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Eruption-related lahars and sedimentation response downstream of Mount Hood: Field guide to volcaniclastic deposits along the Sandy River, Oregon

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ABSTRACT

Late Holocene dome-building eruptions at Mount Hood during the Timberline and Old Maid eruptive periods resulted in numerous dome-collapse pyroclastic flows and lahars that moved large volumes of volcaniclastic sediment into temporary storage in headwater canyons of the Sandy River. During each eruptive period, accelerated sediment loading to the river through erosion and remobilization of volcanic fragmental debris resulted in very high sediment-transport rates in the Sandy River during rain- and snowmelt-induced floods. Large sediment loads in excess of the river's transport capacity led to channel aggradation, channel widening, and change to a braided channel form in the lowermost reach of the river, between 61 and 87 km downstream from the volcano. The post-eruption sediment load moved as a broad bed-material wave, which in the case of the Old Maid eruption took ~2 decades to crest 83 km downstream. Maximum post-eruption aggradation levels of at least 28 and 23 m were achieved in response to Timberline and Old Maid eruptions. In each case, downstream aggradation cycles were initiated by lahars, but the bulk of the aggradation was achieved by fluvial sediment transport and deposition. When the high rates of sediment supply began to diminish, the river degraded, incising the channel fills and forming progressively lower sets of degradational terraces. A variety of debris-flow, hyperconcentrated-flow, and fluvial (upper and lower flow regime) deposits record the downstream passage of the sediment waves that were initiated by these eruptions. The deposits also presage a hazard that may be faced by communities along the Sandy River when volcanic activity at Mount Hood resumes.

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INTRODUCTION

Late Holocene dome-building eruptions at Mount Hood during its two most recent periods of confirmed eruptive activity—the *Timberline* eruptive period (ca. AD 300–600) and the *Old Maid* eruptive period (AD 1780–1801?)—produced multiple dome-collapse lithic pyroclastic flows and lahars, most of which were deposited on a steep pyroclastic debris fan and in confined canyons beyond the toe of the fan on the southwest flank of the volcano (Crandell, 1980; Cameron and Pringle, 1986, 1987; Scott et al., 1997a, 1997b; Fig. 1). Eruption-mobilized volcanic sediments include debris from a flank collapse near the volcano summit (~70 × 10^6 m^3) that probably occurred early in the Timberline eruptive period (Scott et al., 1997b; Iverson et al., 1998).

The Sandy River and a major tributary, the Zigzag River, drain the western part of the debris fan (Figs. 1 and 2), which has been an important source of sediment to the river since the late Pleistocene (Crandell, 1980). Other tributaries probably contribute only a small fraction of total sediment load to the Sandy River. The river is incised ~100–500 m 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). The river valley remains narrowly confined until it reaches its confluence with Columbia River, where it has built a 10 km^2 delta extending ~3 km out into the Columbia River valley. Drainage area of the Sandy River is ~1130 km^2 at a stream gage (U.S. Geological Survey 14142500), 58 km downstream from Crater Rock (Fig. 2; U.S. Geological Survey, 2006). Peak discharge of record at this gage (1964) is 2390 m^3/s. Mean annual flow was 66 m^3/s prior to flow regulation in 1915.

The longitudinal profile of the Sandy River (Fig. 3) can be segmented into distinct reaches: (1) the *debris fan* (0–7 km downstream of the vent); (2) a channelized *sediment-source reach* downstream of the fan (7–36 km from vent), where a thick valley fill of primary and reworked pyroclastic-flow and lahar deposits have accumulated; (3) a slightly steepened *middle reach* (36–61 km from vent) with some lahar terraces but minor fluvial deposition; and (4) a low-gradient *response reach* (61–87 km from vent), which experienced major fluvial deposition resulting from channel aggradation during and following the Timberline and Old Maid eruptive periods. Over the final 4.7 km of the response reach, the Sandy River flows unconfined across the Sandy River delta.

The bed of the river today is armored in most 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 response reach (on low terrace surfaces) comprise moderately to well-sorted, medium to very fine sand with some silty layers.

Erosion from the sediment-source reach and the debris fan provided most of the sediment input to the river during Timberline and Old Maid time. A thick, downstream-thinning wedge of unconsolidated volcanic sediment in the upper sediment-source reach forms a wide, flat valley floor, locally known as Old Maid Flat (Fig. 3; Stop 2). Well logs from geothermal test wells (Priest and Vogt, 1982) and valley cross-section geometries (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. A prominent valley fill continues beyond Old Maid Flat, extending as far as 30 km downstream of the fan and forming the remainder of the sediment-source reach (Figs. 2 and 3). In the Zigzag River, valley-fill deposits extend ~12 km downstream from the fan to the confluence with the Sandy River. 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 (middle cross section in Fig. 3). Average channel gradient

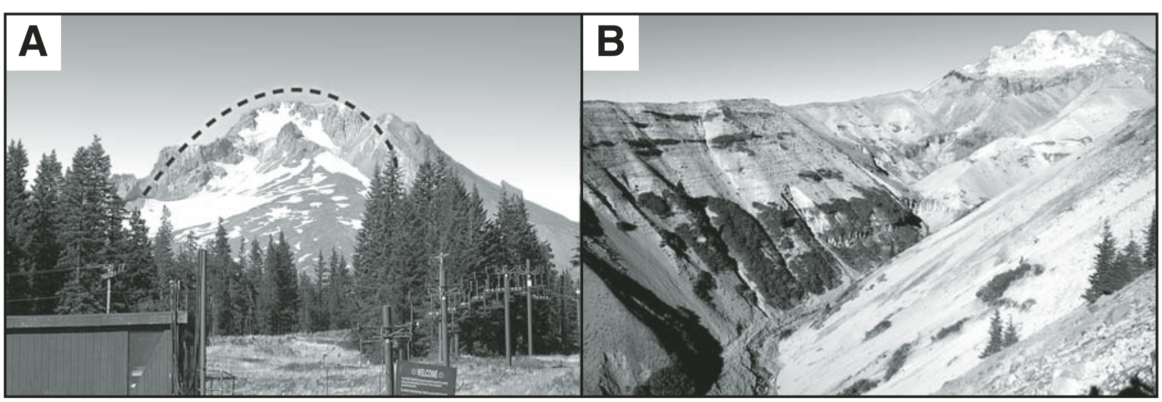


Figure 1. Views of Crater Rock (remnant Old Maid lava dome) and the pyroclastic debris fan downslope of Crater Rock on the SW flank of Mount Hood. (A) View from small ski area at Government Camp at the distal end of the debris fan. Crater Rock is centered in the scar left by the early Timberline collapse (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.

of the entire reach is 0.0074. While some terraces composed of Timberline lahar deposits and older coarse fluvial gravels crop out 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.

The response reach begins where the river channel widens and flattens. Its channel alternates between single-thread and branching forms 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, which are superimposed locally on older fluvial deposits and strath terraces. In the delta segment of this reach, deposits from Mount Hood are interlayered with Columbia River overbank flood deposits (Rapp, 2005). At least three Timberline lahars and one Old Maid lahar traveled the entire 87 km length of the Sandy River; however most lahars were smaller and extended no more than ~30 km downstream from the source lava dome. The three Timberline lahars are well exposed at the delta apex (Fig. 4; Stop 4).

The response reach aggraded at least 28 m during Timberline eruptive activity and at least 23 m during the Old Maid eruptive period (T.C. Pierson, unpublished data). Except for the four lahars just mentioned, channel aggradation in this reach was chiefly by normal fluvial processes, but at higher than normal transport rates. Alluvial terraces that record peak aggradation level and subsequent channel degradation are well preserved at Oxbow Park, in the upper part of the response reach (Fig. 4; Stop 3).

