FINAL TECHNICAL REPORT

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Title of Recipient's application:
Investigation of North-Side-Up Reverse Faults of the Seattle Fault Zone Using Uplifted and Offset Wave-Cut Platforms and Exploratory Trenching: Collaborative Research With Humboldt State University and U. S. Geological Survey

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TECHNICAL ABSTRACT
A critical question for understanding the seismic behavior of the Seattle fault zone is how north-side-up bedding plane reverse faults, which generate late Holocene fault scarps, interact with the roof thrust/floor thrust structural duplex that underlies Seattle. We conclude that the north-side-up bedding plane reverse faults that splay off the roof thrust of the Seattle fault zone are seismogenic apart from the floor thrust because investigations of uplifted shore platforms demonstrate that the reverse splay faults generate localized abrupt uplift at times when there was no regional coseismic uplift of Puget lowland shorelines. A regional uplift at 1,100 years ago involved an earthquake that nucleated at depth involving slip on both the floor and roof thrusts of the roof duplex (the 'wedge thrust'). This earthquake triggered slip on some of the north-side-up, bedding plane reverse faults that splay off the roof thrust. At locales where the north-side-up reverse faults intersect the regionally uplifted 1,100 year old shore platform, we observe that the 1,100 year ago earthquake regionally uplifted the entire shoreline of the Seattle uplift but that an earthquake only hundreds of years earlier only uplifted limited areas within hundreds of meters north of the reverse faults. We infer that the Seattle fault zone can both rupture in earthquakes that produce regional uplift (with or without surface displacement on the reverse splay faults) and produce earthquakes that rupture the bedding plane reverse faults with no rupture of the underlying floor thrust and little or no rupture of the roof thrust. This latter type of earthquake has occurred at least once in the 500 to 1000 year period precursory to the regional uplift. Therefore, the roof of the wedge thrust is not passive as originally proposed but rather can be a point of nucleation of splay fault rupture that propagates to the surface on bedding planes. In the Seattle region, flexural slip faults along bedding planes, which are rooted in deeper low angle structures, are independent seismic hazards because these bedding plane faults release strain in earthquakes at times that the deeper floor thrust continues to store seismic energy.

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NON-TECHNICAL ABSTRACT

The marine terraces that fringe the Puget lowland in the vicinity of Seattle, Washington, are uplifted during earthquakes on the Seattle fault zone. Study of the distribution and number of these terraces indicates that the marine terraces are produced by two types of earthquakes on the Seattle fault zone. One type of earthquake results in abrupt regional uplift of the Seattle area with localized surface rupture of east-west trending reverse faults. The second type of earthquake causes rupture of the ground surface by east-west trending reverse faults but does not cause regional uplift. In the second type, uplift is confined to a region of no more than ~ 300 m north of the reverse faults.

North-Side-Up Reverse Faults of the Seattle Fault Zone: Collaborative Research With Humboldt State University and U. S. Geological Survey

INTRODUCTION

The Seattle fault zone (Fig. 1) has produced multiple earthquakes in the Holocene and these earthquakes pose a major seismic risk to the Seattle urbanized area of the Puget lowland. Bucknam et al. (1992) first recognized multiple meters of abrupt uplift from wave cut platforms straddling the Seattle Uplift in the late Holocene; Bucknam et al. (1992) inferred the uplift to be recent in age, regional in extent, and earthquake caused. Using airborne LIDAR images, several late Holocene fault scarps were discovered in the Puget lowland (Haugerud et al., 2001) and subsequent investigation revealed that the scarps delineate north-side-up reverse faults that slip along bedding planes of the Eocene Blakeley Formation or the Miocene Blakely Harbor Formation. The north-side-up reverse faults on Bainbridge Island have coseismically slipped at least 4 times in the Holocene, with the two most recent earthquakes in the last ca. 1,500 years (Nelson et al., 2003). Atwater and Moore (1992) refined the age of the most recent uplift event on the Seattle fault to be ~1,100 years ago based on debris deposited in the associated tsunami. Based on the extent of the regional uplift 1,100 years ago, the lack of a surface breaking north-vergent frontal fault, observed late Holocene slip on the north-side-up reverse faults producing surface scarps and both aeromagnetic anomalies and seismic reflection data, Brocher et al. (2004) suggest that the Seattle fault zone is a passive roof duplex (a 'wedge thrust') with the north-side-up reverse faults being passive (non-seismogenic) splay faults off the roof of the wedge thrust.

