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Society Field Trips in Pacific Northwest Geology

The Bedrock Geology of Seattle

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by

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and many thanks to George Lightner and Tom Bush for handling logistics!

I. INTRODUCTION

There is remarkably little exposed bedrock in Seanle. Why focus a field trip on such an unpromising topic?

Recent concern about the Seanle fault and the conse¬quent increased (relative to what earth scientists believed 10 years ago) seismic hazard in the central Puget Lowland have led to a number of hypotheses about the bedrock structure beneath Seattle. Conversely, what little we know about the bedrock of the Seattle area has become important for assess¬ing fault geometry and long-term deformation rates. While there is little accessible bedrock outcrop in Seattle proper, there are outcrops along strike to the east and west, and one can reasonably expect subsurface lithologies and structures to be similar to those exposed along strike.

What rocks would be encountered in a deep test hole beneath Seattle? Why are the youngest rocks near Seattle among the most strongly deformed? The apparent basement of the eastern Olympic Peninsula is Eocene basalt of the Crescent Formation, whereas Eocene arkose and andesite crop out to the east of Seattle: is there a major N-S fault beneath Puget Sound that separates these two provinces? Some fore-arc basins (Great Valley in California, Cook Inlet in Alaska) have no exposed bedrock in their centers. Why is there any bedrock outcrop in Seattle? This trip is an intro¬duction to these questions, with an emphasis on the evidence offered by surface rock outcrops.

The last round of extensive study of Seattle's rock was in the 1950s and 1960s (for example, Waldron and others, 1962). Those workers are no longer active, and there now no experts on the bedrock geology of Seattle. Our credentials are limited: Haugerud has read some of the literature on Seattle and points east and is mapping Bainbridge Island. Haeussler recently finished mapping the Uncas quadrangle, SE of Sequim, which includes outcrop of Crescent Formation and overlying sedimentary rocks, and the Wildcat Lake quadrangle, west of Bremerton, which exposes sub-Crescent(?) basement. He is now mapping the Bremerton area.

Others in the local geologic community are knowledgeable on various aspects of this geology. Jody Bourgeois (University of Washington) uses the Blakeley Formation and correlative rocks to the east for teaching exercises. Liz Nesbitt (Burke Museum) is currently working on the macro-fauna of the Tukwila and Blakeley Formations. Richard Stewart (University of Washington) is working on fission-track ages for the Blakeley, and has some interesting questions about the published micropaleontology of the unit. Tim Walsh (Washington DGER) has done extensive research on the coal-bearing rocks of central King County.

Not visited on this trip, but worthy of note, are some other outcrops:

- Blakeley Formation at Alki Point is similar to that on SE Bainbridge Island. Alki outcrops are best seen at low tide. They define an open, steeply north-plunging anticline; beds are overturned at NW end of outcrop.
- Blakeley Formation outcrops along 1-5 in George¬town would require State Patrol permission and strong nerves to examine.
- There is a good section of the Tukwila Fm along Martin Luther King Way in Tukwila, between S. Boe¬ There is no nearby parking.
- Lapilli tuff in Seward Park was assigned to the Blakeley Formation by Waldron and others (1962).
- Waldron and others (1962) show Blakeley Formation throughout the Columbia City-Rainier Valley area.

Limited reconnaissance by Haugemd suggests that most of these outcrops have since been landscaped.

Ask Liz Nesbitt about outcrops of the marine lower Tukwila Formation that are on private property along the Duwamish River.

The large Stoneway rock pit visible north of South-center is in crumbly-weathering, brown, massive, homblende-plagioclase porphyry of the Tukwila For¬mation. Some of the rock is breccia; other rock is mas¬sive and may be flows and (or) shallow intrusions.

Some exploration might find good exposures of the Puget Group in the vicinity of Coal Creek in south Bellevue and Newcastle. There is a good Tukwila Formation outcrop—perhaps that sampled by Turner and others (1983)—along Coal Creek Parkway north of SE 79th Street.

Minard (1985) mapped Miocene sedimentary rock at the base of the west wall of the Snoqualmie valley NW of Duvall.

- Outcrops near Cathcart (lower Snohomish River val ley) have long been correlated with the Blakeley For¬mation. Eocene(?) volcanic rocks crop out along the Bothell-Monroe cutoff (SR 522) just north of the Snohomish River.
- East of the Snoqualmie River valley, Eocene Mount Persis volcanics overlie Mesozoic sandstone, argillite, and greenstone of the western melange belt (Tabor and others, 1993). The volcanic rocks of Mount Persis may be correlative with the Tukwila Formation.

II. SATURDAY: SEATTLE—LITTLE QUILCENE RIVER—GREEN MOUNTAIN— MANCHESTER

From the Kent-Des Moines Park & Ride lot. take 1-5 north about 15 miles to Exit 164B. Follow signs to ferries—right on 4lk Avenue S. right on Royal Brougham Way, and right to side road beneath Alaskan Way viaduct, later turning onto Alaskan Way proper.

We are taking the Washington State ferry to Bainbridge Island, not the Victoria ferry. We hope to catch the 7:40 ferry. The crossing takes about 35 minutes.

From the Bainbridge Island ferry landing, proceed up hill, straight through the first stop light, and follow State Route 305 northwest across the Agate Passage bridge to Poulsbo, about 13 miles. About 2 miles beyond Poulsbo, turn right onto SR 3 towards the Hood Canal bridge some 8 miles to the north.

