

QUIMPER GEOLOGICAL SOCIETY

MARROWSTONE ISLAND—NODULE POINT FIELD TRIP

INTRODUCTION

This half-day field trip is a beach walk along a portion of the east side of Marrowstone Island, leading to a geologic inspection of Nodule Point, where we see cemented concretions (not nodules) in sandstone, a basalt dike that intruded and baked the sandstone, and a concretion-strewn beach (at lower tide levels). It is designed as a group field trip (tens of participants with social distancing, etc., during the pandemic), but it can be done easily by individuals in small groups. *Be prepared to get your feet wet, so comfortable rubber boots or water shoes are recommended.* This casual walk takes three hours for the 4-mile roundtrip, plus an hour to investigate the geology at Nodule Point.

OVERVIEW & HISTORY OF AREA

Nodule Point is on the southeast side of Marrowstone Island, one of two N-S elongate islands east of the Quimper Peninsula. These islands were first named the “Craven Peninsula” in 1841 after Pacific Coast explorer Lt. Thomas Craven, a member of Charles Wilkes expedition (Patrick, 2016). This name has left modern usage; it’s not a peninsula, and the two land masses are called Indian Island (on the west) and Marrowstone Island (on the east; Fig. 1).

Marrowstone Island, our field-trip target, takes its name from Marrowstone Point, the northernmost point on the island. (Russell and Bean, 1978). It was given the name “Marrow-Stone Point” in 1792 by the British explorer George Vancouver after the area’s hard, clay-like soil (mostly likely soil on glacial till).

The Craven Peninsula was populated by native Americans until the late 19th century when they were displaced by homesteaders who came for the farming, fishing, and

forestry. Nordland, the only town on the two islands, was established in 1892 by Peter Norby. The community lived a peaceful rural lifestyle until 1914, when the State was convinced that shipping from Port Townsend to the south would be aided by a more direct route (Russell and Bean, 1978; Patrick, 2016). For a grand sum of \$73,332, the Seattle Bridge and Dredge Co. was hired to cut a 4,000-foot-long, 75-foot-wide channel (formally named the Port Townsend Shipping Canal) through a low natural isthmus that connected Port Hadlock to Indian Island (Fig. 1), thereby isolating the residents from the Quimper Peninsula (location of burgeoning Port Townsend). Construction was more complicated than expected: sandstone had to be blasted from the 15-foot-deep cut. Soon thereafter, a ferry was established just north of the cut. At the time, most resident travelled to Port Townsend by small boat, but motor vehicles were becoming commonplace.

In 1941, with the advent of WWII, the U.S. Government took possession of Indian Island in order to build an ordnance depot and shipping center for the Navy’s Pacific Fleet. There was a fairly large population of military and civilian workers living on the island until about 2004, when the operations were switched to military supervision of subcontractors, and most of the housing was removed. Indian Island is a major U.S. Navy munitions-handling facility. Navy combat ships and Military Sealift Command vessels frequent Indian Island’s dock, receiving and discharging ordinance from the Pacific theatre. The Navy also services refitted Ohio-class missile submarines at Indian Island. This is why public access to that island is prohibited.

After WWII, local residents started to lobby the state to build a bridge across the Port

Townsend Shipping Canal, which by now was 37 years old. In 1952, the 670-foot-long “Portage bridge” was built for a total cost of \$321,000, thereby reestablishing direct transportation on State Route (SR) 116 from Port Hadlock to Nordland and Fort Flagler, one of three military bases that guarded the entrance to Admiralty Strait and the northern Puget Sound. In 2019, Marrowstone Island had a population of about 830, but that is expected to grow because they now have a potable water supply from Port Townsend. The island has suffered from salt-water intrusion in its local aquifers (Sinclair and Garrigues, 1994).

Scow Bay is the water body between Indian and Marrowstone islands. It is a shallow, glacially excavated bay and until recently was closed at the south end by a natural isthmus. This was breached in 2020 by the U.S. Army Corp of Engineers and local partners in order to promote fresh sea-water exchange between Scow Bay and Oak Bay to the south. By the fall of 2020 construction of the new channel and elevated causeway was complete, allowing strong tidal flow through the isthmus and enhancing water quality and fish (salmon) habitat in the bays. It’s becoming a favorite kayak route to circumnavigate either or both islands.

GETTING TO NODULE POINT

From the small community of Port Hadlock (6 miles due south of Port Townsend), take SR 116 to the east (Fig. 1). After passing the south end of Port Townsend Bay (to the north), turn left and continue on SR 116, crossing the Portage bridge (1.75 miles so far). We will pass the secured entrance to Indian Island Naval Reserve and skirt the south end of the island. About 2 miles past the bridge over the cut, we cross the new, low bridge at the south end of Scow Bay. From there, continue left and head north on SR 116 to Nordland. One-quarter mile past Nordland, turn right onto East Beach Road and proceed to the end. There is a small

parking lot (8-10 car capacity) at the county park. Note: a second access point is shown on Figure 1. This access is via a private road, to be used only by permission of the landowners above Nodule Point.

BEDROCK GEOLOGY OF THE ISLAND—OVERVIEW

The bedrock geology of the Marrowstone area is poorly understood mainly owing to limited exposures. The entire surface of Marrowstone Island, and Indian Island to the west, is covered by glacial debris. Thus, exposures of bedrock are limited to low bluffs primarily on the south halves of each island. Unexposed E-W faults are presumed to drop the Eocene bedrock out of view to the north.

