OLYMPIC MOUNTAINS FIELD TRIP GUIDE

September 14-15, 2013

Jim Aldrich

INTRODUCTION

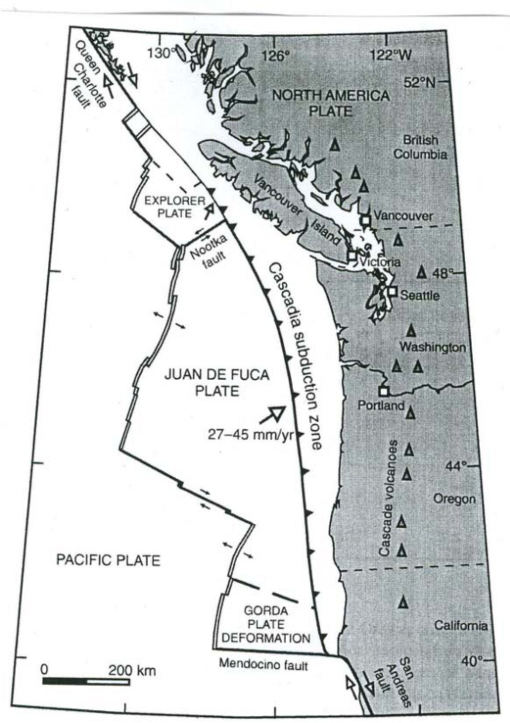

Figure 1. Plate tectonic setting of the Cascadia subduction zone. (From Leonard et al., 2010, Figure 1)

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 sealevel but are exposed on land in the Olympic Mountains (Olympic Structural Complex) (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) (Figure 3). The forearc high is the crest of the accretionary wedge.

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 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-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).

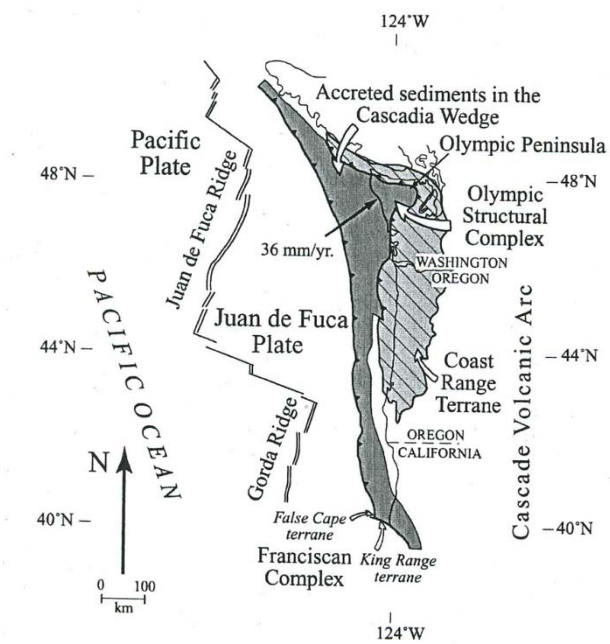

Figure 2. Map showing accreted terranes of the Cascadia subduction wedge, which includes on-land exposures in the Olympic Mountains (Olympic Structural Complex) and the northern California terranes of the Coastal belt. Solid northeast pointing arrow indicates convergence velocity of the Juan de Fuca plate relative to North America at the latitude of the Olympic Mountains. (From Stewart and Brandon, 2004, Figure 1.)

As the subducting Juan de Fuca plate moves toward the overriding North American plate at about 36 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 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 5). The doubly vergent Cascadia wedge has a prowedge (proside)

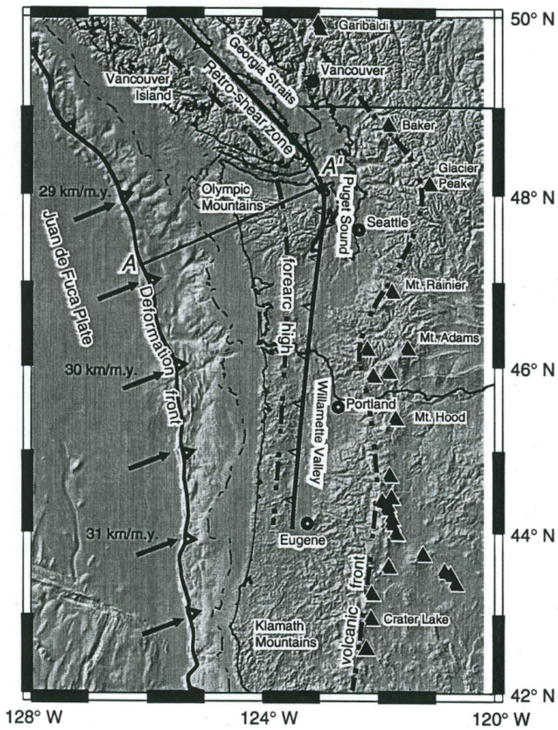

Figure 3. Modern tectonic setting of the Cascadia margin, showing the plate boundary, volcanic arc, and physiography of the modern margin. (From Brandon, 2004, Figure 22.2.3.)

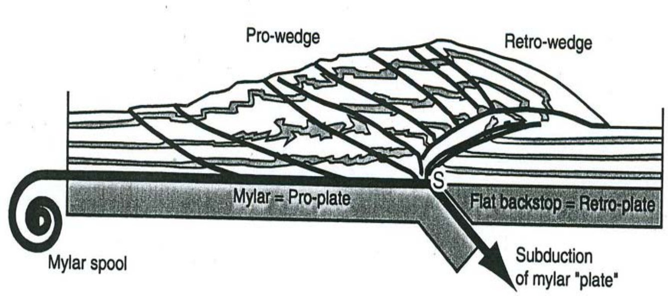

Figure 4. Sandbox experiment producing a double-sided wedge. (From Brandon, 2004, Figure 22.2.2.)

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 6) (Pazzaglia and Brandon, 2001). 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.

