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Cataclysms and controversy—Aspects of the geomorphology of the Columbia River Gorge

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ABSTRACT

Landslides and floods of lava and water tremendously affected the Columbia River during its long history of transecting the Cascade Volcanic Arc. This field trip touches on aspects of the resulting geology of the scenic Columbia River Gorge, including the river-blocking Bonneville landslide of ~550 years ago and the great late-Pleistocene Missoula floods. Not only did these events create great landscapes, but they inspired great geologists. Mid-nineteenth century observations of the Columbia River and Pacific Northwest by James Dwight Dana and John Strong Newberry helped germinate the "school of fluvial" erosion later expanded upon by the southwestern United States topographic and geologic surveys. Later work on features related to the Missoula floods framed the career of J Harlen Bretz in one of the great geologic controversies of the twentieth century.

INTRODUCTION

This guide accompanies the "Kirk Bryan" field trip for the October 2009 Annual Meeting of the Geological Society of America convened in Portland, Oregon. This one-day field trip examines geomorphic features related to the remarkable Neogene and Quaternary history of lava flows, landslides, and cataclysmic flooding in the Columbia River Gorge of Oregon and Washington (Fig. 1). Along the way, the trip passes through landscapes endowed with a rich history of geologic inquiry and controversy, some of which nourished the very foundations of the "American School" of geomorphology, exemplified by Kirk Bryan himself.

This trip focuses on two areas: (1) the rainy heart of the Columbia River Gorge, where Cascade Range uplift together with Columbia River incision have conspired to create great landslides, including the river-blocking Bonneville landslide of ~550 years ago; and (2) the much drier east end of the gorge, where marks of the Missoula Floods have inspired inquiry and debate since the early twentieth century.

Some of the material in this guide derives from our own published work, including O'Connor and Waitt (1995), Benito (1997), Benito and O'Connor (2003), Butler and O'Connor (2004), and O'Connor (2004); but much of it relies on a long list of naturalists and geologists who have traversed this landscape since the 1805–1806 exploration of Lewis and Clark. The guide is structured to provide a general background of the geography and geology of the river corridor, spiced with a bit of local "roots of geomorphology." This introductory section is then followed by brief overviews of landslides in the Columbia River Gorge and the Missoula Floods—the two primary topics of the trip.

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We then describe the trip itself, with brief information on some of the sights en route and more detailed discussion of the stops themselves. No actual road log is presented, but stop locations should be clear from the provided map figures, coordinates, and the route description.

Physiography and Geology of the Columbia River Gorge

The Columbia River Gorge, extending from the Deschutes River confluence west to the Portland basin, is Columbia River's long-held path through the active volcanic arc of the Cascade Range. The gorge exists because of the great erosive power of the Columbia River, which drains 660,480 km^2 of western North America, flowing 2000 km from its headwaters at Columbia Lake in southeastern British Columbia, Canada, to its confluence with the northeast Pacific Ocean near Astoria, Oregon. In terms of drainage area, the Columbia River is the 39th largest river basin in the world, but ranks higher with respect to mean flow, mean elevation, and slope (Vörösmarty et al., 2000). The basin drains several physiographic regions, including the Middle and Northern Rocky Mountains, Columbia Plateau, Cascade Range, and Pacific Border (Fenneman, 1931). Politically, the basin includes parts of British Columbia, Canada, most of Idaho, large parts of Oregon and Washington, and small areas of Montana, Wyoming, Utah, and Nevada.

At low flow, the river is tidally affected 235 km upstream to Bonneville Dam near our first stop (at the historical head of tide). Upstream, the river has been transformed into a series of almost continuous lakes by U.S. Army Corps of Engineers dams. On today's trip, we will pass Bonneville Dam (completed 1937), The Dalles Dam (1957), and John Day Dam (1971), in stepwise manner pooling the river from near sea level to 84 m (276 ft) above sea level (asl). With a mean annual river flow of ~5400 m^3/s, as measured since 1879 at The Dalles, these dams provide hydropower generating capacity totaling 5120 megawatts. Prior to flow regulation, annual peak flows almost always resulted from snowmelt in the interior subbasin, attaining the highest known discharge of 35,100 m^3/s on 7 June 1894 at The Dalles.

A major river draining the interior western North America has passed through the Cascade Range since the early Miocene, making this one of the very few (and certainly the largest) world rivers draining toward an active convergent margin and bisecting a volcanic arc. This atypical geologic environment has led to many dynamic interactions along the lower river corridor. Voluminous lava flows of the Columbia River Basalt Group (CRBG) issued from vents in northeastern Oregon and adjacent Washington and Idaho, mostly between 17 and 12 Ma, blanketing vast plains of eastern Oregon and Washington, and displacing the Columbia River west against the Washington Cascade Range. Several of the basalt flows found their way to the Pacific Ocean through paleovalleys cut through the Cascade Range (Beeson et al., 1989). Within the Columbia River Gorge and to the east, valley walls and, in places, the channel itself, are formed in as much as 1200 m of this lava. The CRBG is locally overlain by Miocene to Quaternary paleo-Columbia River gravel (Troutdale and Alkali Canyon formations), volcaniclastic deposits shed off the Cascade Range (Dalles Formation), and young calc-alkaline lavas and volcaniclastic detritus associated with the modern volcanic arc. Quaternary loess caps most uplands, except where removed by gullies, landslides, the Missoula floods, or covered by their deposits. Quaternary arc volcanism has emplaced lava flows (and cones) along the river corridor as well as directly into the valley bottom.

The central axis of the Cascade Range has risen 700–1000 m during the past 3 m.y. (Tolan and Beeson, 1984; Beeson and Tolan, 1990), approximately matched by incision of the Columbia River. At the eastern end of the gorge, the CRBG has been uplifted less (Fig. 2) but is nevertheless deformed by a series of east-west trending folds and high-angle reverse faults that define many of the broad basins and narrow constrictions the river now flows through.

Early Geologists and Geomorphologists

First motivated by a mix of territorial consolidation, curiosity and new commercial opportunities, European exploration began early in the nineteenth century. The first written records pertaining to the geology and geomorphology were the astute observations in the journals of Lewis and Clark, followed by James Dwight Dana (1841), John Strong Newberry (1855), and Thomas Condon (1850s). Further exploration included brief forays in the late nineteenth century by Clarence King, Samuel Emmons, Grove Karl Gilbert, Clarence Dutton, and Joseph Silas Diller. Details of some early findings and observations will be described in conjunction with the stop descriptions, but Dana and Newberry deserve special mention. As members of the Wilkes

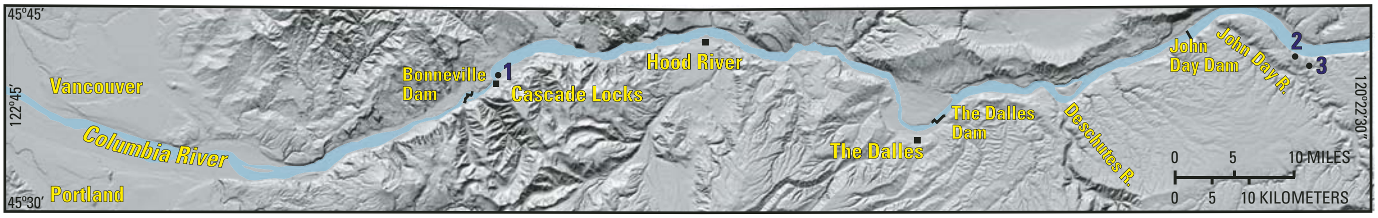

Figure 1. Shaded relief map showing Columbia River Gorge and numbered fieldtrip stop locations. From 10 m U.S. Geological Survey digital elevation data.