A critical question for understanding the seismic behavior of the Seattle fault zone is how the north-side-up reverse faults interact with the roof thrust/floor thrust. Undoubtedly a regional uplift such as 1,100 years ago involved an earthquake that nucleated at depth involving slip on both the floor and the roof thrusts, thereby generating uplift over a broad area. But the north-side-up reverse faults (the bedding plane faults that are imaged as surface scarps on LIDAR) may be seismogenic because our field data on uplifted shore platforms, presented below, show that the splay faults generate localized uplift on surface faults at times when there was no regional coseismic uplift of Puget lowland shorelines.

At several localities along the Seattle fault zone, north-dipping reverse fault scarps intersect the coastline where a 1,100 year-old raised platform is preserved (Figs. 1 and 2). Because the Holocene scarps represent multiple late Holocene earthquakes, the intersection of fault scarps and uplifted wave-cut platforms are critical locales for further understanding the chronology and nature of faulting in the Seattle urban area. We focus our investigations at three coastal study sites with three different north-side -up reverse faults: the Toe Jam fault at the west coast of Bainbridge Island (Fig. 1), the Point Glover fault at Point Glover on the Kitsap Peninsula northeast of Port Orchard (Fig. 1) and the West Seattle fault south of Alki Point in West Seattle (Fig. 2).

RESEARCH APPROACHES

We utilize deformed shore platforms at three coastal study sites that intersect north-side-up reverse fault scarps (Figs. 1 and 2) to determine the timing and magnitude of shore platform uplift and offset associated with late Holocene earthquakes.

We assume that raised late Holocene shore platforms are uplifted coseismically by earthquakes because, in the last few thousand years, tectonically induced vertical displacement is the only viable mechanism to abruptly lower relative sea level by several meters (Bucknam et al., 1992). We also assume that the best measure of the magnitude of coseismic vertical displacement is to compare the elevation of the modern shoreline angle to the elevation of the shoreline angle of the raised platform.

The shoreline angle is the intersection of the inner edge of the shore platform and the base of the sea cliff (small open squares on profile lines, Figs. 3 and 4).

Uplifted shoreline angles are buried by colluvium from the paleo sea cliff and their elevations are determined by digging holes in the uplifted terrace seaward of the colluvial covered shoreline angle, identifying the platform (wave cut strath) in the subsurface and then projecting the strath shoreward to the base of the paleo sea cliff. Elevations (relative to mean lower low water), determined by autolevel, were tied into a tidal benchmark through surveying low tides. Accuracy of shoreline angle elevations is dependent on the elevation uncertainties of the four controlling variables: surveying uncertainty (5 mm, based on the upper limit to survey closures from multiple survey loops), inherent relief of the strath surface (relief of the modern strath surface is 0. 25 m, relief can be as large as one meter but over most of the exposed modern strath relief is about 0.25 m), accuracy of identifying the strath in soil pits (accurate within 10 mm based on observations in pit excavations) and accuracy of projecting the strath surface landward to the paleo seacliff (an extrapolation procedure subject to uncertainty as large as 1.0 m). Therefore the uncertainty in determining a paleo shoreline elevation angle elevation from elevation surveys and soil pits excavations on uplifted shore platforms, approximated by taking the square root of the sum of the squares of the uncertainties, is ~1 m. The uncertainty in projecting the strath surface landward to the paleo sea cliff dominates all other uncertainties.

The elevation of shoreline angles and the regional extent of uplifted platforms together provide data for inferring fault displacement, amount of uplift and nature of earthquakes. We determine vertical displacement on north side up reverse faults by differencing shoreline angle elevations for correlated platforms on either side of the fault. We determine uplift of a platform relative to sea level by differencing the elevation of the uplifted platform shoreline angle from the elevation of the modern shoreline angle. Finally, we identify an earthquake on the Seattle fault zone not associated with regional uplift by identifying an uplifted shore platform of limited extent that is not correlative to the regionally uplifted 1,100 year old platform.

