Number and size of last-glacial Missoula floods in the Columbia River valley between the Pasco Basin, Washington, and Portland, Oregon

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ABSTRACT

Field evidence and radiocarbon age dating, combined with hydraulic flow modeling, provide new information on the magnitude, frequency, and chronology of late Pleistocene Missoula floods in the Columbia River valley between the Pasco Basin, Washington, and Portland, Oregon. More than 25 floods had discharges of $>1.0 \times 10^6$ m^3/s. At least 15 floods had discharges of $>3.0 \times 10^6$ m^3/s. At least six or seven had peak discharges of $>6.5 \times 10^6$ m^3/s, and at least one flood had a peak discharge of $\sim10 \times 10^6$ m^3/s, a value consistent with earlier results from near Wallula Gap, but better defined because of the strong hydraulic controls imposed by critical flow at constrictions near Crown and Mitchell Points in the Columbia River Gorge.

Stratigraphy and geomorphic position, combined with 25 radiocarbon ages and the widespread occurrence of the ca. 13 ka (radiocarbon years) Mount St. Helens set-S tephra, show that most if not all the Missoula flood deposits exposed in the study area were emplaced after 19 ka (radiocarbon years), and many were emplaced after 15 ka. More than 13 floods perhaps postdate ca. 13 ka, including at least two with discharges of $>6 \times 10^6$ m^3/s.

From discharge and stratigraphic relationships upstream, we hypothesize that the largest flood in the study reach resulted from a Missoula flood that predated blockage of the Columbia River valley by the Cordilleran ice sheet. Multiple later floods, probably including the majority of floods recorded by fine- and coarse-grained deposits in the study area, resulted from multiple releases of glacial Lake Missoula that spilled into a blocked and inundated Columbia River valley upstream of the Okanogan lobe and were shunted south across the Channeled Scabland.

Keywords: Quaternary, Columbia Basin, Missoula floods, fluvial features, radiocarbon dating.

INTRODUCTION

Floods from cataclysmic releases of glacially dammed Lake Missoula produced spectacular flood features along many flow paths in the Channeled Scabland of eastern Washington. All these paths converged in the Pasco Basin, below which water funneled through Wallula Gap and followed the Columbia Valley to the Pacific Ocean (Fig. 1A). Here we report on flow modeling, flood features, stratigraphy, and radiocarbon dating between Wallula Gap and Portland, with major emphasis on the reach between Arlington and Hood River, Oregon (Fig. 1B). We speculate on the relationship between results from our study area and observations by others and by us from upstream sites.

Our studies address issues raised regarding the number, magnitude, geomorphic effectiveness, and chronology of late Pleistocene flooding (Waitt, 1985, 1994; Baker et al., 1991; Baker and Bunker, 1985; O'Connor and Baker, 1992; Smith, 1993; Shaw et al., 1999, 2000; Atwater et al., 2000). Specifically, we address the correlation of evidence for >40 late-glacial Missoula floods inferred from rhythmic beds of silty and sandy flood deposits found chiefly at low altitudes in backflooded valleys along the entire flood route (Waitt, 1980, 1985; Atwater, 1986, 1987; Smith, 1993) to the evidence of very large Missoula floods indicated by the high and coarse gravel bars that J Harlan Bretz demonstrated were the work of great cataclysms (e.g., Bretz, 1928, 1969; Bretz et al., 1956).

We document stratigraphic evidence of at least 25 last-glacial floods, not only in slackwater facies but also in coarse, high-energy deposits. Results of step-backwater flow modeling in conjunction with altitudes of flood features show that many of these floods were relatively small, with discharges between 1×10^6 m^3/s and 6×10^6 m^3/s. Few floods had discharges approaching the maximum flow of 10×10^6 m^3/s. By using radiocarbon and tephra dating, we show that it is probable that all of these floods passed through the study area after 19,000 ^{14}C yr B.P.

The Columbia Valley between the Pasco Basin and Portland

Between the Pasco Basin and Portland, the Columbia River flows west through a series of basins and constrictions as it exits the Columbia Plateau province and crosses through the Cascade Range. In constrictions, the valley is bounded by tall, sheer, and stepped cliffs formed primarily of upwarped basalt flows of the Miocene Columbia River Basalt Group (Beeson et al., 1989; Reidel et al., 1989). The rolling uplands flanking constrictions and the bottoms of the intervening synclinal basins are generally formed on post-Miocene fluvial and volcanic deposits and capped by Quaternary loess and soils. Between The Dalles and Portland, the Columbia River flows within the narrow and incised Columbia River Gorge as it transects the core of the Cascade Range before entering the Portland basin.

The physiography of the Columbia Valley between the Pasco Basin and Portland resulted in a single flow route mostly confined by an

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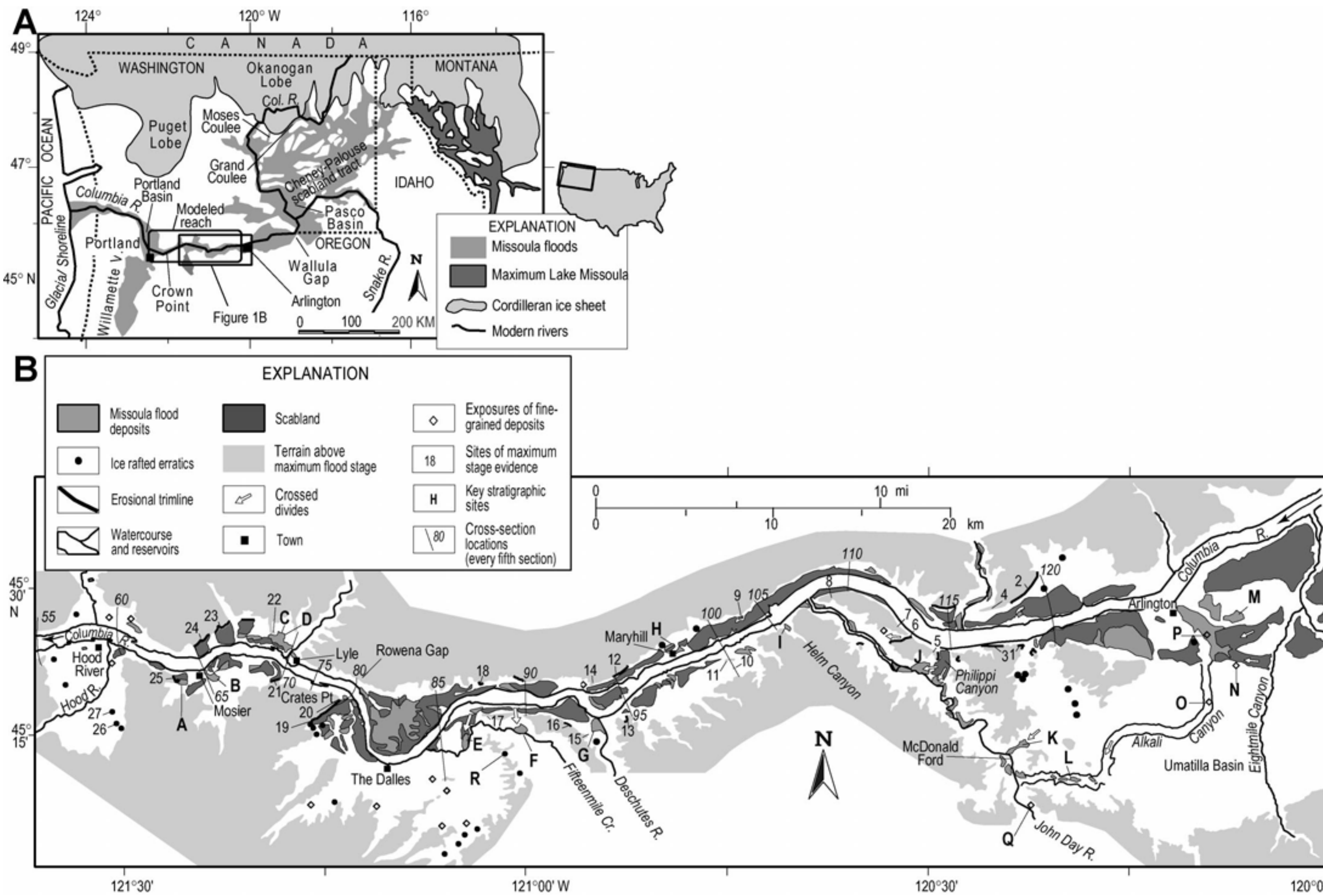

Figure 1. (A) Regional setting of Missoula floods. (B) Major flood features in the study area, including locations of evidence for maximum-flood stages and stratigraphic sites (detailed locations and site data provided in Table DR2 [see footnote 1 in the text]).

existing and unblocked large river valley. By contrast, in the Channeled Scabland of eastern Washington, late-glacial flood routes and discharges were governed by the extent of the Okanogan ice lobe of the Cordilleran ice sheet, by the stage of glacial Lake Columbia (Atwater, 1986, 1987), and perhaps by the erosion of major channel complexes like Grand Coulee and the Cheney-Palouse scabland tract, thus complicating hydraulic calculations. Nevertheless, the gradient and geometry of the Columbia River valley within the study reach, with its constrictions and basins, produced diverse flow conditions, resulting in a variety of well-preserved erosional and depositional features (O'Connor and Waitt, 1995; Benito, 1997).

METHODS

Assessment of the number and chronology of floods was based on stratigraphic studies of flood deposits and erosional features between Arlington and Hood River, Oregon (Fig. 1B). Most exposures of coarse deposits (sand and gravel) are at abandoned sand-and-gravel quarries, whereas finer facies were generally best exposed at road and stream cuts. At many exposures, we described and sketched the stratigraphy, paying particular attention to boundaries of beds of contrasting grain size (Fig. 2). At most exposures, we also searched for datable material such as organic detritus and tephras.

Missoula flood discharges were estimated by relating altitudes of flood features to water-surface profiles calculated for the reach between Arlington and Portland. Evidence of maximum-flood stages was compiled from reports of previous workers, notably Piper (1932), Allison (1933, 1935, 1978), Newcomb (1969), and Allen et al. (1986). To this we have added our own estimates of maximum-flood stages from field evidence and interpretation of aerial photographs. The discharge of the largest flood(s) was further defined by evidence of altitudes that were not flooded—sites where divides were apparently not crossed or loess-covered uplands without evidence of fluvial sculpting, following the approach of Baker (1973, p. 13–14), O'Connor and Baker (1992), and O'Connor (1993). In addition, we recorded altitudes of deposits inferred to record multiple floods. Altitudes were determined by plotting flood features on current 1:24,000 topographic maps, with uncertainties of about one contour interval (generally 12 m), or by hand leveling from known altitudes such as benchmarks or spot altitudes shown on topographic quadrangles. Tabulated locations, elevations, and descriptions of maximum stage evidence and stratigraphic sites are listed in Tables DR1 and DR2.[1]

[1]GSA Data Repository item 2003067, Table DR1: Evidence of maximum Missoula flood stages between Arlington and Portland, Oregon; Table DR2: Sites of stratigraphic observations for Missoula flood deposits in the Columbia Valley between Arlington and Hood River, Oregon, is available on the Web at http://www.geosociety.org/pubs/ft2003.htm. Requests may also be sent to editing@geosociety.org.

