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THE SEATTLE FAULT ZONE ON SOUTHERN BAINBRIDGE ISLAND

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NWGS Field Trip Guidebook Series

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Field Trip Guidebook #45

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***Cover photo**:* View east along south shore of Blakely Harbor at low tide (Stop 3). South-dipping beds in foreground are south-facing lignite of the Miocene Blakely Harbor Formation. Person at upper right is walking on vertical, north-facing sandstone of the Oligocene upper member of the Blakeley Formation. Dashed white line is approximate trace of Rich Passage fault.

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THE SEATTLE FAULT ZONE ON SOUTHERN BAINBRIDGE ISLAND

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I. INTRODUCTION

In an easy day's travel from Seattle one can enjoy pleasant beach walks and see outcrop evidence for deformation in a large active fault system. The trip requires a mid-day low (<2 ft MLLW) tide.

Stop 1, Stop 3, and the walk between Stops 4 and 5 are on private tidelands. In 2005 the Washington Court of Appeals did not uphold the right of pedestrian passage over private tidelands, though Davison (2006) argued that this decision was in error. Please ask for permission to travel across these tidelands. In many days upon Bainbridge beaches I have never been refused permission to travel. Do not carry a hammer. Do not collect shellfish.

The story told in this guide is based on a great deal of indirect evidence and inference. Perhaps most significant are the geophysical data (gravity, aeromagnetic, and active seismic) that indicate an east-west striking, south-side-up fault across the Puget Lowland at the latitude of downtown Seattle; see Blakely and others (2002). As is usual for the Puget Lowland, outcrop on Bainbridge Island is poor except for some upper beach exposures. Time and tide constraints prevent us from seeing all of the evidence—on another day you should walk the beaches at Manchester State Park.

Large parts of this guide are taken from "Geologic map of the Bremerton East 7.5′ quadrangle and part of the Seattle South 7.5′ x 15′ quadrangle, Kitsap County, Washington" (Haugerud, Haeussler, and Troost, in preparation).

Geologic setting

Most of western Oregon and Washington west of the Puget-Willamette trough is underlain by Siletzia, a thick pile of Early Tertiary basalt (Siletz River Volcanics, Crescent Volcanics, Sooke Gabbro, and correlative rocks) that probably formed as an oceanic plateau. Siletzia accreted to the North American plate about 50 Ma ago (in early Eocene time) (Wells and others, 2013; Miller and Umhoefer, 2013).

By latest Eocene to early Oligocene time (35-30 Ma ago) the region was a marine apron to the early Cascade volcanic arc, as shown by the wide distribution of arc-derived marine strata (Lincoln Creek Formation, Blakeley Formation, Pysht Formation, and correlative units).

Paleomagnetic, VLBI, and GPS data (Wells and others, 1998; McCaffrey and others, 2007) show that the Oregon-Washington Coast Range has been is rotating clockwise about a pivot in southeastern Washington at a rate of 1 degree per million years. Rotation has been ongoing for at least the last 15 Ma, and perhaps for most of the Cenozoic. Rotation has been accommodated by shortening (and perhaps escape) at the leading edge of the rotating block—thus the Yakima Fold Belt and its western continuation as west- and northwest-striking thrust and reverse faults in northwestern Washington. GPS data suggest that the region between Vancouver, WA and Vancouver, BC is currently shortening at about 5 mm/yr (Mazzotti and others, 2002).

The Cordilleran Ice sheet last covered the Puget Lowland (including Seattle and southern Bainbridge Island) about 16,000 years ago. As ice advanced and retreated it deposited extensive sediments. Fragmentary geologic evidence in the Puget Lowland and the marine oxygen isotope record demonstrate that numerous similar glaciations occurred in the preceding 2+ Ma. Stratigraphy of the glacial and interglacial sediments is commonly complex and deposits of different ages are not easily differentiated. Coupled with extensive vegetation, the net result is that the geologic history of the central Puget Lowland prior to the last glaciation is remarkably hard to discern.

II. TRAVEL DIRECTIONS

See Figure 1 of southeast Bainbridge Island, with route and stops, at end of this guide.

- Take Bainbridge Island ferry west from Seattle. The crossing takes about 20 minutes. As you exit the ferry,
- Turn left (west) onto Winslow Way (2nd traffic light). Go through downtown Winslow to 4-way stop and
- Turn right (north) onto Madison Ave. Go 0.3 miles up the hill to another 4-way stop and
- Turn left (west) onto Wyatt Way. In 0.9 miles Wyatt Way curves left to become Eagle Harbor Drive. Continue 0.2 miles to a Y; stay right (main strand) on Bucklin Hill Rd, which becomes Blakely Avenue. 4.3 miles from the ferry landing, at the head of Blakely Harbor,
- Turn right onto Country Club Road. In 0.2 miles,
- Turn right onto Fort Ward Hill Road. In 1.5 miles (6.1 miles from the ferry landing) the road switchbacks down to the beach, a long pier occupied by the fish-farming company, and a parking lot. Park here.

Stop 1: Near Beans Point. Tuffaceous member of the Blakeley Formation

Parking lot is on the upper member of the Blakeley Formation. Descend to the beach and walk south to good outcrops of the lower, tuffaceous member of the Blakely Formation. Note the 900CE beach surface carved across the top of the dipping beds. Observe yellow-brown weathering water-laid lapilli tuff with occasional chunks of carbonized wood.

Look for loose cobbles and boulders of distinctive black welded tuff. I haven’t found this tuff as a continuous bed in outcrop, but locally there are cobbles of it in conglomerate layers.

- Return north via Fort Ward Hill Road. At 1.5 miles, at T intersection,
- Turn left on Country Club Road. Go 0.2 miles to T intersection and
- Turn left on Blakely Avenue. In 0.4 miles,
- Veer left onto Oddfellows Road. Go 0.4 miles and

- Turn left onto W Blakely Avenue. At 0.2 miles
- Turn slightly left onto Pleasant Beach Drive. Continue about 0.4 miles into Fort Ward State Park and park at the end of the road. Toilets!

Stop 2: Fort Ward Park. Upper member of the Blakeley Formation

Walk south along beach to admire low-relief outcrops of siltstone and sandstone of the upper member of the Blakeley Formation. Bedding dips ~60° to the NNE.

- Return north via Pleasant Beach Drive and W Blakely Avenue, 0.6 miles, and
- Turn right on Oddfellows Road. In 0.4 miles,
- Merge with Blakely Avenue. At 0.4 miles,
- Turn right on Country Club Road. In 1.1 miles (past Fort Ward Hill Road, past Toe Jam Hill Road)
- Park in pullout on left above the beach. Walk east about 100 yards to Stop 3.

Stop 3: South side Blakely Harbor. Rich Passage fault

If you are feeling nimble, scramble down rip-rap to the beach. Scout about to locate a NE-trending swath of no outcrop that separates the upper member of the Blakeley Formation (to the east) from Blakely Harbor Formation (to the west). See the cover photo.