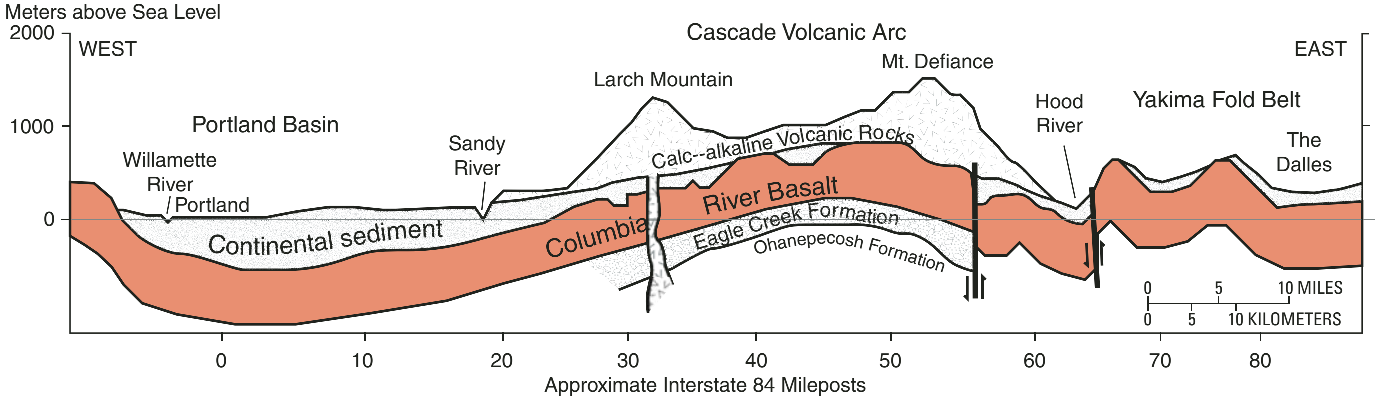

Figure 2. Schematic geologic cross section for south of the Columbia River corridor through the Portland Basin and Columbia River Gorge. Horizontal scale approximate. After Allen (1984, p. 78).

Expedition (Dana) and Pacific Railroad Surveys (Newberry), these two geologists developed tremendous insights regarding the geology and geomorphology of the Pacific Northwest, clearly articulating evidence for concepts such as climate change, eustatic sea-level change, volcanic arcs, fluvial base level, and antecedent and consequent rivers. These observations and insights, and their later influential positions in the emerging American geological community (Dana at Yale; Newberry at Columbia University and as mentor to both G.K. Gilbert and I.C. Russell), almost certainly inspired the fuller and more widely noted development of these concepts with the geological and topographic surveys of the American southwest. As Steven J. Pyne (1980, p. 30) noted in his biography of Gilbert: "Together the mineralogist and the paleontologist founded what, by the end of the century, was clearly recognized as a distinctly American school of geology, one of whose central tenets was the power of fluvial erosion." Clear from reading Dana's (1849) and Newberry's (1856) survey reports is that this "school of fluvial erosion" derived in large part from their observations in the Pacific Northwest.

LANDSLIDES IN THE COLUMBIA RIVER GORGE

First noted by William Clark in 1805, landslides are a prominent feature of the Columbia River Gorge. Between the Sandy River confluence and Hood River, landslides and landslide processes in the western gorge have been long studied for dam location and transportation alignment analyses (Waters, 1973; Palmer, 1977; Sager, 1989; Schuster and Pringle, 2002). Within this reach, mapped landslides cover ~130 km^2, including the large Washougal, Skamania, and Cascade Landslide complexes (Fig. 3; Palmer, 1977).

These large landslide complexes, commonly involving multiple mass movements and encompassing up to 50 km^2, are chiefly on the north side of the river and have resulted in deep-seated southward sliding of diverse rock types into the valley. According to Waters (1973, p. 147), the cause for most of the landslides is a thick clay saprolite developed on zeolitized rocks of the Ohanapecosh Formation beneath the CRBG and underlying Eagle Creek Formation (Fig. 2). Rainwater, penetrating the

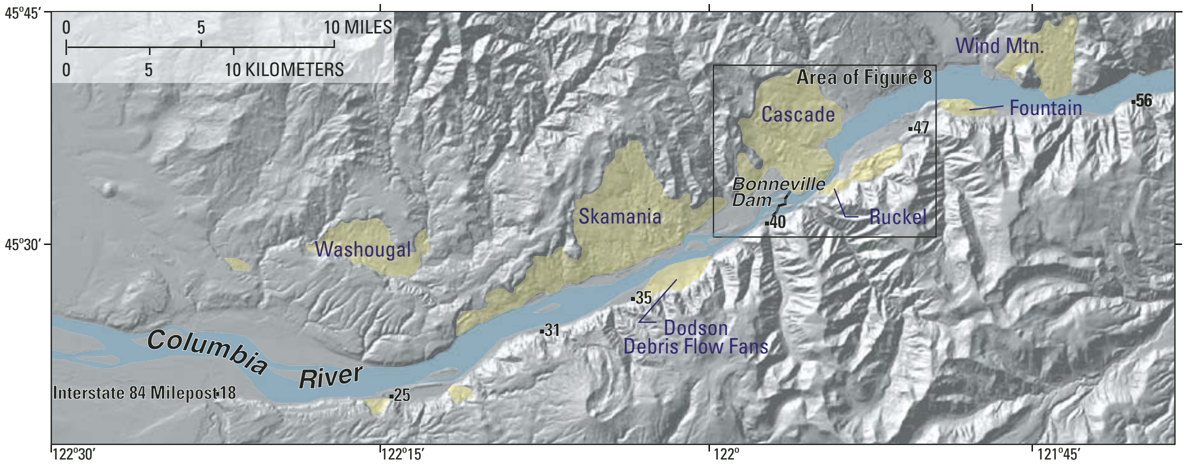

Figure 3. Landslides and landslide complexes of the western Columbia River Gorge, after Palmer (1977).

joints of CRBG and through the coarse-grained Eagle Creek Formation, is concentrated at the saprolite layer capping the Ohanapecosh Formation. The contact and saprolite at the top of the Ohanapecosh Formation slope 2–10° SE south toward the Columbia River, acting as a "well-greased skidboard" (Waters, 1973, p. 147). The north-side landslides have pushed the river against the southern valley wall, and in conjunction with the southward regional dip, have promoted formation and maintenance of the spectacular waterfalls lining the Oregon side of the Columbia River Gorge.

Some of these landslides are more appropriately termed earth flows, and move more or less continuously but at irregular rates. For example, the Wind River landslide now impinging the Columbia River across the valley from milepost (MP) 53, was moving at 2 m/yr in the 1970s but over the last few years has moved little. Others, such as the Bonneville Landslide discussed at Stop 1, probably moved cataclysmically but are now mostly stable (Palmer, 1977). Most of the large landslides are presently inactive, aside from relatively small mass movements chiefly in headscarp areas, and it is likely that most were formed or more active when the valley was 30–100 m deeper during times of lower sea level during glacial episodes. Recent InSAR analyses, however, are revealing areas of movement on some landslides previously thought inactive (T.C. Pierson, U.S. Geological Survey, written commun., 4 June 2008). Some large landslides were possibly activated in conjunction with passage of the Missoula Floods, which would have inundated, saturated, and locally undercut the valley walls to elevations approaching 250 m (800 ft) asl.

Mass movements on the Oregon side are smaller and are mainly rockfalls and slumps. Some, such as the Ruckel slide complex (Fig. 3), resulted from Columbia River undercutting the south valley side. Coalescing debris flow fans have built out into the valley bottom, particularly between MP 35 and 37, where steep and dissected terrain in the Cascade arc volcanic rocks at the canyon rim feed frequent bouldery debris flows down the steep valley drainages. Debris flows in February 1996—paths now delineated by vigorous alder growth—damaged houses, covered and closed Interstate 84, and displaced a freight train from its tracks.

THE MISSOULA FLOODS

Floods from cataclysmic releases of glacially dammed Lake Missoula (Fig. 4) produced a suite of spectacular flood features along several flow pathways between western Montana and the Pacific Ocean. In northern Idaho and eastern Washington, flow exiting glacial Lake Missoula overwhelmed the normal drainage routes, creating a plexus of flow paths as water spread out over the vast loess-covered basaltic plains. As the floods crossed eastern Washington, they eroded large and anastomosing tracts of coulees into the basalt surfaces, leaving immense gravel bars wherever currents slowed. Far-traveled crystalline rocks, first carried by the Cordilleran icesheet, were then floated downstream by huge icebergs in the floods. Lower levels of tributary valleys like the Snake, Yakima, Walla Walla, Tucannon, John Day, Deschutes, Sandy, and Willamette Rivers were mantled with sand and silt carried by water backflooding up these valleys.