At the Hood Canal Bridge, drive beyond the bridge and turn left into the parking lot on the east end of the bridge (north side) to meet the remainder of our group. Continue across the bridge and west on SR 104.

West of Shine, SR 104 traverses a low-elevation plateau. Sandy, pebbly debris in road cuts suggests that the substrate is outwash. Rolling terrain and occasional erratics visible in clearcuts are inconsistent with this area being underlain by recessional outwash, so it must be advance out-wash. Vashon till is here either absent, very thin, or very sandy.

At 14 miles from the east end of the Hood Canal bridge, view ahead of Big Skidder Hill, in the north part of the Uncas 7.5' quadrangle.

15 miles from E end Hood Canal Bridge, at junction with US 101, turn left, south, towards Quilcene and Olympia.

Highway 101 follows the Leland Creek spillway, a 15 km long channel that drained recessional Lake Bretz. As Vashon retreated following its maximum extent at about 17,000 cal-endar years BP (Porter and Swanson, 1998), ice-impounded proglacial Lake Russell drained south, via the Black Lake spillway south of Olympia, to the Chehalis valley and the sea. As pointed out by Thorson (1989), when ice retreated farther and thinned, the Leland Creek spillway opened up and the water level dropped 64 meters to stabilize as Lake Bretz. The current maximum elevation of the Leland Creek spillway is 69 meters, between Crocker Lake and Leland Lake. The Black Lake spillway is at 41 m; the difference of 92 m between the present relative elevations of the Black Lake and Leland Creek spillways and their former relative elevations is a measure of the amount of isostatic rebound in this area since Lake Bretz time.

About 9 miles from the SR 104 junction, % mile beyond milepost 292, turn right (west) onto Lords Lake Loop Road. Follow road up and to west,

High ground to west is underlain by Eocene Crescent Formation. Low country here is in younger sedimentary cover. As we drive west we are heading down section.

About the Crescent Formation

The lower and middle Eocene Crescent Formation consists of submarine and subaerial basalt flows, breccia, and interbedded sedimentary rocks. Pillow lava, pillow and lapilli breccia, amygdaloidal lava flows, dark gray calcare-ous mudstone, basaltic siltstone, and sandstone make up the lower submarine unit.

Tabor and Cady (1978) mapped two units within the Crescent Formation on the Olympic Peninsula. The west¬ernmost (in the Uncas quadrangle) is unit Tcb, which they describe as:

basalt, massive flows, pillows, and breccia; minor diabase and gabbro. Pillows and tube structures are common, rang-ing from centimeters to 3 m across;, some show bedding but most occur as separate pillows and pillow fragments in a tuffaceous matrix. Gabbro and diabase, this probably oc-curring mostlyas sills, are compositionally similar to basalt but with subophitic or hypidiomorphic granular texture.

Unit Tcb is basically a submarine unit. Unit Tcbb, on the other hand, has less evidence of being a submarine unit. Tabor and Cady describe it as:

basalt flows and mud flow breccias. Flows are characterized by closely spaced, random joints and are locally are columnar jointed, or more rarely pil¬lowed. Unit includes many un-mapped interbeds of sedimentary rocks, some gray foraminif-eral limestone.

Tabor and Cady map both of these units as dipping away from the core of the Olympic Mountains, with the submarine unit Tcb lying beneath unit Tcbb. This relationship is similar to that mapped on Green and Gold Mountains in the Wildcat Lake quadrangle, near Bremerton, where submarine basalts and basaltic sediments lie beneath subaerial basalts.

Calcareous nannoplankton from interbedded turbidite siltstone and sandstone at the top of the submarine unit at Bon Jon Pass, 1 km west of the Uncas quadrangle, are re¬ferred to the CP 11 zone, or early Eocene (about 50 Ma), by D. Bukry (written communication, 1998). East of the Uncas quadrangle, Yount and Gower (1991) report foraminifera referable to the Ulatisian stage (early middle Eocene) within marine siltstones and sandstones of the Crescent Formation. Most of the up-per part of the Crescent Formation in the Uncas quadrangle consists of amygdaloidal basaltic flows and breccia. Breccia is monolithologic, and the flows sometimes have rubbly reddish weathering surfaces indicative of subaerial eruption. However, Spencer (1984) noted on the west shore of Quilcene Bay, south of the Uncas quadrangle, there are massive basaltic flows in-terbedded with pillow lavas, indicating complex interfingering of environments typical of oceanic islands. No ages have been deter¬mined from the subaerial part of the Crescent Formation within the Uncas quadrangle. From the Bremerton area, 40 km to the southeast, Duncan (1982) reported an 40Ar/39Ar age of 55 Ma, and Babcock and others (1992) reported an 40Ar/39Ar age of 50.3 ± 1.5 Ma.

No fossil ages have been obtained from subaerial Cres-cent basalts, but the overlying Aldwell Formation has benthic foraminifera and mollusks with ages from upper Ulatisian to lower Narizian (Spencer, 1984). Therefore, subaerial Crescent Formation basalts have ages around 46-50 Ma on the time scale of Berggren and others (1995). That the 40Ar/39Ar dates on the basalt flows analyzed by Duncan (1982) were slightly older could be explained by: 1) recoil effects, because the "*"Ar/^^Ar analyses were whole rock, 2) the Crescent For-mation basalts may be slightly time trans-gressive, and 3) the Crescent Formation basalts being lower Ulatisian rather than upper Ulatisian.