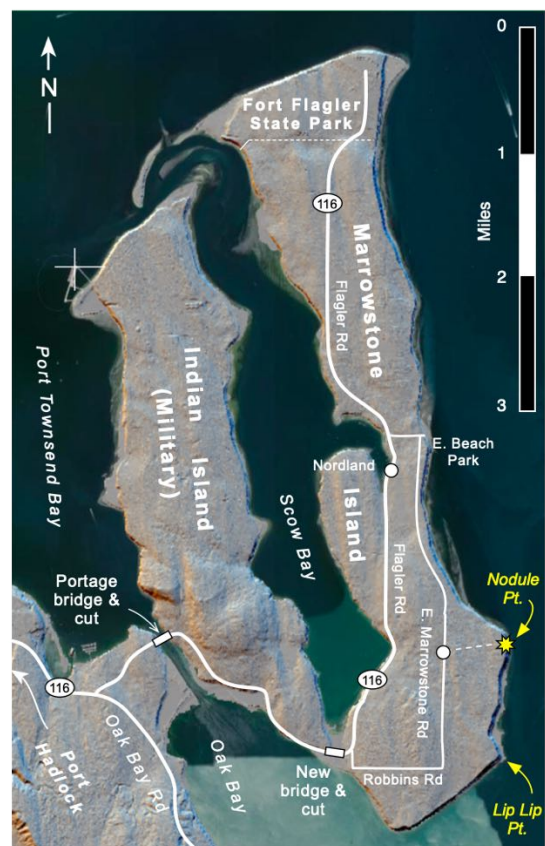


Figure 1. Map of Craven Peninsula showing access points to Nodule Point. Port Hadlock is located on SR 116 just off map. Image from Jefferson County map server.

Two types of bedrock units are exposed on the islands (Sinclair and Garrigues, 1994). The first are Eocene sedimentary rocks: the Marrowstone shale, underlain by Quimper sandstone, and below which is the Scow Bay unit, a marine sandstone and claystone (Fig. 2). These units dip gently to the north, so we climb up section as we go north on the islands. Melim (1984) studied these sedimentary units for a MSc. thesis at Western Washington University in Bellingham. Prothero and others (2009) show the geologic units in Figure 2, although they show the sandstone of Scow Bay as an “unnamed unit.”

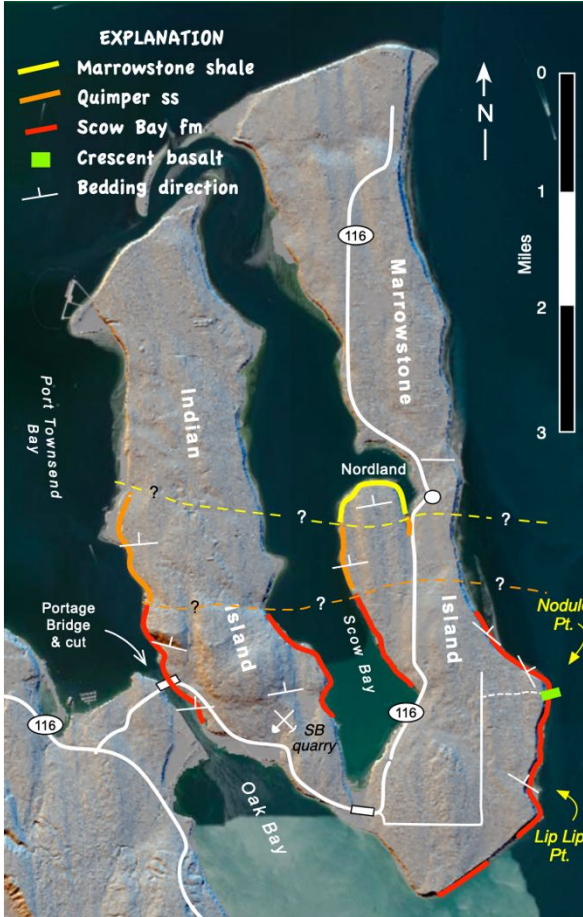


Figure 2. Bedrock map of “Craven Peninsula.” There is no recent mapping of bedrock for most of Indian Island. Units dip gently to north and east (at Nodule Point), whereas dips of 30°-50°N are found beneath Portage Bridge. Geology sources cited in text.

Further details of the bedrock stratigraphy can be found in Armentrout and Berta (1977).

The Marrowstone shale is last seen west of Nordland. From here north, bedrock appears to be downfaulted by faults covered by glacial deposits. Where exposed, such as at Nodule Point, the deposits of the Scow Bay formation (informal unit) are well washed, medium-grained, light gray sandstone intercalated with lesser gray claystone, all of which were deposited by rivers on a broad coastal plain from uplands to the east. These uplands were part of Siletza, an exotic terrain rafted in from the south (Eddy and others, 2017). This happened well before the Olympic Peninsula rose from the Pacific owing to underplating above the Cascadia Subduction Zone. The Scow Bay unit was informally named by Allison (1959) for outcrops along Scow Bay. It will be referred to as the *sandstone of Scow Bay*, hereafter. The age of the Scow Bay unit is based on fossil assignments to the late-early to early-middle Eocene (*Ulatisian* or *Lutetian*), which is now considered to be from about 48 to 41 Ma (Geological Society of America, 2021).

