Magnitude and timing of downstream channel aggradation and degradation in response to a dome-building eruption at Mount Hood, Oregon

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ABSTRACT

A dome-building eruption at Mount Hood, Oregon, starting in A.D. 1781 and lasting until ca. 1793, produced dome-collapse lithic pyroclastic flows that triggered lahars and intermittently fed 10^8 m^3 of coarse volcaniclastic sediment to sediment reservoirs in headwater canyons of the Sandy River. Mobilization of dominantly sandy sediment from these reservoirs by lahars and seasonal floods initiated downstream migration of a sediment wave that resulted in a profound cycle of aggradation and degradation in the lowermost reach of the river (depositional reach), 61–87 km from the source. Stratigraphic and sedimentologic relations in the alluvial fill, together with dendrochronologic dating of degradation terraces, demonstrate that (1) channel aggradation in response to sediment loading in the headwater canyons raised the river bed in this reach at least 23 m in a decade or less; (2) the transition from aggradation to degradation in the upper part of this reach roughly coincided with the end of the dome-building eruption; (3) fluvial sediment transport and deposition, augmented by one lahar, achieved a minimum average aggradation rate of ~2 m/yr; (4) the degradation phase of the cycle was more prolonged than the aggradation phase, requiring more than half a century for the river to reach its present bed elevation; and (5) the present longitudinal profile of the Sandy River in this reach is at least 3 m above the pre-eruption profile. The pattern and rate of channel response and recovery in the Sandy River following heavy sediment loading resemble those of other rivers similarly subjected to very large sediment inputs.

The magnitude of channel aggradation in the lower Sandy River, greater than that achieved at other volcanoes following much larger eruptions, was likely enhanced by lateral confinement of the channel within a narrow incised valley. A combination of at least one lahar and winter floods from frequent moderate-magnitude rainstorms and infrequent very large storms was responsible for flushing large volumes of sediment to the depositional reach. These conditions permitted a sedimentation response in the Sandy River that approached the magnitude of channel aggradation resulting elsewhere from large explosive eruptions and high-intensity rainfall regimes, despite the fact that the Sandy River aggradation was in response to an unremarkable dome-building eruption in a climate dominated by low to moderate rainfall intensities.

INTRODUCTION

During the late eighteenth-century Old Maid eruptive period of Mount Hood in northwestern Oregon, ~1.5 × 10^8 m^3 dense-rock equivalent (DRE) hypersthene-hornblende dacite was extruded in a dome-building eruption (Crandell, 1980). More than 90% of the magma extruded during this eruption was converted to fragmental debris and deposited on the flanks of the volcano by multiple phreatic explosions and dome-collapse lithic pyroclastic flows (Crandell, 1980). About 2 × 10^8 m^3 of volcaniclastic deposits were produced during the Old Maid eruptive period, and roughly half of that total was delivered to two headwater tributaries of the Sandy River, one of the three main drainages on Mount Hood (Crandell, 1980).

Large sediment inputs to drainage systems on the flanks of volcanoes or elsewhere create transient zones of bed-material sediment accumulation in channels (sediment waves), which evolve and migrate downstream of the sediment input zone(s) in response to interactions among channel morphology, sediment transport, and flow (Lisle et al., 2001; Lisle, 2008). The particles making up the excess bed material in sediment waves include not only new sediment that was added to the system, but also ambient sediment in transit within the system and sediment mobilized by bed and bank erosion. Some new sediment may be removed from a sediment wave and placed in long-term storage within a channel as the wave evolves (Lisle, 2008). Viewed over time from one point along a channel, migrating sediment waves result in a rise and then a fall of the channel bed elevation, which can be described as a cycle of channel aggradation and degradation (Nicholas et al., 1995; James, 2006; Lisle, 2008). River channels at varying scales typically respond to episodes of aggradation with some combination of widening of the active channel, development of mobile sandy beds, and braiding, while degradation is accompanied by narrowing of the active channel, bed armoring with gravel, and return to a single-thread channel form (Gilbert, 1917; Davies et al., 1978; Kuenzi et al., 1979; Smith, 1987; Knighton, 1989; James, 1991, 2006; Hoey and Sutherland, 1991; Nicholas et al., 1995; Miller and Benda, 2000; Kasai et al., 2004b; Manville et al., 2005; Gran and Montgomery, 2005; Hoffman and Gabet, 2007; Lisle, 2008; Madej and Ozaki, 2009).

The 1991 eruption of Mount Pinatubo (Philippines) demonstrated that extremely large sediment inputs to rivers and high-intensity monsoonal and typhoon rainfall can result in staggering volumes of sediment being mobilized and transported tens of kilometers downstream within a year, which can cause downstream channel aggradation of 20–40 m (Rodolfo et al., 1996; K.M. Scott et al., 1996; Umbal and Rodolfo, 1996). In this eruption, drainage basins on and near the volcano received 5.5 km^3 of fine-grained, highly erodible pyroclastic flow and tephra-fall deposits (W.E. Scott et al., 1996) in

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GSA Bulletin; January/February 2011; v. 123; no. 1/2; p. 3–20; doi: 10.1130/B30127.1; 10 figures; 3 tables.

a climatic setting where tropical rainfall intensities commonly are in the range of 10–50 mm/h (Rodolfo and Arguden, 1991) and 24 h rainfall totals can exceed 700 mm (Janda et al., 1996).

Currently, there is only limited documentation of magnitudes and timing of downstream sedimentation responses for rivers affected by smaller and different types of eruptions in nontropical climate settings. In this study, we quantify the magnitude and timing of the aggradation-degradation cycle in the Sandy River that occurred in response to a sediment influx during Mount Hood's most recent dome-building eruption during the eighteenth-century Old Maid eruptive period. This eruption delivered coarser volcaniclastic sediment (significant coarse gravel component) and 28 times less sediment volume to the upper flanks of Mount Hood than the 1991 eruption did on the flanks of Mount Pinatubo. Furthermore, the Sandy River watershed is subjected to dominantly low- to moderate-intensity rainfall that is characteristic of the Cascade Range, with daily rainfall totals averaging less than 20 mm. In comparison to Mount Pinatubo, these initial conditions suggest that the Sandy River might have been expected to have a limited downstream sedimentation response. However, channel aggradation related to Old Maid eruptive activity (as well as that from the preceding Timberline eruptive period, approximately A.D. 300–600) has been recognized previously in sedimentary fill sequences tens of meters thick (Crandell, 1980; Cameron and Pringle, 1986, 1987, 1991), i.e., remnants of channel aggradation locally on a par with posteruption sedimentation in some channels at Mount Pinatubo. In this study, we investigate how much aggradation occurred in the lower Sandy River and whether the amount of aggradation was unusually large. Furthermore, aggradation and degradation rates and the overall timing of complete aggradation-degradation cycles downstream of nontropical volcanoes are not well known, either because they have not been adequately documented for historical eruptions or because well-studied recent eruptions such as at Mount St. Helens have not had enough time to complete their cycles. The Old Maid eruption was long enough ago and timing of downstream sedimentation has been sufficiently constrained by dendrochronologic dating and historical accounts to permit us to reconstruct channel response-recovery curves for two locations in the lower Sandy River downstream of Mount Hood.

Both magnitude and timing of downstream channel aggradation and degradation have important hazard implications for rivers draining volcanoes in the Cascade Range. Not only have eruptions with only moderate sediment-production potential been relatively common in the Cascades, but downstream river valleys are experiencing intense residential development pressure.

GEOLOGIC, CLIMATIC, AND PHYSIOGRAPHIC SETTINGS

Mount Hood is located along the crest of the Cascade Range ~120 km east of Portland, Oregon, and 56 km south of the Columbia River (Fig. 1). This volcanic center has been recurrently active for more than 1.5 m.y. Its present edifice, 3425 m tall and ~50 km^3 in volume, is at least 0.5 m.y. old and is composed of andesite and low-silica dacite domes, lava flows, and pyroclastic debris (Wise, 1969; K.M. Scott et al., 1997).

During Mount Hood eruptions within the past 2000 yr, dacite lava has emanated from a vent just southwest of the present summit, where a remnant of a lava dome (Crater Rock) is presently situated (Crandell, 1980; Cameron and Pringle, 1986, 1987; K.M. Scott et al., 1997a; Fig. 2A). Below Crater Rock, a pyroclastic debris fan extends 6 to 10 km downslope from the vent on the southwest flank of the volcano. Headward extensions of the Sandy, Zigzag (a major Sandy River tributary), and White Rivers have formed canyons that incise as much as 250 m into the debris fan and cover roughly 30%–40% of the fan area. These canyons have narrow, parallel drainage patterns, angle-of-repose side slopes, and expose older pyroclastic units and lava flows (Fig. 2B). These were the conduits of most of the downslope debris transport during Old Maid eruption. The rest of the fan surface has experienced only minor surficial erosion and is mantled by older deposits (Fig. 1; Scott et al., 1997a). The fan has an average dimensionless gradient of ~0.30 (17°) and is mantled presently by two small glaciers, several permanent snow fields, and seasonal snowpack. A mid- to late-eighteenth-century Little Ice Age advance of Pacific Northwest glaciers (Sigafoos and Hendricks, 1972; Larocque and Smith, 2003) must have provided a larger surface area of glacier ice on the debris fan than is present today, but glaciers during the last two decades of that century were experiencing negative mass balance indices (ablation) comparable to those at the end of the twentieth century (Lewis and Smith, 2004). Current (1973–2008) maximum annual snowpack depths at the 1800 m altitude on the fan average 3.6 m and can reach 7.5 m (NWAC, 2008).

Precipitation in the Cascades averages 7–17 mm/d from mid-November to mid-March (Taylor and Hatton, 1999). It falls mainly as snow above 1200 m (Major and Mark, 2006), further limiting the immediate availability of water for fluvial sediment transport. Most winter storms seldom have rainfall intensities greater than 100 mm/d, but higher-intensity, decadal-scale "pineapple express" storms involving moisture-laden tropical air masses occasionally deliver heavy rainfall to fresh winter snowpacks between 200 and 1000 m altitude, with rapid snowmelt augmenting rainfall. Daily rainfall totals during these rare events can reach 300–500 mm/d, the equivalent of tropical typhoons (Taylor and Hatton, 1999; Rodolfo and Arguden, 1991). Such storms usually result in major flooding, widespread triggering of alpine debris flows, and heavy sediment production (Harr, 1981; Gallino and Pierson, 1985; Marks et al., 1998). The west flank of the Cascade crest near Mount Hood has 2 yr recurrence-interval rainstorms that average 35 mm/h for 10 min durations and 14 mm/h for 60 min durations, while 100 yr storms average 74 mm/h for 10 min durations and 28 mm/h for 60 min durations (Oregon Department of Transportation, 2005).

The upper Sandy and Zigzag Rivers drain the western part of the debris fan (Figs. 1 and 3), which has been an important source of sediment to the river since the late Pleistocene (Crandell, 1980). Other headwater tributaries appear to contribute only a small additional fraction of total sediment load to the Sandy River. From the flanks of Mount Hood, the Sandy River flows almost 90 km to the Columbia River. The river is deeply incised along almost its entire length into late Tertiary bedrock and early to mid-Quaternary volcanic sediments that have been shed westward from the Cascade crest (Trimble, 1963; Walker and MacLeod, 1991; Sherrod and Scott, 1995). Incision depths up to 500 m are reached in V-notch canyons at the base of the volcano, and the valley is 100–200 m deep and 250–600 m wide in the 20 km just upstream of its Columbia River confluence.

The longitudinal profile of the Sandy River (Fig. 4) can be segmented into (1) the debris fan (0–7 km downstream of the vent), (2) a sediment-source reach (7–36 km from vent), where erosion of a thick valley fill of primary and reworked pyroclastic-flow and lahar deposits from this and older eruptions provides most of the sediment input to the river, (3) a steepened middle reach (36–61 km from vent) with some lahar terraces but little fluvial deposition, and (4) a low-gradient depositional reach (61–87 km from vent), which experienced a major aggradation-degradation cycle during and following the Old Maid eruptive period. Over the final 4.7 km of the depositional reach, the Sandy River flows unconfined across the 10 km^2 Sandy River delta, which extends ~3 km out into the Columbia River valley (Fig. 1).

