The Columbia River Basalt Group—From the gorge to the sea

Ray E. Wells
U.S. Geological Survey, 345 Middlefield Road, MS 973, Menlo Park, California 94025, USA

Alan R. Niem
Department of Geosciences, Oregon State University, Corvallis, Oregon 97331, USA

Russell C. Evarts
U.S. Geological Survey, 345 Middlefield Road, MS 973, Menlo Park, California 94025, USA

Jonathan T. Hagstrum
U.S. Geological Survey, 345 Middlefield Road, MS 937, Menlo Park, California 94025, USA

ABSTRACT

Miocene flood basalts of the Columbia River Basalt Group inundated eastern Washington, Oregon, and adjacent Idaho between 17 and 6 Ma. Some of the more voluminous flows followed the ancestral Columbia River across the Cascade arc, Puget-Willamette trough, and the Coast Range to the Pacific Ocean. We have used field mapping, chemistry, and paleomagnetic directions to trace individual flows and flow packages from the Columbia River Gorge westward into the Astoria Basin, where they form pillow palagonite complexes and mega-invasive bodies into older marine sedimentary rocks. Flows of the Grande Ronde, Wanapum, and Saddle Mountains Basalts all made it to the ocean; at least 33 flows are recognized in the western Columbia River Gorge, 50 in the Willamette Valley, 16 in the lower Columbia River Valley, and at least 12 on the Oregon side of the Astoria Basin. In the Astoria Basin, the basalt flows loaded and invaded the wet marine sediments, producing peperite breccias, soft sediment deformation, and complex invasive relations. Mega-invasive sills up to 500 m thick were emplaced into strata as old as Eocene, and invasive dikes up to 90 m thick can be traced continuously for 25 km near the basin margin. Mega-pillow complexes up to a kilometer thick are interpreted as the remains of lava deltas that prograded onto the shelf and a filled submarine canyon southeast of Astoria, possibly providing the hydraulic head for injection of invasive sills and dikes at depth.

INTRODUCTION

Flood basalts of the Miocene Columbia River Basalt Group (CRBG) are among the most voluminous and far-traveled lava flows on earth (Fig. 1; Tolan et al., 1989; Tolan et al., this volume, Chapter 28). About 10% of the basalt flows that erupted on the Columbia Plateau between 17 and 12 Ma were voluminous enough to pass through the Cascade arc via a wide ancestral Columbia River valley (Beeson et al., 1989), and some of them eventually reached the Pacific Ocean (Choiniere and Swanson, 1979; Niem and Niem, 1985). Some of the larger flows invaded the marine strata, forming mega-invasive flows on the continental shelf and slope.
This three-day trip follows these far-traveled flows from subaerial settings in the western Columbia River Gorge to subaqueous emplacement in the sea. We use field mapping, geochemistry, and paleomagnetism to document: (1) the detailed CRBG stratigraphy in the Columbia River Gorge, lower Columbia River, and Astoria Basin; (2) the transition from subaerial to invasive flows in the basin; and (3) post-CRBG deformation in the Coast Range province. Our route will also retrace the journey of the Lewis and Clark expedition as they traveled down the Columbia River in the fall of 1805.

For a thorough introduction to the age, volume, distribution, stratigraphy, field relations, chemistry, and tectonic setting of the CRBG, please consult the introduction to the CRBG that accompanies the field trip guide (Tolan et al., this volume, Chapter 28). We find the stratigraphic framework developed by these workers over many decades is generally applicable to areas we are mapping in western Oregon and Washington.

In the Columbia River Gorge, CRBG flow units can be discriminated from one another based on their Ti, P, Cr, and Mg contents (Fig. 2A). The higher Ti content of the Wanapum Basalt distinguishes its members from the Grande Ronde Basalt and

---

Figure 2. (A) Percentage TiO₂ versus Cr/P₂O₅ chemical discrimination plot for Columbia River Basalt Group (CRBG) flows in western Oregon and Washington. Data defining the fields is from the western Columbia River Gorge except for the Ginkgo flow, for which data from Hooper (2000) were used. (B) Percentage MgO versus TiO₂ chemical discrimination plots for Grande Ronde Basalt flows in western Oregon and Washington. Data defining fields are post-2003 Washington State University analyses from our samples in the western Columbia River Gorge.
from the few Saddle Mountains Basalt flows that passed through the Cascade Range. The Grande Ronde members also can be discriminated from one another using the same elements (Fig. 2B). We recognize flow groups within the Sentinel Bluffs Member proposed by Reidel (2005), and we can further subdivide the Winter Water, Ortley, Grouse Creek, and Washpilla Ridge members.

Recognition of the slight chemical differences between members and individual flows of the Grande Ronde Basalt is difficult west of the Cascades. The mild, wet climate has produced deep weathering of the CRBG, and many flows, which appear fresh (e.g., contain unaltered plagioclase), have been sufficiently weathered to render chemical discrimination problematic. The most useful indicator of this subtle weathering is the iron content, and we use FeO* <11% as an empirical screen to flag weathered samples. All reference samples from the Columbia River Gorge shown on Figure 2 have FeO* >11 wt% and lack any other indications of chemical weathering. A few samples from the Coast Range discussed on Days 2 and 3 are unavoidably weathered.

We also use paleomagnetic secular variation (PSV) recorded by the flows, in combination with chemistry, for correlation of individual flows and flow packages. Choiniere and Swanson (1979), Magill et al. (1982), and Sheriff (1984) used PSV to correlate between plateau and coastal flows, and Wells et al. (1989) used field mapping, chemistry, and PSV to trace individual flows and packages of flows from the Plateau to the Coast. Since 2001, we have been systematically sampling hundreds of sites in Grande Ronde Basalt reference sections in order to better understand the stratigraphy and probable rapid emplacement of this monotonous unit (Jarboe et al., 2006), which comprises 85% of the CRBG by volume (Tolan et al., this volume, Chapter 28).

**DAY 1: COLUMBIA RIVER BASALT GROUP IN THE WESTERN COLUMBIA RIVER GORGE**

The basic geologic framework of the Columbia River Gorge has been known for over a century (Williams, 1916). In the western gorge, the package of CRBG flood-basalt flows unconformably overlies volcanicogenic rocks of the ancestral Cascade volcanic arc. Vigorous and widespread volcanism characterized the arc from its inception 40 Ma until ca. 18 Ma, when activity greatly declined (Evarts and Swanson, 1994). The arc must have been relatively quiescent during emplacement of the most voluminous CRBG flows, because interflow volcanic sediments are sparse. The larger flows passed through a 50-km-wide ancestral Columbia River valley on their way to the ocean. Owing to late Cenozoic uplift of the Cascade Range and resultant incision by the Columbia River, CRBG flows are now spectacularly exposed in the cliffs and waterfalls of the Columbia River Gorge. The modern gorge roughly follows the northern margin of the broad Miocene valley. Grande Ronde flows clearly abut the northern paleovalley wall formed by early Miocene volcaniclastic rocks of the 19 Ma Eagle Creek Formation.

The broad N-S arch of the Cascade Range is superimposed on the Yakima Fold Belt, a set of WNW- to ENE-trending folds that began to form during Grande Ronde time (Reidel et al., 1989b; Beeson and Tolan, 1990; Fig. 1) and probably are active today. Yakima folds are asymmetric anticlines, with long, shallowly dipping south limbs and short, steeply dipping, and commonly faulted north limbs. These modest but growing structures apparently influenced the distribution of late Grande Ronde and younger flows in the Cascade Range (Beeson et al., 1989; Beeson and Tolan, 1990), and the modern Columbia River Gorge may have been localized by the synclinal trough of a Yakima fold. As a result of the superposition of the Cascade Range arch and Yakima fold, the CRBG section west of Hood River generally dips SW at 1°–2°. Hence, we will be climbing up section as we head west on the field trip route of Day 1.

The slight southward dip of the CRBG section and the underlying Eagle Creek Formation gives the western gorge an asymmetric physiographic cross section. In Washington, failure of weakly lithified Eagle Creek strata that dip toward the river under the load of superincumbent basalt has produced huge landslide complexes composed largely of CRBG debris (Palmer, 1977). In Oregon, where strata dip away from the river, under-cutting of the Eagle Creek Formation instead creates towering cliffs. As a result, the CRBG section south of the river consists of continuous cliffs, whereas to the north the CRBG forms scattered peaks (Greenleaf Peak, Table Mountain, Hamilton Mountain, and Archer Mountain) separated by low-lying terrain underlain by the Eagle Creek Formation or landslide debris. Each of these peaks is actually the southern end of a N-S ridge of CRBG, marking sites where basalt flows backfilled south-flowing tributaries of ancestral Columbia River.

Although preceded by reconnaissance efforts (Swanson et al., 1979a, 1979b), Tolan (1982) was the first to successfully divide the apparently monotonous CRBG section in the Columbia River Gorge west of Multnomah Falls by employing a combination of magnetic polarity, chemical stratigraphy, and lithologic features. He documented the presence of the Nn, Rn, and Nm magnetostratigraphic units of the Grande Ronde Basalt, mapped the high-MgO flows at the top of the Nn, and distinguished the underlying Winter Water flow from other low-MgO flows on the basis of its chemistry and relatively abundant plagioclase phenocrysts. He also mapped two post–Grande Ronde intracanyon flows, a Priest Rapids Member flow (previously recognized by Waters, 1973) and a younger Pomona Member flow.

Our work in the western Columbia River Gorge builds on and extends the work of Tolan, incorporating recent refinements in the chemical and magnetic stratigraphy of the Grande Ronde Basalt (Reidel et al., 1989a; Reidel, 2005; Wells et al., 1989). We conducted traverses at an average spacing of ~1 km through well-exposed sections, attempting to sample every flow. The primary uncertainties relate to: (1) recognition of flow contacts; (2) intraflow chemical variation; and (3) assessing the impact of weathering on chemical compositions. Despite these difficulties, we have developed a robust chemical and magnetic stratigraphy for the Grande Ronde Basalt in the western gorge that meshes well with the stratigraphic framework presented by
Reidel et al. (1989a; Table 1; Fig. 2). Within the Grande Ronde units (members) as defined by Reidel et al. (1989a), we find stratigraphically confined compositional types, based on slight but consistent differences in MgO, TiO₂, P₂O₅, Cr, Ba, V, and Zr, similar to those that Reidel (2005) described for the Sentinel Bluffs Member. These data and paleomagnetic directions have allowed us to develop a flow-by-flow stratigraphy for the western Columbia River Gorge.

Our detailed mapping currently extends from the mouth of the gorge to the vicinity of Beacon Rock (longitude 122° W; Fig. 3). The composite CRBG section in this region contains ~30 flows (Fig. 4), although, owing to erosion of the top of the section and burial of the lower part by extensive talus aprons, no individual section contains more than ~15 flows. The thickest section is ~580 m near Nesmith Point. The number of flows and the total thickness of the section decrease to the west. Only a few of these flows have been found west of the gorge. By contrast, not all flows found in western Oregon are present in the gorge; some, such as the Gingko flow, apparently took more southerly routes through the ancestral Cascade Range. Most flows mapped in the gorge belong to the Grande Ronde Basalt. Younger flows are less extensive, partly because their routes were more strongly controlled by drainages developed during the longer intervals between flows and partly owing to post-eruption erosion. The two youngest flows in the gorge, the Priest Rapids Member and Pomona Member flows, are confined to narrow canyons carved by the ancestral Columbia River. Wanapum Basalt and Grande Ronde Basalt flows typically exhibit a grossly sheet-like morphology, with thickness variations that reflect local paleotopography. Detailed mapping, however, shows that many flows exhibit relatively abrupt lateral variations in jointing patterns, which make tracing of individual flows in the field difficult. Identification of flows based on their chemical and paleomagnetic properties demonstrates that many are of more limited extent than the impression given by the seemingly continuous cliff lines. A stack of offset pancakes is a better analogy than a layer cake for the Grande Ronde section in the gorge. Such stratigraphic complications reflect interactions with variable paleoenvironmental conditions near the margins of the CRBG flow field, and contrast with the more uniform conditions and resulting relatively simple stratigraphy found in central areas in the Columbia Basin to the east.

A summary of CRBG stratigraphy for the western Columbia River Gorge is shown in Table 1. It is provisional and may require minor modification because of ongoing work (the greatest uncertainty is in the Ortley Member). For a complete stratigraphic section of the CRBG, see Tolan et al. (this volume, Chapter 28). Representative chemical analyses and paleomagnetic data are given in Table 1; chemical discrimination plots are shown in Figure 2, and paleomagnetic directions from the gorge are shown in Figure 5.

### Table 1. Columbia River Basalt Group Units in the Western Columbia River Gorge, Lower Columbia River, and Astoria Basin

<table>
<thead>
<tr>
<th>Astoria Basin, Oregon</th>
<th>Cathlamet-Longview, Washington</th>
<th>Western Columbia River Gorge</th>
<th>Formation</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 flow</td>
<td>1 flow</td>
<td>1 flow</td>
<td>Saddle Mountains Basalt</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pomona Member</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Asotin member</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flow of Huntzinger</td>
<td>N</td>
</tr>
<tr>
<td>1 flow</td>
<td>1 flow</td>
<td>1 flow</td>
<td>Wanapum Basalt</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 flow</td>
<td>Priest Rapids Member</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flows of Rosalia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 flows</td>
<td>2 flows</td>
<td>Frenchman Springs Member</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>1 flow</td>
<td>Flows of Sentinel Gap</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>2 flows</td>
<td>2 flows</td>
<td>Flows of Sand Hollow</td>
<td>N</td>
</tr>
<tr>
<td>1 flow</td>
<td>3 flows</td>
<td>1 flow</td>
<td>Flows of Ginko</td>
<td>T</td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>1 flow</td>
<td>Grande Ronde Basalt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>1 flow</td>
<td>Sentinel Bluffs Member</td>
<td>N₂</td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>1 flow</td>
<td>Flows of Museum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>1 flow</td>
<td>Flows of Spokane Falls</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 flow</td>
<td>2 flows</td>
<td>Flows of McCoy Canyon</td>
<td></td>
</tr>
<tr>
<td>1 or 2 flows</td>
<td>1 flow</td>
<td>1 lower Ti and Ba flow, shallow paleomagnetic inclination</td>
<td>Winter Water member</td>
<td>T</td>
</tr>
<tr>
<td></td>
<td>1 or 2 flows</td>
<td>1 higher Ti and Ba flow, steeper paleomagnetic inclination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 flow</td>
<td>4-6 flows</td>
<td>9 flows of 6–7 compositional types (2–3 lower Cr, 3-6 higher Cr)</td>
<td>Ortley member</td>
<td>N₂</td>
</tr>
<tr>
<td>1 flow</td>
<td>1 flow</td>
<td>4 flows of 3 compositional types (1 lower Cr, 2 higher Cr)</td>
<td>Grouse Creek member</td>
<td>R₂</td>
</tr>
<tr>
<td>1 flow</td>
<td>2 flows</td>
<td>4 flows of 3 compositional types (1 higher P₂O₅, 2 lower P₂O₅)</td>
<td>Wapshilla Ridge member</td>
<td>R₂</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 or more flows</td>
<td>Downey Gulch member</td>
<td>N,</td>
</tr>
</tbody>
</table>
Day 1 Road Log

Take I-84 east from Portland ~40 mi to Bonneville Dam exit (Exit 37). Turn left to enter dam area, pass through guard station, and follow main road to the Bradford Island Visitor Center. All Day 1 stops were located using the global positioning system (GPS) and North American Datum of 1927 (NAD 27).

