Near Surface Expression of Megathrust Splay Faults, Western Gulf of Alaska

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Summary

We acquired ~1,500 km of sparker seismic data to identify and characterize Holocene motion on active faults along the Gulf of Alaska continental margin. The survey area is located immediately west of the largest surface ruptures related to the 1964 M9.2 Great Alaska earthquake near Montague Island. Based on estimated tsunami travel times from 1964, we identify thrust faults that produced 5-10 m wave heights in the coastal town of Seward and along the Kenai Peninsula. We identify the Hanning Bay, Patton Bay, and Cape Cleare, as local tsunami sources. These faults moved vertically upwards of 12 m during the 1964 earthquake. Offshore of Montague Island, the Cape Cleare and Patton Bay faults, with (post-glacial) sea floor scarps as large as 69 m and 25 m respectively, has accommodated the greatest vertical uplift during large Holocene earthquakes. We find active faults with decreasing displacements from northeast to southwest across the study area, consistent with plate locking models derived from GPS measurements. The profiles south of Seward, Alaska show active faults with evidence for little motion from the last few great earthquake cycles when compared to profiles near Montague Island. However, deformation within late Quaternary? strata suggest that these faults can activate during future earthquakes to create local tsunamis or ground shaking along the Kenai Peninsula. It is also possible that these faults can rupture independent of a megathrust earthquake. Furthermore, we find mass transport deposits beneath some Kenai Peninsula fjords that may be earthquake triggered. The results from this cruise complement past NEHRP-funded cruises and existing legacy seismic data that have imaged Gulf of Alaska continental margin upper crust that show exhumation rates progressively decrease to the west of Montague Island along the Gulf of Alaska continental margin.

Key Points

Tsunami sources

1964 Great Alaska earthquake

Seismic reflection

Spatial and temporal fault slip

Subduction zone tectonics

Introduction

We acquired ~1,500 km of sparker seismic data to identify and characterize active faults along the Gulf of Alaska continental margin (Figure 1; red lines) across a key tectonic boundary. The survey area is located immediately west of the largest documented surface ruptures related to the 1964 M9.2 Great Alaska earthquake near Montague Island (e.g., Plafker, 1969; Liberty et al., 2013) and represents a transition from a high to low coupling region (Figure 2; Zweck et al., 2003). However, it is presently unclear what the relationship between this post-1964 earthquake coupling model and permanent coseismic deformational that can be observed with seismic reflection images. The results from this cruise complement past NEHRP-funded cruises and existing/unpublished legacy seismic data that have imaged Gulf of Alaska continental margin upper crust (Figure 1; MMS 75-02 - blue lines; USGS 7-81-WG – green lines; USGS TACT profile – orange line). The results from this survey highlight the spatial and temporal distribution of active faults south of the Kenai Peninsula.

Data Collection

The Boise State/USGS cruise departed Homer, Alaska on May 2, 2013 and returned to Seward, Alaska on May 12, 2013. The data were collected on the USGS R/V Alaskan Gyre (Captain Greg Snedgen) using a USGS Applied Acoustics 300-500 Joule sparker seismic system and 24-channel, 3-m spaced Geometrics microEel streamer. Boat speed ranged from 4-8 knots in mostly favorable weather conditions to produce spatial sampling of 2-4 m. Data were sampled at 0.25 ms, nominally for 0.85 s, to image to at least twice the maximum sea floor depth. Due to low (12) fold data, little signal appeared below the water bottom multiple and sparker interpretations are limited to about 300 m below sea floor. Given modern sedimentation rates, the sparker seismic data capture the complete Holocene sediment record to identify and characterize active faults, and in many instances also image older (late –Quaternary) stratigraphy. Survey information was obtained using Trimble GPS systems and source positions were embedded in the seismic headers. The cruise team consisted of Boise State (PI) Liberty and student Shaun Finn, and USGS research scientists Daniel Brothers and Peter Haeussler. Although the focus of data collection was active fault mapping in the open water Gulf of Alaska, detailed seismic surveys were also conducted in the sheltered waters of Harris Bay, Aialik Bay, Resurrection Bay and Day Harbor (Figure 1) to identify (earthquake induced) submarine landslide deposits and post-glacial depositional patterns.