Series	Unit (age)
uppermost Pleistocene	Vashon drift (16-14 kyr)
<i>Major unconformity</i>	
Eocene, lower to middle	sandstone of Scow Bay (48-41 Ma)
	Crescent Fm. (basalt, 53-48 Ma)

Table 1. Units exposed at Nodule Point. Note disparity between age of intruding basalt and sandstone of Scow Bay (*Ulatisian*, 48-41 Ma). Ma, millions of years; kyr, thousands of years.

The second type of bedrock is associated with early Tertiary basalts in the Olympic Mountains, specifically the Crescent Formation.

Although no radiometric dating has been done here, the dike could be a young phase of nonmarine and marine basalt flows that form resistant beds exposed on the north and east margins of the Olympic Mountains. More isolated remnants are mapped along the coast to the south (Mats Mats Bay) and around Port Ludlow, about seven miles due south of Nodule Point. The Crescent basalt is well dated from many areas where it ranges from about 48 to 53 Ma, but younger eruptions must have occurred, such as the intrusive dike at Nodule Point. (See Eddy and others, 2017, for discussion of age determinations.)

COMMERCIAL USE OF SANDSTONE

Early in Port Townsend's history, and after several catastrophic fires, sandstone became the preferred building material (along with brick, later). In the late 1800s, the sandstone of Scow Bay became the local building stone; it was mined from a quarry on the southeast side of Indian Island (Fig. 2) and shipped to town. Bill Kalina, the current biologist/ ecologist for Naval Weapons Center, confirmed that it is the likely location of this long-forgotten quarry, which is now overgrown by trees.

In 1874, the sandstone was used for the building that houses *The Leader*, Port Townsend's weekly newspaper (Fig. 3). It was the first substantial stone building in Port Townsend and the only sandstone of Scow Bay building that still exists in Port Townsend. Its sandstone blocks show the effects of weathering in the past 100+ years; sometime after 1933, the entire exterior of the building was painted to protect it from further weathering.



Figure 3. *The Leader* (Fowler) building is built of sandstone from Scow Bay (date of photograph around 1933 or later); from *The Leader* (2021).

The Chuckanut sandstone was a more commonly used and superior building stone in Port Townsend. The Post Office (Federal) building and downtown buildings such as The Old Whiskey Mill, Earthen Works, and Sirens Pub, to mention a few, are built with the Chuckanut sandstone

Rocks belonging to the Chuckanut Formation are found in northwestern Washington and northward into south-western British Columbia. Its namesake is Chuckanut Mountain, about 5 miles south of Bellingham. The deposits include plant fossils (*e.g.*, palm fronds) that indicate a subtropical coastal plain. The Chuckanut Formation is Eocene, deposited from about 54 Ma to 42 Ma (million years ago) and thus appears to be coeval with the sandstone of Scow Bay. See Wikipedia (2021a) for more information on the Chuckanut Formation.

QUATERNARY GEOLOGY OF THE ISLAND—OVERVIEW

Separating the glacial sediment cover of Marrowstone Island and its bedrock platform is a 40 million-year (Myr)-plus time gap (unconformity). Much of the bedrock must have been eroded in late Tertiary time as the Olympic Mountains were thrust upward as a result of the collision of the underlying tectonic plates. However, another culprit for the

unconformity is the numerous (perhaps a dozen) glacial advances that pushed southward out of coastal British Columbia and northwestern Washington in the Quaternary (past 2.6 Myr). They filled the Puget Sound lowlands and the Straits of Juan de Fuca. These massive glaciers acted as geo-bulldozers, plowing and displacing older rock and glacial deposits as the ice lobes advanced to the west and south, deep into Puget Sound.

The Puget lobe, which is one of the largest and the most recent ice lobe, entered Washington from Canada about 30,000 years ago and was 3,000-4,000 feet thick in our area by about 18,000 years ago (Fig. 4); by 15,000 years ago it had wasted away leaving till and outwash over much of the lowlands of Puget Sound.

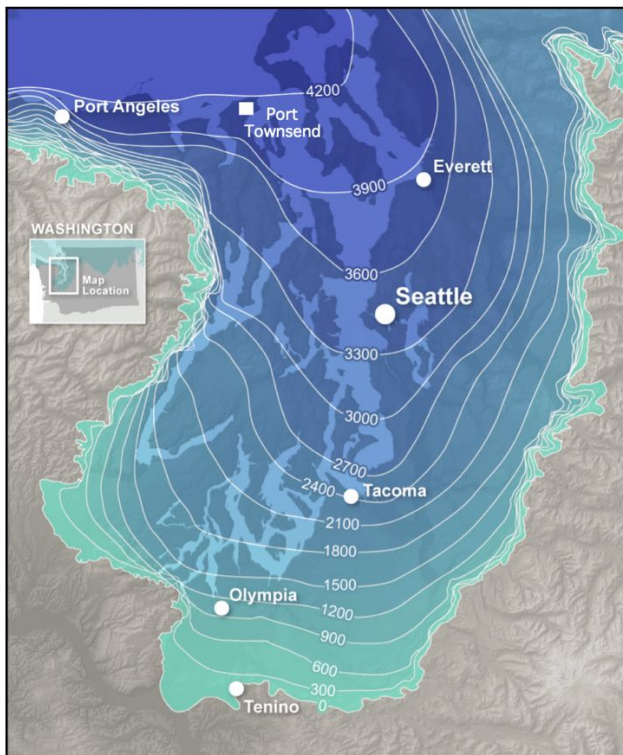


Figure 4. Modeled ice thickness (in feet) at the maximum glacial extent, about 18,000 years ago. This is the Puget Lobe of the Vashon glaciation. Modified from <https://www.dnr.wa.gov/programs-and-services/geology/glaciers>

Lying above the bedrock on Marrowstone Island is a section of Quaternary glacial deposits including till, outwash, and minor colluvium, all poorly exposed except along the bluffs.