During Old Maid aggradation, the river bed rose at a rate of ~2 m/yr until peak aggradation level was reached after a little more than a decade (T.C. Pierson, unpublished data). Numerous

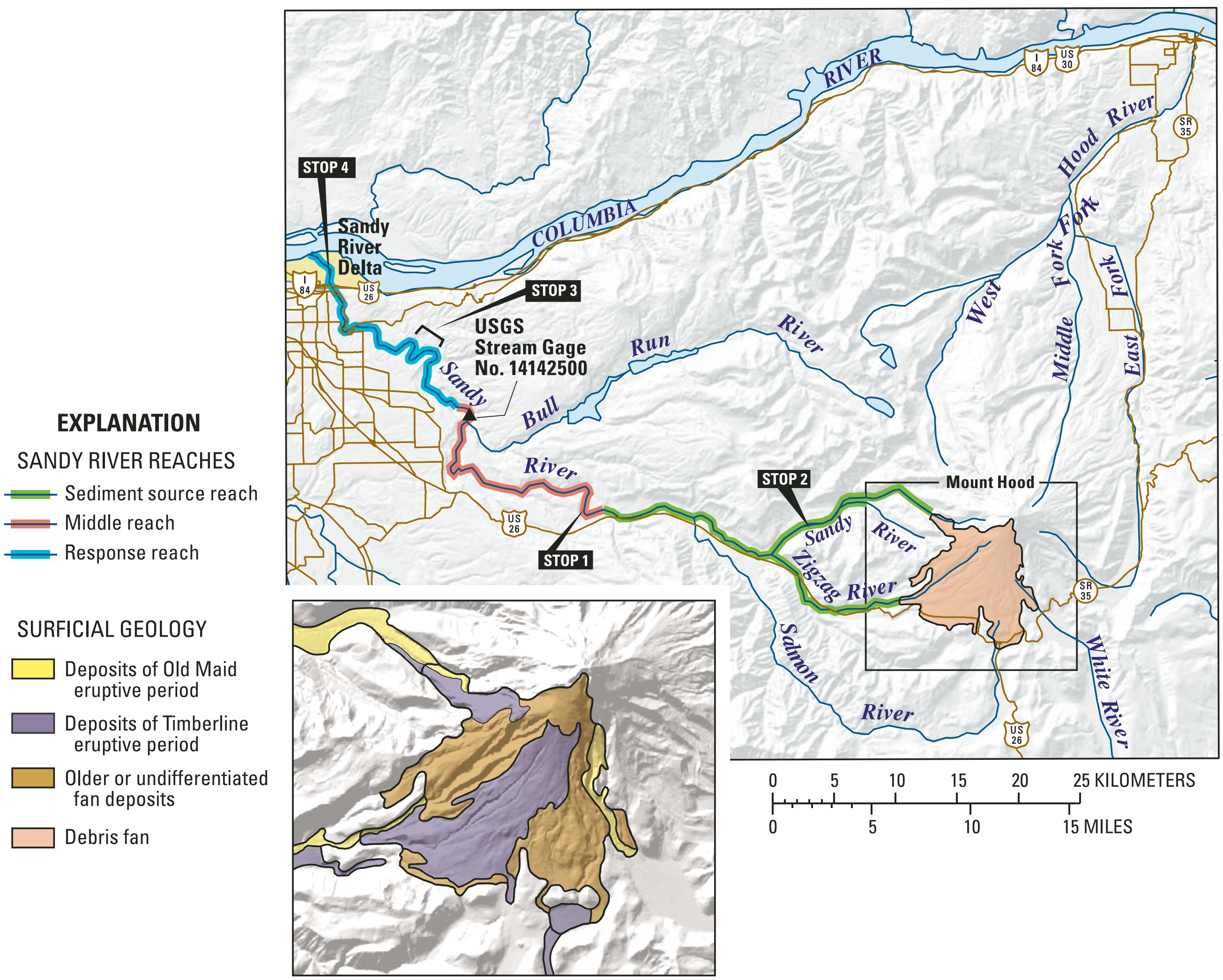


Figure 2. Location map of the Sandy River at Mount Hood, Oregon. Sediment-source, middle, and response reaches of the Sandy River are indicated. Inset map is a simplified geologic map of the debris fan (modified from Scott et al., 1997a), showing recognized deposits of Old Maid and Timberline age (the two late Holocene eruptive periods) on and just downstream of the fan surface. No pyroclastic flows or lahars of Old Maid age entered the Hood River drainage; ~10^8 m^3 of debris entered the White River drainage—a volume similar to that entering the Sandy drainage (Crandell, 1980).

trees were buried in growth position by these aggradational deposits, attesting to rapid fluvial deposition (Cameron and Pringle, 1991). Channel degradation immediately followed aggradation, once the rate of upstream sediment supply waned. The return to equilibrium conditions in the response reach required nearly a century (T.C. Pierson, unpublished data).

LATE HOLOCENE ERUPTIVE PERIODS OF MOUNT HOOD

Timberline Eruptive Period

The age of the Timberline eruptive period has been defined as ca. 1800–1500 uncalibrated ^{14}C yr B.P. or approximately AD 300–600, on the basis of four dated samples (Crandell, 1980). More recent dates generally also fall within this range. Paleomagnetic data from the Mount Hood edifice, however, suggest that eruptive activity was confined to less than two centuries, which is supported by stratigraphic and weathering evidence (Scott et al., 1997a). Within this time window, a hiatus as long as a century is indicated by the accumulation of eolian silt and forest litter between successive Timberline deposits (Crandell, 1980) and the development of peat layers between successive ash cloud deposits (Scott et al., 1997a). Thus, Timberline eruptive activity appears to have involved two major eruptive pulses, each lasting a number of decades.

Timberline eruptive products are chiefly lithic pyroclastic flows and accompanying ash clouds that extended at least 12 km from the vent (Scott et al., 1997a). Multiple gravitational collapses of a growing dacite lava dome, as inferred from numerous clasts in the deposits showing radial fracturing and microvesicular texture, generated the pyroclastic flows. Rapid release of water from mixing of hot pyroclastic debris with snow (Crandell, 1980; Cameron and Pringle, 1986; Scott et al., 1997a), as well as runoff from heavy rain, initiated the lahars. Deposits of Timberline age are found in all of the drainages heading on the debris fan, although they are sparse in the White River (Fig. 2), suggesting that a topographic barrier blocked the head of the White River during this period (Scott et al., 1997a). Timberline deposit thicknesses on the fan are locally as much as 100 m (Cameron and Pringle, 1986). The surficial distribution of Timberline deposits on the fan (Fig. 2) suggests that the source lava dome must have been at or very near the present site of Crater Rock on the upper southwest flank of the volcano.