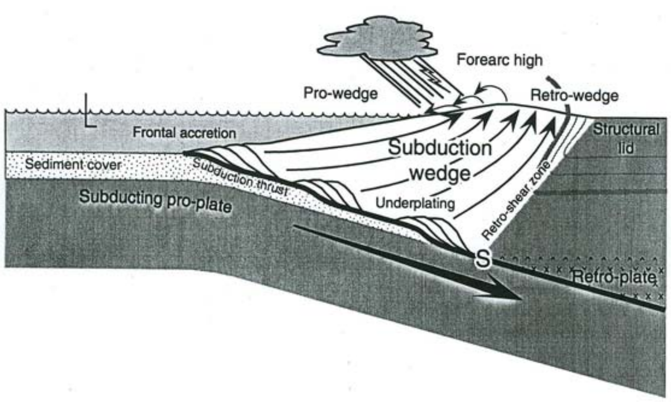

Figure 5. Schematic cross section of a subduction wedge. "S" refers to the point S, the subduction point, where the pro-plate is subducted beneath the retro-plate. (From Brandon, 2004, Figure 22.2.1.)

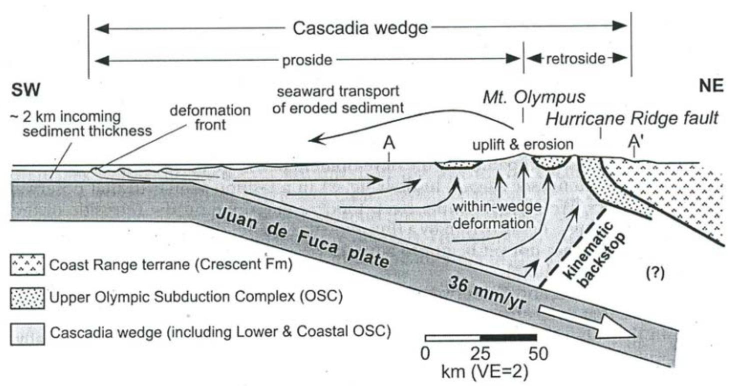

Figure 6. Schematic cross section showing the regional-scale structure of the Cascadia accretionary wedge. (From Pazzaglia and Brandon, 2001, Figure 3.)

STRATIGRAPHY

Rocks in the Olympic Mountains have been divided into two major tectonic sequences (Figure 7). The structurally higher sequence, called Crescent "terrane" by Babcock et al., (1994), Coast Range terrane by Brandon et al. (1998) and Stewart and Brandon (2004), and Siletz by others, consists of Eocene marine sediments and oceanic basalts disconformably overlain by younger marine clastic sediments. Tabor and Cady (1978a) and Babcock et al. (1994) use the term "peripheral rocks" for the basalts and overlying marine sedimentary units while Brandon et al. (1998) called the sedimentary units above the disconformity the "Peripheral sequence". The Coast Range terrane crops out in a horseshoe-shape on the north, east, and south sides of the Olympic Mountains (Figure 8).

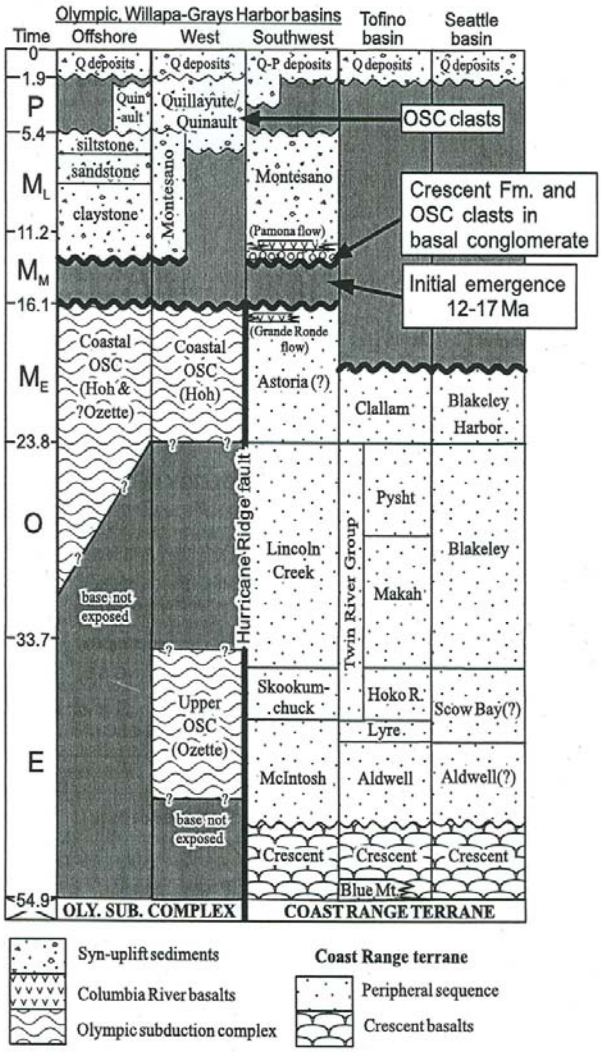

Figure 7. Stratigraphy of the Olympic Structural Complex and the Coast Range terrane. The main focus of this field trip guide is the Tofino basin on the north side of the Olympic Mountains. E = Eocene, O = Oligocene, M_E = Early Miocene, M_M = Middle Miocene, M_L = Late Miocene, P = Pliocene, Q = Quaternary, Fm = Formation. (From Brandon et al., 1998, Figure 3.)

The structurally lower sequence, separated from the Coast Range terrane by the Hurricane Ridge fault, consists of Eocene turbidite sandstones (graywacke) and siltstones, a considerably lesser amount of oceanic basalts, and a small problematical slice of Mesozoic rocks at Point of the Arches in the northwest corner of the Olympic Peninsula. This sequence was called Olympic core rocks by Taber and Cady (1978a and 1978b) and Olympic subduction complex by Brandon and Calderwood (1990) and Brandon and Vance (1992). More recently Stewart and Brandon (2004), following the International Stratigraphic Code (Salvador, 1994), named it Olympic Structural Complex (OSC).