For the heavily urbanized West Seattle site, our field work was restricted to auger holes that allowed us to identify the uplifted platform; however, we did not have enough platform elevation data to infer the elevation of shoreline angles. For the less urbanized Bainbridge and Point Glover sites, we were able to determine the elevation and number of uplifted platforms; therefore, in discussing implications of our results, we focus on the Bainbridge and Point Glover sites.

RESULTS

<u>West Seattle fault on Beach Drive</u>

The 1,100 year-old uplifted shore platform at West Seattle is offset up to the north by the West Seattle fault. The 1,100 year old platform is offset by ~ 1.5 m based on a north-northwest trending auger transect parallel to Beach Drive (Fig. 2). Structure contours drawn on the platform surface (Fig. 2) indicate that the platform is offset across a width of < 5 m. Offset of the platform is the result of either a fault that daylights to the surface, a fold above a blind fault tip at depth or a combination of faulting and folding (Fig. 2).

Deformation in late Pleistocene sediment immediately (tens of m) north of the West Seattle fault may be fault-related. In the modern intertidal zone on the upthrown side of the fault, ca. 27,000 year-old continental deposits are deformed into a series of doubly plunging folds (Kathy Troost, Seattle Urban Hazards Mapping project, personal communication, 2002) (Fig. 2).

Although one of the goals of the work at West Seattle was to further evaluate our initial observation that there may be two platforms north of the West Seattle fault and one platform south of the West Seattle fault, our field work to date does not resolve whether there are two platforms north of the fault. We were unsuccessful in penetrating down to the top of the shore platform north of the fault at sites inferred to be part of an older, higher platform because augering was hampered by > 2 m of colluvium shed off the paleo sea cliff to the east.

Toe Jam Hill fault on west coast of Bainbridge Island

The Toe Jam Hill fault intersects uplifted shore platforms on the west coast of Bainbridge Island. The Toe Jam fault is a north side up reverse fault that was trenched at five sites for paleoseismological investigations (Nelson et al., 2003). Based on three of these trenches that were dug in the sandstone and shale of the Miocene Blakely Harbor Formation, the Toe Jam Hill fault is a steeply dipping reverse fault that slips along bedding planes. Based on buried soils in two of these trenches, two earthquakes have occurred in the last ~ 1500 years, and the most recent earthquake of about 1000 years ago involved ca. 1.5-2.0 m of vertical offset of the ground surface caused by slip along 60° to 80° south-dipping bedding contacts of the Miocene Blakely Harbor Formation (Nelson et al., 2003). Although the Toe Jam Hill fault forms a scarp that trends east-west across the southern part of Bainbridge island, the scarp dies out as it approaches the west coast. The shoreline angle of the lowest uplifted platform north and south of the fault, where it intersects the west coast, is at the same elevation within the ~ 1 m survey accuracy (6.3 m versus 5.7 m) (Fig. 3). Therefore, although the Toe Jam fault ruptured the ground surface in the middle of the island 1,100 years ago, the surface displacement decreased to zero on the western end of the trace.

On the west coast of southern Bainbridge island, there are two uplifted shore platforms just north of the fault but just one uplifted platform south of the fault. The elevation of the shoreline angle of the upper platform is 9.0 ± 1.0 meters, which is the cumulative uplift from an older earthquake that uplifted the platform north of the fault, but not south of the fault, and a younger earthquake that regionally uplifted the lower platform; uplift just from the older earthquake was ~3-3.5 m (9 m minus 5.7 m, Fig. 3). Therefore, on the west coast of Bainbridge Island, there is evidence for two earthquakes in the late Holocene, an earlier earthquake that locally uplifted the platform north of the fault but was not associated with a regional uplift of the Seattle Uplift and a younger earthquake that regionally uplifted the coast-fringing shore platforms within the Seattle Uplift. The Toe Jam bedding plane high angle reverse fault slipped during both earthquakes, and slip during the latter earthquake was variable along strike with undetectable slip at the west coast of the island and measurable slip in trenches in the center of the island.