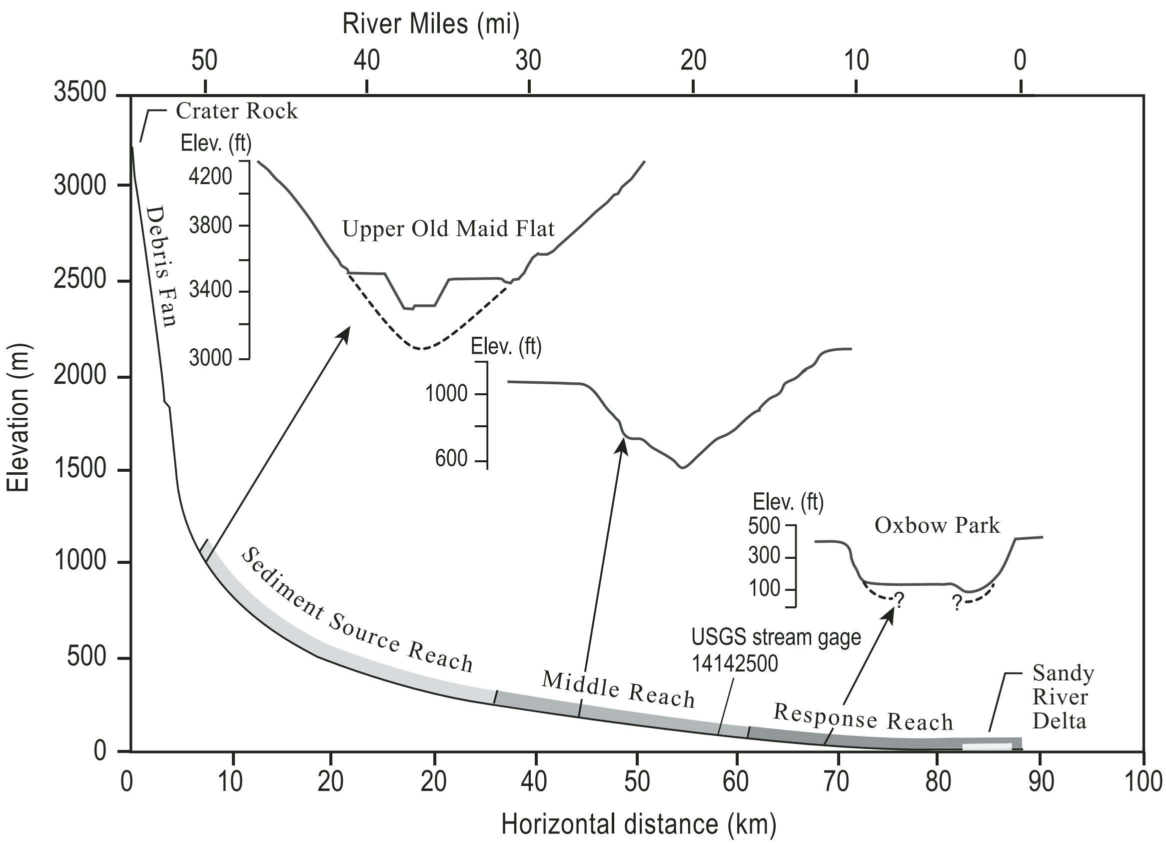


Figure 3. Longitudinal profile of the Sandy River channel, starting at Crater Rock (source volcanic vent) and continuing down to the Sandy River confluence with the Columbia River. River reaches described in the text are indicated, and selected valley cross sections for each reach are shown. Profile derived from U.S. Geological Survey 30 m digital National Elevation Data set and U.S. Geological Survey 1:24,000 digital line graph. Vertical exaggeration is 9.3×.

Old Maid Eruptive Period

Volcanic products from the Old Maid eruptive period were originally dated at "between 200 and 300 years old" (Crandell, 1980). Recent tree-ring dating, augmented by geochemical signatures from wood in individual annual rings of trees affected by ash clouds from pyroclastic flows, has more precisely limited dome growth to between AD 1780 and 1793 (Sheppard et al., 2009). Other tree-ring evidence suggests that pyroclastic flows may have occurred as late as 1801 (Lawrence, 1948; Cameron and Pringle, 1987; Pringle et al., 2002). Eye-witnesses reported further minor explosive activity (possibly phreatic) in 1859 and 1865, and one or both of these events may have deposited scattered pumice lapilli (present in older, near-surface deposits and not necessarily juvenile) on the upper flanks of the volcano (Crandell, 1980). Additional minor activity or steam plumes were witnessed in 1853, 1854, 1869, and on two occasions in 1907 (Sylvester, 1908; Simkin and Siebert, 1994), but no deposits are associated with them. These reported nineteenth and early twentieth century events provided no evidence of continued magmatic activity and may have been only phreatic explosions. Thus, the end of the Old Maid eruptive period is undefined.

Repeated collapses of a growing and unstable lava dome on a ~32° slope during the Old Maid eruptive period produced ~2 × 10^8 m^3 of volcaniclastic debris, more or less evenly distributed between the Sandy River and White River drainages (Fig. 2). The hot debris moved down onto a debris fan that probably was covered with at least as much snow as now. Crater Rock (Fig. 1), the modern remnant of that lava dome, stands ~170 m high and 300–400 m across (Crandell, 1980). Rapid cooling from avalanching of hot dome rock is indicated by numerous prismatically jointed blocks in the Old Maid deposits, and one lahar deposit

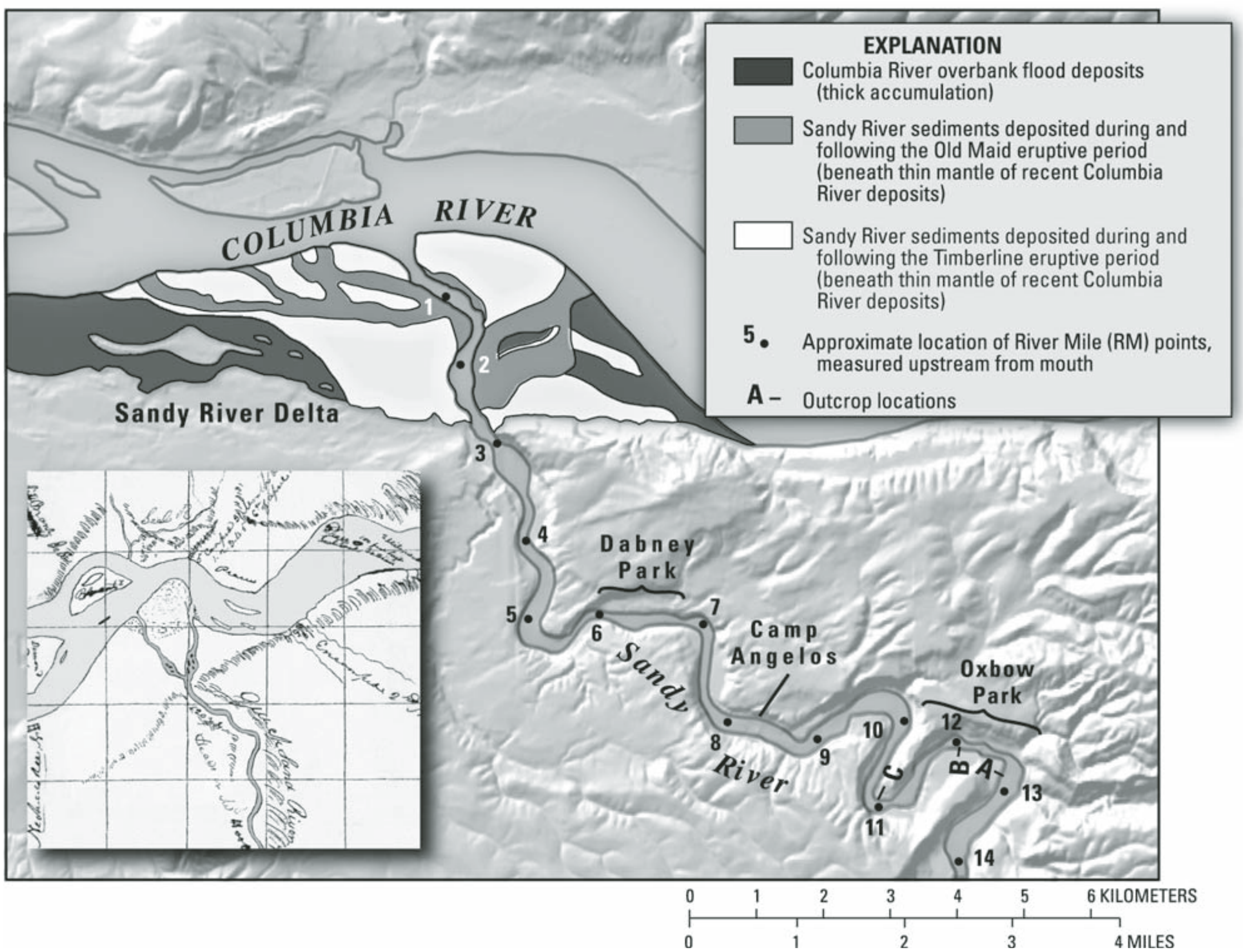


Figure 4. Geologic map of the Sandy River delta (modified from Rapp, 2005) and lower part of the response reach of the Sandy River, showing River Miles from mouth (numbered "•" marks). Stop 3 will examine exposures between River Mile 11 and 13 (Oxbow Park), and Stop 4 is located at River Mile 2.2 (Sandy River delta). Inset in lower left is sketch map of the same area with Sandy River labeled "Quick Sand River" (with bifurcating channel on delta), drawn by Lewis and Clark in 1805–1806 (O'Connor, 2004). The eastern delta distributary channel shown on Lewis and Clark's map, active into the twentieth century, was closed off by an engineering diversion in the 1930s. Capital letters along river show location of deposits in Figure 8 and stratigraphic sections in Figure 13.

contains locally carbonized wood and blocks displaying coincident orientations of thermoremanent magnetism (Crandell, 1980). Rapid snowmelt by hot debris undoubtedly generated many lahars, but it is very likely that some lahars were rain-generated. The total number of pyroclastic flows and lahars carrying sediment into the sediment-source reach is not known but must have been large. Modern collapse rates on actively growing domes (e.g., Ui et al., 1999) suggest that ~12 years of dome growth on the steep southwestern flank of Mount Hood could have produced hundreds to thousands of pyroclastic flows and tens to hundreds of lahars during the Old Maid dome-building eruption, all but one of which were deposited on the debris fan or in the sediment-source reach of the river (T.C. Pierson, unpublished data).