In south-central Washington, the myriad flow routes from the east and north converged into Pasco Basin before the flow funneled through Wallula Gap (Fig. 4). Continuing downstream, the Missoula floods filled the valley of the Columbia River to 340 m (1150 ft) asl, leaving spectacular erosional and depositional features between Wallula Gap and Portland.

A History of Controversy

Scientists and explorers since the mid-nineteenth century have been challenged to weave together a reasonable story linking the bizarre topography, the far-traveled exotic rocks, the immense and rippled gravel bars, and the valley-mantling bedded sand and silt. Famous is J Harlen Bretz's efforts at resolution during the 1920–1950s, ultimately persuading (or outliving) a skeptical geologic community of the merits of his "outrageous hypothesis" of cataclysmic flooding for genesis of what he termed the "channeled scabland" (Bretz et al., 1956; Baker, 1978, 2008). Subsequent controversy centered on the number of floods, especially the idea that scores of colossal floods may have coursed through the channeled scabland (Glenn, 1965; Waitt, 1980, 1984, 1985a, 1985b; Atwater, 1984, 1986; Smith, 1993), rather than just one or a few envisioned by Bretz and other early workers. Discussion has also extended to: (1) possible earlier Quaternary episodes Missoula-like flooding (Patton and Baker, 1978; McDonald and Busacca, 1988; Bjornstad et al., 2001); (2) the role that multiple flows may have had in creating the flood features that we see today (Baker and Bunker, 1985; O'Connor and Baker, 1992; Benito and O'Connor, 2003); (3) possible of sources of flood water other than glacial Lake Missoula (Shaw et al., 1999, 2000; Atwater et al., 2000; Clarke et al., 2005; Miyamoto et al., 2007); and (4) the magnitude, energy and geomorphic effects of Missoula flooding (Benito, 1997; Denlinger and O'Connell, 2010).

Geomorphic features relevant to Missoula flooding in the Columbia valley downstream of Wallula Gap were studied first

Figure 4. Glacial Lake Missoula and path of Missoula floods.

by Bretz (1924, 1925, 1928), Hodge (1931, 1938), and Allison (1933, 1941), although some were photographed by G.K. Gilbert in 1899. Bretz's first work in the lower Columbia Valley was in the summer of 1915, when he assisted Ira Williams (1916) for four weeks in preparing a geologic guide for travelers of the new highway traversing the gorge. Bretz's early work focused on older gravels (Bretz, 1917, 1919), but observations in 1915 undoubtedly underlay some of classic descriptions and discussions in the early 1920s when he unveiled the "Spokane Flood." Between 1923 and 1932 Bretz mapped and described the bars and eroded scabland topography (Fig. 5), arguing that they were the product of huge discharges from a then-unknown source, and that features resulted from channel processes but at a valley scale. Gravel deposits with smooth and rounded forms flanking the valley were not terraces, but flood bars of immense height deposited in reaches of slacker currents or in zones of recirculation. The scabland and eroded rock benches were the result of plucking and erosion at the bottom of deep, vigorous currents that covered the entire valley bottom and sides to depths of hundreds meters.

The main intellectual battlefield of the early debates was the channeled scabland of eastern Washington, where notable Quaternary geologists Oscar E. Meinzer (1918, 1927), William C. Alden (1927) and Richard F. Flint, (1938) all vigorously disputed a catastrophic flood origin (Baker, 1978, 2008). But local workers downstream in the Columbia River Gorge also objected: Edwin T. Hodge (1931, 1934, 1938) of the University of Oregon suggested that the high gravel deposits, ice-rafted erratics, and divide crossings flanking the Columbia River valley recorded not a brief cataclysm, but the gradual entrenchment of the Columbia River through the Cascade Range since the middle Pliocene, stating (1938, p. 836):

> The Columbia in its down-cutting was often choked by icebergs, which caused temporary or permanent local diversions. Many rock benches, chasms, and pot holes were cut, and stranded deposits were left at the successive levels of entrenchment. The river is not yet graded, and the methods by which it produces these curious, but by no means exceptional, features may still be observed.

Ira S. Allison at Oregon State University (1933) examined in some detail field relations between Portland and Wallula Gap, and recognized the indisputable evidence for extremely high water levels. He clearly, however, struggled with the notion of catastrophic floods, and proposed a "new version of the Spokane Flood," believing (1933, p. 676–677):

> ...that the ponding was produced by a blockade of ice in the Columbia River gorge through the Cascade Mountains; that the rise of the Columbia River to abnormally high levels began at the gorge and not on the plateau of eastern Washington; the blockade gradually grew headward until it extended into eastern Washington; that, as the waters were damned [sic] to progressively higher levels, they were diverted by the ice into a succession of routes across secondary drainage divides at increasing altitudes, producing scablands and perched gravel deposits along the diversion routes, distributing iceberg-rafted erratics far and wide, and depositing pebbly silts in slack-water areas. This interpretation of the flood does not require a short-lived catastrophic flood but explains the scablands, the gravel deposits, diversion channels, and divide crossings as the effects of a moderate flow of water, now here and now there, over an extended period of time. It thus removes the flood from the "impossible" category.

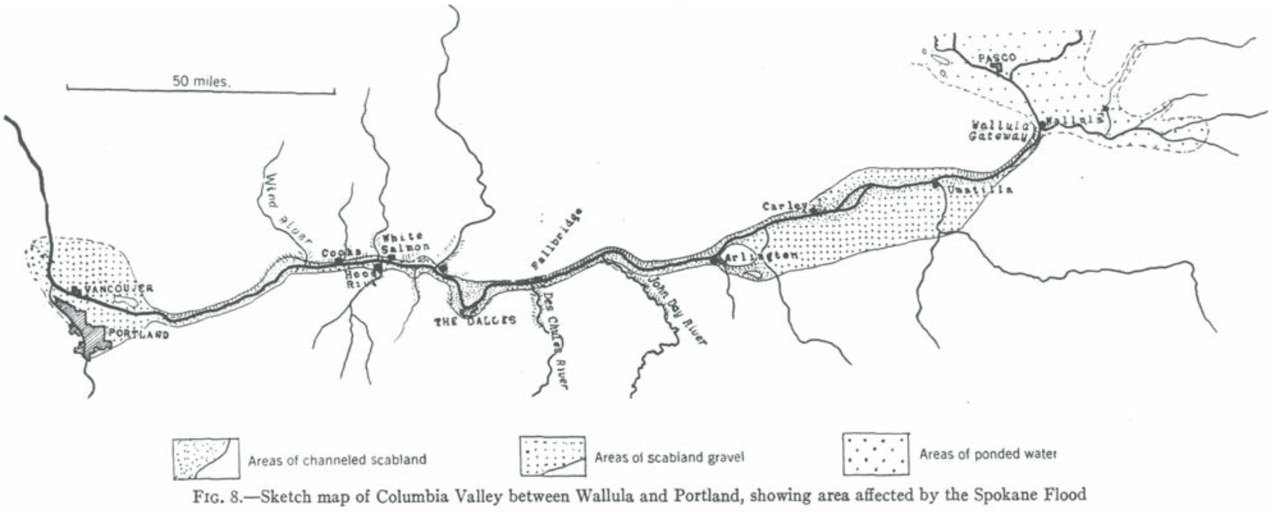

Figure 5. J Harlen Bretz (1925) map of Missoula flood features in lower Columbia River valley. (Copyright University of Chicago Press. Used with permission.)

Recent Work in the Columbia River Gorge

By the mid-1960s, J Harlen Bretz's "impossible" story was widely accepted and work of recent decades has focused on understanding details of the Missoula floods. Most of this recent work has been in eastern Washington—where stratigraphic, glacial, and hydraulic studies have refined our understanding of the chronology, magnitude, and sequence of events. Nevertheless, many questions linger, and our work between Portland and Wallula Gap has focused on further refinement of flood magnitude and timing. The Columbia valley is a good place to address such questions: the features are dramatic and commonly well exposed, and all floods followed the same route downstream of Wallula Gap, thereby avoiding the hydraulic and stratigraphic complexity in eastern Washington resulting from the anastomosing and evolving channel patterns of the channeled scabland.