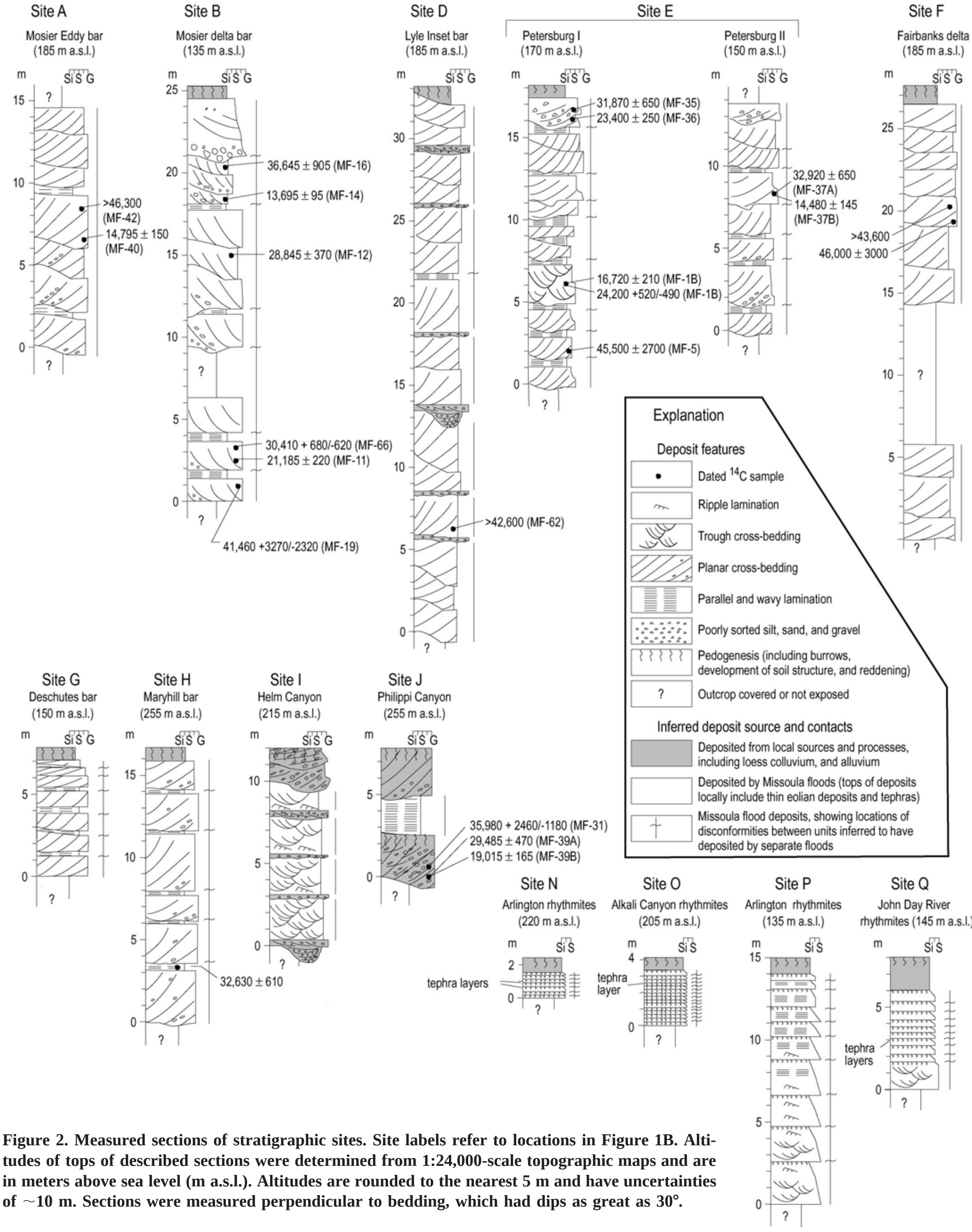

Figure 2. Measured sections of stratigraphic sites. Site labels refer to locations in Figure 1B. Altitudes of tops of described sections were determined from 1:24,000-scale topographic maps and are in meters above sea level (m a.s.l.). Altitudes are rounded to the nearest 5 m and have uncertainties of ~10 m. Sections were measured perpendicular to bedding, which had dips as great as 30°.

Like the studies of O'Connor and Baker (1992) and O'Connor (1993), we have used the U.S. Army Corps of Engineers' HEC-2 Water Surface Profiles computer program (Feldman, 1981; Hydrologic Engineering Center, 1985) to calculate water-surface profiles to use as a basis for flood discharge estimates (O'Connor and Webb, 1988). Water-surface profiles were calculated for a series of 121 cross-valley cross sections for the 196 km reach between Arlington and Portland. Cross sections were measured from topography and bathymetry shown on 1:24,000 scale USGS quadrangles and were spaced and oriented to characterize the effective flow geometry (e.g., O'Connor, 1993, p. 12–15). For each model run, discharge and flow stage were specified at the downstream cross section, and flow was computed stepwise upstream, resulting in an energy-balanced water-surface profile (O'Connor and Webb, 1988). Downstream flow stage for each trial was either assumed to be 120 m on the basis of highest Missoula flood features in the Portland area or calculated on the basis of the Manning equation by using a slope value of 1×10^{-5} (reflecting ponding in the Portland basin). Assignment of energy-loss coefficients, such as Manning *n* (flow resistance imparted by boundary roughness), was based on best estimates developed from experience with modeling other large flood discharges (e.g., O'Connor and Baker, 1992; O'Connor, 1993). For flow over the modern channel and flood plain of the Columbia River, *n* was assigned a value of 0.03; for flow over valley sides and flanking upland, *n* was 0.05. Sensitivity of the resulting discharge estimates to Manning *n* was assessed by trials with a range of *n* values. Expansion and contraction energy-loss parameters were assigned values of 0.3 and 0.1, respectively. Although no specific trials of sensitivity to these values were conducted for this study, results from previous studies (e.g., O'Connor and Webb, 1988) indicate that reasonable ranges of these values have little effect, especially in reaches such as this one where there are sections of critical flow.

RESULTS AND DISCUSSION

Flood Features and Stratigraphy

Missoula flood features between Wallula Gap and Portland include tracts of eroded basalt (scabland), diversion and overflow channels cut through overlying loess and alluvium, large gravel bars, and in almost every back-flooded tributary valley, as much as 10 m of bedded sand and silt.

Types of Deposits

Gravel bars left by the Missoula floods are found in locations that would logically be zones of diminished velocity (Bretz, 1928). Tractive bar deposits are composed of sediment we infer was transported as bedload and are generally the coarsest and most poorly sorted. Clasts in tractive bars were mostly deposited in downstream-directed foresets, are angular to rounded, and almost everywhere attributable to local sources. Abundant soil and loess clasts, some with diameters >1 m, also attest to short transport distances.

Tractive deposits common along the Columbia River valley between Wallula Gap and Portland include large delta-like bars formed by flow spilling from high upland channels into back-flooded tributary valleys (Figs. 3, 4; Bretz, 1925, p. 244; 1928, p. 693; Allison, 1933, p. 196). These bars, commonly fan shaped in plan view, are composed of downstream-dipping foresets overlain by subhorizontal beds. Where the original morphology is preserved, the downstream ends of the bars terminate with smooth 30° slopes concordant with foreset bedding (Fig. 3C). Many of these bar surfaces have current dunes on their surfaces (Fig. 3A).

At many of the tributary junctions with the Columbia River between Wallula Gap and Portland, large, round-topped, gravel deposits (Bretz, 1925, 1928) partially block tributary mouths. These ''eddy bars'' are composed of clasts ranging from sand to small cobbles commonly deposited in foresets dipping *up* tributary valleys. Eddy-bar sediments are generally finer and better sorted than tractive-bar sediments and are interpreted to have been deposited from the flood's suspended load in zones of flow recirculation that developed in the canyon reentrants at tributary junctions (O'Connor, 1993, p. 58–62).

Sand and silt mantle parts of almost every back-flooded valley along the flood route between glacial Lake Missoula and Portland (e.g., Bretz, 1929; Allison, 1933, 1941; Glenn, 1965; Waitt, 1980, 1985, 1994; Atwater, 1986, 1987; Smith, 1993). Between Wallula Gap and Portland, back-flooded valley deposits near the Columbia River are generally composed of coarse sand, locally containing gravel, and at some locations are traceable to eddy bars at tributary mouths. Fine sand and silt predominate at higher and more distal sites. In the John Day and Deschutes River valleys, such deposits are found as far as 100 km upstream from the Columbia River confluence. The sand and silt deposits are thickest and most extensive on the valley bottoms, generally at low altitudes, but are also found as a thin blanket (<1 m thick) on upland surfaces up to about maximum-flood stage, although at higher altitudes it is difficult to distinguish Missoula flood silt from late Pleistocene loess.

A distinctive feature of the sand and silt deposits, especially in the valley bottoms, is their rhythmic bedding manifested by sequences of graded beds or couplets of contrasting grain sizes. Thicknesses of individual rhythmite beds range from >20 cm to >2 m, and beds generally thin and fine up-section (Fig. 2). Where studied elsewhere, evidence of subaerial exposure or hiatuses between individual beds within these generally low-lying rhythmites—such as varves, burrows, mudcracks, and fallout tephra (Glenn, 1965; Waitt, 1980, 1984, 1985, 1987, 1994; Atwater, 1986; Smith, 1993)—led to the hypothesis that there were as many as 89 releases from glacial Lake Missoula. This evidence, however, has been contested by Shaw et al. (1999), followed by rebuttal by Atwater et al. (2000).

Evidence for Multiple Floods in Coarse Deposits

Many of the tractive and eddy bars between Wallula Gap and Portland contain prominent stratigraphic discontinuities that we interpret to mark boundaries between deposits of separate floods. But evidence of multiple floods in deposits of coarse sand and gravel is generally less compelling and probably less complete than in finer-grained rhythmite sections, where successive rhythmites are conformable and where upper parts of many rhythmites contain burrows, channels, loess, and tephra layers. By contrast, stratigraphic discontinuities within coarser facies are generally sweeping unconformities juxtaposing gravel against gravel, locally with intervening sand and silt layers or coarse boulder layers (Fig. 4). Such discontinuities may be ascribed to pulses within a single flood. Their close inspection, however, reveals features similar to those at contacts between rhythmites, including features we interpret as illuviated silt, colluvium, burrows, and fallout tephra.