The sediment-source reach is floored by a thick, downstream-thinning wedge of unconsolidated volcanic sediment that forms a wide

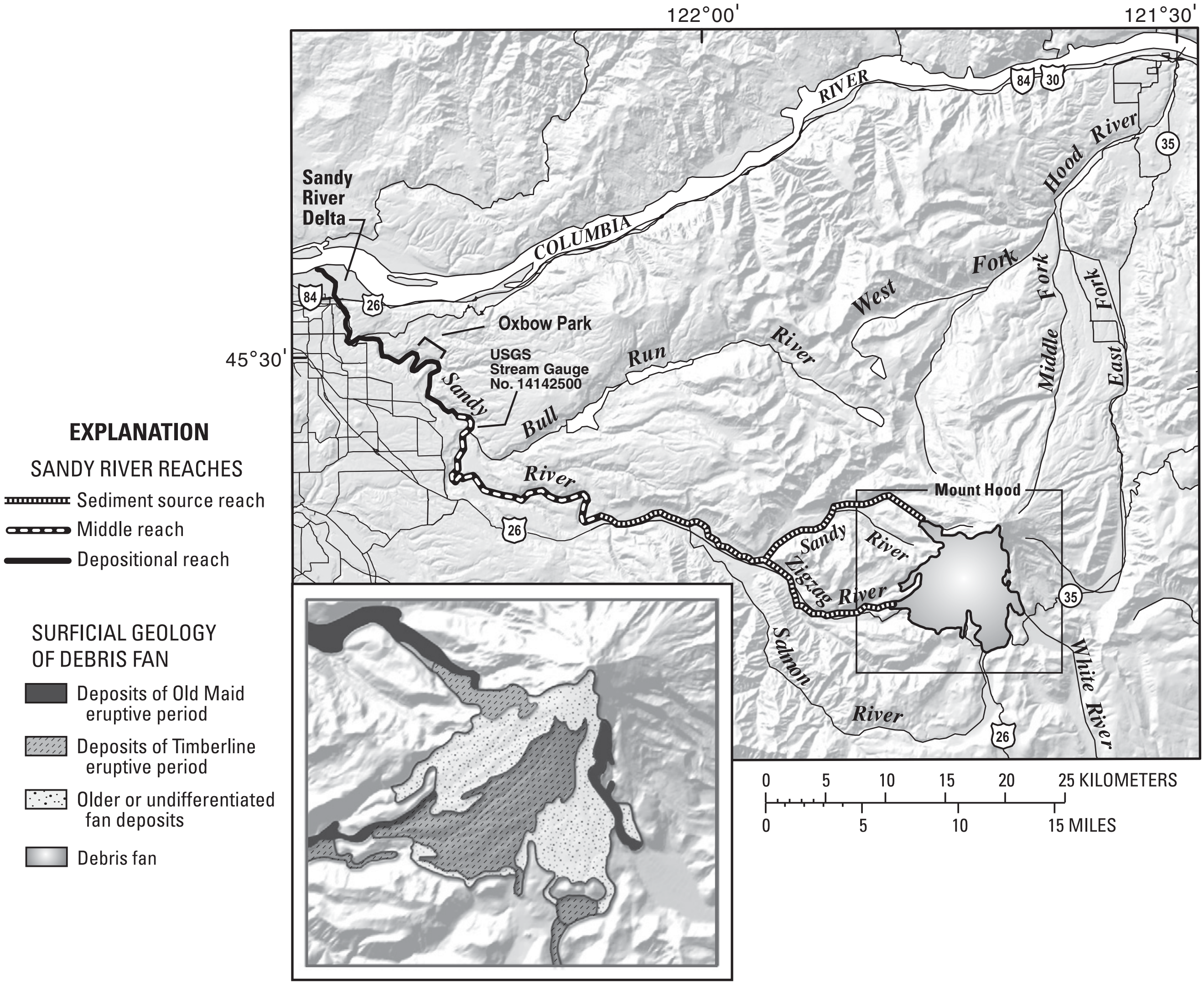

Figure 1. Location map for the Sandy River at Mount Hood, Oregon. Sediment-source, middle, and depositional reaches of the Sandy River are indicated. Inset map is a simplified geologic map of the debris fan (modified from Scott et al., 1997a), showing recognized deposits of Old Maid and Timberline age (the two late Holocene eruptive periods) on and just downstream of the fan surface. Old Maid sediments also entered the White River drainage (not studied), but none entered the Hood River drainage.

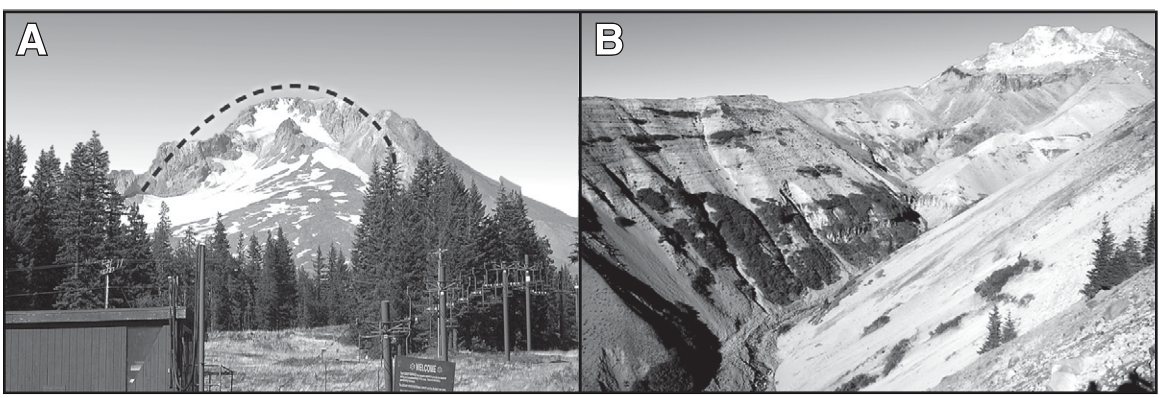

Figure 2. Views of Crater Rock (remnant Old Maid lava dome) and the pyroclastic debris fan downslope of Crater Rock on the SW flank of Mount Hood. (A) View from small ski area at Government Camp at the distal end of the debris fan. Crater Rock is centered in the scar left by a flank collapse early in the Timberline eruptive period (indicated by dashed line). (B) Zigzag Canyon, cut into the debris fan and underlying lava flows at the 5200 ft level on the debris fan. Canyon here is ~250 m deep. U.S. Geological Survey photos by T. Pierson, 2003.

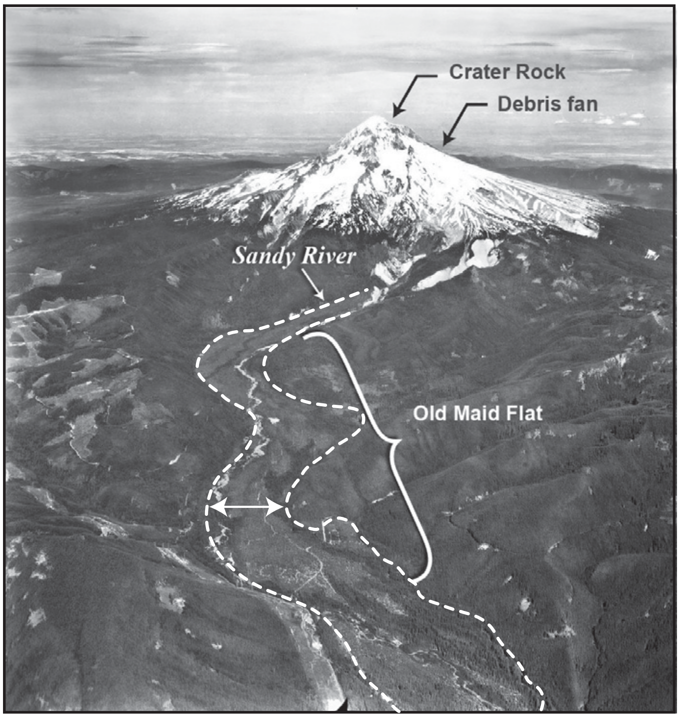

Figure 3. Aerial oblique photograph of the western flank of Mount Hood and the wide, flat-floored valley known as Old Maid Flat in the upper part of the sediment-source reach of the Sandy River. Valley width at arrow is 720 m. U.S. Geological Survey photo by Austin Post, 1980.

flat-floored valley fill, the upper part of which is locally known as Old Maid Flat (Fig. 3). Well logs from geothermal test wells (Priest and Vogt, 1982) and extrapolation of valley side slopes (Fig. 4) suggest that total fill thickness of late Pleistocene and Holocene deposits in upper Old Maid Flat (2800 ft level) is 110–120 m. Farther upstream, terraces composed of Timberline-age deposits capped by deposits of Old Maid age are up to 45 m above present river level (Crandell, 1980). Old Maid Flat extends from near the lower edge of the debris fan to ~16 km downstream, with a continuing flat-floored valley fill extending to nearly 30 km downstream of the fan and forming the remainder of the sediment-source reach (Fig. 1). In the Zigzag River valley, fill deposits extend ~12 km downstream from the fan to the confluence with the Sandy. Channel gradient averages 0.027 through the sediment-source reach.

The middle reach begins at a gradient of 0.0035 but steepens to 0.012 where the river descends a narrow, bedrock-floored gorge (Fig. 4). Average channel gradient of the entire reach is 0.0074. While some terraces composed of Timberline lahar deposits and older coarse fluvial gravels may be found in this reach, alluvial terraces formed in response to Old Maid activity are largely absent, indicating that most of the sediment mobilized in response to Old Maid eruptive activity was transported through this reach with little deposition.

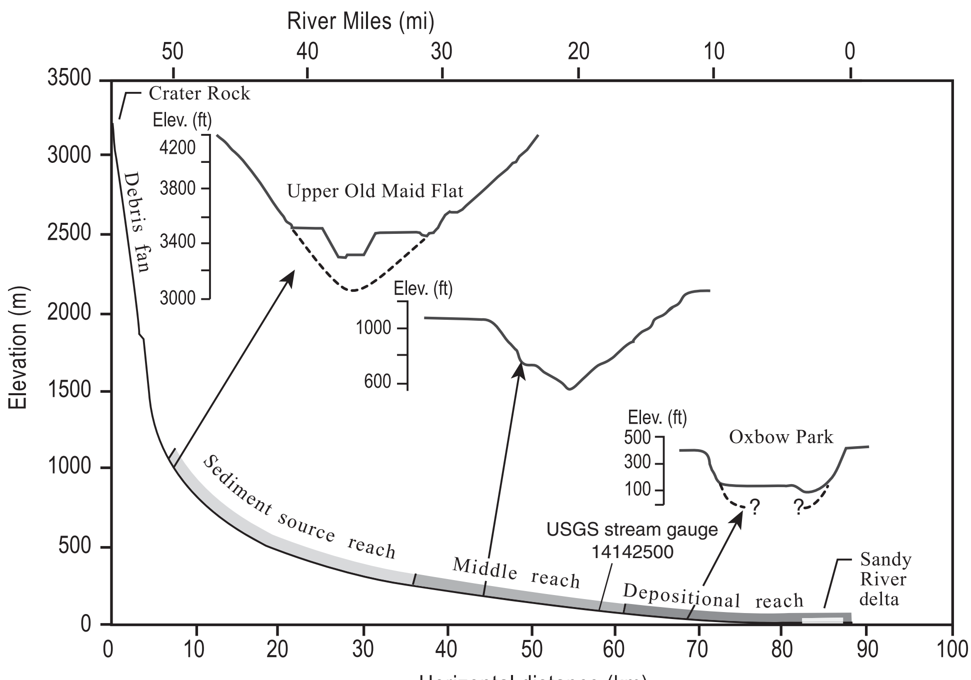

Figure 4. Longitudinal profile of the Sandy River channel, starting at Crater Rock (source volcanic vent) and continuing down to the Sandy River confluence with the Columbia River. River reaches described in the text are indicated, and selected valley cross sections for each reach are shown. Profile data were derived from U.S. Geological Survey (USGS) 30 m digital National Elevation data set and USGS 1:24,000 digital line graph (DLG). Vertical exaggeration is 9.3×.

Where the middle reach transitions to the depositional reach, the river channel widens and flattens (Figs. 1 and 4). The depositional reach has a single-thread to branching channel form and is well armored with pebble/cobble (locally boulder) gravel. It has an average gradient of 0.0022 and is bounded by multiple levels of late Holocene alluvial terraces. In the Sandy delta segment of the depositional reach (Fig. 5), volcaniclastic sediments from Mount Hood are interlayered with Columbia River overbank flood deposits (Rapp, 2005).