Blakeley Formation here is sandstone and siltstone, mostly with indistinct vertical bedding that strikes west, with bed tops to the north. Blakely Harbor Formation here is lignite and conglomerate that strike a bit north of east and dip moderately to the south. With some luck you may be able to find crossbeds or scours that demonstrate that the beds are upright—that is, tops are to the south. Farther west the Miocene beds face north. On the north shore of Blakely Harbor there is some suggestion that an isoclinal fold hinge is exposed on the beach.

The contact between the Blakeley and Blakely Harbor formations is the Rich Passage fault. Interpretation of industry seismic reflection data by Johnson and others (1994) and the SHIPS seismic reflection and refraction data (ten Brink and others, 2002) suggest that the Blakely Harbor Formation is at least 3 km thick in the subsurface. Yet no more than 1.5 km of Blakely Harbor section is present at the surface north of here, which leads me to infer that at this point the Rich Passage fault places Oligocene marine beds of the upper Blakeley Formation above Miocene fluvial conglomerate that is somewhere in the middle of the Blakely Harbor Formation.

Brian Sherrod (Sherrod and others, 2002; written communication, 2014) collected a tuff sample at this location that yielded a 13.3 Ma fission track age for the lowest exposed part of the Blakely Harbor Formation.

- Return to vehicles and retrace route 1.1 miles and
- Turn right on Blakely Ave. In 0.2 mile
- Continue on Blakely Hill Rd 0.1 miles, then
- Continue on NE Halls Hill Road 0.6 miles and
- Pull over at Rockaway Park and unload.

Vehicles and drivers then continue north 1.1 miles and turn right into Pritchard Park. One vehicle returns with drivers. We will walk north on the beach to Pritchard Park and send a car back to Rockaway Park.

Stop 4: Rockaway Park. Blakely Harbor Formation

This will probably be our lunch stop.

After lunch, descend to the beach and walk south a few 10s of yards to excellent exposures of the Blakely Harbor Formation. What was the depositional environment? Can you find facing indicators? Admire the fossil wood that is still flexible.

From Rockaway Park, walk north about 1.1 miles on private tidelands to Pritchard Park. The amount of outcrop varies from time to time as the veneer of beach sediment moves about. The best, and most abundant outcrops, are in the upper beach. Keep your eyes open for, in succession,

- The northern (upper) limit of the Blakely Harbor Formation
- Outcrops of the waxy silt and sand of the Rockaway Beach unit, which in places and at times looks swirled.
- Till (or conglomerate) with granitic pebbles, succeeded by thin-bedded clay, silt, and fine sandstone. This unit was not evident in Spring 2014.
- Irregularly bedded polymict conglomerate and sandstone. Break to obtain a fresh surface, use your hand lens, and observe a light colored diagenetic matrix. Zeolite?

Stop 5: Southeast corner of Pritchard Park. Deformed Esperance Sand

Good bluff exposures of sand with minor gravel. I mapped this as the Esperance Sand Member of the Vashon Drift, though the gravelly layers are unusual. Look for faulting.

Walk north to where you can easily leave the beach, read the sign about the Superfund site, and then walk the path south to where the cars should be parked. Send one car south to Rockaway Park to retrieve the car left there. Then

- Travel west along Eagle Harbor Drive 2.6 miles and
- Turn slight right onto Wyatt Way. In 0.9 miles,
- Turn right onto Madison Avenue. Ggo 0.3 miles, and
- Turn left onto Winslow Way. Go 0.2 miles and

Turn right into Bainbridge Ferry Terminal to wait for the next boat to Seattle. Eastbound passengers are free. Fares are collected for cars and drivers only.

III. STRATIGRAPHY

Blakeley Formation (Tbt, Tbu)

Fossiliferous marine strata that crop out on the south end of Bainbridge Island were named the Blakeley[1] Formation by Weaver (1912), who identified Restoration Point as the type section. These strata have been

[1] Fulmer (1975, p. 211) noted "this formational unit received its name from the nearby village of Port Blakely and its harbor. The more common geographic spelling was not retained by Weaver, possible because the name "Blakely" had been previously used by Ulrich in 1911 for a sandstone unit of Lower Ordovician age." Ulrich's Blakely crops out in Arkansas.

further described by Weaver (1916a, b, c, d; 1937), Fulmer (1954, 1975), Waldron (1967), McLean (1968, 1977), and Prothero and Nesbitt (2008). The Blakeley Formation comprises siltstone, sandstone, lapilli tuff, and rare conglomerate. Siltstone and sandstone are largely thin- to medium-bedded. Sandstones are rich in feldspar and volcanic rock fragments. Scattered grains of white mica are evident in many hand specimens. Cements are siliceous and locally calcareous. McLean (1968, quoted in Fulmer, 1975) identified clinoptilolite as a common secondary mineral.

On Bainbridge Island the Blakeley Formation strikes roughly east-west and dips moderately to steeply to the north. From Beans Point to South Point (Sec 13, 14, and 15, T24N, R2E), the unit comprises abundant thick (1 to 3 m) beds of water-lain impure lapilli tuff, with associated thin-bedded siltstone, fine-grained sandstone, and rare conglomerate. Carbonized wood fragments are common, disarticulated shells are locally present, and McLean (1977) reports that siltstone beds usually contain abundant microfossils. Thick tuff beds locally show internal cross-bedding; associated thin fine-grained beds are commonly plane-laminated. The tuff beds weather to a yellow-brown color and rounded, massive shapes. Planar bedding and lack of bioturbation in the thin-bedded part of the unit suggests deposition in deep water. Strewn upon the beach in this region are angular to rounded boulders as large 2 m in diameter of distinctive welded silicic tuff with cm-thick flattened lenses of black glass in a gray matrix of flattened pumice shards, crystals, and lithic fragments. Cobbles of the same tuff are present in conglomerate beds, suggesting that the large boulders were eroded from this unit. These beds belong to the Orchard Point Member of Fulmer (1975) and lithofacies A and B of McLean (1977). We map these beds as the lower tuffaceous member (`Tbt`) of the Blakeley Formation.

Interbedded fine-grained sandstone, siltstone, and claystone overly the tuffaceous beds. Much of this part of the unit is thin-bedded. These upper beds crop out at Restoration Point (Sec 7, T24N, R3E and most of Sec 12, T24N, R2E) and also for about a mile along the northeast shore of Rich Passage (in Sec 10, T24N, R2E). Strata are uniformly plane-bedded and locally massive. Not all bed margins are planar: incomplete bioturbation has commonly rendered the tops of sand beds irregular. Shell fragments and fossil burrows are common, as are carbonized wood fragments. These beds belong to the Restoration Point Member of Fulmer (1975) and lithofacies C of McLean (1977). We map these beds as the upper member (`Tbu`) of the Blakeley Formation.

Southwest of Rich Passage most outcrops are of the lower tuffaceous member. Exceptions are at Point Glover, and in the small bay north of Middle Point where upper-member beds lie in the core of a faulted syncline. Change in thickness of the upper member across this syncline axis, fold geometry, and changes in dip indicate that from Point Glover south to Manchester there are three panels of the lower tuffaceous member separated by north-dipping thrust faults.