Outcrops of Crescent Formation at Lords Lake are in the upper, Tcbb, part of the unit, and are amygdaloidal. Beyond Lords Lake, for the next 3 miles or so, outcrops along the road are massive basalt flows of Tabor and Cady's unit Tcbb. Un-less someone protests strongly, we will not stop in the upper Crescent.

At about 4 miles from US 101, signs for Olympic National Forest. At 5 miles, pass unlocked gate. At T/i miles, junc¬tion. Stay right on Forest Road 28. At about 8 miles, sign on right shoulder indicates this is Forest Tour stop 3. Pull left into quarry.

Stop 1. Crescent Formation, **Little Quilcene River fault.** There is a large NW-striking dextral fault with a 6-m-wide gouge zone exposed in this quarry. This fault lines up with the NW-trending Little Quilcene drainage, and thus we infer the drainage lies along the SE extension of this fault. On the SW side of the fault are pillow and lapilli breccia and calcareous mudstones. On the NE side of the fault are pillow basalts, overlain by a diabase sill(?), overlain by mudstone. This outcrop is within Tabor and Cady's (1978) unit Tcb. If it is clear, admire the view southeast to the Puget Low-land, Seattle, and maybe Mount Rainier. Mountains and the curvature of the Earth prevent one from seeing all the way to northeast Oregon, but we are close to, if not on, the Olympic-Wallowa Lineament.

How might the NW-trending fault at this location fit into the tectonic pattern of the Puget Lowland? Of the Pacific Northwest?

Continue up Road 28 about 1/2 mile to pullout on left. Park here and walk 100m up road to

Stop 2. Sedimentary rocks in lower Crescent Forma-tion. What inferences about depositional environment can you draw from the bedding style here? Is there evidence that the beds are upright?

The shape of the valley here suggests this was a high-volume ice-marginal drainage channel. Key features are the wide, irregular bottom, low gradient, and minimal talus on valley walls.

Continue up Road 28 to Bon Jon Pass (Vi mile). Take road 2810 (Road 28 is currently blocked by a washout) to northwest.
1.5 miles beyond Bon Jon Pass, roadcut on right with basalt pillows. Pull over.

Stop 3. Pillow basalt in Crescent Formation.

Continue NW on Road 2810. In 0.4 miles, pass trailhead. 0.8 miles farther, junction with Road 210. Continue left on Road 2810, about l'/i mile to junction with Road 28, then an-other l'/i mile to junction with Road 210. Continue 0.2 miles on Road 28 to junction with Road 2840. Turn right on 2840.

Follow Road 2840 3 miles to junctions with roads 070 and 071 (both on left). Keep right on 2840. In another I'A mile, turn sharply right on Road 2845.

Continue 3 miles up Road 2845 to

Stop 4. Lyre conglomerate. The Lyre in the Uncas quad is mapped as having two conglomerate members, with andesite tuff and breccia lying in between. The lower con¬glomerate consists of chert, basalt, and conglomerate clasts, whereas the upper conglomerate also has chert, but also includes metasedimentary, igneous, quartz, and graywacke clasts. The conglomerates are both clast and matrix supported. Commonly there is no preferred orientation for the clasts, which indicates deposition by debris flows in a submarine fan environment. This outcrop is in the upper conglomerate.

In the southern part of the Uncas quadrangle, the Lyre Formation lies on the Aldwell Formation. Along the western edge of the quadrangle, and northeast of the quadrangle, the Lyre Formation lies directly on the Crescent Formation. Spencer (1984) observed the contact in the upper Snow Creek drainage, and described it as irregular and undulatory. The contact northeast of the quadrangle contains basaltic cobble and boulder conglomerate. From these observations, Spencer (1984) inferred considerable relief on the surface beneath the Lyre Formation. Spencer (1984) measured 418 paleocurrent indicators in the Lyre Formation and found a consistent south-southwest direction of transport. The base of the section has a higher percentage of basaltic clasts indicating erosion of the underlying Crescent Formation. Chert and phyllite clasts are also common in the conglomerates, and Snavely and others (1993) and Garver and Brandon (1994) concluded similar clasts in the Lyre Formation at the northwestern tip of the Olympic Peninsula were derived from Mesozoic sediments on southern Vancouver Island.

There is no direct fossil control on age of the Lyre here, but it is sandwiched between the lower Narizian Aldwell Formation and the upper Narizian sandstone of Snow Creek. Yount and Gower (1991) report K-Ar ages of 35.5 and 41.0 Ma from hornblende in a an andesite boulder from the Lyre, collected near Mt Zion just west of the Uncas quadrangle. These ages are younger than is allowed by Spencer's (1984) biostratigraphy, and thus we infer some argon loss. Northwest of the Uncas quadrangle, Lyre Formation contains foraminifera referable to the upper Narizian stage (Snavely and others, 1993).