The glacial deposits at Nodule Point are only 20-30 feet thick, having been removed by post-glacial erosion that formed a low bench along the margin of the island.

Towards the center of the island, the Quaternary deposits are better preserved and are 200 feet thick or more (perhaps much more at north end; Sinclair and Garrigues, 1994). The general topography is one of broad N-S glacial corrugations that were created as 4,000 feet of ice overrode the island on its way to the Vashon terminus just south of Olympia. The topography is well shown on Lidar imagery, which is the base layer for Figures 1 and 2.

Glacial erratics abound in the area; more than 100 clasts >6 ft. in diameter were found in a community challenge in 2019. (For details see QuimperGeology.org.)

BEACH WALK TO NODULE POINT

Local geologists Dan McShane (2010) and Dave Tucker (2010, 2011) discuss the glacial deposits between East Beach Park and Nodule Point in their blogs and field guides. It's about a 2-mile walk to Nodule point (see Fig. 5) and is best done on an ebb tide to a minus level. The walk south, with stops to inspect the bluff geology takes 90 minutes to 2 hours. We'll spend an hour to 90 minutes at Nodule Point, and an hour for the walk back to East Beach Park.

As stated before, please check the local tidal charts before proceeding. In addition, be prepared to get your feet wet, so wear comfortable rubber boots or water shoes.

The first part of the beach hike provides great exposures of Vashon drift. The lower parts of the bluff consist of advance outwash, which is cross-bedded, and commonly

capped with till or glaciomarine drift. The outwash (alluvium) consists mostly of sand and fine gravel that was probably deposited by outflowing glacial streams as the ice advanced southward into what is now Puget Sound, approximately 20,000 years ago, during the most recent great glacial advance.

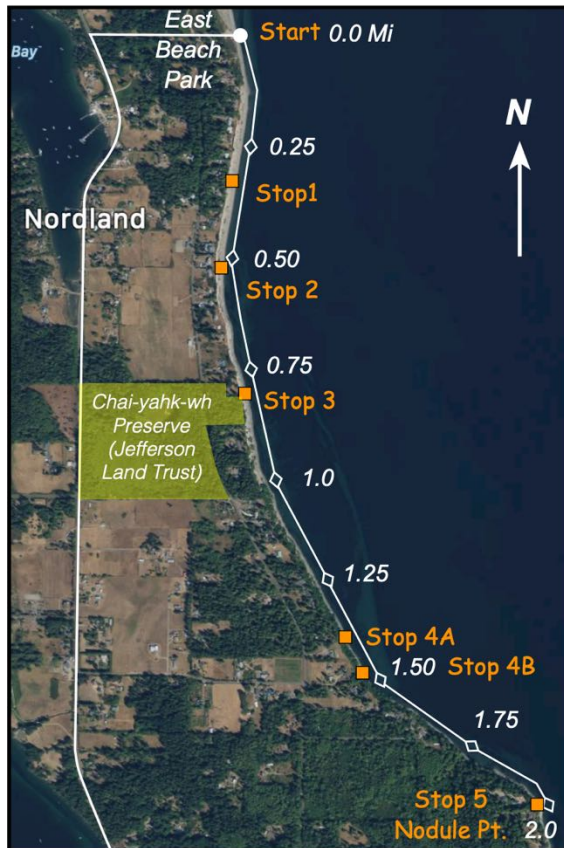


Figure 5. Walking route map from East Beach Park to Nodule Point, a distance of about 2 miles. Beware of tide cycles and tide levels.

The upper part of the bluffs is Vashon till, which is largely unbedded; it was deposited directly by thousands of feet of advancing ice (this is lodgment till). Think of the glacier as a massive geologic bulldozer, pushing and scraping off whatever it overrode. By 17,000 years ago (?), advance of glacial ice of the Puget lobe had stopped and by about 13,000-15,000 years ago, the ice was gone from the Marrowstone area and all the way to Olympia, its southernmost extent. As the glacier melted away, it deposited its load as ablation till. Most noticeably, large blocks of

bedrock (called erratics) were carried south from the San Juan Islands, Canada and northernmost Washington. Many erratics have been on the Quimper Peninsula and Marrowstone Island; virtually all the boulders >3 feet in size are glacial erratics (see QuimperGeology.org).

TILL, OUTWASH, AND GLACIOMARINE

According to Dave Tucker's (2010) terminology, 'drift' is material deposited either directly from ice or from meltwater issuing directly from ice. Drift includes 'till', which is laid down directly by ice, but drift also includes outwash—sand and gravel deposited by streams flowing from the front of the glacier. Thus, drift is a broad catch-all term.

Conversely, glaciomarine drift (gmd) is sediment that rains down from floating ice to the floor of the sea or a lake. To be recognized unequivocally as gmd, marine fossils such as forams, or shells of clams or other molluscs in growth position (meaning intact with hinges closed) need to be present. These are often pretty scarce and require persistent, diligent searching. Dropstones are common; they are released from melting ice, fall, and deform clay on the floor of a body of water. Dropstones could be present in either marine or lacustrine drift. Tucker reiterates: All till is drift; not all drift is till.