Fulmer (1975) reported Refugian (latest Eocene) benthic foraminifers from outcrops along the shoreline between Waterman and Waterman Point that he thought were at the base of his Orchard Point member. Other outcrops, including much of his Orchard Point member and all of his Restoration Point member, yielded benthic foraminifers that he considered to be Zemorrian (Oligocene). Sherrod and others (2002) reported a 31.6 ± 2.1 Ma fission-track age from a pumiceous layer at Manchester State

Park. This sample is almost certainly from the lower, tuffaceous member. Rau and Johnson (1999) summarized the micropaleontology and physical stratigraphy of several deep petroleum test borings in the region. They described the Blakeley Formation as comprising lower, coarser, volcanic fragment-rich strata of Refugian age and upper, finer-grained strata of Zemorrian age. Prothero and Nesbitt (2008) reported a paleomagnetic study of the upper part of the Restoration Point section, discussed molluscan biostratigraphy, re-interpreted Fulmer's (1975) observations, and suggested that the upper member is latest Oligocene and earliest Miocene. This suggestion is not consistent with Fulmer's (1975) foraminiferal assemblage data, with foraminiferal data from the California type stages, or with the foraminiferal zonations for the Pacific Northwest (K. McDougall, USGS, personal communication, April 2013). We follow Rau and Johnson (1999) on the age of the Blakeley and show the lower tuffaceous member as latest Eocene (Refugian) and the upper member as Oligocene (Zemorrian). Elizabeth Nesbitt (personal communication, July 2013) suggests that in the Pacific Northwest the Zemorrian stage may span the Oligocene-Miocene boundary (see also Nesbitt and others, 2010).

Thickness of the Blakeley Formation is not well constrained. Neither base nor top of the unit is exposed in the map area. Our mapping suggests that the lower, tuffaceous member is at least 600 m thick (cross section B) and that the upper member is at least 880 m thick (cross-section C), for an aggregate thickness of at least 1,480 m. Earlier estimates of 1,900 m (Fulmer, 1975) and 2,500 m (McLean, 1977) for the thickness of the exposed section are inflated by structural repetition. Rau and Johnson (1999) reported thicknesses of 1,481 m to 1,966 m for intervals that they correlate with the Blakeley Fm. In all cases the sections they describe are truncated by Pleistocene erosion and original thicknesses were greater. Ten Brink and others (2002), in an interpretation of the SHIPS seismic reflection and refraction data, found the Blakeley Formation to be 1,400–1,600 m thick. Johnson and others (1994) interpreted seismic reflection records to show that within the deepest part of the Seattle basin, immediately northeast of the map area, the Blakeley is 3,900 m thick, but this estimate stems from uncertain picks for the base and top of the Blakeley and interpreted seismic velocities for which there is no direct evidence.

McLean (1977) interpreted the Blakeley Formation as deposited for the most part by turbidity currents in a submarine-fan setting. We note that more-prevalent bioturbation in the upper member suggests that it was deposited in shallower water than, or more slowly than, the lower tuffaceous member. The Blakeley is correlative with the Lincoln Creek Formation of southwest Washington (e.g., Armentrout, 1987) and parts of the Twin River Group (Snavely and others, 1978) of the northern Olympic Peninsula. The lower tuffaceous member is likely a distal equivalent of the Ohanapecosh Formation (Fiske and others, 1963) of the western Cascades province.

Blakely Harbor Formation (Tbh)

Fulmer (1975) named conglomerate-rich non-marine strata that crop out on the shores of Blakely Harbor and farther north the Blakely Harbor Formation. Weaver (1912) had included these strata in his Blakeley Formation. Most outcrops are massive to cross-bedded, basalt-pebble conglomerate and interbedded sandstone. Outcrops of sandstone, siltstone, and lignite are less common, though these less resistant lithologies almost certainly comprise the bulk of the unit. Fossil wood—much of which can still be cut with a knife—is abundant. Sandstone of the Blakely Harbor is rich in volcanic rock fragments—many of them rounded—that are pervasively altered to clay. The extent of alteration does not appear to correlate with depth below the surface, thus we infer alteration to be diagenetic and not a consequence of recent weathering. Both conglomerates and sandstones weather to a yellow brown to dark orange-brown color.

We encountered orange-brown weathering sand and mafic pebbles in an auger-hole north of Point White, on the boundary between Sec 4 and 5, T24N, R2E, and tentatively map this area as underlain by Blakely Harbor Formation.

The base of the Blakely Harbor Formation is not exposed. About 750 meters of north-dipping and north-facing Blakely Harbor strata are present along the southern end of Rockaway Beach. The preserved top of the formation is at this point closely defined, though the actual contact was not observed; overlying strata are of probable Pleistocene age. Farther south, limited outcrop along the shore of Blakely Harbor indicates folding of at least local extent. Seismic data (ten Brink and others, 2002) suggest the Blakely Harbor Formation is about 2.7 km thick. We note that if ten Brink and others' interpretation is correct, only the upper part of the unit is exposed.

Sherrod and others (2002) report a 13.3 ± 1.3 Ma fission-track age from the south side of Blakely Harbor, as well as late middle Miocene pollen.

Rockaway Beach unit (Qpor)

On the central part of Rockaway Beach, directly overlying orange-brown weathering clay-altered sandstone and conglomerate of the Blakely Harbor Formation, are distinctive, disrupted, gray waxy silt, clay, and fine sand of the Rockaway Beach unit (Qpor). Disruption of these beds ranges from irregular plastic folding—in places giving the impression that the unit was stirred with a spoon—to angular intraclasts of waxy silt in a massive fine sand matrix. Perhaps the disruption records slumping of sediments shortly after they were rapidly deposited on a subaqueous slope. The facies suggests ice-proximal deposition, and thus the weak inference of a Quaternary age. This unit is recognizable in stream exposures and roadcuts as far west as the intersection of Old Mill Road and McDonald Road in the SE ¼ of Sec 34, T25N, R2E. Along Rockaway Beach this unit appears to be about 300 m thick, though structural repetition cannot be ruled out. The irregular trace of the basal contact west of Rockaway Beach suggests an unconformity with more than 100 m relief on the top of the underlying Blakely Harbor Formation. As these beds are pre-Vashon, and are probably glacial, they must be older than the Olympia interglaciation.

Older glacial deposits (Qpog)

On Rockaway Beach, above the Rockaway Beach unit, a single basal bed of indurated pebbly till (or conglomerate), with minor granitoid clasts, is succeeded by thin-bedded clay, silt, and fine sandstone that are approximately 150 meters thick. Undisturbed planar bedding, fine grain size, and lack of bioturbation all suggest deep-water deposition of the bulk of this unit. Ripple cross-lamination in the fine sands provides excellent evidence that these north-dipping beds are upright. These outcrops include several 1- to 2-m thick layers of complexly disrupted bedding that appear to record syndepositional slumping. Basal till and evidence of rapid deposition indicate a glacial and periglacial origin.