Estimating the number of separate floods recorded in gravel-bar exposures is difficult because not all contacts show compelling evidence of subaerial exposure, and one must judge whether gravel beds bounded by prominent contacts or beds of finer sediment indeed record separate floods. Additionally, for several tall exposures we could not closely inspect each contact and could only estimate the number of separate floods represented by counting beds separated by prominent unconformities. Our experience with bringing many geologists to some of these study sites is that

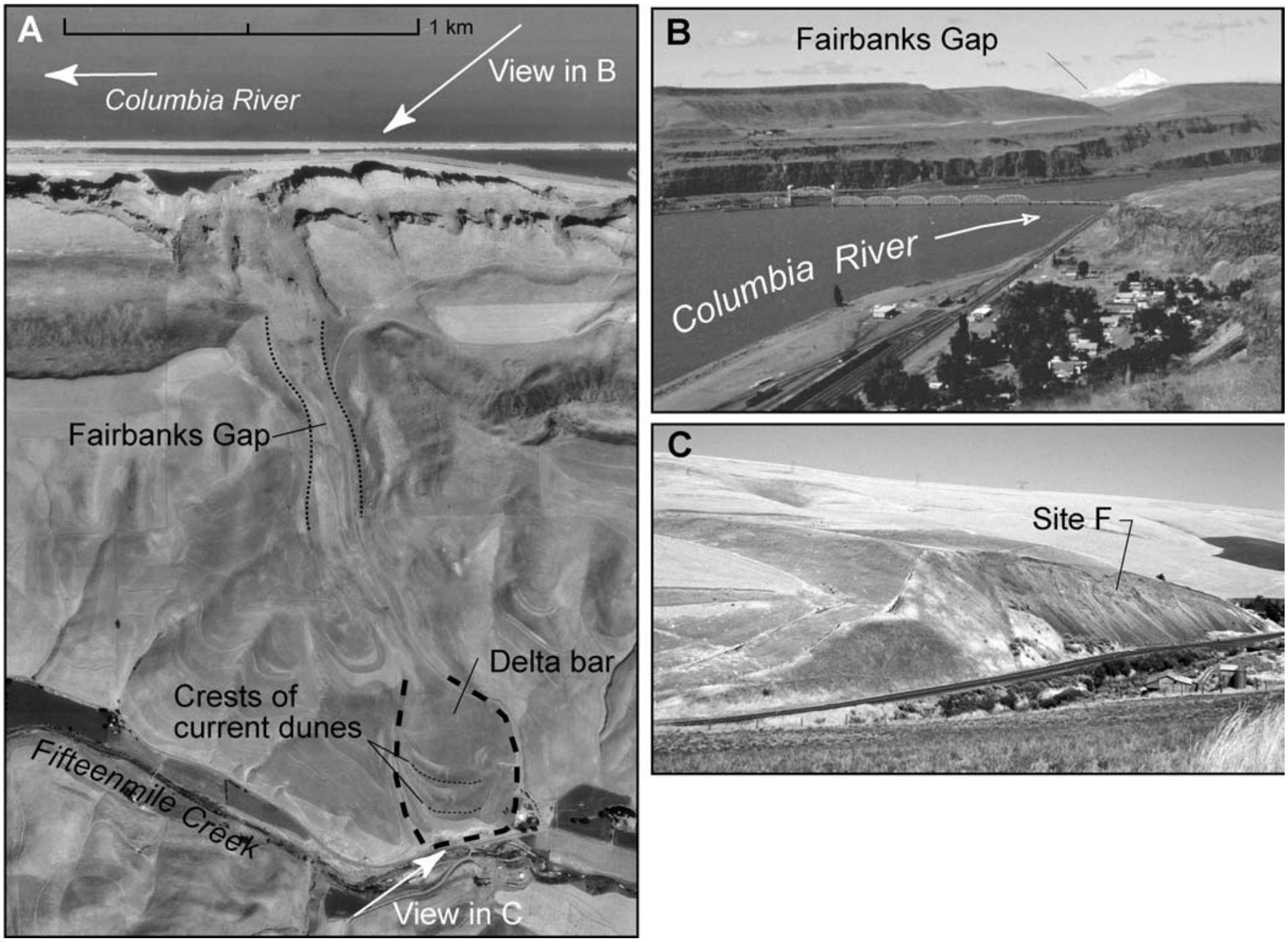

Figure 3. The Fairbanks delta bar, formed by Missoula floodwaters spilling southward out of the Columbia River valley and into the valley of Fifteenmile Creek. (A) Vertical overview from USGS digital orthophotograph (1994). (B) View southwestward across the Columbia River to Fairbanks divide. The divide is 200 m above the present impounded water level of the Columbia River and 220 m above typical pre-dam river level. For overtopping, discharge had to exceed 5 × 10^6 m^3/s. (C) Northwestward view of the delta bar and site F.

flood counts might vary by a factor of two, depending on one's definition of ''prominent unconformity.'' For this analysis, the number of floods ascribed to each deposit is based on counting deposits between disconformities marked by widespread boulder concentrations (commonly associated with erosion of the underlying bed), deposits from local sources, or other evidence of subaerial exposure. Many of the bars probably record more floods than we infer from them, a problem compounded by limited exposure at most bars.

Evidence for multiple flows is found in all types of bars along the Columbia River valley between Arlington and Hood River, but the delta bars deposited into tributary valleys are particularly suitable: not only are they typically well exposed, but they only record floods large enough to cross the upland divides between the deposit and the Columbia River valley. Thus, the altitude of the divide crossing can be related to hydraulic-modeling results to determine the discharge that floods must have exceeded to form the deposits. For example, the bar at Petersburg (site E in Fig. 1) was deposited by flows spilling south out of the Columbia River valley and into Fifteenmile Creek valley via a 2-km-long, 1.5-km-wide divide crossing eroded down through loess and Pliocene deposits. The altitude of the bottom of the divide is 180 m above sea level (~155 m above the preimpoundment altitude of the Columbia River). The core of the bar is composed of boulder-to-pebble gravel and sand deposited in foreset beds, apparently as the delta bar prograded into Fifteenmile Creek valley (Fig. 4A). Many of the contacts between thick gravel beds are unconformable and are locally associated with sand lenses, coarse boulder lags, or both (Fig. 4B). Exposures 0.5 km to the northeast at the east edge of the bar also show several sand and gravel couplets that are finer, thinner, and more gently dipping than the deposits in the core of the bar (Fig. 4C). The exposure of the core of the bar shows nine prominent beds, which we infer resulted from that many separate floods large enough to vigorously overtop the 180 m divide crossing.

Not all such bars show similar evidence of multiple flood deposits. Five kilometers to the east, flow from the Columbia River valley spilled into Fifteenmile Creek valley via another divide crossing at Fairbanks Gap (site F, Fig. 3), which, at an altitude of 250 m, is 70 m higher than the divide at Petersburg. A 30-m-high road cut that is perpendicular to the

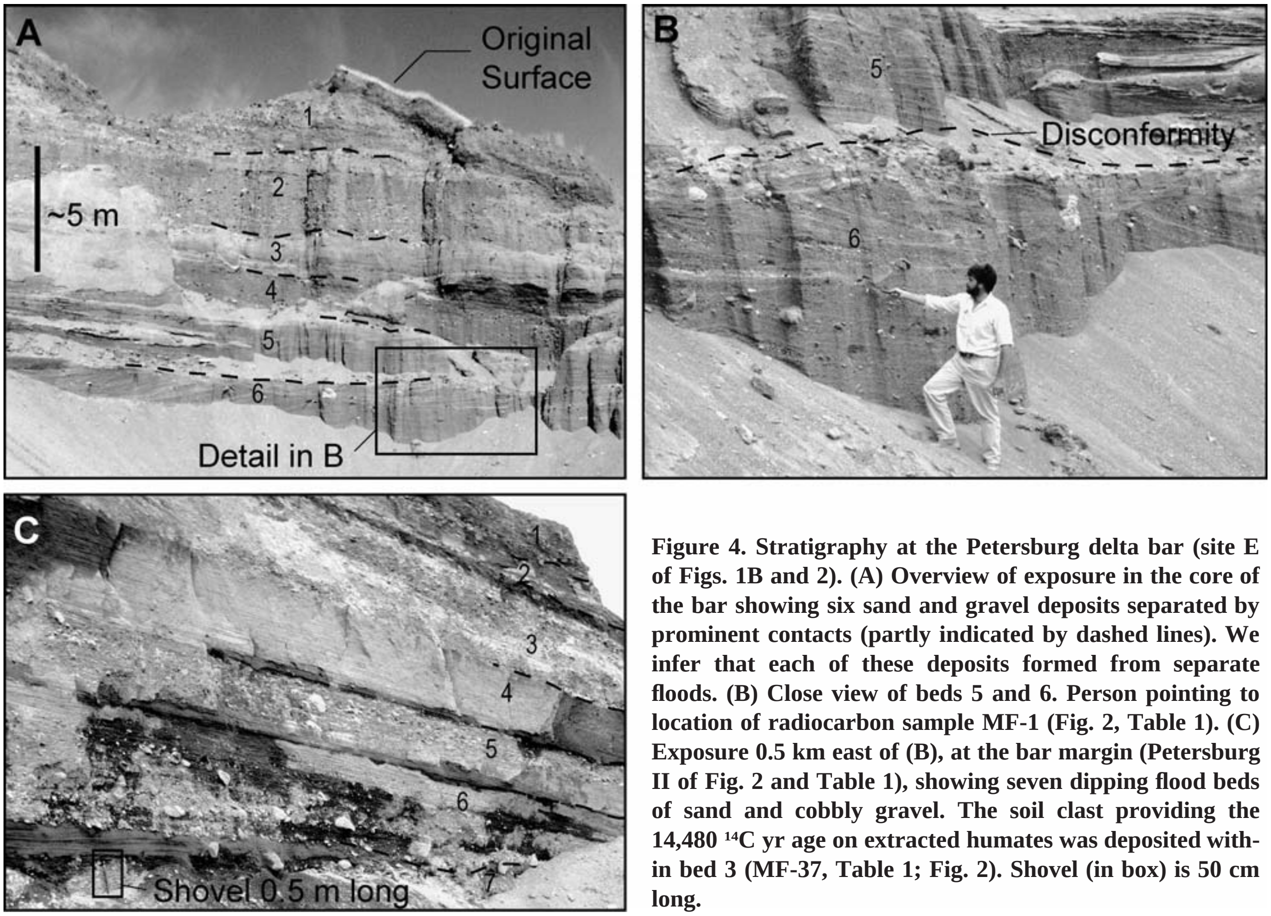

Figure 4. Stratigraphy at the Petersburg delta bar (site E of Figs. 1B and 2). (A) Overview of exposure in the core of the bar showing six sand and gravel deposits separated by prominent contacts (partly indicated by dashed lines). We infer that each of these deposits formed from separate floods. (B) Close view of beds 5 and 6. Person pointing to location of radiocarbon sample MF-1 (Fig. 2, Table 1). (C) Exposure 0.5 km east of (B), at the bar margin (Petersburg II of Fig. 2 and Table 1), showing seven dipping flood beds of sand and cobbly gravel. The soil clast providing the 14,480 ^{14}C yr age on extracted humates was deposited within bed 3 (MF-37, Table 1; Fig. 2). Shovel (in box) is 50 cm long.

delta front partly exposes bouldery gravel without the sweeping unconformities seen in the bar near Petersburg (Figs. 2, 4C). Possible explanations for the lack of unconformities include (1) the contacts are not visible because separate boulder deposits are juxtaposed without detectable contrast in grain size or evidence of subaerial exposure, (2) the deposits of the last overtopping flood conceal deposits of earlier floods, or (3) only one flood was large enough to vigorously overtop this higher divide.