Above the Crescent: A note

The middle Eocene Aldwell Formation overlies the Crescent Formation, but within the Uncas quadrangle is only found in one small exposure in the southeastern comer along Highway 101. We will not see the Aldwell. Regionally, the Aldwell Formation consists of thin-bedded slope mudstone and thin-bedded turbiditc sandstone (Tabor and Cady, 1978). Massive to well-bedded basaltic conglomerate and lithic sandstone occur locally. Along Quilcene Bay, southeast of the Uncas quadrangle, basal Aldwell Formation in-terfingers with basaltic sediments, and the contact is placed where coarse, massive to thick-bedded volcaniclastic sediments give way to the more thinly bedded sandstone and siltstone of the Aldwell (Spencer, 1984, p. 24-25). The upper contact of the Aldwell Formation is not exposed, but it may be unconformable based on relations with the overlying Lyre Formation elsewhere on the Olympic Peninsula. Foraminifera from the Aldwell Formation are referable to the lower Narizian or upper Ulatisian stages. Calcareous nanno-plankton from the Aldwell are referable to the CP 14a zone (upper middle Eocene, about 44-41 Ma) at Quilcene Bay (Bukry, written communication). These fossil data indicate the Aldwell Formation is coeval with the middle Eocene basaltic sediments described above. The paleoecology of faunas collected from the Aldwell Formation are indicative of cool to cold water in the bathyal zone (Spencer, 1984), quite different from neritic water depths and warm temperatures during deposition of the upper Crescent Formation sediments.

Strata overlying the Aldwell on the east side of the Olympic Peninsula go by fairly different names than those to the northwest. There are problems in how the units are defined and correlated. In the Uncas quadrangle, the Lyre Formation and the informally named sandstone of Snow Creek overlie the Aldwell. Perhaps the Lyre and the sandstone of Snow Creek should be combined into one formation, with the Snow Creek sandstone as a member. Spencer (1984) notes the Snow Creek unit and the rest of the Lyre Formation are related because of a conformable contact and because there is an abundance of chert and metamorphic clasts in both units, which indicates a similar source area.

Moreover, Tabor and Cady (1978) and Yount and Gower (1991) map the Snow Creek unit as the Twin River Formation. Spencer (1984) included the Snow Creek unit in the Lyre Formation. Haeussler et al. (1999) mapped the Snow Creek unit as a separate unit similar to the Hoko River Formation of the western Olympic Peninsula (Snavely and others, 1993), thus formally avoiding expanding the Lyre Formation, and avoiding using the term "Twin River," which has been used as a Group name to refer to several formations that range in age from upper Narizian (uppermost middle Eocene) to Miocene time (e.g. Garver and Brandon, 1994). The lowermost of the formations in the Twin River Group is the Hoko River Formation, which is similar in composition and age to the sandstone of Snow Creek, as used in this study. See Figure 2.

Retrace route 1.7 miles back down Road 2845 and turn right onto Road 2852. In about 2.3 miles, look on left of road for

Stop 5. Sandstone of Snow Creek. (Haeussler recalls outcrop somewhere in this area. Haugerud, reconnoitering for this trip, found only rubble.)

Silty sandstone and sandstone turbidites which overlie conglomerate of the Lyre Formation in this vicinity constitute the sandstone of Snow Creek. The section in the upper Snow Creek drainage is 567 m thick; foraminifera are referable to the upper Narizian stage and are "... indicative of cool to cold water temperatures and water depths in the lower bathyal zone" (Spencer, 1984, p. 135). Petrography of the sandstones indicates chert and quartz predominate, with chert being a significant proportion of the clasts (Spencer, 1984). Deposition of the sandstone of Snow Creek appears to have been localized because it is not found northeast of the Uncas quadrangle, where the Townsend Shale lies un-conformably on the Lyre Formation (Thorns, 1959) and the Snow Creek member is missing.

Continue down road 2852 about 1/2 mile to junction with Road 2850. Turn right onto 2850.

One mile from 2852-2850 junction, we leave the Olympic National Forest. A sign states "Douglas Fir Plantation

Planted 1928." The trees are no more than 2' diameter at breast height.

Five miles from ONF boundary, turn sharply left at road junction. One mile farther, junction with Highway 101. Turn left. Take US 101 north 4 miles to junction with SR 104. Exit onto 104 and go east to Hood Canal bridge.

At east end of bridge, turn right to Bremerton. (Stop and pick up cars left here in morning). Follow SR 3 south some 20 miles.

The Seattle fault: Why bedrock crops out in Seattle

For the rest of the trip we will look at outcrops within a complex faulted anticline in the hanging wall of the east-west Seattle fault. Overall the Seattle fault appears to be a north-verging thrust that brings up older strata on the south side (Johnson and others, 1994). Uplift on the south side of the fault, and greater erosional resistance of the older bedrock, has produced the anomalous east-west topographic high comprised of Green and Gold mountains, Newport Hills, Cougar Mountain, Sauk Mountain, and Tiger Mountain.

Total stratigraphic throw on the/ Seattle fault is on the order of 10 km (Johnson and others, 1994). Assuming a reasonable dip (e.g. Pratt and others, 1997), overall shortening may be on the order of 30 km. Shortening is in response to overall N-S contraction of western Washington, caught in a vise between the stable (relative to most of North America) and rigid Coast Mountains of British Columbia and the north-moving, clockwise-rotating, rigid Oregon Coast Ranges block (Wells and others, 1998). The Oregon Coast Ranges are being driven north by the north-moving Sierra Nevada block, with a pivot in the Sierra Nevada. The Sierra Nevada block is dragged north by shear of the Pacific plate—not all displacement is taken up on the San Andreas fault. Net north-south contraction across western Washington is on the order of 4 mm/yr (R.E. Wells, personal commun., 2000).