Undifferentiated pre-Vashon deposits (Qpv)

Irregularly-bedded polymict conglomerate with thin layers of soft sandstone crops out at the north end of Rockaway Beach (NW ¼ Sec 36, T25N, R2E). Abundant cut-and-fill structures and irregular bedding suggest fluvial deposition. Unlike most Quaternary deposits on Bainbridge Island, the sandstone, as well as underlying thin-bedded fine sandstone of glacial(?) origin, has a light-colored, probably diagenetic, matrix. Irregular bedding may in part reflect subsequent deformation. Sandstone and conglomerate here appear to be about 100 m thick, and are overlain by Esperance Sand exposed in the beach bluff and in a house excavation (as of late 2005) at the north end of Rockaway Beach. The base of the bluff exposes overlying coarse cross-bedded (deltaic?) gravel that may be of pre-Vashon age.

Vashon Drift (Qve, Qvt)

During Fraser Glaciation the Cordilleran ice sheet gathered in the mountains of British Columbia and flowed south, reaching its maximum southern extent near Olympia about 16,000 ybp. The ice then retreated rapidly. Ice covered Bainbridge Island for no more than 1,500 years (Mullineaux and others, 1965; Porter and Swanson, 1998) and reached a thickness of about 1 km (Thorson, 1980).

Meltwater issuing from the advancing ice carried clay, silt, sand, and gravel deposited first as the Lawton Clay and then as the Esperance Sand. The overriding glacier then eroded, shaped, and smoothed its outwash and deposited a discontinuous blanket of lodgment till. A complex sequence of fluvial, deltaic, lacustrine, and marine sediments were deposited as the ice retreated. These glacial deposits were named the Vashon Drift by Willis (1898; see also Crandell and others, 1958).

At the north end of Rockaway Beach there are large outcrops of probable Esperance Sand. Regionally, the Esperance Sand Member of the Vashon Drift is composed of thick, commonly homogeneous, fine to medium sand, usually poorly consolidated, locally pebbly, locally with gravel layers, in places coarsening upwards. Recently published maps of the central Puget Lowland (e.g. Booth and Waldron, 2004; Troost and others, 2005) have mapped equivalent strata as "Vashon advance outwash deposits (Qva)". Subsoil developed on this unit is loose sand. These beds are advance outwash, deposited in front of the advancing Vashon glacier. At lower elevations much of the unit is massive to plane-bedded and probably was deposited in a large proglacial lake by mass sediment gravity flows avalanching off delta faces. At higher elevations, some of this unit is strongly cross-bedded and clearly fluvial. Our present understanding of Vashon glaciation (e.g. Booth, 1994) requires that at the latitude of the map area, advance outwash deposits at lower elevations (below 42+ m) cannot be fluvial; conversely, fluvial deposits beneath Vashon till at low elevations must be older than Vashon glaciation.

The Cordilleran ice sheet covered much of the Puget Lowland with a layer of lodgment till. Vashon till is mostly compact diamict rich in sand and well-rounded pebbles. Most pebbles are less than 10 cm in diameter. Only rarely are clasts larger or angular. Most debris in the till appears to have been reworked from underlying outwash; only a minor amount was carried within, or on top of, the ice sheet.

Lenses of sorted, layered material (silt, sand, gravel) are common in the till, no doubt reflecting the near-pervasive presence of flowing water beneath the Vashon glacier.

Good outcrops of Vashon till are common in shoreline bluffs. Particularly accessible and instructive are outcrops on the west side of Point White. Wave-etched outcrops commonly show foliation that is rarely evident in upland outcrops. Presumably, foliation records simple shear induced by traction from the overlying ice. Minor folds in the till, where evident, commonly have north-south axes: the rotation of folds into the transport direction indicates large shear strain.

Mapping the extent of Vashon till is challenging. Throughout the central Puget Lowland, the uppermost meter of unlithified deposits is marked by extensive bioturbation, minor addition of eolian material, clayey alteration, and variable oxidation. Many road- and stream-cuts in this low-relief landscape are confined to this weathered zone. Even where the underlying material is fine grained, the top meter is commonly pebbly and in places difficult to distinguish from weathered lodgment till. The genesis of such deposits is unclear: in some places the pebbles may be derived from up-slope exposures of pebbly deposits, but it is likely that, upon deglaciation, much of the landscape was littered with a thin skim of silt- and clay-poor ablation till that is now entirely within the weathered zone. The tendency of Vashon till to reflect the composition of subglacial materials that lie within a few kilometers in the ice-source direction compounds the difficulty: a sandy, brown subsoil with abundant small pebbles may be derived from underlying oxidized sand and gravel or may be derived from till derived from such a deposit.

IV. STRUCTURE OF THE SEATTLE FAULT ZONE

The Seattle fault zone runs east-west across the southern Bainbridge Island. The Seattle fault was first identified by its gravity anomaly (Danes and others, 1965). Bucknam and others (1992) realized that the extensive fossil beach platform on southern Bainbridge Island recorded a single magnitude 7 or larger earthquake that occurred ~1,100 years ago (the "~900 CE event"). Johnson and others (1994) suggested that the Seattle fault is a south-dipping thrust, a conclusion verified by the SHIPS seismic survey (ten Brink and others, 2002) and modeling studies that have shown that aeromagnetic anomalies and observed surface displacement are best fit by a south-dipping master fault (Blakely and others, 2002; Muller and Harding, 2005; ten Brink and others, 2002, 2006). High-resolution lidar topography and swath bathymetry have facilitated the identification of at least 7 post-glacial surface-rupturing faults within the Seattle fault zone. All are north-side-up. The three faults that have been trenched are north-dipping (Nelson and others, 2003a, 2003b; Brian L. Sherrod, personal communication, 2003).

Geologic mapping adds further details. Three classes of east-west-trending faults are evident at the surface: older, south-verging, mostly bedding-parallel thrusts that imbricate the Blakeley Formation; north-verging thrust faults, including the Rich Passage fault which separates the Blakeley Formation from the Blakely Harbor Formation; and north-dipping, south-verging reverse faults that offset the Vashon surface, for the most part are parallel to bedding, and have no obvious kinematic linkage to the other faults.

Older south-verging thrust faults

Contrast in thickness of north-facing and south-facing beds exposed in the shore of the bay north of Middle Point (see cross-section B-B′) requires that the "hinge" of this apparent syncline be faulted. We interpret this *Fort Ward fault* to extend west-southwest along an obvious topographic depression. To the east, we extend it across Rich Passage and southern Bainbridge Island along bedding in the Blakeley Formation. North of the Fort Ward fault, the anticline at Wautauga Beach appears to be a fault-bend fold related to the subjacent hanging wall cutoff. On the assumption that the fault is—at least at the surface—parallel to footwall bedding, and projecting hanging-wall bedding into the subsurface, the fault panel above the Fort Ward fault can be defined, and in this panel the tuffaceous lower Blakeley Formation is about 600 m thick. The great apparent thickness of tuffaceous lower Blakeley Formation south of Middle Point indicates the presence of the *Clam Bay fault*. We interpret the anticline at Wautauga Beach and a less well defined anticline at Manchester State Park as fault-bend folds related to subjacent hanging wall cutoffs.