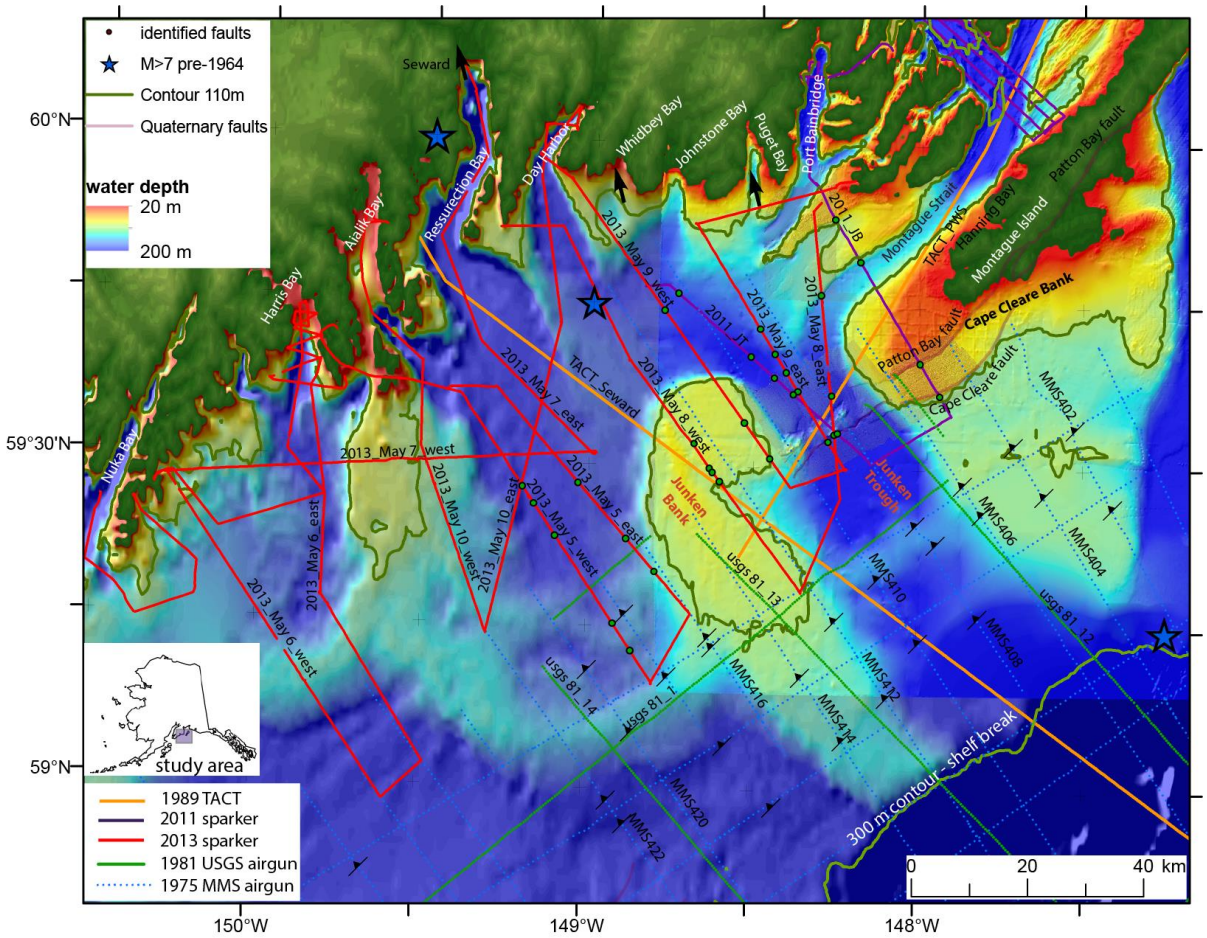

Figure 1. Study area south of the Kenai Peninsula in southern Alaska showing bathymetry and seismic profile tracklines. The new sparker seismic data are shown in red, green dots represent identified faults from the survey, and blue stars represent pre-1964 M>7 earthquakes from the USGS NEIC database. The blue dots are the locations of a 1975 MMS seismic survey and green lines represent a 1981 USGS airgun seismic survey.

The M w 9.2 1964 earthquake and related tsunamis

The 1964 Mw 9.2 Great Alaska earthquake was the second-largest earthquake ever recorded instrumentally. The earthquake rupture extended over an area approximately 800 km long by 250 km wide, and generated tsunamis that devastated local communities across southern Alaska and damaged distant communities along the North American coast (Plafker, 1969). The earthquake initiated beneath the area immediately north of Prince William Sound (PWS) at a depth of about 25 km, and had two high moment release areas with about 21 m of slip beneath PWS and 15 m of slip near Kodiak Island (e.g., Plafker, 1969; Christensen and Beck, 1994; Johnson et al., 1996; Zweck et al., 2003; Suito and Freymueller, 2009). The earthquake initiated at the boundary between the downgoing Yakutat plate and

