High resolution imaging of megathrust splay faults in Prince William Sound, Alaska

Project Award Number: # G09AP00049

Award Dates: April 2009-June 2010

Submission date: September 30, 2010

Lee M. Liberty
Associate Research Professor

Shaun Finn
Graduate Assistant

Center for Geophysical Investigation of the Shallow Subsurface (CGISS)
Department of Geosciences
Boise State University
Boise, Idaho 83725-1536
Phone: 208-426-1166
Fax: 208-426-3888
lml@cgiss.boisestate.edu
http://cgiss.boisestate.edu/~lml

Program Element: II

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number G09AP00049. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Abstract

Two splay faults ruptured during the 1964 M9.2 megathrust earthquake in southern Prince William Sound (PWS), generating local and trans-oceanic tsunamis and more that $100 million in damage. We collected ~400km of multi-channel high-resolution sparker seismic data to identify and characterize active faults in the upper few hundred meters below sea floor related to this event and older megathrust earthquakes. We identify at least three seismic facies that we infer as late Quaternary and younger sediments and numerous high-angle faults that cut these strata. Given the proximity to surface ruptures from the 1964 event and sea floor offsets in southern and eastern PWS, we identify these faults as active. We conclude that a zone of uplift and faulting broader than what is presently documented from the 1964 M9.2 megathrust earthquake has shaped the area. Growth faulting and the shallow depth to Tertiary rocks suggest reactivation of older structures and long-term regional uplift. Within eastern PWS, lineations mapped on land and sea floor tie to these active faults, suggesting regional-scale deformation and possibly independent seismogenic sources capable of supporting >M6.5. Additional analyses of newly acquired data, in combination with legacy seismic surveys, should help improve seismic hazard assessments and tectonic models for the area.

Introduction

The 1964 Mw 9.2 Alaska megathrust earthquake was the largest recorded earthquake in North America. Although the megathrust earthquake caused considerable damage to southern Alaska, tsunami-related damage and loss of life occurred around the Pacific. The quake, centered beneath Prince William Sound (PWS) (Figure 1a), produced more than $100 million in damage and more than 100 deaths, destroyed 30 city blocks in Anchorage (120 km from the epicenter) and approximately $10 million in tsunami-related damage and 13 deaths in California alone (e.g., Sokolowski, 1991). Analysis of surface rupture and splay fault geometries from subduction areas around the Pacific Rim including the Great Sumatra-Andaman Earthquake in 2004 (e.g., Lay et al., 2005; Rajendran et al, 2007), the Nankai Trough (e.g., Moore et al., 2007) and the 1964 PWS event (e.g., Plafker, 1972) suggest fault geometries and rupture properties of accretionary wedge thrusts related to megathrust events are critical to tsunami generation. During the 1964 earthquake, the Patton Bay fault recorded upwards of 15 meters of absolute vertical displacement. The earthquake triggered submarine landslide-generated tsunamis, which produced wave heights to 67 m within PWS in Port Valdez and transoceanic tsunami wave heights that exceeded 4 m in Crescent City, Ca. The rupture of crustal faults in PWS and the Gulf of Alaska largely controlled regional tsunami generation, yet the distribution of crustal faults, fault lengths, and uplift history is largely unknown.

The megathrust in PWS represents the contact between the subducting Yakutat Terrane and the North American plate (e.g., Plafker, 1972; Brocher et al., 1994; Fuis et al., 2008). The Yakutat Terrane is moving northward approximately 46 mm/yr relative to North America (e.g., Fuis et al., 2008). The estimated 18 m asperity slip from the 1964 event was largely controlled by the presence of the relatively buoyant Yakutat block, which is loosely coupled to the Pacific plate (Doser, 2004; Figure 1). The buoyant Yakutat Terrane dips northward approximately 3-4 degrees (Brocher et al., 1994). The asperity appears to be strongly locked (Zweck et al., 2002), with repeat times for rupture of the asperity within PWS estimated to be 700 to 800 years (Nishenko and Jacob, 1990; Hamilton and Shennan, 2005; Wesson et al., 2007). The western boundary of the Yakutat Terrane lies immediately west of PWS at the Slope Magnetic Anomaly, linked to the subducted and likely inactive Transition Fault (Griscom and Sauer, 1990; Plafker et al., 1994; Gulick et al., 2007; Fuis et al., 2008).

In addition to the geometry of faulting as it relates to tsunami generation, repeat times for smaller magnitude (M>6) still potentially damaging earthquakes are poorly constrained. Since 1964, smaller earthquakes (>M5) have occurred in the upper few km on crustal faults that may have ruptured in 1964 (Figure 1b; Doser et al., 1999). Megathrust splay faults that ruptured during the 1964 event exceed a few hundred km in length (e.g., Plafker et al., 1994) and may support >M7 earthquakes independent of megathrust seismicity from the release of accumulated strain in the upper crust (though very little strike-slip motion has been recorded on these faults). Therefore, crustal faults within PWS are a significant hazard to southern Alaska cities (e.g., Anchorage, Valdez, Seward, Cordova) and multibillion dollar infrastructure (tanker/cruise ship/ferry terminals, pipelines, tourism, fishing) (e.g., Larson et al., 2007). To date, the extensive waterways of the PWS area and few geophysical surveys have limited detailed characterization of these faults.

We acquired new seismic reflection data set to identify and characterize Holocene motion on crustal faults within PWS to; 1) further the understanding of the hazards associated with these faults as independent seismic sources; 2) address how the geometry of these faults have influenced tsunami propagation both locally and globally; 3) constrain the recurrence intervals and motion on these faults; 4) compare fault geometries and uplift rates on identified faults with faults identified along other regions of the Pacific Rim (e.g., USGS database for other parts of Alaska) to determine, for example, if the subducting slab geometry relates to patterns of surface ruptures and crustal faulting during megathrust events. This report includes seismic images from all newly acquired profiles. We present a detailed analysis of selected profiles that provide details on fault locations, fault properties, and recurrence intervals.