Dips at Point Glover are about 30° to the north. To the south, for example at Waterman Point, dips are 60° to 70°. The difference indicates a ramp angle of about 30°. When these faults formed, flats were presumably horizontal and ramps thus had dips of about 30°. Present steeper dips probably reflect subsequent tilting above an underlying ramp on the Rich Passage fault. To the east, displacement on these faults appears to increase, leading to local flat-on-flat geometry and steeper dips.

North-verging thrust faults

On the south shore of Blakely Harbor the contact between Blakeley Formation and Blakely Harbor Formation is closely constrained to lie between upright south-dipping beds of the Miocene Blakeley Harbor Formation and, a few meters to the southeast, vertical, north-facing Oligocene beds of the Blakeley Formation (Figure 1). The discordant bedding and older-over-younger relationship requires that this juncture be a fault, which we name the *Rich Passage fault*. To the west, along the northeast shore of Rich Passage, bedding in the two units is also discordant and the Blakely Harbor Formation appears to dip gently beneath the Blakeley Formation. Between these locales we did not find enough outcrops to precisely locate this fault or ascertain its dip. Stratigraphic offset requires that the fault be north side down. To the west, the surface trace of the fault must lie north of Point Glover, beneath the waters of Rich Passage. To the east, the Rich Passage fault appears to be cut off by the eastwards projection of the Toe Jam Hill fault. There is no evidence for post-Vashon slip on the Rich Passage fault.

Attitudes and facing directions in the Miocene sandstone and conglomerate around Blakely Harbor suggest the presence of a complex anticlinorium. We interpret this anticlinorium to be a (or a series of) fault-propagation folds at the tip of a younger fault, beneath and sub-parallel to the Rich Passage fault. It is not clear whether this fault propagated to the present level of exposure; we show it only in the subsurface. Much of the tilting of Pleistocene strata exposed along Rockaway Beach—the *Rockaway Beach monocline*—is probably related to the growth of this fault.

Faults that offset the Vashon-age surface

Several north-side-up faults offset the Vashon-age surface. From north to south these are (1) an unnamed fault southwest of Creosote; (2) the *Macs Pond fault* (Islandwood fault of Kelsey and others, 2008), which has been trenched and is north-dipping (Brian L. Sherrod, personal communication, 2003); (3) the *Toe Jam Hill fault*, described by Nelson and others (2003a), which is north-dipping; 4) the *Point*

Glover fault; 5) the *Waterman Point fault*, described by Nelson and others (2003b), which dips to the north; 6) an unnamed fault west of Little Clam Bay; and 7) *the Orchard Point fault*, clearly evident in swath bathymetry east of Orchard Point. All of these are shown on the map as reverse faults because they accommodate shortening, appear to have moderate to steep dips, and only coincidentally are parallel to bedding.

The Toe Jam Hill fault may be traced via bathymetry as far east as Restoration Point and must truncate the Rich Passage fault. We hypothesize it also extends west at least as far as Point Glover. The Orchard Point fault may extend west along the south side of the Manchester Fuel Depot, where a crease in the sea floor is suggestive of post-Vashon offset. None of these faults offsets the ~900 CE shoreline platform. Kelsey and others (2008; cf. ten Brink and others, 2006) have argued for local offset of the platform by slip on the Toe Jam Hill and Point Glover faults shortly before the ~900 CE event.

~900 CE uplift of the coastal platform was more extensive than described by ten Brink and others (2006). In many locales the fossil coastal platform is not evident in the topography, but is nicely preserved beneath a mantle of landslide debris. Exposures provide minima for the amount of uplift, as they present the modern shoreline angle and a fragment of the former beach at some unknown elevation below the former shoreline angle. Along the west shore of Colvos Passage, immediately south of the map area, uplift in the ~900 CE event was at least a meter (Figure 2).

Interpretation of the Seattle fault zone

Structures of the Seattle fault zone belong to three episodes characterized by distinct deformation modes. Earliest are thin-skinned south-verging thrusts that form an imbricate fan within the Blakeley Formation. These faults were probably active early in Blakely Harbor time. The fan comprises hinterland-verging faults (backthrusts) in front of an advancing fault-cored anticline that shed debris into the Blakely Harbor basin.

The Rich Passage fault then initiated beneath the former master thrust and carried the previously-formed imbricate fan piggyback over much of the Blakely Harbor section, rotating the imbricate fan. A new fault then developed in the footwall beneath the Rich Passage fault and a complex fault-propagation fold formed in Blakely Harbor strata above the tip of the advancing fault. Significant backthrusts are not evident during this stage.

Present-day deformation, as evident from the uplifted ~900 CE coastal platform and post-Vashon north-dipping reverse faults, includes both slip on a yet-deeper blind master fault that is required in order to explain the pattern of uplift of the coastal platform (ten Brink and others, 2002; Muller and Harding, 2005; ten Brink and others, 2006) and slip on surface-rupturing reverse faults that probably root into a south-verging thrust which roofs the north-driving wedge that lies above the master fault (Brocher and others, 2004).

Transitions between deformation modes probably reflected the changing geometry of the fault system as it evolved, accumulation of the Blakely Harbor Formation and consequent change in rheology of the upper crust, and—perhaps—erosion and deposition associated with Pleistocene glaciation that also would have affected the dynamics of upper-crustal deformation.

Structure within the fault zone is complex and demonstrably not cylindrical. Sections through the fault zone of necessity are largely conjectural. Sections B-B' and C-C' were drawn with the following considerations:

- Mapped distribution of geologic units, observed bedding attitudes, and observed fault scarps.

- Holocene deformation includes both top-to-the-south slip on reverse faults that reach the surface and top-to-the-north slip on a deeper, large, south-dipping fault that generated uplift in the ~900 CE earthquake, labeled “main active strand of the Seattle fault” on section C-C’.. This large south-dipping fault does not reach the surface: there is not a near-surface fault passing through Eagle Harbor, at the north edge of the map area. The absence of a fault is indicated by seismic reflection data (Johnson and others, 1994; Pratt and others, 1997; ten Brink and others (2002) and this conclusion is consistent with geomorphic evidence.

- Top of the Blakeley Formation at the north edge of the map area is at a depth of ~3.7 km, the subsurface Blakeley Formation is about 1.5 km thick, and it overlies ~1.5 km of Eocene sedimentary rocks which overlie Eocene basalt and associated strata of the Crescent Formation (ten Brink and others, 2002).

- There is a south-verging imbricate fan (see above) within the Blakeley Formation between Point Glover and Manchester.

- Steeper dips near Restoration Point record greater shortening within the imbricate fan farther east.

- Crescent Formation is present at a shallow depth in the southern part of the map area, as indicated by aeromagnetic and gravity anomalies (Blakely and others, 2002) and seismic tomography (ten Brink and others, 2002).

- The complex deformation within the Blakeley Harbor Formation seen in shoreline exposures around Blakeley Harbor reflects a (possibly faulted) north-verging fault-propagation fold

- Absent local evidence for the relative ages of structures, we assume that deformation steps down-section and into the foreland (footwall) with time, as seen in thrust belts throughout the world.