Similar delta bars resulted from overflow into Alkali Canyon near Arlington (site L), the John Day River valley near Philippi Canyon and near McDonald Ford (sites J and K), and into the Mosier Creek valley near Mosier (site B). Best exposed is site B, where from one outcrop we infer at least seven floods (Fig. 2).

Exposures within two high tractive bars on uplands flanking the Columbia River valley also show strong evidence for being formed by multiple floods. Near Maryhill is a bar (site H), 1 km long, with a crest at an altitude of 255 m. A gravel pit shows three-dimensional exposure of west-dipping foreset beds of alternating sand and gravel containing clasts as large as 30–40 cm (Fig. 5). Most of these foreset beds are conformable and probably record the passage and deposition of dunes on slip faces as the bar grew westward during individual floods. By contrast, however, at least five contacts between foreset layers disconformably overlie a coarser cobble framework filled with a brown silty matrix. We infer the coarser tops of each of these foreset beds to have resulted from armoring during later, sediment-depleted periods of individual

Figure 5. Northward view of an exposure of the tractive bar near Maryhill (site H) showing downstream-dipping foresets of cobbly and sandy gravel. The top of the bar has been removed from this part of the exposure. The disconformity locally truncates underlying deposits and is locally marked by accumulation of interstitial silt in the underlying gravel.

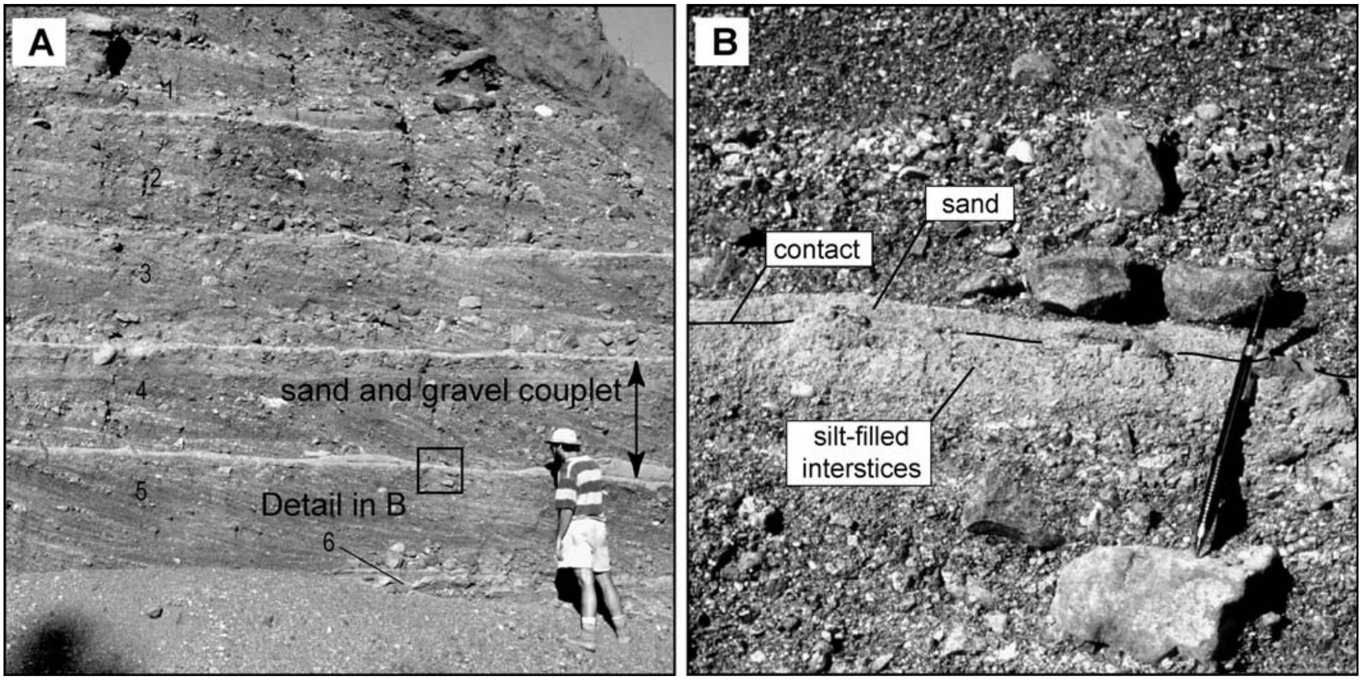

Figure 6. Stratigraphy of the eddy bar near the confluence of the Deschutes and Columbia Rivers (site G). (A) Eastward view of four depositional beds (couplets of sand and gravel) and parts of two others. Each bed is separated by planar disconformities and is composed of cobbly and sandy gravel and a thin silty cap. Foresets within the gravel parts of the couplets dip southward, away from the Columbia River and up the Deschutes River valley. Many of the couplets contain a basal layer of medium sand, up to 30 cm thick, deposited with northward-dipping foresets. We infer that each sand and gravel couplet was deposited during a single flood. (B) Close view of contact between couplets showing 1 cm of sand at the base of one couplet overlying coarser sand and gravel of the underlying couplet. In the uppermost 3 cm of the sandy gravel, clasts are more randomly oriented than below, and their interstices are filled with silt and fine sand. From these features we infer surface disturbance and eolian infilling during subaerial exposure. Pencil is 15 cm long.

floods. The brown silt contained in the upper few centimeters of each bed is inferred to be of eolian origin that illuviated into interstices while the gravel bar was exposed subaerially. Where this silt is present, tracing the contact laterally leads to disconformities where cobbly lags cut across bedding of the underlying deposits, apparently recording erosion before or during deposition of the overlying gravel foreset beds (Fig. 5). The incompletely exposed Maryhill bar shows six sets of foreset beds separated by silty, unconformable contacts, implying that at least that many floods transported gravel across the surface of the bar.

A similar bar near Arlington (site M) was trenched in the early 1980s, revealing the whole stratigraphy from underlying Tertiary sediment to capping soil (Baker and Bunker, 1985; R.C. Bunker, 1994, personal commun.). The bar ranges from 245 to 255 m above sea level and comprises five or six sets of foreset beds that dip north and away from the adjacent overflow channel. The foreset beds overlie subhorizontal, cross-bedded gravel, which unconformably overlies Tertiary sediment. Groups of foresets are separated by contacts like those at Maryhill bar, including one contact where the Mount St. Helens set-S tephra is locally preserved, indicating subaerial exposure between two separate floods (Baker and Bunker, 1985). If the other similar contacts in this deposit also represent periods of subaerial exposure, this bar also records six or seven flows, including two or three that postdate the set-S tephra.

Large eddy bars lie in almost every tributary mouth and canyon reentrant along the Columbia River valley (Bretz, 1925, 1928). Exposures of these also reveal evidence for multiple flows. One of the highest (185 m above sea level) is ~2 km northwest of Lyle (site D), where east-dipping foreset beds of well-sorted gravel and coarse sand were apparently deposited in a large eddy on the north side of the Columbia Valley. Seven prominent stratigraphic breaks are exposed (Fig. 2), each defined by 0–20 cm layers of sand and gravel with silt-filled interstices disconformably overlain by as much as 25 cm of steeply dipping (≤35°) sandy gravel. We infer that the silt illuviated into the upper few centimeters of the sand and gravel during times between floods, and we view the steeply dipping sandy gravel lenses as talus from raveling, between floods, of flood-deposited gravel on a sloping flank of the bar. If each of the stratigraphic breaks records a hiatus between floods, the outcrop records eight separate floods. This deposit is apparently inset against an even higher (surface is 220 m above sea level) and coarser deposit tucked into a small tributary valley to the north (site C), but only ~1 m of its stratigraphy is exposed.

Another large and high eddy bar formed at the mouth of the Deschutes River (Bretz, 1928, p. 458; site G) and has a maximum altitude of 150 m above sea level. A gravel pit near its top reveals at least seven subhorizontal couplets, each consisting of cross-bedded medium sand, as much as 30 cm thick, unconformably overlain by up to 120 cm of foreset-bedded sandy gravel (Fig. 6A). Couplet thickness decreases up-section from 120 cm to ~30 cm. The top ~3 cm of the sandy gravel of each couplet has silt-filled interstices between granules that lack sedimentary structure (Fig. 6B). We infer the silt to be windblown dust illuviated into the top of each deposit during subaerial exposure. The seven sand and gravel couplets thus indicate that at least seven separate floods formed this eddy bar. The couplets of sand overlain by sandy gravel probably result from changes in local eddy circulation during separate floods—the lower sand deposited during waxing flow while the site was inundated, but was away from currents within the back-flooded tributary mouth, whereas the gravel was deposited later during the same flood, but near the time of peak stage when flow recirculation over the site was more vigorous.

Quarries in an eddy bar tucked against the valley margin of Helm Canyon (Fig. 2, site I) expose four deposits of bedded sand and gravel up to an altitude of 215 m above sea level. Each of the sand and gravel beds is separated by discontinuous diamicts of angular basalt clasts within a silty matrix. We infer the lenses of angular basalt to be colluvium that accumulated on top of flood deposits during times between floods, thus implying at least four separate floods recorded by the beds of sand and gravel.

Rhythmites

We have not mapped and analyzed all rhythmite deposits in the study area because they are generally at altitudes so low that they do not necessarily indicate discharges as great as those required by higher, coarse-grained deposits. Nevertheless, some fine-grained deposits are exposed at high altitude (Fig. 2, sites N, O, P, and Q), and their geomorphic relationships with adjacent high-energy facies and the local presence of the Mount St. Helens set-S tephra aid in correlation between slackwater and coarse facies.

About 10 km southeast of Arlington, a road cut exposes at least six cycles of fining-up sequences of fine sand and silt deposited between ~215 and 220 m above sea level (Fig. 7A; site N). The cycles themselves thin and fine upward from 20–30 cm thick near the bottom of the exposure (Fig. 7B) to a few centimeters thick at the top. The base of the rhythmites is not exposed. Three thin (<1 mm) and discontinuous tephra layers lie within the rhythmites, two near the top of the fifth visible cycle from the top and one at the next overlying cycle (Fig. 7C). Although these tephra layers have not been geochemically or petrographically identified, their similar stratigraphic position, the almost identical grain size and field appearance, and the number of layers indicate that they are almost certainly components of the Mount St. Helens set-S tephra found in similar rhythmite exposures in Oregon and Washington (Mullineaux et al., 1978; Waitt, 1980, 1985; Bunker, 1982), including the discontinuous tephra chemically identified as set-S at the nearby site M (Baker and Bunker, 1985). If the presence of fallout tephra indicates subaerial exposure and if similar contacts between rhythmite cycles also represent periods of subaerial exposure (Waitt, 1980, 1985), site N records at least six floods.

A thicker but lower (205 m above sea level) sequence of rhythmites is exposed in Alkali Canyon, 8 km south of Arlington (site O). The bottom of the rhythmites is not exposed here either, but 15 fining-up cycles of bedded fine sand and silt were counted in the 4-m-tall section. The three uppermost cycles overlie a fallout tephra, also inferred to be set-S. If the cycles all record separate floods, at least 15 floods reached an altitude of 205 m, and three of them postdate the set-S tephra.