Drainage area of the Sandy River is ~1130 km^2 at a stream gauge (USGS 14142500) near the end of the middle reach, 58 km downstream from Crater Rock (RM 18.3; Figs. 1 and 4) (USGS, 2006). Peak discharge of record at this gauge (1964) is 2390 m^3/s. Mean annual flow was 66 m^3/s prior to flow regulation in 1915. The bed of the river today is armored in many reaches by cobbles and boulders, and bed material is composed dominantly of pebble-cobble gravel and medium to coarse sand, although the channel is on bedrock in parts of the middle reach. Modern overbank flood deposits in the depositional reach (on low terrace surfaces) are composed of moderately to well-sorted, medium to very fine sand.

METHODS

This study uses (1) elevations of river terraces with respect to modern low-flow river stage (a proxy for river bed elevation), (2) minimum ages of terraces determined from dendrochronology, (3) sedimentology of terrace deposits, and (4) estimated paleochannel bed elevation to reconstruct the magnitude and timing of downstream channel aggradation and degradation resulting from the accelerated influx of sediment during volcanic activity. Recent field work has supplemented earlier detailed mapping and dating of late Holocene deposits in the Sandy River basin, carried out by U.S. Geological Survey (USGS) colleagues and a graduate student in conjunction with volcano hazard assessments for Mount Hood (Crandell, 1980; Cameron and Pringle, 1986, 1987, 1991; J.W. Vallance, 1996, personal commun.; Scott et al., 1997a, 1997b; Pringle et al., 2002, 2010; Rapp, 2005). This work, in turn, was built upon earlier studies by Lawrence (1948) and Wise (1969).

The depositional reach of the Sandy River has multiple levels of inset alluvial terraces (Fig. 6). Terrace surface (tread) age is defined by its year of abandonment (as active floodplain) by the river—the year that the terrace surface first became a stable substrate on which immersion-intolerant Douglas fir (*Pseudotsuga menziesii*) could germinate and survive infrequent flooding. Heights of terrace surfaces were determined by theodolite surveys when sites were accessible by roads, and by hand level in more

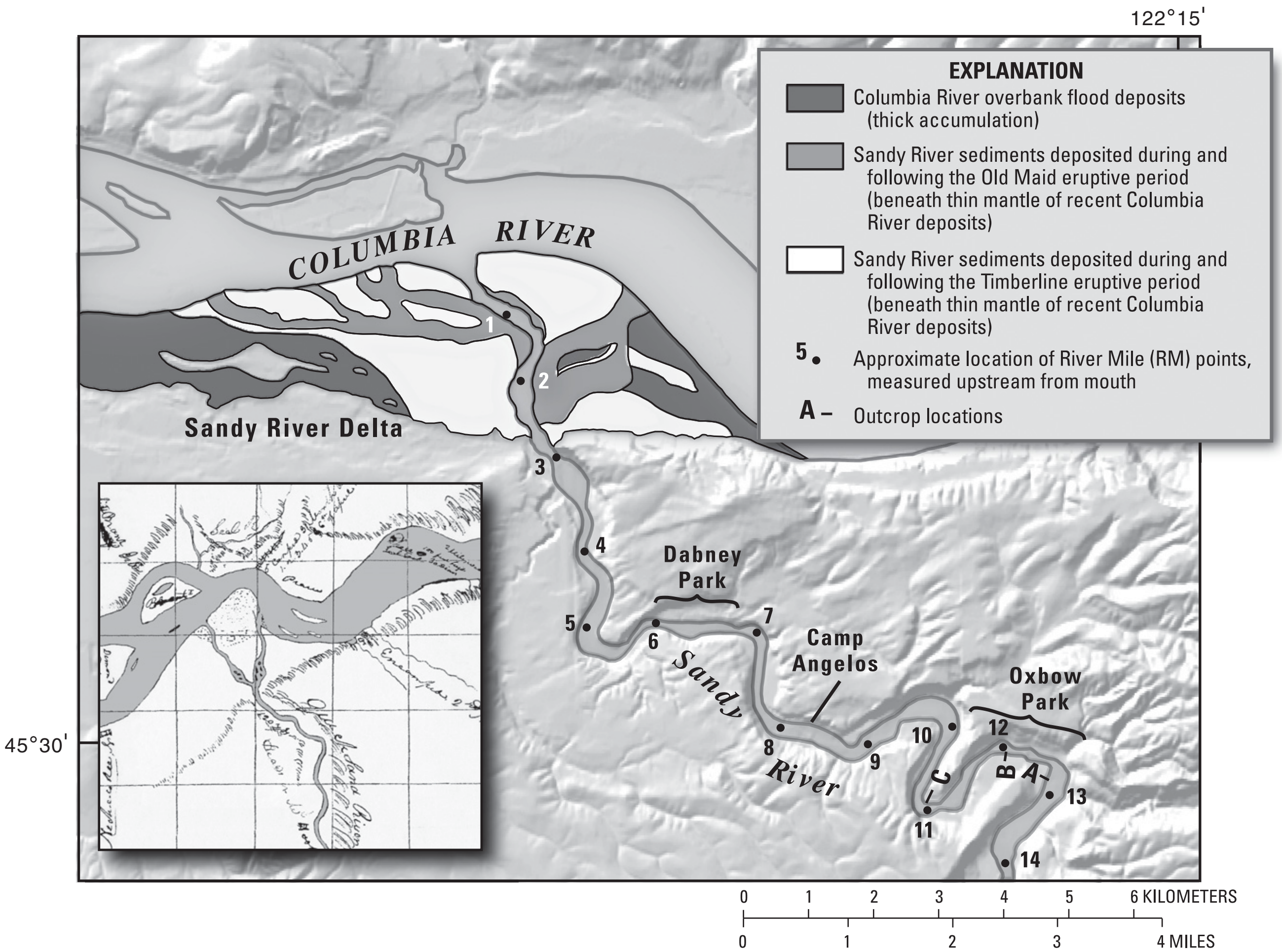

Figure 5. Geologic map of the Sandy River delta (modified from Rapp, 2005) and downstream part of the depositional reach of the Sandy River, showing river mile (RM) distances and locations of key outcrops of Old Maid deposits. Inset in lower left is sketch map of the same area (with bifurcating channel on delta) drawn by Lewis and Clark in 1805–1806. Capital letters show locations of outcrops and geologic sections in Figures 7 and 8. The right distributary channel on the delta was closed off by an engineering diversion in the 1930s.

remote locations; terraces at the upstream end of the depositional reach have not been surveyed due to access difficulties. Due to the paucity of survey benchmarks in the area, terrace elevations were surveyed with respect to each other, and then tied to a reference low-water river stage (30–31 August 2006), which roughly approximates mean river bed elevation. Locations of sites along the Sandy River are designated both by distance downstream from Crater Rock in kilometers and distance upstream from the mouth of the river in "river miles" (RM), which are labeled on USGS topographic maps.

Bed elevation of the lower Sandy River at the beginning of the Old Maid aggradation-degradation cycle is estimated to have been at least 3 m below reference river stage, on the basis of the elevation of the lowest pre–Old Maid paleoterrace exposed by erosion in Oxbow Regional Park (Fig. 5, locations B and C), 68–71 km downstream from Crater Rock. This old surface, now ~1.4 m above reference stage, was supporting a forest of mature Douglas fir prior to the onset of aggradation and was capped by silty overbank deposits of Old Maid age. Within this reach today, modern overbank deposits that are similarly fine-grained are only found on terrace surfaces at least 4–5 m above reference stage (deposited close to peak flood stage), and Douglas fir grow abundantly only on modern terraces that are at least 4 m above reference stage. The absence of overbank flood deposits older than Old Maid age on the paleoterrace suggests that pre–Old Maid floods were not able to reach this surface until aggradation began. Present-day terraces free of modern overbank flood deposits are at least 5–6 m above reference stage. These minimum heights subtracted from +1.4 m elevation of the lowest paleoterrace require that the pre–Old Maid channel bed had to have been at least 3 m lower than the modern channel.

Sediments of Old Maid age were distinguished from older units by radiocarbon dating of incorporated woody debris. Times of terrace formation in the depositional reach are presented in calendar years and were determined by several dendrochronologic approaches: (1) dating the largest (and presumed oldest) living Douglas firs on terrace surfaces, or counting rings on available stumps, to get minimum terrace ages (Pierson, 2007); (2) obtaining the approximate year of tree death by cross dating standing dead trees or logs (Phipps, 1985); (3) obtaining the year of cambial injury, partial burial, or removal of nearby competitor trees for surviving living trees by noting the onset of abrupt changes in tree-ring width in increment cores—narrowing for injury or burial, widening for growth release (Phipps, 1985; Yamaguchi, 1989); and (4) noting the appearance of traumatic resin canals formed following cambial injury in rings of trees surviving lahar abrasion (Stoffel and Bollschweiler, 2008). A ring-diameter template was used to estimate the number of missing rings in cores when the tree center was not intersected (i.e., intersection angles of inner rings in tree cores are matched to curvatures on a nested set of concentric circles). Dendrochronologic dating of geologic events may have an inherent error of ±1 yr due to seasonal variation in the timing of radial tree growth (Yamaguchi, 1989). Additional errors of up to ±7 yr arise from possible missing and false rings, the uncertainty in locating the oldest tree on a terrace, and error from variations in time of tree establishment on abandoned floodplains (Pierson, 2007).

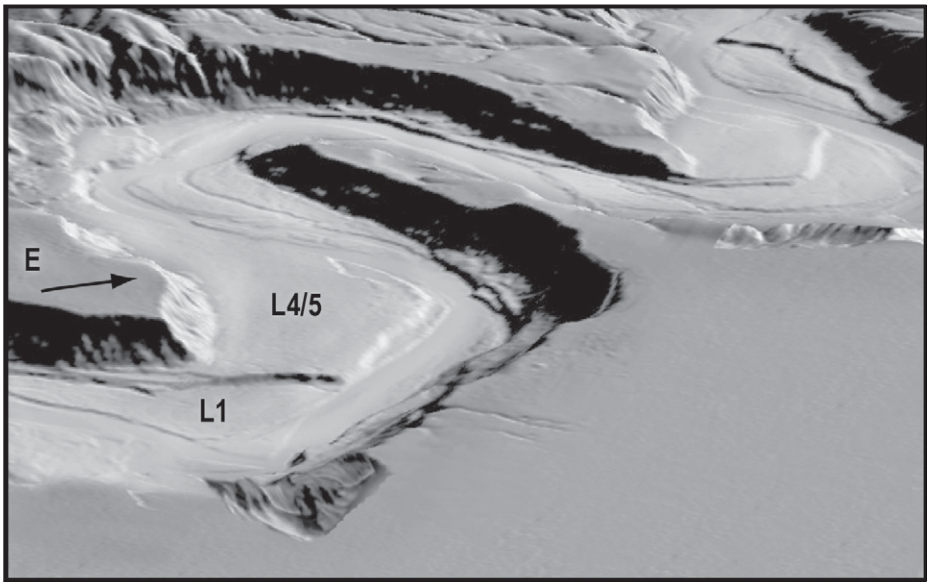

Figure 6. Oblique light detection and ranging (LiDAR)–derived, bare-earth 2 m digital elevation model (DEM) of the upper part of the Sandy River depositional reach, which includes Oxbow Park. The arrow points north; view is downstream. The width of the valley where the north arrow is pointing is 520 m. The broad, flat, relatively low alluvial terraces in the valley represent river bed levels achieved during Timberline and Old Maid aggradation. The L4/5 surface (Table 2) represents the highest level of channel aggradation related to Old Maid eruptive activity that was achieved at that location. The L1 surface (Table 2) is the lowest terrace forested with Douglas fir; the "L1" label is approximately at location A in Figure 5. Thin slivers of intermediate terrace levels (L2, L3) can be seen to the left of the "L1" label. The high terrace, labeled "E," is a late? Pleistocene surface composed of Estacada Formation deposits (Trimble, 1963).

SEDIMENT PRODUCTION DURING THE OLD MAID ERUPTIVE PERIOD

Recent tree-ring dating, augmented by geochemical signatures from individual annual rings of trees affected by ash clouds from pyroclastic flows, indicates that major Old Maid eruptive activity began in A.D. 1781 and lasted until 1793 (Sheppard et al., 2010). Other tree-ring evidence suggests that pyroclastic flows may have continued to ca. 1800 in the White River valley (Lawrence, 1948; Cameron and Pringle, 1987; Table 1). Credible eyewitness accounts of minor eruptive activity were reported in 1859 and 1865, with unconfirmed reports of minor activity in 1853, 1854, 1869, and 1907 (Simkin and Siebert, 1994). However, the small eruptions in 1859 and/or 1865 deposited only scattered pumice lapilli on the upper flanks of the volcano, which are nowhere thick enough to form a continuous layer (Crandell, 1980). A precise end of the Old Maid eruptive period has not been defined.