- There has been progressive N-S shortening since the beginning of Blakeley Harbor deposition.

Perhaps the most important conclusion from the cross sections is that the top of the Crescent Formation is preserved in the shallow subsurface in the southern part of the map area, in the hanging wall of the Seattle fault. SHIPS seismic reflection and refraction data show the top of the Crescent Formation in the footwall of the Seattle fault to be at a depth of about 6.7 km (ten Brink and others, 2002), thus there is about 6 km of structural relief on the Seattle fault in the map area. Onset of Seattle fault deformation is probably recorded by the onset of Blakely Harbor Formation deposition, which is not well dated—indeed, the base of the Blakely Harbor is not exposed. A 13.3±1.2 Ma age obtained by Sherrod and others (2002) appears to be from somewhere in the middle of the Blakely Harbor section. If deposition began at about 15 Ma (ten Brink and others, 2002), the long-term uplift rate is 0.4 mm/yr. Average uplift in the ~900 CE earthquake was about 6 m (ten Brink and others, 2006). If all uplift occurs in similar earthquakes, the long-term average recurrence interval is ~15,000 years, consistent with morphologic evidence in the map area for only one post-glacial rapid uplift event, and at odds with the suggestion by Tabor and others (2011) that there were 3-4 large post-glacial earthquakes on the Seattle fault farther west. Earlier inception of Blakely Harbor deposition, and thus a slower uplift rate and a greater long-term earthquake recurrence interval, is plausible.

Total slip on the Seattle fault *in the plane of the section* can be calculated from the depth to the top of the Crescent Formation in the footwall, the elevation of the perhaps-eroded top of the Crescent Formation in the hanging wall, and the dip of the master fault ramp(s). Suggested dips on the master ramp range from ~60º (Johnson and others, 1994), to 40º (ten Brink and others, 2002), to 20º (Pratt and others, 1997), corresponding to total slips of 7 to 17½ km. We favor a master ramp dip of about 35º, thus total slip of about 10 km. If deposition began at about 15 Ma, the long-term slip rate on the Seattle fault is about 0.67 mm/yr. Earlier inception of Blakely Harbor deposition implies a slower long-term slip rate.

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FIGURES

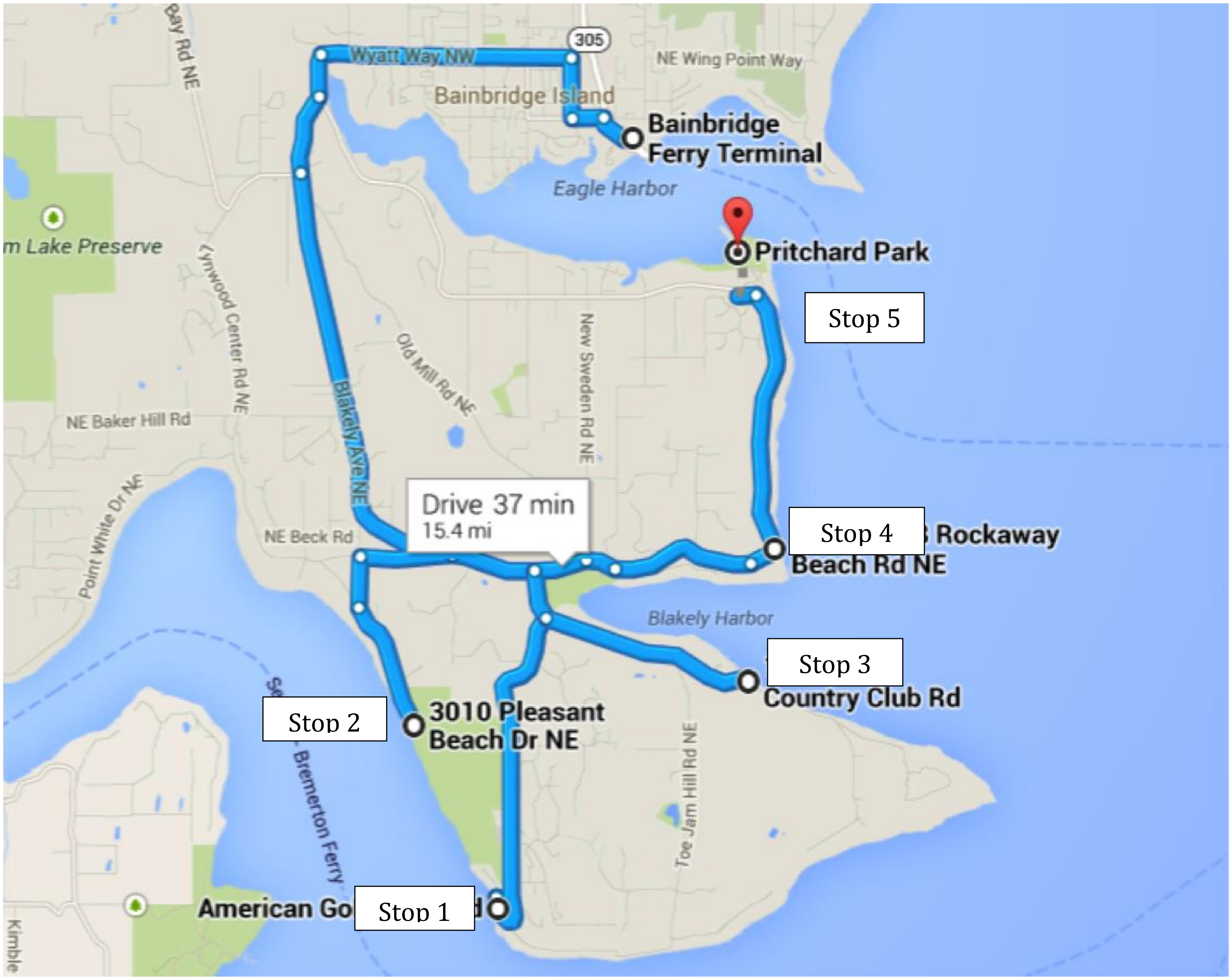

Figure 1. *Roadmap of southeast Bainbridge Island, with stops. From Bainbridge Ferry Terminal, go west on Winslow Way, north on Madison Avenue, west on Wyatt Way, south on Blakely Avenue, south on Country Club Road, and south on Fort Ward Hill Road to*

Stop 1, Tuffaceous member of Blakeley Formation
Retrace route to Blakely Avenue, then west via Oddfellows Road, W Blakeley Avenue, and Pleasant Beach Drive to
Stop 2, Upper member of Blakely Formation. Toilets.
Retrace route to Country Club Road and travel east along south shore of Blakely Harbor. Park at obvious spot where road meets shoreline and walk east to
Stop 3, Rich Passage fault
Retrace route to Blakely Avenue, turn right, and proceed to
Stop 4, Blakely Harbor Formation. Lunch?
From Stop 4 walk north along Rockaway Beach (cobbles, not sand!) about 1.1 miles to
Stop 5, Bluff outcrop of Esperance Sand