Point Glover fault at Point Glover

The headland of Point Glover is cut by the east-west trending Point Glover north-side-up reverse fault (Fig. 4). There are two uplifted platforms north of the fault but only one regionally uplifted platform south of the fault; the regionally uplifted platform south of the fault is the lower platform north of the fault (Fig. 4). The lower platform has, within a meter, the same shoreline angle elevation (~10 m) along the 0.75 km coastal extent of the platform around Point Glover from where the Point Glover fault intersects the coast on the east to where the Point Glover fault intersects the coast on the west. Furthermore, the shoreline angle of the lower platform north of the fault is, within a meter, at the same elevation as the shoreline angle of the single, regionally uplifted platform south of the fault. Therefore the Point Glover fault did not have surface displacement during the 1,100 year ago earthquake that regionally elevated the shore platform.,

The Point Glover fault vertically offsets the higher platform even though it does not offset the lower platform, and the lower platform is regionally extensive whereas the upper platform only occurs immediately north of the Pont Glover fault. Similar to Bainbridge Island, there is evidence for two late Holocene earthquakes, the older earthquake uplifted the wave cut platform just north of the north-side-up reverse fault but did not uplift a platform south of the fault and the older earthquake did not generate a regional shore platform uplift in the Seattle uplift. The older earthquake locally uplifted the platform north of the fault by ca. 3.5-4 m (12.7 minus 9.0 m, Fig. 4); this uplift was caused by slip on the Point Glover bedding plane fault. Locally the Blakely Formation dips 55°-65° north. The younger earthquake regionally uplifted the younger shore platform around the coastal fringe of Point Glover by 6-7 m (9 to 10 m minus 3 m; Fig. 4) but did not involve surface rupture of the Point Glover fault.

DISCUSSION

At sites where the north-side-up reverse faults intersect the regionally uplifted 1,100 yr old terrace, we observe that the 1,100 year ago earthquake regionally uplifted the entire shoreline of the Seattle uplift but that an earthquake only hundreds of years earlier only uplifted limited areas immediately (~300 m) north of the bedding plane reverse faults. We infer that the Seattle fault zone can both rupture in earthquakes that produce regional uplift (with or without surface displacement on the bedding plane faults) and produce earthquakes that rupture the bedding plane faults and produce only localized uplift.

Based on two observations, we infer that the earlier earthquake on both the Toe Jam Hill fault and the Point Glover fault was less than a thousand years earlier than the 1,100 year ago earthquake. First, radiocarbon ages of the last two earthquakes on the Toe Jam Hill fault, from trench data (Nelson et al., 2003), are so close as to be indistinguishable considering the resolution of the radiocarbon dating (within the 200 to 300 year uncertainty of the charcoal-derived radiocarbon ages). Second, the paleo seacliffs separating the higher and lower shore platforms immediately north of both the Toe Jam Hill fault on Bainbridge Island and the Point Glover fault at Point Glover are less than 2 m high whereas the modern sea cliff at these sites is 2.5-4.0 m high. Assuming that the sea cliff increases in height with time through the process of shoreline retreat, then the lesser height of the paleo sea cliff compared to the modern sea cliff implies that the paleo sea cliff fronting the higher of the two raised platform had less than 1,000 years to develop before it was coseismically uplifted out of reach of storm waves.

The higher and older uplifted shore platform immediately north of the Toe Jam Hill and Point Glover faults in both cases is of limited extent, extending no more than 350 m north of the respective fault scarps. Such limited uplift is indicative of slip on a steeply dipping fault incapable of producing regionally extensive uplift at the ground surface. In the case of the Point Glover fault, the extent of uplift at the ground surface is at least 250 m north of the fault (to the northern extent of Point Glover (Fig. 4)) but does not extend more than an additional ~100 m further north because the Point White peninsula on Bainbridge island (Fig. 1) does not have two uplifted shore platforms. On Bainbridge Island, the extent of uplift to the north of the upper shore platform is ~350 m because the upper platform merges with the lower platform at a distance of ~350 m north of the Toe Jam Hill fault.

CONCLUSION

We conclude that the north-side-up reverse faults that splay off the roof thrust of the Seattle fault zone are seismogenic because the distribution of uplifted shore platforms demonstrates that the splay faults generate localized coseismic uplift at times when there was no regional coseismic uplift. We infer that bedding plane reverse faults are rooted in the roof thrust and that neither the roof thrust nor the reverse faults are passive but rather can be points of initiation of earthquakes, with the resultant slip propagating to the surface on bedding planes.

