Quimper Geologic Society

OLYMPIC MOUNTAINS FIELD TRIP

June 22, 2019

The Olympic Mountains of northwestern Washington are the result of the Juan de Fuca plate descending beneath the North American plate at the Cascadia subduction zone, accreting oceanic crust onto the Cascadia subduction wedge (**Figure 1**). The accreted oceanic sediments, structurally overlain on the east by Coast Range terrane, are largely below sea level but are exposed on land in the Olympic Mountains (**Figure 2**). The Cascadia forearc, the area between the volcanic arc and subduction zone, has a topographic low (from north to south the Georgia Straits, Puget Sound, and Willamette Valley) and high (Insular Range of Vancouver Island and Coast Range of Washington and Oregon). The forearc high is the crest of the accretionary wedge.

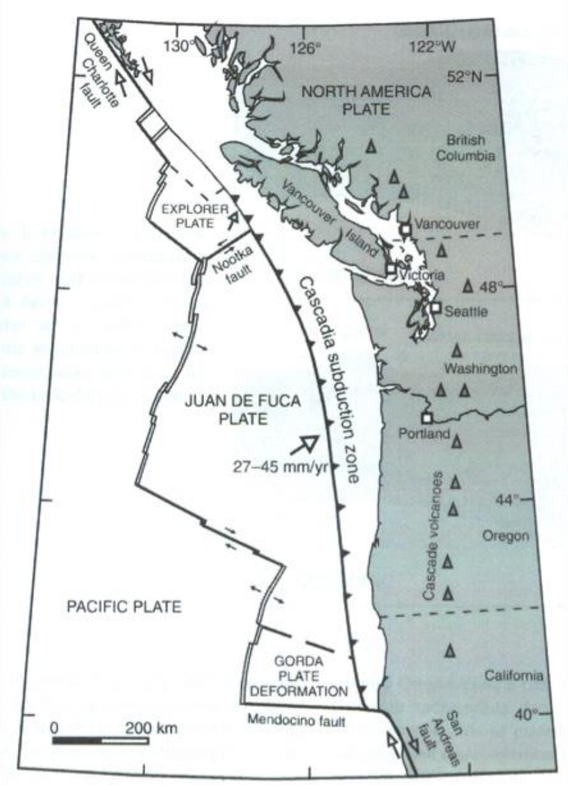

Figure 1. *Plate tectonic setting of the Cascadia subduction zone. (From Leonard et al., 2010, Fig. 1)*

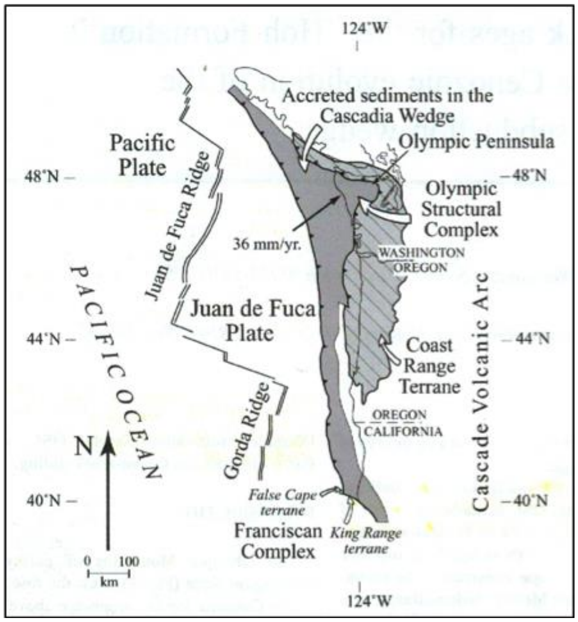

Figure 2. *Map showing accreted terranes of the Cascadia subduction wedge, which includes on-land exposures in the Olympic Mountains (Olympic Structural Complex) and the northern California terranes of the Coastal belt. Convergence velocity of the Juan de Fuca plate relative to North America, at the latitude of the Olympic Mountains, is closer to 43mm/yr than the 36 mm/yr shown. (From Stewart and Brandon, 2004, Fig. 1).*