LAHAR DEPOSITS—DEPOSITION BY DEBRIS FLOWS AND HYPERCONCENTRATED FLOWS

Lahars are rapidly flowing, high-discharge, saturated mixtures of rock debris and water from a volcano, mixed together at higher sediment concentrations than in normal floods and encompassing types of flow defined as *debris flow* and *hyperconcentrated flow* (Smith and Fritz, 1989; Smith and Lowe, 1991; Vallance 2000). Debris flows are coherent slurries of sediment and water, similar to wet concrete and capable of holding gravel-sized particles in suspension, even when flowing slowly (Pierson and Costa, 1987). Solid and fluid fractions move downstream more or less in unison, and solid and fluid forces both play significant roles in the mechanics of flow (Iverson, 1997; Vallance, 2005). More dilute hyperconcentrated flows have sufficiently high suspended fines contents to allow large amounts of sand (and even fine gravel) to be held in prolonged dynamic suspension, dominantly by fluid motion and properties—turbulence, viscosity, and buoyancy, with some dynamic particle interactions (Beverage and Culbertson, 1964; Pierson and Costa, 1987; Pierson, 2005).

Sediment concentration boundaries between flow types vary, depending on grain-size distribution and sediment composition of the mixtures, flow energy, and possibly other variables (Pierson, 2005; Vallance, 2005). For volcanic debris flows involving poorly sorted, clay-poor sediment, volumetric sediment concentrations typically range from ~50–70 vol% (Pierson, 1986; Pierson et al., 1996). At this upper end of the concentration range, particles approach closest possible packing for volcanic debris (Iverson and LaHusen, 1993). Volumetric sediment concentrations for hyperconcentrated flows in volcanic settings typically range from ~10–50 vol%. Note that this concentration range differs somewhat from that defined by Beverage and Culbertson (1964), i.e., 20–60 vol%, for nonvolcanic hyperconcentrated flows. Both debris flows and hyperconcentrated flows are represented in Timberline and Old Maid lahar deposits exposed in vertical cuts along the Sandy River (Figs. 5 and 6), and lahars from each eruptive period reached the Columbia River, 87 km from source.

Most of the debris-flow-phase lahar (DF lahar) deposits exposed in the sediment-source reach of the Sandy River are coarse, massive, extremely poorly sorted slightly muddy gravelly sands or sandy gravels (Fig. 5A). Their low contents of clay-sized material (<5%) place them in the category of granular debris flows, which can be easily diluted by entrained stream water and transformed to hyperconcentrated flows (Pierson and Scott, 1985; Pierson, 2005). Coarsest clasts transported range up to several meters in diameter. Tree wells in the 1781 lahar deposit on Old Maid Flat are up to 7 m deep (Cameron and Pringle, 1991), indicating that the largest Old Maid lahar was at least that deep along the valley sides and much deeper along the main axis of the valley. Several DF lahar units are well exposed on Old Maid

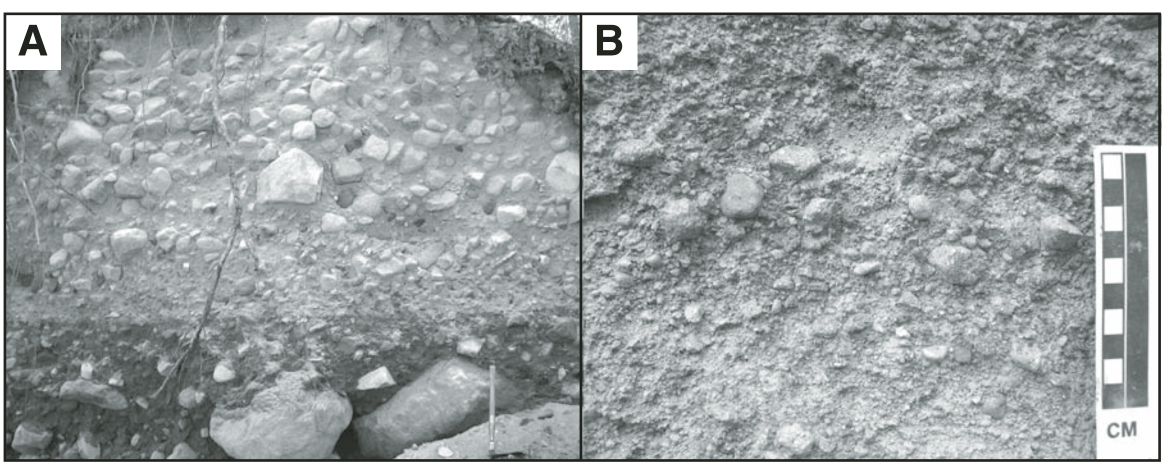


Figure 5. Debris-flow-phase lahar (DF lahar) deposits exposed along the Sandy River. (A) Two massive, bouldery, granular DF lahar deposits at Old Maid Flat (Stop 2), deposited during the Old Maid eruptive period. Horizontal change in tone marks contact; note inverse grading at base of upper unit. Shovel handle (lower right) is 53 cm long. (B) Massive, pebbly, granular DF lahar deposit at the apex of the Sandy River delta, 83 km downstream from the source lava dome (Stop 4; RM 2.4 in Fig. 4) and deposited during the Timberline eruptive period. It also exhibits inverse grading in transition from HF facies upward to DF facies. U.S. Geological Survey photos by T. Pierson, 2006–2008.

Flat at Stop 2. DF lahar deposits at Old Maid Flat are interbedded with hyperconcentrated-flow lahar (HF lahar) deposits at most localities, including Stop 2. These deposits vary from massive to faintly horizontally bedded, poorly sorted, coarse sands to gravelly sands (Figs. 6A–6D). Low-angle cross-bedding may be present, but high-angle cross-bedding is characteristically absent. Isolated outsized clasts, emplaced as rolling bed-load clasts trapped and buried in the rapidly aggrading sand bed, are common (Fig. 6D). Enough fines are present to give these deposits a coherence or firmness that distinguishes them from loose, moderately to well-sorted fluvial sands that ravel easily in outcrop when dry.

DF lahar deposits exposed at Stops 3 and 4 in the response reach are massive, very poorly sorted slightly muddy gravelly sands, generally similar to the DF lahar deposits upstream, except that they have become progressively depleted in coarse clasts (Fig. 5B). Pebble-size clasts generally are the largest present in Stop 4 outcrops. Commonly observed inverse grading in DF lahar deposits results from bottom-up accretion by longitudinally sorted flows depositing incrementally on channel beds, as well as from vertical sorting by kinetic sieving during flow (Vallance, 2000, 2005). The HF lahar deposits at Stops 3 and 4 are generally similar to those farther upstream, but they tend to have well-developed, sub-horizontal, fine-sandy to silty partings that form in lateral margin deposits by rapid dewatering during pauses between surges (Fig. 6B; Cronin et al., 2000). Continued dewatering along vertical water-escape pathways can lead to development of dish structures (Fig. 6C; Pierson, 2005)

FLUVIAL DEPOSITS—DEPOSITION DURING HIGH RATES OF SEDIMENT TRANSPORT

The highest and second highest alluvial terraces preserved in the response reach of the Sandy River reflect the peak levels of aggradation reached during the Timberline and Old Maid