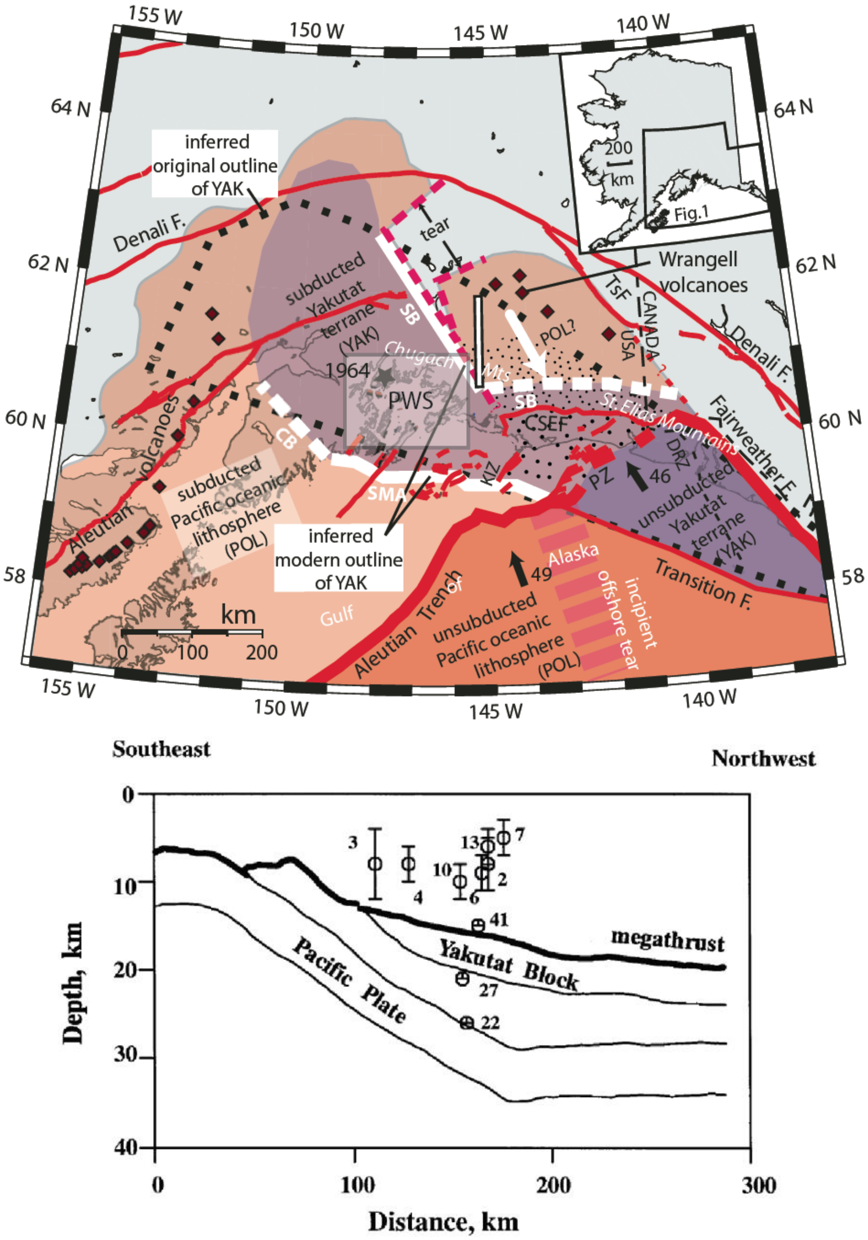

Figure 1. a) Tectonic map of Alaska (simplified from Fuis, 2008) showing the interplay between Pacific and North American plates and the northward subducting Yakutat terrane. Proposed study area and 1964 epicenter in PWS is shown in the centered box; b) Simplified cross section showing earthquake hypocenters in Prince William Sound since 1964 with respect to the subducting Yakutat Terrane. Nearly all M>5 earthquakes since 1964 appear on the upper plate, likely related to crustal faults (from Doser et al., 1999).

Previous Studies

Identification, mapping, and characterizing the crustal architecture and faults within PWS have been limited to geologic mapping on the mainland and islands (e.g., Plafker, 1969; 1972; Nelson et al., 1985) and regional geophysical surveys. These surveys include potential field surveys (e.g., Barnes, 1991; Barnes and Morin, 1990; Griscom and Sauer, 1990; Saltus et al., 2007) crustal seismic reflection and refraction surveys related to the TACT experiments (e.g., Brocher et al., 1994; Fuis et al., 2008), earlier analog datasets (e.g., VonHuene et al., 1967), and industry exploration. Recently, multibeam data to map the sea floor has identified lineaments that likely identify additional faults related to the 1964 earthquake and possibly older events (Haeussler, personal comm.). Detailed analysis of Holocene motion related to mapped and unmapped faults within the waterways of PWS has yet to be undertaken prior to this study.

Sedimentation rates within PWS are estimated at 0.30 cm/yr near Hinchinbrook Entrance to 0.57 cm/yr in the center of PWS, translating into a 30-57 m Holocene record (Klein, 1983; Figure 2). However, Carlson and Molnia (1978) interpret upwards of 200 m of Holocene sediment from analog minisparker data that translate into a 2.0 cm/yr sedimentation rate for portions of PWS. We determined Holocene sedimentation rates from new seismic reflection data by identifying a seismic horizon that we interpret as a regional unconformity. We depth convert our seismic images using water column and unconsolidated sediment velocities and assume the unconformity represents a 10,000 yrs old boundary.

Seismic Reflection Studies

From August 23-August 31, 2009, we acquired ~450 km of seismic reflection data in PWS to identify and characterize active faults. We acquired data on the 59 ft USGS R/V Alaskan Gyre (Figure 3). We departed Valdez to first survey Orca and Gravina Bays where prominent lineations on multibeam data (NOAA) suggested active faulting (Figure 4). We then surveyed the Hinchinbrook Entrance to determine whether the Patton Bay fault extends east to Hinchinbrook Island and farther east. Finally, we surveyed Montague Strait where multibeam lineations parallel mapped faults on Montague, Latouche, and Knight Islands. Electrical problems on board the boat and extensive transit time on-route to/from ports (Valdez and Homer) and between sites limited our acquisition to ~7 hours per day for 8 days (including a stop in Cordova for repairs and weather). However, even with significant down time for repairs and weather, we averaged acquisition rates of 55 km per day. A complete collection of seismic profile images are available at
http://cgiss.boisestate.edu/~lml/Alaska/BoiseState_2009_unmigrated_images.pdf