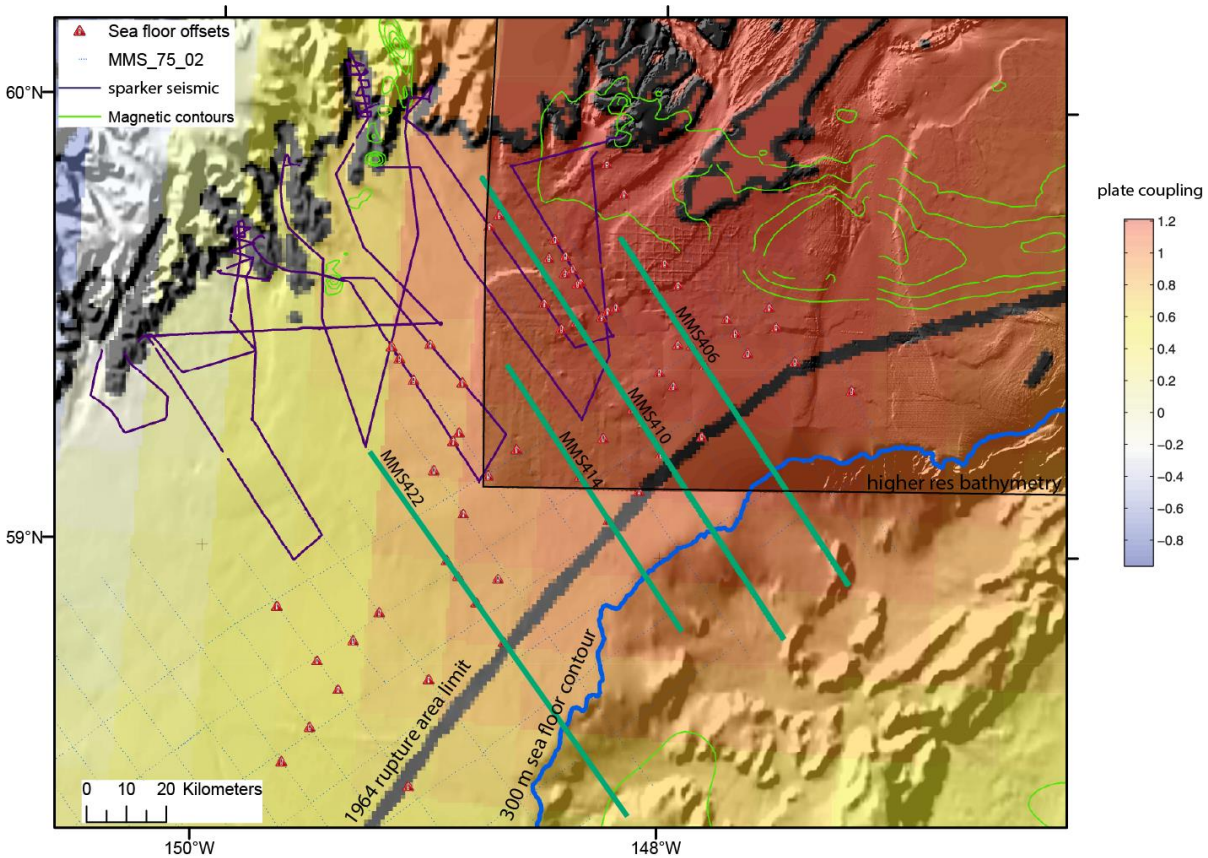

Figure 2. Study area south of the Kenai Peninsula in southern Alaska showing plate coupling along the Kenai Peninsula (Zweck et al., 2003), bathymetry, magnetic contours, and seismic profile tracklines. The new sparker seismic data are shown in purple, green lines represent select MMS profiles discussed in text.

North American plate, but rupture propagated along splay faults through the subducted Yakutat terrane and overlying accretionary complex (Plafker, 1969; Brocher et al., 1994; Eberhart Phillips et al., 2006; Fuis et al., 2008). The earthquake shifted PWS southeast about 21 m and lifted portions of the PWS region more than 12 m (Plafker, 1969; Figure 3). A surface uplift as great as 7 m was documented across the Patton Bay fault on southwestern Montague Island, with additional surface uplifts of 5 m documented in Hanning Bay on Montague Island and 3.5 m on Middleton Island (Figures 1-3). Here, we examine the western extent of these faults to determine earthquake rupture history for the region south of the Kenai Peninsula and Seward, Alaska (Figures 1 and 2).

Tsunami run up from tectonic sources were documented from numerous sites on Kodiak Island, Kenai Peninsula, PWS, Middleton Island, and the Alaska panhandle (Plafker, 1969) (purple arrows on Figure 3). Tsunami travel times ranged from minutes to hours and point to numerous near-shore continental shelf sources. Splay faults that extend across the study area are consistent with the Suleimani et al. (2011)

tsunami model, which showed that a source on the continental shelf is needed to produce the tsunami that arrived at Seward about 30 minutes after the earthquake. Travel times from tsunami run up sites in Whidbey Bay and Puget Bay are consistent with tectonic sources located approximately 40-60 km south of the Kenai Peninsula shoreline (Figure 2). Tsunami sources are likely related to Patton Bay, Cape Cleare, and Middleton faults that all were active in 1964 (Plafker, 1969; Liberty et al., 2013). However, prior studies have not mapped these faults to the west of the Junken Trough survey area described by Liberty et al. (2013). Furthermore, Plafker (1969) and Kelsey et al., (2015) identify tsunami source deposits from and run ups from 1964 along the length of the Kenai Peninsula, suggesting the possibility that additional continental margin faults activated in 1964 to the west of the Junken Trough.

Tectonic Setting

The PWS seismic asperity, defined as a region of high moment release (e.g. Lay et al., 1982; Scholz and Campos, 2012), was centered beneath the southwest end of Montague Island near a prominent magnetic high that defines the western boundary of the subducted Yakutat terrane (Figures 2 and 3) (Bruns, 1985; Giscom and Sauer, 1990; Brocher et al; 1994; Johnson et al., 1996; Zweck et al., 2002; Eberhart-Phillips et al., 2006). The megathrust beneath PWS is the contact between the accreted Yakutat terrane and the overlying Prince William terrane (Brocher et al., 1994). West of Montague Island, the Yakutat plate is absent and the Pacific Plate subducts directly beneath the North American plate (e.g., Brocher et al., 1994; Eberhart-Phillips et al., 2006). The relatively buoyant Yakutat terrane is moving north-northwest approximately 50 mm/year relative to North America while the Pacific plate is subducting in a slightly more northerly direction at 51 mm/year (Figure 1) (Elliot et al., 2010). The buoyancy of the Yakutat plate results in a subduction angle of approximately 3° beneath PWS compared to the steeper 8° dip along the Kodiak segment (e.g., Brocher et al., 1994; Eberhart-Phillips et al., 2006; Doser and Veilleux, 2009). The maximum slip from the 1964 earthquake was largely coincident with the southwestern edge of the subducted Yakutat terrane, which appears to be largely coupled to the underlying Pacific plate (Zweck et al., 2002; Doser et al., 2004; Eberhart-Phillips et al., 2006; Ichinose et al., 2007). Sea floor ruptures identified on MMS and USGS profiles are consistent with this asperity region, where at least three faults ruptured the sea floor (Figures 1 and 2).

Geodetic measurements in the PWS area show movement at the Pacific-North America plate rate, which indicates a locked asperity (Zweck et al., 2002) with repeat times for large megathrust earthquakes of 330-900 years (summary in Carver and Plafker, 2008). This locked asperity lies adjacent to a region of

presumed very low seismic coupling along the Kenai Peninsula and western Gulf of Alaska that is may accommodate plate convergence mostly by aseismic slip (Figure 2; Zweck et al., 2002). However, the seismic reflection results presented in this report suggest that the Kenai Peninsula offshore area contains many active thrust faults that offset the sea floor. Although the rate of uplift on the splay faults along the Kenai Peninsula appear to have lower Quaternary slip rates than areas near Montague Island, Holocene coseismic ruptures appear across the entire region from Kodiak to Middleton Islands. Our results are consistent with asperity models from seismic, tsunami, and geodetic measurements (Ichonese et al., 2007), but the distribution of both active and dormant faulting is more widespread than previously documented.