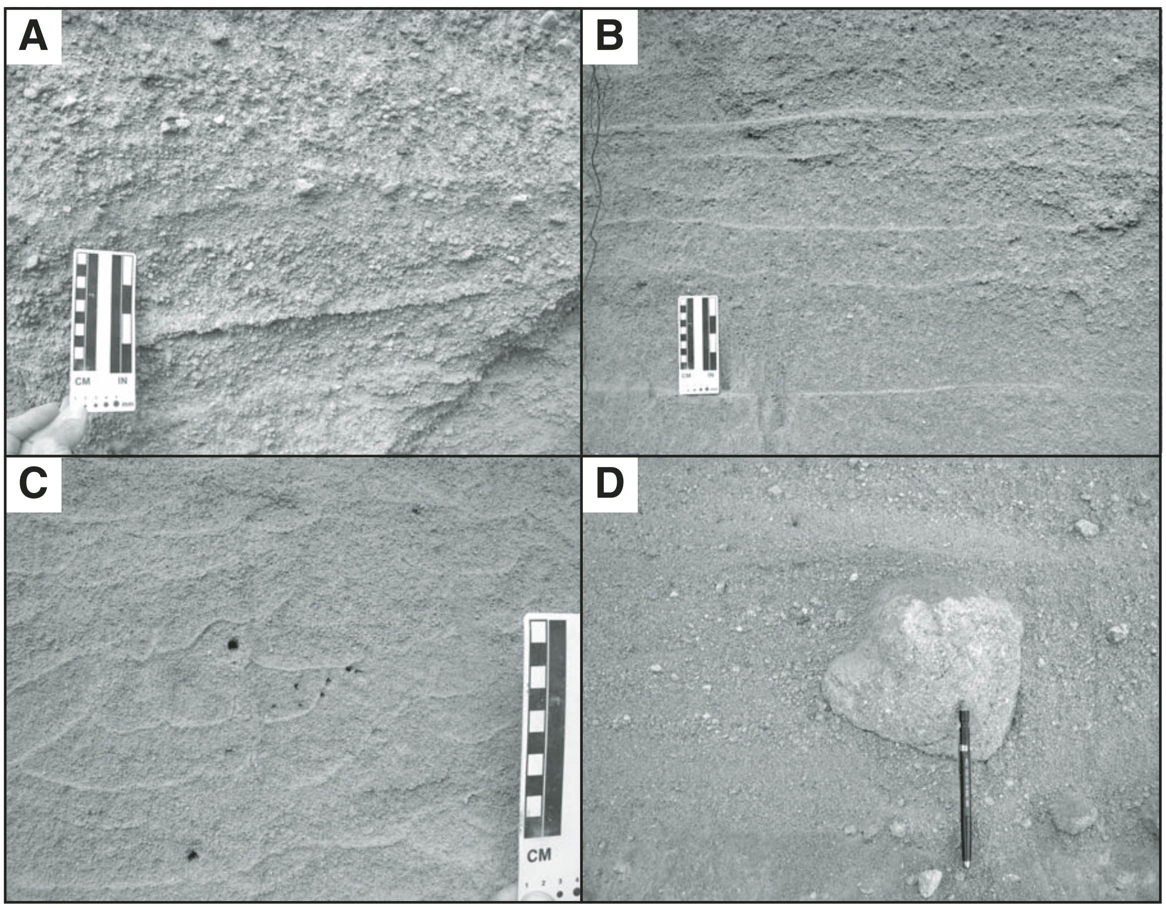


Figure 6. Hyperconcentrated-flow lahar deposits exposed along the Sandy River. (A) Sandy gravel unit showing beginnings of poorly developed stratification in part of the youngest Timberline lahar deposit exposed at the delta apex (Stop 4). (B) Faintly horizontally bedded coarse sand with fine-sandy to silty partings between packets deposited by individual surges in Timberline lahar deposit exposed at delta apex (Stop 4). (C) Same unit as in B but where upward-flowing pore water during deposit consolidation has disrupted silty partings to form dish structures. (D) Outsized clast in faintly horizontally bedded coarse sand in Old Maid lahar deposit exposed at Old Maid Flat (Stop 2). U.S. Geological Survey photos by T. Pierson, 2006–2009.

eruptive periods, which were at least 28 m and 23 m, respectively (T.C. Pierson, unpublished data; Fig. 7). Subsequent downcutting through the channel fill following each period of eruptive activity led to the sequential formation of degradational terraces that step down to post-eruption channel levels reflecting newly established balances between sediment load and channel grade (Fig. 7). Response-reach sediments demonstrate that lahars were not major contributors to the aggradation in this distal reach, as is common in some other, more proximal volcanic settings (e.g., Smith, 1987a, 1987b, 1991; Pierson et al., 1996). The textures and lithofacies of the deposits demonstrate that channel form was braided during aggradation and partly during degradation (Smith, 1987a, 1987b, 1991; Miall, 1996; Manville et al., 2005). The incised valley walls limited the width of the active braid plain to 250–600 m. Vertical aggradation totals for both the Timberline and Old Maid sedimentation responses to eruptive activity are based on inferred pre-eruption channel levels (Fig. 7).

The sediments composing the channel fill deposits in the response reach are dark gray, immature volcanic sands and gravels. Most of the rock types making up the sediment are the types that were erupted during the Timberline and Old Maid eruptions, although some of the volcanic sediment was remobilized from older reworked volcaniclastics and a small fraction are epiclastics. The sediments composing the highest alluvial terraces in the response reach, i.e., sediments deposited during aggradation, are dominantly cross-bedded, medium to coarse fluvial sands with minor gravel lenses. The sediments in the top few meters of the lower degradation terraces appear more gravelly and more crudely bedded. Preliminary sedimentologic data define three dominant lithofacies, which are similar to those defined by Smith (1987a). These lithofacies can be described as:

(*A*) Moderately to well-sorted medium to very fine sand—ripple-cross-laminated, trough-cross-bedded, and massive—commonly capped by a <1 cm layer of silt (Fig. 8E);

(*B*) Poorly to moderately sorted medium to coarse sand, locally including fine gravel—trough-cross-bedded, planar-cross-bedded, and ripple-cross-laminated (Figs. 8C and 8D); and

(*C*) Poorly sorted coarse to very coarse sand, gravelly sand, and sandy gravel—horizontally bedded (with coarse gravel lenses), low-angle cross-bedded, and massive (Figs. 8A and 8B).

Lithofacies *A* (Fig. 8E) is observed at the base of Old Maid stratigraphic section wherever it rests on a pre–Old Maid

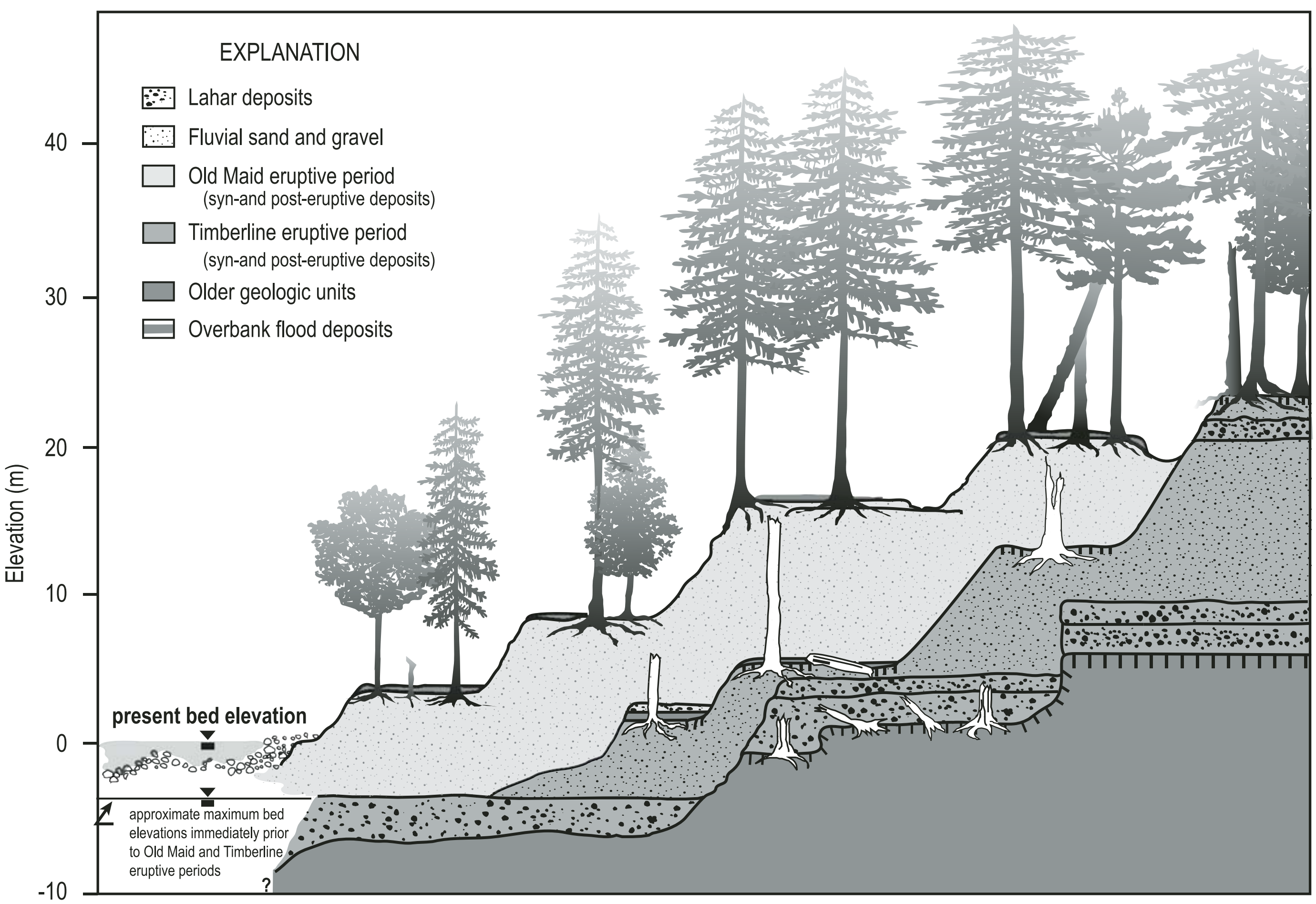


Figure 7. Schematic stratigraphic relationships between present and former channel levels, levels of exposed terrace surfaces, buried paleoterraces, and buried forests in the Timberline and Old Maid deposits at Oxbow Park, 68–70 km downstream from Mount Hood (Stop 3).