A much lower exposure of rhythmites in Alkali Canyon, 2 km south of Arlington (site P) shows at least 10 rhythmites. This sequence partly fills the valley bottom and forms a prominent surface at 130–145 m that is inset against the gravel delta that prograded into the valley from the overflow channels to the east. Despite searching, we did not find tephra in this set of rhythmites.

Several other rhythmite sections are also exposed in the study area. Of at least 10 sandy rhythmites in the John Day Valley (site Q; Figs. 7C, 7D), five overlie a tephra inferred to be set-S. An exposure 3 km southeast of The Dalles (in part described by Cordero, 1997) also reveals ~10 fine sand and silt rhythmites, including at least three that overlie the set-S tephra.

In addition to the low and well-bedded rhythmites, isolated exposures of fine-grained sediment approach the maximum flood limit. South of The Dalles, Allison (1933, p. 353) described a ''thin silt sheet'' up to 290 m. We have seen similar deposits at several locations, generally composed of less than 1 m of tan to gray, very fine sand and silt, locally laminated but generally lacking sedimentary structures. These deposits conformably overlie massive to blocky tan silt and fine sand that appear to have been the underlying land surface of actively accumulating loess. The contact is sharp and, at one location (site R in Fig. 1), was marked by a granite cobble, apparently ice rafted by a large Missoula flood.

Ages of Flood Deposits

In exposures between Wallula Gap and Hood River, detrital organic material is sparse but present within and below Missoula flood deposits. Radiocarbon ages of such material, together with the local presence of the Mount St. Helens set-S tephras and the geomorphic and stratigraphic relationships of enclosing deposits, help clarify the chronology of the late Pleistocene Missoula floods.

Most samples collected for radiocarbon dating were from gravel deposits and consisted of charcoal, soil organic material, dung, bones, and fibrous clasts of organic-rich silt (probably mats of cyanobacteria). We obtained radiocarbon analyses on 25 samples from various sites, yielding ages from older than 40,000 to 13,700 ^{14}C yr B.P. (Table 1). Because all these ages are from transported material within or below the Missoula flood deposits, they are maximum-limiting ages for the floods. The wide range of resulting ages is not unexpected with such diverse samples. Some ''charcoal'' samples that gave ages older than 40 ka are probably pre-Quaternary coal. Other very old charcoal samples, including one friable sample that cleaved along growth rings, were probably derived from sites where they had been protected from decay for many thousands of years.

The large number of samples that gave ages between 20,000 and 30,000 ^{14}C yr B.P. were probably entrained from sites of sediment accumulation and soil formation prior to the floods, and their ages reflect carbon photosynthesized during thousands of years before the floods. Humate extracts and plant fragments, isolated from larger bulk soil and sediment clasts collected either within or below Missoula flood deposits (and below the range of modern soil formation processes), gave ages substantially younger than those derived from corresponding bulk samples (Table 1) and probably limit the age of the floods more closely. Many of the older ages are discordant (out of stratigraphic order) with ages younger than 20,000 ^{14}C yr B.P. commonly found stratigraphically below much older ages (Fig. 2).

Mount St. Helens set-S tephra was blown widely across south-central Washington during several late Pleistocene eruptions, forming up to four distinct layers within rhythmite sequences in the Yakima and Walla Walla River valleys (Mullineaux et al., 1978; Waitt, 1980, 1985). In the most complete section in the Yakima River valley, the top of one rhythmite contains a prominent tephra couplet >6.5 cm thick (Waitt, 1980), and each of the rhythmites above and below is capped by <1-mm-thick layers of fine ash (Waitt, 1985). The set-S tephra has been geochemically and petrographically correlated with proximal deposits at Mount St. Helens for several sites in south-central Washington (Mullineaux et al., 1978;

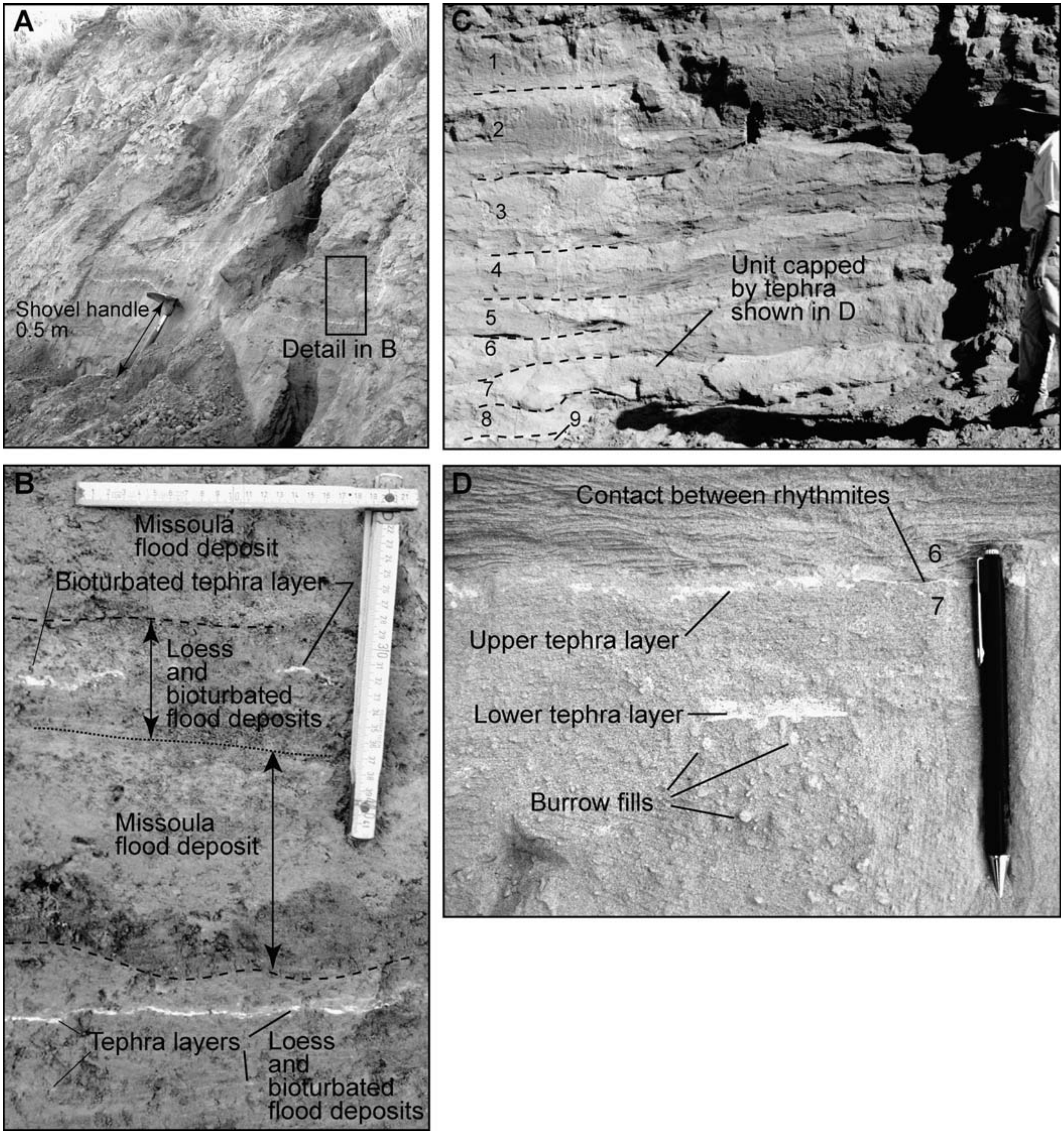

Figure 7. Rhythmite exposures in the study area. (A) Westward view of sand and silt rhythmites at site N. The six or seven flood beds are not clearly visible, but can be counted based on grain-size variation. (B) Close view of site N, showing bed 4 and parts of beds 3 and 5. A single, partly destroyed, tephra layer was deposited near the top of bed 4, and two tephra layers fell while bed 5 was the land surface. Of this couplet capping bed 5, the lower tephra layer is mostly bioturbated, similar to the exposure at site Q. Carpenter ruler segments are 22 cm long. (C) Southward view in the John Day River valley (site Q) showing nine fining-up cycles of sand and silt. (D) Close view of contact between beds 6 and 7 of C, showing two ash layers that are probably part of the Mount St. Helens set-S tephras. Few primary sedimentary structures are visible in the upper 15 cm of the bed containing the tephra layers (in contrast to the well-preserved ripple structures at the base of the overlying flood bed), and the lower, thicker tephra has been mostly destroyed by burrowing (tephra visible in small burrow fills under the original layer). Because the upper tephra layer is more continuous, much of this bioturbation probably dates from the time between deposition of the ash layers. The next flood layer was apparently deposited soon after the second tephra fall, judging from the continuity of the layer. Pencil is 15 cm long.

TABLE 1. RADIOCARBON AGES FROM MISSOULA FLOOD DEPOSITS IN THE COLUMBIA VALLEY BETWEEN ARLINGTON AND HOOD RIVER, OREGON

Lab number	Field number	Material dated†	Pretreatment§	Age (C^{14} yr B.P. ± 1σ)	Comments
Mosier eddy bar (site A)					
AA-9283	MF-40	Charcoal	ABA	14,795 ± 150	Clast in Missoula flood deposit
AA-9284	MF-42	Charcoal	ABA	>46,300	Clast in Missoula flood deposit. Sample possibly coal
Mosier delta bar (site B)					
A-6534	MF-19	Cyanobacteria	ABA	41,460 +3270/–2320	Clast in Missoula flood deposit
A-6538	MF-66	Cyanobacteria	ABA	30,410 +680/–620	Clast in Missoula flood deposit
AA-9275	MF-11	Cyanobacteria	A	21,185 ± 220	Clast in Missoula flood deposit
AA-8291	MF-12	Cyanobacteria	ABA	28,845 ± 370	Clast in Missoula flood deposit
AA-8292	MF-14	Dung	ABA	13,695 ± 95	Clast in Missoula flood deposit
AA-8293	MF-16	Cyanobacteria and plant fragments	ABA	36,645 ± 905	Clast in Missoula flood deposit
Secondary pit adjacent to described section					
A-6535	MF-27	Charcoal and wood	ABA	35,150 +1400/–1200	Clast in Missoula flood deposit
AA-9285	MF-50	Charcoal	ABA	40,300 ± 1500	Clast in Missoula flood deposit
Lyle high eddy bar (site C)					
A-6526	MF-3	Cyanobacteria		23,000 +520/–490	Clast in Missoula flood deposit
Lyle inset eddy bar (site D)					
AA-9287	MF-62	Charcoal	ABA	>42,600	Clast in Missoula flood deposit. Sample possibly coal
Petersburg delta bar: I (site E)					
GX-16867	MF-1A	Cyanobacteria	ABA	24,200 +520/–490	Clast in Missoula flood deposit
AA-7588	MF-1B	Cyanobacteria	ABA	16,720 ± 210	Clast in Missoula flood deposit
AA-8259	MF-5	Cyanobacteria	ABA	45,500 ± 2700	Clast in Missoula flood deposit
AA-9276	MF-35	Cyanobacteria	A	31,870 ± 650	Clast in Missoula flood deposit
AA-9277	MF-36	Cyanobacteria	A	23,400 ± 250	Clast in Missoula flood deposit
Petersburg delta bar: II (site E)					
AA-9278	MF-37A	Organic-rich soil clast	A	32,920 ± 650	Clast in Missoula flood deposit
AA-9278	MF-37B	Humic acid extract from soil clast	ABA	14,480 ± 145	Age from humic acid extracted from soil clast MF-37
Fairbanks delta bar (site F)					
AA-8294	MF-29	Charcoal	ABA	>43,600	Clast in Missoula flood deposit. Sample possibly coal
AA-8290	MF-30	Charcoal	ABA	46,000 ± 3000	Clast in Missoula flood deposit. Sample possibly coal
Maryhill tractive bar (site H)					
AA-9286	MF-59	Charcoal	A	32,630 ± 610	Clast in Missoula flood deposit
Philippi eddy bar (site J)					
A-6529	MF-31	Soil clast	ABA	35,980 +2460/–1880	Soil clast from bedded slope deposits beneath Missoula flood deposit
AA-9281	MF-39A	Soil clast		29,845 ± 470	Soil clast from bedded slope deposits beneath Missoula flood deposit
AA-9282	MF-39B	Humic acid extract from soil clast	ABA	19,015 ± 165	Age from humic acid extracted from soil clast MF-39