Stop 1-1: Bonneville Dam Visitor Center
45.6417° N, 121.9423° W

Bonneville Dam was constructed between 1933 and 1935 as the first of eight federal hydroelectric plants on Columbia and Snake Rivers. A second powerhouse on the Washington shore was brought online in 1981. The observation deck at the visitor center affords excellent views of CRBG outcrops on both sides of Columbia River. To the north, CRBG flows are well exposed in the headwall scarps of large landslide complexes that extend almost continuously along the north shore of the river in the western Columbia River Gorge (Palmer, 1977). The youngest major slide is the Bonneville landslide, which occurred near A.D. 1450 (P.T. Pringle, 2008, personal commun.; O’Connor and Burns, this volume). This slide temporarily dammed the Columbia River and created the Cascades of the Columbia (namesake of the Cascade Range) that severely challenged the Lewis and Clark expedition and remained a major transportation barrier until drowned by Lake Bonneville. The north end of the younger powerhouse rests on the toe of the Bonneville slide. The landslide complex remains active; in midwinter 2007–2008, part of the headwall between Table Mountain and Greenleaf Peak gave way, burying ~16 ha of forested terrain.

The CRBG-capped high points are, from west to east, Hamilton Mountain, Table Mountain, and Greenleaf Peak. All of the exposed flows belong to the N4 magnetostrophic unit of the Grande Ronde Basalt. The lower flows with thick entablatures and thin basal colonnades are in the Ortley Member, which is overlain by the Winter Water Member and the Sentinel Bluffs Member.

The south face of Hamilton Mountain (Fig. 6) exposes a cross section through a ~200 m thick Ortley intracanyon flow. On the west, a thin basal colonnade rests on more than 100 m of steeply north-dipping pillow breccia (“pillow-palagonite complex”) compositionally similar to the overlying basalt. On the east side, the flow abuts the Eagle Creek Formation of the paleocanyon wall. The opposite valley wall, out of sight to the northwest, is a Wapshilla Ridge Member flow. The wedge of pillow breccia is a delta that formed in a temporary lake created when the basalt flow blocked a south-flowing tributary of the ancestral Columbia River. Later in the eruption, lake water drained away, allowing basalt to flow over and down the face of the delta, cooling to form the typical entablature and colonnade jointing pattern.

Figure 3. Sketch map showing distribution of Columbia River Basalt Group (CRBG) in western Columbia River Gorge, selected cultural and geographic features, and field-trip stops for Day 1.
This same Ortley flow is the uppermost of the three thick flows exposed in the south face of Table Mountain (Figs. 7 and 8B). It is one of the thickest and most continuous flows mapped in the western gorge, commonly 50–100 m thick. The Ortley flow beneath it also fills a tributary paleovalley; although from here it appears to be a simple sheet flow. Note, however, that at the eastern edge of the outcrop, the basal colonnade abruptly bends from subhorizontal to subvertical adjacent to pillow lava, marking the margin of the flow (Fig. 8C), and on the rocky spur extending south from Table Mountain, this flow thickens abruptly from ~70 m to more than 200 m thick. Similar relationships have been mapped at Greenleaf Peak and on the south side of the gorge. Winter Water and Sentinel Bluffs flows above the thick Ortley flows are thinner and exhibit more irregular blocky and columnar jointing patterns and locally overlie or grade into pillow lava and hyaloclastite (Fig. 8A).

North of the Columbia River, CRBG flows clearly onlap the underlying Eagle Creek Formation that formed the north wall of the Miocene valley. Traveling northward, progressively younger flows overlie Eagle Creek beds, and ~5 km north of Hamilton and Table Mountains, the youngest Grande Ronde flow in the western gorge (the Museum flow of the Sentinel Bluffs Member) sits directly on the Eagle Creek Formation. These relationships indicate that the modern gorge roughly follows the northern edge of the broad ancestral Columbia River valley. The abrupt but localized thickness variations of individual basalt flows and the abundant evidence for interaction with water are best explained by flood-basalt flows backfilling the valleys of tributary streams flowing into the main valley from higher terrain to the north. Hamilton Mountain, Table Mountain, and Greenleaf Peak each exemplify inverted topography marking these ancient stream courses. After an eruption, emplacement of the basalts would force the tributaries to carve new channels into the less resistant Eagle Creek Formation, channels that would be occupied by basalt from the next major eruption. The paleovalleys at Hamilton and Table Mountains may have been carved by the same stream, which was displaced westward by a large Ortley flow only to be filled by the next Ortley flow to reach this area a few centuries or millennia later. Waters issuing from the south-flowing tributaries probably would have been shunted westward along the margin of the flood-basalt field, rapidly carving a marginal channel in the relatively soft Eagle Creek Formation. Such a west-flowing trunk stream would have intercepted sediment eroded from the northern highlands, explaining why so little interflow sediment (except for rare eolian? silt and clay) is found in the basalt section south of the river.

Figure 4. Schematic composite stratigraphic column for the Columbia River Basalt Group in the western Columbia River Gorge. On right are names of members in the Grande Ronde Basalt and (above Vantage horizon) Wanapum Basalt. On left are stratigraphically restricted compositional groups (those in the Sentinel Bluffs Member after Reidel, 2005). Not shown are post-Frenchman Springs intracanyon flows (Rosalia flow of Priest Rapids Member, Wanapum Basalt and Pomona flow, Saddle Mountains Basalt).
Leave Bonneville Dam and take ramp to I-84 westbound (Portland). Roadcuts directly west of Bonneville provide excellent exposures of typical Eagle Creek Formation laharic breccias, conglomerate, and sandstone. The CRBG overlies Eagle Creek beds ~100 m above the freeway. In 4.5 mi, take Exit 35 (Ainsworth State Park), continue straight through intersection with Tumult Road, and pull off road at grassy area on left.

Stop 1-2: Dodson
45.6028° N, 122.0427° W

This location offers good views of the CRBG section on both sides of the Columbia River.

View to the north. Basalt-capped Hamilton Mountain is to the east, and Archer Mountain is to the northwest; the lower terrain between them is the large Skamania landslide complex (Palmer, 1977). The rocky spire rising from the north shore is Beacon Rock, named by the Lewis and Clark expedition in 1805. The 245-m-high monolith is a 57 ka basaltic andesite plug; the cinder cone that originally encased it was completely stripped away by the Missoula Floods ~17,000 years ago.

View to the south. We are on the lower part of an alluvial fan, the apex of which is the narrow canyon between Katani Rock (informal name) to the east and Saint Peters Dome to the west; the prominent point behind and west of Saint Peters Dome is Rock of Ages. The top of the ridge above Katani Rock is Yeon Mountain. Farther east is Nesmith Point (1176 m elevation), the sheer north face of which offers a cross section through a Pleistocene basaltic vent. The lower barren cliffs are formed by the upper part (N, and R2 magnetostratigraphic zones) of the Grande Ronde Basalt section: Wapshilla Ridge (two flows), Grouse Creek (three flows), Ortley (three flows), Winter Water (one flow), and Sentinel Bluffs (three flows). The Downey Gulch Member below the Wapshilla Ridge flows is buried by talus here. The pronounced slope break at the top of the bare cliffs marks the contact with overlying Plio-Pleistocene basalt and basaltic andesite of the High Cascade Range, in places interbedded with gravel and hyaloclastic sandstone of the Troutdale Formation. The upper surface of the CRBG is an erosional unconformity with as much as 250 m of relief. Local highs on this paleosurface preserve a Frenchman Springs (Sand Hollow) flow, whereas at low points, as on Katani Rock, Pliocene flows sit directly on the Ortley Member.

Alluvial fans exist below all of the short, steep canyons on the Oregon side of the Columbia River Gorge. Debris flows regularly debouch from the canyons during heavy winter rains, and in 1996, 1997, and 2001, debris flows reached the freeway. The 1996 flows buried the both lanes of Interstate 84 and the adjacent...
railroad lines at Dodson, just east of here, closing them for over a week (Burns et al., 2002; Wang et al. 2002).

Continue west on exit road toward Ainsworth State Park. Beyond underpass, enter the Historic Columbia River Highway, a National Historic Landmark and remarkable early twentieth century engineering feat. Multnomah County appropriated funds for the highway in August 1913, and within two years the road from Portland to the county line was surveyed, built, and open to traffic. By 1922, a paved road extended through the entire gorge to The Dalles. Portions of the highway, such as that east of here, were obliterated during construction of Bonneville Dam in the 1930s and Interstate 84 in the 1970s, but from here to the mouth of the gorge, the old road remains intact and will be our route for the remainder of the day.

At 1.5 mi, Horsetail Falls spills over a Downey Gulch Member flow. At 1.9 mi, cross the bridge over Oneonta Creek, and park in area on left.

Stop 1-3: Oneonta Gorge
45.5898° N, 122.0742° W

Oneonta Creek has carved a slot through two Downey Gulch Member flows. Their well-developed colonnade and entablature jointing with overhanging entablatures is visible in the cliff face directly east of the creek (Fig. 9). The basal contact of the lower flow runs just above road level. Note the weathered, vesicular top of the underlying flow and the scattered, subhorizontal cylindrical hollows in the lower part of the flow. These are tree molds, which commonly contain fragments of carbonized or silicified wood. Allen (1957) counted 65 such molds, some as large as 1 m in diameter, in this flow and noted that they are preferentially oriented E-W. Extending well up into the flow is a zone of alteration that may reflect interaction with water from overrun vegetation or wet soil.

The narrow bridge and tunnel are parts of the original Columbia River Highway. Because of safety concerns, the road was rerouted to the north, and the tunnel filled with debris in 1948. In recent years, the Oregon Department of Transportation (ODT) has been restoring the highway and converting abandoned sections into bicycle and pedestrian pathways. The Oneonta tunnel was cleared of debris, replicas of the original wooden portals were constructed, and the tunnel was reopened to foot traffic earlier this year.

Continue west to Multnomah Falls parking area ~2.2 mi ahead.

Stop 1-4: Multnomah Falls
45.5780° N, 122.1159° W

Multnomah Falls is the second highest waterfall in the United States and the most visited natural feature in Oregon. Multnomah Falls Lodge at its base was built in 1925. The falls drops in two steps that total 189 m. The lower falls is in a Downey Gulch flow (the uppermost flow seen in the cliff at Oneonta Creek) with internal jointing variations. The plunge pool of the upper falls (165 m) is located at a thin claystone interval that separates the upper colonnade of the Downey Gulch (N1) flow from flows of the overlying R2 magnetostratigraphic unit.

The beautifully exposed cliff face here illustrates the difficulty of defining flow boundaries in the Grande Ronde Basalt of this area. The upper part of the cliff consists of crudely columnar basalt above a layer of pillow lava; this is a Grouse Creek flow, the lowest of three in the western gorge. The lower part of the cliff face, directly above the plunge pool of the upper falls, consists of two Wapshilla Ridge Member flows, each composed largely of entablature. In the middle of the cliff is a zone of complex jointing; some areas exhibit small, variably oriented columns; others look pillowed. Where would you place the basal contact between the Grouse Creek and Wapshilla Ridge flows? Chemical analyses show that this zone consists of a
third Wapshilla Ridge flow, distinguished from those beneath it by a higher P₂O₅ content (Fig. 2). The Grouse Creek pillow lava has been traced in the cliff outcrops for ~5 km and reaches a maximum thickness of more than 120 m thick.

Across the Columbia River to the north, the Grande Ronde Basalt forms continuous cliffs in the 5-km-long landslide scarp that extends from Archer Mountain on the east to Prindle on the west. The section there is equivalent to that in Multnomah Creek above the pillowed Grouse Creek flow: two to four Ortley Member flows overlain by two Winter Water flows and three Sentinel Bluffs flows. Fletcher Flat, the gently sloping surface at the top of the cliffs, marks the Vantage horizon, a thin but persistent sedimentary interbed that separates the Grande Ronde Basalt from the Wanapum Basalt. Local erosional remnants of the Frenchman Springs Member (Sand Hollow and Sentinel Gap flows) are found on Fletcher Flat. In Multnomah Creek valley above Multnomah Falls, the Vantage is found at an elevation of ~500 m, ~70 m below that of Fletcher Flat.

Continue west on Historic Highway. In 0.5 mi, cross Wahkeena Creek, which cascades over complexly jointed Wapshilla Ridge flows above the road. About 2.0 mi farther, the highway skirts the top of an abandoned quarry in a Wapshilla Ridge flow. The international geochemical standards BCR-1 and BCR-2 were obtained from this quarry. At intersection 0.5 mi ahead, bear left to remain on Historic Highway. About 0.7 mi beyond, road crosses Bridal Veil Creek just above Bridal Veil Falls. Take next right into parking area for Bridal Veil State Scenic Overlook. Follow path that takes off from west end of parking lot to overlook.

Figure 8. Close-up views of features in Columbia River Basalt Group flows on Table Mountain. (A) Upper part of exposure showing blocky and columnar jointing, hyaloclastite zones, and abrupt lateral changes in jointing patterns. (B) East end of uppermost thick Ortley flow showing the thin basalt colonnade and irregular fine-scale columnar jointing typical of entablatures. (C) East end of middle thick flow showing its basal colonnade turning steeply upward against pillow lava.

Figure 9. Downey Gulch Member flows with thick entablatures in roadcut on Historic Columbia River Highway at Oneonta Creek (Stop 1-2).
Stop 1-5: Bridal Veil Viewpoint
45.5548° N, 122.1826° W

The bench that we are standing on is developed on the top of the uppermost, high-phosphorous (P), Wapshilla Ridge flow that we saw at Multnomah Falls. The Grouse Creek Member crops out on the slope above the bench. Directly across the Columbia River is Cape Horn in Washington (Fig. 10). The sheer, 75-m-high cliff of entablature that rises from water level is the same flow we are standing on. Its thin basal colonnade is visible at the shoreline. The similar cliff above it consists of two Ortley flows, the upper one of which is the same as the intracanyon flow at Hamilton Mountain. A Grouse Creek flow lies between the Wapshilla Ridge and Ortley Members but is largely buried by talus. The same Grouse Creek flow, matched by chemistry and paleomagnetic direction, crops out on the slope above the Bridal Veil bench. This is a different flow than the pillowed Grouse Creek at Multnomah Falls; that flow pinches out and is absent here. Above the Washington State Highway 14 viaduct at Cape Horn is a third Ortley flow. A Winter Water flow and two Sentinel Bluffs flows crop out on the steep forested slope above the highway, and a thin layer of deeply weathered Frenchman Springs Member (Sand Hollow Basalt) is found on the flat surface above.

The low terrain directly east of Cape Horn is a landslide, and the rocky outcrops along the railroad line at river level are huge slide blocks. This slide, like most of the other large slides in the gorge, results from failure of Eagle Creek Formation loaded by the CRBG. The contact, buried by post-slide talus at the base of the headwall, climbs up to the saddle between Cape Horn and Prindle. Local basalt-water interaction is evidenced by local pillow lava and bedded hyaloclastite at the base of some CRBG flows. Phoca Rock, the small island in the middle of the river, is a landslide block of pillow lava compositionally identical to the middle Ortley flow in the cliffs above.

The Grouse Creek and Wapshilla Ridge members are considerably thinner on the Washington side of the gorge than in Oregon, each consisting of a single flow. The Grouse Creek Member has not been identified east of Archer Mountain, but the high-P Wapshilla Ridge flow has been traced east as far as Hamilton Mountain. On the Oregon side, this high-P flow is present at Multnomah Falls (but recall how much thinner and less massive the flow was there) but is absent east of there.