paleoterrace surface, and also on the surfaces of some degradation terraces. It is interpreted to have resulted from one or more episodes of overbank flood deposition that occurred (1) as the aggrading channel bed brought paleoterrace surfaces within vertical range of flood deposition, or (2) on floodplains that were soon left beyond the range of inundation by floods as the channel incised. On the lowest paleoterraces at the base of the Old Maid section, lithofacies *A* could have been deposited by a sediment-charged wave of river water being pushed ahead of the 1781 lahar (cf., Cronin et al., 1999). All of these overbank sediments were laid down by shallow, low-velocity overbank flows, which also deposited woody debris on paleoterrace surfaces and gently buried layers of undisturbed forest duff. Lithofacies *B* (Figs. 8C and 8D) reflects dune and ripple migration at conditions of subcritical flow on the channel bed with a moderate rate of sediment transport (Miall, 1996), which is common in shallow, aggradational, braided systems (Manville et al., 2005). Lithofacies *C* (Figs. 8A and 8B) 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 but while sediment transport rates are still very high. These are conditions common in the deeper parts of braided rivers (Smith, 1987a; Miall, 1996).

FUTURE HAZARDS AT MOUNT HOOD

Mount Hood is an active volcano. It continues to have episodic swarms of earthquakes beneath its edifice and active fumaroles near Crater Rock. The next eruption will likely be similar to those of the Timberline and Old Maid eruptive periods, and it would probably include the growth and collapse of a lava dome in the vicinity of Crater Rock, small explosions, pyroclastic flows, and lahars in the Sandy and/or White Rivers (Scott et al., 1997b; Gardner et al., 2000; see Figure 9). Lahars threaten the greatest number of people because they can travel rapidly and may reach into downstream residential communities. Eruption-induced downstream sedimentation and channel aggradation is also a potential hazard, because as the channel fills with sediment and widens, flood waters from winter storms can inundate areas that were previously safe from flooding, and prolonged aggradation can buried roads, bridges, buildings, and other infrastructure.

ROAD LOG

This field trip begins in front of the Oregon Convention Center (OCC) in NE Portland, departing at 8:00 a.m.

Directions to Stop 1

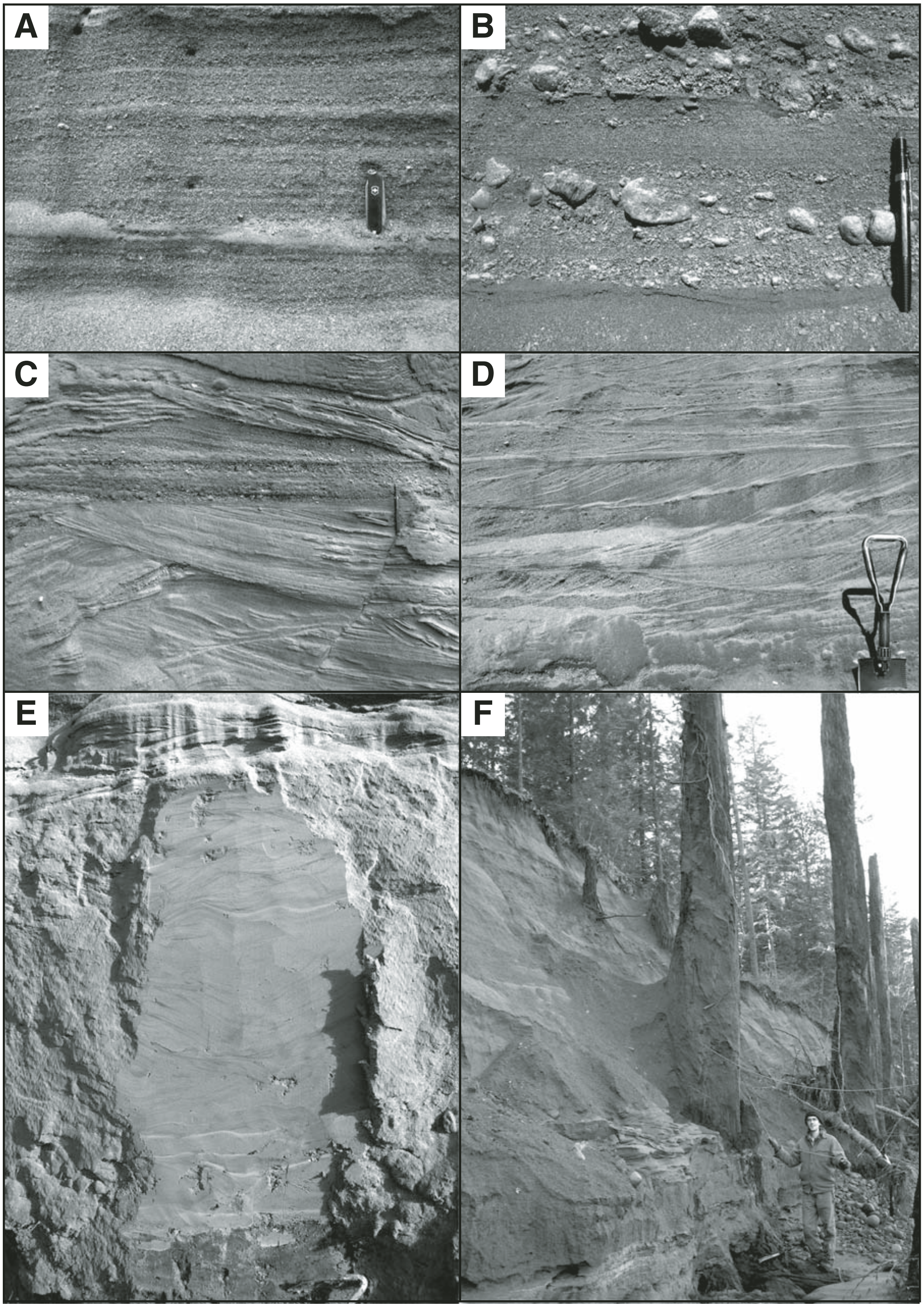
Cumulative Mileage	*Time*	*Route*
0.0	08:00	Depart OCC. Drive south on MLK Blvd several blocks; turn left on Everett Street, following signs for I-84 East; at first traffic light veer left onto onramp for I-84 (Banfield Freeway). Continue east on I-84.
14.4	08:20	Take Exit 17 (Marine Drive/Troutdale), going straight through first traffic light and go ~0.5 mile past several truck stops. Turn right at next traffic light, crossing over a bridge, and continue straight on this road (257th Drive/Kane Drive) for ~5 miles, going past Mount Hood Community College. When 257th dead ends at a light, turn diagonally left onto Orient Drive; go only 1 block and then turn right on Palmquist Road. Go another 2 blocks to junction of Mount Hood Highway (U.S. Highway 26). Turn left and continue on Highway 26 for ~9 miles to town of Sandy.
27.9	08:40	On edge of downtown Sandy, where Highway 26 splits into 2 one-way segments, turn left on Bluff Road (traffic light); go ~1 mile to Jonsrud Viewpoint (on right).
28.9	08:45	Arrive at Jonsrud Viewpoint, Stop 1 (weather-permitting). No restrooms at this site. Duration of stop = 45 minutes.