Early investigations of the subduction process envisioned a snowplow model with accreted material being piled up against a rigid backstop in the overriding plate; however, the backstop material was deforming along with the accreted sediments in many convergent plate boundaries. Sandbox experiments by Davis et al. (1983) provided a solution to the backstop problem. The experimental box (**Figure 3**) consisted of horizontal layers of sand (upper plate) overlying a sheet of Mylar on a flat rigid base with adjustable dip. As the Mylar sheet was pulled beneath the sand forward- and backward-verging thrusts formed creating a double-sided wedge (a pro-wedge and retro-

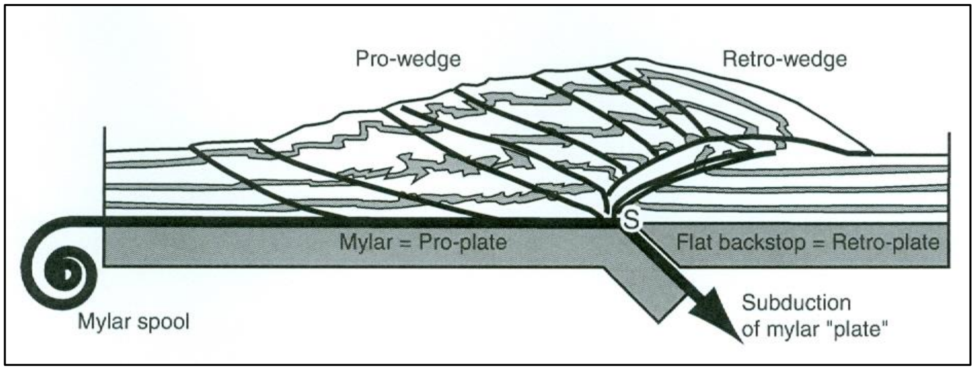

Figure 3. *Sandbox experiment producing a double-sided wedge. (Depiction by Brandon, 2004, Fig. 22.2.2 of experimental results of Davis et al, 1983.)*

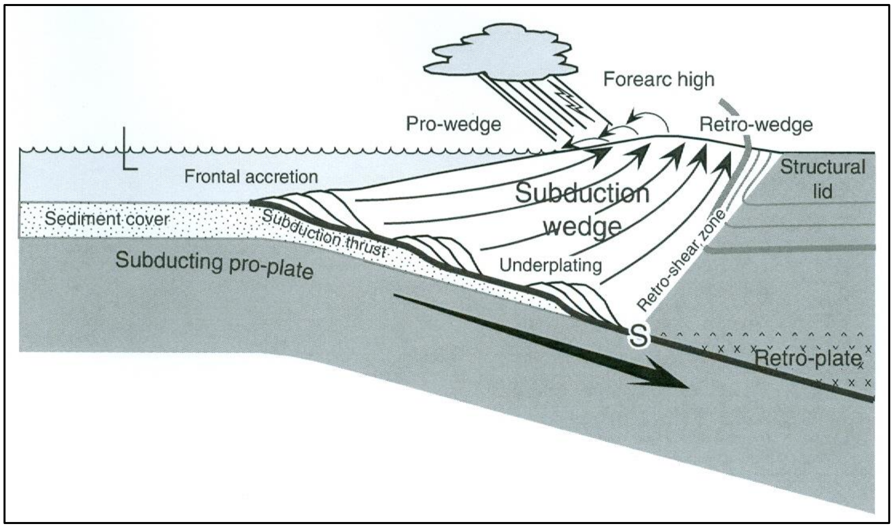

Figure 4. *Schematic cross section of a subduction wedge. "S" refers to the S point, the subduction point, where the pro-plate is subducted beneath the retroplate. (From Brandon, 2004, Fig. 22.2.1.)*

wedge). At the point S the “subducting” plate (pro-plate), moved below the overriding plate (retro-plate) (**Figure 4**). These experiments served as the basis for an accretionary wedge model in which the crust of the overriding plate drapes over the subduction zone of mantle (at S or retro-shear zone), causing it to deform over a broad area while creating a doubly vergent wedge (Willett et al., 1993).