Coast Range terrane

The Coast Range terrane lies above the Hurricane Ridge fault and is present in the Tofino basin on the north side of the Olympic Mountains and on the southern end of Vancouver Island (Figure 9). It is approximately 6 km (3.7 miles) thick (Tabor and Cady, 1978a; Snavely et al., 1980; Armentrout, 1987; Garver and Brandon, 1994) and consists of the Eocene Blue Mountain unit and Crescent Formation overlain disconformably by the "Peripheral sequence" of Brandon et al. (1998). The Peripheral sequence is in the Tofino basin on the north side of the Olympic Mountains and includes, from oldest to youngest, the Aldwell and Lyre formations, Twin River Group, and Clallam Formation. Tabor and Cady (1978a) use the term "Peripheral rocks" for the entire stratigraphic section above the Hurricane Ridge fault, not restricting it to the strata above the Crescent Formation.

Blue Mountain unit. The Blue Mountain unit is an informal name for marine sediments that underlie and are interbedded with Crescent basalts (Tabor and Cady, 1978a). It is overlain by basalts of the Crescent Formation except in the northeastern part of the "horse-shoe" where it is directly overlain by the basal formation (Aldwell) of the upper sedimentary section, apparently filling the area between two volcanic centers (Babcock et al., 1994). Detailed investigations by Einarsen (1987) show the contact is faulted in the eastern part of the Olympic Peninsula as well as in the northwest. Babcock et al. (1994) report baked zones at the contact in two locations, one of which is along the road to Deer Park. The Blue Mountain unit largely consists of thinly-bedded turbidites but also has massive sandstones beds and a lesser amount of massive siltstone beds. The sediments probably reflect various parts of depositional fans in which the thinly-bedded turbidite deposits are middle to outer fan deposits and the massive siltstone beds are distal fan deposits. Einarsen (1987) identified a plagioclase-rich feldspathic arenite facies and chert-rich lithic arenite facies in the unit. He interpreted the sources of the sediments to be from the north to northeast with the feldspathic facies coming from the Coast Plutonic Complex and the chert-rich facies from the San Juan Islands provenance. The few paleocurrent data of Snavely and Wagner (1963) indicate southwest flow for the Blue Mountain unit, consistent with Einarsen's suggested sources for the sediments. There are no radiometric dates or fossil data for the unit. It is assumed to be the same age or older than the Crescent Formation (Rau, 1964).

Crescent Formation. The Crescent formation was named by Arnold (1906) for basalts that crop out at Crescent Bay. Canadian geologists call equivalent volcanic rocks on southern Vancouver Island Metchosin Volcanics (e.g. Clowes, et al., 1987) despite the precedence of Arnold's work. Tabor et al. (1972) and Cady et al. (1972a, 1972b) divided the Crescent Formation into two units, an oceanic lower basalt unit and upper subaerial upper basalt unit. The lower unit consists of mostly pillowed basalts with diabase dikes and sills and beds of volcanic breccias with

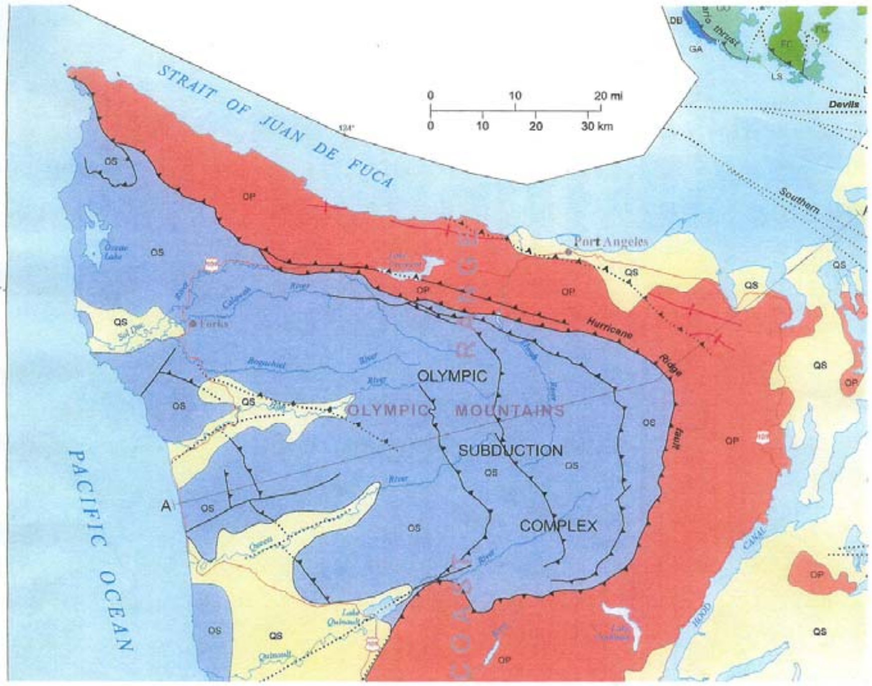

Figure 8. Tectonic map of the Olympic Peninsula . OP = Olympic Peripheral Rocks. Early Eocene to Early Miocene age strata. On the north side of the Peninsula OP includes the Blue Mountain unit of Tabor and Cady (1978a and 1978b), Crescent Formation, Aldwell Formation, Lyre Formation, Twin River Group, and Clallam Formation. OS = Olympic Subduction Complex, now called Olympic Structural Complex. (Map from Brown, E. H. and Dragovich, J. D., 2003.)

minor basaltic sandstone, chert, and red limestone. (e.g. Tabor and Cady, 1978a; Suczek et al.,1994). The upper unit consists primarily of massive basalt flows with occasional oxidized tops and paleosols.

Foraminifera ages and radiometric dates constrain the age of the Crescent Formation. Rau (1981) identified Penutian (lower Eocene) to Ulatisian (middle Eocene) foraminifera in interbedded Crescent sediments consistent with $^{40}Ar/^{39}Ar$ dates. Crescent submarine basalts from the east and north sides the Olympic Mountains have yielded $^{40}Ar/^{39}Ar$ dates ranging 56.0±1.0 Ma to 45.4±0.6 Ma (see Babcock et al., 1994). Duncan (1982) reported a date of 57.8±0.8 Ma for the equivalent Metchosin volcanics on southern Vancouver Island. The foraminifer data and radiometric dates indicate the Crescent Formation is late Paleocene to early Eocene and possible as young as middle Eocene.