STOP 1 (GPS: 48°03'06"N, 122°41'02"W)

At this stop we see glacial till over outwash (Fig. 6), which is a consistent theme for the next 1.5 miles. The till consists of a mix of unbedded (chaotic) sand, gravel, and silt with some boulders. Because the till is deposited directly by the ice, the grains have not been sorted by flowing water (streams). In contrast, the underlying outwash is well sorted (fairly uniform grain sizes) and well bedded, showing prominent fine laminar bedding and festoon cross-bedding. Such features are rare in till or glaciomarine deposits, but very common in alluvial and

fluvial deposits, such as the outwash that accumulates in front of a glacier.

One problem encountered here is the direction the bedding dips—mainly north. If this is outwash of a southward advancing glacier, its beds should dip south. Is this outwash from older waning glaciation?

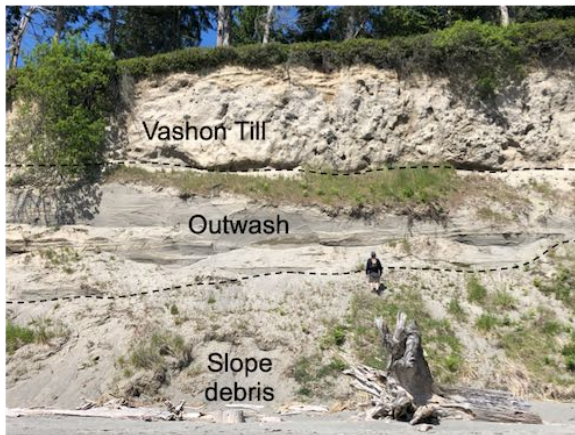


Figure 6. Two drift units: Massive (structureless) Vashon till overlies well-bedded outwash. Lower slope is debris that collapsed or washed off the cliff. Man in midslope is about 6 feet tall.



Figure 7. Till over outwash at Stop 2. Upper part of slope has weak (latest Pleistocene) soil formed on outwash (?). Area highlighted in brown is former tree root mass exposed about 15 years ago. (See photo in Tucker, 2010.)

The root mass shown in Figure 7 is now longer present owing to recent collapse of the till (see discussion of bluff retreat Stop 2).

STOP 2 (GPS: 48°02'57"N, 122°41'05"W)

In addition to the good exposures of till and outwash here, this bluff provides excellent examples of shoreline bluff erosion. When Dave Tucker was on this shoreline, most of the lower bluff slopes were grass covered; now they are being stabilized with abundant shrubs, particularly scotch broom (Fig. 7).

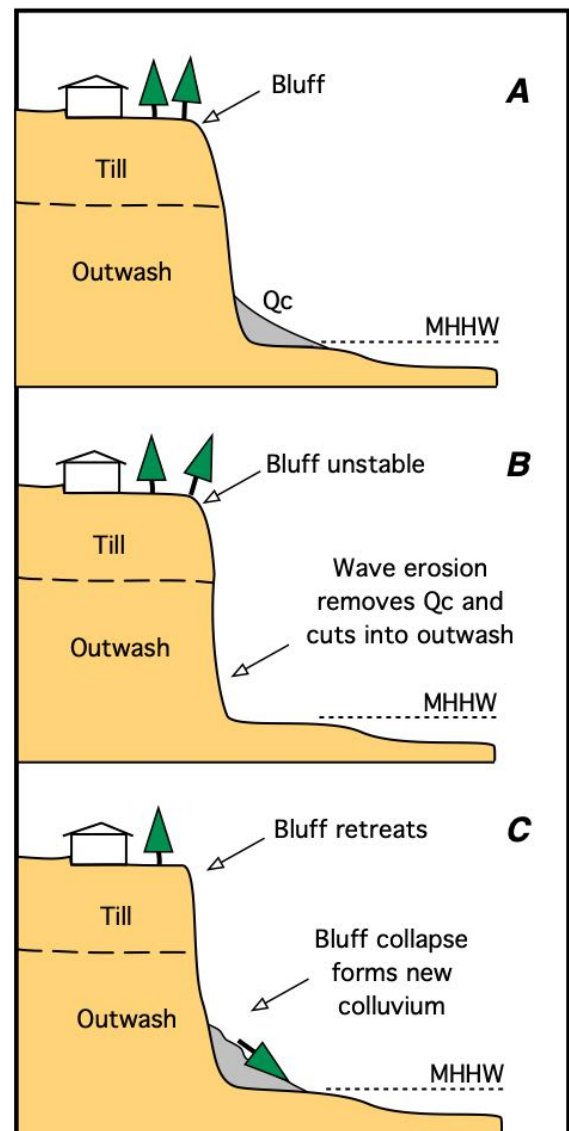


Figure 8. Block diagrams (cartoons) of bluff retreat. A, Present condition; B, erosion by storm waves or during high tides remove apron of colluvium (Q_c) and undermine the bluff; C, collapse leads to new colluvium at base. Over time, the bluff retreats, threatening structures built near the bluff. MHHW, mean high-high water level.

On a June 2021 run of this field trip, we noticed lots of relatively new collapses of the bluff. These threaten the built structures above on the bluff. Normally, the bluff face is steep, but seems stable with a wedge of fine-grained sandy colluvium at the base of the slope. This material commonly accumulates at its angle of repose, which is the steepest angle at which a sloping surface formed of a particular loose material is stable. For dry sands this is 33° to 35°.