Cape Horn is the westernmost outcrop of Grande Ronde Basalt on the Washington side of the gorge. The quarry along the railroad tracks ~1.2 km west of Cape Horn is in the 12 Ma Pomona Member of the Saddle Mountains Basalt, overlain by a thick sequence of Troutdale Formation conglomerate. The Pomona flow was confined to a deep canyon cut into the Grande Ronde Basalt (Fig. 11). The flow did not fill the canyon, allowing the ancestral river to reoccupy and re-incise it, leaving terrace-like erosional remnants clinging to the valley walls (Tolan and Beeson, 1984). One such remnant crops out above us on the east valley wall of Bridal Veil Creek, and another is found in Coopey Creek, ~1.5 km east of here. The Pomona Basalt is one of the CRBG flows that we will follow on Days 2 and 3 of this trip as it continued down the ancestral Columbia River valley and eventually reached the Pacific Ocean.

Return to vehicles and continue west on Historic Highway. In ~0.8 mi, the road crosses Young Creek at Shepperds Dell. Limited parking is available on both sides of the highway just east of the bridge.

Stop 1-6: Shepperds Dell
45.5483° N, 122.1945° W

Here, Young Creek spills down through complexly jointed Ortley Member basalt. Note the complicated and irregular variations in jointing including discontinuous columnar zones. The roadcut to the east was blasted through a classic colonnade and entablature couplet, suggesting that the base of flow is near highway level. The colonnade, however, cannot be traced laterally into Shepperds Dell, and no obvious break is visible in the creek-bed outcrops beneath the bridge or in the cliffs above. Basalt along the railroad line 70 m below road level is pillowed and associated with hyaloclastite, as is basalt in roadcuts west of the bridge. Chemical analyses and field relations indicate that all of this basalt belongs to a single flow more than 150 m thick. Ortley flows to the east and west are compositionally different, suggesting that this flow occupies a narrow paleocanyon similar to the one we saw at Hamilton Mountain, but here incised into older flood basalts rather than into the Eagle Creek Formation.

Continue west on Historic Highway. In ~1.2 mi, pull into parking area for Latourell Falls.

Stop 1-7: Latourell Falls
45.5388° N, 122.2172° W

The rocks at road level here are platy, sparsely plagioclase-phyltic, Oligocene dacite of the ancestral Cascade arc that predates...
the CRBG. A short trail leads to Latourell Falls, which spills 76 m over a Sentinel Bluffs Member flow that unconformably overlies the dacite (Fig. 12). This flow belongs to the Museum compositional type of Reidel (2005) and was produced by one of the last Grande Ronde eruptions. It fills a small canyon and is separated from the dacite by a bit of cobbly stream gravel; note how the basal colonnade climbs up steeply to the west against the paleocanyon wall. In the creek above the falls, the Museum flow is overlain by one or two Frenchman Springs (Sand Hollow) flows. The fact that the youngest Grande Ronde flow here rests on pre-CRBG bedrock indicates this area was a paleotopographic high in mid-Miocene time. Although this Museum flow is widespread at the top of the Grande Ronde Basalt of the western Columbia River Gorge section in Washington, this is the only location where we find it south of the Columbia River.

Continue west on highway. Roadcuts for next 1.5 mi are in Oligocene basaltic andesite lavas. At 1.7 mi, small gulch marks steep contact with the Priest Rapids Member of Wanapum Basalt, which we will discuss at next stop; note complex jointing variations and local pillow lava. Road climbs to top of Crown Point and parking lot at recently refurbished Vista House. Vista House, constructed a few years after this stretch of the Columbia River Highway was completed, offers great views of the gorge, and houses interpretive exhibits that describe construction of the highway and the area’s natural history. For the next 0.5 mi, the highway cuts across the headwall of the active Rooster Rock landslide, exposing the upper part of Troutdale Formation and an interbedded lava flow that flowed westward down a paleo—Columbia River valley ca. 3 Ma. One mile beyond Crown Point, turn right into Portland Women’s Forum Scenic Viewpoint.

Stop 1-8: Chanticleer Point Viewpoint
45.5346° N, 122.2593° W

This site provides an excellent view back into the western Columbia River Gorge, and may be the most photographed scene in the Pacific Northwest. From here, we can see many of the
features north of the Columbia River that we viewed earlier in the day. Directly east, across the Rooster Rock landslide is Vista House at Crown Point. The bench on which it sits was formed 17,000–13,000 years ago when the colossal Missoula Floods stripped the Troutdale Formation off the top of an intracanyon CRBG flow. This is the 14 Ma Rosalia flow of the Priest Rapids Member, Wanapum Basalt, which completely filled a deep narrow canyon that the ancestral Columbia River had carved along the contact between older CRBG sheet flows and the paleotopographic high of Oligocene arc volcanic rocks. At Crown Point the intracanyon flow is 155 m thick and overlies 60 m of poorly sorted, crudely bedded, hyaloclastic sediments (Fig. 13) compositionally equivalent to the overlying flow. According to Tolan and Beeson (1984), the hyaloclastite formed when the Rosalia flow entered a lake east of the Cascade Range. The hyaloclastite was then flushed downstream, deposited in the Columbia River paleocanyon, and shortly thereafter overridden by the advancing flow. From this vantage point, we see the thick entablature of the Rosalia flow; the hyaloclastic rocks are out of sight to the east. The Rosalia flow has been traced across the Cascade Range to Crown Point (Tolan and Beeson, 1984), and it underlies Chanticleer Point on which we stand but has not been found to the west of here. Rooster Rock in the Columbia River is a landslide block of Rosalia basalt. Unlike the other large landslides we have seen, the Rooster Rock landslide is not related to the Eagle Creek Formation, which is absent here. The failure plane here seems to be within a thick lateritic paleosol developed on the Oligocene volcanics prior to CRBG emplacement (Lowry and Baldwin, 1952; Trimble, 1963). At this location, the unconformable contact dips northward toward the river.

Continue west on the Historic Highway. Pass through village of Corbett, and, ~1.5 mi from Chanticleer Point, turn right and sharply downward onto Corbett Hill Road (sign to I-84). The winding road drops down through poorly exposed, loess-covered Troutdale Formation, and then crosses an elongate bench marking the top of the CRBG. Just past sharp bend ~0.6 mi from the turnoff, pull onto right shoulder along straight segment of road.

Stop 1-9: Sand Hollow Flow on Corbett Hill Road
45.5396° N, 122.2845° W

The lower part of the Corbett Hill Road transects a sequence of three Wanapum Basalt Frenchman Springs Member flows and two Grande Ronde Sentinel Bluffs Member (McCoy Canyon) flows. The hard, black, blocky jointed basalt here is a Sand

Figure 13. Rosalia intracanyon flow at Crown Point as sketched by Aaron Waters (1973), a pioneer of Columbia River Basalt Group geology. This somewhat schematic rendition (labels are slightly modified from the original) portrays the bipartite character of the cliff outcrop, with dense basalt overlying stratified, poorly sorted hyaloclastite of the same composition (Tolan and Beeson, 1984). The pillow lavas at the flow margin are thought to have formed in water ponded as the rising flow blocked small tributaries, and are not related to the bedded hyaloclastite (Tolan et al., 1984); spiracles are irregular vuggy zones interpreted by Waters (1960) to form when flow-heated water flashes into steam and forces its way up into the flow.
Hollow flow. At the upper eastern) end of the roadcut, it is overlain by a Sentinel Gap flow. The flow contains scattered large to 1-cm-long) plagioclase phenocrysts, commonly slightly iron-stained to an amber color. The presence of such large crystals is characteristic of Frenchman Springs flows and serves to readily distinguish them from Grande Ronde flows in the field. In addition, Frenchman Springs flows are chemically quite different than Grande Ronde flows, with significantly lower SiO₂ and higher TiO₂ and P₂O₅ (Fig. 2).

Continue down Corbett Hill Road to I-84 interchange, passing roadcuts in locally pillowed Sentinel Bluffs (McCoy Canyon) flow at ~0.4 mi. Quarry next to road at bottom of grade is the same Sand Hollow flow seen at last stop, down-faulted along a N-S normal fault; a parallel fault a few hundred meters to the west drops CRBG below sea level. Borehole data show that CRBG flows floor much of the Portland Basin, and they reappear in the Coast Range to the north and west where we will spend the next two days.

Continue toward Portland via I-84 westbound ~12.5 mi to interchange with I-205. Take I-205 northbound (Seattle) exit just east of Rocky Butte, an extinct basaltic andesite volcano in the late Pliocene and Pleistocene Boring Volcanic Field (Evarts et al., this volume). I-205 crosses the Columbia River on the Glenn L. Jackson Memorial Bridge and, ~11 mi to the north, merges with I-5 northbound. Follow I-5 to Longview and overnight accommodations.

DAY 2: CRBG TRANSITION TO INVASIVE FLOWS, LOWER COLUMBIA RIVER, WASHINGTON

About 30 Grande Ronde, Wanapum, and Saddle Mountains Basalt flows are known to have crossed the Cascade arc into the coastal lowlands (Beeson et al., 1989; Niem and Niem, 1985; Wells, 1981; Wells et al., 1989; Fig. 1). These sheet flows and intracanyon flows crossed the Coast Range through several structural lows and are now exposed along the coast from Seal Rock, south of Newport, Oregon, to Grays Harbor, Washington, a distance of 275 km (Snavely et al., 1973). This part of the field trip examines the transition from subaerial to invasive flows in the northern part of the Astoria Basin, near the mouth of the Columbia River.

Subduction-related deformation has substantially deformed the CRBG in the forearc. The basalts have been broadly arched over the Coast Range uplift, reaching elevations above 1 km. In the adjacent Willamette trough, the flows have locally subsided below sea level, and in the forearc basins offshore, the flows are more than a kilometer below sea level. Although the Coast Range was less of a barrier in the Miocene, the basal Grande Ronde Basalt flows of the N, Downey Gulch and R, Wapshilla Ridge members in the northwest Willamette Valley form large pillow complexes and have wide variations in thickness and distribution, suggesting infilling of paleotopography against the Coast Range. Along the lower Columbia River, the flows unconformably cross a broad arch in older rocks that is coincident with the present axis of the Coast Range uplift (Fig. 14; Wells, 1981).

Where CRBG flows entered the coastal basins, they produced fluvial and submarine pillow delta complexes and ultimately invaded the marine sedimentary section as mega-invasive flows, producing peperites, (rootless) vent complexes, and massive sills and dikes (Snavely et al., 1973; Niem and Niem, 1985; Wells, 1989). Originally, the Miocene basalt intrusive complexes along the coast were thought to be CRBG magmas derived from source vents on the coast (Snavely et al., 1973). The Miocene coastal intrusions of CRBG chemistry had many of the characteristics of central vent complexes, with radial and ring dikes, central plugs, and intrusions into rocks as old as Eocene. Beeson et al. (1979), however, argued that they were invasive flows intruding soft sediments and were the distal ends of far-traveled CRBG flows.

Our route to the sea along State Highway 4 follows 18 flows of the CRBG down the Columbia River, from subaerial flows at Longview to invasive flows near Willapa Bay, Washington (Table 1; Fig. 14). Here, the Columbia River follows the Columbia River Syncline, a major structural low through the Coast Range. This post-CRBG syncline, an asymmetric Yakima-style fold, plunges west to form the axis of the Astoria Basin. It coincides with a pre-CRBG structural low that allowed the flows to cross the Coast Range.

Stratigraphic sections for the Longview–Willapa Bay section of the field trip are shown in Figure 15, and chemical analyses and paleomagnetic directions are shown in Table 3. On the Washington side of the river, the transition from subaerial to invasive Grande Ronde flows occurs at the Brookfield cannery site (~28 mi, or 45 km west of Longview), where flows of the Ortley Member are tilted steeply south along the Columbia River syncline (Figs. 14 and 15). The base of the flow is exposed, and large invasive tubes and pods can be traced downward into the underlying Miocene Astoria Formation. West of Brookfield, the main synclinal axis is offset to the north, and three mega-invasive sills with Ortley, Pomona, and Huntzinger chemistry and paleomagnetic directions are exposed for more than 30 km in the synclinal complex now occupied by Willapa Bay (Fig. 14).

Because the CRBG extends from the craton to the forearc, it is a good marker for late Cenozoic deformation. Clockwise paleomagnetic rotations of the CRBG are widely documented in western Oregon and Washington, and especially along the route of this field trip (Magill et al., 1982; Sheriff, 1984; Wells et al., 1989). The rotations are a signature of regional Pacific–North America dextral shear, which has been interpreted as block rotation of Oregon and the westward increase in rotation as distributed strike-slip faulting and small block rotations.

Block rotations continue today. GPS rotation rates are similar to those recorded by the CRBG (1°–2°/Ma; McCaffrey et al., 2007) and are interpreted as clockwise rotation of Oregon about a pole in eastern Oregon. This results in northward compression of Washington against Canada, producing the Yakima folds and
Figure 14. Geologic map of the north side of the Columbia River showing field trip stops, Willapa Bay to Longview, Washington. Compiled from Wolfe and McKee (1968) and Wells (1981, 1989) by M. Sawlan and R. Wells.
Figure 15. Stratigraphic sections of Columbia River Basalt Group (CRBG), Longview to Willapa Bay, Washington. Flows sampled for chemistry and paleomagnetism shown by adjacent sample number. Chemical analyses for representative samples (sample numbers RW80…) are shown in Table 2 (available in the GSA Data Repository; see footnote 1).
similar structures (e.g., Columbia River Syncline) in the forearc (Wells et al., 1998). These structures overprint and segment the broader, subduction-related Coast Range, Puget-Willamette Lowland, and arc. Local GPS and CRBG paleomagnetic rotation rates up to 2°/Ma in the Coast Range are interpreted as an additional permanent, distributed dextral shear of 1.2 mm/yr between the coast and Portland, suggesting a significant earthquake hazard.

Day 2 Road Log

Stop 2-1: Storedahl and Sons Quarry, Longview, Washington
46.1831° N, 123.0355° W (All locations for Day 2 are from Google Earth.)

The Storedahl quarry is 7.4 mi (12 km) west of Interstate 5 on Highway 4, just west of Longview. Access is by written permission, and Occupational Safety and Health Administration (OSHA) safety equipment must be worn. This large, active quarry exposes four high-MgO N₂ flows of the Sentinel Bluffs Member of the Grande Ronde Basalt interbedded with fluvial channel gravels and overbank muds (Fig. 16A). The flows rest unconformably on sandstone of the Eocene Cowlitz Formation (Tess of Fig. 14) and Eocene Grays River Volcanics (Tegv). Livingston (1966), in a study of the aluminum ore potential of CRBG laterites, was the first to differentiate the CRBG from the underlying late Eocene basalt. Cowlitz sandstone, with sills of Tegv, are exposed along the access road to the quarry.

Three Sentinel Bluffs Member flows comprise the active north wall of the quarry. The top two flows are medium gray, diktytaxitic, sparsely plagioclase phryic (small tabular, 5–10 mm), and are chemically correlative with the flows of Museum, which have lower Ti and higher Mg and Cr than underlying flows of McCoy Canyon (Fig. 17; Table 3 [see footnote 1]). The top flow has a steep NW paleomagnetic direction similar to that of the top Museum flow of the Sentinel Bluffs Member at Sentinel Gap and Bingen (Fig. 18 and Wells et al., 1989).