Repeated collapses of a growing and unstable lava dome at Mount Hood on an ~32° slope during the Old Maid eruption shed volcaniclastic debris across a debris fan that probably was covered with snow and ice year-round. Crater Rock, the modern remnant of that lava dome, now stands ~170 m high and 300–400 m across (Fig. 2; Crandell, 1980). If dome growth had been more or less continuous, as suggested by the dendrogeochemical evidence (Sheppard et al., 2010), mean extrusion rate would have been ~0.4–0.5 m^3/s. Lahars were triggered by rapid snowmelt caused by block-and-ash flows from

TABLE 1. DATES (FROM HISTORICAL ACCOUNTS, TREE-RING AGES, AND RADIOCARBON DATES) CONSTRAINING TIMING OF MAJOR SEDIMENT INPUTS TO THE UPPER SANDY RIVER AND DOWNSTREAM SEDIMENTATION RESPONSE DURING AND FOLLOWING THE OLD MAID ERUPTIVE PERIOD

Date no.	Sampler/Observer (reference)	Analysis type	Calendar date or age	Dendrochronologic and stratigraphic details
Sandy River and tributaries				
1	F.F. Henshaw (field notes of stream gauging measurement showing Aug. 20, 1911 low-water elevation 0.87 ft above gauge datum); archive of USGS Oregon State office, Portland (USGS gauging station 14142500)	River elevation	A.D. 1911	Modern gauge datum has not been surveyed with respect to sea level (NGVD 1929), so assuming that May 20, 1910 water surface elevation roughly approximates bankfull stage, and also assuming that modern river surface elevation from a 2-ft contour map made from March 1971 aerial photographs also roughly approximates bankfull stage at the gauge site, the 1911 low-flow water level is approximately 0.3 m +/- 1 m above the A.D. 2000 low-flow water level. This assumes that the 1910 regional datum was 1.5 +/- 0.2 ft lower than the NGVD 1929 datum (as reported by Dale Benson, USGS, NMD, Denver).
2	John Dubuis (field notes from April 27, 1910 survey of temp.benchmark); archive of USGS Oregon State office, Portland	River elevation measurement	A.D. 1910	Survey of temporary benchmark "at water's edge" at USGS gauging station 14142500 (Sandy River blw Bull Run River, nr Bull Run, OR) indicates that the bankfull water surface in 1910 was within about 1 m of the present bankfull water surface. This gauging station is at RM 18.2, about 9 km upstream from Oxbow Park.
3	Cameron and Pringle, 1986	Tree-ring	A.D. 1808	Latest possible date for deposition of a lahar on Old Maid Flat, based on innermost ring in a stump growing on deposit surface. Innermost ring dated at 1811, but minimum 2 years added to age for time to grow to stump height, and minimum 1 year added for germination.
4	Cameron and Pringle, 1987	Tree-ring	A.D. 1806	Latest possible date for deposition of a lahar on Old Maid Flat, based on innermost ring in a stump growing on the deposit surface. Innermost ring dated at 1809; minimum 2 years added to age for time to grow to stump height, and 1 year added for minimum germination lag time.
5	P. Pringle, unpublished data, core #86100401	Tree-ring	A.D. 1800	Growth release (ring widening) beginning in 1801 in living old-growth survivor tree (D. fir) on south margin of lahar deposit on Old Maid Flat, at confluence with Lost Creek.
6	T. Pierson, sample 000823-T2 (Pringle et al., 2002)	Tree-ring	A.D. 1800	Survivor old-growth Douglas fir on the southern margin of Old Maid Flat ca. 1.5 km upstream of Lost Creek. The 1801 annual ring begins a sequence of wider rings—abrupt growth release, probably resulting from removal of competitor trees, and the 1801 ring contains traumatic resin canals, probably resulting from cambial damage by lahar abrasion.
7	Pringle et al., 2002	Tree-ring	A.D. 1787	Approximate date of injury (based on drastic narrowing of rings, missing rings, and appearance of resin canals, starting with 1788 ring) of a tree apparently injured by an outbreak flood from a lake in the Muddy Fork tributary that was dammed by the 1781 lahar deposit.
8	P. Pringle, unpublished data, core #86100401	Tree-ring	A.D. 1781	Onset of abrupt ring suppression with 1782 ring in living tree that was partly buried by a lahar on south margin of lahar deposit on Old Maid Flat, at confluence with Lost Creek. Unusually thin 1781 late wood suggest tree injury occurred in fall of 1781.
9	T. Pierson, core # 000823-T2 (Pringle et al., 2002)	Tree-ring	A.D. 1781	Onset of extreme ring-supression with 1782 ring in living tree on Old Maid Flat that was partially buried by a lahar; tree probably suffered some abrasion damage and oxygen starvation to roots. Thin 1781 late wood suggests injury occurred in fall of 1781.
10	P. Pringle, K. Cameron (Pringle et al., 2002)	Tree-ring	A.D. 1781	Cross-dated death dates of two trees in upper Sandy and Zigzag valleys that were buried in Old Maid deposits.
11	P. Pringle, K. Cameron (Pringle et al., 2002)	Tree-ring	A.D. 1781	Abrupt growth release starting with 1782 ring in several undamaged living trees adjacent to lahar path on Old Maid Flat, probably due to removal of competitor trees by lahar in previous growing season.
12	Cameron and Pringle, 1987	Tree-ring	A.D. 1782	Latest possible date for depostion of Old Maid-age lahar in Zigzag River valley, based on earliest ring in stump dating to about 1785. A minimum 2 years added to age for time to grow to stump height, and 1 additional year added for minimum germination lag time.
13	T. Pierson, unpublished data, core #050202-T1	Tree-ring	A.D. 1779	Cross-dated death date of log at base of Old Maid-age stratigraphic section at Oxbow Park; log had been resting on (or was deposited on) terrace surface, was covered first by overbank deposits and then buried by coarse channel deposits. Thus aggradation started at this location sometime after 1779.
14	Crandell, 1980 (citing Rubin and Alexander, 1960)	Tree-ring	A.D. 1777	Latest possible date for lahar deposition at Old Maid Flat, from stumps of 2 trees growing on deposit surface; rings counted in 1956 (though trees possibly cut earlier); both stumps had 176 rings, which gives a center ring date of no later than 1780; adding 2 years to age for minimum growth time to stump height (assuming stump ~1 m above ground and 1 year added for minimum germination lag time) gives minimum age of 179 yr or latest possible date of 1777. However, rings are counted in field on rough-cut stumps, which increases chance of counting error; date is tentative.
15	T. Pierson, unpublished data, sample #000816-2Z	AMS radiocarbon	210 ± 30 uncalib yr BP	Radiocarbon date on Douglas-fir cone imbedded in silty overbank flood deposit at base of Old Maid sequence at Casterline terrace (left bank, RM 8.5, Fig. 5). Calibrated age ranges (1σ) are A.D. 1650 to 1680 (24.7% prob.), A.D. 1760 to 1800 (31.1% prob.), and A.D. 1930 to 1939 (12.3% prob.). Calibrated 2σ age ranges are A.D. 1640 to 1690 (30.0% prob.), A.D. 1730 to 1810 (48.8% prob.), and A.D. 1920 to 1939 (16.7% prob.).

(*continued*)

TABLE 1. DATES (FROM HISTORICAL ACCOUNTS, TREE-RING AGES, AND RADIOCARBON DATES) CONSTRAINING TIMING OF MAJOR SEDIMENT INPUTS TO THE UPPER SANDY RIVER AND DOWNSTREAM SEDIMENTATION RESPONSE DURING AND FOLLOWING THE OLD MAID ERUPTIVE PERIOD (*continued*)

Date no.	Sampler/Observer (reference)	Analysis type	Calendar date or age	Dendrochronologic and stratigraphic details
Upper White River				
16	Cameron and Pringle, 1987	Tree-ring	Ca. A.D. 1812	Latest possible date for lahar deposition in upper White River valley, based on earliest ring from stump cut in mid-seventies; earliest ring was about 1815, so adding 2 yr to age for growth to stump height and 1 year for minimum germination lag time gives an approximate date of 1812; tree had been growing on the deposit.
17	Lawrence, 1948	Tree-ring	Ca. A.D. 1800	Release date of 1808 (abrupt widening of rings) in living tree that was surrounded by dead trees presumably killed by tephra fall or a pyroclastic surge in upper White River valley. Lawrence surmised that the tree-killing event would have injured this tree also, so that a few years were requred for healing before growth could accelerate. He estimated the tree-killing event to have occurred in 1800.
Sandy River delta				
18	T. Pierson, unpublished data, sample #020905-2		A.D. 1810	Tentative death date from cross-dating of log found near top of Old Maid-age aggradational sand section, right bank of Sandy River, 1.55 km upstream from river mouth on distal part of delta.
19	Lewis and Clark expedition (Moulton and Dunaly, 1990; O'Connor, 2004)	Historical observations	A.D. 1805 (Nov.) and 1806 (Apr.)	Observation that Sandy River at its mouth and for several km upstream was much wider (~275 m) than at present (30–150 m) and had a number of large mid-channel sand bars (on their map, inset in Fig. 5). They reported the river was transporting a large sediment load and that "the bed of this stream is formed entirely of quicksand" (impossible to wade across). The current was described as swiftly flowing and "not more than 4 inches deep". On April 1, 1806, expedition members explored the lower 10 km of the river and noted that the turbid, shallow river was overflowing its low banks (where today the channel is bordered by terraces up to 17 m high).
20	Cameron and Pringle, 1987	Historical observation	A.D. 1792	Presumed high sediment discharge coming from Sandy River, based on observation by Lt. Broughton (of Capt. Vancouver's Expedition) that a shallow sand bar extended out from the mouth of the Sandy River in 1792. This is a narrow reach of the Columbia and the current is swift; a bar could not have been maintained without abundant sediment supply. However, this observation was made before channel avulsion shifted the mouth of the river to the two distributary channels that were observed entering the Columbia River in 1805 (by Lewis and Clark) 2 kilometers upstream of the 1792 mouth. It is assumed, therefore, that significantly more channel aggradation occurred after 1792.

the dome, as evidenced by numerous prismatically jointed blocks in the Old Maid deposits and one lahar deposit containing both locally carbonized wood and lithic blocks displaying coincident orientations of thermoremanent magnetism (Crandell, 1980).

It is likely that many pyroclastic flows moved fragmental rock debris into the incised canyons on the debris fan and beyond, in some cases, directly into the Sandy River headwaters, although limited vertical exposures of deposits and indistinct boundaries of individual flow units limit direct evidence of this. Among modern analogs, 26 sustained dome-collapse events at Soufriere Hills volcano (Montserrat) produced large pyroclastic flows traveling up to 6.5 km, and more than 100 discrete smaller flows traveling <1–3 km, between the start of the eruption in late 1995 and the end of 1997 (Cole et al., 1998). During this period, magma discharge rates varied from 0.5 to over 10 m^3/s, and total DRE volume of the pyroclastic-flow deposits was ~10^8 m^3 (Sparks et al., 1998). Another analogous lava dome at Unzen volcano (Japan), growing on a steep slope at extrusion rates between 1 and 5 m^3/s during the 1990–1995 eruption, produced over 5000 mostly small pyroclastic flows and a total deposit volume of 2.1×10^7 m^3 (Nakada et al., 1999; Ui et al., 1999).

While rapid snowmelt by block-and-ash flows undoubtedly generated many lahars on the glacier- and snow-covered debris fan, it is also very likely that lahars were triggered by rainstorms during autumn, winter, and spring. Lahars and rainfall runoff moved the pyroclastic sediment from the debris fan to the sediment-source reach of the Sandy River. Exposed lahar deposits of Old Maid age at Old Maid Flat are at least 8 m thick, although only 5–6 individual flow units have been resolved due to the limited vertical exposure. At Unzen, dozens of lahars were generated by intense rainfall during typhoons and rainy season storms, both during and following the eruption (Miyabuchi, 1999), and these lahars caused up to 3 m of aggradation below the pyroclastic debris fan at Unzen (Micyabuchi, 1999).