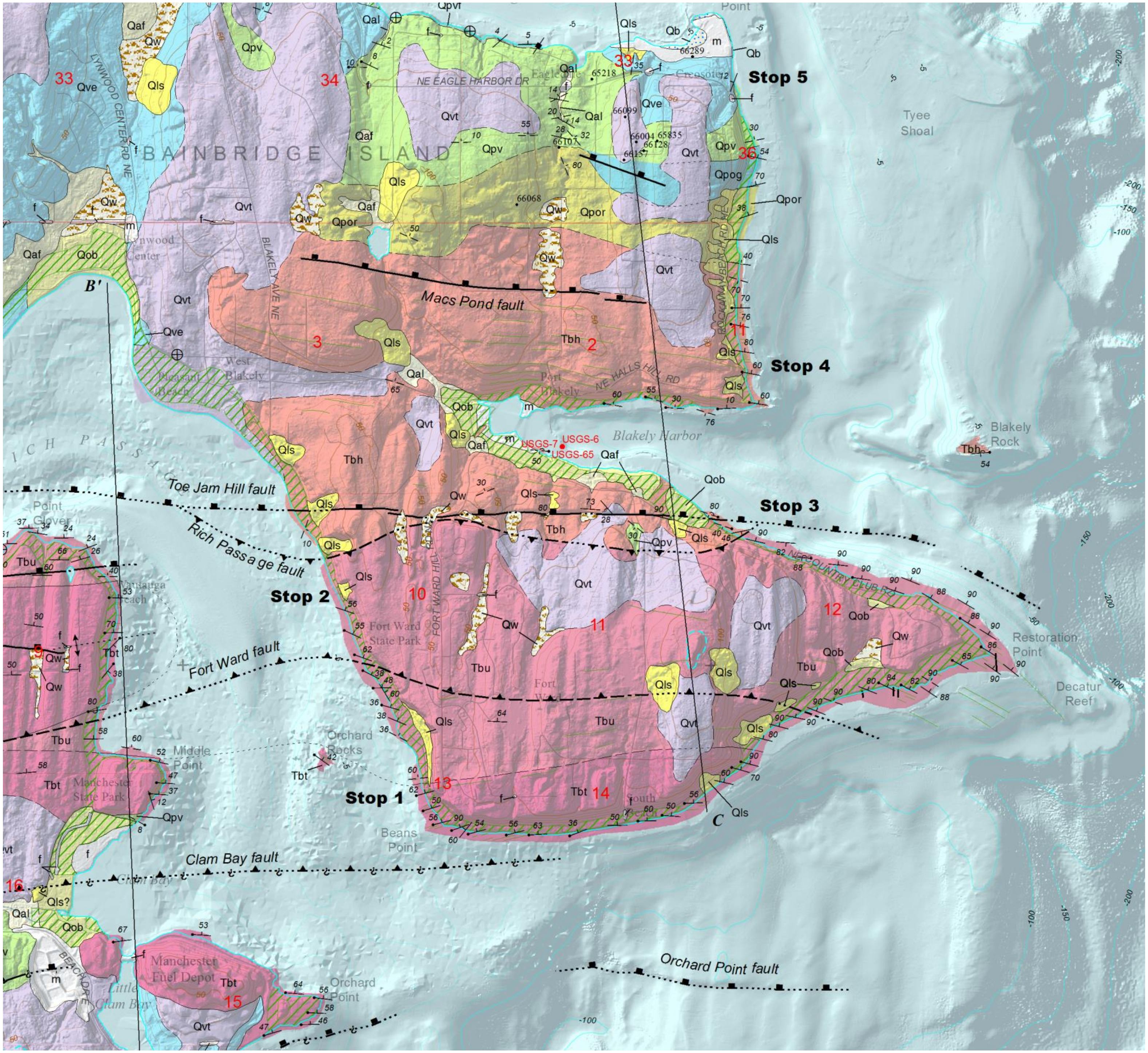

Figure 2. *Geologic map of southeast Bainbridge Island, with stops.*

m Modified land

Qb Beach deposits

Qaf Alluvial fan

Qw Wetland deposits

Qls Landslide deposits

Qob Older beach deposits

Vashon Drift

Qvt Till member

Qve Esperance Sand Member

Qpv Pre-Vashon deposits

Qpog Older glacial deposits

Qpor Rockaway Beach unit

Tbh Blakely Harbor Formation (Miocene)

Blakeley Formation (Oligocene and Eocene)

Tbu Upper member

Tbt Tuffaceous member

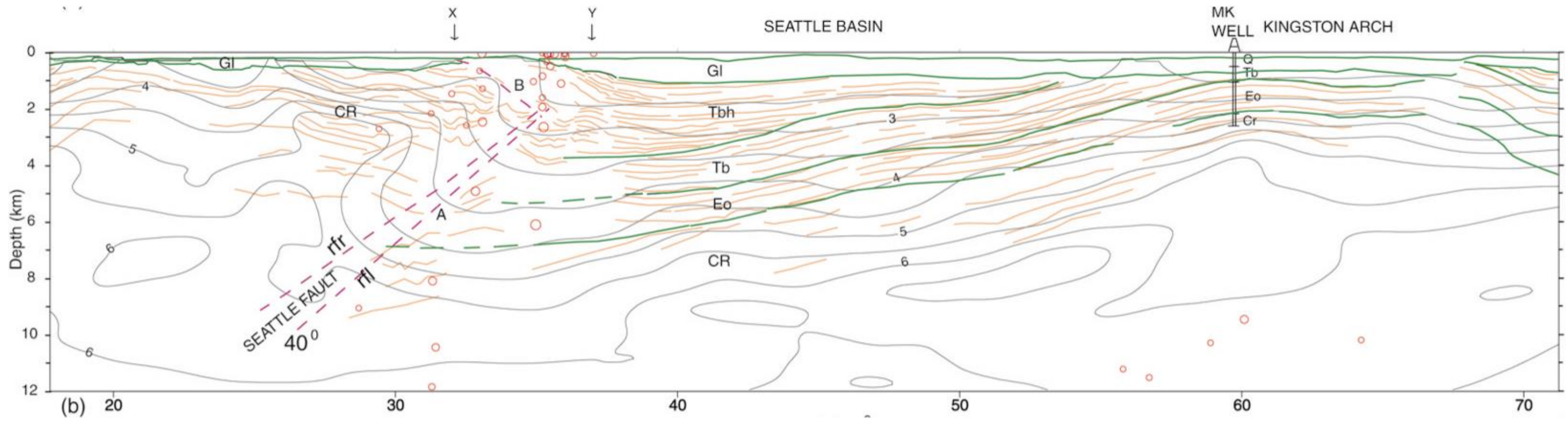

Figure 3. *Interpretation of SHIPS seismic reflection data by ten Brink et al. (2002; their Figure 2b). South at left, north at right. Horizontal axis marked in kilometers from south end of line. Southern Bainbridge Island lies west of region marked by X and Y. Gl-glacial deposits, Tbh-Blakely Harbor Formation, Tb-Blakely Formation, Eo-Older Eocene sedimentary rocks, CR-Eocene Crescent Volcanics.*