As the subducting Juan de Fuca plate moves toward the overriding North American plate at about 43 mm/yr, accretion of oceanic sediments occurs mostly at the leading edge (referred to as “frontal accretion”) of the North American plate, creating a doubly vergent (i.e. structures are inclined in opposite directions) wedge that progressively increases in size, maintaining a self-similar form as it grows. A far lesser amount of the sediments move down the subduction thrust fault and are added to the bottom of the wedge, a process called “underplating” (**Figure 4**).

The doubly vergent Cascadia wedge has a prowedge (proside) that overrides the subducting Juan de Fuca plate accreting oceanic sediments and a retrowedge (or retroside) on the east side of the Coast Range. In the Cascadia wedge the change in vergence occurs at the crest of the forearc high. The proside of the Cascadia wedge consists of accreted marine sediments while the retroside has both accreted oceanic crust and Coast Range terrane. Mount Olympus is the approximate location of change in vergence in the Olympic Mountains, from west vergence on the proside of the wedge to east vergence on the retroside (**Figure 5**). The retro-shear zone in the Olympic Mountains is a large east vergent fold taking up shear between the forearc low and the eastern/retro component of the double-sided wedge.

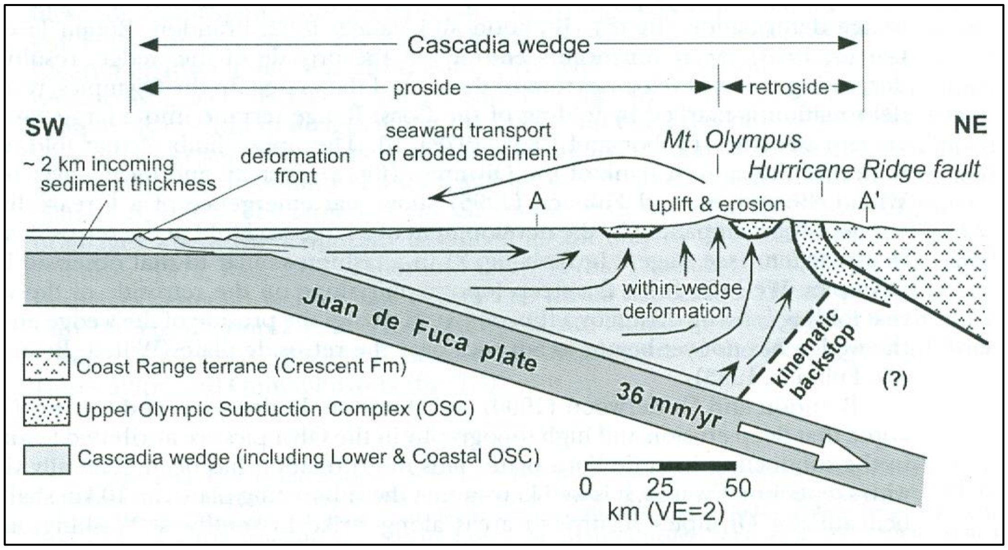

***Figure 5.** Schematic cross section showing regional-scale structure of the Cascadia accretionary wedge. (From Pazzaglia and Brandon, 2001, Fig. 3., after Brandon et. al., 1998.)*

ROADLOG

OLYMPIC MOUNTAINS FIELD TRIP

June 22, 2019

Meet at Olympic National Park Visitors Center parking lot at 9:30 am

Mile .

0.0 Bear right onto Hurricane Ridge Road.

1.7 It is approximately here that you begin passing the first vegetation covered roadcuts of the Twin River Group.

2.8 This is where you first begin to see roadcuts not heavily covered with vegetation.

4.3 Overlook on left. Poor exposure of Crescent Formation basalts in the roadcut. Basalts are better exposed over next 0.2 miles.

5.0 Intersection with Lake Dawn Road.

5.2 Ranger station.

5.3 Turn off on left for Heart of the Hills Campground.

7.5 Large roadcut of Crescent Formation basalt.

8.7 Start of continuous roadcuts of Crescent Formation just south of the entrance of the first of three tunnels cut through the basalts.