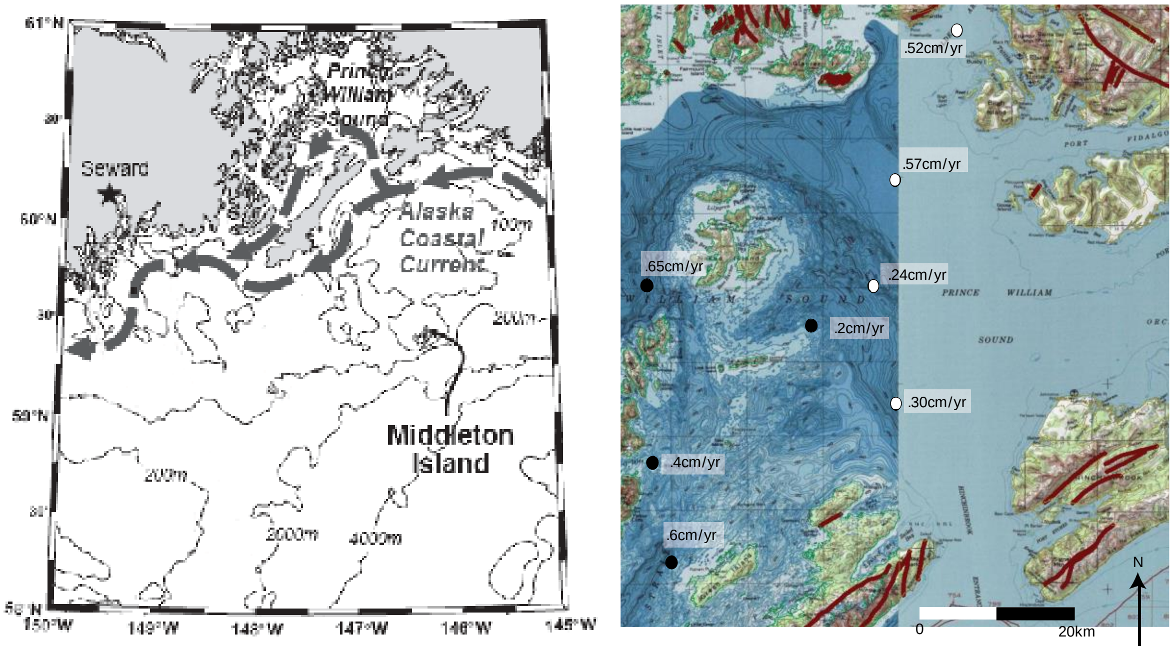

Figure 2. (left) Alaska coastal current map for southcentral PWS and Gulf of Alaska. Coastal current divides near Hinchinbrook Entrance with a component of the current circulating through PWS. (right) Map of central PWS with sedimentation rates from USGS (black dots) and from Klein (1983) (white dots). High deposition rates appear near Valdez and along western PWS toward Montague Strait.

We acquired seismic data using an Applied Acoustics sparker source at both 200 and 300 Joule settings (site dependent energy level). We used sparker units from the University of Washington and from Golder Associates. We recorded the sparker data using a 12-channel, 3-m spaced Boise State solid state streamer and a Geometrics Stratavisor seismograph. A single-channel streamer was recorded as a backup to the multichannel streamer. We recorded 50 kHz sub-bottom profiles with a Lowrance profiler and recorded GPS positions with both the Lowrance unit and a Trimble unit. The deployment geometry is characterized in Figure 3.

Multichannel seismic data processing steps included geometry, filters, velocity and amplitude corrections, and post-stack Kirchoff migration (Yilmaz, 2002). Bandpass filter (200-900 Hz) removed boat and streamer noise; normal moveout and migration velocities were derived from water temperature and salinity values in the water column, core analysis in Holocene sediments (Kulm et al., 1973) and refraction velocity values in late Quaternary and older rocks (Brocher et al, 1994).

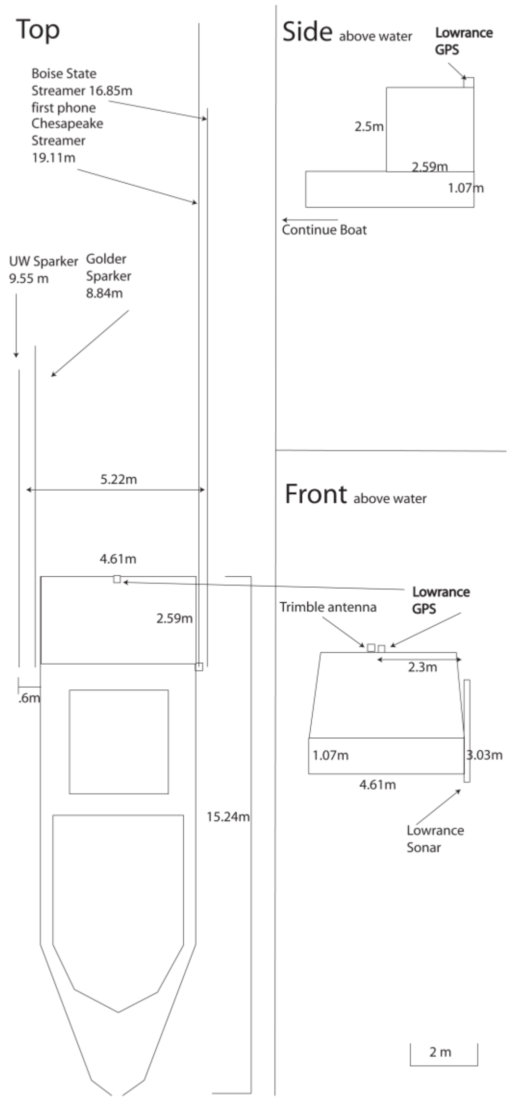

Figure 3. R/V Alaska Gyre (above) and seismic deployment schematic (left).

Orca Bay

The Orca Bay (Figure 3) survey yielded >100 km of high-quality seismic data to image the upper few hundred meters of sediment. Figure 5 shows multibeam and seismic data from Orca Bay where water bottom lineations show upwards of 8 m of relief (lineations A and B). Additionally, clear evidence for modern submarine landslide deposits appear in multibeam data along the south margin of Orca Bay. The seismic data that cross the multibeam lineations document near vertical growth faults that offset the interpreted base of Holocene deposits (Green unit) by up to 20 meters. We assume a regional unconformity at 30-50 meters below sea floor represents post-glacial sedimentation because Klein (1983) recorded modern sedimentation rates of 0.3-0.5 mm/yr throughout central PWS and glacial geomorphology suggests shallow water areas were fully glaciated (including all of Orca Bay).