The top blocky jointed flow fills a subtle channel and rests on weathered and altered fluvial conglomerate, cross-laminated sandstone, and carbonaceous mudstone. These sediments overlie another Museum flow, which consists of a forested pillow delta complex prograding to the northwest. This flow overran a forest, and in the northwest corner of the pit on the upper deck is a standing tree engulfed by pillow basalt. The tree is rooted in dark-gray, moist carbonaceous mud containing fibrous, woody roots. The third flow from the top (the floor of the upper deck, Fig. 16) is probably a Museum flow based on Cr content, but major elements are affected by weathering. This flow rests on a thin sedimentary interbed, which separates it from the underlying flow of McCoy Canyon chemical type, not accessible at the field trip stop.

From Storedahl quarry, drive 2.7 mi (4.4 km) west on State Highway 4, past poorly exposed outcrops of tilted Eocene Grays River Volcanics unconformably beneath the CRBG. Park in the paved pullout along the Alder Bluff quarry face on the north side of the highway.

Stop 2-2: Alder Bluff Quarry
46.1878° N, 123.0900° W

The Alder Bluff quarry adjacent to State Highway 4 has a 300-m-long headwall exposing two flows of the low-MgO N₂ Ortley Member of the Grande Ronde Basalt at its base (Fig. 16B). The lower flow consists of a thick entablature and vesicular flow top, and it is overlain by the blocky colonnade base of the upper flow. More deeply weathered flows (135 m of section) are hidden in the trees above. Even the basal flow is a bit weathered, as reflected in its chemistry (Fig. 17; Table 3). The paleomagnetic direction of the lower Ortley flow is easterly (declination 72°, CL5 on Fig. 18), similar to Ortley flows at Bingen and in the Columbia River Gorge. The Ortley flows are incised deeply by a fluvial channel filled with quartzite-bearing basalt gravel exposed at the east end of the headwall. High on the western headwall, the gravel is overlain by horizontal columns interpreted by Snively et al. (1973) to be intracanyon Pack Sack Basalt and by Wells (1981) to be Pomona Member of the Saddle Mountains Basalt.

The outcrop is inaccessible, but blocks on the quarry floor are light gray, abundantly plagioclase phryic, and have compositions similar to the Pomona member based on 1960s chemistry. The Pomona forms a sheet flow that caps the broad plateau between here and Cathlamet and laps unconformably against the Willapa Hills anticlinorium to the north.

Drive 4.3 mi (7 km) to intersection with Oak Point Road and park in parking area on right. Along the way, State Highway 4 follows the Vantage horizon westward into the axis of the Columbia River Syncline, where Sand Hollow flows of the Frenchman Springs Member of the Wanapum Basalt drop to river level (Fig. 14). This west-plunging synclinal trough in the CRBG is a Coast Range manifestation of north-south shortening that produced the Yakima Fold Belt, and it controls the location of the Columbia River.

Stop 2-3: Oak Point, Washington, Old State Highway
Right of Way
46.1886° N, 123.1770° W

The old highway along the base of the cliff is built on the Vantage horizon. The cliff above consists of two flows of Sand Hollow of the Frenchman Springs Member of the Wanapum Basalt. The Frenchman Springs Member is widespread in the lower Columbia River (Wells, 1981; Niem and Niem, 1985). Flows of the Frenchman Springs Member are fine to medium grained, plagioclase-phryic and form massive, blocky colonnades. When compared to the Grande Ronde Basalt, Wanapum flows have lower SiO₂ and higher TiO₂ and P₂O₅ (Fig. 2A, Table 3). The Sand Hollow flows are sparsely plagioclase-megacrystic with a normal magnetic direction similar to that at Devil’s Canyon on the Plateau (Fig. 18 and Wells et al., 1989).

The cliff below the old road is the Sentinel Bluffs Member of the Grande Ronde Basalt.

The Vantage horizon here consists of at least 3 m of lithic arkosic sandstone and mudstone exposed beneath the rubble of fresh basalt blocks at the base of the upper cliff. Trees rooted
Figure 16. (A) Stop 2-1: Museum flows of Sentinel Bluffs Member (high-MgO N₂) Grande Ronde Basalt at Storedahl Quarry, Longview, Washington. Foreset pillows dip NW and are overlain by cross-laminated sand and gravel. (B) Ortley Member (low-MgO N₂) of Grande Ronde Basalt at Alder Bluff Quarry, west of Longview, Washington. Channel gravels are overlain by Pomona intracanyon flow. (C) Ortley Member (low-MgO N₂) Grande Ronde flow becomes invasive at Brookfield Cannery site. Stop 2-4a: Steeply dipping flow has basalt tongues at base of flow burrowing into underlying Miocene Astoria Formation. Map (modified from Wolfe and McKee, 1968) shows invasive bodies cut downsection to west. Easterly paleomagnetic direction (see Fig. 18) is similar to Ortley flow at Alder Bluff, 37 km to the east and at Bingen in the eastern Columbia River Gorge.
in a paleosol in the Vantage horizon have been engulfed by the Wanapum Basalt, and trees are locally exposed between here and Skamokawa. In Abernathy Creek, a few kilometers northeast of our stop, Beeson and Tolan (2002) identified the Huntzinger flow of the Asotin Member of the Saddle Mountains Basalt on top of the Wanapum Basalt and beneath the rim capping flow of the Pomona Member. We have not mapped its full extent, but it has a paleomagnetic direction similar to the Huntzinger flow on the Plateau (Fig. 18).

Drive 20 mi (32.4 km) on State Highway 4 to the town of Skamokawa. Between Oak Point and Cathlamet, the road climbs up the south limb of the syncline, roughly along the Vantage horizon, with cliffs of Wanapum Basalt above. The road traverses several large landslides as we go around Cape Horn (one of several places with that name along the Columbia) and back down to river level. Cape Horn was the campsite of Lewis and Clark on 6 November 1805. They had traveled 29 mi from their previous camp at Prescott beach, across the river from Kalama.

Figure 18. Paleomagnetic directions for subaerial and invasive flows from SW Washington compared to directions from flows on the Columbia Plateau (site numbers are from tables in Wells et al., 1989). Plateau reference directions are shaded; coastal flows are mostly clockwise rotated from Plateau reference directions. Selected coastal invasive flows are labeled. Directions for selected, chemically analyzed flows are in Table 2. Symbols as in Figure 5.

Figure 17. Chemistry of selected Grande Ronde flows in SW Washington compared to Grande Ronde Basalt members in the Columbia River Gorge, shown by outlines.
Washington. As we climb up onto the bench east of Cathlamet, the roadcuts on the north side of the road expose two Sentinel Bluffs Member flows overlying an Ortley flow. South of the road in a now reclaimed quarry (Fig. 15), a Sentinel Bluffs Member flow of McCoy Canyon overlies a low-MgO section of three N2 Ortley flows, one Grouse Creek flow (R2), and two R2 Wapshilla Ridge flows at river level.

North of Cathlamet, the road drops down to river level and crosses the axis of west-plunging Columbia River Syncline. The low hills to the east are the mudstone of Gnat Creek (Niem and Niem, 1985), which overlies the Frenchman Springs Member and is overlain by the rim-capping Pomona Member of the Saddle Mountains Basalt. The road turns west as it encounters a wall of steeply south-dipping CRBG forming the north limb of the syncline. Quarries (now reclaimed) on Alger Creek, northeast of the highway, exposed two Museum flows, Vantage horizon sands with a tree in growth position, and a Frenchman Springs Member flow of Sand Hollow, all dipping 90° to the south. Looking southwest, the north-dipping limb of the syncline forms the dip slope of Nicolai Mountain in Oregon, which consists of Wanapum Basalt over Grande Ronde Basalt. Here the river flows along the axis of the syncline and may conceal a blind, north-dipping thrust producing the steep dips in the basalt.

At Skamokawa, the road follows Skamokawa Creek through the south-dipping basalt flows. The flows may be right-laterally separated a few hundred meters by a fault through the water gap. The only probable Winter Water flow on the north bank of the river is exposed in a quarry west of town.

From the center of Skamokawa, drive north 2.1 mi on Highway 4, and turn left on BF 100 County Road. Drive 6 mi along the main road (becomes gravel road) to the site of the former Brookfield cannery on the river. All spur roads off the main road are gated and locked. At the river, the main road turns north to the Brookfield quarry, where it is gated. Entrance to the quarry requires a key, safety gear, and permission from the landowner.

**Stop 2-4: Brookfield, Washington (Site)**

46.2664° N, 123.5547° W

Invasive top and bottom contacts of an Ortley flow of the Grande Ronde Basalt are exposed at Brookfield, which is along strike and 2.5 km downstream from steeply dipping subaerial and pillowed Grande Ronde Basalt exposed along the river at Three Tree Point (Fig. 16C; Wolfe and McKee, 1968). Between the Point and Brookfield, the basalt invades the underlying sandstone of the Miocene Astoria Formation, producing peperites and irregular intrusive bodies. At Brookfield, the road along the river cuts through vegetation-covered blocky basalt dipping 50°–90° south. In the roadcut, the south-dipping, nonvesicular basalt flow top appears to be chilled against overlying sandstone of the Astoria Formation. Chemistry and the unusual easterly paleomagnetic direction are similar to the thick basal Ortley flow at Alder Bluff, 37 km to the east and at Bingen in the eastern Columbia River Gorge (Fig. 18). Beyond the locked gate at the end of the county road, a quarry at the top of the hill above Brookfield exposes the steeply dipping flow and its base. Large basalt tongues at base of flow have burrowed into the underlying Miocene Astoria Formation (Fig. 16C). At Brookfield, the Astoria Formation is at its thinnest, and the point of invasion is near the structurally highest point of the unconformity. West of here, the invasive bodies cut downsection until they are cut off by a major north-trending fault that forms the eastern margin of the Astoria Basin (Fig. 14).

Looking downriver, the high cliffs consist of south-dipping Frenchman Springs Member flows forming thick pillow-breccia complexes. These pillowed flows extend 10 km downstream, past the Pillar Rock campsite of Lewis and Clark, named for a monolith of Frenchman Springs Member basalt rising out of the river 20+ m (10 m today—it’s been topped to install a navigation light). It is here in early November 1805 that the expedition thought they had reached the Pacific.

“... we are in view of the opening of the Ocean, which Creates great joy. ...” [Clark, 7 November 1805]

**Optional Stop 2.4b: Unnamed Quarry**

46.274891° N, 123.615882° W

This stop allows examination of one of the isolated invasive bodies at an unnamed quarry 3.5 mi west of Brookfield on an unnamed logging road. Here the upper contact of the invasive flow is 100% exposed. The quarry is in low-MgO N2 Grande Ronde Basalt, which has invaded and strongly altered the overlying Astoria Formation. Chemistry and the unusual easterly paleomagnetic direction are similar to the flow at Brookfield and the thick basal Ortley flow at Alder Bluff, 37 km to the east and at Bingen in the eastern Columbia River Gorge (Fig. 18).

Return to Highway 4 via the same BF 100 County Road. Turn left on Highway 4 and drive 23 mi to Naselle, Washington. Along this route, Highway 4 westbound traverses Astoria basin fill of outer shelf mudstones of the Oligocene Lincoln Creek Formation (Tos in Fig. 14) and shelf sandstones and mudstone of the Miocene Astoria Formation (Tms in Fig. 14). Hundreds of small invasive bodies of Grande Ronde Basalt are locally exposed along the road and in the backcountry. Southeast of Naselle is Bald Ridge, the axis of the Naselle Syncline, held up by the invasive Huntzinger flow of the Asotin Member of the Saddle Mountains Basalt (Tismh in Fig. 14). This sill was originally thought to be correlative with the Pack Sack Basalt (Wolfe and McKee, 1972; i.e., Pomona flow), but it has normal polarity (Wells et al., 1989). Its steep paleomagnetic direction is similar to the Huntzinger flow west of Longview and on the Plateau (Fig. 18), and the 1960s-vintage, high-MgO chemistry is consistent with a Saddle Mountains Basalt origin (Reidel and Fecht, 1987). Due west of Naselle on the skyline is Bear River Ridge, a 16-km-long, massive invasive sill of low-MgO N2 Grande Ronde Basalt. It is similar to the invasive bodies at Brookfield and the Ortley flow at Alder Bluff, and we will examine it at our next stop.

Continue north 4.3 mi on Highway 4 to junction with U.S. 101. Follow 101 south toward Long Beach, along the eastern shore of Willapa Bay, ~3 mi to the entrance road for the Templin rock pit. The entrance road has a locked gate; permission from the
landowner is required. Detailed instructions for travel within the pit will be given on the entrance road. Exercise caution along the road because gravel trucks and log trucks have the right of way.

Stop 2-5: Templin Rock Pit, Mega-Invasive Grande Ronde Basalt Sill
46.3991° N, 123.9298° W

This large, active pit exposes the basal contact of the Bear River Ridge sill, an invasive flow of low-MgO N2 Ortley Member of the Grande Ronde Basalt, based on chemistry in Snavely et al. (1973) (Fig. 19). The sill is up to 400 m thick and concordantly intrudes late Eocene and Oligocene tuffaceous mudstone near the base of the Lincoln Creek Formation. The mudstone is now hornfels up to 150 m thick on the top and bottom of the sill. The lower contact of the sill over hornfels is exposed in the headwall of the northern, inactive part of the quarry (Fig. 19). The sill is exposed for 16 km along strike and is folded by the Naselle River syncline; its near vertical opposite limb crops out northeast of Naselle, 10 km from Bear River Ridge. The sill is medium to coarse grained, except near the contacts, where it is fine grained. No major segregations or pegmatitic zones are noted in the sill. The thick hornfels is much thicker than typical contact metamorphism seen in other Coast Range intrusions, and it suggests that the sill was a conduit for lava flowing farther downslope. The sill is intruded into the late Eocene and Oligocene Lincoln Creek Formation, outer shelf and slope mudstones, presumably at considerable depth beneath the Astoria Formation sediments filling the Miocene basin. The sill is shattered and sheared by post-CRBG folding and faulting—an 8-m-wide, strike-slip shear zone cuts the south wall of the quarry (Fig. 19). The flat surface at the top of the headwall is a Pleistocene terrace mantled with bedded, quartzite cobble-bearing sand and gravel at 150 m above sea level (asl). The sill has been sampled for chemistry and paleomagnetism in both limbs of the fold. It is of Ortley chemistry and has the same easterly magnetic direction found in the Ortley flows at Brookfield, Alder Bluff Quarry, and Bingen in the eastern Columbia River Gorge (Fig. 18).

From the pit, take the main road east out of the quarry and up the hill to another locked gate on Nature Conservancy property (permission required). Go through the gate and drive 7 mi south along the ridge top on unnamed logging roads in dense second-growth forest, past a pit in baked sediments on top of the sill, to the Nature Conservancy rock pit. Drive slowly; the hornfels is used as road metal, and it is very hard on tires. Park in pit.

Figure 19. Stop 2-5: Basal contact of Bear River Ridge sill, Templin Rock Pit. Invasive flow of Ortley Member of Grande Ronde Basalt overlies hornfelsed late Eocene mudstone. Hornfels and sill are quarried for road rock. Sill has easterly magnetic direction similar to invasive Ortley Member at Brookfield, and basal Ortley Member flow at Alder Bluff Quarry west of Longview; see Figure 18. Upper contact is eroded away here; Pleistocene terrace deposits with quartzite cobbles unconformably overlie basalt.
Stop 2-6: Nature Conservancy Pit
46.3592° N, 123.8955° W

At this intermittently active quarry, the upper contact of the invasive Bear River Ridge sill is exposed. Dark-gray to black, fine-grained basalt is in contact with baked, spotted hornfels containing relict sedimentary structures. The invasive contact is non-vesicular, chilled, sharp, and dips NE. Relict bedding in hornfels is roughly concordant with the top of the sill. The hornfels and altered zone above the sill is over 100 m thick. Eye protection is required when hitting the hornfels with a hammer; fragments are very sharp. From the upper slopes of the quarry, one can view Radar Ridge at an elevation of 1922 feet to the northeast. Radar Ridge is the location of the last stop, and it is held up by an invasive sill of the Pomona Member of the Saddle Mountains Basalt.