Peripheral sequence.. On the north side of the Olympic Mountains post-Crescent shallow and deep marine sediments were deposited in the Tofino basin that extended northwest approximately parallel to the Strait of Juan de Fuca and north to Vancouver Island (Figure 9, page 18). From oldest to youngest, the stratigraphic units of the sequence are the Aldwell and Lyre formations, Twin River Group (Hoko River, Makah, and Pysht formations), and Clallam Formation (e.g. Babcock et al., 1994; Brandon et al., 1998). Tabor and Cady (1978a) include the Montesano Formation, found in the southwestern Olympic Peninsula, in the Peripheral sequence.

The basal Aldwell Formation consists mostly of thin-bedded siltstone, with interbedded sandstone, and minor conglomerate and pillow basalt (Tabor and Cady, 1978a) deposited in cold, deep water (Rau, 1964). Foraminifera ages indicate the unit is Narizian (middle Eocene) (Rau, 1981); however, mapping by Squires et al., (1992) suggest the lower part of the unit may be Penutian (lower Eocene), at least in the eastern part of the Olympic Peninsula.

Uplift of southern Vancouver Island contributed coarse clastics to the basin, forming the conglomerate-rich upper Eocene Lyre Formation (Brown et al., 1956; Snaveley et al, 1986, 1989; Snaveley and Wells, 1996). The age of the unit is based on late Narizian (late Eocene) foraminifera (W. W. Rau cited in Snaveley, 1983). Differences in the sediments in the west and east indicate they had separate sources (Babcock et al., 1994).

The Twin River Group intertongues and overlies the Lyre Formation and includes the Hoko River, Makah, and Pysht formations. The middle Eocene Hoko River Formation consists largely of massive to thin-bedded siltstone. The overlying Makah Formation is late Eocene to Oligocene in age and consists of mostly thin-bedded siltstone with interbedded sandstone. It has a water-laid tuff and an olistostrome (a debris-flow deposit consisting of a chaotic mass of intimately mixed homogeneous materials, such as

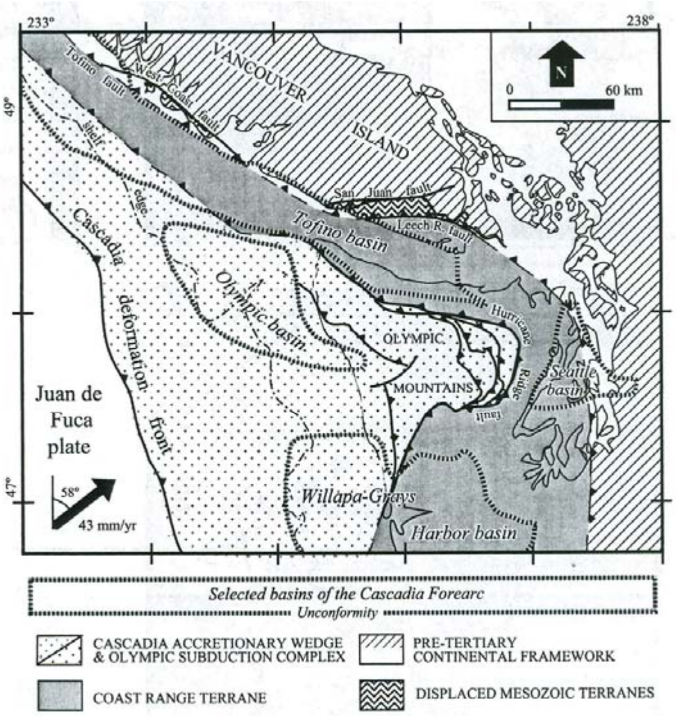

Figure 9. Generalized geologic map of the Cascadia margin in western Washington and southern Vancouver Island. The ruled lines enclose the modern basins (Miocene and younger) of the Cascadia forearc. (From Brandon et al, 1998, Figure 2.)

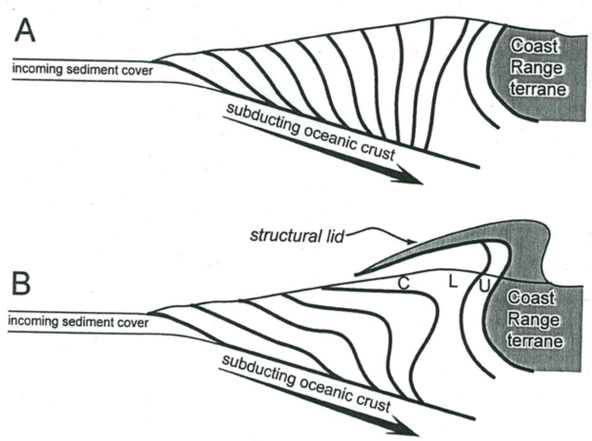

Figure 10. Schematic cross sections of the Cascadia wedge. (A) Steep imbricate structure as proposed by Ray (1975, 1979) and Tabor and Cady (1978a, 1978b), and (B) domal imbricate structure as proposed by Brandon and Calderwood (1990) and Brandon and Vance (1992). Abbreviations refer to tectonic units exposed in the Olympic Mountains: U – Upper OSC, L – Lower OSC, and C – Coastal OSC. (From Stewart and Brandon, 2004.)

blocks and muds, that accumulated by submarine gravity sliding or slumping of unconsolidated sediments). The Pysht Formation is upper Oligocene in age, has a gradational contact with the Makah Formation, and consists of mudstone and sandy siltstone and a pebble and boulder conglomerate at its base. The Twin River Group is approximately 5,000 m. thick.

The Clallam Formation conformably overlies the Pysht Formation, the upper unit of the Twin River Group. It is approximately 800 m. thick. Marine fossils indicate its predominantly feldspathic and lithic sandstone and conglomerate, that contain abundant wood fragments, were deposited in shallow water. Babcock et al, (1994) suggest the sedimentary sources for the Clallam Formation may have not been restricted to Vancouver Island and the Coast Plutonic Complex like those of the Twin River Group but also included contributions from the Coast Range.