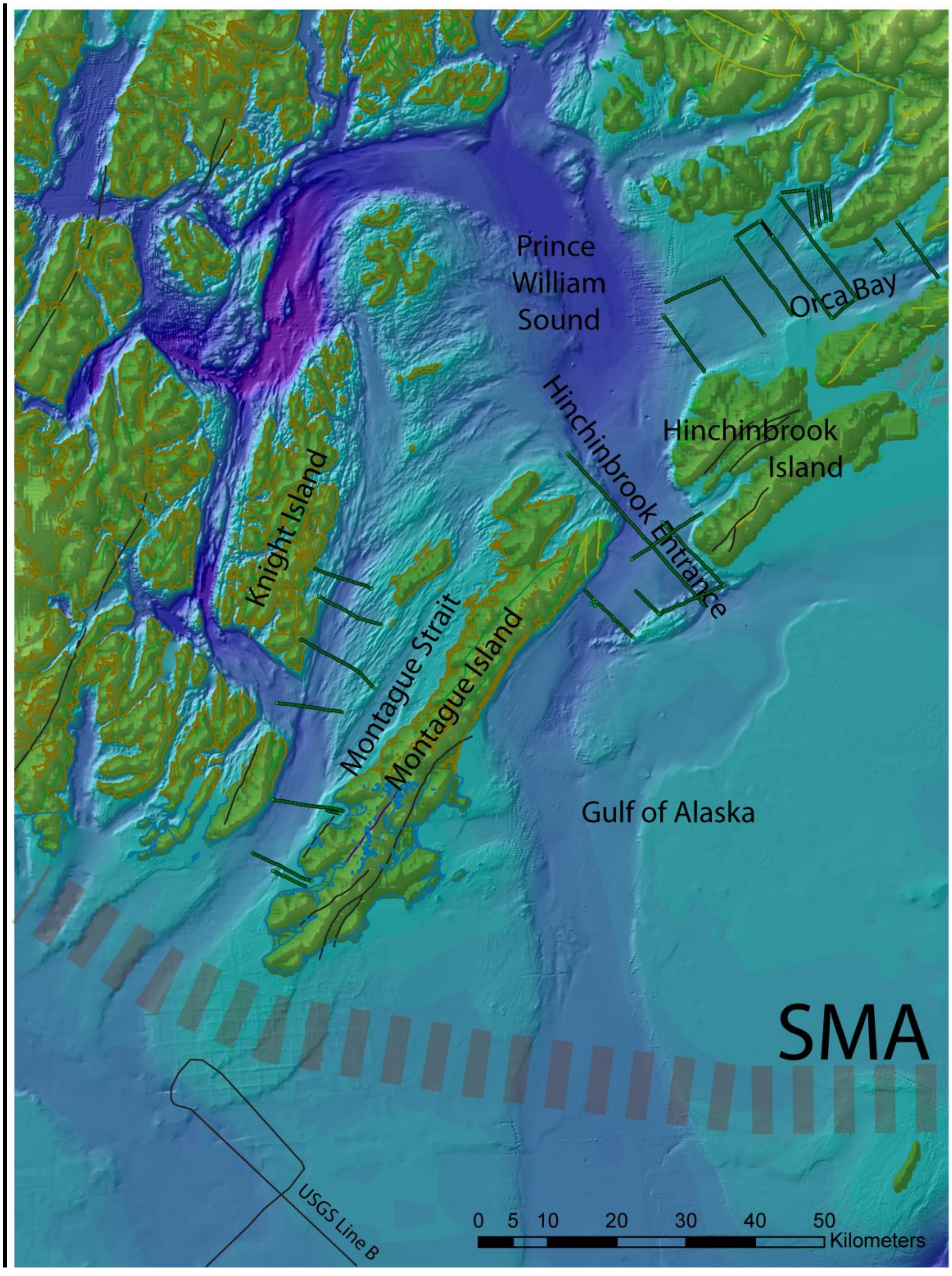

Figure 4. Bathymetric map of PWS with geologic units and identified faults (NOAA; Wilson and Hults, 2008). FY2009 survey lines are in green. SMA=Slope Magnetic Anomaly, the presumed southwestern boundary of the subducted Yakutat Terrane. Unpublished USGS Line B crosses lineations outside the SMA.

We interpret Orca Bay as an extensional basin with normal faults and landslide deposits throughout the Bay (Figure 5; Finn et al., 2010). We interpret at least 5 sedimentary units and upwards of 50 m of Holocene sediments overlying older Quaternary and Tertiary strata. The shallowest strata comprise mostly flat-lying reflectors that we interpret as Holocene sediments. These sediments are laterally truncated by transparent reflection zones that we interpret as landslide deposits. We identify two growth faults (A and B) that offset the water bottom and deeper reflectors and we consider these faults active. The water bottom expression of Faults A and B extend approximately 10 km within Orca Bay, but seismic profiles show the faults laterally continue, buried beneath landslide deposits (see profile Orca 5 - Yellow unit). Vertical slip rate measurements vary considerably from profile to profile. For example, Fault B shows ~20 m of vertical displacement on profile Orca 8 at the base of Holocene strata, but offsets decrease to the east and west. Reflections below the interpreted Holocene unconformity suggest late-Pleistocene strata (Blue unit) appear above highly deformed Tertiary bedrock, but sediment depocenters on the older unit has migrated, perhaps indicating fault migration as the Yakutat and Pacific plates subduct beneath North America. Given recurrence intervals for large earthquakes of ~700 years (Carver and Plafker, 2008), we estimate 15 large post-glacial events are recorded within Orca Bay, each producing upwards of 1.5 m vertical displacement. Vertical slip rates of this magnitude and fault length (~20 km) suggest these faults are capable of independently supporting >M6.5 earthquakes (Wells and Coppersmith, 1994) or are part of a larger fault system directly related to larger magnitude megathrust splay faults.

Hinchinbrook Entrance

The Rude River fault, a N45E-striking reverse fault mapped on Hinchinbrook Island, Hawkins Island and onto the mainland near Cordova, did not rupture during the 1964 earthquake. This fault, along strike with the Patton Bay fault on Montague Island, deforms late Pleistocene glacial deposits and landforms and offsets Holocene sediments (Figure 6). Carver and McCalpin (1998) suggest this fault represents slip occurring on a different megathrust splay. We acquired ~150 km of new sparker data in the Hinchinbrook Entrance area to characterize deformation between mapped faults on Montague and Hinchinbrook Islands. Additionally, we analyzed unpublished USGS analog seismic profiles immediately south of Montague Island to trace offshore faults related to the Patton Bay fault system.

Whereas upwards of 7 m of displacement was documented on the Patton Bay fault on Montague Island in 1964 (Plafker, 1969), no clear fault appears along strike in the Gulf of Alaska (USGS analog data or 2009 survey data). We suggest the Patton Bay fault parallels southern Montague Island, immediately offshore, along a prominent bathymetric lineament (Figure 6) where no legacy or new seismic data were acquired. Figure 4 shows the 2009 seismic profile HB6 across the Hinchinbrook Entrance that records significant accumulations of sediment above a prominent unconformity. We interpret the near-surface reflectors to represent