Note: Sites for localities refer to Figures 1B and 2.
†Material identification primarily from hand lens inspection except for cyanobacteria (blue-green algae) for which the preliminary field identification (collected as thin friable clasts commonly containing macroscopic plant fragments) is supported by electron-microscope analysis by C. Ascaso at the Centro de Ciencias Medioabientales, Spain.
§Pretreatment: ABA, acid-base-acid standard pretreatment; A, acid only.

Waitt, 1980; Bunker, 1982; McDonald and Busacca, 1988; Busacca et al., 1992).

The set-S tephras are usually considered to be ca. 13,000 radiocarbon years old on the basis of radiocarbon dating of charcoal and wood within the tephra layers and associated volcanic deposits near the volcano (Crandell et al., 1981; Mullineaux, 1986, 1996). Consistent with this interpretation are dates as young as 13,326 ± 185 and 14,060 ± 450 ^{14}C yr B.P. from shells in the third rhythmite below a Mount St. Helens S-set couplet in the Yakima River valley (Baker and Bunker, 1985, p. 20; Waitt, 1985, p. 1284). The age of set-S is made somewhat uncertain, however, by the evidence that Begét et al. (1997, p. 143) presented of ''distal tephra deposits [primarily north of the volcano] [that] are apparently geochemically correlative with set-S [that] predate 14,500–14,000 [^{14}C] yr B.P. and may be as old as 16,000 [^{14}C] yr B.P.'' Additionally, thermoluminescence dating of loess stratigraphically bracketing a set-S tephra in eastern Washington indicates that the tephra is 18,500 ± 1500 cal. (calendar) yr B.P., equivalent to ca. 15,500 ± 1500 ^{14}C yr B.P. (Berger and Busacca, 1995). For now, we rely on the radiocarbon dates in southern Washington and consider the tephras enclosed within Missoula flood deposits in north-central Oregon to date to ca. 13,000 ^{14}C yr B.P., but if the tephras in our field sites are not the set-S tephras, or if the set-S tephras are indeed significantly older than 13,000 yr B.P., our conclusions regarding flood timing will require modification.

The radiocarbon results, the local presence of the set-S tephra, and the weak soils capping the high gravel bars indicate that most, if not all, of the coarse Missoula flood deposits in the Columbia River valley are from a last-glacial episode of flooding. For example, we obtained (1) samples dated at 16,720 ± 210 and 14,480 ± 145 ^{14}C yr B.P. from the delta-like bar near Petersburg (site E), (2) a date 13,700 ± 95 ^{14}C yr B.P. from dung incorporated into the delta bar near Mosier (site B), (3) a date 14,795 ± 150 ^{14}C yr B.P. from charcoal within the high eddy deposit near Mosier (site A), and (4), a date 19,010 ± 165 ^{14}C yr B.P. from humates extracted from a soil clast in colluvium beneath flood deposits near the divide crossing at Philippi Canyon (site J). These ages and the set-S tephra imply that many floods occurred after 15,000–13,000 ^{14}C yr B.P., although some very large floods, such as the one that formed the bar near the divide crossing at Philippi Canyon, are only known to postdate 19,010 ± 165 ^{14}C yr B.P. The evidence of several floods that postdate the set-S tephras may indicate (1) Missoula floods continued somewhat past 12,700 ^{14}C yr B.P., the time that Waitt and Atwater (1989) postulated for the demise of glacial Lake Missoula, or (2) the set-S tephra is older than 13,000 yr B.P., as proposed by Berger and Busacca (1995) and Begét et al. (1997). We have not yet found any coarse deposits in the study area that have soils or radiocarbon results that indicate pre-Wisconsin episodes of Missoula flooding, such as identified in eastern Washington by Bjornstad et al. (2001), although Cordero (1997) inferred older flooding recorded in fine-grained deposits preserved below last-glacial Missoula-flood rhythmites near The Dalles.

Flood Discharges

Flow-Modeling Results

Water-surface profiles were calculated for discharges between 1×10^6 m^3/s and 10×10^6 m^3/s at increments of 1×10^6 m^3/s (Fig. 8). Steps in the calculated water-surface profiles are due to flow funneling through valley

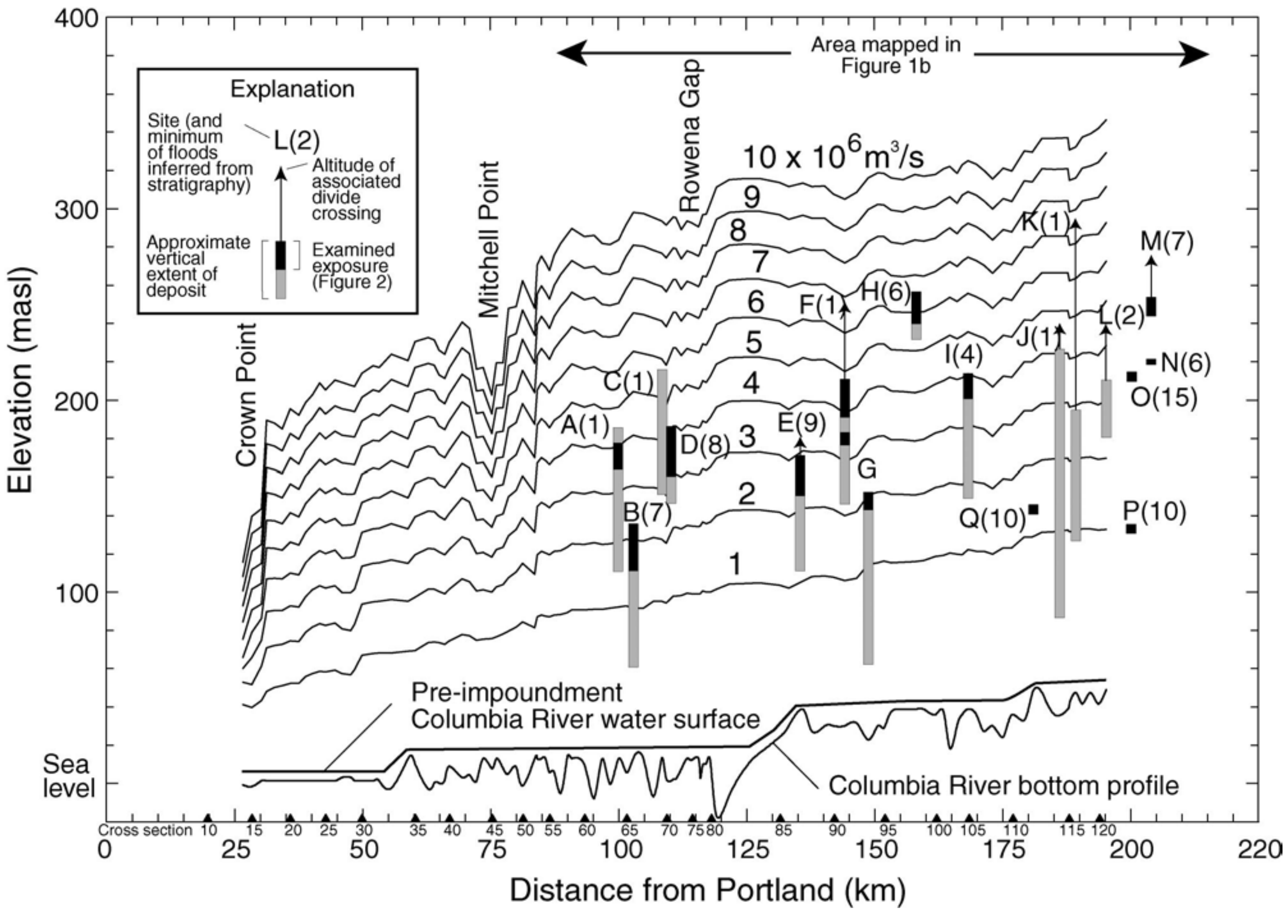

Figure 8. Step-backwater water-surface profiles for discharges between 1 × 10^6 m^3/s and 10 × 10^6 m^3/s and their relationship to stratigraphic evidence of multiple floods in the study area. The altitude ranges shown for the described parts of the deposits are only approximate because the sections were measured perpendicular to bedding, which had dips as great as 30°. Lettered sections correspond to sites described in Figure 2. Columbia River water-surface and bottom profiles generalized from bathymetry and topography shown on topographic maps. Flow was calculated by assuming a slope of 10^{-5} at cross section 1 (at Portland), but the uncertainty in this value has negligible influence upstream of Crown Point, where flow was critical or nearly so at all modeled discharges.

constrictions near Crown Point, Mitchell Point, and to a lesser extent at Rowena Gap. At Crown and Mitchell Points, flow was critical or nearly so for all discharges and reasonable boundary conditions. Because of the hydraulic control created by these constrictions, water-surface profiles upstream of Crown Point are insensitive to the boundary conditions specified at the downstream end of the reach. Additionally, profiles upstream of the Crown and Mitchell Points are less sensitive to choices of energy-loss coefficients (parameters that can only be guessed for flows of this scale) than would be the case for flow through a more uniform channel (O'Connor, 1993, p. 12–15, 34–35). Flow-modeling results for several cross sections downstream of the two constrictions with critical flow are unreliable because of the unquantified energy loss resulting from transitions between supercritical and subcritical flow downstream of such constrictions. But for this study, most of the analyzed flood evidence is upstream of these two constrictions and unaffected.