Olympic Structural Complex

The Olympic Structural Complex, also called core rocks, were subdivided into two major terranes by Tabor and Cady (1978b), western and eastern core terranes. The western core of Eocene to Miocene age extends to the Pacific Coast. It is nonslaty and complexly folded and faulted, although it has areas that are largely stratigraphically continuous. Locally along the coast it contains mélange. The eastern core consists of Eocene to early Oligocene slaty rocks that are highly sheared. Based largely on differences in sandstone petrology and to a lesser extent their age and deformation, Tabor and Cady (1978a and 1978b) defined five informal lithotectonic assemblages in the Olympic core rocks. From west to east, they are the Hoh lithic assemblage, Western Olympic lithic assemblage, Elwha lithic assemblage, Grand Valley lithic assemblage, and Needles-Gray Wolf lithic assemblage. They consist primarily of marine turbidite deposits (which include a large amount of graywacke sandstones) and a lesser amount of pillow basalts and are highly deformed by imbricate thrusts and folds. The ages of the assemblages largely increase from west to east; however, based on a few fossils Tabor and Cady (1978b) suggest a probable Late Eocene age for the Needles Gray-Wolf lithic assemblage and an Early to Middle Eocene age for the Elwah lithic assemblage. They interpret the Western Olympic lithic assemblage to be Late Eocene to Early Oligocene based on its lithologic continuity with other fossiliferous rocks. Citing detrital-zircon fission-track ages for the “Hoh Formation” and other geologic data, Stewart and Brandon (2004) found a younging of rocks westward from ~19 Ma at Mount Olympus to ~14 Ma at the Pacific coast.

The Hoh lithic assemblage, also called Hoh Formation (Weaver, 1916, 1937), Hoh rock assemblage (Rau 1975, 1979) was formally named Coastal unit of the Olympic Structural Complex (Coastal OSC) by Stewart and Brandon (2004). It consists of mostly of turbidite sandstones and siltstones and mélange. Fossils in Coastal OCS (“Hoh Formation”) rocks indicate the sediments were deposited in varying depths of marine waters. Foraminifera in the siltstones have ages ranging from late Eocene to middle Miocene (Rau 1973, 1975, 1979; Rau and Grocock, 1974). Megafossils of Miocene age indicate some of the Coastal OSC was deposited in very shallow water, in the range of 10 to 30 m (Rau 1975, 1979). Based on fission-track dates for detrital zircons from 34 sandstone and 2 volcanic ash samples and other criteria Stewart and Brandon (2004) determined the Coastal OSC sediments came from an active volcanic arc and older units, including Cretaceous metamorphic rocks, during the lower Miocene (ca. 24 – 16 Ma).

TECTONIC OVERVIEW

Two major geologic features make up the Olympic Mountains segment of the Cascadia subduction wedge: an accretionary complex, called Olympic Structural Complex (OSC), and the peripheral Coast Range terrane,. Rau (1975, 1979) and Tabor and Cady (1978a, 1978b) proposed a steep imbricated structure model for the Olympic Mountains (Figure 10A). More recently, Brandon and Vance (1992) and Brandon et al, (1998) proposed a domal

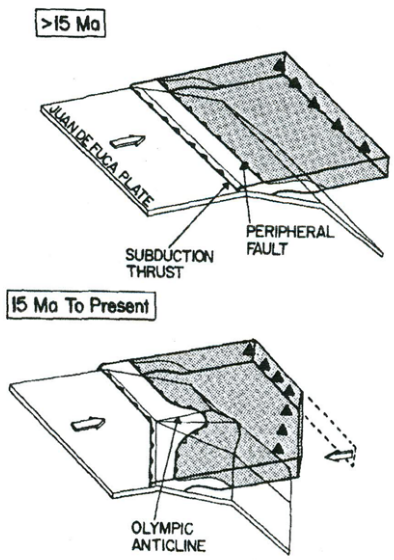

Figure 11. Schematic illustration of development of slab arch beneath Olympic Mountains. (From Brandon and Calderwood, 1990, Figure 3.)

imbricated structure model in which the Coast Range terrane is a structural lid on the accreted part of the wedge (Figure 10B).

The overall structure of the Olympic Mountains is an antiform. The structurally lower OSC consists of highly deformed Eocene to middle Miocene marine sediments with minor igneous rocks. The structurally higher Coast Range terrane, also called "Siletzia" terrane (e.g. Schmandt and Humphreys, 2011), is a fault-bounded slab of marine rocks consisting of lower Eocene basalts and diabase overlain by sediments. The slab's lower boundary fault, the Hurricane Ridge fault, is exposed in the Olympic Mountains. The suture boundary of the slab is not exposed in the Olympic Mountains but is exposed on the southern end of Vancouver Island as the Leech River fault (Clowes et al., 1987).

Brandon and Calderwood (1990) superimposed the position of the subducting Juan de Fuca slab on cross sections, based on earthquake locations that represent the Benioff zone, and found it consistent with cross sections of all available geophysical data (seismicity data, refraction and gravity data, reflection data, and teleseismic receiver function analysis). The cross sections show the slab beneath the Olympic Peninsula has a shallower dip (and depth ~10 km) than areas to the north and south. They suggest development of the bowed arch in the Juan de Fuca plate began at about 15 Ma and produced most of the extant structural relief of the Olympic Mountains (Figure 11). The Cascade arc, which began forming at ~36 Ma, is farther inland east of the Olympic Mountains than to the north or south, consistent with a shallower dip for the slab to reach the depth (~150 km) at which the Cascade magmas could form.