Stop 1. Jonsrud Viewpoint: Overview of Mount Hood and the Sandy River

This stop gives a good view of the Mount Hood edifice, 45 km (27 mi) to the east, and an incised meander bend in the middle reach of the Sandy River, ~150 m lower in altitude. Mount Hood is situated along the crest of the Cascade Range ~80 km east of Portland and 36 km south of the Columbia River. This volcanic center has been recurrently active more than 1.5 m.y., and its present edifice, 3425 m tall and ~50 km^3 in volume, is at least 0.5 m.y. old. It is composed of andesite and low-silica dacite domes, lava flows, and pyroclastic debris (Wise, 1969; Scott et al., 1997a).

The south and north profiles of the volcano are strikingly different. The smoothly sloping southwest flank below the steep summit area (Fig. 10) is a fan composed of deposits of lithic pyroclastic flows (block-and-ash flows) and lahars of late glacial (Polallie eruptive period) and late Holocene (Timberline and Old Maid eruptive periods) age. The pyroclastic flows originated in collapses of portions of growing lava domes. Late glacial domes grew at the summit, while late Holocene domes grew in a landslide scar on the upper southwest flank (Figs. 1A and 10). Because of glacial erosion, mass-wasting scars, and limited accumulations of fragmental deposits at higher elevations, the west and north flanks form exceptionally rugged and steep slopes.

The viewpoint stands on a deeply weathered westward-sloping surface underlain by volcaniclastic and alluvial deposits of Pleistocene age, in part from ancestral Mount Hood. The surface was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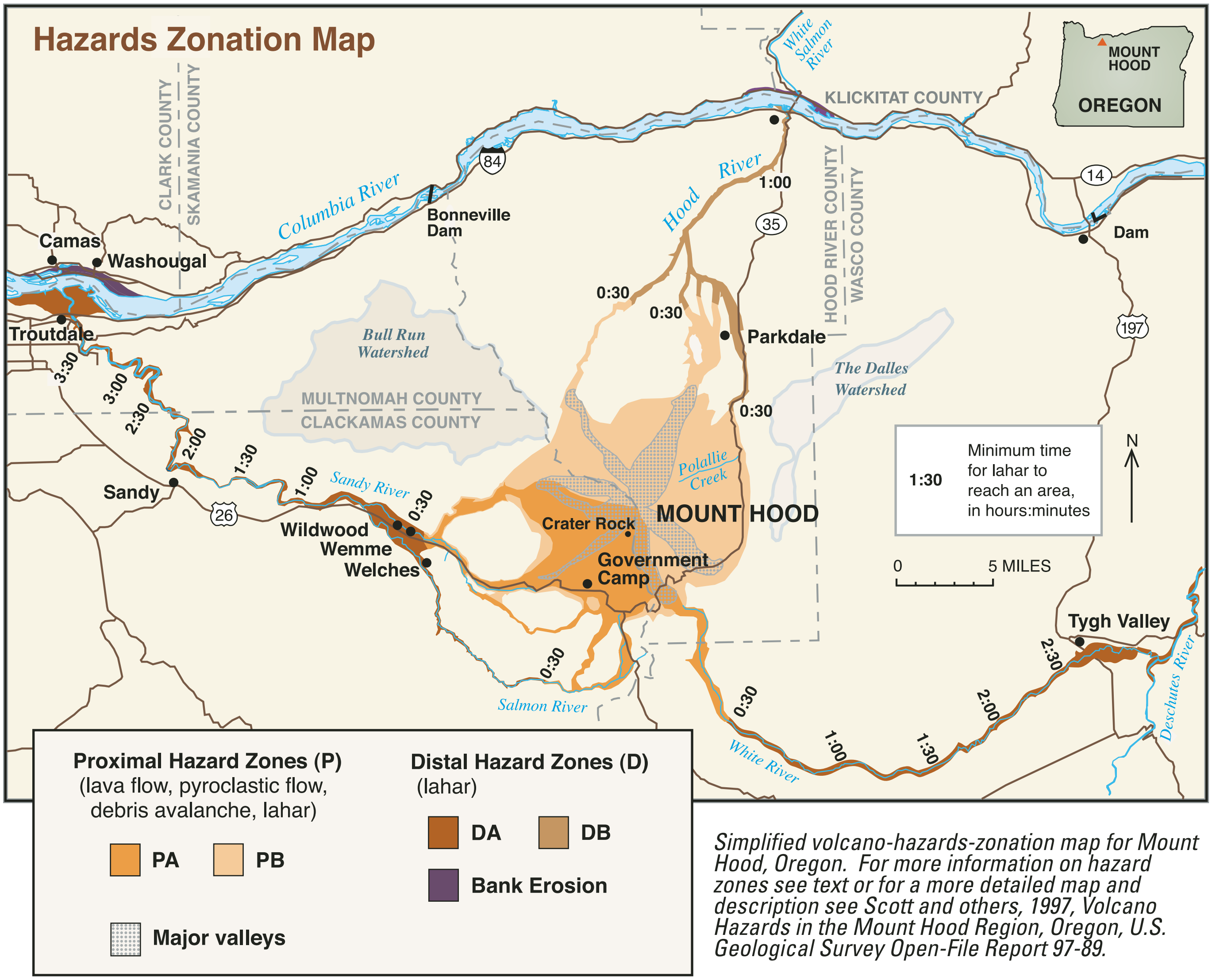

Figure 9. Simplified hazard zonation map for Mount Hood, Oregon (modified from Gardner et al., 2000). Numbers along channels indicate estimated travel times for lahars to those points. More detailed information on hazard zones can be found in Scott et al. (1997b).

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Figure 8. Fluvial deposits exposed in alluvial terraces along the response reach of the Sandy River in Oxbow Park (Stop 3). (A) Channel deposit: horizontally bedded coarse sand with minor very fine gravel (Lithofacies *C*) at top of 16 m Old Maid terrace at RM 11 (loc. C) in Figure 4 (early degradation terrace). Pocket knife for scale is 47 mm long. Flow was from right to left. (B) Channel deposit: horizontally bedded coarse sand and gravel (with some low-angle cross-bedding) in upper third of terrace described in A. Flow was from right to left. (C) Channel deposit: trough cross-bedded medium to coarse sand with minor fine gravel layers (Lithofacies *B*) in highest (20 m) Old Maid aggradation terrace at RM 12.2 between loc. A and B (Fig. 4). Flow was left to right and toward camera. (D) Channel deposit: high-angle cross-bedding in coarse sand with minor very fine gravel (Lithofacies *B*) at RM 11 (loc. C in Fig. 4) left by migrating dunes in middle of terrace described in A; both fore-set and top-set bedding visible. Flow was from right to left. (E) Overbank flood deposit: cross-bedded, fine to very fine sand (Lithofacies A) resting on O/A horizons of paleosol developed on paleoterrace surface at base of Old Maid aggradational sequence at RM 12.2 between loc. A and B (Fig. 4.). Note infilling of voids (burrows?) in paleosol and thin, light-colored silt parting in overbank sand (probably separating individual flood events). Laminated channel sands rest on this unit at top of photo. Flow was from left to right. Curved silver shaft of scraper at bottom of photo is 6 mm thick. (F) Recently exposed bluff face of highest Old Maid alluvial terrace at Oxbow Park, looking downstream and showing buried trees in growth position at RM 12.2 between loc. A and B (Fig. 4). Surface of paleoterrace on which trees were growing is even with the man's waist. U.S. Geological Survey photos by T. Pierson, 2008, 2009.

abandoned after the Sandy River attained its current northward course to the Columbia River. Trimble (1963) describes the incision of the surface and creation of multiple terrace levels that record middle(?) to late Pleistocene glacial and volcanic events. Below the viewpoint and immediately upstream is a broad terrace of outwash gravel of last-glacial age that is covered with lahar deposits of Polallie age. The terrace surface is ~55 m above the channel.

The City of Sandy, with a population of ~8000, is located on the Barlow Road segment of the Oregon Trail (now U.S. Highway 26 in this area). The Barlow Road was blazed by Samuel K. Barlow in 1845, from The Dalles to near Oregon City, going around the south side of Mount Hood. Sandy's first settlers opened a trading post to serve the thousands of pioneers passing through on their way to the Willamette Valley.