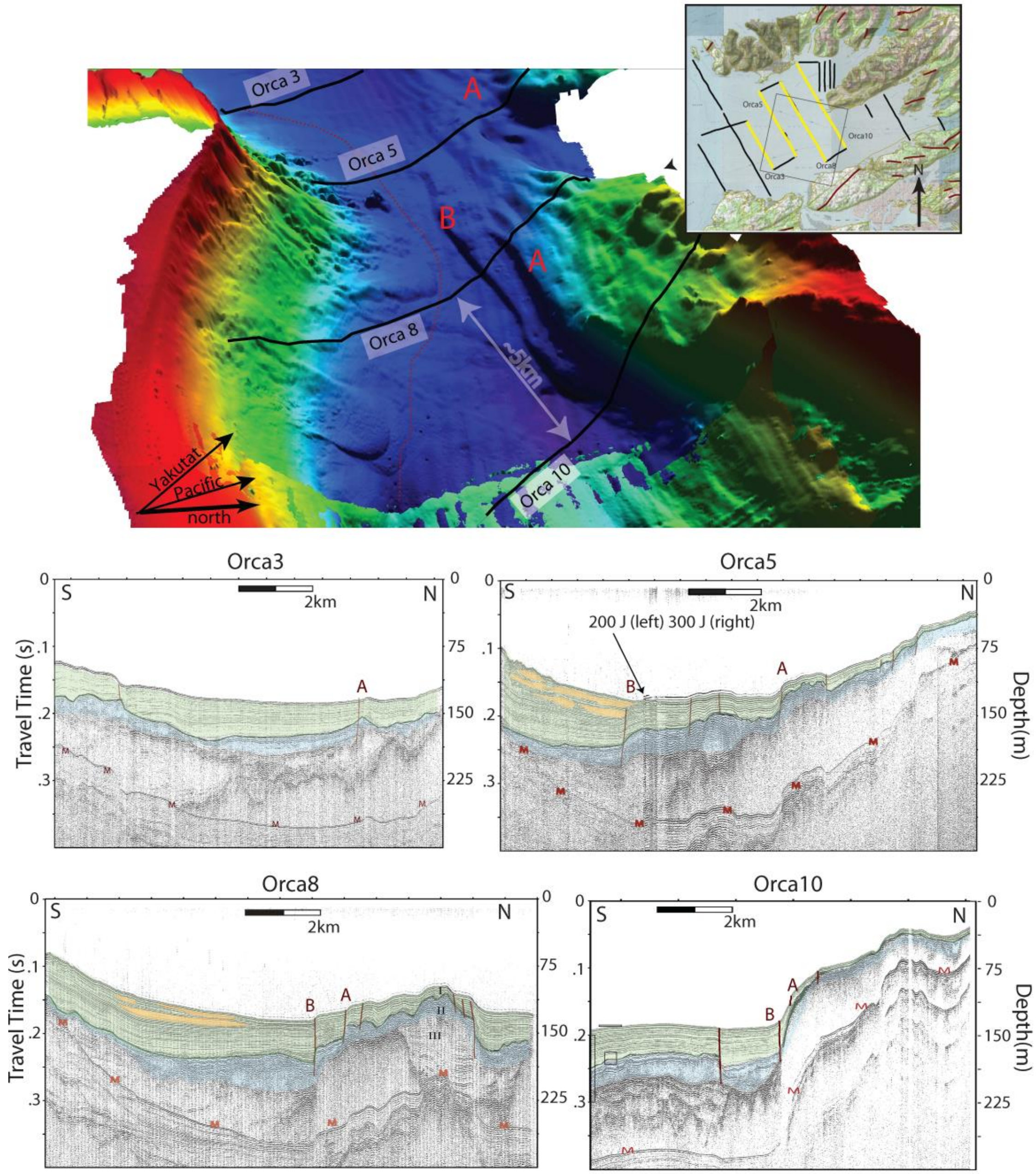

Figure 5. (top) Multibeam data showing water bottom scarps (A and B) in Orca Bay, eastern PWS that reveal ~8 m water bottom displacement. The south channel margin shows evidence for submarine landslides. Red dotted line shows the northern extent of landslide deposits. Inset map shows the study area (below) Interpreted Orca Bay sparker profiles. These profiles show water bottom scarps represent growth faults with increasing reflector offsets with increasing depth. Yellow unit represents buried land slide deposits, Green unit represents Holocene strata, Blue unit represents late-Pleistocene sediments and M= water bottom multiple. Note the change in sparker power on Orca 5. Lower power (200 J) provided adequate signal penetration to image Holocene strata with higher frequencies (higher resolution).

upwards of 200 m of broadly uplifted Holocene strata with water bottom lineations (~15 m offsets) along strike with the Rude River fault that likely record a backthrust to the megathrust splay fault (down to the north). We interpret the bathymetric high that surrounds Seal Rock to represent an additional segment of the Patton Bay (megathrust splay) fault that steps seaward to the east. We infer that the broad uplifted strata within Hinchinbrook Entrance is related to Holocene uplift of the megathrust splay fault, spatially similar in dimension to that measured after the 1964 event (Plafker, 1969; Figure 4). The change in fault orientation mapped in Hinchinbrook Entrance and Orca Bay suggests either fault segmentation or rotation beneath Hinchinbrook Entrance.

Montague Strait

We acquired ~150 km of sparker data in Montague Strait to characterize deformation related to the 1964 Great Alaska earthquake and older megathrust events. Figure 7 shows multibeam data from the Montague Strait and mapped faults on land (Wilson and Hults, 2008). A prominent northeast-trending lineament along the southeast margin of Latouche and Knight Islands represents surface rupture from recent earthquakes, likely including the 1964 event. This lineament offsets the water bottom by ~80 m, is parallel to mapped faults on adjacent islands, and offsets a ~100 m deep basin. We interpret these lineations to represent landward continuation of active faulting related to megathrust splay faults. Increasing strata offsets with depth within Montague Strait suggests these growth faults have been active throughout Holocene deposition. These lineations continue north-northeast, suggesting active faulting may extend to the northern limits of PWS, near community infrastructure and coastal towns. Additionally, these lineations extend southwest into the Gulf of Alaska and across the edge of the subducted Yakutat terrane. If these faults extend for more than 200 km and are independent seismogenic sources, the faults necessitate an updated seismic hazards model for the region. Regardless, Montague Strait seismic and bathymetry data suggest active faults within PWS are more extensive than previously documented.

The Patton Bay and Hanning Bay faults are mapped on Montague Island as reverse faults that strike N37-47E (Figure 3; Plafker, 1967; 1972; Plafker et al., 1994; Carver and McCalpin, 1998) whereas normal faults within Montague Strait strike N15-20E, with a stepover separating 2 subparallel fault strands (lineations C and D). Exhumation rates from new Apatite-He suggest ~7x difference between two sites across Montague Strait (Figure 6; Arkle et al., 2010). We suggest extension within Montague Strait accommodates the observed variation in uplift rates and that a new tectonic model to include these faults is needed.