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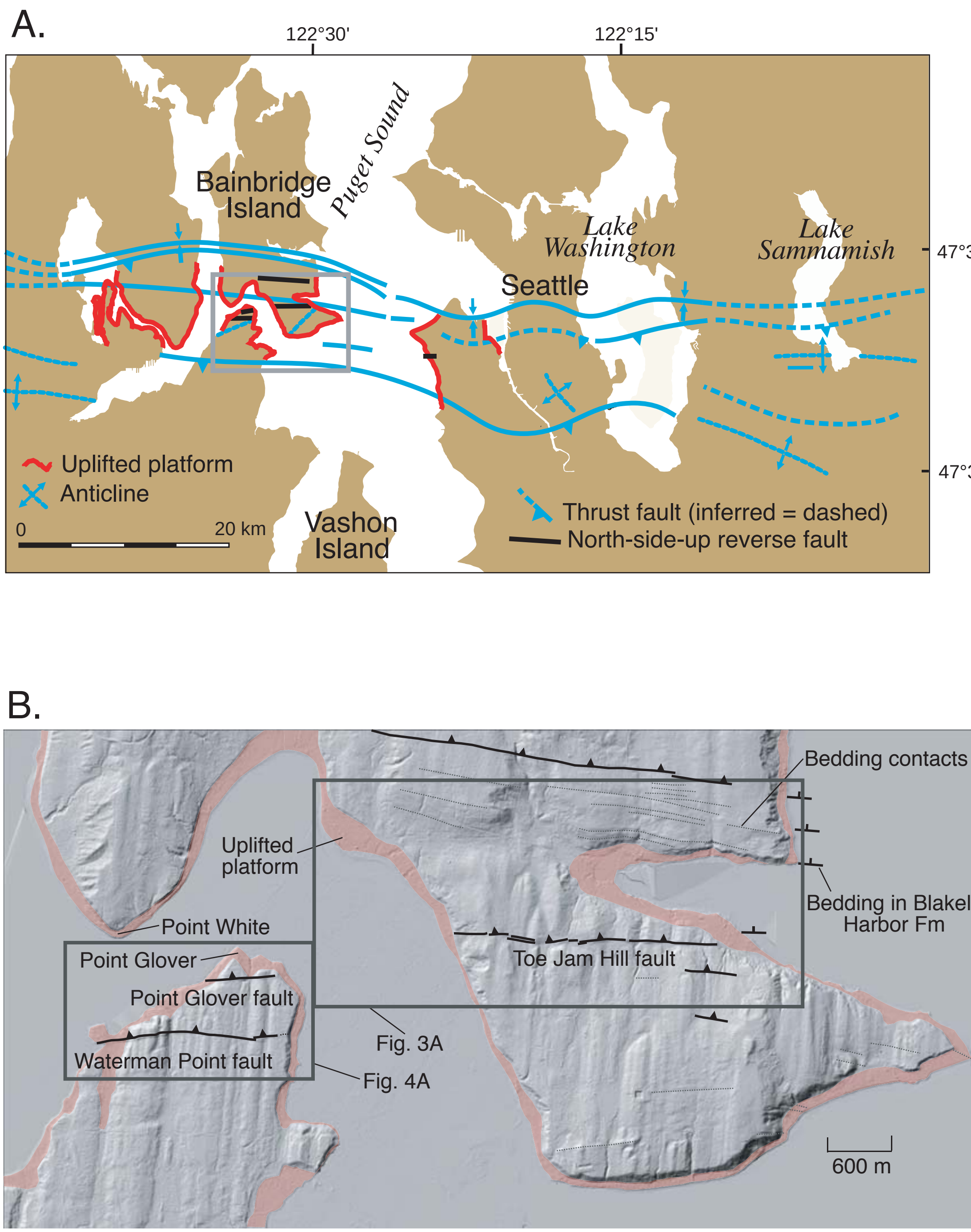

Figure 1. A. Map of the Seattle fault zone modified from Blakely et al. (2002) showing major blind faults (blue) and scarps of north-side-up reverse fauts (black). B. LIDAR image of southern Bainbridge Island and Waterman Point-Point Glover peninsula. The coastline is fringed by a shore platform (depicted in pink) that emerged 1,100 years ago (Bucknam et al., 1992). The platform is cut by three north-side-up revere faults, the Toe Jam Hill, Waterman Point and Point Glover faults.

