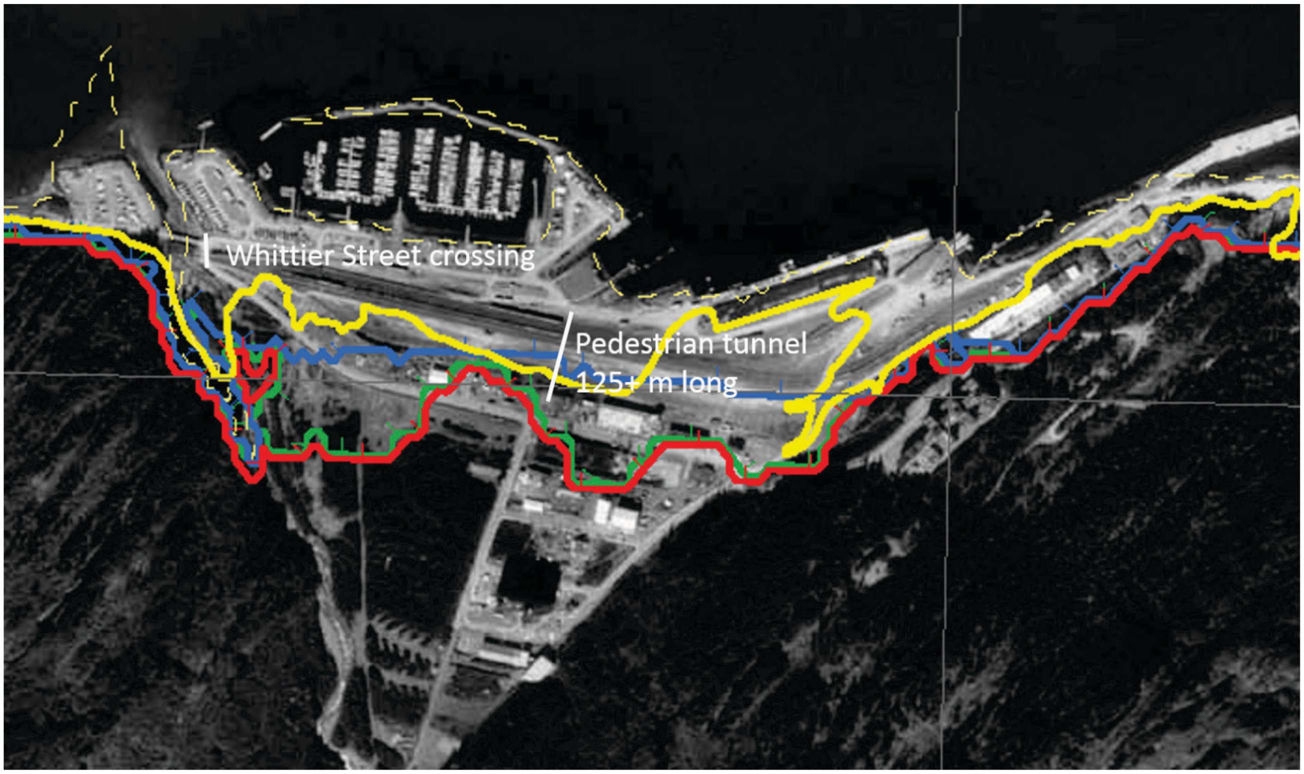


Figure W5. Maximum combined inundation extent and flow depths over dry land from all 13 modeled scenarios. Red=maximum run-up extent; blue=2.0 m (6.6 ft, or just above head height) flow depth; green=0.5 m (1.6 ft, or knee height) flow depth; yellow=observed 1964 inundation limit; dashed yellow line=present-day MHHW shoreline.