Evidence for the timing of lahars at Old Maid Flat is largely congruent with eruption dates. Multiple tree-ring dates (Table 1), based on evidence of traumatic impacts to trees growing along the margins of the lahar deposits, suggest that major pulses of sediment probably occurred in the late summer or early autumn of 1781 (large lahar), in 1787–1788 (outbreak flood, based on location of the tree along the outlet channel of a formerly dammed tributary), in 1791 (lahar?), and in 1801 (lahar?). An unknown number of smaller lahars that did not injure trees along the valley sides also contributed sediment during the eruption. Two tree-ring counts reported from stumps on Old Maid Flat (Rubin and Alexander, 1960; reported in Crandell, 1980; Table 1) suggest that an earlier lahar may have been emplaced by 1777. However, this is a questionable date, because these ring counts were performed in the field on rough-cut stumps, which greatly increases the chance of counting error. Ages of trees growing on lahar deposits at Old Maid Flat suggest that forest vegetation became established over much of that surface by 1805 (Table 1). Parts of the original depositional surface at Old Maid Flat have been carved by erosional channels from 2 to 15 m deep and up to ~50 m wide. From the maturity of trees growing within these channels today, much of the erosion on the surface of Old Maid Flat appears to have occurred shortly after lahar deposition, but erosion of these deposits continues, principally by lateral erosion within the modern channel.

FLUVIAL RESPONSE TO SEDIMENT INFLUX

The debris-fan canyons and valley-fill sediment reservoirs in the upper Sandy and Zigzag valleys were the primary sources of sediment for downstream reaches during and following the Old Maid eruptive period. The volume of sediment eroded from Old Maid Flat following lahar deposition, estimated from valley cross sections, is ~5×10^6 m^3. Smaller volumes appear to have come from the upper Zigzag valley and from the debris fan. Total sediment eroded from the sediment-source reach appears to have been less than 10^7 m^3 (5%–10% of the sediment deposited there by eruptive activity); sediment was also eroded from older underlying volcaniclastic units.

Old Maid lahar deposits in the Sandy River having granular debris-flow textures are common as far downstream as 30 km from Crater Rock (Cameron and Pringle, 1987), and several depositional units have textures characteristic of hyperconcentrated flow. Only one lahar deposit (a debris flow) has been recognized in the depositional reach (Cameron and Pringle, 1991). This unit (Fig. 7) has been found in only two locations at the base of the Old Maid aggradational sequence, resting directly on a low paleoterrace surface and capped by the overbank flood deposits that begin the Old Maid sequence in other outcrops. Based on its stratigraphic position, this deposit was probably emplaced by the large 1781 lahar documented on Old Maid Flat, and it was at least 4 m deep at Oxbow Park. All Old Maid deposits lying stratigraphically above this deposit

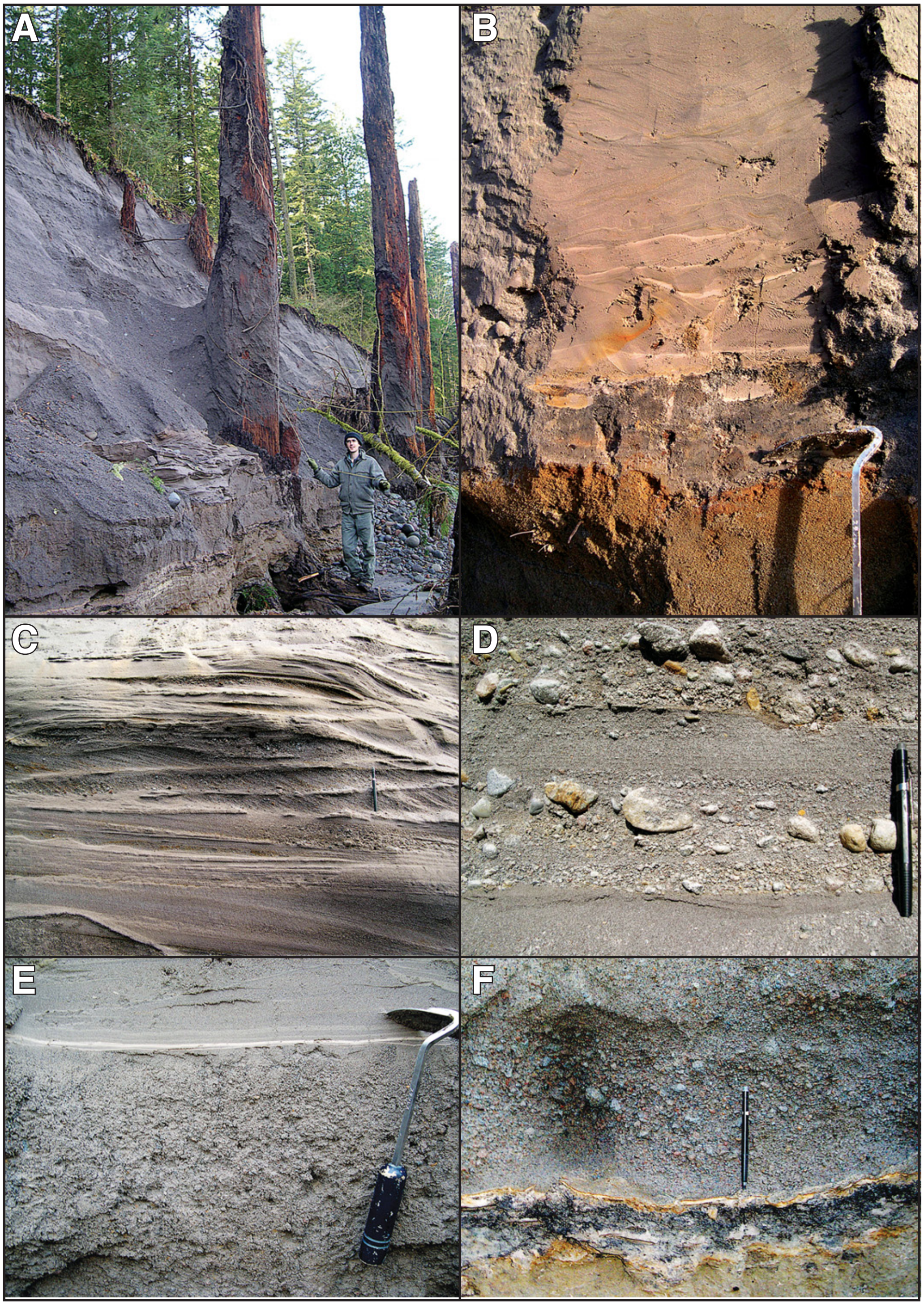

Figure 7. Outcrops of sedimentary units with distinctive lithofacies associations (LAs) in the depositional reach of the Sandy River emplaced between A.D. 1781 and ca. 1793 (U.S. Geological Survey photos by T.C. Pierson). A, B, C, E, and F were taken at location B in Figure 5, which is also shown in section B in Figure 8. Photo D was taken at location C. (A) Recently exposed bluff face of highest alluvial terrace at Oxbow Park, looking downstream and showing trees that were rapidly buried in growth position; surface of paleoterrace on which trees were growing is just above man's knees. (B) Overbank flood deposit (fine to very fine sand, LA1) resting on O and A horizons of soil developed on paleoterrace surface; note infilling of voids/burrows in soil and thin, light-colored silt partings in overbank sand (probably separating individual flood events). Flow direction was left to right. (C) Cross-bedded medium to coarse sand (LA2) in lower third of the 20 m terrace. Flow was from left to right. (D) Horizontal bedding and low-angle cross-bedding in alternating coarse sand and fine gravel layers (LA3) in 16 m terrace. Flow was from right to left. (E) Normally graded top of lahar deposit at base of Old Maid section; flow was from left to right. Note thin, almost white silty layer at top of lahar unit, presumably a cap layer formed during dewatering of the deposit. LA1 deposits lie on top of the lahar unit. (F) Inversely graded base of lahar deposit resting on thin silty layer showing groundwater iron staining (dilute lahar flow front?) that overlies O/A horizons of buried soil on paleoterrace.

are fluvial sands and gravelly sands. Thus, with the exception of the initial lahar, aggradation in the depositional reach was accomplished by purely fluvial sediment-transport processes.

The record of Old Maid aggradation and subsequent degradation in the depositional reach is preserved within the incised Sandy River valley by a sequence of alluvial fill terraces that occur at: 16–20 m, 11–14 m, 8–10 m, 5–6 m, and 3–5 m above reference stage (Fig. 8; Table 2). Terrace surfaces were colonized by Douglas fir and other tree species following stabilization (i.e., when no longer regularly swept by floods); most sites are still forested, and some have never been logged. Locally, morphologic features on terrace surfaces include shallow ridges and swales left by abandoned bars and channels and chute-bypass channels on the insides of bends. Terrace surfaces are progressively younger at lower levels (Table 2), and channel sediments mantling the surfaces are somewhat coarser as tread elevations step down to present river level (Fig. 8). Coarsening of channel deposits during degradation also has been described for aggradation-degradation cycles elsewhere (Manville et al., 2005; Madej et al., 2009).

Magnitude and Characteristics of Depositional Reach Sedimentation

Maximum aggradation of the river bed at 68–71 km downstream of Crater Rock was at least 23 m above pre-eruption river level; it was ~8 m on the delta, 83–87 km downstream (Rapp, 2005). Exposures of the full aggradational sedimentary sequence (Fig. 7A) show no evidence of a depositional break, and the complete burial of forest trees by these deposits (Figs. 7A and 8) (Cameron and Pringle, 1991) further supports steady, rapid aggradation and widening of the channel bed as the sediment wave entered the depositional reach. Maximum width of the active channel and floodplain, 250–600 m, was limited by the incised valley walls.

Channel-fill sediments in the depositional reach are dark gray, dominantly cross-bedded, medium to coarse fluvial sands with minor gravel lenses, composed of volcanic lithic fragments

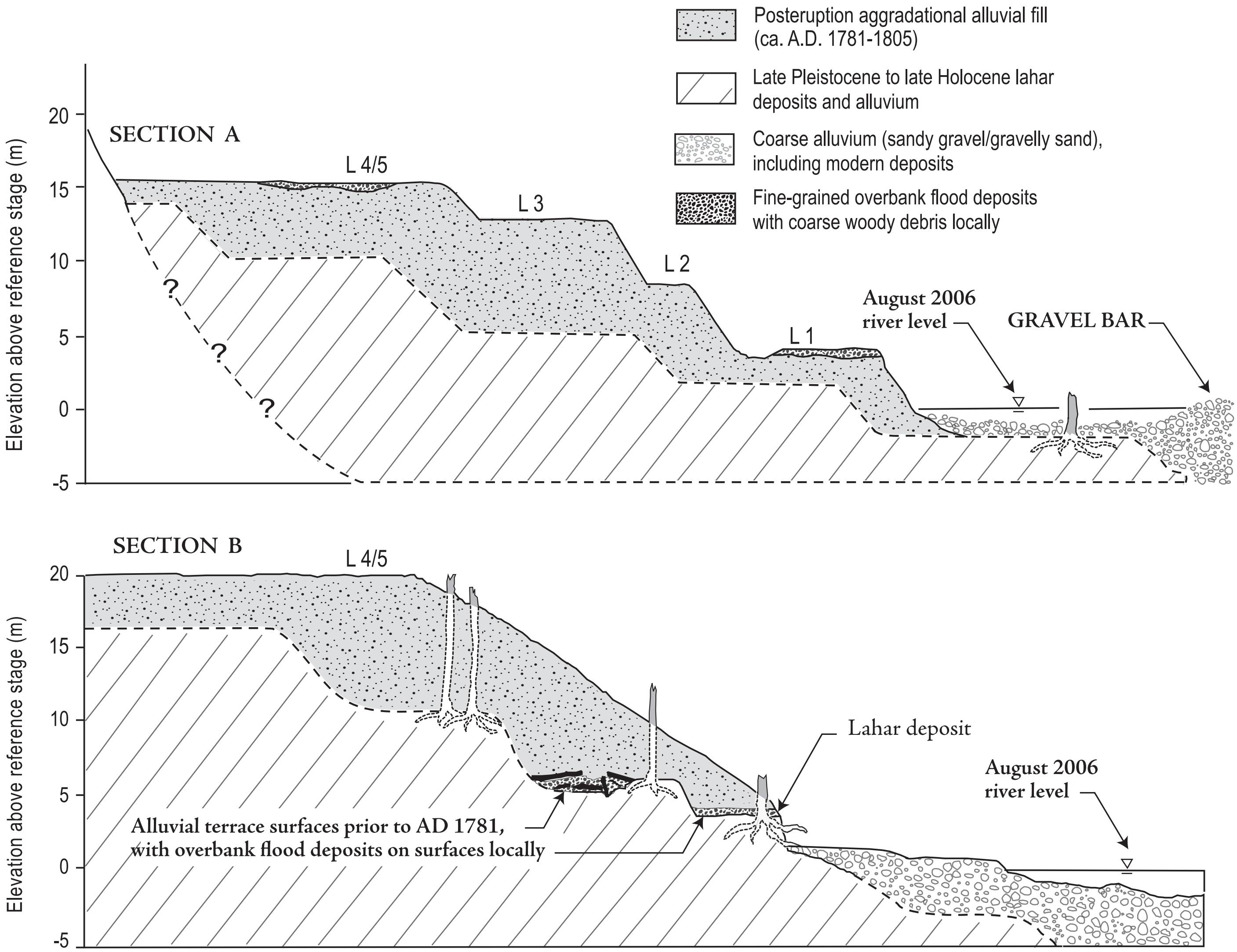

Figure 8. Simplified stratigraphic sections along the depositional reach of the Sandy River in Oxbow Regional Park, between river miles 11 and 13 (locations shown in Fig. 5). Terrace levels (Table 2) are labeled L1 through L4/5. Buried paleoterraces (dashed lines where inferred) are shown beneath Old Maid channel-fill deposits. Stump shown in channel in section A has a conventional radiocarbon date of 1940 ± 50 yr B.P. (inner rings), indicating that this tree was growing on an older paleoterrace that had been buried by Timberline-related channel aggradation.