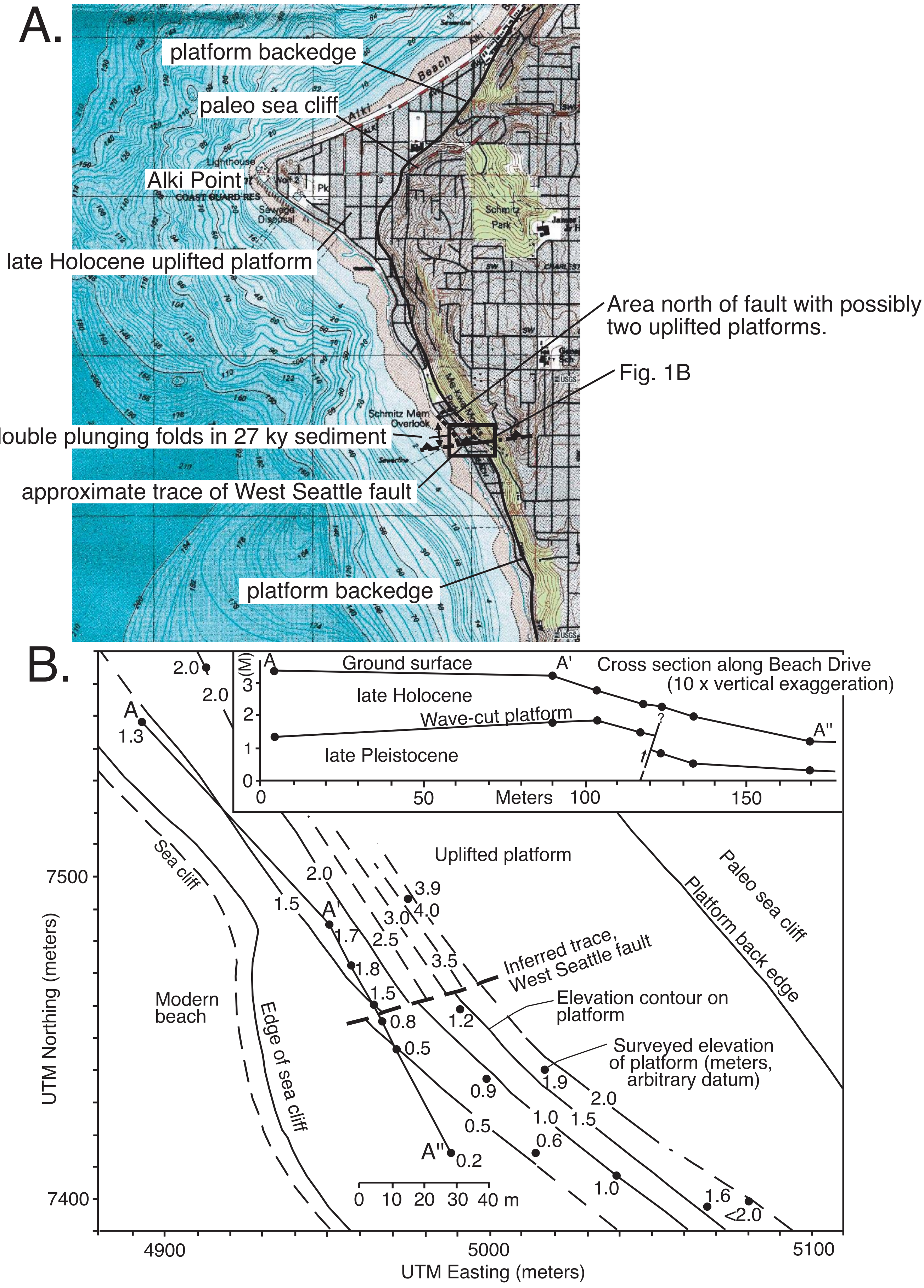

Figure 2. A. Location of trace of West Seattle fault in West Seattle. The fault was first recognized where it offsets the uplifted 1100-year-old shore platform. B. Structure contour map, derived from auger data, of the uplifted 1100-year-old shore platform. Contour interval is 0.5 m. Cross section A-A’ depicts the offset of the platform along Beach Drive.