When the Seattle fault began moving is not clear. Johnson and others (1994) suggested that motion began at the beginning of Blakeley time (latest Eocene or early Oligocene), as they believed that the Blakeley Formation thickens in the Seattle basin, on the north side of the fault. The apatite fission-track age reported by Haeussler and others (2000) supports this inference. However, Haugerud doesn't see the Blakeley Formation in the Seattle basin in the seismic reflection lines published by Johnson and others (1994)—and any interpretation depends on uncertain velocity corrections. Tom Brocher (personal commun., 2000) doesn't see north-to-south thickening in SHIPS tomography. The tomography, while less precise than the seismic reflection survey, contains no unconstrained velocity corrections. An alternate view is that displacement on the Seattle fault began in Blakely Harbor time (mid-Miocene), as the Blakeley Harbor Formation clearly thickens to the south in both reflection and tomographic profiles.

Exit for Chico Way NW. Turn right onto Chico Way, pro¬ceed about 2/3 mile, and turn right onto Northlake Way. In '/i mile veer right onto Seabeck Highway.

In about 3 1/2 miles, turn left on NW Holly Road.

About 2 miles farther, about 'A mile west of the parking area for the state park, turn left at locked orange gate. We have DNR permission to drive beyond here to

Stop 6. Leucogabbro at base of Crescent Formation. The rock column exposed on Green and Gold Mountains, referred to as the 'Bremerton rocks' by Clark (1989), is somewhat like that of an ophiolite with basal gabbro beneath a locally sheeted dike complex, beneath submarine basalts and volcaniclastic rocks, beneath subaerial basalt flows. Clark (1989) found more than 60 m of basal leuco-gabbro and pegmatoid. Numerous diabase and basaltic dikes intrude the upper part of this unit and are mapped separately. The overlying sheeted dike complex is approximately 150-m thick and consists entirely of dikes of diabase and basalt. The submarine volcanic unit consists of basalt flows inter-bedded with basaltic sandstone, siltstone, tuffs, and basaltic breccia. Overlying the submarine volcanic unit are subaerial basalt flows more than 180-m thick. Trace-element data from intrusive and extrusive rocks are similar, suggesting they are related (Clark, 1989).

The Bremerton pseudostratigraphy differs from idealized ophiolite stratigraphy in several important ways (Clark, 1989): 1) It lacks a basal ultramafic complex, 2) the Green and Gold Mountain dike complex has a thickness of about ISO m, in contrast to more than a kilometer of sheeted dikes in typical oceanic crust, 3) Green and Gold Mountain dikes are not ubiquitously, sheeted, and 4) the Green and Gold Mountain sequence is capped by subaerial basalt, whereas most ophiolites are overlain by deep marine sediments. Clark (1989) found that the geochemistry of the gabbro and basalts is transitional between normal mid-ocean ridge ba¬salt (MORB) and enriched oceanic island basalt.

Preliminary modeling of aeromagnetic and gravity data over Green and Gold Mountains (P. J. Haeussler and R.J. Blakely, unpublished work) indicate there are highly magnetic, dense rocks within a few kilometers of the surface beneath Green and Gold Mountains. Therefore, there probably is a basal ultramafic complex. Despite the differences between the Green and Gold Mountains rocks and ophiolites, the presence of the dike section on Green and Gold Mountains and the overall pseudostratigraphy of an ophiolite indicate that these rocks formed in an extensional environment.

Note the variability in grain size in the leucogabbro in outcrop and among the various rip-rap pieces on the ground. We will not go to the top of the outcrop, but it is leucogab¬bro all the way to the top of the quarry (there's a bunch of vegetated benches) and the vertical exposure is probably 150 m or more. There is one 20 cm basaltic dike cutting the leucogabbro.

A Pb-Pb age on zircon of 50.5 ± 0.6 Ma was obtained from a sample from this quarry. An apatite fission track age of 32 ± 5 Ma was obtained from the same sample. Haeussler and others (2000) interpret this to indicate that Green Mountain started going up at the time that Johnson and others (1994) inferred that the Seattle basin began to subside.

A short distance north of here are volcaniclastic rocks of the upper Crescent Formation, indicating a couple of km of down-to-the-north throw on an intervening, and unexposed, splay of the Seattle fault.

Return east on Holly Road. Seabeck Highway, and North-lake Way, and Chico Way. But turn right onto SR 3 and follow it south through Bremerton to Gorst (about 7 miles from Chico Way intersection.)

Near Gorst, at the head of Sinclair Inlet, we pass basalt flows on the right (W) side of the road. There are nice amygdules and red, oxidized horizons at the tops of lava flows. Lava flows are very thick-commonly 10 m or so. The flows are dipping to the SE.

At Gorst, go left (east) on SR 16 to Port Orchard. From Port Orchard, continue on Beach Drive, traveling NE along the south side of Sinclair inlet, winding around Waterman Point and then driving south. Turn left on Hilldale Road to enter Manchester State Park.

Stop 7. Blakeley Formation at Manchester State Park. Very nice exposures of the Blakeley Formation here are most easily accessed at lower tides, but the outcrops can also be gained by walking along the terrace-top trail and then dropping down where access is permissible. There are wonderful sedimentary structures in the rocks: beautiful flute casts, graded bedding, channels, and debris flows. At one point there is a 3-4 m welded tuff boulder in a bed that contains large rip-ups and a few clasts in the 30-cm size range. What brought this boulder so far?

Fulmer (1975) divided the Blakeley into two members; we are near the contact between his lower, conglomeratic, Orchard Point member and his upper, finer-grained, Restoration Point member. The difference between the two members is primarily grain size. Clasts are primarily volcanic; Fulmer described coarse basaltic clasts in a matrix of felsic glass shards, now commonly altered to zeolite and carbonate. Other rock types include tuffaceous brown sandstone, tuffaceous thin-bedded siltstone, and shale.