However, new collapses commonly have large, compacted blocks of till that give the colluvium a rough surface. With time the blocks degrade and weather out into their constituents: clay, silt, sand and gravel. So, the smoothness of the colluvial surface is a clue as to its age: new or old (vegetated).



Figure 9. An exotic ultramafic rock on beach near Stop 2. This rock type is not present on Marrowstone, Quimper Peninsula, or Olympic Mountains, hence its classification as an erratic. Six-inch long ruler for scale.

At this locality, there are some erratics (Fig. 9). Remember that erratics are blocks of bedrock carried to distant locations. For example, there are no intrusive rocks (such as granites) exposed in the Olympic Mountains or Quimper Peninsula. The rock shown in Figure 9 is an exotic ultramafic rock likely from north in the Juan Islands or Canada. In essence, almost all of the rocks on local beaches are imports from the north; just the

ones larger than a couple feet in diameter are called out as erratics.

STOP 3 (GPS: 48°02'44"N, 122°41'44"W)

Here the drift is particularly thick, making up most of the bluff. This illustrates the undulatory nature of the contact between till above and outwash below.

The fence shown in Figure 10 marks the edge of a cemetery that is on the very north-east corner of the Chai-yahk-wh Preserve (Fig. 5). This 51-acre preserve showcases a Marrowstone Island mature forest. (The open space to the south of the preserve is Washington State University's 26-acre Twin Vista Ranch, which is protected by a Jefferson Land Trust conservation easement.)

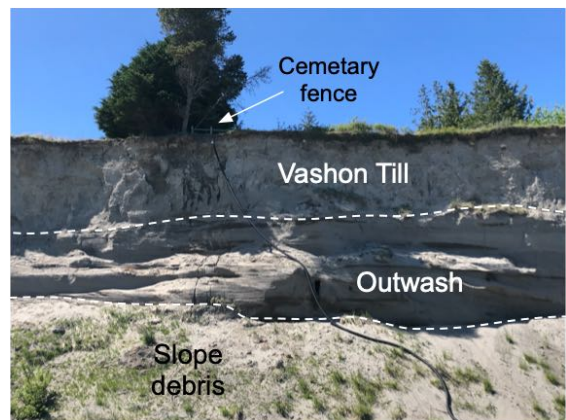


Figure 10. Typical exposure of drift units. Here, boundary fence of an old cemetery is being undermined by retreat of bluff (dust to dust to sediment?). Notice the tightline, which is a flexible pipe that takes surface runoff to beach level.

South of the cemetery, the lower outwash unit pinches out, and the drift becomes bouldery. A little farther on, bedrock starts to be exposed at beach level. Glacial drift can be composed predominantly of the local material beneath the ice. So, although the drift so far on the walk is sandy due to the underlying outwash sand, it now is composed of the underlying sandstone bedrock. At Stop 4A, the walk reaches the northern extent of bedrock at the surface; it's part of the middle- to late-Eocene sandstone of Scow Bay

(Allison, 1959), which we'll see in more detail at Nodule Point (Stop 5).

STOP 4A (GPS: 48°02'16"N, 122°40'44"W)

We've reached bedrock here, but it has been excavated by glaciers, deposited and overrun as the ice advanced to the south. These are the earliest deposits of the Vashon Glaciation seen on our walk. The open-work nature of the bouldery till suggests that is an ice-contact deposit (Fig. 13); the open (void) spaces were probably filled with ice. Just to the south of this site, we start to find large sandstone blocks, then intact sandstone, both at the base of the bluff and as a bedrock platform.



Figure 13. Ice-contact deposits of the Vashon glaciation. Note the voids in plowed up till.

STOP 4B (GPS: 48°02'10"N, 122°40'38"W)

At this location, low tide uncovers a broad platform of east- to southeast-dipping sandstone and lesser finer grained beds of shale. The bedding is apparent from the way it winnows out gravel; pebbles and cobbles tend to become concentrated between more resistant beds (Fig. 14).

Bedrock is exposed all the way from here to Nodule Point. The sandstones are riddled with small displacement faults. As we approach the point, sandstone is exposed above sea level for 10 to 15 ft, and some of these same faults are visible in vertical outcrops.

(These features are explained in more detail in Appendix A.)



Figure 14. East-dipping beds of sandstone and shale interbeds. Erosion and winnowing cause beach gravels to form stripes. View to south.



Figure 15. Aerial view of Nodule Point, Stop 5. Dike extends N55°E across beach; walls are formed by baked sandstone. North is up on this figure. Google Earth Pro image, 2021.

STOP 5, NODULE POINT (GPS: 48°01'51"N, 122°40'08"W)

The point was originally named Nodule Point in 1792 by British explorer George Vancouver, whereas in 1841 the American Wilkes Expedition renamed it Ariel Point. (Wilkes' group originally named Indian and Marrowstone islands the Craven Peninsula; Fig. 2). In the long run, the U.S. Geological Survey went with the more descriptive (but geologically incorrect) name, Nodule Point.

BEDROCK AT NODULE POINT

The bedrock at Nodule Point is interesting for two reasons: concretions (*sic*, nodules) and the presence of basalt that has intruded the sandstone of Scow Bay.