TABLE 2. LIMITING TREE-RING AGES OF ALLUVIAL TERRACE SURFACES IN THE DEPOSITIONAL REACH OF THE SANDY RIVER DURING AND FOLLOWING THE OLD MAID ERUPTIVE PERIOD

Location	Increment core sample No.	Tree diameter at BH (cm)	Elevation of terrace surface above reference stage (m)	Number of rings in core at BH	Additional rings estimated from distance offcenter (using template)	Ring total (corrected BH tree age)	Correction for CTG*	Estimated age of terrace surface (years before tree-ring sampling)	Estimated year of terrace abandonment by river†	Comments
Oxbow Park, left bank (RM 13, near Group Camp 2)										
L1 surface	1998 12 16 - T2	79	3.8 ± 0.2	123	13	136	4	140	A.D. 1858	Latest possible date
	1998 12 16 - T3	66	3.8 ± 0.2	80	4	84				
	1998 12 16 - T4	59	3.8 ± 0.2	103	13	116				
	1998 12 16 - T5	58	3.8 ± 0.2	109	7	116				
	1998 12 17 - T12	74	3.8 ± 0.2	118	5	123				
	1998 12 17 - T13	84	3.8 ± 0.2	126	2	128				
	2004 07 28 - T1	86	3.8 ± 0.2	106	10	116 (110§)				
	Mean of 5 largest trees					124	11	135	A.D. 1862 ± 7	
L2 surface	1998 12 16 - T1B	78	9.0 ± 0.8	146	6	152 (160§)				
	2006 09 05- T6	139	9.0 ± 0.8	127	11	138				
	2006 09 05 - T7	95	9.0 ± 0.8	150	5	155				
	2006 09 05 - T8	127	9.0 ± 0.8	154	10	164				
	2006 09 05 - T9	142	9.0 ± 0.8	157	9	166	4	170	A.D. 1835	Latest possible date
	Mean of 5 largest trees					157	11	168	A.D. 1837 ± 7	
L3 surface	2006 08 31 - T1	96	12.8 ± 0.9	146	9	155				
	2006 08 31 - T2	86	12.8 ± 0.9	137	18	155				
	2006 08 31 - T3	116	12.8 ± 0.9	153	5	158	4	162 (min)	A.D. 1843	Latest possible date
	2006 08 31 - T4	114	12.8 ± 0.9	139	11	150				
	2006 08 31 - T5	104	12.8 ± 0.9	139	8	147				
	Mean of 5 largest trees					153	10	163	A.D. 1842 ± 7	
L4/5 surface	2006 09 05 - T!	129	17.3 ± 1.5	185	15	200				
	2006 09 05 - T2	123	17.3 ± 1.5	190	12	202				
	2006 09 05 - T3	109	17.3 ± 1.5	195	6	201				
	2006 09 05 - T4	136	17.3 ± 1.5	194	14	208	4	212	A.D. 1793	Latest possible date
	2006 09 05 - T5	128	17.3 ± 1.5	160	7	167				
	1993 07 26 - T1	94	17.3 ± 1.5	176	5	181				
	Mean of 5 largest trees					196	10	206	A.D. 1799 ± 7	
Oxbow Park, right bank (RM 11, on Gordon Creek block)										
L1 surface	2005 06 30 - T1	80	4.7 ± 0.3	88	0	88				
	2005 06 30 - T2	75	4.7 ± 0.3	85	3	88				
	2005 06 30 - T3	65	4.7 ± 0.3	93	2	95	4	99	A.D. 1905	Latest possible date
	2005 06 30 - T4	75	4.7 ± 0.3	82	0	82				
	2005 06 30 - T5	73	4.7 ± 0.3	63	6	69				
	2005 06 30 - T6	49	4.7 ± 0.3	63	0	63				
	Mean of 5 largest trees					84	11	**95**	**A.D. 1909 ± 7**	Late date due to flood disturbance?
L2 surface	2005 06 30 - T7	64	5.3 ± 0.4	100	5	105				
	2005 06 30 - T8	65	5.3 ± 0.4	94	18	112				
	2005 06 30 - T9	61	5.3 ± 0.4	103	2	105				
	2005 06 30 - T10	63	5.3 ± 0.4	106	4	110				
	2005 06 30 - T11	60	5.3 ± 0.4	96	8	104				
	2005 06 30 - T12	95	5.3 ± 0.4	121	2	123				
	2005 06 30 - T13	90	5.3 ± 0.4	123	3	126	4	130	A.D. 1874	Latest possible date
	2005 06 30 - T14	80	5.3 ± 0.4	115	3	118				
	Mean of 5 largest trees					118	11	129	A.D. 1875 ± 7	
Dabney Park, right bank (RM 6)										
L2 surface	1993 06 17 - T4	77	7.9 ± 0.5	110	5	115	4	119	A.D. 1873	Latest possible date
	1993 06 17 - T6	49	7.9 ± 0.5	67	7	74				
L3 surface	1993 06 17 - T2A	92	12.1 ± 0.8	123	6	129				
	1993 06 18 - T8	63	12.1 ± 0.8	162	1	163				
	1993 06 18 - T9	105	12.1 ± 0.8	129	12	141				
	1993 06 18 - T10	76	12.1 ± 0.8	127	8	135				
	1993 06 18 - T11	75	12.1 ± 0.8	161	4	165	4	169	A.D. 1823	Latest possible date
	1993 06 18 - T12	87	12.1 ± 0.8	129	7	136				
	Mean of largest 5 trees					141	11	155	A.D. 1837 ± 7	

*CTG = 10 yr for single trees, 11yr for 5-tree means (Pierson, 2007); for minimum ages, BHGT = 3 yr and GLT = 1 yr.
†Terrace abandoned at least 1 year prior to surface becoming stable potential substrate for conifer seedling germination.
§Correction for earlier sampling.

and crystals, mostly fresh. The sediments in the top few meters of the lower terraces appear more gravelly and more crudely bedded, although analysis of deposit sedimentology is still in progress. Preliminary sedimentologic data define three dominant lithofacies associations (LAs) (Fig. 7): LA1 is moderately to well-sorted medium to very fine sand units—ripple cross-laminated, trough cross-bedded, or massive—commonly capped by a <1 cm layer of silt; LA2 is poorly to moderately sorted medium to coarse sand, locally including fine gravel—trough cross-bedded, planar cross-bedded, or ripple cross-laminated; and LA3 is poorly sorted coarse to very coarse sand, gravelly sand, and sandy gravel—horizontally bedded, low-angle cross-bedded, or massive (with coarse gravel lenses).

LA1 is observed in the confined part of the depositional reach at the base of Old Maid section wherever the section rests on a pre–Old Maid paleoterrace, and it is found also on the treads of some modern inset (degradational) terraces. It is interpreted as deposition from one or more episodes of overbank flooding, which began when the aggrading channel brought terrace surfaces within vertical range of peak-flow flood deposition. Its occurrence on the modern inset terraces must have resulted from overbank flooding during the time window when the degrading channel bed was still within 4–5 m of the terrace surface, before the terraces were literally left high and dry beyond the range of flood inundation. Thin silty strata are also present beneath the lahar deposit on the lowest paleoterrace at the base of the Old Maid section, but the uppermost of these may have been deposited by a sediment-charged wave of river water being pushed ahead of the 1781 lahar (cf. Cronin et al., 1999). LA1 sediments are laid down by shallow, low-velocity overbank flows, which also deposited woody debris on terrace surfaces and gently bury undisturbed layers of forest duff. LA2 reflects dune and ripple migration at conditions of subcritical flow on the channel bed, reflecting a moderate rate of sediment transport (Miall, 1996) that is common in shallow, aggradational, braided systems (Manville et al., 2005). This is the dominant lithofacies association in exposures of the aggradational sequence at Oxbow Park. LA3 is typical of high sediment transport rates and high bed shear stress at the transition between subcritical and supercritical flow (Miall, 1996), probably reflecting narrowing and deepening of active channels as degradation begins and sediment transport rates increase. These conditions also can be found in the deeper channels of braided rivers (Smith, 1987; Miall, 1996).

Old Maid deposits on the delta are dominantly LA2. They are commonly interbedded with Columbia River overbank flood deposits (predominantly feldspathic fine sand to silt, light gray to tan in color and finely laminated). Maximum observed thickness of Old Maid deposits on the delta is 8 m, and maximum aggradation level above reference stage is ~5 m (Rapp, 2005).

Timing of Depositional Reach Sedimentation

The large lahar at Old Maid Flat was probably triggered by a lithic pyroclastic flow and deposited in the autumn of 1781, as inferred from thin late wood in the 1781 ring (Table 1; Pringle et al., 2002, 2010). An estimated minimum volume of this lahar deposit in the sediment-source reach is 7×10^6 m^3, based on an empirical relation between volume and planimetric area (Iverson et al., 1998) for the deposit at Old Maid Flat, and it was probably the largest lahar generated during the Old Maid eruptive period. Aggradation in the Sandy River depositional reach at Oxbow Park (Figs. 4 and 5) began with the 1781 lahar (Fig. 9), followed by overbank flooding on low terraces and then an unbroken sequence of channel deposits (Fig. 7). A cross-dated log, deposited by a flood on a low paleoterrace and buried in LA1 deposits, died in 1779 (Table 1), which is consistent with this timeline. Aggradation at Oxbow Park reached its maximum level by 1793, when the highest terrace had stabilized and channel degradation had already begun at this location (Fig. 9). These constraining dates suggest a minimum average aggradation rate at this location of 2 m/yr, although large lahars likely induced surges in the aggradation rate. The longitudinal profile of maximum aggradation level for the 26-km-long depositional reach is incomplete (Fig. 10). Height of the highest Old Maid terrace is relatively constant, varying between ~17 and 20 m over most of the lower 21 km. A few hundred meters upstream of the delta apex, maximum terrace height drops to ~8 m above the river bed.

Historical evidence (Table 1) suggests that aggradation was under way on the Sandy River delta but not yet at maximum level in 1792, based on a historical observation by Lt. Broughton (of the Vancouver expedition) of a shallow sand bar forming at the river's mouth—a location where the Columbia River's current was and is particularly swift and where a sand bar would not last long without continuous sediment supply (Cameron and Pringle, 1987). Members of the Lewis and Clark expedition described and mapped the mouth of the Sandy River (naming it the Quicksand River) on 3 November 1805, and explored it further on 1 April 1806 (Cameron and Pringle, 1986, 1987; Moulton and Dunlay, 1990; O'Connor, 2004). Their map (Fig. 5 inset) and description suggest that the Sandy River was then a broad, turbid, shallow, sand-bedded braided stream with numerous midchannel islands, at most ~4 in. [~10 cm] deep and about double its present width, transporting predominantly sand-size sediment at a high rate on an unstable, unarmored bed (Table 1). They compared the Sandy River channel to that of the shallow, sediment-choked Platte River that they had seen in Nebraska at the beginning of the expedition. On their return in the spring of 1806, a party explored upstream to approximately the location of Dabney State Park today (Fig. 5). They noted that the river had only low banks that were being overtopped by high water—a location where today there is a terrace 18 m above the channel. They must have seen the Sandy River very close to the time of maximum aggradation (Fig. 9).