Drive north on unnamed logging roads ~8 mi through two locked gates (permission and key required) to the junction with Parapala Road; turn left, westward toward Highway 101. Turn right on 101 and proceed northbound ~3.2 mi to Dionne Lane. Turn right on Dionne and follow mainline logging road 2.6 mi to quarry at the top of the ridge. Watch for logging trucks, and park on the top of the ridge above the quarry. The ridge is informally named Radar Ridge for an old railroad installation now occupied by numerous communication towers.

Stop 2-7: Radar Ridge Pit
46.43266° N, 123.8131° W

The Radar Ridge rock pit is developed in the Pomona invasive sill. The sill is intruded at the late Eocene unconformity between Eocene marine mudstone and the dominantly Oligocene mudstone of the Lincoln Creek Formation. The sill consists of coarse-grained plagioclase phyric, olivine-bearing diabasic basalt. It is folded into a doubly plunging syncline that forms an unusual boat-shaped basin ringed by hills of inward-dipping basalt (Figs. 14 and 20). The center of the basin is underlain by hornfels and baked sediment above the sill. The sill had been identified as Pack Sack Basalt (Snively et al., 1973), chemically correlative with the Pomona Member of the Saddle Mountains Basalt (Wells, 1989). Subsequent paleomagnetic sampling has confirmed that the type Pack Sack and this sill have reversed paleomagnetic directions similar to the Pomona Member flow west of Longview and on the Plateau, but clockwise rotated (Magill et al., 1982; Fig. 18). Because there is only one Pomona Member flow on the Plateau, sourced from vents near the Idaho border, this sill is interpreted to be invasive Pomona Member. Uplift of the Coast Range and subsequent erosion has removed the transition from subaerial to invasive flow. Just how the Pomona Member invaded Eocene sedimentary rocks is a subject for discussion. To the west is a view of the Ortley invasive sill that forms Bear River Ridge. It forms the western limb of the Naselle River syncline, and the Naselle River below flows along its axis. A major NE-dipping thrust fault is interpreted to separate the Naselle River syncline from the Radar Ridge Syncline.

From the ridge top, we retrace our route back to Highway 101, where we turn left (south) toward Naselle. At the junction with State Highway 401, turn left (southeast toward Naselle). Drive ~22 mi south to Astoria, Oregon, on Highway 401 following the axis of the Miocene basin (Fig. 14). We rejoin the Columbia River at the site of Knappton cannery, where resistant, steeply dipping Oligocene sandstone juts into the river. Portuguese Point, visible 4 km upstream is a resistant sill of invasive Ortley Member and the campsite of Lewis and Clark on 8–9 November 1805. Downstream from Knappton, the road follows the river across a north-plunging anticline cored by Eocene pillow basalt and rhythmically bedded sandstone. Just before the left turn onto the Astoria Bridge is the Dismal Nitch Rest Stop, named for the campsite where the Lewis and Clark expedition was trapped against the steep bank by a Pacific storm and high tides 10–14 November 1805. In part camped on driftwood floating on high tide, they described it as the most disagreeable time on their journey. After moving downriver to Station Camp (McGowan, just west of the bridge) on 15 November, the entire expedition voted to cross the river and winter over at what is now Fort Clatsop, to take advantage of a more benign landscape and more plentiful game.

Continue on Highway 101 across the bridge to Astoria and overnight accommodations.

DAY 3: CRBG INVASIVE FLOWS AND SUBMARINE PILLOW BRECCIAS, NORTHWEST OREGON

On Day 3, we will examine: (1) the CRBG in submarine canyon head and shelfal paleogeographic settings, (2) geologic features of invasive flow emplacement and re-eruptive processes, (3) CRBG invasive flows that formed thick mega-sills and dikes west of the Miocene strandline, and associated submarine pillow lavas, breccias, and a deep-marine sedimentary interbed, and (4) post-CRGB regional wrench faulting in NW Oregon. Regional correlations of flows from NW Oregon to SW Washington, the western Columbia River Gorge, and the Columbia Plateau will be discussed based on preliminary geochemistry and paleomagnetic data. A stratigraphic section of the CRBG in the Astoria Basin is shown in Table 1 and chemical analyses in Table 4 (see footnote 1).

At the time of arrival of the Miocene Grande Ronde, Wanapum, and Saddle Mountains flows, the Astoria forearc basin of NW Oregon was occupied by the mouth of an ancestral Columbia River, and its adjacent shelf and slope was cut by tributaries of a deep-marine ancestral Astoria submarine canyon system (Smith, 1975; Niem, 1976; Cooper, 1981; Murphy and Niem, 1982). Tributaries of the present Astoria canyon head complex occur several km offshore from the river mouth and extend across the middle and outer shelf and upper slope, and are an analog to this Miocene setting. The subjacent and interbedded Miocene sedimentary facies are preserved as the lower to middle Miocene (Saucesian foraminiferal stage) Astoria Formation that underlies the Grande Ronde and Frenchman Springs basalts and as the upper Miocene (Luisian foraminiferal stage) Gnat Creek Formation, a 200-m-thick interbed between the Frenchman Springs Member and the Pomona Member (Murphy, 1981; Murphy and Niem, 1982; Niem et al., 1994) (Fig. 21), Grande Ronde
Figure 20. Stop 2-7: Invasive sill of Pomona Member, Radar Ridge, northeast of Naselle, Washington. Diabasic olivine basalt in quarry has Pomona chemistry and paleomagnetic direction and is very likely invasive Pomona flow. This location is 40 km downstream from westernmost subaerial Pomona flow. (A) Geologic map from Wells (1989); key on Figure 14. (B) Google Earth view of boat-shaped Radar Ridge Syncline looking northwest. (C) View looking southwest from Radar Ridge quarry, with invasive Pomona Member in foreground. Naselle River in the distance flows down the axis of the Naselle Syncline to the ocean. Bear River Ridge on the skyline is underlain by the east-dipping Ortley Member invasive sill (Stops 2-5 and 2-6). Another Pomona invasive sill underlies the ridge north of the mouth of Naselle River.
Columbia River Basalt Group: From the gorge to the sea

Figure 21. Generalized geologic map of the south side of the Columbia River, Astoria Basin, NW Oregon, emphasizing Columbia River Basalt Group (CRBG) units and structure (faults) (from Niem and Niem, 1985). Heavy dark-blue dashed lines outline approximate position of a Miocene Grande Ronde submarine canyon head complex, based upon mapped field distribution of bathyal submarine pillow breccias, paleoflow direction indicators, and CRBG flow unit(s) distribution. Black short dashed lines mark the western and eastern limits of CRBG invasive bodies. Heavy black dashed line delineates general area of subaerial flows to shelf and slope lava deltas.
and Frenchman Springs lava deltas and thick Grande Ronde deep-marine breccias with minor bathyal mudstone, debris flow basalt gravel, and turbidite arkosic sandstone interbed(s) now form the uplifted and faulted, erosionally resistant inverted topographic remnants of a once more continuous submarine canyon head complex fill incised into Miocene and Oligocene–Eocene shelf and slope strata (Figs. 21 and 22).

The transition from subaerial flows and interbedded fluvial, crossbedded, arkosic to basaltic sandstone and basalt conglomerate to shelfal lava deltas, deep sea submarine pillow and pillow breccia flows, and associated invasive Grande Ronde and Frenchman Springs flows occurs between Nicolai Mountain and Wickiup Mountain (note heavy black dashed line on Fig. 21). Flows of Sand Hollow, Sentinel Bluffs, Winter Water, Ortley, and Wapshilla Ridge dip gently northward into the asymmetrical Columbia River syncline in SW Washington. The base of these subaerial flow couplets consists of large lava delta foresets, some with shallow-marine fossils between pillows and others with thin deep-marine, foraminiferal mudstone interbeds and associated invasive sills and dikes (Niem et al., 1973; Murphy, 1981; Niem et al., 1994). The subaerial flows have been mapped several km westward and southward over lower to middle Miocene shelfal Astoria Formation sandstone and deep-marine mudstone units that once, in part, formed paleocanyon walls near Big Creek and Wickiup Mountain (Murphy, 1981; Niem and Niem, 1985; Niem et al., 1994). These features and field relationships were emphasized in an earlier field.

Miocene coastal paleogeography in NW Oregon and SW Washington
Cartoon of invasive CRBG basalts and syn-Grande Ronde submarine canyon head fill

Figure 22. Cross-section cartoon depicting a model for invasive mechanisms and paleogeography of Columbia River Basalt Group (CRBG) flows into the marine sedimentary Astoria Basin, NW Oregon and SW Washington. Paleogeographic positions and geologic features seen on Day 3 stops are identified within and at the top of the cartoon.
Formation deltaic, shelf, slope, and submarine canyon head facies.

onto water-saturated, semilithified sediments (Miocene Astoria canyon head complex. The submarine Grande Ronde lava loaded onto the Miocene shelf and continental slope and into a SW-trending submarine basin (note fine black dashed line on Fig. 21).

South of Nicolai Mountain, a set of three major, parallel, low-MgO Grande Ronde dikes can be mapped for more than 25 km into Miocene, Oligocene, and upper Eocene marine sedimentary host rocks (Fig. 21). Some invasive CRBG mega-sills form coastal sea cliffs more than 300 m high and extend more than 54 km into the offshore portion of the Oregon Astoria forearc basin and possibly into the Miocene subduction zone preserved beneath the continental shelf and upper slope (Niem et al., 1990, 1994).

**Invasive Processes and Mechanisms**

The processes by which such mega-invasive features were created are difficult to imagine. Contrasts in bulk density and viscosity and other mechanical and physical properties between fluid basalt lava and water-saturated marine sediment and sedimentary rock, preexisting structural and stratigraphic control, and paleogeographic setting are all important contributors to invasion of the Tertiary marine strata by CRBG lavas.

The mega-invasive flows developed from widespread and thick lava deltas and submarine breccias prograded into the marine environment. Emplacement of mega-invasive flows (sills and dikes) are envisioned in the following preliminary model (Fig. 22): (1) initiation of invasion and mainly downward movement of the invasive flow; (2) lateral movement of the invasive flow; and (3) inflation and re-eruption.

(1) Initiation and mechanism of invasion: Insulated by a thick carapace of sea water–quenched and cooling pillow lava and breccias, invasive lava tube(s) are fed by inflated subaerial flows to the east. Thick westward- to southwestward-prograding CRBG lava delta lobes and forested-bedded submarine isolated pillow breccia with inclined pillows and filled lava tubes advanced onto the Miocene shelf and continental slope and into a SW-trending submarine canyon head complex. The submarine Grande Ronde lava loaded onto water-saturated, semilithified sediments (Miocene Astoria Formation deltaic, shelf, slope, and submarine canyon head facies). Contact with wet seafloor sediment caused pneumatic steam blasting, formation of peperite and sedimentary breccia, and soft-sediment plastic deformation of the Miocene sediment.

The denser invasive lavas continued to sink and move downward and obliquely tens to hundreds of meters displacing the shallow-buried soft, semiconsolidated sediment. Downward, deeper movement of invasive flows may have been accomplished by the increasing weight of the dynamically moving invasive lava column, invasive lava fracturing or hydraulic fracturing along preexisting down-to-the-basin normal faults and joints in older more indurated and brittle Oligocene–Eocene sedimentary rock units, and/or invasion along headscarp fractures of large pre-CRBG translational landslides.

(2) Lateral flow: Lateral flow largely began where bulk density, viscosity, and other physical and mechanical properties of the invasive lava and more deeply buried strata equalized and downward movement of the lava ceased. Invasive lava then moved laterally as irregular sill-like pods and dikes, following some strata that depositionally dipped gently seaward toward the Astoria Basin center, following preexisting subhorizontal fractures or joints in the Miocene–Oligocene–Eocene sedimentary strata, and/or possibly some moving along basal slide planes of large, older, subma- rine translational paleolandslides. Some invasive lavas may have flowed along unconformities between soft Miocene sediment and more consolidated and brittle Oligocene–Eocene strata.

(3) Inflation and re-eruption: Inflation of the invasive lavas at weak zones (thinned sedimentary fill) and, in some cases, re-eruption of invasive lava on the Miocene seafloor was driven by hydraulic head and continual feed by inflated lava flows. As a result, these invasive flows (?) lifted the overlying, less dense shelfal and slope sediments and sedimentary rocks. Some invasive mega-sills grew thick (hundreds of meters) by inflation and baked the host rocks for hundreds of meters from the margins of the invasive bodies.

Subsequent pneumatic steam blasting, fracturing of water-saturated, semiconsolidated, near-surface Miocene sediments, mainly at the top and flanks of the invasive mega-sills, created dike-like apophyses, peperite dikes, and sedimentary breccias near dike margins. Plastic semiconsolidated Astoria slope turbidites and shelfal and deltaic sands, caught between apophyses, were deformed into tight chevron, isoclinal, or more open folds or formed chaotic sedimentary breccia. Some invasive lava, driven by artesian lava head, re-erupted on the Miocene seafloor resulting in local buildups of pillow lava, isolated pillow breccia, and hyaloclastites. Locally, a few invasive flows also invaded upward through older CRBG intrusive sills and submarine basalt pillow breccias. A few rootless autoinvasive dikes within the submarine breccias filling the submarine canyon head were locally fed by foreset lava tubes or lobes below.

**Day 3 Field Trip Stops**

Day 3 consists of six stops with two alternative stops. Three of the six primary stops and one alternative stop (Stop 3-5a) are CRBG view stops that require clear viewing weather (Stops 3-1,
3-3, and 3-6; Fig. 21). The principal roads for access to the stops are U.S. 101, U.S. 26, and Oregon Highway 53 (Fig. 21). Permission to enter private timberland and quarry property and key(s) to locked logging road gates are required for some stops (i.e., Stops 3-2, 3-5, 3-5a, and 3-6).

**Day 3 Road Log**

From the Astoria Holiday Inn Express, turn left (east) onto Marine Drive (U.S. 30). Drive 0.7 mi into downtown Astoria. Turn right (south) onto 8th Street and then left (south) onto Commercial Street. Proceed 0.5 mi in the right lane of Commercial Street. At the intersection with 16th Street, turn right and follow the green road signs to the Astoria Column, proceeding 5 blocks up the steep hill. Turn right onto Jerome Avenue. In one block, turn left onto 15th Street and continue uphill 0.2 mi. Then turn left onto winding Coxcomb Drive 0.7 mi to the Astoria Column at the top of the hill. Park and assemble at the Astoria Column at the top of the hill. Park and assemble at the Astoria Column.

**Stop 3-1: Astoria Column**

46.18149° N, 123.81738° W

Panoramic views of SW Washington and NW Oregon and the Columbia River mouth. The highest ridges to the north beyond the Columbia River are Bear River Ridge and Radar Ridge composed of Ortley and Pomona basalt invasive sills (stops 2-5, 2-6, and 2-7). To the southeast, the headland at the southern end of Clatsop Spit is Tillamook Head, an invasive flow of Winter Water basalt that dips gently southeast (stops 3-2 and 3-3). The low forested hills in front of Tillamook Head are capped by Ginkgo pillow basalt.