According to Fulmer (1975) the Orchard Point mem¬ber is Zemorrian and Refugian, while the Restoration Point member is Zemorrian alone. He suggests that both units were largely deposited by turbidity currents in deep cold water, and that warm-water corals in the Blakely fossil as¬semblage record remobilization of shallow-water sediments.

The Blakeley is the fore-arc basin equivalent of the Ohanepecosh and Fifes Peak formations within the Cascade volcanic arc. It is similar in age and lithofacies to the Lin¬coln Creek Formation of southwest Washington.

[Fulmer (1975) noted that Weaver named the Blakeley Formation for Blakely Harbor, which has always been spelled with only one “e”. He hypothesized that Weaver added the final “e” to avoid conflict with an earlier recognized Blakely sandstone unit of Lower Ordovician age. When Fulmer recognized younger fluvial strata as the separate Blakely Harbor Formation, he removed the offending vowel.]

Retrace route to Port Orchard and Gorst. At Gorst, go north (right) towards Bremerton. In 2 miles, take SR 304 into downtown Bremerton, and then follow SR 303 north across Port Washington Narrows. One mile north of bridge, turn right on Sylvan Way towards Illahee State Park, our campsite for the night.

III. SUNDAY: BLAKELY HARBOR—TUKWILA—PRESTON—LAKEMONT—VASA PARK—SEATTLE

From Illahee State Park, return west to SR 303. Turn right, north, and follow SR 303 north and west about 9 miles to SR 3. Go right, north about 4 miles and take SR 305 through Poulsbo to Bainbridge Island (about 6 miles).

On Bainbridge, about 6 miles beyond the Agate Passage bridge, turn right on High School Road, go west 0.8 miles and turn left on Finch Road, and south ‘/i mile to a T inter¬section with Wyatt Street.

Turn right on Wyatt and follow it around to the left as it becomes, in ‘/i mile, Blakely Ave NE. Follow Blakely Avenue south 1’/] miles and turn left on Oddfellow Road. Go east 0.6 miles and turn right on Country Club Road. About 1 mile down Country Club Road, where the road approaches the beach, park and descend onto tide flats

Note that access to the beach here, and farther west at Restoration Point, requires crossing private property. Contact residents or the Port Blakely company.

Stop 1. Blakely Harbor Formation, south side of Blakely Harbor

The Blakely Harbor Formation comprises conglomerate, volcanic sandstone and siltstone, mudstone, and local peat. Abundant logs and crossbedding within conglomeratic strata attest to the fluvial origin of the unit. Pebbles in the conglomerate (see next stop) are mostly basalt, suggesting local unroofing of the Crescent Formation during Blakely Harbor time.

Fulmer (1975) suggested a Miocene age for the Blakely Harbor on the basis of common coal and the lack of fossils, and stratigraphic(l) position above the Blakeley Formation. Brian Sherrod (personal commun., 2000) has confirmed the Miocene age with a 13 Ma fission track age from tuffaceous layer in the lowest exposed part of the unit.

The Blakely Harbor Formation is not known to crop out beyond southeastern Bainbridge Island.

Interestingly, where we have trenched 3-4 meters into Blakely Harbor siltstone and sandstone they are typically clay-rich and plastic. To this depth, at least, volcanic rock fragments are pervasively altered to clay. Elsewhere in the Puget Lowland, post-Vashon weathering profiles are 1-2 m thick. Either an unusually thick weathering zone, of possible pre-Vashon age, is preserved on southeastern Bainbridge Island, or the clayey alteration is diagenetic and likely to be present at great depth within Blakely Harbor strata.

Fulmer (1975) thought the Blakely Harbor Formation was conformable with the underlying Blakeley at this point. Waldron (1967) got it more right: there is a fault here. Two different lithologies are juxtaposed across a contact that is discordant to bedding in both units. It just happens that bedding on both sides of the fault has nearly the same orientation. If the tide is low enough, go prove this to yourself. While out on the tideflats, admire the beds of petrified chipboard.

Retrace route on Country Club road to head of Blakely Harbor, turn right and then right again on 3-T road. We have permission to park on private property and walk down to the beach.

Stop 2. Blakely Harbor Km, north side of Blakely Harbor. Most natural outcrops of Blakely Harbor Formation are conglomerate. We are stopping here to see some of this conglomerate. The conglomerate produces a strong positive aero-magnetic anomaly (Blakely and others, 1999a). The Blakeley Formation, in contrast, produces a diffuse aero-magnetic low. The combination is distinctive and allowed Blakely and others (1999b) to trace the hanging wall of the Seattle fault many km to the east.

Going north along Rockaway Beach, around the point from here, the amount of outcrop decreases, with progressively greater spacing between ribs of conglomerate and coarse sandstone. Scratching in the low-tide beach reveals that the intervening areas are underlain by fine sandstone and siltstone. The unit fines upwards, at least in this area.

Return east, continue across head of T intersection with Country Club road, and follow Blakely Avenue to head of Eagle Harbor, where it turns right and becomes Wyatt Street.

Follow Wyatt east to intersection with Madison Avenue, turn right, go I block to Winslow Way, turn left, and go Vi mile to ferry landing. Take ferry to Seattle.

Crossing the Sound: Is there a big Eocene fault?