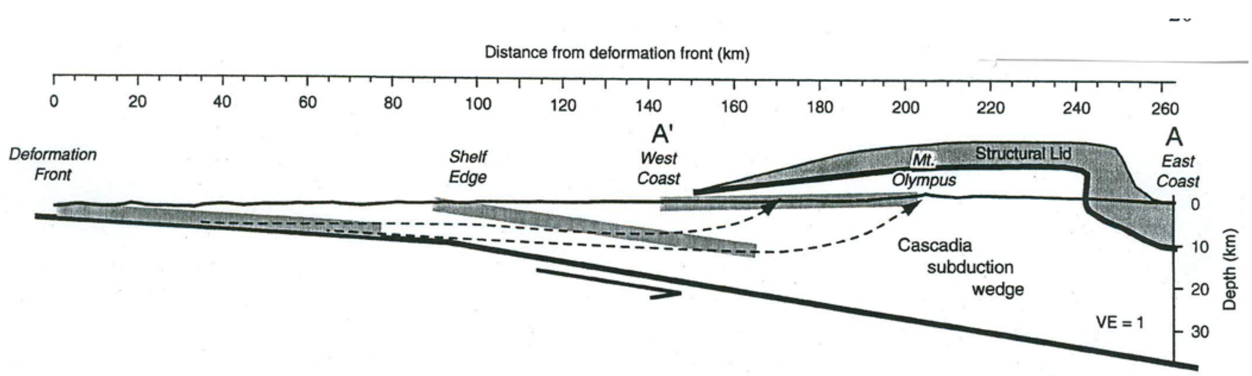

Figure 12. Inferred displacement path for lower Miocene sedimentary rocks accreted to the Cascadia subduction wedge. Rectangular gray boxes mark successive locations of the Coastal OSC where it is exposed in the western Olympic Mountains. (From Stewart and Brandon, 2004, Figure 12.)

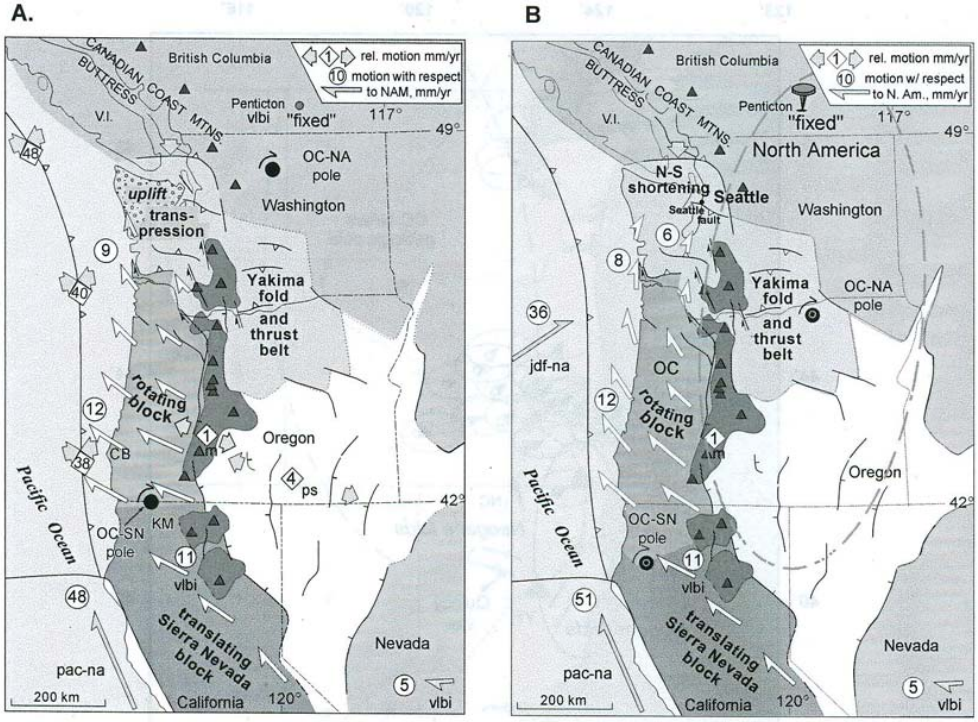

Figure 13. (A) Velocity field for Oregon forearc calculated for Oregon Coast (OC) – North America (NA) pole (from Wells et al., 1998). (B) Revised microplate model showing different location for OC-NA pole. The paleomagnetic rotation of coastal Oregon was linked by a Klamath Mountains pole to geodetically and geologically determine motion of the Sierra Nevada block to derive a new Oregon Coast-North America (OC-NA) pole. (From Wells and Simpson, 2001, Figure 4.)

The active wedge is some 200 – 250 km wide and is bounded by on the east by the forearc low and on the west by the Cascadia trench, located ~140 km west of Olympic Peninsula coastline. Stewart and Brandon (2004) viewed the Coast Range terrane as part of the active wedge because of its folding and uplift associated with development of the doubly vergent wedge. Based on the suturing of the Coast Range terrane onto the North American plate at ~38 Ma along the Leech River fault, the onset of volcanism at ~36 Ma in the Cascade volcanic arc (Armstrong and Ward, 1991; Brandon and Vance, 1992), and when slip occurred on the Hurricane Ridge fault, Brandon et al. (1998) infer the Cascadia subduction zone developed at ~35 Ma in the late Eocene rather than at ~50 Ma as interpreted by previous investigators (e.g. Wells et al., 1984; Heller et al., 1987; Snavely, 1987). More recently Schmandt and Humphreys (2011) concluded the Cascadia subduction zone developed its current configuration by ~ 40 Ma, following accretion of the Siletzia microplate to North America at ~55 Ma. Their conclusion is fundamentally consistent with Brandon and Vance's (1992) inference that the Cascadia subduction zone initiated at ~35 Ma.

Development of the Cascadia subduction zone resulted in extensive imbrication of the western Coast Range terrane, and possibly major westward displacement of Coast Range terrane on the Hurricane Ridge fault as Brandon et al. (1998) suggest. Subsequently the Coast Range terrane was eroded away exposing Olympic Subduction Complex. As the Juan de Fuca and North American plates converge, currently at a rate of 36 mm/yr (Demets and Dixon, 1999), apparently all of the sediment is accreting onto the wedge (e.g. Davis and Hyndman, 1989; Pazzaglia and Brandon, 2001). Zircon fission-track data (Brandon and Vance, 1992) and apatite fission-track data indicate the central core of the Olympic Mountains first began emerging above sea level in the early Miocene at ~18 Ma and in the northwest corner of the Peninsula at ~12 Ma as sedimentary rocks were continually accreted to the wedge (Brandon et al., 1998) (Figure 12). Analysis of seismic data indicates sediments 2-3 km thick are transported into the subduction zone and increase in thickness to 20 km at the Peninsula's coast and ~35 km below the core of the Olympic Mountains. Eroded sediment is transported into the Pacific Ocean and recycled back into the accretionary wedge with a steady-state balance erosional outflux and accretionary influx (Pazzaglia and Brandon, 2001).