South along Youngs River, the middle ridge beneath the low hills of Eocene–Miocene sedimentary rock is Lone Ridge, an erosion-resistant middle Miocene horseshoe-shaped invasive diabasic mega-dike of the basalt of Sand Hollow (Fig. 21). Southeast of Lone Ridge, the higher nearly flat-topped Eels Ridge and Green Mountain are composed of diabase sills of the Frenchman Springs Member of the Wanapum Basalt (Sand Hollow) that invaded Oligocene and Miocene marine sedimentary rocks. In the far distance to the south, the rugged high peaks of Sugarloaf Mountain and Onion Peak (stops 3-5 and 3-5a) are mainly Winter Water submarine pillow breccias. These mountains are faulted, erosional remnants of the thick sequence that filled a submarine canyon head.

The distant high knobby peaks of Saddle Mountain (elevation 1000 m) and Humbug Mountain (stop 3-6) to the southeast are formed of thick submarine basaltic breccias of the N2 Sentinel Bluffs Member and R2 Wapshilla Ridge Member, respectively. East of the Astoria Column are Nicolai and Wickiup mountains, composed of several thick CRBG subaerial flow units and associated submarine basaltic lava deltas (Sand Hollow, Sentinel Bluffs, Winter Water, Ortley, and Grouse Creek) that prograded westward and southwestward onto the shelf (Figs. 21 and 22) (Murphy, 1981; see Niem et al., 1994).

Concealed beneath the Columbia River and Quaternary deposits is a major left-lateral post-CRBG strike-slip fault trending northeastward from Clatsop Spit beneath the Astoria-Megler bridge and up the Columbia River. Its presence is inferred from seismic reflection profiles, offset aeromagnetic anomalies, and geologic map relationships (Fig. 21) (Wells, 1981, 1989; Niem et al., 1990; Liberty et al., 2003). The east-west peninsula of Astoria (Coxcomb Hill) is held up by a thick invasive sill of low-MgO Grande Ronde Basalt.

**Directions to Stop 3-2**

Complete the Coxcomb Hill loop road and descend the hill to 15th Street. Turn left (south) onto 15th Street. In one block, turn right (west) onto Niagara Avenue. Drive eight blocks and turn left (south) onto 7th Street. Drive downhill to the intersection with OR 202 (Olney Avenue) and turn right toward Astoria. In 0.1 mi take the curving exit to the left (south) onto Alternate (Alt.) U.S. 101 (Business 101) to cross Youngs Bay via the old Youngs Bay bridge. The axis of the Youngs Bay syncline lies beneath Youngs Bay (Fig. 21). Approximately 1.6 mi south of the north end of the old Youngs Bay bridge, turn right (west) at the T-intersection with Youngs River Road and continue west on Alt. 101. In 0.8 mi, cross the bridge over the Lewis and Clark River.

In an additional 1.6 mi, pass the intersection with Fort Clatsop Road to the Lewis and Clark historic site (Fort Clatsop National Memorial visitor center) where a replica of the expedition’s 1805–1806 winter quarters has been reconstructed. Continue an additional 2 mi on Alt. 101 to the large green road sign to Warrenton and turn right (north). At the traffic light junction with U.S. 101, turn left (south) toward Seaside. Drive 10 mi south over north-south–trending ridges of Holocene sand dune and interdunal lakes through the town of Gearhart to the bridge over Neawanna Creek at the northern boundary of the town of Seaside. Continue on U.S. 101 through the business district of the resort town of Seaside (~1.4 mi). Proceed south on U.S. 101 ~3.0 mi, crossing the bridge over the Necanicum River. Note the large quarry on the hillside to the north (south), which is the Stop 3-2 location (Fig. 23). Two-tenths of a mile past the bridge, turn right (south) on Rippet Road and drive 0.1 mi to the green gate leading to the second landing of the large private quarry (permission needed for access).

**Stop 3-2: Rippet Quarry**

45.95088° N, 123.93088° W

This 60-m-high quarry face exposes an invasive flow (sill) of diabasic basalt with large vertical columnar joints and some subhorizontal platy joints with extensive brown to tan weathered surfaces. The fresh, dark-gray, medium to coarsely crystalline basalt contains scattered 3- to 5-mm-long plagioclase phenocrysts. Several 10-m-long, dike-like apophyses extend upward from the irregular top of the main sill body into the overlying laminated to massive, Astoria (Cannon Beach Member) deep-marine mudstone (Fig. 23). The medium-gray, indurated mudstone has been...
baked and bleached by the intrusive bodies next to the contact for several meters. Some blocks of baked mudstone have sloughed off the upper quarry face onto the quarry landing where they can be examined. The geochemistry and steep inclinations of this sill are similar to some high-TiO$_2$ Winter Water flows in the gorge (sites N2 and N3 on Fig. 24).

The basalt sill in the Fisher-Tiven quarry (N3 on Fig. 24), 0.5 mi to the southeast, has high-TiO$_2$ variant Winter Water geochemistry, similar declination and steep inclination, and the same lithologic characteristics as the diabase in the Rippet quarry. However, the top contact of the sill with baked and bleached Astoria Formation (Cannon Beach Member) mudstone in the Fisher-Tiven quarry is 30 m lower than the contact in the Rippet quarry. Neel (1976) and Niem and Niem (1985) mapped the northwest-trending, oblique-slip Necanicum fault, which parallels the Necanicum River valley and U.S. 101 between these two quarries. This fault offsets the uplifted Tillamook headland sill ~1 km in a right-lateral sense compared to the sill in the Fisher-Tiven quarry on the northeast block (Fig. 21). The Necanicum fault lies at the western end of the Gales Creek–Mount Angel fault, a major right-lateral fault zone through the northern Oregon Coast Range and northern Willamette Valley mapped by Wells et al. (1995) and Niem and Niem (1985) (Fig. 21).

**Directions to Stop 3-3 or 3-3a**

Return to the intersection of Rippet Road and U.S. 101; turn right (south) onto U.S. 101. In 0.7 mi at the intersection of U.S. 101 with U.S. 26, keep left on U.S. 101 over the bridge toward Cannon Beach. South of the intersection the route passes some road exposures on the left and right of the Tillamook Head sill. Approximately 3.9 mi south of the intersection, pass a roadcut exposure on the right of a Ginkgo dike and take the first exit into the community of Cannon Beach. At the stop sign at the bottom of the hill (intersection of 5th Street and Fir), turn right onto 5th Street. In 0.2 mi, turn right toward Ecola State Park. Follow the narrow, winding park road for 1.5 mi to the fee station booth. Turn left (west) 0.2 mi to the main parking lot. If inclement weather obscures the view at Stop 3-3, proceed south to alternative Stop 3-3a through the town of Cannon Beach (see directions that follow the description of Stop 3-3).

**Stop 3-3: Ecola Point Viewpoint, Ecola State Park**

45.91844° N, 123.9744° W

The parking lot is in the midst of a recently active landslide (Niem et al., 1973). Uphill from the parking lot is a 25 m scarp of the landslide that occurred in 1961 (Schlicker et al., 1961).

Walk 200 m west along the curving paved path at the SW end of the parking lot to the wooden-fenced platform viewpoint on the narrow headland (Ecola Point).

The nearby knob and arcuate cove just north of the viewpoint are the wave-eroded toe of the Ecola Park landslide. The sea cliffs beneath the viewpoint are composed of Astoria Formation (Cannon Beach Member) deep-marine delta slope mudstone and turbidite sandstone and thin invasive sills of low-MgO Grande Ronde Basalt and Wanapum Basalt (Basalt of Ginkgo). The cove to the far north (with parking area and restroom) is Indian Beach, from which a low-MgO Grande Ronde (Winter Water?) peperitic sill in the sea cliff yielded a K/Ar date of 15.9 ± 0.4 Ma (Niem and Cressy, 1973). Beyond is a 250-m-high sea cliff and forested headland formed by the thick invasive Tillamook Head sill in contact with light-gray baked and unaltered darker gray Cannon Beach Member mudstones at the top of the sea cliff. The diabasic sill has Winter Water chemistry (Fig. 25) and a characteristic paleomagnetic shallow inclination and northerly declination, similar to that of subaerial Winter Water flows in the western gorge (N4; Fig. 24).

To the northwest, offshore, the lighthouse is constructed on Tillamook Rock, a sea stack sculpted from the Tillamook Head invasive sill. This mega-invasive flow is recognized on a multichannel seismic reflection profile(s) as a strong acoustic downfaulted reflector near the lighthouse. It extends 54 km westward and penetrates downward 1000+ m across the gently folded lower Miocene and Eocene–Oligocene sedimentary section beneath the inner to mid-continental shelf (Niem et al., 1990). The reflector may be offset by late Miocene subduction zone thrust and oblique-slip faults (Miocene Hoh mélange) farther offshore beyond the Nehalem Banks on the outer continental shelf and slope. Nearby sea stacks (including Sea Lion Rock with sea arch) to the southwest of the viewpoint also are erosional remnants of the upper part of the Tillamook Head (Winter Water) invasive sill.

Field mapping by Neel (1976), Niem and Niem (1985), and ongoing work, as well as continuous ridge topographic expression, suggest that the diabase sill in the western part of Tillamook Head connects to the diabase sill in the Rippet quarry 5 km to the east (Fig. 21) (Stop 3-2). At both locations, the upper contact of the sill bakes Astoria Formation (Cannon Beach Member) mudstones (Fig. 21). However, the paleomagnetism of the Winter
Water Basalt in the southwestern part of the Tillamook Head sill viewed here has shallower inclination and a more NNW declination (Fig. 24). The geologic reasons for varying paleomagnetic inclination and declination for different sites in sills and submarine pillow breccias with Winter Water chemistry in NW Oregon (Fig. 24; sites N2, N3, N4, N6, N8, N11, N12, N13, N14, and N20) are the subject of continuing research.

Return 100 m via the paved path to a second scenic viewpoint on the grassy knob near the picnic shelter with the stone fireplace to look to the south down the beach (Fig. 26).

Figure 24. Paleomagnetic directions for Columbia River basalts in NW Oregon. (A) Subaerial and invasive Grande Ronde Basalt and Wanapum Basalt flow units from Day 3 stops compared to similar Days 1 and 2 fields. (B) Invasive Saddle Mountains Basalt (Pomona and Huntzinger?) sills compared with paleomagnetic directions for the chemically same subaerial flow and invasive units in SW Washington (Day 2; Fig. 18). Symbols as in Figure 5.
Looking southeast, the rugged 900-m-high peaks include Onion Peak (Stop 3-5), Sugarloaf Mountain, and Angora Peak, which are composed of mainly hundreds of meters of Winter Water breccias and pillow lavas. Note the clearcut U-shaped valleys between Onion Peak and Sugarloaf Mountain in the distance (see Stop 3-5a for further discussion of valley morphology). The farthest two headlands visible far to the south are Cape Falcon (Ortley? invasive sill; Wells, 1989) and Arch Cape (Winter Water invasive sill; sample N11 on Fig. 24). Haystack Rock, the large pyramid-shaped sea stack adjacent to the beach, is a Ginkgo basaltic pillow breccia re-eruptive center with dikes and sills. The twin peaks southeast of Haystack Rock and behind the community of Tolovana Park are called Double Peak (low-MgO Grande Ronde Basalt breccia). The resort town of Cannon Beach is built on Astoria Formation (Cannon Beach Member) mudstone and Quaternary marine terrace, beach, and dune sand (Niem and Niem, 1985).
At the south end of Crescent Beach, the prominent basalt headland is Chapman Point (Fig. 26), a Sentinel Bluffs invasive sill with Spokane Falls(?) geochemistry (see Chapman Point sample plotted on Fig. 25). We have found a similar paleomagnetic direction in some Spokane Falls and McCoy Canyon flows in the Sentinel Bluffs basalt at the eastern end of the gorge at Bingen, Washington (Wells et al., 1989).

The 30-m-high sea cliff at the north end of Crescent Beach exposes synsedimentary chevron-folded, rhythmic, thin to medium beds of turbidite sandstone and mudstone (lower Cannon Beach Member) (Niem and Van Atta, 1973; Fig. 27). Similar soft-sediment folds are exposed beneath the Ecola Point viewpoint (Fig. 22). The Saucesian foraminiferal assemblage from the mudstones indicates an outer neritic to upper bathyal depositional environment, possibly at depths of 150 to 500 m (Rau, in Niem and Van Atta, 1973). These tightly soft-sediment folded strata were intruded, enveloped, and steam-blasted by an invasive sill of Winter Water Basalt with many dike-like apophyses. This sill has scattered plagioclase phenocrysts, Winter Water geochemistry, and steep inclination (N6 on Fig. 24). It probably is also part of the Tillamook Head sill.

**Directions to Alternative Stop 3-3a (Haystack Rock)**

Return via the park road to the intersection of 5th and Fir Streets. Turn right (south) onto Fir Street and cross the bridge over Ecola Creek toward the town center of Cannon Beach. The original bridge was destroyed by the tsunami generated by the 1964 Alaska earthquake. Continue south to 3rd Street; turn right. Travel two blocks to Spruce Street. Turn left onto Spruce and then right onto 3rd Street. In one block, turn left onto Hemlock Street and travel 0.25 mi through the business area of the village of Cannon Beach. Cannon Beach is the southwesternmost point reached by members of the Lewis and Clark expedition. They came to this area on 8 January 1806, to trade for whale blubber and oil from the “Killamuck” tribe. Continue south on Hemlock Street. At the south end of the business district, Hemlock Street climbs up onto a marine terrace and then downhill. At 0.5 mi, turn right (west) onto W. Gower Street and park in the paved Haystack Rock parking area. Walk 75 m down W. Gower Street to Ecola Court and to the beach. Haystack Rock alternative Stop 3-3a can be viewed from here, if the weather is inclement or if time is short. However, if the beach is accessible, walk 0.5 km along the beach to the south side of Haystack Rock (viewed best at low tide).

**Alternative Stop 3-3a: Haystack Rock Beach Viewpoint**

45.88408° N, 123.96799° W

Haystack Rock is an erosional remnant of a small submarine eruptive center or complex of Frenchman Springs pillow lava and breccia on the middle Miocene deep seafloor (Figs. 22 and 28). The adjacent slender sea stacks (called The Needles) are also part of the bifurcating feeder peperite dikes and some breccias. The chemistry of this basalt corresponds to the Frenchman Springs Member of the Wanapum Basalt (Neel, 1976). The submarine pillow breccia has a paleomagnetic direction similar to the Basalt of Ginkgo elsewhere in the Coast Range (N7 on Fig. 24). It also contains characteristic abundant to scattered phenocrysts of plagioclase (up 1 cm long) which can be best examined in the basalt gravels surrounding Haystack Rock at low tide. The north–south–striking Astoria Formation directly underlying the submarine pillow lava and breccia is steeply upturned to the west (as much as 40°). These strata are deep-marine, foram-bearing, very thin-bedded mudstone, microcross-laminated sandy micaceous siltstone, and a 2-m-thick overlying arkosic sandstone (uppermost Cannon Beach Member). Feeder dikes and a pod-like irregular...
invasive sill bifurcate, splay, and brecciate upward through these deep-marine strata; some dikes extend through the contact and up into submarine pillow lavas and basaltic breccias (Fig. 28). A few near-vertical, 4 to 5 m, elongate, irregular pods of lighter gray, baked mudstone can also be seen in the pillow lava, breccia, and invasive dikes and were presumably entrained from the seafloor and incorporated into the overlying eruptive center. The basalt-sediment contact is visible at minus low tides but now lies within a protected national wildlife and seabird (e.g., Puffins) nesting area (no climbing on the rock). Shallow invasive sills and dikes of Ginkgo basalt mapped onland nearby by Smith (1975) and Niem and Niem (1985) (e.g., one with coastal Ginkgo paleomagnetic directions, N9 on Fig. 24) may be the feeder sources for these re-eruptive brecciated dikes, pod-like sills, and the overlying submarine pillow breccia lavas.