Over the past 20 years, we have sporadically worked on the stratigraphy, chronology, and hydraulic conditions of the Missoula floods along the Columbia Valley between Wallula Gap and Portland. Piecing together the stratigraphy and hydraulic conditions from multiple sites, we see evidence of at least 25 floods of discharge greater than 1 million m^3/s, including at least six of more than 6.5 million m^3/s. At least one flood had a peak discharge of 10 million m^3/s, 300 times the greatest historical Columbia River flow (Benito and O'Connor, 2003). Radiocarbon and optically stimulated luminescence (OSL) dating indicate that most if not all of the flood features in the Columbia River Gorge and Portland basin are from the last-glacial episode of flooding. Evidence for maximum flood stages shows that the flood surface descended substantially between Wallula Gap and Portland, from ~365 m (1200 ft) in the Pasco Basin near the entrance to Wallula Gap (O'Connor and Baker, 1992) to ~120 m (400 ft) near Portland 325 km downstream. More than 80 percent of this fall was in the 130 km Columbia River Gorge between The Dalles and Portland (Fig. 6; Benito and O'Connor, 2003).

EN ROUTE TO CASCADE LOCKS

From Portland, the trip starts east on Interstate 84. The eastern Portland basin is a small forearc basin filled with Neogene and Quaternary sediment and volcanic rocks from the Columbia River and Cascade Range but also peppered with small Quaternary monogenetic volcanic centers (Evarts et al., 2009a, this volume). The Portland basin was vigorously inundated by the Missoula floods jetting out of the Columbia River Gorge, leaving channels and gravel bars spread across east Portland, now nicely illustrated in images of recent high-resolution topography acquired for the region (Fig. 7). The trip follows one such channel until MP 8, where Interstate 84 climbs out of the deep scour hole in front of the Quaternary volcanic plug of Rocky Butte. Leaving the Portland basin the trip enters the Columbia River Gorge National Scenic Area at the Sandy River confluence near MP 17 and remains within

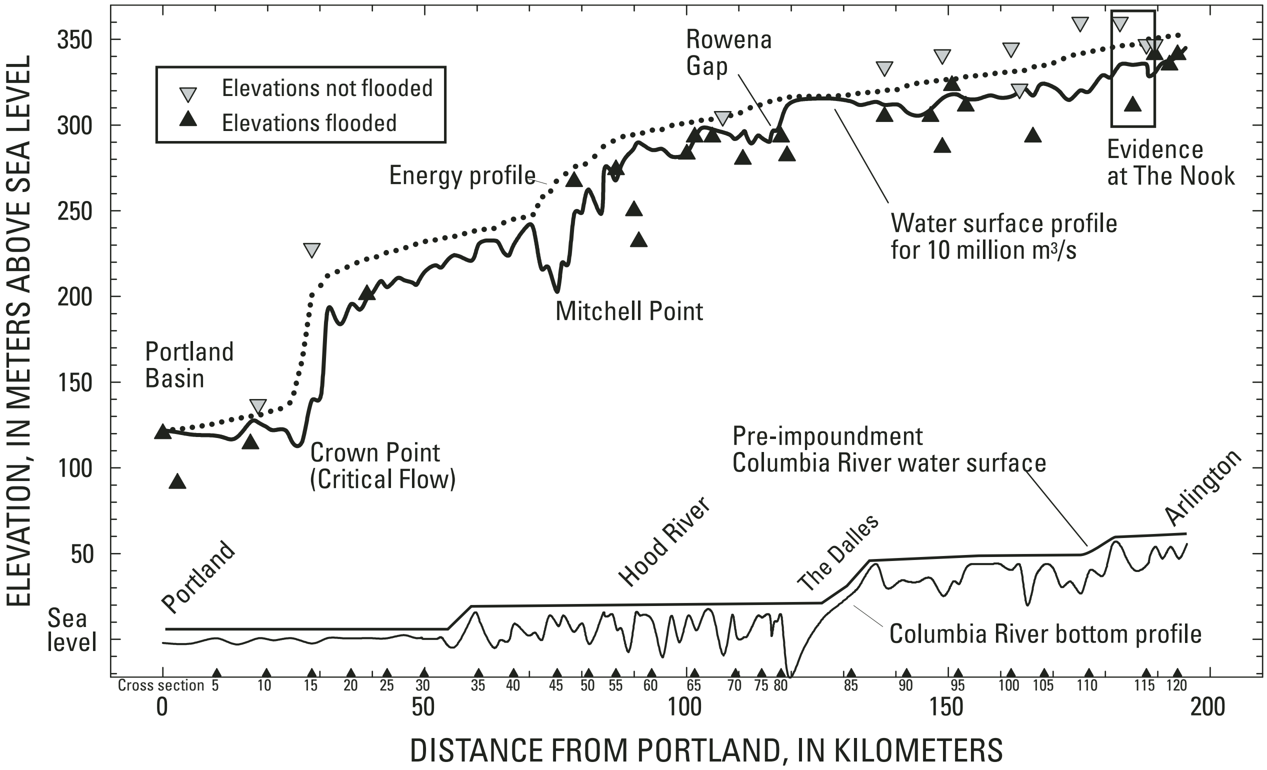

Figure 6. Evidence for maximum Missoula flood stages in lower Columbia River valley and step-backwater flow calculation results for a discharge of 10 million m^3/s. Modified from Benito and O'Connor (2003).

the Scenic Area through the Cascade Range and to the Deschutes River confluence at MP 93. The Columbia River Gorge National Scenic Area, established in 1986 and administered by the U.S. Forest Service, is a designation aimed at preserving the scenic quality by regulating land use and development.

For the next half-hour or so, the cliffs get higher, greener and wetter as the trip proceeds at river-level into the core of the Cascade Range. The ubiquitous layered basalt flows forming the walls of the Columbia River Gorge, and indeed flanking the Columbia River in eastern Washington, Oregon, and through to the Pacific Ocean are of the Columbia River Basalt Group (CRBG). Locally greater than 1200 m thick in the Columbia River Gorge, these voluminous basalt flows issued from vents in eastern Idaho, northeastern Oregon, and southeastern Washington. In total, more than 300 flood-basalt flows between 17 and 6 Ma covered 164,000 km^2 with a total volume of 174,000 km^3 (Tolan et al., 1989). Of the total volume, 96 percent erupted between 17 and 14.5 Ma. The lava flows followed (and locally buried) existing topography, and several of the largest flows followed the ancestral Columbia River corridor to the Pacific Ocean. The distribution and chronology of the flows shows that the Columbia River followed a path through the Cascade Range, Portland Basin, and Coast Range very close to the present one by 12 Ma (Tolan and Beeson, 1984). Episodic but small river realignments—chiefly northward displacements—resulted from filling and diversion of paleo-river valleys by the lava flows. The present alignment of the Columbia River through the western gorge, adopted ca. 3.0 Ma (Evarts et al., 2009b), has transected some of the former routes, leaving erosion-resistant plugs of paleo-canyon–filling basalt as massive points and cliffs flanking the present Columbia River corridor, including features such as Crown, Chanticleer and Mitchell points in the western Columbia River Gorge.