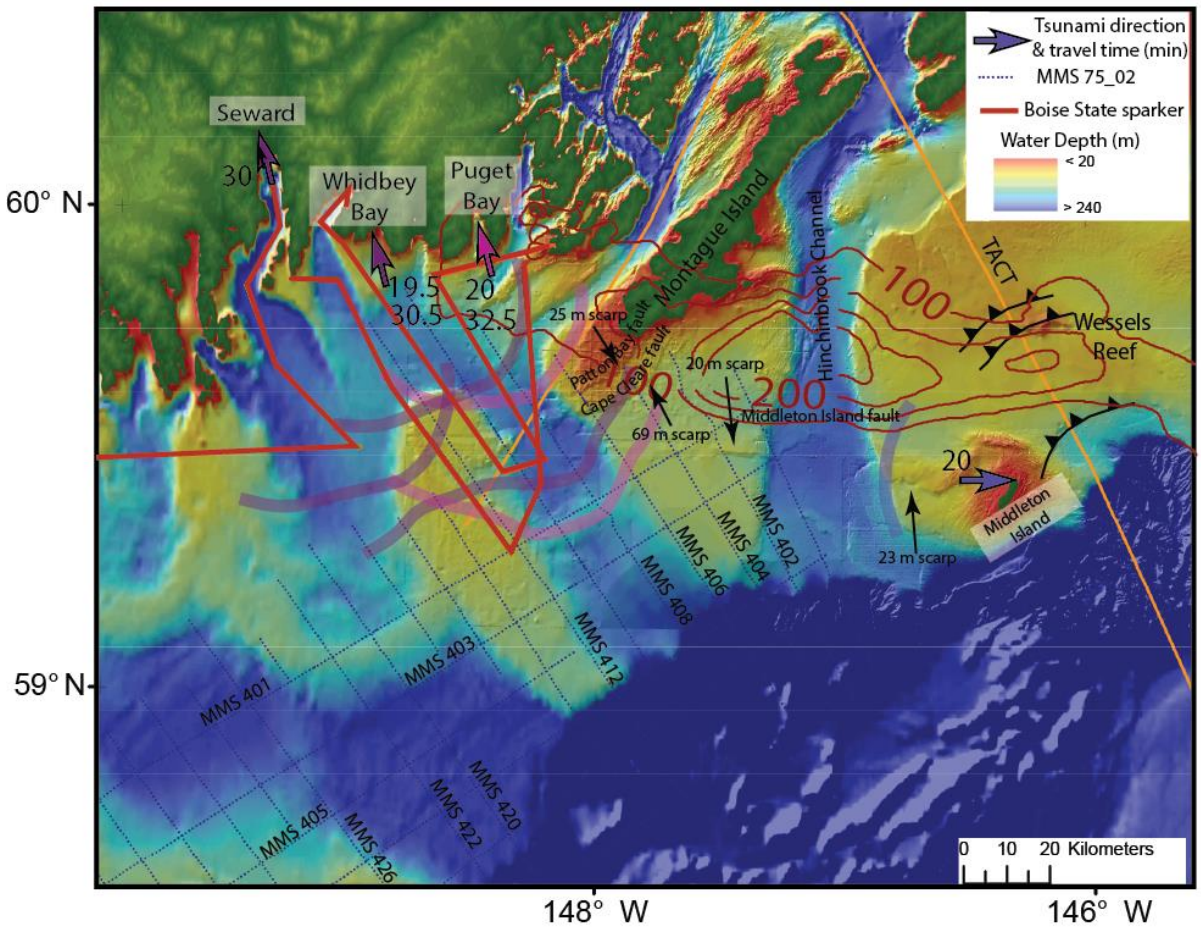

Figure 3. Bathymetric map showing estimated location for the tectonic tsunami sources associated with the 1964 M9.2 earthquake. The purple lines represent the calculated location of the tectonic sources based on estimated travel times compiled by Plafker (1969) for Seward, Whidbey and Puget Bays. Red lines represent new sparker seismic profile locations and contours represent total magnetic field that represents the high slip region related to the trailing edge of the Yakutat terrane that mimics the 1964 asperity region.

Seismic Results

Sparker seismic results

Figure 4 shows the results from seven new sparker seismic profiles. The north-south profiles progress from east to west, from known fault locations to newly identified fault locations. The seismically transparent bedrock that we interpret as Tertiary Orca Group rocks appear at the sea floor along the profiles within the Junken Trough along the hanging wall of the Cape Cleare fault. The same or similar bedrock high surface appears at progressively greater depths along the profiles to the west. Because the depth below sea floor to the upper unconformity is roughly consistent across the region, we infer that modern rates of deposition are similar within the deeper sediment troughs of the Gulf of Alaska. Therefore, the increased depth to bedrock suggests a decreased fault activity to the south of Seward compared to the region that surrounds western Montague Island. Although a decrease in fault slip is observed from northeast to southwest, we still classify the landward portion of the Gulf of Alaska shelf between Seward and Montague Island as a high hazard region. Rates of deposition and depositional patterns are complex along these seismic profiles. The profiles show multiple unconformities, alternating fine and coarse-grained sediments that reflect changing climate conditions, and sea floor erosion, as evidenced from scour in the footwall of the Cape Cleare and Patton Bay faults.

MMS profiles

Figure 5 shows four select north-south MMS profiles acquired in 1975 (See Figures 1-3 for profile locations). The northern portions of these profiles overlap the sparker seismic profiles and provide supporting evidence for active growth faults along at least a 50 km wide zone. The identified high angle thrust faults bound a Miocene and younger forearc basin (Turner et al., 1988) that we term the Junken Basin. Because there is no evidence for significant growth faulting, the deposition of sediments within this basin likely preceded the bulk of motion along the active faults to the north. This suggests significant Quaternary motion on these near shore continental shelf faults. Since this basin rides upon the underlying decollement, we classify this as a piggyback basin. The interpreted southern rupture area limit or aftershock area during the 1964 M9.2 earthquake (Plafker, 1969) loosely correlates with the southernmost limit of thrust faulting that forms the northern margin of the Junken Basin. We suggest that the northern basin boundary that roughly matches 1964 rupture area limit has remained stationary for much of the Quaternary record. Furthermore, we classify the Junken Basin as a low hazard region when compared to the region of abundant thrust faults to the north and south.