Studies of tectonic shortening in the Olympic Mountains mostly focus on the deformation attributed to northeast-southwest compression associated with northeast-directed 36 mm/yr subduction of the Juan de Fuca plate beneath

North America (eg. Tabor and Cady, 1978b; Brandon et al, 1998). However, there is considerable evidence that there is also a significant component of north-south contraction. Evidence near the Washington coast for northward shortening cited by McCrory (1996) includes steeply dipping and faulted glaciofluvial strata at the crest of an east-northeast trending ridge; thrust and reverse faults farther east on the ridge striking northeast (N65^{0}E to N80^{0}E) and dipping northwest (25^0 to 55^0) offset Pleistocene gravel beds; borehole break-out data of Magee and Zoback (1992) that yield principal compressive stress orientations of N14^{0}E and N5^{0}W; and Pleistocene gravels oriented N80^{0}W, 26^{0}N in an east-trending ridge. This ridge and the other ridge, appear to be anticlinal folds produced by blind thrusts. Wells et al. (1998) and Wells and Simpson (2001) attribute the north-south compression to the Neogene rotations of the Sierra Nevada block moving N47±5^{0}W at 11±1 mm/yr from Global Positioning System (GPS) data (Dixon et al., 2000) and a semi-ridged Oregon coastal block rotating clockwise at an average Cenozoic rate of 1.19±0.10^0/my. In the revised rotation model of Wells and Simpson (2001) the Olympic Peninsula, which is under uplift and transpression in the Wells et al. (1998) model, is a region of north-south shortening and ~6 mm/y of shortening with respect to North America (Figure 13) due to the migrating forearc block abutting against the comparatively stationary Mesozoic and older rocks of southwestern Canada and northwestern Washington (Johnson et al., 1996; Wells et al., 1998; Johnson et al., 2004). McCaffrey et al. (2007) found the vertical rotation axes determined from GPS velocities of northwestern U.S. and adjacent southwestern Canada are consistent with paleomagnetic declination anomalies indicating the rotations have been generally steady for 10-15 Ma and GPS velocities fitting substantially better when Vancouver Island and the Coast range to the south move as a block relative to North America. They suggest shortening across the Puget region of western Washington (Astoria, OR to Bellingham, WA) is 4.4±0.3 mm/yr. Pazzaglia and Brandon (2001) proposed 3mm/yr northeast-southwest shortening in the Olympic Mountains. The apparent larger shortening rate in the Puget region may reflect a combination of northeast-southwest driven by the subducting Juan de Fuca plate and north-south shortening driven by, the previously described, rotating blocks.

Slip on the basal/subduction thrust, also called the Cascadia fault, of the Juan de Fuca plate during mega-earthquakes apparently accommodates most of the convergence with the North American plate and a lesser amount of convergence by shortening in the subduction wedge. Subduction zone earthquakes on the Cascadia fault are thought to have a recurrence interval of about 500 years. The linkage of geologic data from investigations in Washington and historic records of tsunamis arriving on the coast of Japan show that the most recent of these giant earthquakes occurred on January 26, 1700 (Atwater, B. F. et al., 2005).

GEOLOGY STOPS

DAY 1
Mile 0.0 Mileage for Day 1 is measured from the intersection of U.S. 101 and Washington 112 on the west side of Port Angeles, Washington.

Mile 13.1, STOP 1. Lake Crescent Overlook. Roadcut in Crescent Formation, Tcb unit of Tabor and Cady (1978a). Flows of black pillow basalt striking approximately east-west and dipping steeply (~85^0) north; dense to highly vesicular; contains microphenocrysts of clinopyroxene [Fe, Mg, Ca, Na, SiO_2, and Al] and calcic to soda plagioclase [(Ca, Na) (Al,Si) $AlSi_2O_8$]. A submarine flow at Crescent Lake, just below the contact with the overlying Aldwell Formation yielded an $^{40}Ar/^{39}Ar$ date of 52.9±4.6 Ma while the base of the submarine Crescent Formation flows on Hurricane Ridge Road yielded an $^{40}Ar/^{39}Ar$ date of 45.4±0.6 Ma. These two dates suggest the Crescent Formation, while mapped as a single unit between these two locations, had more than one eruptive center (Babcock et al., 1994). There is disagreement among investigators as to whether the chemistry of the basalt justifies separating the formation into lower and upper members. Glassley (1974) and Muller (1980) maintain that the chemistry points to two members – a lower mid-ocean ridge basalt (MORB) and upper oceanic island basalt (OIB) member. Cady (1975) and Babcock et al, 1994) argue there is no clear difference in chemistry between the upper and lower members. More work needs to be done to resolve this issue.

Mile 38.8 Intersection of U.S. 101 and Washington 113.

Mile 50.5 Forks, Washington city limits.

Mile 64.4 Intersection U.S. 101 and Upper Hoh Road (to Hoh Rain Forest)

Mile 82.5, STOP 2. Beach 4. Wavecut outcrops north of end of trail from parking lot. Hoh rock assemblage of Rau (1975) consists of massive to thick-bedded graywacke (informal term for coarse-grained sandstone with poorly sorted subangular to angular quartz, feldspar, and rock fragments all mixed together in a clayey matrix); thin to medium bedded siltstone and sandstone; and coarse- to very coarse-grained graywacke, grit, and conglomerate. The rocks, mapped as Hoh lithic assemblage by Tabor and Cady (1978a), include thick-bedded coarse-grained lithic and feldspatholithic sandstone, with angular locally well-sorted grains and minor thin-bedded siltstone and sandstone. Ripple drift cross-laminations, groove, flute, and flame casts are present in thicker beds as well as crossbedding and channels.