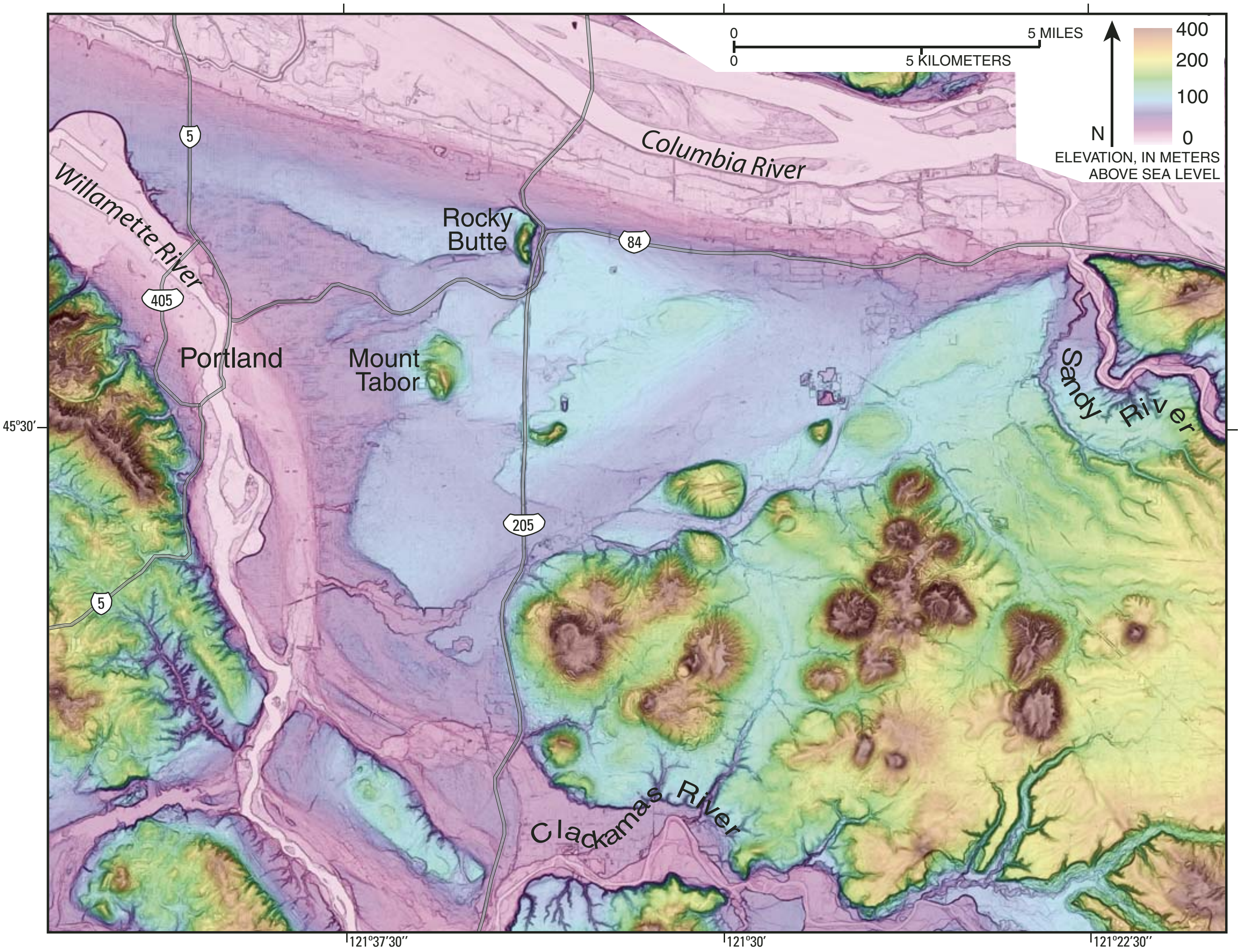

Figure 7. Portland basin digital elevation model for Portland area, based on lidar topographic measurements. The upper limit of Missoula flooding approximately at 125 m asl corresponds to the transition between blue and green. Image courtesy of the Oregon Lidar Consortium and Ian Madin of the Oregon Department of Mining and Geology.

Visible from MP 18, prominent Crown Point (capped by the Vista House) on the south side of the river, together with Cape Horn on the north side of the river, formed one of the major constrictions along the entire Missoula Flood route. While flood evidence is sparse in the "green hell" section of the gorge (legendary description of geological mapping conditions attributed to J. Hoover Mackin and confirmed by all subsequent mappers), the maximum stage of the largest Missoula flood descended from 250 to 270 m (820–860 ft) asl upstream of Crown Point to 120–150 m (400–500 ft) asl in the Portland basin. Flood flow through this section was probably critical with velocities exceeding 35 m/s. Hydraulic ponding behind these Columbia River Gorge constrictions probably impeded flow as far upstream as Pasco Basin (Benito and O'Connor, 2003).

East of Crown Point, the gorge deepens, waterfalls notch the cliffs, large now-vegetated Holocene sand dunes separate the freeway from the river (MP 25), debris-flow fans bury houses (MP 35.5), the north valley wall becomes an almost continuous mass of landslide complexes, and Beacon Rock (MP 37), a 57 ka volcanic neck, pokes out of the valley bottom (age provided by Robert Fleck, U.S. Geological Survey, written commun., 2008). The trip speeds by these geomorphic diversions to MP 44, where we exit and proceed through downtown Cascade Locks before turning left and under the railroad tracks to Stop 1 at Cascade Locks Marine Park.

STOP 1: CASCADE LOCKS AND BONNEVILLE LANDSLIDE

(UTM Zone 10, NAD 83, 585860E, 5057820N) (WGS 84; 121.898W, 45.668N)

This stop at Cascade Locks Marine Park provides for a good overview of the Bonneville Landslide and the Bridge of the Gods (Fig. 8). Cascade Locks and Canal were completed in 1896, permitting steamboat navigation between the coast and The Dalles. Previously, navigation was hampered by the Cascades of the

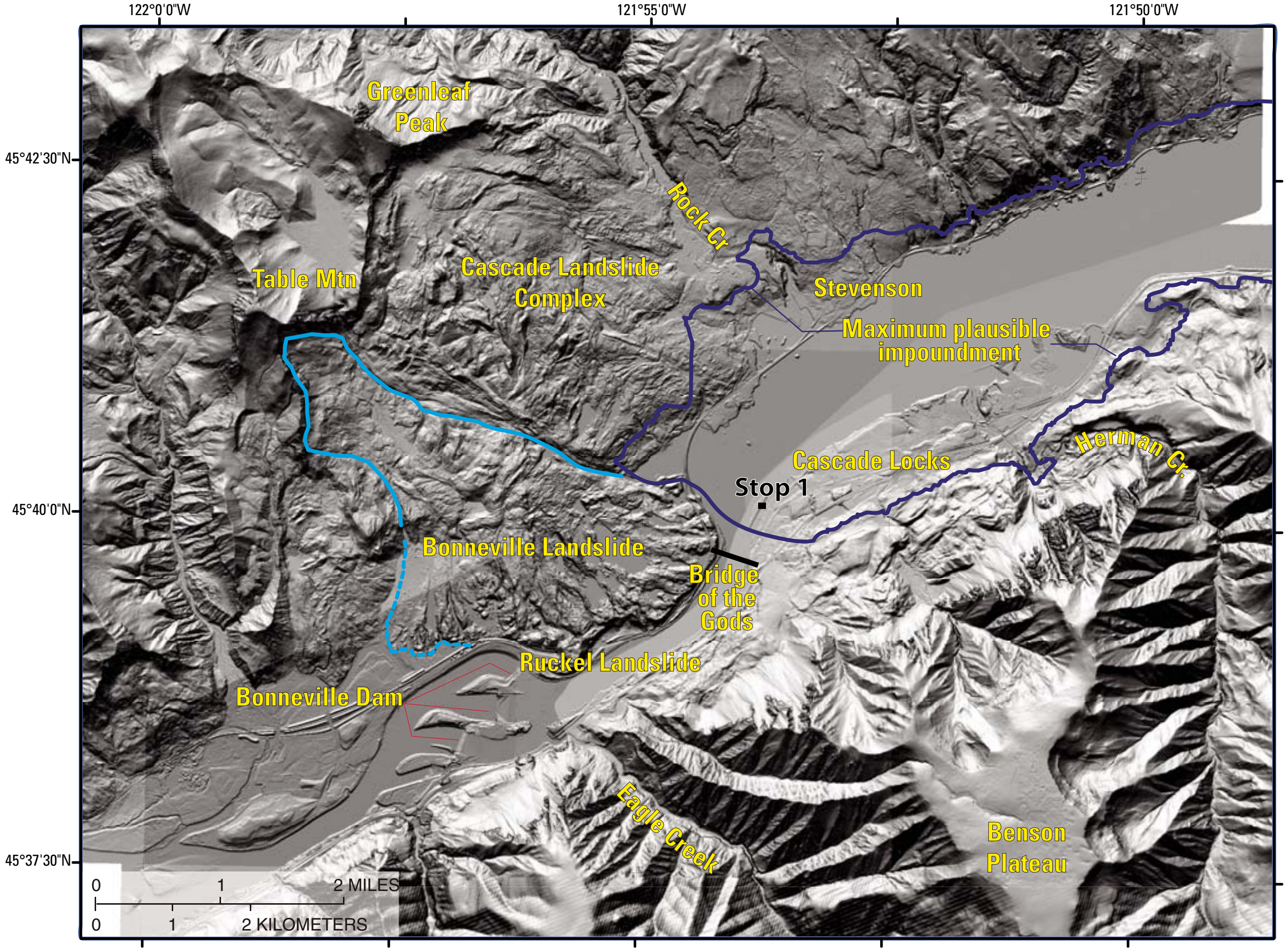

Figure 8. Shaded relief map from lidar topographic data in vicinity of the Bonneville landslide. Topographic data from Washington Department of Natural Resources, U.S. Geological Survey, and Oregon Lidar Consortium. Maximum plausible ponding level drawn at 90 m (300 ft) asl.