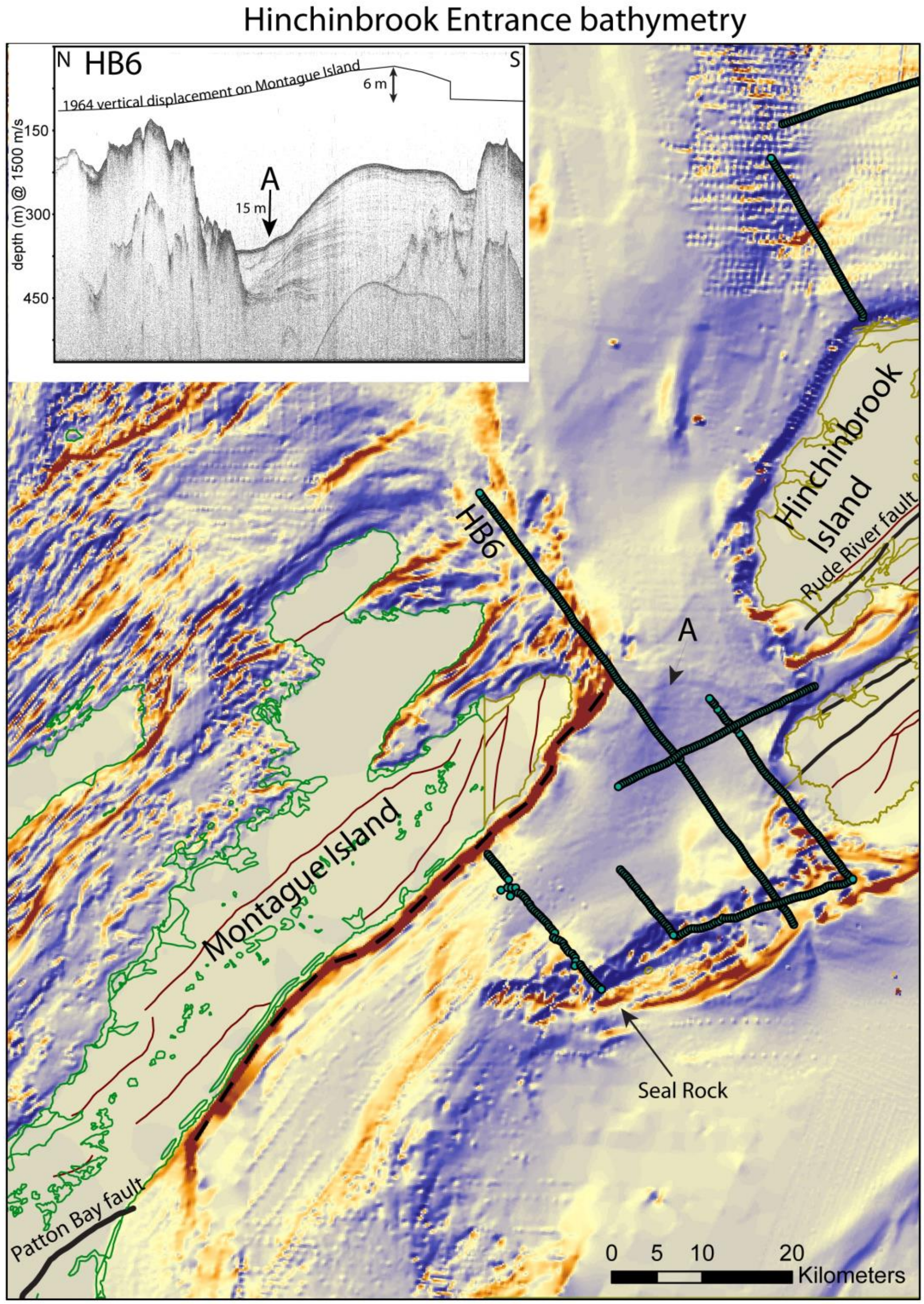

Figure 6. Bathymetry for Hinchinbrook Entrance with inset Hinchinbrook seismic profile that documents broad uplift of Holocene and older strata. Two water bottom lineations cross Hinchinbrook Entrance appear in seismic profiles as a channel margin and inflection of broad warping of sediments. Lineation A represents a 15 m water bottom offset that spans the Hinchinbrook Entrance. Vertical exaggeration on profile HB6 is ~10:1. Above the seismic image is the vertical displacement measured across Montague Island post 1964 (Plafker, 1969).

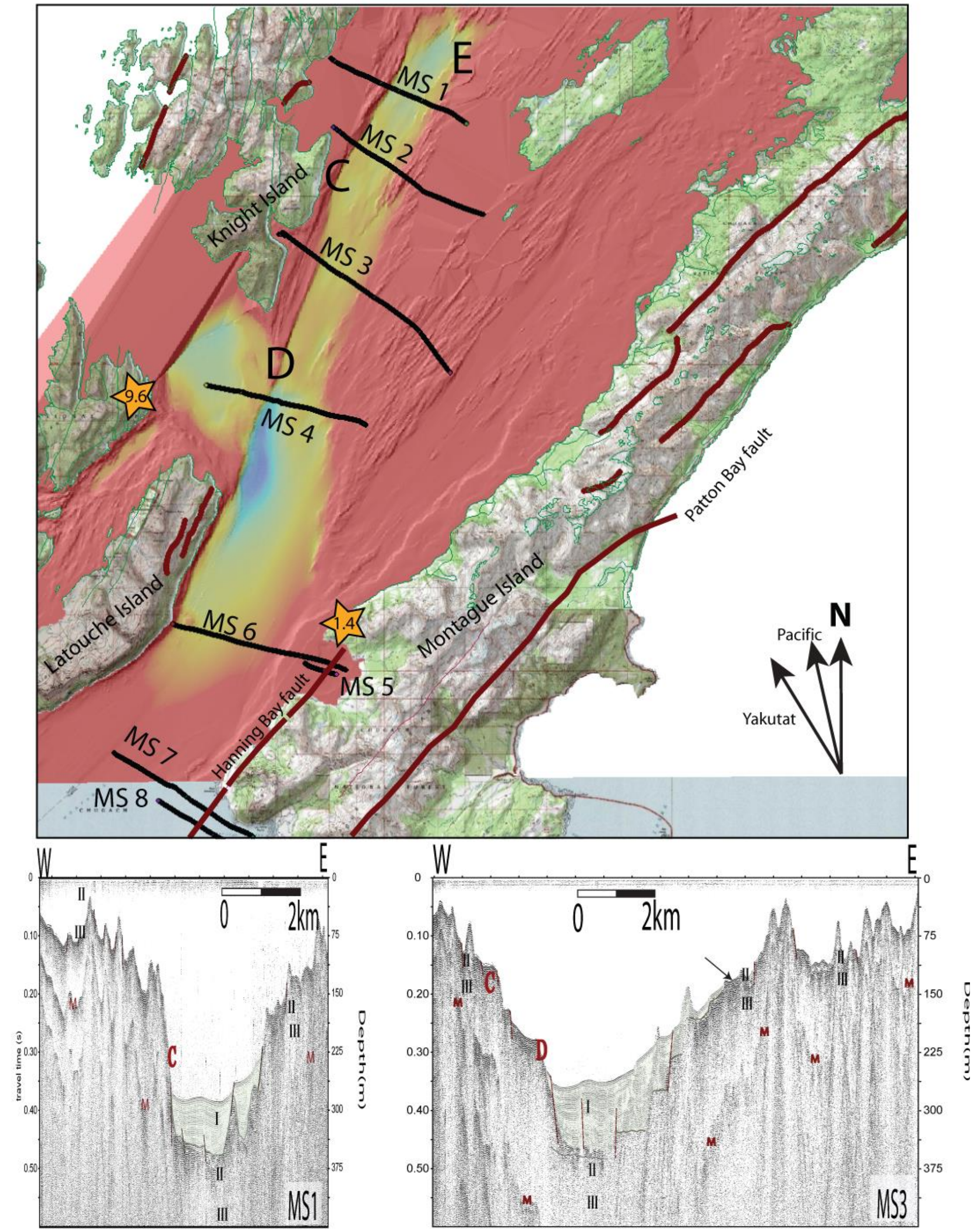

Figure 7. (top) Montague Strait multibeam image with seismic profiles (black) and faults (red). (bottom) Two FY09 seismic profiles showing Holocene sediments (Unit I), late-Quaternary sediments (Unit II) and Tertiary bedrock (Unit III). We interpret the Montague Strait graben as accommodating landward extension of the megathrust splay faults on Montague Island. Stars represent Apatite-He exhumation rates suggesting Montague Island is uplifting ~7x faster than islands to the north (Arkle et al., 2010).