In summary, maximum aggradation level was reached at Oxbow Park by 1793, more than a decade before it was reached at the Sandy delta sometime close to the 1805–1806 visit by Lewis and Clark (Fig. 9; Table 1), although aggradation probably was initiated at both locations by the 1781 lahar. The beginning of degradation at Oxbow Park by 1793 coincides with the end of known magmatic activity (Sheppard et al., 2010) and likely reflects some degree of diminishment of sediment supply to the river. By 1835, a terrace surface ~9 m below maximum aggradation level at Oxbow Park had been colonized by Douglas fir. By 1858, a terrace ~4 m above present river level had stabilized and was colonized, suggesting that the river level was already within ~1–2 m of its present elevation. Assuming a nonlinear recovery of channel bed elevation, present channel level was probably achieved at both locations during the second half of the nineteenth century. Present channel conditions were confirmed in 1911 at the upper end of the depositional reach with a surveyed gauge elevation and description at a USGS gauging station (Table 1) and on the delta in 1916 by a survey for the 1918 edition of the USGS Troutdale Quadrangle topographic map, which shows a single-thread channel with approximately its present width. These data suggest that the aggradation-degradation cycle triggered by the Old Maid eruption of Mount Hood took 80–100 yr to complete at each location.

DISCUSSION

The geomorphic response of the Sandy River to sediment loading during the Old Maid eruptive period has characteristics in common with other disturbed fluvial systems and flume experiments where channels respond to large sediment inputs:

(1) Excess sediment was transported downstream as a sediment wave (in the sense of Lisle,

2008) that resulted in a cycle of aggradation and degradation at fixed points along the channel. The wave was composed of predominantly sand-size bed material, with mobilized sediment being finer than the present and presumed preexisting bed material (cf. Knighton, 1989; Nicholas et al., 1995; Madej and Ozaki, 1996; Wathen and Hoey, 1998; Miller and Benda, 2000; Sutherland et al., 2002; Cui et al., 2003; Kasai et al., 2004a, 2004b; Hoffman and Gabet, 2007; Madej et al., 2009).

(2) Sediment began moving downstream immediately following major sediment input (cf. Knighton, 1989; Simon, 1989); aggradation began in the lower Sandy River with a large lahar, within a year after eruption onset.

(3) Aggradation rate in the depositional reach was relatively rapid (2 m/yr) (cf. Kuenzi et al., 1979; Meyer and Janda, 1986; Pierson et al., 1996; K.M. Scott et al., 1996; Madej et al., 2009).

(4) Aggradation resulted in channel widening and braiding (cf. Meyer and Janda, 1986; Knighton, 1989; Hoey and Sutherland, 1991; Nicholas et al., 1995; Hayes et al., 2002; Segschneider et al., 2002; Manville et al., 2005).

(5) Aggradation was accompanied by formation of highly mobile sand-bedded channels (cf. Kuenzi et al., 1979; Montgomery et al., 1999; Hayes et al., 2002; Gran et al., 2006).

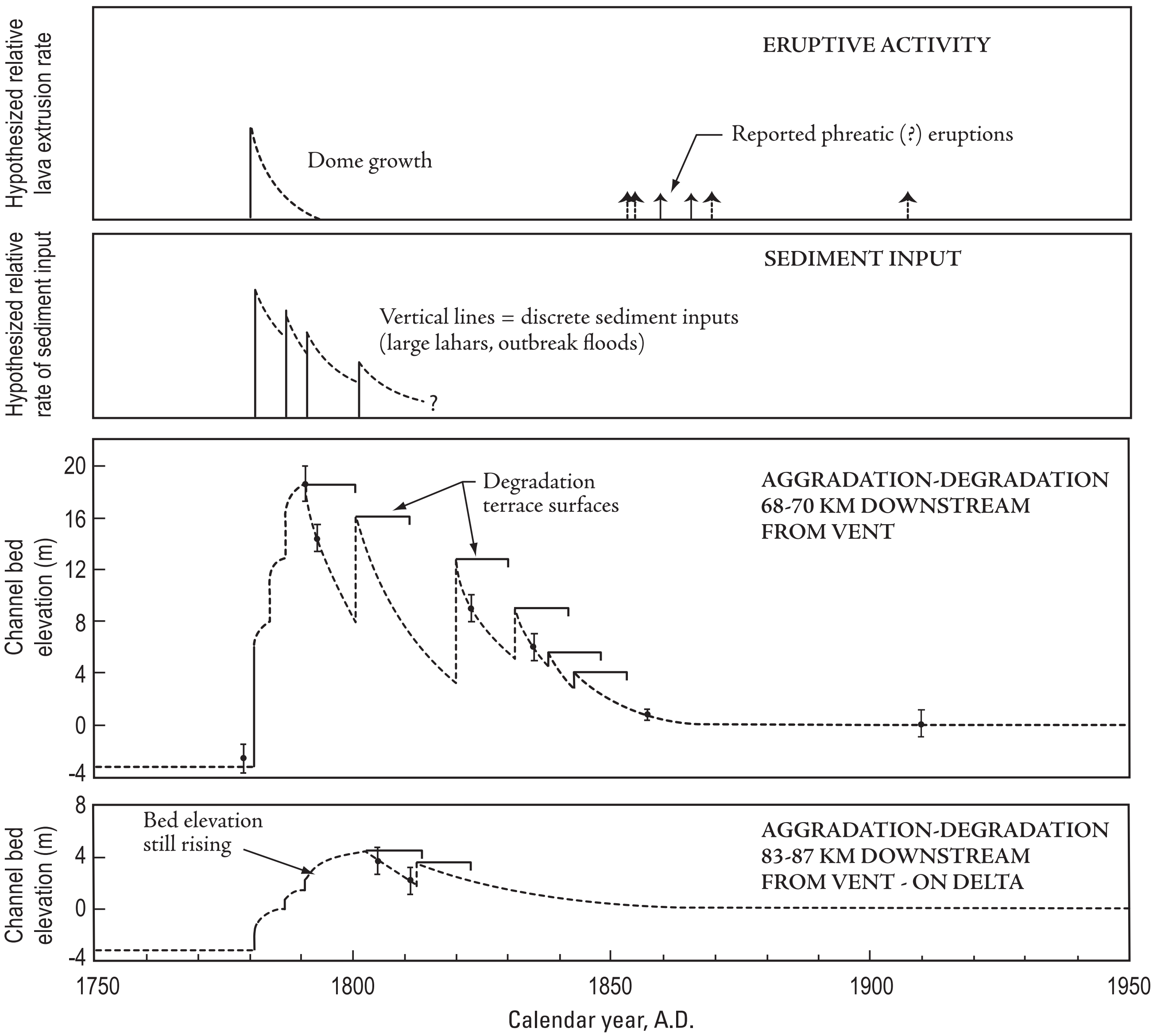

Figure 9. Timing of Old Maid eruptive activity, sediment input, and the resulting cycle of aggradation and degradation at two locations in the depositional reach of the Sandy River downstream from Mount Hood. Bed elevation curves are constrained by (A) minimum ages of terrace surfaces determined from the ages of the presumed oldest trees growing on those surfaces (Table 2; older trees might have existed but were not sampled), (B) cross-dated logs buried in the sediment (Table 1), and (C) historical observations (Table 1). Bed elevations are approximate and relative to August 2006 reference stage. Elevations of existing degradation terrace surfaces are shown resulting from hypothetical short-term reversals in degradation caused by discrete sediment inputs (cf. Madej and Ozaki, 2009). Note that channel bed stabilized at a higher elevation than it had prior to eruptive activity.

(6) Channel degradation following the waning of sediment input was manifested by channel incision, channel narrowing, coarsening of channel bed material, and return from a braided channel pattern to a branching or single-thread channel pattern (cf. Smith, 1987; Dietrich et al., 1989; Knighton, 1989; Lisle et al., 1993; Manville et al., 2005; Kasai et al., 2004b; Gran and Montgomery, 2005; Gran et al., 2006; Madej et al., 2009).

(7) Downcutting through the aggradational channel fill led to sequential formation of degradation terraces stepping down to the new equilibrium channel bed (cf. Manville et al., 2005).

(8) According to the classification of Nicholas et al. (1995), the eruption-induced sediment influx to the Sandy River was a "superslug," resulting in major valley-floor adjustment.

(9) Rate of recovery to predisturbance conditions was nonlinear, and full recovery required more than half a century (Meade, 1982; Knighton, 1989; James, 1991; Schumm and Rea, 1995).

The results of this study are inadequate for determining whether the sediment wave responsible for the aggradation-degradation cycle migrated downstream by translation or by dispersion (cf. Lisle et al., 2001; James, 2006; Lisle, 2008). Criteria for wave translation include (1) downstream migration of the leading and trailing edges, the apex, and the center of mass of the wave (Lisle et al., 2001); and (2) the highest remnant terraces having a more or less constant height marking the downstream advance of a translating wave. The sediment in translating sediment waves also tends to be finer than the ambient bed material in the channel (Lisle et al., 2001; Cui et al., 2003). In dispersing sediment waves, a downstream-thinning wedge of sediment leaves remnant terraces that become progressively lower in the downstream direction, and the wave sediment tends to be of equal or coarser grain size than the ambient bed sediment (Lisle et al., 1997, 2001). In either case, the leading edge of the wave advances downstream, and there is a time lag in the transition from aggradation to degradation in the downstream direction (James, 2006; Lisle, 2008). Although the average grain size of the Old Maid sediment wave is finer than the present bed material (and presumably finer than the bed material in 1781), the data on remnant terrace heights (Fig. 10) are insufficient to determine the downstream trend in maximum aggradation level. Terraces have more or less constant height in the middle part of the depositional reach but show a decrease in height prior to reaching the delta apex.

Recovery of the channel profile during degradation to its present level in the depositional reach took more than half a century, and likely occurred at a gradually decreasing rate (Fig. 9). Data points are too few to determine the precise shape of the recovery curves for the lower Sandy

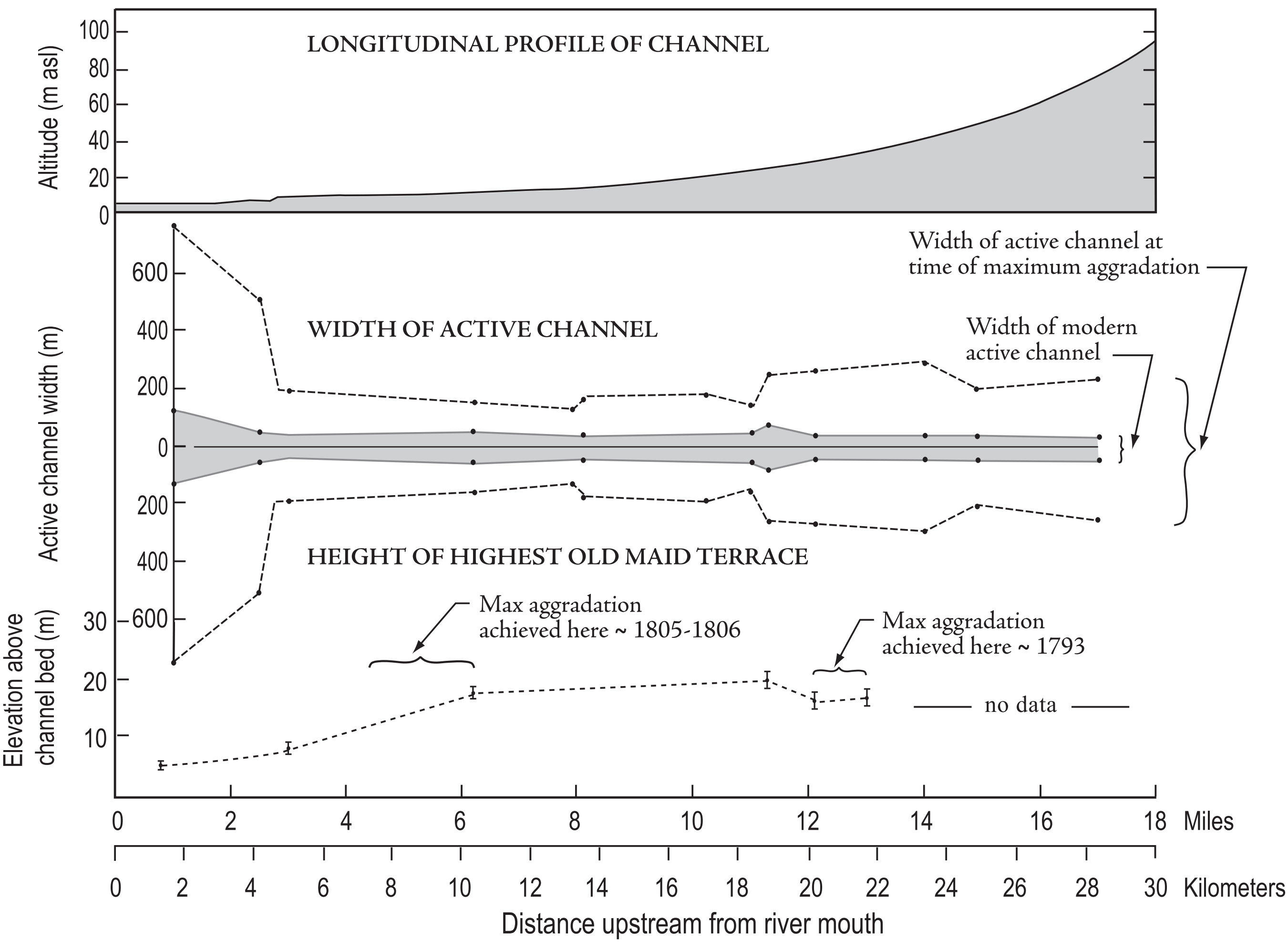

Figure 10. Valley morphology and terrace height in the lowermost 30 km of the Sandy River, downstream from Mount Hood. In this plot, the depositional reach extends from 0 to 26 km. The first 4.7 km of channel are on the unconfined Sandy River delta. Width of active modern channel is approximate, based on width measured from a 1952 U.S. Geological Survey topographic map.