Tsunami Evacuation

A significant public-safety issue for Whittier is evacuation of the waterfront area in the event of a tsunami, particularly during summer when hundreds of tourists may be visiting at any one time, most of whom remain along the waterfront, either in the boat harbor, visiting shops near the boat harbor, at the cruise ship dock (upper left of fig. 15, postdating the aerial photo), or waiting for a state ferry. The railroad loading yard, which extends the full width of the town, prevents safe pedestrian passage to higher ground and is fenced off during summer. The only existing pedestrian crossings of the railroad are Whittier Street, at the west end, and a pedestrian tunnel with waterfront entrance near the ferry dock (fig. 15), both of which are in the inundation zone. Pedestrians near the Whittier Street crossing may be able to reach safe high ground if they react immediately following strong shaking, and move quickly. However, they must travel nearly one-quarter mile to get past the modeled maximum inundation limit. The 125-m-long (400 ft) pedestrian tunnel is clearly a poor, and likely fatal, choice for evacuation considering the imminent arrival of a local tsunami wave.

A potentially viable solution for providing waterfront occupants and visitors a means to escape a tsunami at Whittier may be vertical evacuation structures of the type shown in figure W6. Several of these structures placed strategically along the parking area, and assured a solid foundation, could provide a safe and quick means of evacuation for most pedestrians along on the waterfront. However, other means of evacuation must be considered for those with impaired mobility, parents with strollers, and occupants of the boat harbor for whom there may be insufficient time to reach these structures.

A crucial component of tsunami evacuation is education, especially for visitors who may be unfamilair with local tsunami risk. With limited time available for public warning systems to effectively alert the public to the imminent arrival of landslide-generated waves, a variety of educational materials must be available to explain that strong shaking may be the only warning of a possible tsunami and that people should immediately evacuate to high ground or a safe, high structure.

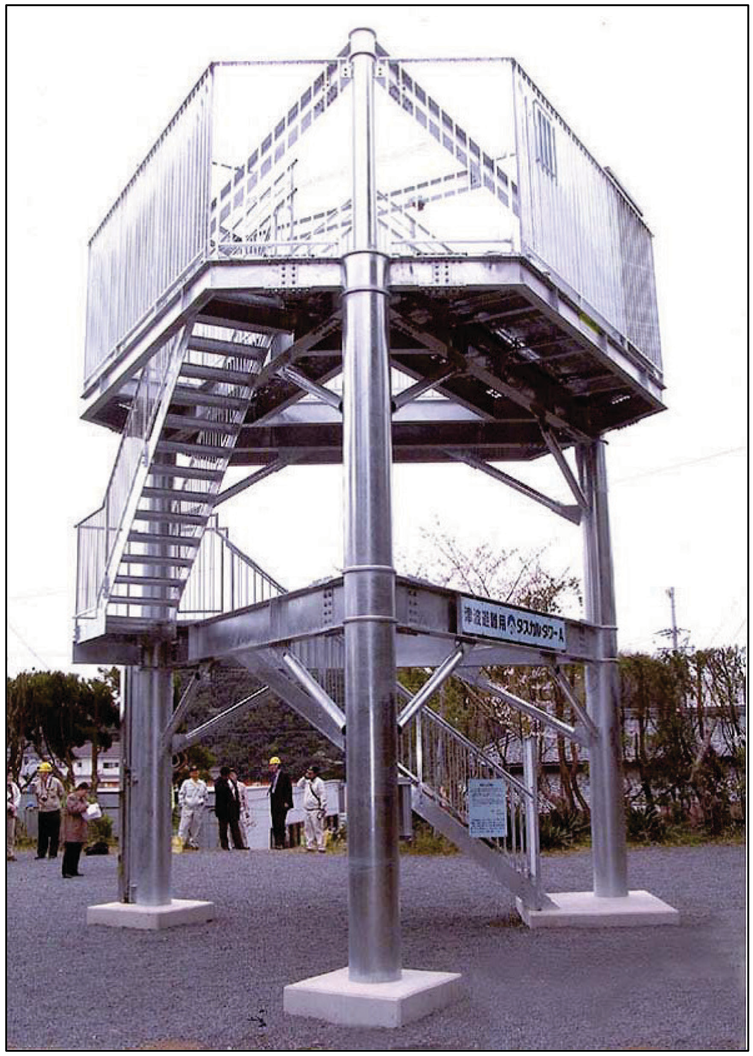


Figure W6. Vertical evacuation structure in Japan that was developed as a simple and economical vertical evacuation option (from FEMA report P646A: Vertical Evacuation from Tsunamis: A Guide for Community Officials).