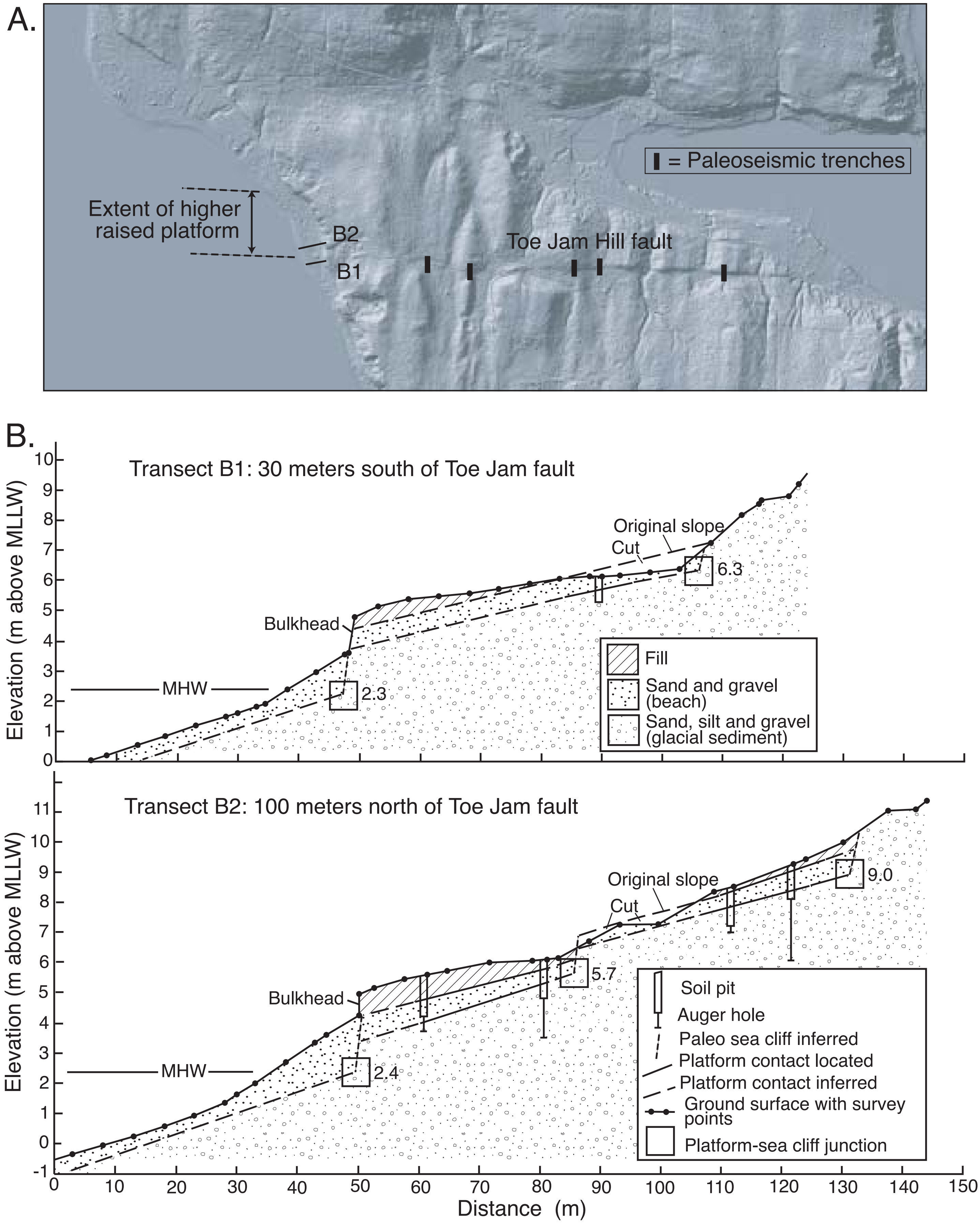

Figure 3. A. LIDAR image of a portion of southern Bainbridge Island, showing raised platforms, trace of the Toe Jam Hill fault, paleoseismic trench locations and locations of two transects (B1, B2) at west end of fault trace. B. Two coastal transects near west end of Toe Jam Hill fault, one is 30 m south of the fault trace and the other is 100 m north of the fault trace.