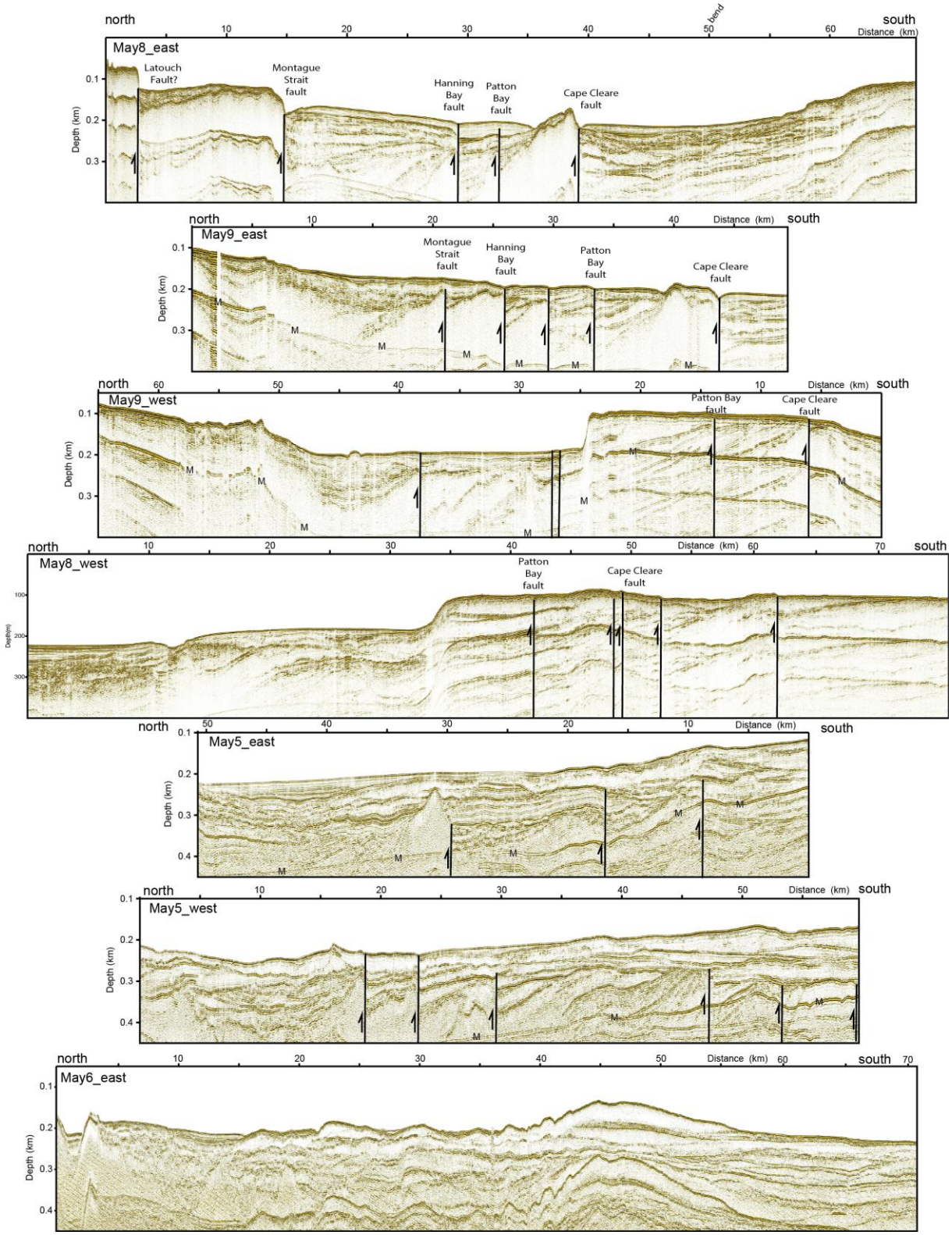

Figure 4. Seismic profile results from select north-south profiles that cross the Gulf of Alaska (Figure 1 shows profile locations). Faults are identified from reflector truncations, sea floor offsets and changes in reflector dip.