**Directions to Stop 3-4**

Leave the Haystack Rock parking lot. At the intersection of W. Gower Street and Hemlock Street, turn right (south) onto Hemlock Street. Follow Hemlock Street 2.1 mi past a road view west (no stopping) of Haystack Rock and through the village of Tolovana Park to the T-intersection of Hemlock Street with U.S. 101. Turn right (south) onto U.S. 101 and proceed south on U.S. 101 1.1 mi, passing two wide pullout viewpoints at Silver Point. Pull off to the right (west) at Arcadia Beach state wayside gravel parking area (restrooms) and walk 50 m down the beach trail to the beach and then 75 m north to Humbug Point Headland.

**Stop 3-4: Humbug Point Headland, Arcadia Beach State Wayside**

45.84335° N, 123.96104° W

The headland and elongate east-west sea arch of Lion Rock are composed of a 30-m-wide, upward bifurcating invasive dike of aphyric basalt with Ortley geochemistry and a steep easterly Ortley paleomagnetic direction (N10 on Fig. 24). This dark-gray to black dike with incorporated block of Astoria Formation (Fig. 29) displays subhorizontal columnar joints and brecciated (peperitic) borders of angular, light greenish-gray, clay-altered basalt fragments. The fragments are, in part, cemented by white sparry calcite and/or are locally laced with a spider web–like network of white sparry calcite veinlets. The well-indurated host Miocene Astoria Formation strata (Angora Peak Member sandstone) along the dike margins have been steam-fragmented for several meters into a chaotic mixture of angular pebble–to boulder-size blocks of bleached white to light yellow-gray, baked, micaceous arkosic sandstone. The laminated, fine-grained sandstone blocks are suspended in a homogenized matrix of coarse lithic arkosic sand and rounded polymict pebbles of chert, quartzite, pumice, and intermediate volcanics. Locally, thick pods of yellow, coarse-grained sandstone along the dike margins are homogenized or fluidized.

Looking south 2 km along the beach from Humbug Point is the next headland of Hug Point. This headland is composed of cross-bedded and laminated deltaic micaceous arkosic sandstone of the Miocene Astoria Formation (Angora Peak Member) in Hug Point State Park (accessible at low tide) (Niem, 1975; Niem et al., 1973). The 600-m-thick, coal-bearing, micaceous arkosic to volcanioclastic Angora Peak Member and the overlying 200- to >1000-m-thick Cannon Beach Member contain scattered channelized beds of pumice, andesite, and other extrabasinal pebbles, cobbles, and sand (e.g., sedimentary quartzite, granite, schist; Cressy, 1974; Smith, 1975). These two members of the Astoria Formation are interpreted to be an interfingering wave-dominated deltaic (or river mouth) and deep-marine delta slope forearc deposit of the ancestral early Miocene Columbia River that drained the Western Cascade arc and the metamorphic and granitic terranes of eastern Oregon-Washington.

In Hug Point State Park and in the yellow sea cliff immediately north of the Hug Point headland, the Angora Peak sandstone is intruded by Winter Water sills and peperite dikes that have soft-sediment–deformed the sandstone into broad ¼ km amplitude antilines and synclines and near-vertical contorted strata. In addition, a 10-m-wide zone of vertical sandstone beds and chaotic sedimentary breccias lie in narrow fault-controlled(? zones or paleoslump head scarp on the eastern edge of Hug Point (Niem, 1975; Niem et al., 1994) (Fig. 22). The association of numerous, small invasive bodies with these locally deformed nearly coeval strata (e.g., at Ecola Park [Stop 3-3], Hug Point, and Humbug Point [Stop 3-4]) suggests that pneumatic steam blasting and invasion from larger and thicker inflated invasive sills below were responsible for this uplift, plastic deformation, and soft-sediment slumping of these semiconsolidated, water-saturated sediments at shallow depth (Fig. 22) (Niem, 1975).

Large positive aeromagnetic anomalies of the thick sills exposed at Neahkahnie Mountain, Cape Falcon, and Tillamook Head and underlying the coastal area from Hug Point to Arch Cape extend offshore as mapped by Finn et al. (1984) and R.J. Blakely (2009, personal commun.). The map patterns suggest these thick invasive mega-sills were once more continuous prior to Coast Range uplift and faulting.

**Directions to Stop 3-5 and Stop 3-5a**

Return to vehicles. Turn right (south) onto U.S. 101 and drive south 1.6 mi, passing the entrance to Hug Point State Park and roadcut exposures of Angora Peak sandstone. After crossing a small bridge, turn sharply left (east) into a logging road entrance with a locked timber company gate. This logging road is called the Hug Point Road. Note: round trip driving time to Stops 3-5 and 3-5a is 40 min to 2 h, respectively, on gravel logging roads. If the weather is inclement, drive only as far as Stop 3-5.

Logging company permission and a gate key are necessary for both stops. In addition, permission to access Onion Peak (Stop 3-5a) is required from the Nature Conservancy.

Drive 0.75 mi uphill on Hug Point Road, passing two logging spur roads on the left and exposures of Angora Peak sandstone to a small quarry that exposes a 4-m-thick, columnar jointed (vertical), low-MgO Ni Grande Ronde Basalt sill into well-bedded, baked white Angora Peak sandstone that dips southeast. Continue east uphill another 1.1 mi past a low-MgO Grande Ronde Basalt sill on the left and passing two spur roads to the T-intersection at the ridge line with the Onion Peak Road. Turn right (south) onto the Onion Peak Road. An east-west fault near this intersection juxtaposes Cannon Beach mudstone and an invasive sill against downdropped Grande Ronde submarine pillow breccia (Niem and Niem, 1985). Continue ~0.75 mi past roadside cliffs of low-MgO Grande Ronde pillow breccia, some mudstone interbeds, and landslide colluvium to a four-way intersection (first switchback). Turn sharply left (nearly 180°) and drive north uphill for 0.5 mi through forest-covered landslide zones, bearing right past two spur roads on the left. At the second switchback just beyond a three-way intersection (i.e., two spur roads on the left), turn sharply right (180°) uphill to follow the main road. Pull over at the first pillow breccia outcrop on the left.

**Stop 3-5: Base of Submarine Winter Water Basalt, Onion Peak Road**

45.8100° N, 123.8946° W

Logging road cliff exposures at the base of the 470-m-thick sequence of isolated pillow breccias and pillow lavas of high-TiO₂ variant of Winter Water basalt with shallow inclination (Figs. 24 and 25). The basal sequence exposed here overlies a thin (<2 m) Winter Water invasive sill and deep-marine mudstone in a borrow pit near the switchback. Starting at the invasive sill and laminated micaceous mudstone, walk uphill across the 30-m-wide covered contact and into the weathered basal Winter Water isolated pillow breccia and overlying 10-m-thick closely packed pillow lava (1- to 1.5-m-diameter pillows). Overlying the breccia are 12 m of isolated pillow lava with a partial longitudinal cross section of a filled lava tube or mega-pillow (filled inflated flow lobe?) oriented approximately S40W. Winter Water pillow lava consists of poorly sorted, 30 cm to 1 m diameter pillows and pillow fragments with black, partially altered glassy (sideromelane) rinds and radial joints. Altered pillow fragments in the isolated pillow breccia are set in a finer yellowish-orange palagonite groundmass, composed of comminuted, angular sand- to fine pebble-size fragments of palagonite, brown to black tachylyte, and sideromelane cemented by dark-green nontronite and celadonite (clay minerals) and/or white bladed zeolite (clinoptilolite and heulandite) and calcite. The Winter Water basalt is aphyric to microphyric and contains scattered small plagioclase phenocrysts and spoke-shaped glomerocrysts (Reidel et al., 1989a).

The Onion Peak area and nearby peaks (i.e., Sugarloaf Mountain, Angora Peak, Kidders Butte, and Rock Mountain) include 45 km² of resistant submarine pillow lava and breccia...
of low-MgO Grande Ronde Basalt (mainly Winter Water), 400–600 m thick, and associated underlying Winter Water mega-sills (e.g., Tillamook Head [Stop 3-3], Rippet Quarry [Stop 3-2], Neahkahnie Mountain) (Fig. 21) (Cressy, 1974; Smith, 1975; Neel, 1976; Niem and Niem, 1985). Shallow inclinations and NNW declination typical of the Grande Ronde Basalt (Winter Water unit) and the geochemistry indicate that the high-TiO₂ variant of the Winter Water is exposed along this traverse from the base of the 470 m submarine breccia pile (Stop 3-5) to near the top of Onion Peak (Stop 3-5a) (N14, N13, and N12 on Figs. 24 and 25). The association of deep-marine turbidite sandstone and mudstone beds (Astoria Formation, Cannon Beach Member) and this thick nonvesicular breccia sequence with south-oriented foreset bedded hyaloclastites and inclined pillows and filled lava tubes indicates a source to the northeast. In addition, these units, together, suggest emplacement in narrow tributary channels(?) of a submarine canyon head cut into the Miocene shelf and upper slope (Figs. 21 and 22). Post-late Miocene faulting and extensive erosion have resulted in isolated thick piles of pillow breccia. This location also provides an excellent photo opportunity and view of Tillamook Head (Winter Water sill), Haystack Rock (Ginkgo re-eruptive center), and the Pacific Ocean.

In good weather and if time permits (allow an additional 2 h), proceed 3.3 mi uphill on Onion Peak Road to Onion Peak (Stop 3-5a). Otherwise, return to U.S. 101 and follow the directions to Stop 3-6 (Humbug Mountain) that follow the description of Stop 3-5a.

Directions to Stop 3-5a

Continue driving south uphill on Onion Peak Road. At 0.8 mi, after passing a logging spur road on the left, the road turns abruptly right (west) and flattens out. In another 0.1 mi, a borrow pit exposes breccia, and large boulders of pillow breccia line the road. This pillow breccia weathers to an oxidized reddish-orange color, typical of weathered Winter Water submarine flows in the Coast Range (Fig. 30). This section of the road provides a scenic view of the 400-m-deep, incised valley of Arch Cape Creek and the steep, forested slopes of Angora Peak (summit elevation 817 m). Angora Peak is Winter Water breccia with a 3 m auto-clastic Winter Water dike near the top of the peak (Cressy, 1974; Niem and Niem, 1985). In another 1.2 mi, Onion Peak Road turns abruptly left (north), providing scenic views of the barren, rugged, vertically jointed, 200-m-high cliff of Onion Peak (Fig. 31). Continue an additional 0.7 mi, passing a decommissioned Y-intersection (spur road on the left), to the cul-de-sac at the end of Onion Peak Road. Park and proceed on foot 400 m along a curving overgrown logging road uphill on the east side of the cul-de-sac to an old logging landing near the base of the barren cliff face. (Note: this old road and Onion Peak are property of the Nature Conservancy; permission to enter is required.)

Stop 3-5a: Walking Traverse near Top of Onion Peak
45.80698° N, 123.90575° W

Along the 1.6 km walking traverse to the logging landing at the base of Onion Peak cliff face, note the views to the northwest of steep, broad “U-shaped valleys,” “cirque-like” valley heads, and narrow, barren “arête-like” ridges reminiscent of glacial features. Similar barren, steep cliffs, U-shaped valleys, and amphitheater or cirque-like landforms occur in thick sequences of basalt flows on Hawaiian islands (Macdonald and Abbott, 1970). Such features in Hawaii are a product of tropical weathering, groundwater sapping (Kochel and Piper, 1986), debris flows, rock avalanches, and other mass wasting phenomena. Many of these glacial-like features occur dominantly on the shaded northwest and northeast flanks of these highest mountains and peaks of thick Grande Ronde submarine breccia (e.g., Onion Peak, Angora Peak, Humbug Mountain, and Saddle Mountain). On these shaded slopes, annual Pleistocene

Figure 30. Weathered reddish-orange submarine Winter Water, poorly sorted pillow palagonite breccia, borrow pit boulders along Onion Peak Road between Stops 3-5 and 3-5a. White spots are lichens.

Figure 31. Stop 3-5a: A north view of the vertically jointed, 200 m, cliff face of Onion Peak. The barren cliffs expose submarine Winter Water pillow breccia with subhorizontal to southerly inclined filled lava tubes (dark shaded recesses labeled Lt). South- to southeast-dipping foreset-bedded coarse- and fine-grained hyaloclastites (Hc) in upper half of peak are hard to see in photo. Tall standing dead white tree trunk at bottom of 1984 photo is 30 m long.
snow fields may have been thick and possibly semi-permanent; frost wedging, expansion crack exfoliation, and topping along vertical joints may have influenced development of the distinctive round top and steep, barren, cliff topography of Onion Peak and Saddle Mountain, for example. A remnant of a once more widespread Pleistocene alpine flora grows on the summit of Onion Peak and is protected by the Nature Conservancy. Today, surficial slides of thin, water-saturated soils, rock slides, and debris slides occur during the wet winter and spring months down landslide chutes, continuously exposing basaltic breccia bedrock. Debris flows rush down the steep slopes and spread out over the broader valley floors underlain by mudstone, contributing to the U-shaped valley geometry. More recent underfit streams are incised below the U-shaped valley floors creating narrower V-shaped valleys.

From the logging landing viewpoint, the 100 m cliff face of Onion Peak exposes isolated pillow palagonite breccia complexes, filled lava tubes, and bedded, fine and coarse, blocky hyalo-clastites (up to 50 m thick) (Fig. 31). The 10- to 30-m-diameter filled tubes or mega-pillows (or filled inflated submarine lava lobes?) form cave-like hollows within the breccia on the cliff face. The filled tubes and forest bedded hyalo-clastites have south and southeasterly paleoflow orientations. A roadcut at the logging landing displays a 10-m-diameter filled lava tube with hackly to entablature-like radial jointing, as well as the surrounding isolated pillow breccias. Paleomagnetic inclinations, scattered plagioclase phenocrysts, and geochemistry indicate this is the high-Ti variant of the Winter Water basalt (Fig. 25 and N12 on Fig. 24).

The scenic view from the logging landing to the south and southeast is the floodplain of the North Fork of the Nehalem River and surrounding low forested hills underlain by Eocene and Oligocene deep-marine sedimentary rocks (Fig. 21). The forested flat-topped, mesa-like hills and narrow elongate higher ridges on both sides of the Nehalem River valley are more erosion-resistant invasive sills and dikes of Winter Water, Ortley, and N Downey Gulch (or a high-TiO2 Winter Water variant), and Pomona and Huntzinger (?) flows of the Saddle Mountains Basalt (Rarey et al., 1984) (Fig. 24B). These basal unit identifications are based upon geochemistry, paleomagnetic directions, petrography, and lithologic character. Middle Eocene tholeiitic to alkalic subaerial to submarine lavas of the 3000-m-thick, high-TiO2, high-FeO Tillamook Volcanics (40–43 Ma) form the rugged, more distant, forested highlands and the core of the broad northern Coast Range anticline (Fig. 21; Niem and Van Atta, 1973; Niem et al., 1994; Wells et al., 1995). The Tillamook Volcanics have been interpreted as an oceanic island developed over a hot spot (Duncan, 1982; Wells et al., 1984; Niem et al., 1994). Directly to the east are forested hills of middle Eocene Cole Mountain basalt that overlies the Tillamook Volcanics (Fig. 21). Thick, pillows, invasive sills and dikes of the Cole Mountain basalt have a low-TiO2, low-FeO alkalic chemistry identical to the 36–38 Ma Goble Volcanics of the Western Cascade arc (exposed near the town of Goble; Evarts, 2002). The Cole Mountain Basalt is postulated to be invasive flows of the Goble Volcanics from the early Cascade arc into the forearc (Fig. 21) (Rarey, 1985; Niem et al., 1994).