The Largest Flood(s)

The highest altitude of ice-rafted erratics, flood deposits, and erosional features define a profile of the maximum stage achieved by the largest flood(s) between Wallula Gap and Portland (Fig. 9). Maximum-flood stages dropped substantially between Wallula Gap and Portland, from at least 366 m in the Pasco Basin near the entrance to Wallula Gap (O'Connor and Baker, 1992) to ~120 m 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, through which maximum-flood stage descended from 320 m to 120 m above sea level.

A discharge of 10 × 10^6 m^3/s results in a profile that most closely matches the maximum-flood evidence, especially upstream of the constriction at Mitchell Point, where there is abundant geologic evidence of maximum-flood stages (Fig. 9). This discharge estimate is similar to that obtained at Wallula Gap by O'Connor and Baker (1992), but less sensitive to choice of energy-loss coefficients (Fig. 10) because of the hydraulic control imposed by the constrictions in the Columbia River Gorge. Hydraulic ponding behind the constrictions at Mitchell Point and Crown Point resulted in decreased water-surface gradients upstream of Hood River and probably impeded flow through Wallula Gap (also increasing the uncertainty of the O'Connor and Baker [1992] discharge estimate). Within the hydraulically ponded reaches, flow velocities were relatively slow; for example, maximum calculated velocities ranged between 5 and 20 m/s for the reach between Arlington and The Dalles. But within constrictions, velocities were tremen-

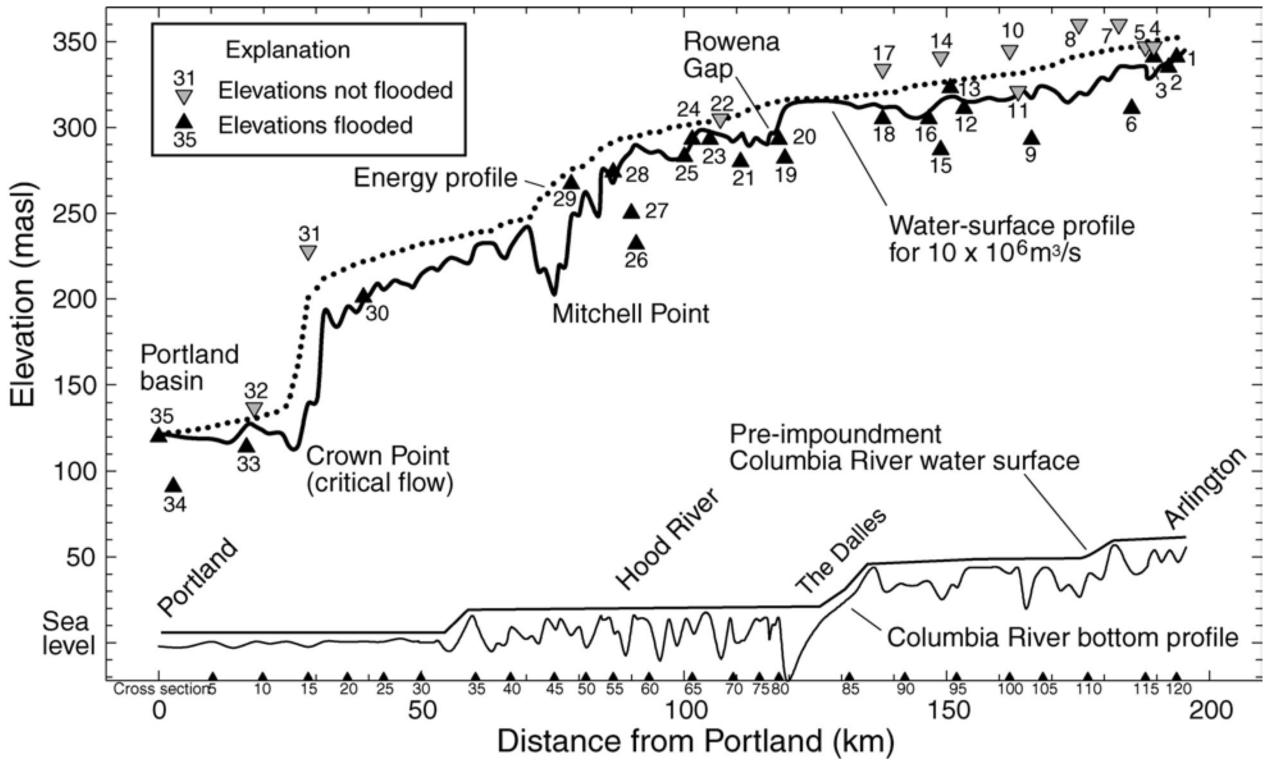

Figure 9. Step-backwater water-surface and energy profiles for a flow of 10 × 10⁶ m³/s and their relationship to evidence of maximum Missoula flood stage between Portland and Arlington. Numbered evidence of maximum-flood stages refers to descriptions in Table DR1 (see footnote 1 in text). Flow was calculated by assuming a water-surface elevation of 120 m above sea level at Portland. Upstream of the section of critical flow near Crown Point (cross sections 12 and 13), the calculated water-surface profile is identical to the 10 × 10⁶ m³/s profile shown in Figure 8.

dous, attaining 35 m/s at the Mitchell Point and Crown Point constrictions.

Discharges of Multiple Floods

The condition of critical flow within the Columbia River valley, in conjunction with a single flow route for all last-glacial floods of all magnitudes, allows us a firm basis from which to use calculated water-surface profiles to estimate discharges corresponding with the evidence for multiple flooding. Discharges associated with specific deposits were determined by comparing deposit altitude—or in the case of each delta bar, the present altitude of the lowest point of the crossed divide—to stage-discharge curves plotted for the closest cross section. As shown in Figure 10 for sites near Petersburg (and more schematically for all sections in Fig. 8), overtopping the 180 m divide at Petersburg (site E) requires a discharge of ~3 × 10⁶ m³/s, indicating that the nine inferred flood deposits in the downstream delta bar (Fig. 2) all record discharges of >3 × 10⁶ m³/s. Similarly, the delta bar near Mosier (site B) implies at least seven floods of >2 × 10⁶ m³/s, and the poorly exposed delta bar formed downstream of Alkali Canyon (site L) may record at least two floods of >3.5 × 10⁶ m³/s. These discharges associated with the delta bars are minimums because floods undoubtedly eroded these divide crossings, perhaps lowering them by as much as 30 m, judging from the altitudes of the adjacent uplands, thus increasing the discharge values by up to 2 × 10⁶ m³/s for the first floods to overtop the divides.

The longitudinal bars near Maryhill (site H) and Arlington (site M) contain the evidence for the largest multiple floods. Overtopping the bar surface at Maryhill requires a discharge of 6.5 × 10⁶ m³/s, implying at least six floods of at least that discharge. Likewise, the 245–255 m altitude of the exposure at Arlington, recording six or seven floods, requires a discharge of 5 × 10⁶ m³/s, and perhaps 6 × 10⁶ m³/s if deposition of gravel required flow over the 275-m-altitude streamlined hill to the east.

Eddy deposits also record multiple floods with large discharges. The 180 m altitude of the exposed eddy bar near Lyle (site D) requires a discharge of ~4.5 × 10⁶ m³/s to be overtopped, indicating eight floods of that discharge. The 215 m surface of the higher, adjacent, bar (site C) implies at least one flood in excess of 5.5 × 10⁶ m³/s. Similarly, the four floods inferred from deposits at Helm Canyon (site I) must have been deposited by discharges of >4 × 10⁶ m³/s.

The two well-exposed gravel bars that do not show evidence of multiple floods are the delta bar downstream from Fairbanks Gap (site F, Fig. 3) and an eddy bar near Mosier (site A). The 250-m-high divide at Fairbanks Gap required a discharge of 5 × 10⁶ m³/s to be overtopped (Figs. 8, 10) and probably a discharge of substantially more than 6 × 10⁶ m³/s to entrain much material from the divide crossing that was probably 10 to 30 m higher before erosion. The gravel eddy bar near Mosier requires a discharge of >4 × 10⁶ m³/s to be overtopped.

The altitudes of most rhythmite deposits in the Columbia Valley generally require floods of less than 3 × 10⁶ m³/s. Exceptions are sites N and O, near Arlington. At least six rhythmites at site N imply discharges of at least 4 × 10⁶ m³/s. Fifteen rhythmites at site O imply at least 15 floods of >3 × 10⁶ m³/s. Three or four of these floods at both sites postdated the set-S tephra.

The lower sequence of 10 rhythmites in Alkali Canyon, near Arlington (site P), could have been formed by discharges as small as 1 $\times$ 10^6 m^3/s. These rhythmites at site P are inset into a delta bar formed from flow that crossed uplands to the east and therefore must postdate all flows of $>$3 $\times$ 10^6 m^3/s, because any subsequent flows over these 210–280 m uplands would have destroyed the inset rhythmites. This inference is consistent with the absence of the set-S tephra in the low-lying rhythmites at site P, because deposits at nearby sites M, N, and O show that three or four post–set-S floods had discharges of $>$3–4 $\times$ 10^6 m^3/s. A similar conclusion was reached by Waitt (1994) for an exposure near Wallula Junction, Washington, where 21–25 rhythmites well exposed near river level contain no signs of the set-S tephra.

Summary of Discharges, Number of Floods, and Chronology in the Columbia Valley

The high-water evidence, stratigraphic inferences, age constraints, and modeling results can be summarized to support several inferences about the timing, number, and magnitude of Missoula floods in the Columbia River valley between Wallula Gap and Portland:

1. The altitudes of the maximum-stage evidence and the flow-modeling results show that at least one flood had a discharge of 10 $\times$ 10^6 m^3/s. The weak soil development on fine-grained flood deposits near maximum-flood stage indicates this flood (or floods) was during the last glaciation. This age is corroborated by a radiocarbon date of humates from a soil clast underneath high flood deposits near Philippi Canyon (site J; Table 1), indicating that the highest coarse-grained flood deposits were emplaced after 19,015 $\pm$ 165 ^{14}C yr B.P.

2. The longitudinal bar at Maryhill (site H) indicates at least six floods of $>$6.5 $\times$ 10^6 m^3/s. Likewise, the high longitudinal bar east of Arlington (site M) shows that at least six or seven floods had discharges of $>$5–6 $\times$ 10^6 m^3/s and that at least two or three of these floods postdated the set-S tephra. Additionally, radiocarbon ages from within the Petersburg delta bar (site E) and eddy bar at Mosier (site A) show that multiple bar-building floods had discharges of $>$3–4 $\times$ 10^6 m^3/s after ca. 15,000 ^{14}C yr B.P. (Table 1; Fig. 2).

4. The sequence of rhythmites in Alkali Canyon (site O) shows that at least 15 floods had discharges of $>$3.0 $\times$ 10^6 m^3/s, of which at least three were after the set-S tephras.

5. A lower sequence of rhythmites in Alkali Canyon (site P) provides evidence for at least ten floods that had discharges between 1.0 $\times$ 10^6 m^3/s and 3.0 $\times$ 10^6 m^3/s and probably postdated set-S.