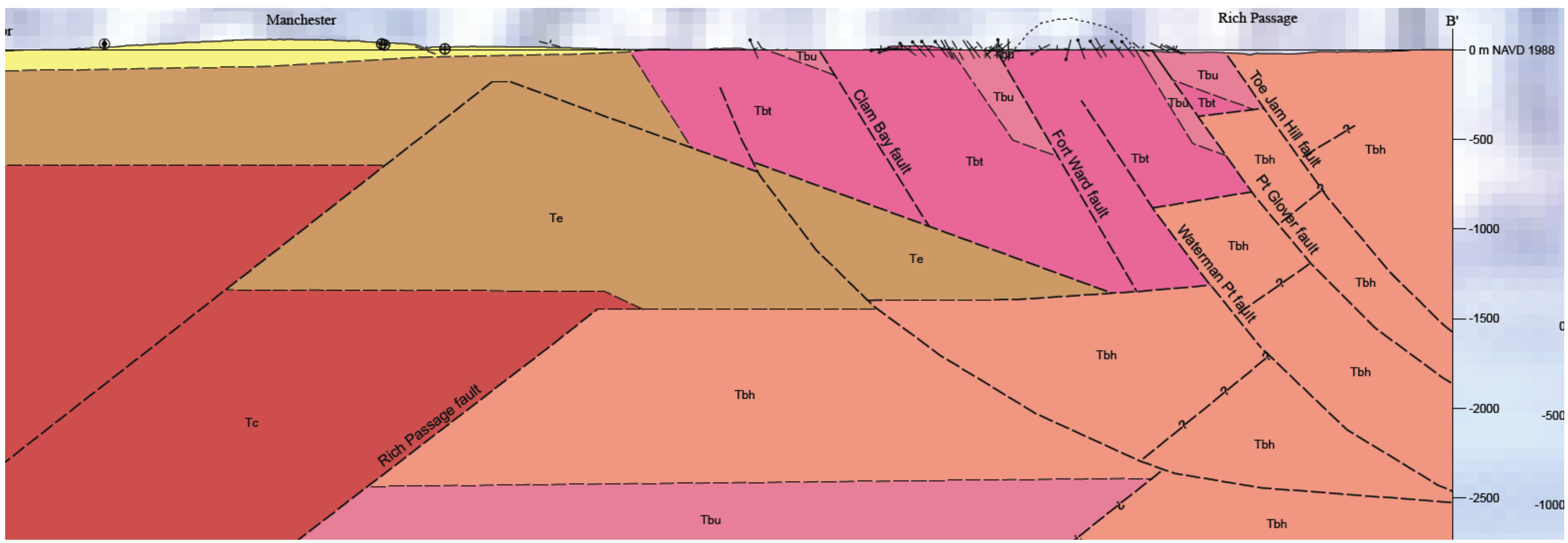

Figure 4. *North end of section B-B', through Manchester. North to right. Te = unnamed sub-Blakeley Eocene strata, Tc = Crescent Volcanics. Other units as shown on geologic map. Depths in meters. No vertical exaggeration.*

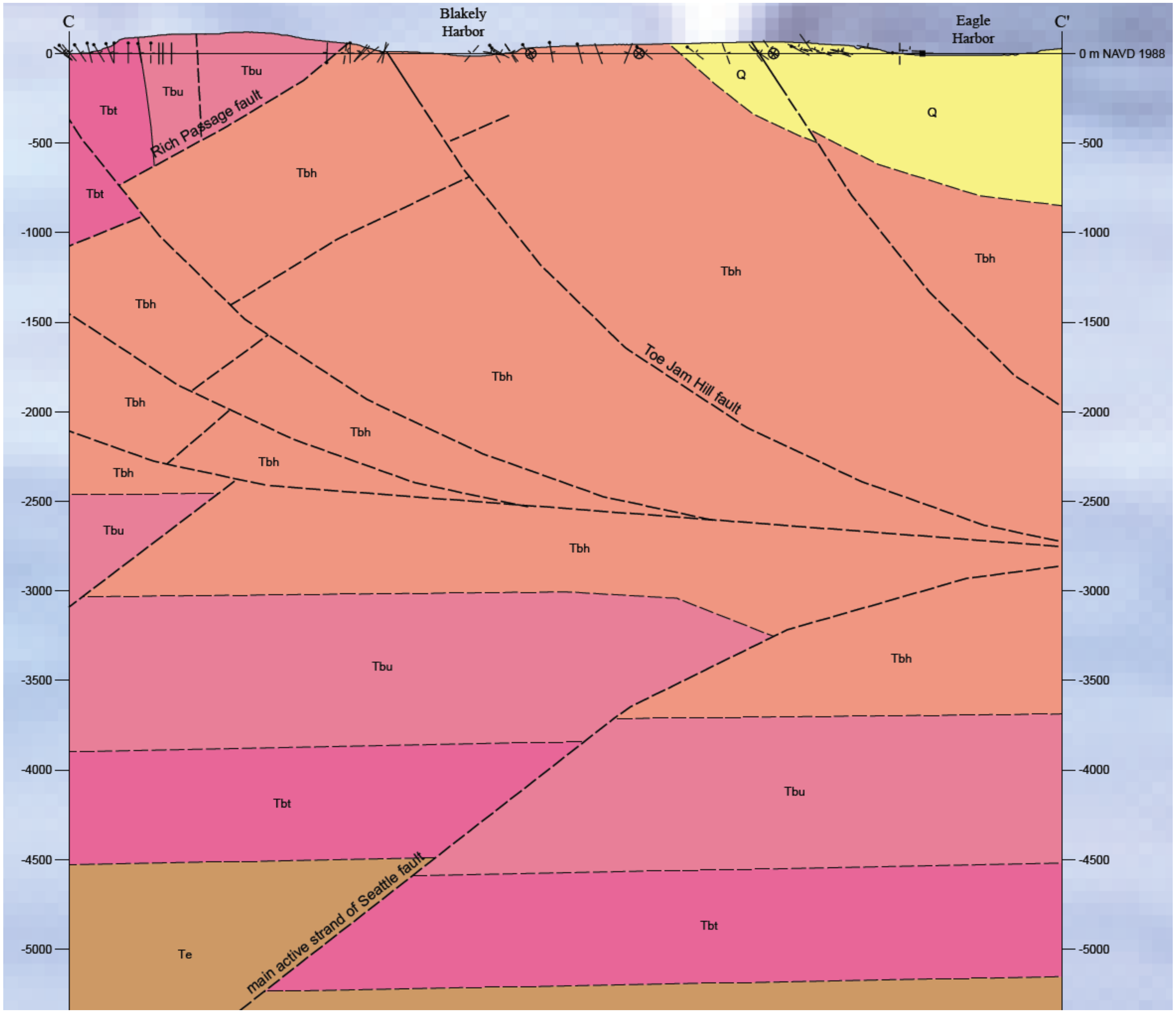

Figure 5. *Section C-C', across southeast Bainbridge Island. North to right. Depths in meters, no vertical exaggeration. Te = unnamed Eocene strata beneath Blakeley Formation. Other unit labels as on geologic map.*