Columbia, a set of rocky rapids (Fig. 9) descending >7 m over ~600 m and then another 9 m over the next 12 km to tidewater (Hodge, 1932). The rapids as well as much of the locks and canal were drowned by the 1938 completion of Bonneville Dam.

Cascade Rapids were the remnants of the toe of the Bonneville landslide which completely crossed the Columbia River (Fig. 8). The Bonneville landslide is part of the Cascade landslide complex, consisting of multiple separate mass movements (Wise, 1970); the largest ones, including the Bonneville landslide, head from the 500 m escarpment along the southern margins of Table Mountain and Greenleaf Peak. The total area of landslide debris is ~35 km^2. The Bonneville landslide, the youngest of the complex, is a 14 km^2 rock slide or debris avalanche that headed from 1040-m-asl Table Mountain on the north rim of the Columbia River Gorge. Its toe is a 90–120-m-high lobe of bedrock blocks and granular matrix spread more than 2 km across the Columbia River valley bottom (Palmer, 1977).

The Bonneville landslide almost certainly gave rise to the Native American legend of the Bridge of the Gods. Oral histories of the region, summarized by Lawrence and Lawrence (1958, p. 33), indicate that the Native Americans "could cross the river without getting their feet wet" and that "the falls are not ancient, and that their fathers voyaged without obstruction in their canoes as far as The Dalles." The Native Americans also recounted "that the river was dammed up at this place, which caused the waters to rise to a great height far above and that after cutting a passage through the impeding mass down to its present bed, these rapids first made their appearance."

Early explorers, including Lewis and Clark in 1805, noted large stands of partially submerged tree stumps between Cascade Rapids and The Dalles (Fig. 10). The origin of this "submerged forest" was controversial among explorers, settlers, and geologists, including a who's who list of prominent geographers and geologists (notably Newberry, LeConte, Emmons, Dutton, Diller, and Gilbert) and merited a footnote in Lyell's (1833, p. 190) *The Principles of Geology*. Engineering geologist Ira Williams (1916) first clearly stated the current thinking: that the submerged forest resulted from a 10–15 m rise in river level after landslide blockage followed by less-than-complete incision of the Bonneville Landslide dam.

Despite basic understanding of the role of the landslide in forming Cascade Rapids and the submerged forest, many questions remain. When was it? What triggered the landslide? To what elevation and for what duration was the Columbia River impounded? What were the downstream consequences upon breaching of the landslide dam? We and colleagues have been working on these questions, building on several earlier efforts, notably Lawrence (1936), Lawrence and Lawrence (1958), Palmer (1977), Pettigrew (1981), and Minor (1984). This work has provided new information on the age of the landslide, as well as evidence for an upstream lake that eventually contributed to downstream flooding when the landslide dam breached.

Figure 9. Oblique aerial view west-southwest (downstream) of Cascade Rapids and Bridge of the Gods in 1928; photograph courtesy U.S. Army Corps of Engineers. Bridge span approximately one kilometer.

Age of the Bonneville Landslide

Judging from the fresh appearance of the drowned snags, Lewis and Clark first speculated that the blockage formed just a couple of decades prior to their journey (Moulton, 1991; v. 7, p. 118). Lawrence and Lawrence (1958), on the basis of early radiocarbon dates of 670 ± 300 ^{14}C yr B.P. and 700 ± 200 ^{14}C yr B.P. for two of the partly submerged stumps, concluded that the landslide occurred about AD 1100. We have recently reanalyzed two of Lawrence's original samples, with wiggle-matching of several radiocarbon analyses giving the time of tree death (and presumably the landslide) to be between AD 1425 and 1450. Pat Pringle (Centralia College) and colleagues are working on dating the landslide more precisely by dendrochronology, although we have been challenged by the few trees sufficiently old to cross date with the Lawrence samples.

Impoundment and Lake of the Gods

Both the valley-bottom morphology and the extensive coring program in the vicinity of Bonneville dam (Hodge, 1932; Holdredge, 1937; U.S. Army Corps of Engineers, 1976) show that the Columbia River channel was locally buried by more than 100 m of landslide debris and diverted 2 km south toward the southern margin of the landslide toe. But before establishing a new channel, the Columbia River was at least temporarily impounded by the landslide. Judging from the topography of the remaining part of the landslide toe, the maximum possible ponding level of the Lake of the Gods was 85–90 m (275–300 ft) asl. The southern margin of the landslide adjacent to the present channel of the Columbia River is bounded by a scarp that mostly exceeds 75 m (240 ft) asl, indicating that the initial overtopping may have been close to that level. From this we conclude that maximum impoundment was between 75 and 90 m (240 and 300 ft) asl. These geomorphic constraints are supported by the presence of deltaic deposits of gravel, sand, and silt at tributary confluences upstream of the landslide, and aggraded tributary fans at elevations as high as 80 m (260 ft) asl, which also indicate that impoundment was maintained for at least several years. Prominent surfaces at lower levels, especially at 40 m (130 ft) asl, indicate episodic downcutting through the landslide dam before reaching its ultimate historic low-water elevation of ~13 m (45 ft) asl—before the 1938 closure of Bonneville Dam provided a bout of déjà vu by ponding water to 22 m (72 ft) asl.

The elevations of various possible lake stages have implications regarding the area inundated, the time required for filling, and the volume and magnitude of dam-breach floods. For maximum likely lake levels of 75–90 m asl (240–300 ft; Fig. 4) before erosion of a new channel around the landslide, the corresponding lake volumes are $4.9 \cdot 10^{10}$ to $1.2 \cdot 10^{11}$ m^3 (0.02–0.04 the

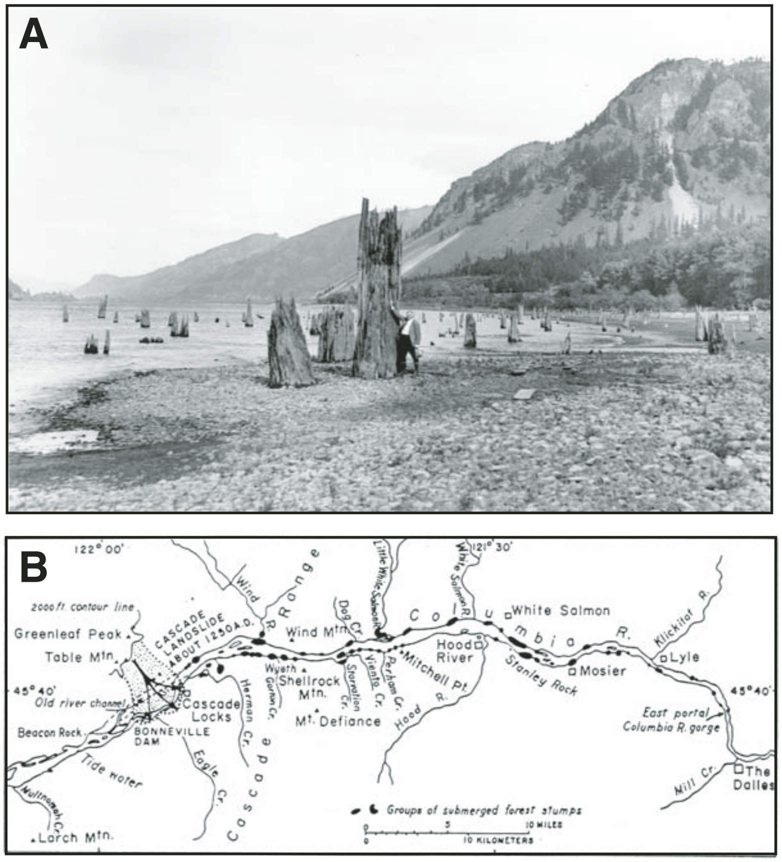

Figure 10. Submerged forest of the Columbia. (A) D.H. Lawrence photo, 1933, courtesy of the Oregon Historical Society (#3931). (B) Distribution of submerged forest snags; modified from Lawrence and Lawrence (1958).