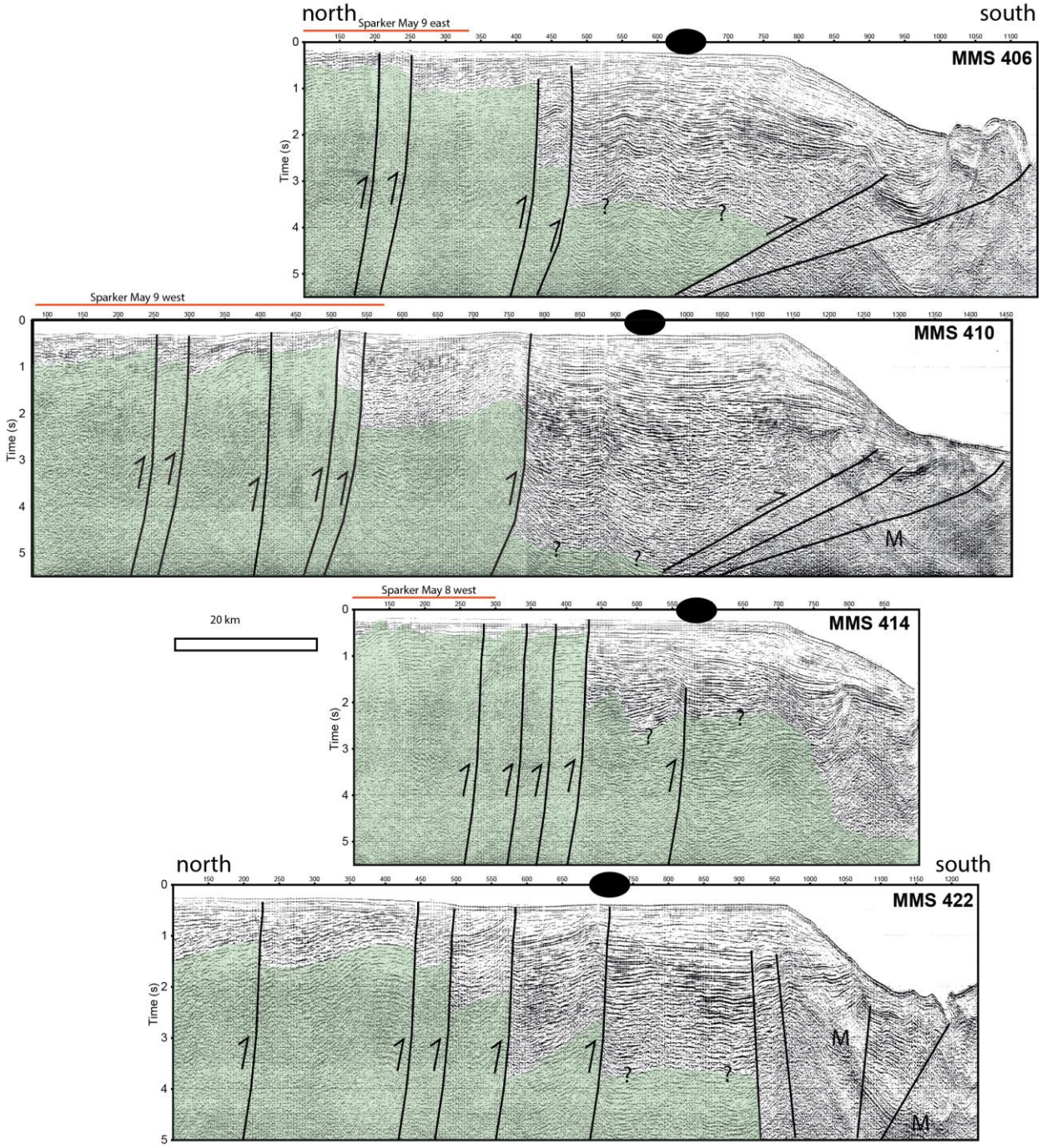

Figure 5. Select MMS profiles that extend south from new sparker seismic data. These data show thrust faults that bound a forearc basin immediately north of the continental margin slope break. The ovals represent the interpreted limit of uplift during the 1964 M9.2 earthquake (Plafker, 1969) and green areas represent interpreted Orca Group and older rocks.

Fjord seismic

In addition to acquiring new sparker seismic data along the Gulf of Alaska continental margin, we also acquired sparker data within fjords along the Kenai Peninsula. The withdrawal of late Wisconsin ice margins occurred 10-12 ka along the Kenai Peninsula (e.g. Wiles and Calkin, 1994). Multiple late Holocene ice advances, as well as the initial retreat of Holocene ice margins may be reflected in the seismic record of these fjords.

Deposition rates beneath the proximal glacial fjords can be more than one meter/year. Additionally, slope failures and tsunami deposits may be captured within the sediment record of these fjords (e.g. Kelsey et al., 2015).

Harris Bay

Harris Bay is located west of Seward, Resurrection Bay and Aialik Bay (Figure 1). The seismic results (Figure 6) show upwards of 300 m of sediment lying on top of a seismically transparent basin. The depth to bedrock increases from north to south. Alternating high amplitude and low amplitude seismic reflectors within the basin suggest a sediment record that has captured both climate and tectonic signals. There is no evidence for active faults or large mass failure deposits beneath Harris Bay, but this basin captures the post-glacial sediment record.

Aialik Bay

Aialik Bay is located west of Seward and Resurrection Bay and east of Harris Bay (Figure 1). Seismic results (Figure 7) show a similar depositional style compared to Harris Bay, but the total sediment thickness is less than beneath Harris Bay. A semitransparent layer less than 5m below the sea floor on many of the profiles suggest slope failures or mass transit deposits. Given relatively rapid modern rates of deposition, we suggest this upper unit is related to slope failures during the 1964 earthquake. Kelsey et al. (2015) show evidence for tsunami deposits along the Aialik Bay shores, consistent with our observations.