Yesterday and this morning we saw most elements of a coherent stratigraphy that extends from lower to middle Eocene Crescent Formation, locally with coeval igneous basement, up to Miocene fluvial strata of the Blakely Harbor Formation. Intervening sedimentary strata are marine and largely have a basaltic (Crescent), mixed-metamorphic (Vancouver Island), or volcanic (Cascade Arc) provenance. Basaltic and mixed-metamorphic sandstones are Eocene; Cascade-arc-derived sandstones are latest Eocene to Oligo-cene and younger. This stratigraphy is typical of much of the Oregon and Washington Coast Ranges.

We are now traveling into another geologic province. Eocene strata of the Cascade foothills, eastern Washington, north-central Oregon, and most of British Columbia are characterized by continental sandstone of granitic-metamorphic provenance, commonly micaceous arkose. Associated volcanic rocks are felsic (rhyolite, dacite, locally andesite) or locally bimodal (rhyolite-basalt). Some of us know this as the Challis province. Challis-province rocks around Seattle are the Puget Group. The change from Coast Range to Challis provinces has been interpreted as reflecting a fault (the Puget Lowland fault of Johnson, 1984), or as fundamentally stratigraphic, as basaltic Crescent-Siletz volcanics are locally overlain by arkosic Challis strata in northwest Oregon and southwest Washington. Both interpretations have merit.

Comparing stratigraphies on east and west sides of the Puget Lowland is hindered by uncertainty about the ages of various units. The major problems are: (1) Radiometric ages of uncertain reliability and (or) low analytical precision. (2) Few age constraints of any kind in several units, due to unfavorable lithologies (for example, fluvial arkose; basaltic tuff-breccia). (3) Uncertainty about the nature and extent of middle and late Eocene—Narizian and Refugian— foraminiferal stages: McDougall (1980) considered the zones in these stages to be time-transgressive and facies-controlled in the Pacific NW (Nesbitt, 1998). (4) Dependence on floral ages of dubious validity, as discussed by Turner and others (1983).

Comparison of published correlation diagrams (Figure 4) illustrates the problems. Note the placements of the Refugian-Narizian boundary.

These problems are not unique to the Puget Group. Strata of the probably-correlative Chuckanut Formation, Barlow Pass Volcanics of Vance (1957), Naches Formation, and Chumstick Formation are equally poorly dated. Also, see the discussion above on radiometric ages from the Crescent Formation.

From Seattle ferry terminal turn right and head south on Alaskan Way, SR 519. This eventually turns into East Marginal Way/SR 99.

Continue on East Marginal Way past Boeing Field to intersection, some 8 miles from ferry terminal, with Pacific Highway South (right), and S Boeing Access Road (left). This intersection may not be well signed. Look for Checker Limos on far left side of intersection; maybe you will see their stretched Humvee! Turn left onto S Boeing Access Road and then turn right. Park on right shoulder before outcrop.

Stop 3. Tukwila Formation of the Puget Group. Walk east, up-section, to see volcanic conglomerate, volcanic breccia, and tuffaccous sandstone. What is the composition? Can you find way-up indicators? Is there any alteration? Internal deformation?

Here and to the east, the Puget Group comprises, in ascending order, the arkosic Tiger Mountain Formation, the volcanic Tukwila Formation, and the arkosic Renton Formation. To the southeast, in the Green River area, the Puget Group lacks significant volcanic rocks and has not been divided. All units are largely continental. Coal in the Puget Group has been economically important. A century ago Renton, Newcastle, and Issaquah were coal-mining towns. The Renton Formation has also supplied clay for brick making. More recently, volcanic rocks of the Tukwila have been a major source of rockery boulders.

Immediately south of here, a thin marine section at the lowest level of Tukwila exposure contains a rich assortment of shelly macrofossils. Liz Nesbitt (1998) has most recently studied this fauna, and finds that it is very similar to the late middle Eocene fauna of the Cowlitz Formation of southwest Washington. Radiometric ages constrain the Cowlitz fauna be about 39 to 41.5 Ma old (Irving and others, 1996).

A Tukwila sample from Newcastle, east of Lake Washington, yielded a 41 Ma fission track age and a 42 Ma hornblende K-Ar age (Turner and others, 1983).

Continue ahead and north on Airport Way. At first stop light, just past Associated Grocers warehouse, turn left to¬wards King County Airport, make a U-turn, turn right on Airport Way, and return to S Boeing Access Road east-bound. Cross BNSF rail yard, cross 1-5, and turn right onto 1-5 north.

Go north to 6 miles to 1-90 (exit 164B) and take 1-90 east towards Bellevue and Spokane.

Drive 19 miles to Exit 22, Preston. At end of off-ramp, turn right and right again onto SE Preston Way and park on shoulder. Walk back to intersection and down east-bound on-ramp to

Stop 4. Raging River Formation, Preston

The Raging River Formation crops out for about 6 miles along the core of a northwest-trending anticline. We are at the northwest limit of outcrop. Johnson and O'Connor (1994) divided the exposed Raging River Formation into 3 members, based on sedimentary facies and lithologies. Unit 1 records a shallow-marine transgression, unit 2 is fluvial. and unit 3 records marine shelf to bathyal slope conditions. The base of the Raging River Formation is not exposed. Exposed strata may be about 1 km thick. The Raging River Formation is overlain by prodelta(?) marine-shelf and fluvial arkosic sandstone and mudstone of the lower Tiger Mountain Formation, the lowest unit of the Puget Group (Johnson and O'Connor, 1994; Vine, 1969).