Legacy seismic data

In 1974, the USGS acquired more than 1,000 km of analog airgun and sparker data throughout the Gulf of Alaska for the purposes of oil and gas leasing (http://walrus.wr.usgs.gov/infobank/t/t374eg/html/t-3-74-eg.meta.html). Many of these paper records have been identified, scanned, and converted to SEG-Y format. These data show thin to non-existent Holocene deposits offshore PWS and tightly folder Tertiary strata. Exposures of Tertiary bedrock on outer islands, the bathymetric expression (Figure 3), and seismic refraction velocities (Brocher et al; 1994) all suggest a broad uplift zone seaward of the megathrust splay faults with an overprint of post-Tertiary shortening (Figure 8).

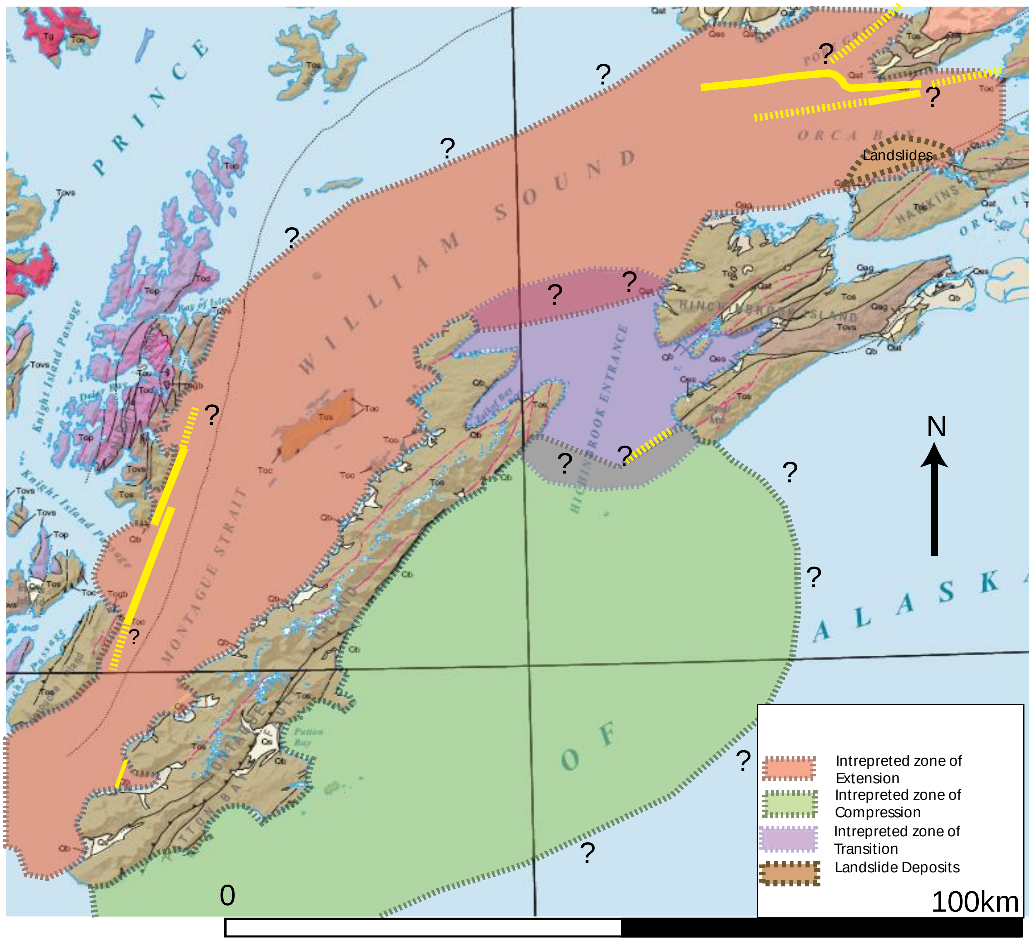

Figure 8. Regions of uplift and subsidence within PWS with newly mapped active normal faults. The red area within PWS shows fault-bounded regions where sediment is accumulating. The green zone represents areas where uplifted Tertiary strata appear at or immediately below the sea floor. The transition zone within Hinchinbrook Entrance may represent uplift and thrust faulting, however, sediment deposition from the Copper River delta exceeds uplift rates.

Southwest of Montague Island, absolute vertical displacements upwards of 20 m are identified on the sea floor (Figure 3). Unpublished USGS seismic data from 1981 along strike of the Patton Bay fault, 20 km southwest of Montague Island and west of the Yakutat subducted plate, show water bottom offsets of 12 and 5 m across two steeply dipping faults that merge at approximately 2 km depth (Figure 9). A reflector that represents the (interpreted) base of Holocene appears approximately 50 m below the water bottom, assuming 0.5 cm/yr sedimentation rate (Klein, 1983). The geometry of the identified faults on the airgun profile suggests normal faults control a half-graben that has been active throughout late Quaternary (based on progressively tilted strata). If indeed these faults represent the Patton Bay fault segments that ruptured in 1964, extension along normal faults and may significantly contribute to active deformation and tsunami generation.

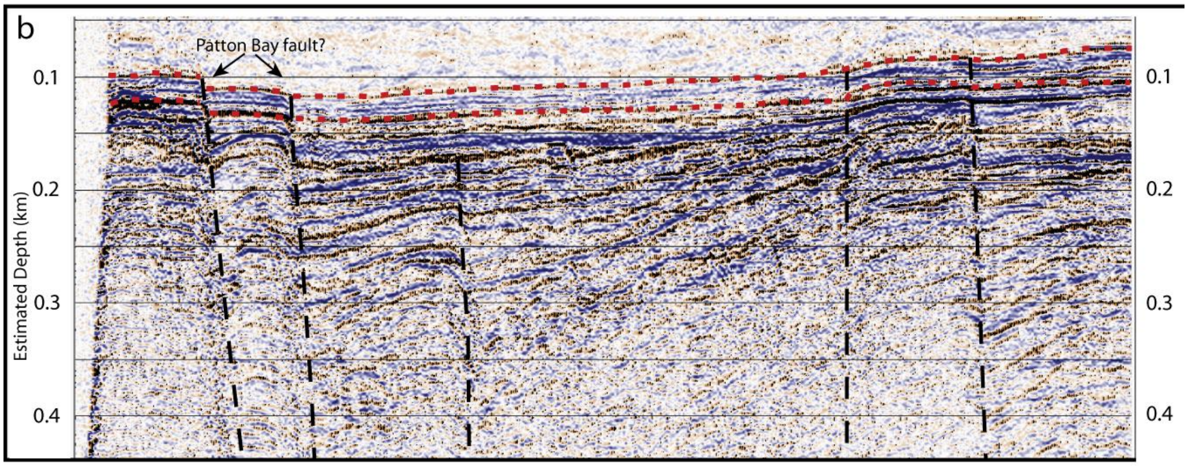

Figure 9 a) Unpublished 1981 USGS airgun profile from the Gulf of Alaska along the projected Patton Bay fault (Line B; Figure 2); I interpret graben-forming active normal faults along strike of the Patton Bay fault. Dotted line represents estimated base of Holocene deposits.