The Coastal OCS outcrops at this stop consist primarily of thick- to thin-bedded turbidite sandstone (graywacke) and siltstone. At the end of the trail are steep, east-dipping sandstones. Their orientation (right-side up or overturned) can be determined from primary sedimentary structures. (Examine the outcrop and determine the orientation of bedding.) The beach here is underlain by a Pleistocene wave-cut surface. Notice the numerous paddock clam borings. Just north of the end of the trail is well-exposed angular unconformity of Pleistocene gravels on the steeply-dipping turbidite deposits. A short distance farther north the beds have been deformed into a series of folds (fold train). The folds have northeast-striking axial planes and are truncated at the base of the outctrop by a low angle thrust fault. The geometry of the folds and other structural criteria indicate they formed by a combination of flexural slip and flexural flow.

Return north on U.S. 101

Mile 86.3, STOP 3. Ruby Beach. Wavecut cliffs and seastacks north of end of trail from parking lot. Hoh rock assemblage of Rau (1975) made up of graywacke sandstone, mélange rocks of intensely sheared claystone and siltstone containing blocks of indurated siltstone and graywacke sandstone and altered volcanic rocks, and undifferentiated volcanic rocks with very large blocks within mélange rocks. (The term mélange refers to a body of rock, large enough to be mapped, that is characterized by a lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmental matrix of fine-grained material.) The outcrops were mapped by Tabor and Cady (1978a) as the same Hoh lithic assemblage unit as at Beach 4, except for a small offshore outcrop of the Lyre Formation. The rocks at Ruby Beach don't look anything like those at Beach 4 and were more properly mapped by Rau, at a scale of 1:62,500, as mélange. The Tabor and Cady (1978a) map is half the scale (1:125,000) of Rau's map, justifying using the same unit designation as at Beach 4. The description of the unit, however, could have been improved by mentioning the presence of mélange.

Several different origins for Hoh mélange have been proposed including gravity tectonism, shear zones between large structural blocks, and diapirism. Earlier studies by Rau (1973, 1975, 1979) and Rau and Grocock (1974) identified both shear-zone and diapiric mélanges in the Coastal OSC. Orange (1990) and Orange et al. (1993) have done detailed investigations of Hoh mélanges that demonstrate the complexity of geologic conditions under which they form. Studying middle Miocene mélanges in the Coastal OSC, Orange (1990) developed criteria to distinguish shear-zone and diapiric mélanges. Diapiric mélanges have radial scaly foliation that is well-developed at their margins and poorly-developed in the centers, opposite fold vergent directions from margin to margin, rare exotic clasts. The clasts range in shape and orientation from elongate with a strong preferred orientation at the margins to angular and mostly random orientation in the center. Shear-zone mélanges have a strongly developed and pervasive scaly foliation that maintains the same orientation across outcrops, uniform fold vergent directions, exotic clasts. The clasts are mostly elongate and have a strongly developed long-axis preferred orientation.

The cliff at this stop has the appearance of a shear-zone mélange. Large eye-shaped structural blocks bounded by faults and high angle faults accommodated tectonic shortening.

End Day 1. Return to Port Angeles.

DAY 2

Mile 0.0 Intersection South Mount Angeles Road and Hurricane Ridge Road. Watch for mile markers. All mileages are based on distance from this intersection.

Mile 19.1, Stop 4. Hurricane Hill Trail. The Hurricane Hill trail crosses three stratigraphic units of Tabor and Cady (1978a). Approximately the first 0.7 km (2000 ft) of the trail traverses the Tnm unit of 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.

Leaving the trail head there's a very low topographic dip in it, a short distance 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, what 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 northeast, cleavage striking west-northwest and dipping steeply north-northeast, steeply plunging pencils trending south-southeast to south, and steep to moderately steep plunging fold axes trending 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 the trail is on the Blue Mountain unit. 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, 1978) 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.

Mile 16.0, Stop 5. Hurricane Ridge Road (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 steeply dipping bed dipping south and north, right side up and overturned, and highly disrupted by imbricate faults. 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.

Slate present within the Needles Gray-Wolf lithic assemblage here, and at the previous stop, 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 (Stewart, 1974, in the western part of the Olympic Structural Complex and Hawkins, 1967, in the Mount Olympus area). Brandon and Calderwood (1990) concur with Tabor and Cady's metamorphic zonation. Based on fission-track dates for sandstones from the eastern zone they place its temperatures 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, Brandon and Calderwood (1990) identified 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. Assuming the rocks have an overall density of 2,700 kg/m^{3,} they calculated 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.

Mile 10.7, Stop 6. Hurricane Ridge Road (Mile Marker 10.7). 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.

There are two basic models for the origin of the Coast Range basalts (Crescent and Siletz formations), a seamount/plume model (a spreading ridge reorganization model is a variation of this) and a marginal basin model. In the seamount/plume model a seamount chain, that formed over a mantle plume, was accreted to the continent (Simpson and Cox, 1977; Duncan, 1982). Its variation, the spreading ridge reorganization model, involves reorganizations of 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 (Wells et al., 1984; Babcock et al., 1992; Snaveley and Wells, 1996). A study by Chan et al. (2012) of Pb isotopes in the 42 – 37 Ma Grays River volcanics indicates these younger Coast Range basalts at least partly shared a common mantle source with the older (ca. 56 – 45 Ma) Crescent Formation basalts. J. H. Tepper (written communication, 2013) suggested the Crescent basalts may reflect a combined seamount/plume and marginal basin model, like the model proposed by Chan et al. (2012) for the Grays River volcanics. In their model the Grays River volcanics (MORB) erupted in a marginal basin, formed in response to oblique subduction of the Kula-Farallon spreading ridge, while oceanic island basalts (OIB) from a mantle plume fed into it.

Schmandt and Humpreys (2011) place the accretion (of the "Siletzia microplate") at ~55 Ma in the early Eocene while Brandon and Vance (1992) favor a younger age of 42-24 Ma for accretion. Brandon and Vance (1992) base the time of accretion primarily on the movement history of the Leech River fault on Vancouver Island, the only place where the continental suture boundary of the Coast Range terrane is exposed.

End Day 2. Return to Port Angeles.

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