SANDSTONE OF SCOW BAY

The sandstone here is medium to coarse grained and well sorted. It is generally gray. Bedding is typically massive, but some cross-bedding is seen in outcrop, especially where the sandstone is finer grained or associated with claystone. However, at Nodule Point the star of the show is giant (6-12") concretions in this unit. The concretions weather out of vertical exposures and tumble onto the beach, where wave action at high tide distributes them laterally.

CONCRETIONS

From Wikipedia (2021b), modified for our use here: “A **concretion** is a hard, compact mass of matter formed by the precipitation of mineral cement within the spaces between particles . . . in sedimentary rock. Concretions are can be ovoid or spherical in shape, although irregular shapes also occur. Some concretions are elliptical and some have grown together suggesting various anatomical terms best left to the imagination. The word ‘concretion’ is derived from the Latin *con* meaning together and *crescere* meaning to grow.”

Concretions form within layers of sedimentary strata (Fig. 12) early in the burial history of the sediment, before the sediment is hardened (compressed) into rock. These concretions are usually cemented by calcium carbonate, which generally makes the concretion harder and more resistant to weathering than the host stratum. There is an important distinction to draw between concretions and nodules. Concretions are formed from mineral precipitation around some kind of nucleus, whereas a nodule is formed by replacement or displacement of material (*i.e.*, silica).

In contrast to the spherical concretions at Nodule Point, an interesting variation exists at Lip Lip Point, about a mile to the south. At Lip Lip, the concretions resemble lips or compressed donuts (see photo in Tucker, 2011), suggesting partial formation of a thick before the soft sands were compressed, probably by the overlying sediment load.



Figure 12. Thick layer of sandstone containing dark, weathered concretions. The sandstone has been slightly metamorphosed by the basalt dike, which is in the alcove behind the students. View to the north.



Figure 13. Outcrop north of the dike showing bowling-ball-size (8 inch and larger) concretions that weather out of sandstone and concentrate on the beach. Photograph taken in June 2012.

BASALT DIKE

The basalt is likely associated with the Crescent Formation, a series of thick, marine and

nonmarine basalt flows that form resistant beds exposed on the north and east margins of the Olympic Mountains. Babcock and others (1994) say the dike at Nodule Point is “petrographically similar” to subaerial Crescent basalt flows, so the sandstone of Scow Bay be coeval with a young phase of the Crescent Formation. (See discussion by Tucker, 2011.)



Figure 16. The basalt dike has intruded the sandstone of Scow Bay. Dike is preferentially weathered and well exposed only at the head of this alcove. Maggie, a mature Labrador retriever, for scale.

Outcrops of the Tertiary basalt have been mapped along the coast to the south (Mats Mats Bay) and around Port Ludlow, about 7 miles south of Nodule Point. The basalts in the Crescent Formation are well dated from many areas, but not at Nodule Point. Basalts in the Crescent Formation range from about 47 to 53 Ma, but younger eruptions must have occurred (*i.e.*, the intrusive dike at Nodule Point), such as here where it intrudes the sandstone. Radiometric dating and paleomagnetic analysis of the basalt may help solve this apparent dilemma.

Preferential weathering of the basalt has led to an inversion of the normal topography that we would expect with a dike (Fig. 16). Low-grade metamorphism—baking associated with the intrusion—has made the sandstone more resistant to erosion than the basalt. The sandstone is baked for about 3 feet on either

side of the dike. The freshest basalt is exposed in the backwall of the alcove.

FAULTS WITHIN THE DIKE (SEE EXPANDED VERSION IN APPENDIX A)

A roughly 1 ft-wide zone of closely spaced fault slip surfaces is exposed in the margin of the basalt dike at the head of the linear alcove (Figs. 16, 17). These roughly planar surfaces on the right (northwest) side of the dike are oriented subparallel to the overall dike trend of N55°E. Slip surfaces here range in strike from about N40°E-N50°E and dip 85°-87° NW. The structures are expressed in outcrop as smooth, weakly polished surfaces containing faint to prominent, subparallel grooves or striations known as *slickenlines* (Fig. 17).

Slickenlines form due to frictional wear and scoring as rocks on one side of a fault slide past rocks on the other side, as when a coarse file scores a soft wood surface when it is slid along it. The plunge of slickenlines here form three distinct sets: 20°-25° NE, 0° (horizontal), and 20°-25° SW; the first set is most prominent.



Figure 17. Near-horizontal slickenlines on basalt that indicates motion was lateral (side to side). Dime for scale.

From these observations alone we can infer that the fault zone has experienced lateral (*strike-slip*) movement, but with minor

components of *dip slip*. (See Appendix A for further explanation.)

So, the fault shows mainly lateral displacement, but in what directions? That is, was the fault displacement *right* lateral or *left* lateral? To determine slip sense, we can look for distinct features that are offset directly, such as bedding or even other faults. Without offset features at Nodule Point, subtle secondary features preserved on slip surfaces can suggest the sense of movement. Here, some secondary, white calcite veins are present at the margin of the Nodule Point dike (Fig. 18). The distribution of this vein material and fine-scale slip indicators are suggest a *left-lateral* sense of motion here.

The total amount of displacement across the fault zone is unknown. However, similar basalt dike rock and bordering baked zones on either side of the fault zone suggest that displacement is not large, perhaps on the order of 3 feet at most.



Figure 18. Northwest margin of the dike. Light-colored rock is baked sandstone, gray rock is faulted portion of the dike, and white patches are vein-filling calcite. Scott Minor, structural geologist, for scale (6 ft. tall).