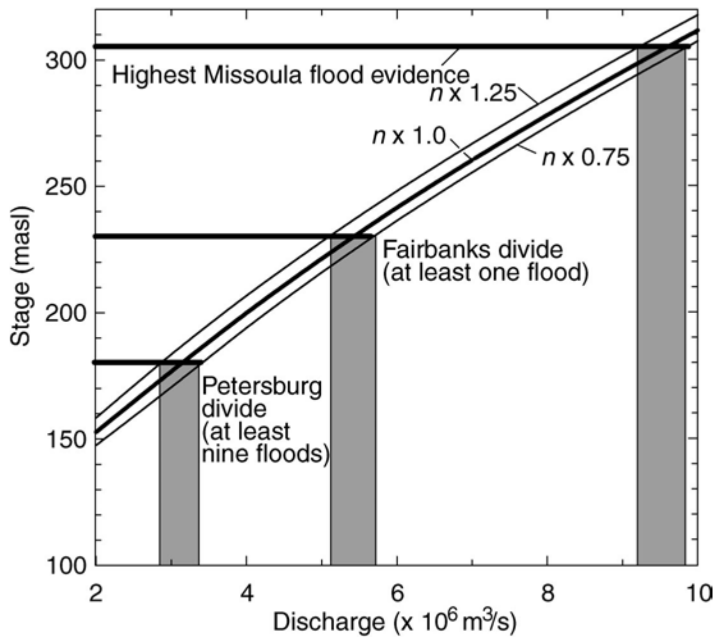

Figure 10. Stage rating curves constructed from step-backwater results near the Fairbanks Gap and Petersburg divide crossings (cross section 88). Each gray bar shows the range of discharges computed to correspond with a single flood-inundation level. The sensitivity of the step-backwater calculations to uncertainty in Manning *n* values (flow resistance imparted by boundary roughness) is shown by the three separate curves. The primary model (heavier middle curve) results from a Manning *n* value of 0.03 for flow over the present channel and flood plain of the Columbia River and 0.05 for flow over valley sides and flanking uplands, whereas for the two other curves, *n* is shifted each direction by 25%. Because of the hydraulic control imposed by downstream constrictions, the discharge estimates are relatively insensitive to uncertainties in Manning *n* values compared to reaches of more uniform flow. The highest flood evidence near Fairbanks Gap requires a discharge of 9 to 10 × 10^6 m^3/s.

Because no exposures are complete (except for the trenched bar at site M), the number of floods specified in each of these conclusions probably *underestimates* that actual number of floods that were within stated discharge values. Evidence found so far, however, requires only one flood of $>$7 $\times$ 10^6 m^3/s.

Discharge Estimates from Elsewhere along the Flood Routes

The 10 $\times$ 10^6 m^3/s discharge estimate for the maximum flood(s) in the Columbia Valley is consistent with O'Connor and Baker's (1992) estimates of $>$17 $\times$ 10^6 m^3/s near the ice dam and 10 $\pm$ 2.5 $\times$ 10^6 m^3/s for flow exiting the Pasco Basin through Wallula Gap (although the discharge could have been as high as 15 $\times$ 10^6 m^3/s if flow was critical through the Wallula Gap constriction). Step-backwater flow modeling for the Columbia River valley and Channeled Scabland routes upstream from Wallula Gap implies that a total discharge of at least 22 $\times$ 10^6 m^3/s converged onto the Pasco Basin during the largest flood(s) (Harpel et al., 2000; Waitt et al., 2000). Such inflow into the Pasco Basin, released at a rate of 10 $\times$ 10^6 m^3/s through Wallula Gap and the lower Columbia Valley, is consistent with more than half of the total volume of maximum glacial Lake Missoula hydraulically ponding upstream of Wallula Gap (Baker, 1973, p. 21; Waitt, 1980; O'Connor and Baker, 1992).

The results of Waitt (1994), Harpel et al. (2000), and Waitt et al. (2000) also show that glacial Lake Missoula released at least one large flow of $>$15.5 $\times$ 10^6 m^3/s before blockage of the Columbia River by the Okanogan lobe of the Cordilleran ice sheet. This flow included 10 $\times$ 10^6 m^3/s down the northwest segment of the Columbia Valley, 5.5 $\times$ 10^6 m^3/s down Grand Coulee, and perhaps 5.5–11 $\times$ 10^6 m^3/s down Moses Coulee. Without blockage of the Columbia River, less than 3×10^6 m^3/s crossed the scabland tracts east of Grand Coulee. In contrast, when the Okanogan lobe blocked the Columbia River valley, Moses Coulee, and at times Grand Coulee, 7.7 to 11×10^6 m^3/s coursed across the eastern part of the Channeled Scabland (Waitt et al., 2000). High-water evidence from flow through these eastern routes and down the lower Snake River valley defines a profile grading to ponding altitude of ≤325 m upstream of Wallula Gap, which is >40 m lower than the 366 m upper limit of the maximum flood(s) (Waitt, 1994). The 366 m flood stage upstream of Wallula Gap must therefore have resulted from the earlier flood(s) flowing through an unblocked northern Columbia Valley (O'Connor and Baker, 1992; Waitt, 1994, Waitt et al., 2000). For conditions of critical flow through Wallula Gap, ponding to an altitude of 366 m results in a discharge of 15×10^6 m^3/s, whereas a 325 m ponding level implies a critical-flow discharge of 10×10^6 m^3/s (from Fig. 5 of O'Connor and Baker [1992]). But because all flows were similarly impeded by the downstream constrictions in the Columbia River Gorge, the downstream maximum discharge corresponding with a maximum stage of 366 m in the Pasco Basin likely corresponds with the 10×10^6 m^3/s discharge matching the highest flood evidence in the downstream Columbia River valley, whereas the floods crossing the eastern part of the Channeled Scabland and causing the Pasco Basin stages of only 325 m likely had peak discharges of 6–7×10^6 m^3/s, reflecting the two-thirds ratio between critical-flow discharge relationships at Wallula Gap. Not factored into any of these volumes are possible releases from glacial Lake Columbia that may have been coincident or caused by Missoula floods.

Relative flood magnitude and timing have also been estimated by the thickness and maximum grain size of flood-laid beds and the altitudinal variation of the number of post–set-S rhythmites in the Channeled Scabland and back-flooded valleys (Waitt, 1980, 1985, 1994; Baker and Bunker, 1985; Smith, 1993). These results have been supplemented by varve counts and radiocarbon dating where lacustrine deposits are interbedded with flood deposits (Atwater, 1986, 1987). These relationships imply that during the last-glacial episode of flooding, flood magnitude generally decreased with time, owing to a thinning Purcell Trench lobe and shorter intervals between ice-dam failure (Atwater, 1986). This result is consistent with the less complete evidence in the lower Columbia River valley, which shows at least 10 floods of 1 to 3×10^6 m^3/s that postdated at least 15 floods with discharges of $>3 \times 10^6$ m^3/s, as well as the 24 post–set-S rhythmites (Waitt, 1994; O'Connor and Waitt, 1995) that lie at low altitude near Wallula Gap.

The timing of the largest flood or floods is more ambiguous. Varve counts, flood-bed thickness, and grain-size patterns in a 115 m glaciolacustrine section recording ~89 separate floods led Atwater (1986, 1987) to infer that eight or nine floods between 15,200 ± 400 and 14,750 ± 375 ^{14}C yr B.P were the largest late-glacial floods. These floods, however, are recorded in glacial Lake Columbia, a lake impounded in Columbia Valley in northern Washington by the Okanogan lobe of the Cordilleran ice sheet. Large floods entering this lake spilled onward primarily across the eastern scabland tracts and may in part correlate to the six or seven floods in our study area that had discharges of at least 6×10^6 m^3/s. Earlier last-glacial flood(s) predated the Okanogan lobe (Waitt, 1977, 1994) and thus the 15,550 ± 450 ^{14}C yr B.P. base of the glacial Lake Columbia section described by Atwater (1986). The flood(s) during an ice-free Columbia River, with peak discharges of at least 15.5×10^6 m^3/s into the Pasco Basin, likely correspond to the post–19,015 ± 165 ^{14}C yr B.P. flood(s) of $\sim 10 \times 10^6$ m^3/s in our study area recorded by the highest flood deposits and ice-rafted erratics. This flood or floods may correspond to one or more of several megaturbidites in the eastern Pacific Ocean ascribed to late-glacial Missoula floods and apparently predating 15,480 ± 100 ^{14}C yr B.P. (Zuffa et al., 2000).

CONCLUSIONS

Within the Columbia River valley between Wallula Gap and Portland, the evidence for maximum-flood stages and the hydraulic flow modeling indicate that at least one Missoula flood reached 10×10^6 m^3/s. The maximum-stage evidence and the step-backwater flow modeling both indicate that flow was hydraulically impeded by constrictions in the Columbia River Gorge. The result was high stages and temporary hydraulic ponding that affected flow stages as far upstream as the Pasco Basin.

Among the flood deposits left in the Columbia Valley, several contain evidence of multiple late Pleistocene Missoula floods. As at other locations along the Missoula flood route (e.g., Glenn, 1965; Waitt, 1980, 1985; Baker and Bunker, 1985; Atwater, 1986, 1987; Smith, 1993), sand and silt beds show that tens of floods occurred during the last glaciation. Moreover, at least 25 floods had discharges of $>1.0 \times 10^6$ m^3/s. Many of these floods are also recorded in high gravel bars that imply such large discharges more directly than do rhythmites of sand and silt. High gravel bars at two locations provide evidence of at least six or seven Missoula floods with peak discharges exceeding $\sim 6 \times 10^6$ m^3/s, and several lower bars also contain evidence of being formed by multiple flows. But most of the other >40 to 89 Missoula floods recorded at other sections along the flood route (e.g., Glenn, 1965; Waitt, 1980, 1985; Atwater, 1986, 1987) were too small to leave deposits in the high gravel bars and rhythmite sections along the Columbia Valley.

Radiocarbon dating, tephras, and soil development all indicate that most if not all of the flood deposits in the study area resulted from the latest episode of Pleistocene Missoula floods. The flooding apparently began sometime after 19,015 ± 165 ^{14}C yr B.P. and continued through 13,695 ± 95 ^{14}C yr B.P. and perhaps substantially past 13,000 ^{14}C yr B.P., depending on the age of the Mount St. Helens set-S tephra.

Taken together, the stratigraphy of the deposits, the results of the hydrologic modeling, and the chronologic information show that many of the high-altitude and high-energy Missoula flood features are indeed the products of multiple late Pleistocene Missoula floods, thus partly establishing the link between high-energy facies and multiple floods that Baker and Bunker (1985) stated was necessary to prove ''multiple cataclysms.'' However, most floods recorded in lake deposits and low-elevation rhythmite sections along the flood routes were probably too small to carve the scabland tracts and leave the high gravel deposits in the Columbia Valley downstream of Wallula Gap. Additionally, the highest flood evidence in the study area may have been from at least one distinctly larger flood that came primarily down the Columbia River valley before blockage at Grand Coulee by the Okanogan ice lobe; this distinctly larger flood predated the 89 or so floods recorded in glacial Lake Columbia (Atwater, 1986, 1987), which were shunted eastward though Grand Coulee and the Channeled Scabland.

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