River, but it appears to be nonlinear. Recovery curves following pulses of sediment loading in rivers elsewhere are nonlinear, variously described as negative exponential functions (Graf, 1977; Simon and Robbins, 1987; Maita, 1991; Schumm and Rea, 1995; Kasai et al., 2004b; Madej and Ozaki, 2009), hyperbolic functions (Williams and Wolman, 1984), or power functions (Simon, 1989; Madej and Ozaki, 2009). Nonlinearity could be due in part to a nonlinear diminishment in sediment supply (Suwa and Yamakoshi, 1999). However, abrupt reductions in sediment supply can also result in nonlinear incision rates (Williams and Wolman, 1984).

The longitudinal profile of the depositional reach appears to have reached a dynamic equilibrium condition following the Old Maid aggradation-degradation cycle, with little or no change in bed elevation in the past 100 yr. However, the channel has not fully regained its pre–Old Maid bed elevation. Abundant, easily erodible sediment still remains in the upper tributary canyons of the Sandy River, and significant bank erosion was noted on Old Maid Flat and in Oxbow Park during a large flood in November 2006. It may be that modern sediment input rates are still higher than pre-eruption rates, which has enabled a new equilibrium profile to become established. It is also possible that the active channel has been shifted laterally onto a more cohesive, erosion-resistant substrate that is resisting further incision to the original bed level (James, 1991). An older cohesive lahar deposit, a cemented gravel deposit, and bedrock straths all crop out on the valley floor near the present level of the channel bed. A third possibility, inferred from the experimental results of Madej et al. (2009), is that the magnitude of the Old Maid sediment input caused a shift in the balance of variables controlling the bed profile, so that although present and pre-eruption sediment inputs may be similar, the higher bed elevation is accommodated by a new balance of controlling variables.

Perhaps the most important result of this study for future volcano hazards in the Cascades is the magnitude of aggradation that occurred. The minimum 23 m of aggradation in the Sandy River depositional reach is large with respect to the volume of sediment input when normalized for drainage area and compared to sedimentation responses at other volcanoes (Table 3). It is also large in view of the fact that deposition by lahars played only a minor role in the channel aggradation on the lower Sandy River. Lahars commonly play a major role in causing volcano-sourced rivers to aggrade during and following eruptions (Waldron, 1967; Pierson et al., 1996; Rodolfo et al., 1996; K.M. Scott et al., 1996; Major et al., 1996), so major aggradation by mostly fluvial sediment transport in the Sandy River is noteworthy.

We hypothesize that the primary reason for vigorous channel aggradation in the lower Sandy River is valley physiography. The Sandy River depositional reach is confined within a narrow entrenched valley (250–600 m wide) upstream of the delta. The river could not spread the sediment out much during migration of the sediment wave. At other volcanoes in less dissected terrain, much larger sediment inputs to volcanic drainage basins result in less aggradation (generally <10 m) in most areas, because river channels can widen unhindered and spread sediment over channel widths of several kilometers (Table 3). However, aggradation levels increase dramatically in narrow channel reaches (Table 3). Also in the Sandy River, valley confinement in the depositional reach was combined with a steep, mostly nondepositional middle reach, resulting in very efficient sediment transport to that zone of deposition. For this river, the abrupt transition from predominantly nondeposition to major deposition appears to have occurred at a channel gradient between 0.003 and 0.005. An additional effect of valley physiography may have been that confinement of source sediment in narrow entrenched valley heads on the lower flanks of Mount Hood resulted in more focused and more efficient erosion of the source sediment produced during the eruption.

Another factor that likely enabled the relatively large sediment response in the lower Sandy River is the combination of infrequent very large rainstorms (including "rain-on-snow" events) and frequent moderate-magnitude rainstorms that occur in the Cascades. The relationship between river discharge and sediment transport has not been investigated for rivers at Mount Hood, but it has been studied at Mount St. Helens (Major, 2004), which is 98 km northwest of Mount Hood and in a similar climatic setting. Infrequent large storms (recurrence interval >100 yr) at Mount St. Helens can transport as much as 50% of the annual suspended sediment load in a single day. While such storms can be important, Major (2004) concluded that the much more frequent moderate-magnitude rainstorms typical of Cascade winters (triggering floods greater than mean annual floods but less than 2 yr floods) transported the majority of suspended sediment in rivers draining Mount St. Helens for the 20 yr following the 1980 eruption. These frequent, moderate discharges have produced annual suspended sediment yields as much as 500 times above typical background levels (Major et al., 2000) and channel aggradation of 5–10 m in a 1-km-wide channel (Table 3). When these frequent storms are combined with infrequent but high-intensity "pineapple express" storms that are also typical for the Cascades, it suggests that more than enough sediment transport capacity was available to deliver large sediment volumes to the depositional reach of the Sandy River.

CONCLUSIONS

Large influxes of unconsolidated volcanic sediment to the headwaters of the Sandy River during a dome-building eruption of the Old Maid eruptive period caused the downstream migration of a large sediment wave that resulted in channel aggradation of at least 23 m in the lowermost reach of the river, 61–87 km downstream of Mount Hood. Maximum aggradation was achieved in the upper part of this river reach at about the time dome growth ceased, 12 yr after the onset of eruptive activity. Fluvial sediment transport (rather than lahars) deposited most of the channel fill. Following rapid aggradation, channel degradation (incision through the aggradational fill) continued for more than half a century before the river was able to reestablish a new state of dynamic equilibrium above its former bed elevation.

Compared to other volcanoes, the amount of eruption-induced aggradation of the Sandy River channel was large with respect to the type and magnitude of eruptive activity. Confinement of the river within a narrow entrenched valley and the occurrence of mostly high-frequency but moderate-magnitude flood flows are hypothesized to have been a combination that allowed exceptional levels of channel aggradation to occur in the downstream-most 26 km of Sandy River. A similar level of channel aggradation certainly would be hazardous to human life and property along the river if it were to occur today. A number of rivers draining other Cascade Range volcanoes, where physiographic and climatic settings are similar, likewise could be affected by significant channel aggradation following future eruptions.

ACKNOWLEDGMENTS

The geomorphic evidence of high rates of post-eruption sedimentation on the Sandy River was first described in a volcano hazard assessment by Dwight "Rocky" Crandell (Crandell, 1980) and more extensively defined through unpublished field mapping by Jim Vallance. Field assistance for this study was ably supplied at various times by Dan Turner, Colleen Riley, and Jasper Hardison, and work in Oxbow Park has been greatly facilitated by Park Manager Bill Doran. Geographic information system (GIS) assistance was furnished by Dave Ramsey, and figures were prepared by Robert Crist and Lisa Faust. Gordon Grant, Tom Lisle, MaryAnn Madej, Vern Manville, Chris Newhall, Jim O'Connor, and Willie Scott provided very helpful manuscript reviews and discussions.

TABLE 3. SEDIMENT LOADS ADDED TO DRAINAGE BASINS BY VOLCANIC ERUPTIONS, GIVEN BOTH IN TOTAL AMOUNTS AND RELATIVE AMOUNTS (NORMALIZED BY DRAINAGE AREA) AND DOWNSTREAM AGGRADATION RESULTING FROM THE SEDIMENT INFLUX FOR "DEPOSITIONAL REACHES" OF THE AFFECTED RIVERS

Volcano, year of eruption, eruption type (VEI*)	Contributing drainage basin	Volume of sediment deposited in drainage basin (km^3)	Types of source deposits	Drainage area of volcanically disturbed drainage basin (km^2)	Eruption-contributed sediment load per unit drainage area (m^3/km^2)	Aggradation in depositional reach (m)	Channel width where aggradation measured (km)	Downstream distance from limit of primary sediment source to measured aggradation site (km)	Data source
Taupo caldera, A.D. 210, plinian (6+)	Rangitaiki River	2.85	PF, T	2816	1.0	3 to 6	5	~50†	Manville et al. (2005)
Santa Maria, 1902, plinian (6?)	Río Samalá	4§	T, PF, L	1503	2.7	10 to 15	4	10 to 50 (depositional reach average)	Kuenzi et al. (1979)
St. Helens, 1980, plinian (5)	North Fork Toutle River (above Green River confluence)	2.6	DA, L, T	410	6.3	5 to 10	1	4 to 6	Lehre et al.(1983); Major and Mark (2006)
St. Helens, 1980, plinian (5)	South Fork Toutle River (500 m upstream of USGS stream gauge 14241490	~0.1	L, PF, T	182	0.5	13	0.2	18	Janda et al. (1981); Letsinger (1994); Major (2004)
Pinatubo, 1991, plinian (6)	O'Donnell River	0.6	T, PF, L	89	6.7	3 (after 2 mo)	0.1	18	K. Scott et al. (1996); W. Scott et al. (1996); Daag (2003)
Pinatubo, 1991, plinian (6)	Pasig-Potrero River	1.3 in combined Pasig-Sacobia watershed; stream capture shifted sediment delivery between rivers	PF, T, L	64	20.3	4 (after 1 mo)	0.15 (levee confined)	31	K. Scott et al. (1996); W. Scott et al. (1996); Daag (2003)
Pinatubo, 1991, plinian (6)	Sacobia River	1.3 in combined Pasig-Sacobia watershed; stream capture shifted sediment delivery between rivers	PF, T, L	64	20.3	>25 (after 15 mo)	2	12	K. Scott et al. (1996); W. Scott et al. (1996); Daag (2003)
Pinatubo, 1991, plinian (6)	Marella - Sto. Tomas River	1.3	PF, T, L	70	16.4	15 (after 3 mo)	2	10	Rodolfo et al. (1996); Umbal and Rodolfo (1996); Daag (2003)
Pinatubo, 1991, plinian (6)	Marella - Sto. Tomas River	1.3	PF, T, L	70	16.4	38 (after 2 yr)	0.1	6	Rodolfo et al. (1996); Umbal and Rodolfo (1996); Daag (2003)
Pinatubo, 1991, plinian (6)	Bucao River	3.1	PF, T, L	262	11.8	14 (after 2 yr)	1.5	13	Rodolfo et al. (1996); Daag (2003)
Unzen, 1990-95, dome-building	Mizunashi River	0.2	PF, T	~14	14	3 maximum (1-2 average)	1	3	Miyabuchi (1999); Unzen Restor. Proj. Office (2007)
Hood, 1781-1793, dome-building	Sandy River, this study	0.1	PF, L	117	0.85	>23	0.6	30 to 35	Crandell (1980); Herrett et al. (2003); this study

*VEI is "volcanic explosivity index" (Newhall and Self, 1982), which is based on measures of eruptive energy (i.e., volume of tephra ejected, height of eruption cloud, outer limit of ballistics); VEI ratings for eruptions from Simkin and Siebert (1994).

†Distance from limit of ignimbrite deposit and 50 cm tephra-fall isopach.

§Deposit eroded; original volume of source sediment unknown.

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Manuscript Received 9 July 2009
Revised Manuscript Received 6 November 2009
Manuscript Accepted 10 December 2009

Printed in the USA