9.0 STOP 1. Lookout Rock. This stop is just before the tunnels. The low hills to the northeast were smoothed by the Cordilleran continental glacier. Inlets and islands carved by the ice sheet can be seen farther to the north. Granite cobbles and boulders carried by the glacier are present up to an elevation of about 3,500 feet around the northeast and north end of the Olympic Mountains. These rocks must have come from the North Cascade Mountains and/or the British Columbia Coast Ranges. The southward-moving Cordilleran ice sheet split around the Olympic Mountains, one branch flowing west along the Strait of Juan de Fuca and the other flowing south in the Puget Lowland, past the city of Olympia. Much smaller alpine glaciers flowed down the valleys of the Olympic Mountains, joining the Cordilleran glacier. The gorge to the southeast is Morse Creek, cut after or during melting back of the ice sheet about 13,000 yrs. ago. This creek, flowing for several miles to the north, eroding its valley in comparatively soft sandstone, siltstone and shale, takes a sharp turn to the west-southwest when it reaches a ridge of resistant Crescent Formation basalt. It's interesting to consider why this drainage changes direction to flow within the basalt ridge.

Across the road are outcrops of Crescent Formation basalt.

9.1 Entrance to first tunnel.

9.4 Exit third tunnel

11.0 The Crescent basalts here have some of the better developed pillows that we will see.

11.7 Overlook on left.

13.8 Approximate location of the contact of the Crescent Formation and Blue Mountain unit. We will discuss the nature of this contact at STOP 2.

14.9 Switchback Trail head.

16.0 Hurricane Ridge fault and contact of the Blue mountain unit and Needles Gray Wolf lithic assemblage. This is STOP 5 on the return trip.

17.4 Sharp curve in road. Roadcut of Needles Gray-Wolf lithic assemblage, Upper Olympic subduction complex, on right.

17.5 Roadcut of Upper Olympic subduction center.

17.9 Hurricane Ridge visitors center. Continue straight ahead to Hurricane Hill road. NOTE: this is a narrow windy road with a 15 mph speed limit.

18.3 U curve! Keep as far right as possible when navigating this very sharp curve in the event you meet someone coming the other way.

19.0 STOP 2. Hurricane Hill Trail. Parking lot of Hurricane Hill trail. Take the (paved) trail toward Hurricane Hill. This trail crosses three stratigraphic units of Tabor and Cady (1978a). Approximately the first 0.7 km (2000 ft) of the trail traverses the Needles Gray-Wolf lithic assemblage, which they describe as a micaceous sandstone, with less than 60% siltstone and slate. The angular, medium-grained, lithic to feldspathic sandstone is poorly sorted. Calcite and slate chips are common. It is thin to very thick bedded with small crossbeds, and rare graded beds, ripple marks, and load casts. Slate is micaceous and highly fissile; it grades to siltstone.

Past the trail head there's a very low topographic dip in it, a short distance farther on you will see the first outcrops of the Needles Gray-Wolf lithic assemblage. In this area it is thinly- to thick bedded graywacke sandstone, siltstone and slate. The most pervasive structure in these outcrops is a pencil cleavage, slivers of rock (pencil-like) formed by the intersections of two or more cleavages or, more typically, the intersection of cleavage (a planar fabric created by the rock tendency to split in a particular direction) and bedding. The pencil cleavage may reflect an intermediate stage in the development of slaty cleavage (a foliation defined by elongate domains of quartz or feldspar aggregates separated by anastomosing mica-rich laminae) and, therefore, occur only in weakly metamorphosed rocks, like those on this trail.

Tabor and Cady (1978b) found pencil cleavage in the western and northeastern parts (where we are now) of the eastern core lying in bedding. In the central part of the core pencils generally do not lie in bedding but are formed by two cleavages and are perpendicular to fold axes. Because they found pencils to be the most consistent structural element in the core they used pencil orientations to divide it into two large structural domains that they subdivided into 19 subdomains. In the field the boundary between the two main domains, they called Domain East and Domain West, is identified by opposing dips and plunges. In Domain East the planar structures dip west to southwest and pencils plunge west. In Domain West planar structures dip east and northeast and pencils plunge east. The boundary which winds roughly north-northwest across the core, passing about 8 km east of Mount Olympus, separates the west verging structures in the Olympic Mountains from the east verging structures. Hurricane Hill Trail falls within Tabor and Cady's Domain East, Subdomain 1. Their contour diagrams of Subdomain 1 data show bedding mostly striking northwest and dipping steeply southwest, cleavage striking west-northwest and dipping steeply south-southwest, steeply plunging pencils trending south-southeast to south, and steep to moderately steep plunging fold axes plunging moderately to steeply northeast to northwest.