size of maximum Glacial Lake Missoula, but 100–200 times that of today's Bonneville pool). Such a maximum level lake would have covered an area of 320–570 km^2 and would have extended 220–275 km upstream to the vicinity of Wallula Gap. At the mean annual Columbia River flow of $1.85 \cdot 10^{11}$ m^3/year, the impounded Columbia River valley would have filled in 3–7.5 months before overtopping. The temporarily stable lake at 35–40 m asl was much smaller, with an area of 95–110 km^2 and containing a volume of between $3.4 \cdot 10^9$ and $5.3 \cdot 10^9$ m^3. This lake would have extended ~85 km upstream, drowning much The Dalles of the Columbia and perhaps the ~40 m asl top of Celilo Falls.

Landslide Breaching and Flood of the Gods?

The manner of transformation from a large landslide-blocked lake at 75–90 m asl to the historical conditions of 13 m asl is still unresolved but has significant cultural and fish-passage implications. Was incision catastrophic, leading to downstream flooding? Or was incision gradual or episodic over a number of years or decades? So far the geomorphic and stratigraphic evidence suggest both. Prominent deltaic surfaces at 75–80 m and 40 m asl indicate several years at near maximum blockage level, followed by at least one interim stable lake level before lowering to the final historical elevation of 13 m asl. At least one of the episodes of lake level lowering was cataclysmic; bouldery flood bars and bedded sands immediately west of the landslide (Fig. 8) and distinctive beds of relative coarse sediment in floodplain and estuary deposits further downstream and pre-dating AD 1479–82 Kalama-age eruptions of Mount St. Helens (O'Connor et al., 1996; Atwater, 1994) indicate a large flood within a few decades of the landslide. Simple calculations, assuming critical flow through the present breach geometry, indicate a maximum plausible discharge for a 75 m to 40 m asl breach to be ~110,000 m^3/s. Similarly, a breach from 40 m to 13 m asl could produce flows of 60,000 m^3/s. These values exceed the historical high flow of 35,100 m^3/s. Given these preliminary values and chronologic constraints, the most plausible scenario for creating the downstream flood features is partial breaching from a stabilized 75–80 m asl level to at least the 40 m asl level decades after the AD 1425–1450 formation of the landslide but prior to the A.D. 1479–82 Mount St. Helens eruptions. The timing and nature of further incision to historical levels is uncertain, but may have been not too long before Lewis and Clark's visit judging from the condition of the drowned forest.

EN ROUTE TO THE NOOK

From Cascade Locks the trip continues east on Interstate 84 to the high and elongate peninsula known as The Nook at the John Day River confluence, the site of the final two trip stops. East from the axis of the Cascade Range, landslides are fewer as the CRBG descends back to river level (Fig. 2) and the climate dries (from 2 m/yr of precipitation at Cascade Locks to ~40 cm/yr at The Dalles). On this leg the trip also passes notable geomorphic features, including the 340 ± 70 ka basalt of Trout Creek Hill (Korosec, 1987) which flowed down Wind River (Washington side, ~MP 49) and blocked the Columbia River from the north (Waters, 1973), forming a lake to elevation to at least 120 m (400 ft) asl. Farther east, in the vicinity of Hood River, several more Quaternary and late Tertiary lava flows apparently entered the Columbia River, and, more recently, a large Pleistocene Mount Hood lahar crossed the river (Vallance, 1999). From Hood River east, marks of the Missoula floods become evident; the town of White Salmon (Washington side, about MP 64) sits atop a large gravel bar, with scrubbed hillslopes flanking the upstream constriction. Likewise at Lyle, also on the Washington side at about MP 75. At MP 76, Interstate 84 enters Rowena Gap, a narrow gap bisecting folded and faulted Columbia Hills anticline, and also an important constriction for the Missoula floods. From here eastward, this anticline, part of the Yakima Fold Belt, bounds the river valley to the north.

Just east of the city of The Dalles, which occupies a broad syncline in the CRBG, The Dalles Dam blocks the river near MP 88. The dam is founded on CRBG, and the rocky river bed just downstream from the dam is the downstream vestige of The Dalles of the Columbia, a classic section of bedrock channel now drowned by the pool of The Dalles dam. Prior to 1958 closure, the low-flow water-surface of the Columbia River dropped 25 m in the 19 km between the head of Celilo Falls and present site of The Dalles dam. At low water, Celilo Falls (MP 97) had a sheer drop of ~6 m (Fig. 11). For the entire 19 km, the valley bottom was sculpted into a series of narrow chutes up to several kilometers long and locally narrower than 50 m, separated by large and deep holes, some more than 40 m deep and reaching 30 m below sea level. At low water, the Columbia River was confined to the chutes and holes but at high water during spring runoff, the entire basalt-floored valley bottom was inundated. It isn't clear to us if the valley and channel bottom topography here is largely a relict of passage of the Missoula floods, or if Holocene flows sculpted the present channel. Bretz (1924) suggested that the present channel morphology was the work of post-Missoula flood river action, but that the processes ("pluck[ing] rather than abrasion") and topography at this site served as a good analogy for Missoula flood features in the channeled scabland. Historically this region supported a tremendous fishery and cultural center for Native Americans, and was described by William Clark in 1805 as the "Great Mart of all this Country" (Moulton, 1991, v. 7, p. 129). Archeological excavations here reveal evidence of Native American occupation and salmon consumption for at least the last 9000 yr (Butler and O'Connor, 2004).

Continuing eastward, the trip passes the mouth of the Deschutes River (MP 93), Miller Island (MP 93, with Missoula flood gravel appended to its downstream end), and John Day Dam (MP 111) before leaving Interstate 84 at MP 123. Ascending Philippi Canyon, the trip passes a large eddy bar mounded into the canyon mouth. The road junction on top sits in the col of a major divide crossing between the Columbia and John Day River valleys (Fig. 12). Examined in detail by Bretz (1928,

p. 686–690), he called this area "The Narrows," using it as a cornerstone in his case for huge flows down the Columbia valley. The trip turns right (west) at the intersection and follows the unpaved county road flanking the north edge of a channel and cataract complex that has been eroded through Tertiary gravel and CRBG basalt. Down-flood of this spectacularly eroded terrain, filling the bottom of the John Day River valley, lies an immense bar, 150 m (500 ft) high and mantled with rounded 2–3 m diameter boulders.

STOP 2: 1196′ TRIANGULATION STATION; COLUMBIA RIVER VISTA

(UTM Zone 10, NAD 83, 694280E, 5062390N)
(WGS 84; 120.502W, 45.687N)

Private property: obtain permission before leaving road right-of-way. **No smoking:** fire danger extreme.