The isolated northern outcrops of unit 2 along Interstate Highway 90 are intruded by a sill (T. Walsh, Washington Department of Geology and Earth Resources, written commun., 1993) and dikes and are relatively indurated. These strata consist of gray pebble conglomerate and interbedded sandstone. Conglomerate beds are as thick as a few meters and are bounded by low-angle (<10°) erosional surfaces. Beds are internally structureless or crudely stratified and uncommonly graded. Conglomerate clasts are subrounded to rounded, poorly to moderately sorted, generally dispersed in a granular matrix, and uncommonly imbricate. The mean size of the largest clasts in a bed is typically about 12 cm. Several large blocks of conglomerate were collected and slabbed for pebble counting. A count of 1,180 clasts (fig. 10) indicates that lithic sandstone, chert, and aphanitic green or black volcanic rocks are the most common clast types.

Unit 2 strata are interpreted as mainly alluvial deposits. ... (Johnson and O'Connor, 1994, p. A8) *Clasts in the Raging River Formation are dominantly lithic, in contrast to the arkosic debris and intrabasinal volcanic rocks of the overlying Puget Group*. Johnson and O'Connor (1994) suggest the primary source for the Raging River Formation was probably subjacent Mesozoic melange of the eastern and western melange belts of Tabor and others (1993).

Benthic foraminifera from the upper part of the Raging River—Johnson and O'Connor's unit 3—indicate a lower Narizian age (W.W. Rau, written commun., 1991, cited in Johnson and O'Connor, 1994).

Turn around and return to 1-90, heading west back towards Seattle.

Outcrop north of 1-90 one mile west of Preston is mafic volcanic breccia and amygdaloidal basalt of the Tukwila Formation.

Exit at West Lake Sammamish Parkway/Lakemont Boulevard (Exit 13). Turn left and go about miles up Lakemont Boulevard.

At 171th Ave SE (first traffic light), turn left into Lakemont Village mall. Park towards rear and walk 700 m (about 10 minutes) to next stop. Cross footbridge over creek, turn left and walk around retention-detention ponds. Stay left of baseball field, outside fence. Take trail left and down towards Louis Creek. Trail reaches creek, follows creek for 120 m, and then crosses creek. At creek crossing,

Stop 5. Renton Formation. Booth and Minard (1992, with most bedrock data from Walsh, 1984) and Yount and Gower (1991), show this locale as underlain by Oligocene Blakeley Formation. Composition (quartzofeldspathic), bedforms indicative of fluvial deposition (crossbeds, scour at base of coarse layers), and locally abundant coal indicate that this is the Renton Formation. Look for leaf fossils, way-up indicators, detrital muscovite. There is room for improvement in existing geologic maps!

Suppose you were mapping this area at 1:24,000 or larger scale. How would you know where you are?

Return to cars. Exit shopping mall, turn left on Lakemont Boulevard and descend to stop light at SE Newport Way. At light, turn right and park on shoulder. Walk back to intersection, cross at crosswalk, and walk left some 30 m, beside and below Lakemont Boulevard.

Stop 6. Blakeley-equivalent strata. This outcrop is mostly featureless, low-density, volcanic sandstone. Get out your hand lens and look for pumice fragments. Near the south end of the outcrops, you may find a clam mold and fragments of petrified wood. The absence of visible bedding may reflect extensive bioturbation. We trust that you will agree that the rocks at the last stop are not the same unit as this.

One-half mile farther west along SE Newport Way are additional outcrops of Blakeley-equivalent strata, which many of us have visited with various geology classes. There is passable parking on the north (westbound) shoulder. Bedding and fossils are common.

Back at cars, make U-turn and head west on Newport Way. At Lakemont Boulevard intersection, turn right (north) and pass under 1-90. Continue north along West Lake Sammam-ish Parkway 1.2 miles.

At SE 38th1 Street, turn left and park in Vasa Park Ballroom lot. Note that this parking lot is private. We are here with permission. The outcrops we are here to see are also on private property, which we have obtained permission to visit. We promised the residents that we would neither excavate nor collect. Please leave hammers and digging implements in the vans! If you absolutely must have samples, look for outcrops in the public right-of-way along West Lake Sammamish Parkway.

Stop 7. Miocene strata near Vasa Park. As noted by Yount and Gower (1991), the light-colored, tuffaceous, silty, sandy, and rarely conglomeratic strata here are unlike the basaltic, conglomeratic Blakely Harbor Formation. They are more like the Hammer Bluff Formation of south King County (Glover, 1941; Mullineaux, 1970) and the Ellens-burg Formation of the east slope of the Cascades.

Yount and Gower (1991) reported two K-Ar ages from a single sample of air-fall tuff from this outcrop. Relevant data are reproduced here:

Material analyzed	%K,0	% radiogenic Ar	Age ± 2 a
Green hornblende	0.251	29.3	14.7 ±1.8
Brown hornblende	0.234	8.0	9.3 ± 0.9

The significant conclusion that can be drawn from these data is that the analyses don't tell us much about how old this deposit is. Hornblende should have about 1% K2O: 0.2 -0.3% K2O suggests significant actinolite (or chlorite). The radiogenic yields are too low: either the samples were im¬pure or the argon extraction line was leaking too much. Con¬flicting ages from the same sample weaken the proposition that either age is geologically valid. Nonetheless, given the position stratigraphically(?) above Oligocene rocks, poor lithification, and similarity to Miocene deposits elsewhere, a Miocene age seems reasonable.

From here, drive south on W Lake Sammamish Parkway to 1-90. Go west on 1-90 to 1-405 or 1-5 and head south to the Kent-Des Moines Park & Ride lot.

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