The first sign on the trail is titled "Folded Rock". The fold opposite the sign is a shear fold - a fold in which shearing or slipping takes place along closely spaced planes parallel to the fold's axial surface, also called a similar fold. The axis of this well-developed fold trends northeast. Notice the steeply dipping fault that cuts across the axial plane, creating a small apparent offset of bedding. A short distance farther on the trail very thick graywacke sandstone beds are present. They are devoid of the cleavage that is so prominent in the thinly-bedded layers.

The map by Tabor and Cady (1978a) shows the Hurricane Ridge fault crossing the trail where its grade changes steeply up on the west side of the saddle located about 2,000 feet from the trail head. When you cross the fault you are walking on the Blue Mountain unit, which is part of the Coast Range terrane. Tabor and Cady describe it as sandstone and argillite (a compact rock derived from claystone, siltstone, or shale that has undergone a somewhat higher degree of induration but is clearly less laminated than shale and without its fissility, and that lacks the cleavage distinctive of slate) - very fine to medium-grained lithic sandstone, volcanic rich; fair to poorly sorted and angular with thin to thick beds.

The rocks in the area of the Hurricane Ridge fault are more highly deformed, probably reflecting a wide zone of deformation associated with displacement along the master fault. The map pattern of the fault (Tabor and Cady, 1978a) shows it is nearly vertical here. Bedding orientations change significantly over short distances and there are a significant number of faults with widely varying orientations, many with low dips. The trail sign "Wind the Sculptor" is west of the fault on the Blue Mountain unit. Higher up (about 4,500 feet from the trail head) the trail crosses the contact with the Crescent Formation, which caps Hurricane Hill.

Return to parking lot and drive to picnic area for lunch stop. **Drive to the Hurricane Ridge Visitors Center. Reset vehicle odometer to zero (0)** and proceed down Hurricane Ridge Road.

Mile
0.0 Hurricane Ridge Visitors Center.

1.0 Stop 3. Roadcut in Needles Gray-Wolf lithic assemblage. This assemblage is a feldspathic sandstone with detrital muscovite and biotite and a lesser amount of siltstone and slate. It has thin to very thick bedding, ripple marks and load casts. Graded beds are rare, The slate is the result of shale and mudstone being subducted into the accretionary wedge, subjecting it to increased temperatures and pressures. Tabor and Cady (1978b) found a general increase in the metamorphic grade from west to east based on the presence of various index minerals in samples they collected in the central and eastern Olympic Mountains and other workers concur with Tabor and Cady's metamorphic zonation. Based on fission-track dates for sandstones from the eastern zone its temperatures were between 100 ± 10^0 and 200 ± 50^0 C, the blocking temperatures for apatite (a mineral consisting of some combination of fluorine, chlorine, hydroxyl or carbonate) and zircon. The slate in the Needles Gray-Wolf rocks was, very likely, formed within this range of temperatures. In the area of Mount Olympus, the topographically highest part of the mountains, is an adjacent zone with an assemblage of minerals that indicate higher temperature (~190 ^{0}C) and pressure (~300 MPa or 3000 kg/cm^2) conditions. These pressure temperature condition indicate the rocks in this zone were subducted to a depth of 11 km (6.8 miles) before they began their upward ascent to the surface.

1.8 STOP 4. Hurricane Ridge Road Hurricane Ridge fault (Mile Marker 15.9). This is an excellent location to see the Hurricane Ridge fault, the contact of the Blue Mountain unit and the Needles Gray-Wolf lithic assemblage of the core rocks, the same units we saw at Stop 4. The geologic map by Tabor and Cady (1978a) shows the road passes over fault at about mile marker 16.0. The roadcuts west and east on this mile marker have beds dipping steeply south and north, right side up and overturned, and highly disrupted by imbricate faults. Rocks such as these with highly disrupted strata are called broken formation.