Two major oblique-slip, post-CRBG faults (e.g., God’s Valley fault and “Helloff fault” on Fig. 21) uplift an east-west horst-like block of Tillamook Volcanics against Oligocene–Eocene sedimentary rocks. These two faults extend farther west offsetting and uplifting blocks of the Ortley invasive mega-sill at Cape Falcon (Wells et al., 1984) and a 300-m-thick Winter Water diabase sill at Neahkanie Mountain against Astoria Formation (Angora Peak Member) deltaic strata, Oligocene Smuggler Cove Formation, and Winter Water submarine breccias at Angora Peak and Rock Mountain (Fig. 21). Anticlinal fold axes in the deltaic sandstone trend 30° to the two oblique-slip fault traces and shear (gouge) zones display subhorizontal slickensides in the basalt sills, characteristic of a wrench-style fault pattern (Cressy, 1974; Niem and Niem, 1985; Rarey, 1985; Mumford, 1988; Niem et al., 1994).

Directions to Stop 3-6
Retrace the Onion Peak and Hug Point logging roads from Onion Peak back to U.S. 101. At 1.2 mi downhill from Stop 3-5a, sets of 30-m-long, moss-covered, curving expansion crack sheets parallel the slope on the right side of the road. At the intersection of Hug Point Road with U.S. 101, turn right onto U.S. 101 and travel 8.8 mi north, past the Cannon Beach exits, to the intersection of U.S. 101 and U.S. 26. Turn right (east) onto U.S. 26 toward Portland. Continue 9.4 mi east on U.S. 26 to the junction with OR 53. The route passes Klootchy Creek County Park (2.5 mi east of U.S. 101) and crosses bridges over the Necanicum River, Mail Creek, and Lindsley Creek. Along the route, low-MgO N2 Grande Ronde sills form the flat-topped hills on both sides of the highway (note the quarry exposure of a columnar jointed basalt dike in the ODOT maintenance station on the left).

Pass the U.S. 26/OR 53 intersection, continue east on U.S. 26. At 0.7 mi, pass the exit to Saddle Mountain State Park and continue uphill 4.1 mi. At 0.3 mi west of the crest of the hill at the yellow highway sign that reads “Right lane ends,” turn sharply left (northeast) across three lanes of U.S. 26 onto the gravel Humbug logging road. This logging road is 0.3 mi west of the sign “David Douglas summit” on U.S. 26 on the crest of the hill. Drive 0.2 mi to the white locked logging road gate.

Directions on Humbug Mountain Mainline Logging Road from the White Locked Gate to Stop 3-6
Permission to enter and key to the locked gate are required. Follow the Humbug Mountain mainline logging road 0.5 mi to a Y-intersection. Bear left (west) and drive uphill 0.8 mi winding past a 10-m-high quarry in R, Wapshilla Ridge irregular invasive sills with a pod of light-gray (baked) to dark-gray mudstone and very fine-grained laminated arkosic sandstone of the Cannon Beach Member (Astoria Formation). Continue uphill passing through the contact with the overlying Wapshilla Ridge pillow breccia on the right. At the Y-intersection, bear right (north) and at 1.6 mi stop just before the triangular road intersection. Park on the wide grassy pullout area on the right. Walk uphill (round-trip traverse takes 2 h) on Humbug Mountain road to Stops 3-6a, 3-6b, and 3-6c. A four-wheel drive vehicle can negotiate the traverse in ~1 h round trip.
Directions to Stop 3-6a
Start at the triangular parking area. Walk uphill 100 m past the vertical contact of yellow-gray Astoria micaceous arkosic sandstones with basal Wapshilla Ridge pillow breccia on the Humbug logging road. Continue walking uphill 150 m on this steep portion of logging road to a narrow logging landing (Stop 3-6a) on near-vertical isolated pillow palagonite breccia with dark glassy fragments and pillow rims and some filled lava tubes. This thick basal breccia is abundantly plagioclase microphyric and has a high-TiO₂ chemistry and has typical reversed Wapshilla Ridge paleomagnetic direction (Fig. 25 and N18 on Fig. 24).

Stop 3-6a: On a clear day, Mount Saint Helens is visible to the east, Mount Rainier to the northeast, and the Eocene Tillamook Highlands (oceanic volcanic rocks) and Mt. Rainier to the northeast, and the Eocene Tillamook Highlands (oceanic volcanic rocks) and Cole Mountain basin to the southeast (Fig. 21). Wickiup Mountain and Nicolai Mountain (lava deltas and subaerial flows of Grande Ronde and Frenchman Springs basalts) rise above the low hills to the northeast. Also to the east and northeast is a set of three narrow parallel ridges, 10 to 25 km long, of invasive dikes (Northrup Creek, Beneke, and Fishhawk Falls dikes, Fig. 21). These 10- to 90-m-wide invasive dikes are composed of low-MgO Grande Ronde Basalt chemical types with normal and reversed polarities (Northrup Creek Winter Water dike, Olbinski, 1983; R₂ Wapshilla Ridge Beneke dike, and R₂ Wapshilla Ridge Fishhawk Falls dikes, Nelson, 1985) (Fig. 21). Pfaff and Beeson (1989) hypothesized from gravity profiles across the Beneke and Fishhawk Falls dikes that these “intrusions” are rootless and extend only ~30 m below the surface. However, seismic reflection profiles (Niem and Niem, 1985; Niem et al., 1990) and geochemistry of basalt cuttings from nearby exploration wells indicate invasive sills of Ortle, Grouse Creek, Wapshilla Ridge, Ginkgo and Sand Hollow, Sentinel Bluffs, and other CRBG units occur at depths 300–2200 m below these three dikes and other invasive sills and dikes in Clatsop County (Martin et al., in Niem and Niem, 1985; Fig. 21).

The set of three parallel invasive dikes could have been injected upward into Eocene, Oligocene, and Miocene strata under invasive lava head from these deeper invasive sills along preexisting NE-SW fracture sets (faults or joints) or possibly up along NE-SW headscarp grabens of incipient mega-translational landslide blocks sliding northward into the Miocene Astoria submarine canyon or the Astoria Basin center (Fig. 22). Alternatively, based upon tracing part of the Beneke Wapshilla Ridge dike to within 150 m of Wapshilla Ridge lava delta and pillow basalt with the same paleomagnetic declination and inclination, the three dikes may have been injected obliquely, laterally, and downward from these pillow lavas and lava tubes in the Nicolai Mountain–Porter Ridge area (Fig. 21; Nelson, 1985; Goalen, 1988). Injection may have been accomplished by pneumatic steam blasting and invasive lava fracturing or by reverse diapirism loading of denser lava on soft, wet, seafloor sediment (Fig. 22). Invasive lava may have flowed along preexisting down-to-the-basin faults or fractures (tectonic joints) or pull-away headscarp grabens (Fig. 22).

These three vertical dikes and other invasive dikes also act as piercing points, showing post-CRBG displacement by NW-SE–trending, right-lateral, oblique-slip faults and NE-SW–trending, left-lateral, oblique-slip, conjugate faults (Fig. 21). Detailed field mapping and proton precession magnetometer traverses indicate displacement ranges from a few meters to tens and even hundreds of meters (Olbinski, 1983; Nelson, 1985; Niem and Niem, 1985; Goalen, 1988). Shear zones along faults in the basalt quarries consist of gouge, a few cm to 1 m wide, with subhorizontal slickensides in the basalt (Nelson, 1985). Two paleomagnetic sites, separated by an oblique-slip fault in the Beneke quarry (Fig. 21), showed 11° of clockwise rotation of the paleomagnetic means and no overlap of the α₉₅, suggesting small block tectonic rotation (Nelson, 1985; DN1 and DN2 on Fig. 24). The pattern of conjugate faults and tectonic joints reflects motion on two major oblique-slip faults and wrench-slip fault zones. One of these major zones, southeast of this viewpoint, is the Mount Angel–Gales Creek fault zone, which trends through the rugged northern Tillamook highlands (Wells et al., 1995) and Cole Mountain basalt and may truncate the southern end of the Beneke dike (Fig. 21). This wrench-style fault zone extends to Seaside through the right-lateral, NW-trending Necnican fault via splays and east-west oblique-slip, high-angle faults and fault stepovers (e.g., Quartz Creek fault and Gods Valley fault, Fig. 21). The other major oblique-slip fault, northeast of this viewpoint, is the right-lateral Clatskanie-Scappoose fault system, which trends through the forested northeastern flank of the northern Oregon Coast Range. This fault subparallels and is a stepover of the Portland Hills fault (off Fig. 21; Niem and Niem, 2002).

Directions to Stop 3-6b
Continue walking or driving up the Humbug Mountain logging road 500 m to a 5-m-high roadcut exposure of the sedimentary sequence that overlies the thick R₂ Wapshilla Ridge breccia. This roadcut is part of a thick interbedded, largely Miocene deep-marine foraminiferal mudstone (Penoyer, 1977), that caps much of Humbug Mountain (Niem and Niem, 1985). The sedimentary sequence in the cut includes Miocene deep-marine micaceous mudstone, scattered thin-to-very thick-bedded, parallel laminated to convolute bedded, fine-grained, micaceous arkosic turbidite sandstone, and a very poorly sorted channelized debris flow deposit of rounded microphyric Wapshilla Ridge boulders to cobbles (some vesicular; Fig. 25) in framework- to mudstone matrix-support. The basalt conglomerate and deep-marine mudstone are disrupted by and partly incorporated into a 3- to 4-m-thick Grande Ronde peperite dike.

Directions to Stop 3-6c
Continue up the road 250 m and pass a 10-m-high roadcut through another Grande Ronde invasive dike and baked dark-gray mudstone. Then proceed another 300 m up the road through...
the mudstone overlain by a 30-m-thick Grande Ronde sill to the quarry at the top of Humbug Mountain.

**Stop 3-6c:** The Humbug Mountain quarry contains the upper 15 m of the 30-m-thick invasive aphyric sill of Ortley or Grouse Creek chemistry (Fig. 25 and N17 on Fig. 24). The invasive sill is medium gray, aphanitic to finely crystalline, and vertically polygonal columnar jointed. It caps the eastern part of Humbug Mountain and forms the high point (elevation 747 m) for the nearby microwave relay tower.

Forty km east of Humbug Mountain, near Pittsburg and Mist, Oregon, on the east flank of the northern Oregon Coast Range, a subaerial stratigraphic sequence is correlative to the deep-marine sequence on Humbug Mountain. There, a basal subaerial Wapshilla Ridge microphyric vesicular flow is overlain by a fluvial, framework-supported, rounded cobble-boulder conglomerate of Wapshilla Ridge basalt clasts and arkosic sandstone. That fluvial conglomerate is, in turn, overlain by subaerial R, Grouse Creek lava and N, Ortley flows (Eriksson, 2002). These two similar stratigraphic sequences support the emplacement and paleogeographic model of correlative subaerial CRBG flow units and fluvial basalt gravels and arkosic sands entering an ancestral Columbia River mouth, spreading across a narrow shelf and partly filling and invading the upper submarine canyon head with thick sequences of submarine pillow lavas and breccias and submarine debris flow conglomerate and micaceous arkosic turbidite sandstone (Fig. 22).

The scenic view looking north from the Humbug logging road quarry is of Saddle Mountain (Figs. 32 and 21), which consists of 600 m of monolithologic submarine pillow breccia of N, high-MgO Grande Ronde, Sentinel Bluffs Member. West of Saddle Mountain, two Frenchman Springs (Sand Hollow) diabase sills form the flat-topped, forested ridges of Eels Ridge and Green Mountain (Peterson, 1984). In the far distance beyond Astoria and the Columbia River are Bear River Ridge and Radar Ridge, Ortley and Pomona diabase sills, respectively, visited on Day 2 at Stops 2-5, 2-6, and 2-7.

An autoinvasive dike, viewed from this locality, forms a high, erosion-resistant vertical wall within the Sentinel Bluffs breccias that comprise the western end of Saddle Mountain (Fig. 21 and N19 on Fig. 24). This and two other autoinvasive dikes parallel NE-trending vertical tectonic joints (Fig. 32). The high-MgO content and TiO\(_2\) content of the Saddle Mountain dike and enclosing breccia are typical of the McCoy Canyon Member chemical type of Reidel (2005) (Fig. 25). They are also chemically correlative to lava delta and subaerial flows at Stop 2-1 near Longview, Washington. The nearest subaerial Sentinel Bluffs flows in NW Oregon are exposed in the Nicolai Mountain escarpment located 27 km to the NNE. Along U.S. 30, which crosses the escarpment, two McCoy Canyon subaerial flows are separated by thin fluvial, crossbedded basaltic-arkosic sandstone (Fig. 21). These subaerial flows prograded west-southwestward onto a narrow shallow shelf as lava deltas that locally contain marine echinoid spines and gastropod shell hash in the interstices between pillows at Gnat Creek (Murphy, 1981). They then apparently flowed down a submarine canyon system cut across the shelf of Astoria Formation and underlying Oligocene–Eocene strata (Fig. 22). There is a locus of N, Sentinel Bluffs thick invasive sills and joint-controlled dikes in the area around Saddle Mountain and numerous R, Wapshilla Ridge invasive dikes and sills around and partly beneath Humbug Mountain, some of which could have acted as feeder invasive flows to form these possibly re-erupted(?) thick submarine pillow breccia piles in a deep-marine setting (Fig. 22).

Optional walk 80 m uphill from the quarry to the microwave relay tower. Views to the southwest are of Kidders Butte and Sugarloaf Mountain (Fig. 21). These peaks are underlain by 200–400 m of Winter Water breccias, pillow lavas, minor interbeds of deep-marine mudstone, and a rounded basalt cobble-boulder conglomerate interbed that overlies thick invasive Winter Water sills. Also the nearby unnamed forested mountains to the west are Wapshilla Ridge breccia locally overlain by a thick interbed of deep-marine mudstone, lithic arkosic sandstone, and debris flow channel conglomerate, similar to the basalt and sedimentary interbed stratigraphy on Humbug Mountain.

From the top of Humbug Mountain, walk downhill to the vehicles. Retrace Humbug mainline logging road to U.S. 26. Turn left (east) onto U.S. 26 and drive 60 mi through the northern Oregon Coast Range and Tualatin Valley to Portland.

**ACKNOWLEDGMENTS**

Mapping of the CRBG has been a collaborative effort among the USGS, Terry Tolan of GSI Water Solutions, and the late Marv Beeson of Portland State University, Steve Reidel and Rick Conrey of Washington State University, Ian Madin of the Oregon Department of Geology and Mineral Industries, Robert

![Figure 32. Oblique aerial view to NW of Saddle Mountain, which is composed of 600 m of high-MgO N, Sentinel Bluffs (McCoy Canyon) submarine breccia (Tgsb-mc) that overlies an unconformity on Miocene Astoria Formation deep-marine mudstone (Tac) in the lower forested and clear-cut area. Autoinvasive dikes form vertical walls in the breccia, which also displays prominent tectonic joints. Saddle Mountain is the highest elevation in the northern Oregon Coast Range. Green Mountain is a thick, invasive sill of Sand Hollow basalt.](image-url)
REFERENCES CITED


Jarboe, N.A., Coe, R.S., Renne, P.R., and Glen, J.M., 2006, *Age* of the early Columbia River Basalt Group: Determining the Steens Moun-