Discussion and Conclusions

A compilation of seismic images shows a pattern of sedimentation and active faulting within PWS from Montague Strait to Orca Bay. Although fault orientations rotate approximately 30 degrees to parallel Montague and Hinchinbrook Islands, a clear pattern of normal faulting suggests active extension landward of megathrust splay fault traces (Figures 5 and 7). This extension is consistent with forearc basin evolution observed in other subduction zone systems (e.g., Park et al., 2004; Moore et al., 2007; Collot et al., 2008; Figure 10). Sedimentation rates are higher in Orca Bay compared to Montague Strait. This may result from higher observed slip rates near Montague Strait and Montague Island or it may result from a larger influx of sediment from the Copper River delta that is deposited within Orca Bay.

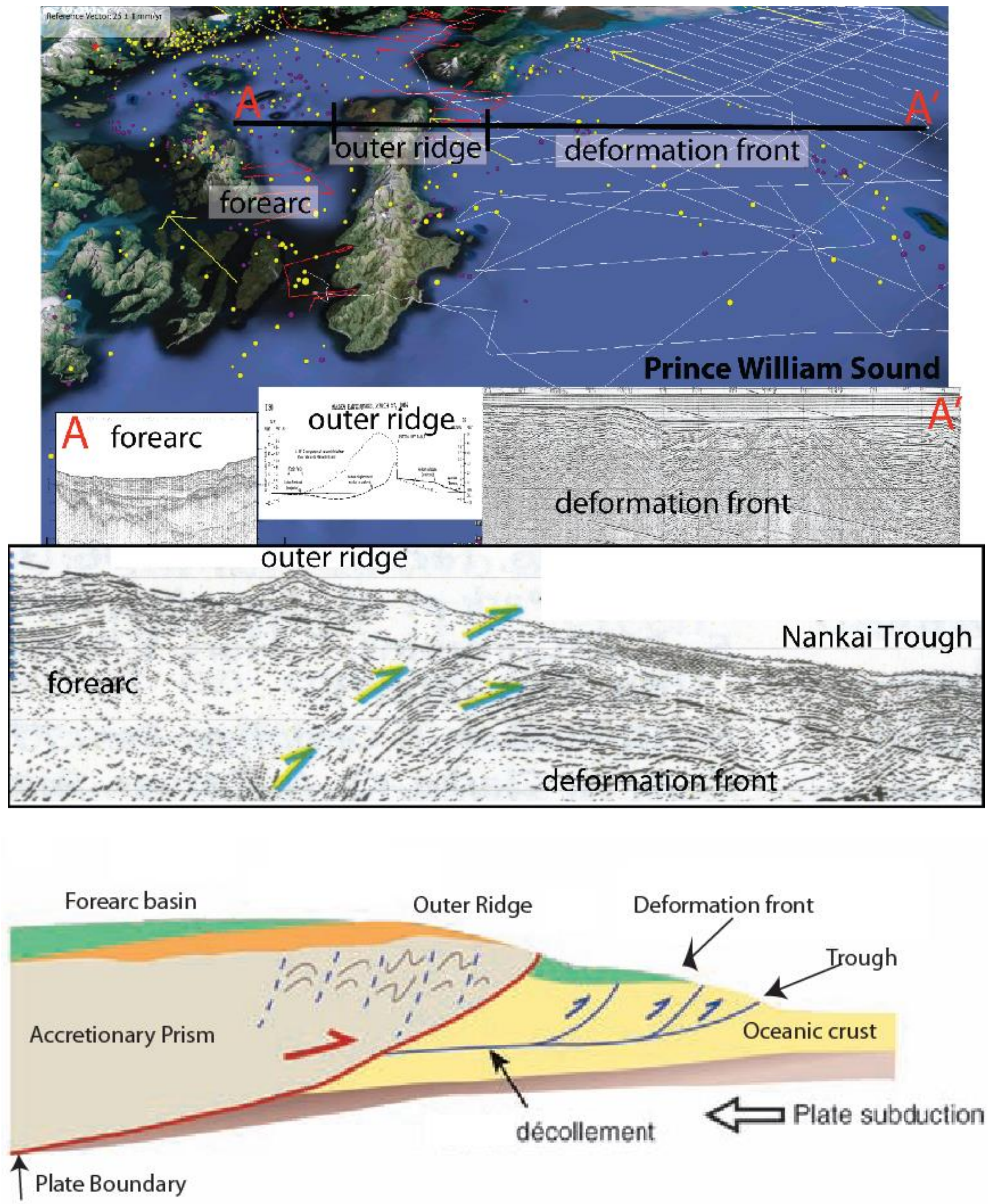

Figure 10. (top) Perspective view of PWS from the southwest showing legacy seismic profiles in the Gulf of Alaska, newly acquired profiles within PWS and seismicity. We define 3 tectonic zones, the forearc within PWS where sediment deposition and normal faulting dominate (Orca Bay, Montague Strait), the outer ridge, represented by Montague and Hinchinbrook Islands and the Hinchinbrook Entrance, and the deformation front within the Gulf of Alaska. (bottom) Seismic reflection section from the Nankai Trough showing analog to the megathrust splay fault system of PWS (Park et al., 2002) and anatomy of a generalized subduction zone in profile (revised from Moore et al. 2007).

On Montague Island and Hinchinbrook Island, uplift and megathrust splay faults surface to form the outer ridge of the subduction zone system. A broad uplift within the Hinchinbrook Entrance and bathymetric expression suggest the Patton Bay fault system extends across the region (Figures 3 and 6), but steps seaward and rotates clockwise ~30 degrees to the east. This clockwise rotation appears along strike with the Transition fault system of the Yakutat plate (e.g., Gulick et al., 2007), but may also relate to oblique extension with respect to modern GPS plate motion.

Offshore in the Gulf of Alaska, legacy seismic data reveal folded and faulted Tertiary strata immediately beneath the sea floor is analogous to the deformation front of the subduction zone system (Figure 10). Southwest of PWS, legacy seismic data suggest the Patton Bay fault system extends beyond the edge of the Yakutat block.

Acknowledgements

We would like to thank the USGS Alaska Science Center for the use of the R/V Alaskan Gyre and boat captain Greg Snedgen for his assistance in making this a professional, safe, successful, and pleasant science cruise.

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