Graded bedding and cross laminations are present in some of the thin greywacke sandstones. On the south side of the mile marker a large elongate (~ 1 meter) block of graywacke is surrounded by thin beds of slate, siltstone and sandstone, that is like the exotic blocks found in tectonic mélange. There are several well-developed faults in these exposures. The fault closest to mile marker 16 may be the master fault of the fault zone or what Tabor and Cady (1978b) call the zone of disruption. Bedding is nearly vertical on both sides of the fault. Drag on the beds flanking the fault and very small drag folds on the fault indicate the north side moved steeply up and west relative to the south side. Look for the tight isoclinal fold about 50 feet south of mile marker 16 and for steeply-dipping splay faults and beds sheared off by well-developed cleavage within the fault zone.

6.2 **STOP 5 Ancient Lake Morse.** Overlook and parking area. In the distance you can see a broad low divide between Round Mountain (on the left) and Blue Mountain. The front of the Cordilleran ice sheet moved across the divide for it is covered with outwash from the icecap. The smooth shape of Round Mountain is certainly the result of the ice moving over it. The ice sheet pressed against the mountain front damming the streams (like Morse Creek) causing the valley at the toe of the glacier to fill with water. Icebergs, with rocks from the Cascades and Canada, broke off from the ice sheet and floated out into the lake. They melted slowly, eventually dropping the rocks onto the lake bottom. Granite boulders from the icebergs are present in Morse Creek valley at elevations up to 3,500 feet.

Apparently the glaciers which carved the higher rugged peaks have affected the rate of uplift of the Olympic Mountains. Exhumation rates of the Olympic Mountains determined from thermochronometer ages on apatite and zircon (e.g. Brandon et al., 1998) show an elliptical pattern and range between 0.25 and 0.9 km/m.y. These rates are thought to reflect tectonically driven uplift and the age pattern the configuration of the subducted plate. Additional age determinations by Lorenz et al. (2018) show the 0.25 to 0.9 km/m.y. rate of uplift was relatively constant from 18 Ma to 5 Ma but in the high core of the range (at headwaters of the Hoh, Queets, Quinault, and Elwah rivers) increased 50-150% (0.43-1.5 km/m.y. to 0.63/2.3 km/m.y.) during the past 2-3 m.y. They noted this accelerated rate of exhumation is coeval with Pliocene-Pleistocene alpine glaciation and suggested the rate of tectonic uplift has been impacted by glacial erosion, which increased the material flux from the mountains.

7.1 **STOP 6. Crescent Formation.** This roadcut in the Crescent Formation is dominated by a volcanic breccia and pillow basalt. It provides an excellent display of the faulting experienced by the basalt, juxtaposing different rock types. Note the presence of both moderately dipping and steeply dipping faults and what appears to be large conjugate shears filled with secondary minerals.

Several models have been proposed for the origin of the Crescent and Siletz basalts (referred to as Siletzia, a microplate, and Siletz terrane) a seamount/plume model, a spreading ridge reorganization model that is a variation of the seamount/plume model, a marginal basin model, and Yellowstone plume model. In the seamount/plume model a seamount chain, that formed over a mantle plume, was accreted to the continent. Its variation, the ridge reorganization model, spreading on the Kula-Farallon ridge between 61 and 48 Ma resulted in Coast Range basalts erupting as seamounts and volcanic ridges along leaky transform faults and fractures during changes in spreading directions. The marginal basin rift model involves the outpouring of oceanic basalt during rifting of the continental margin as a result of highly oblique motion of the Kula and Farallon plates relative to the North American plate. The Yellowstone plume model, now the most widely accepted model for the formation of Siletz terrane, involves the formation of an oceanic plateau in the Pacific Ocean between 56-49 Ma from outpourings of the Yellowstone hotspot onto the seafloor (Wells et al., 2014). The plateau (a large igneous province) accreted to the continent between 51 and 49 Ma. North America overrode the hotspot at about 42 Ma. Clockwise rotation of the Oregon microplate has translated Siletzia northward about 250 km northward from the hotspot track (Wells et al., 2014).

END OF TRIP

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