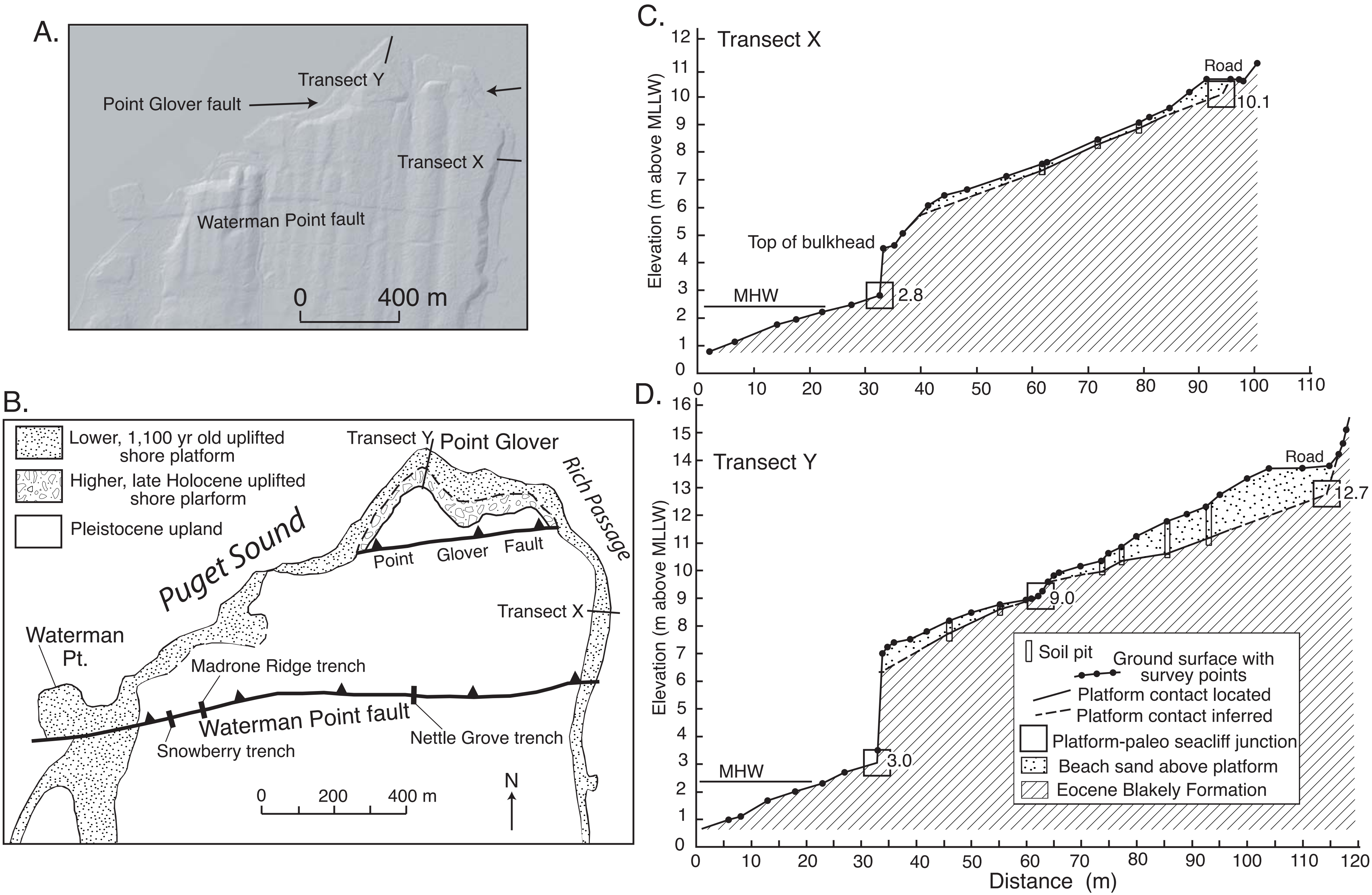

Figure 4. A. LIDAR image of the Point Glover area showing both the Point Glover and Waterman Point faults and the uplifted shore platform. B. Simplified geologic map of the Point Glover area showing the two faults, paleoseismic trench sites on the Waterman Point fault and the higher and older shore platform that is preserved only north of the Point Glover fault. C. Surveyed, annotated geologic cross section south of the Point Glover fault showing the elevation of the one uplifted platform and the thickness and extent of paleo beach deposits. MHW, Mean high water. D. Surveyed, annotated geologic cross section north of the Point Glover fault showing the elevation of the two uplifted platforms and the thickness and extent of paleo beach deposits. MHW, Mean high water.