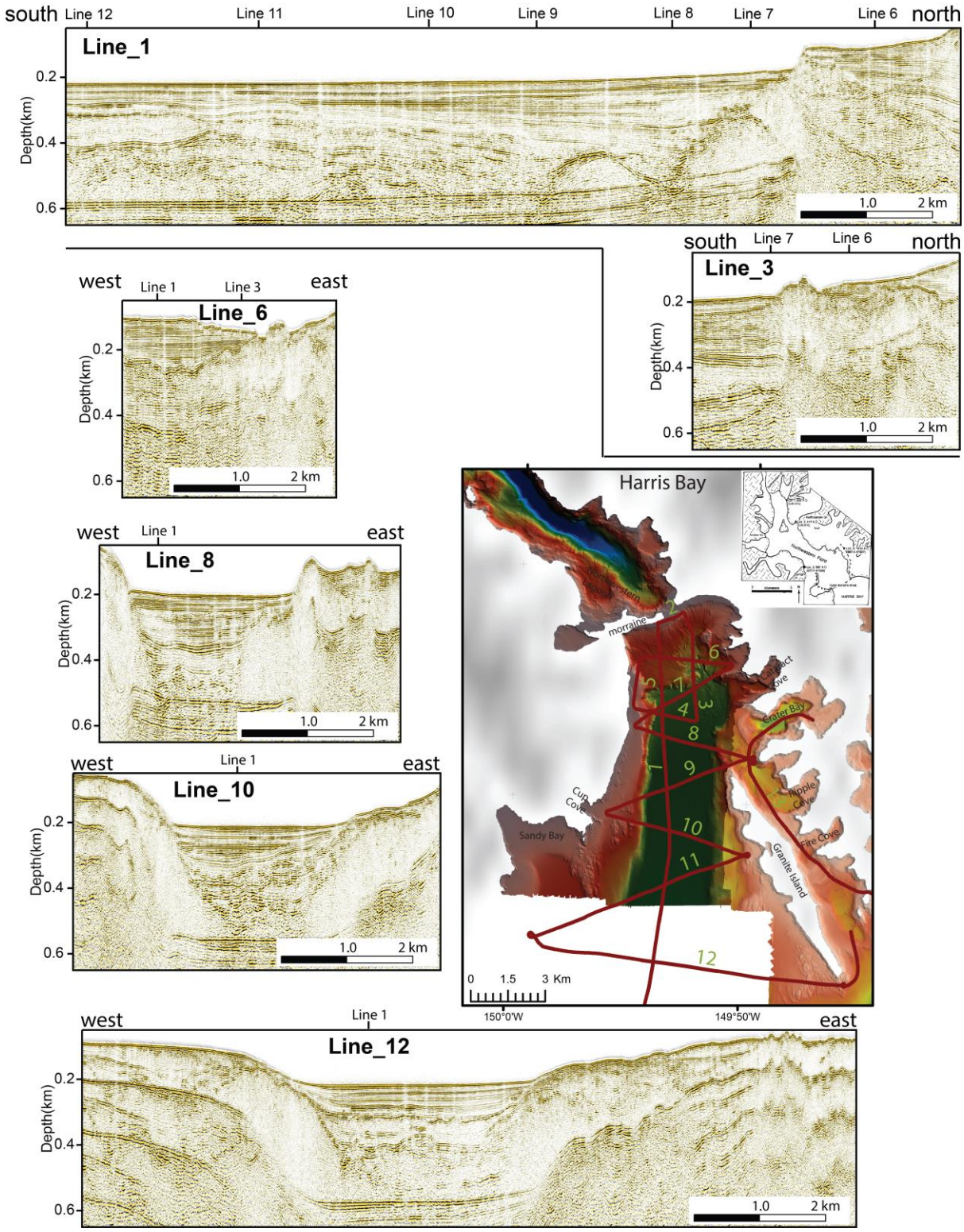

Figure 6. Harris Bay seismic results with survey location map. There is no compelling evidence for mass failure deposits in the late Holocene sediment record.

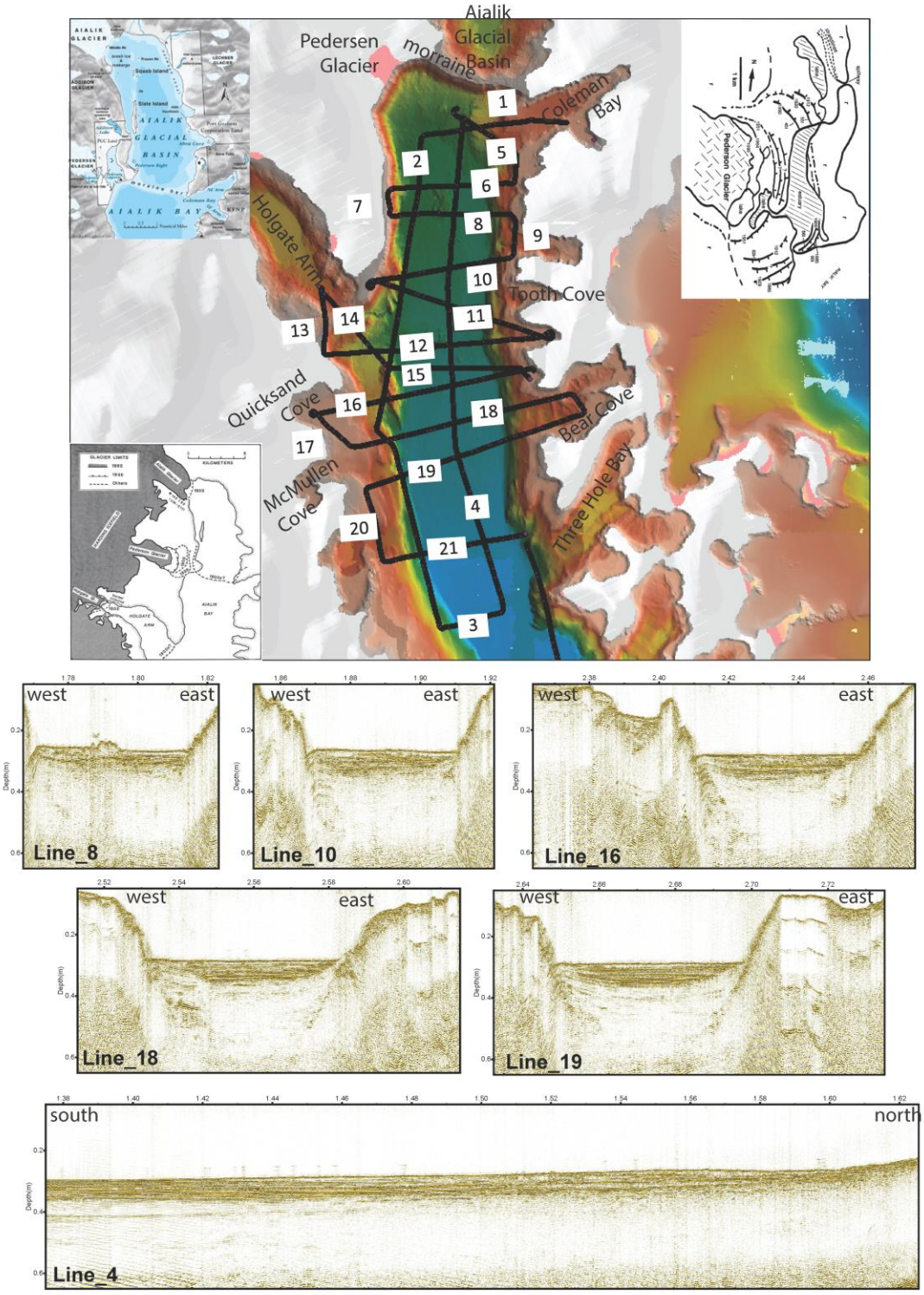

Figure 7. Aialik Bay seismic results with map showing upwards of 50 m of late Holocene sediment that lies above older strata and bedrock. The upper semitransparent unit may represent slope failure deposits from the 1964 earthquake.