This location presents a superb view of the valley of the Columbia River from 310 m (1020 ft) above the normal river level, now drowned 25 m by the John Day Dam. An early Columbia River valley inhabitant, if here at the right time, would have been a safe but frightful witness of the largest Missoula flood(s) from this position just 15–30 m (50–100 ft) above the maximum flood stage. Here, the maximum flood stage can be confidently constrained as being below 345 m (~1130 ft) by a divide 300 m to the east that was apparently not crossed. About 5 km west, however, laminated sand and silt mantle loess to an elevation of at least 330–340 m (1080–1120 ft) and the floor of another divide crossing, 2 km west, is above 310 m (1020 ft) with evidence that it eroded down from ~340 m (1120 ft). Besides being key constraints for initial one-dimensional flow modeling indicating a maximum flood discharge of 10 million m^3/s (Benito and O'Connor, 2003), these elevations supported more recent two-dimensional flow modeling (Denlinger and O'Connell, 2010). The key chronologic information from this area is a radiocarbon date from a soil clast in a colluvial deposit *below* a single Missoula-flood deposit north of the large bar. The bulk radiocarbon analysis of the clast yielded a result of 29,845 ± 470 ^{14}C yr B.P. Analysis of extracted humic acids, however, resulted in 19,015 ± 145 ^{14}C yr B.P. that probably more closely represents the age of deposition. In this case, these dates—one the few closely limiting maximum ages—confirm that the most recent flow(s) over this divide were during the late Wisconsin (Benito and O'Connor, 2003).

EN ROUTE TO STOP 3

From here we continue 1.7 mi west to the 310 m (1020 ft) divide crossing where the largest flood(s) overtopped a low point in the ridge between the two rivers, eroding through Tertiary gravel (Alkali Canyon Formation), but not entrenching into the CRBG basalt that floors the channel. The trip turns around here and returns east to the junction with Philippi Canyon Road, where it turns south for 0.2 mi before pulling off roadside.

STOP 3. WILD SCABLAND

(UTM Zone 10, NAD 83, 695985E, 5060910N)
(WGS 84; 120.483W, 45.674N)

Private Property: obtain permission before leaving road right-of-way. **No smoking:** fire danger extreme.

This stop entails exploring this "amazingly wild scabland" (Bretz, 1928, p. 688) abounding with closed rock basins and basalt protrusions, and steep-sided waterless chasms with floors sloping in various directions. Much of the coarse debris eroded from this scabland was deposited in two large bars whose apices

Figure 11. 1930 view east-northeast of Celilo Falls and the uppermost Dalles of the Columbia before 1958 inundation by the pool behind The Dalles Dam. U.S. Geological Survey photographs by A.M. Piper.

lay just down-current from each of the two sets of cataracts formed by water overflowing into the John Day valley (Fig. 12). The smaller bar, south of the southeastern flow route, has giant crescentic current structures on its surface. Together, these bars displaced the John Day River south onto a shelf of basalt where the river has cut a narrow canyon over the past ~15 k.y. From our flow-modeling results, flow over the divide at Philippi Canyon required a discharge of 5 million m^3/s, but a much greater flow was probably responsible creating the features.

The John Day valley is mantled by rhythmically bedded sand and silt deposits from its mouth to more than 30 km upstream (Fig. 12). These deposits have not been examined in detail, but apparently they were deposited by several Missoula floods that backflooded up the valley, probably by smaller flows that did not overtop the divides here. From stratigraphic evidence at a similar situation farther east, Benito and O'Connor (2003) infer at least 10 floods with discharges between and 1 and 3 million m^3/s (in addition to >15 floods of greater than 3 million m^3/s).

RETURN TO PORTLAND

The trip returns to Portland by turning around and proceeding north on Philippi Canyon Road back to Interstate 84, for which the westbound lanes lead directly back to the city. This trip can be extended by many options detailed in the trip guides of O'Connor and Waitt (1995) and Waitt (1994).

A FINAL IRONIC NOTE

In 1965, the International Union for Quaternary Research sponsored a trip to a variety of western U.S. locations, including the channeled scabland. J Harlen Bretz, invited but unable to

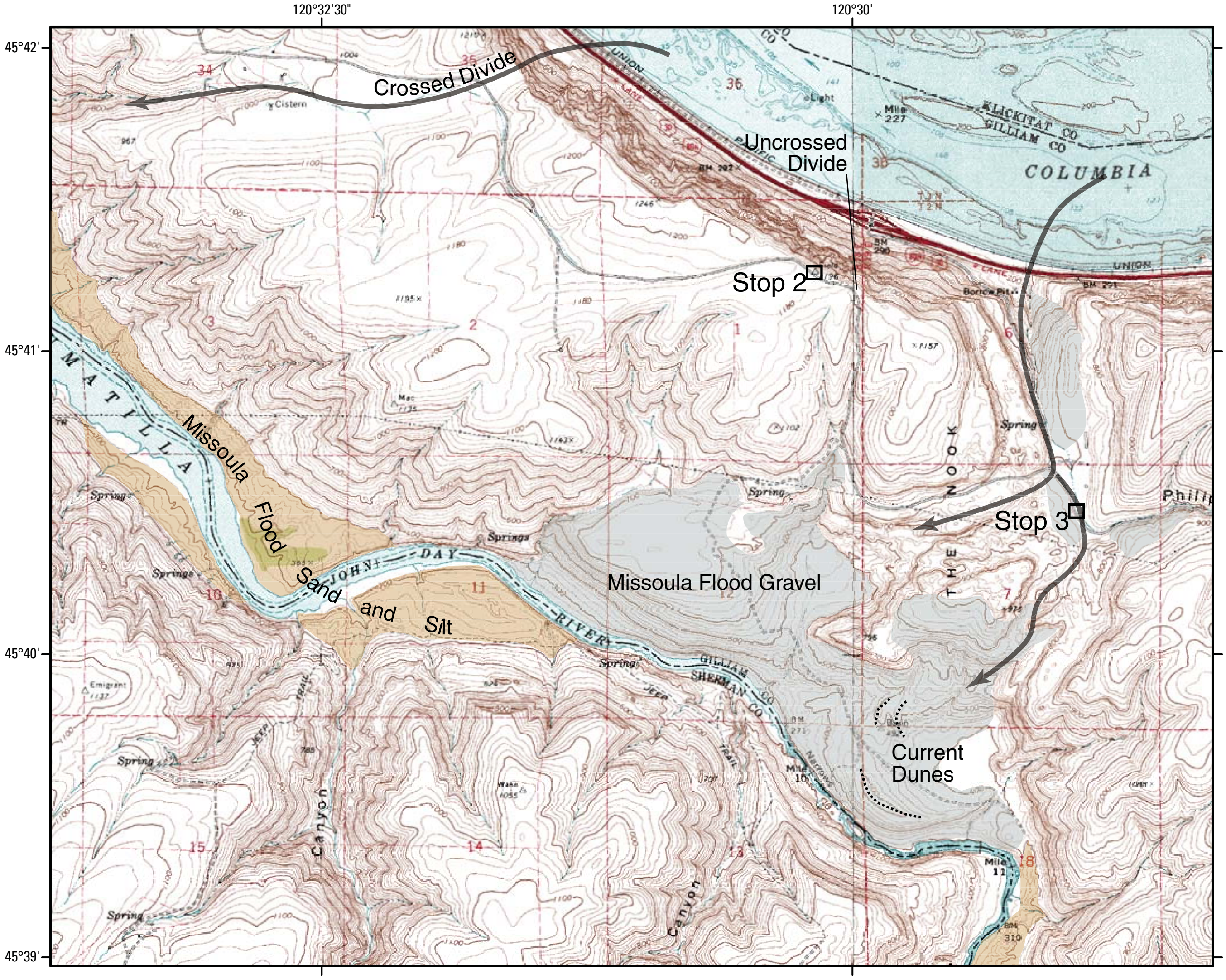

Figure 12. Field trip stop locations and Missoula flood features in vicinity of Philippi Canyon and The Nook. Topographic base from Quinton and Sundale NW USGS 7½′ topographic quadrangles.

attend, asked trip leader Gerald Richmond to leave eight empty seats on the bus for the "ghosts of eight geologists who had gone to their graves as unbelievers" (Soennichsen, 2008, p. 230). Among others, Bretz's especially reserved spaces seated the spirits of W.C. Alden, O.E. Meinzer, and *Kirk Bryan*.

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Colleagues Gerardo Benito, Alex Bourdeau, Russ Evarts, Patrick Pringle, Thomas Pierson, Nathan Reynolds and Richard Waitt have contributed to the findings reported here. Property owners Blair and Darlene Philippi permitted access for Stops 2 and 3. This guide benefitted from reviews by Russ Evarts, Thomas Pierson, and Jon Major.

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