Several other small-displacement (<3 feet) faults can be seen during lower tides on the wave-cut bedrock platform just north of Nodule Point. Some of these faults strike northeast, parallel to the dike fault, whereas others strike east. It is likely that these faults

are roughly the same age and have *kinematic* (movement) histories similar to the faults at the dike. Such faults, especially where cemented, are commonly more resistant to erosion and form long linear ribs in the beach outcrop.

This faulting must postdate solidification of the basalt. However, caution should be exercised in interpreting the state of stress at the time of faulting. In an early paleomagnetic study, Prothero and others (1997) showed that the sandstones on both Indian and Marrowstone Islands are rotated counterclockwise about 35°, consistent with volcanic units in the region. Conversely, Brocher and others (2017) have shown that Tertiary and older rocks in the Puget Sound area have been rotated in a clockwise motion owing to collision of the Pacific and North American plates. Further discussion of these structural issues is beyond the scope of our beach walk.

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APPENDIX A

FAULTED DIKE: TECHNICAL DISCUSSION BY SCOTT MINOR

ORIENTATION AND SLIP VECTORS

A narrow, ~1-foot-wide zone of closely spaced fault slip surfaces is exposed in the margin of the basalt dike visible at the head of the linear alcove at Nodule Point. These roughly planar surfaces, which can be seen on the right (northwest) side of the dike exposure, are oriented subparallel to the overall dike trend of N55°E. Slip surfaces measured in the exposure range in strike from about N40°E to N50°E and dip 85° to 87° NW. The structures are expressed in outcrop as relatively smooth, weakly polished surfaces containing faint to prominent subparallel, roughly horizontal grooves or striations known as *slickenlines* Fig. A-1).



Figure A-1. *Slickenlines in basalt. Prominent direction is NE plunge. Blue ruler is 6 in long.*

Slickenlines, such as these, form due to frictional wear and scoring as rocks on one side of a fault slide past rocks on the other side, in the same manner as when a coarse file scores a soft wood surface when it is slid along it. Slickenline orientations in the dike exposure exhibit some variability from

surface to surface. The plunge (i.e., departure from horizontal) of the slickenlines form three sets: 20-25° NE, 0° (horizontal), and 20-25° SW; the first is the most prominent set. Based on these observations alone we can infer that the fault zone has primarily experienced lateral, or *strike-slip* movement, but with minor components of *dip slip*.

INTERPRETATION OF FAULT MOVEMENT

To get a more complete picture of the fault movement, we also need to determine the *sense* of slip. That is, was the fault displacement *right* lateral or *left* lateral? To determine slip sense, one can look for distinct features that are offset directly, such as bedding or even other faults. Lacking such offset features, as is the case at Nodule Point, one can often use subtle secondary features preserved on slip surfaces to infer sense of movement. Some secondary white calcite veins are present at the margin of the Nodule Point dike; these were emplaced into the dike rock sometime after it was intruded and cooled. They appear to have undergone shear deformation within the fault zone. Striated patches of the white carbonate on a few of the slip surfaces are preferentially found on the northeast sides of small asperities (bumps), in places accompanied by small steps on the distal edges of the carbonate patches. Sliding one's hand over such features parallel to the slickenlines reveals an 'easy' versus 'rough' sliding direction, just as happens with the grain of wood. The interpretation is that the carbonate material, and perhaps some accompanying fault gouge, were preferentially *accreted* and (or) precipitated on the lee, or down-slip, sides of the asperities during slip (e.g., Petit,

1987). Thus, the easy hand-slide direction represents the direction of slip of the missing block, in our case indicating a left lateral slip sense. Also present on some of the dike slip surfaces are weakly developed, small-scale (less than an inch wide) shear fractures resembling fish scales that project slightly below the surface into the wall rock. Where such shears are better developed on fault slip surfaces observed at other localities, they are generally found to dip in uniform, low-angle directions into the wall rock in an imbricate fashion. It has been demonstrated that these subsidiary features, known as *Riedel shear fractures*, dip in the direction of slip of the missing block (Petit, 1987). Questionable imbricate Riedel shears observed on some patches of the Nodule Point dike's slip surfaces give conflicting or equivocal senses of slip, that is, both left- and right-lateral slip. Although this observation is suggestive of two episodes of slip with opposing senses of movement, a left-lateral slip sense is the preferred interpretation at the dike locality based on the distribution of carbonate vein material as described above.

The total amount of displacement accommodated by the dike fault zone is unknown due to the lack of any directly observed offset geologic features in outcrop. However, similar basalt dike rock and bordering baked zones are present on either side of the fault zone, suggesting that the displacement is not large, perhaps on the order of 3 feet at most.



Figure A-2. Subtle small displacement faults in bedrock platform just north of Nodule Point. Major set parallel to trend of dike, but several different orientations noted.

OTHER FAULTS NEARBY

Several other small-displacement (< 3 feet) faults can be seen during lower tides on the wave-cut bedrock platform just north of Nodule Point (Fig. A-2). Some of these faults strike northeast roughly parallel to the dike fault, whereas others strike roughly east. It is likely that these faults are roughly the same age, and have similar *kinematic* (movement) histories, as the dike fault. The bedrock platform structures are *deformation-band* faults, a type of small-displacement fault formed in porous sandstones and characterized by a narrow (less than an inch wide) zone of distributed shear and grain breakage, comminution, and compaction. As a result, such structures are commonly more resistant to erosion and form long linear ribs in outcrop, as they do north of Nodule Point.