Resurrection Bay

Resurrection Bay is the home to Seward, Alaska. Haeussler et al (2006) and Suleimani et al. (2011) showed compelling evidence for submarine slope failures throughout the region. We focused our seismic survey on the "bathtub" region north to the Fourth of July Creek area where Haeussler et al. (2006) documented upwards of 10 m of transported material from 1964 (Figure 8). The documented difference in pre and post 1964 depth to the sea floor is consistent with the thickness of semitransparent materials that we identify immediately below the sea floor. We interpret this ~10 m thick zone of semitransparent reflectors as slope failure materials that were mobilized in 1964. Below this zone, approximately 50 m of highly reflective strata likely represents late Holocene deposits. We see no significant regions where similar semitransparent reflectivity would suggest earlier slope failures materials, perhaps suggesting that 1964 was unique in the late Holocene record.

Conclusions

We identify active thrust faults related to subduction across the length of the Gulf of Alaska continental shelf from Resurrection Bay (Seward area) to Montague Island. The documented uplift from the 1964 earthquake from both land and sea measurements, large sea floor scarps, and steep dipping hanging wall reflectors indicates that uplift is greatest (and scarps more abundant) near Middleton and Montague Islands along the Patton Bay, Cape Cleare, and Middleton Island faults. Bathymetry and seismic results suggest these faults are subparallel and likely extend in an en echelon pattern across the region. These faults likely activated in 1964, as evidenced by offsets along the sea floor and related tsunamis that were documented along the Kenai Peninsula. Seismic surveys from Resurrection Bay and Aialik Bays suggest numerous slope failures in 1964, but Harris Bay shows no similar evidence.

Acknowledgments

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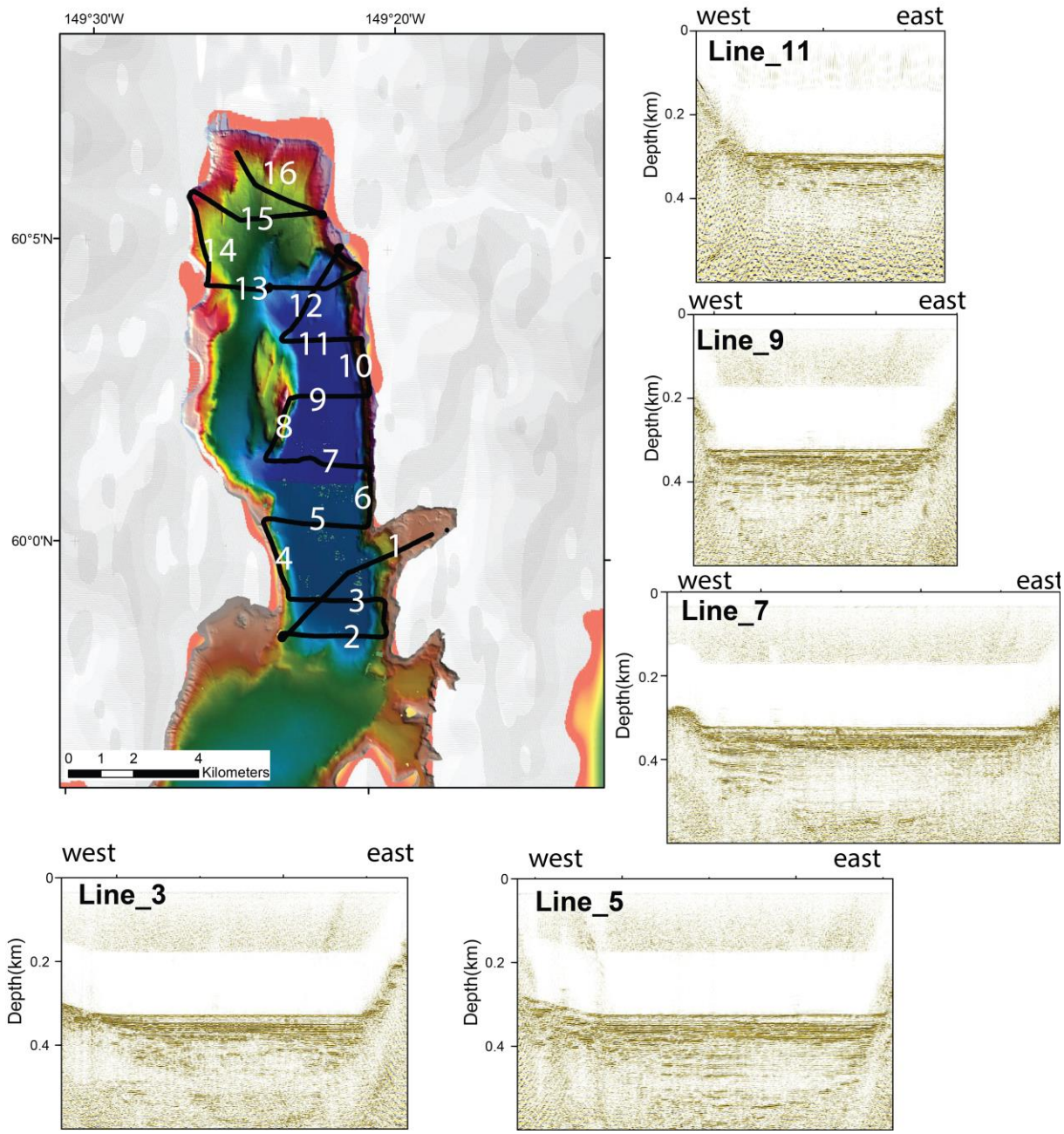

Figure 8. Resurrection Bay seismic results with map. Seward is located at the northwest end of Resurrection Bay and the bathtub region is located between profiles 5 and 12. Note the semitransparent zone of reflectivity for the upper 10 m below sea floor for the related profiles. We interpret this region as a sediment trap from material mobilized during the 1964 earthquake.

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