The Sandy River was originally named the Quicksand River by Lewis and Clark in 1805 (Moulton and Dunlay, 1990). Expedition members noted that the river (a) was ~275 m wide at its mouth and for several kilometers upstream on the delta (30–150 m wide there today); (b) had a number of mid-channel sand islands; and (c) had flow that was turbid and very shallow (resembling the Platte River in Nebraska, they noted). It was given its name because "the bed of this stream is formed entirely of quick sand."

Directions to Stop 2

Cumulative Mileage	*Time*	*Route*
28.9	09:30	Depart Stop 1. Return to Highway 26 on Bluff Road. At traffic light, turn left on Highway 26, driving through the town of Sandy. Note: 25 mph speed limit is strictly enforced. Continue east for ~17 miles. Turn left on Lolo Pass Road (near Zigzag Ranger Station). Public portable toilet available at Ranger Station. Cross the Zigzag River and then the Sandy River and proceed ~4.5 miles. Look for large sign saying you are entering Mount Hood National Forest. Turn right on the next road (Forest Service Road 1825). Go a several hundred feet and turn right across bridge spanning the Sandy River. Proceed past the entrance to the Fred McNeil campground, and go

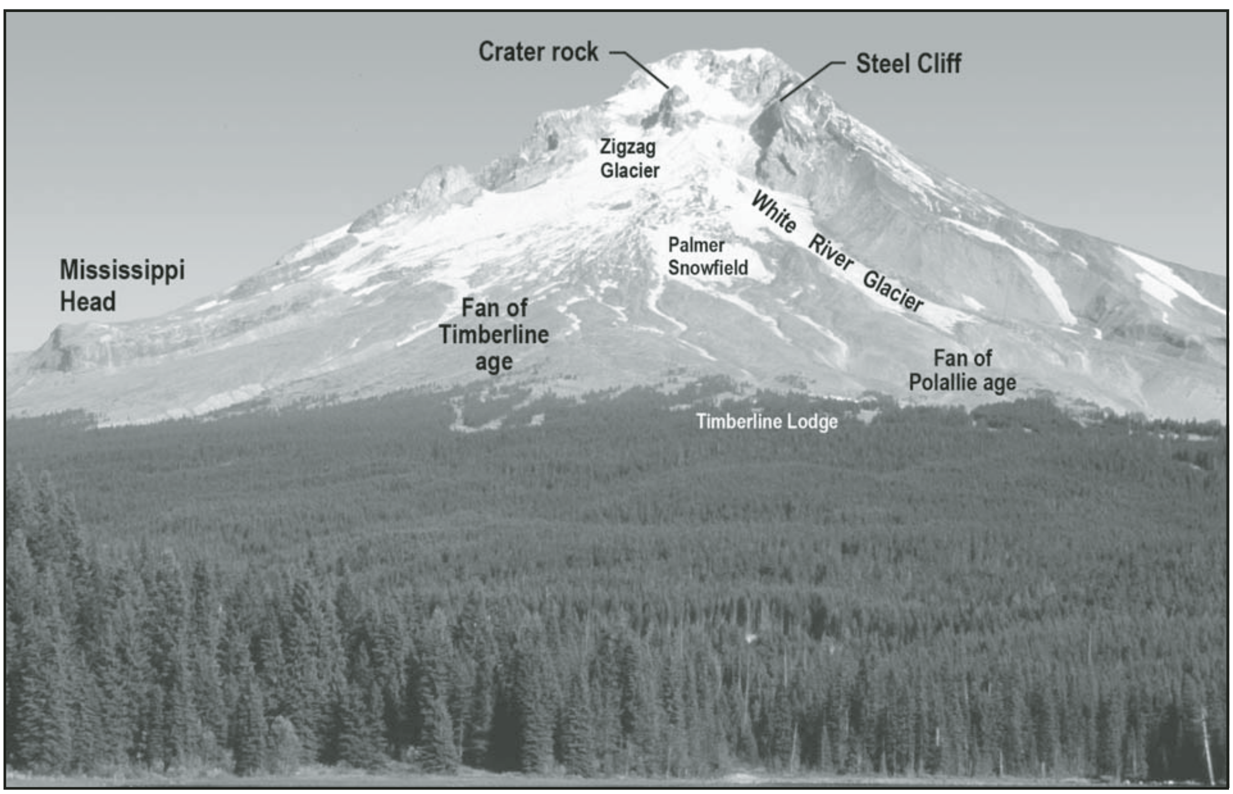

Figure 10. Southwest flank of Mount Hood, viewed from Trillium Lake, showing Crater Rock lava dome and the broad debris fan derived from dome collapse pyroclastic flows and lahars. Much of the center of the fan is of Timberline age; a dissected surface of Polallie age lies east of Timberline Lodge. Pyroclastic flows of Old Maid age were funneled down the White River valley and over the present site of Zigzag Glacier, along the base of Illumination Rock, and down an unnamed tributary of the Sandy River to Old Maid Flats (Stop 2). Tree line on this side is at about the 1830 m (6000 ft) elevation. Summit is 3425 m (11,235 ft). U.S. Geological Survey photo by D. Wieprecht.

		~0.4 mile and turn left at the next unimproved dirt road. Go to end and park. Proceed north on foot to the vertical section along the south bank of the river.
52.0	10:20	Arrive at Stop 2: Old Maid Flat stratigraphic section. Duration of stop = 1 hour. Note: restrooms will be open at the Riley Horse Camp (entrance on right just after Fred McNeil campground).

Stop 2. Old Maid Flat Stratigraphic Section

This stop provides the opportunity to examine a variety of lahar deposits at Old Maid Flat (Fig. 11), emplaced both by debris flows and by hyperconcentrated flows in the 1780s in response to sediment loading during the Old Maid eruptive period. These units show a variety of sedimentary textures and features. The Sandy River channel itself is very active during winter high flows in this reach. It provides good evidence of the erosional and depositional processes that occur in steep montane river channels transporting large volumes of coarse volcanic sediment. Be on the lookout for newly exposed snags (trees rapidly buried in growth position by these lahars during the Old Maid eruptive period). **Note: These banks are composed of unconsolidated sediment, contain large boulders, and are unstable. Please be careful.**

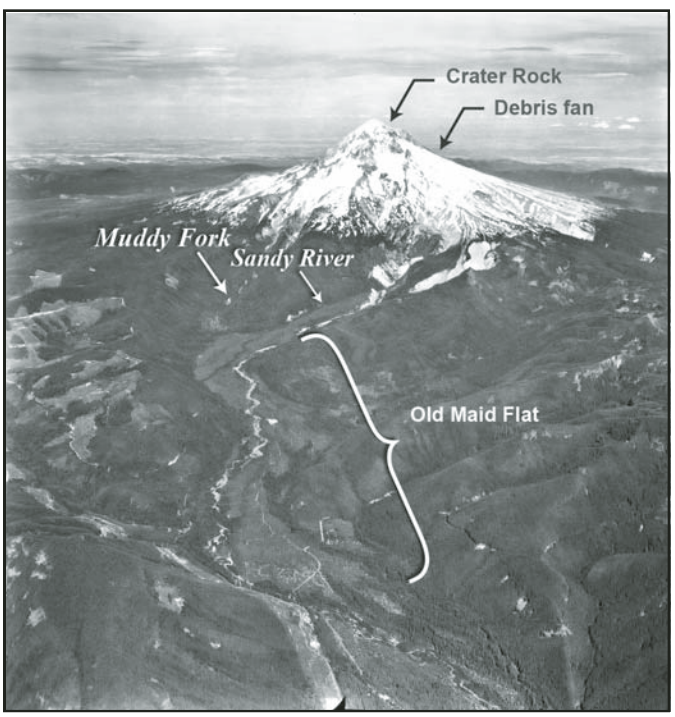

Figure 11. Aerial oblique photograph of the western flank of Mount Hood and the wide, flat-floored valley known as Old Maid Flat in the upper part of the sediment-source reach of the Sandy River. U.S. Geological Survey photo by Austin Post, 1980.

Directions to Stop 3

Cumulative Mileage	*Time*	*Route*
52.0	11:20	Depart Stop 2. Backtrack to the town of Sandy and Bluff Road. Turn right on Bluff Road. Drive past Jonsrud Viewpoint and follow road for ~4.8 miles. Turn right on Cottrell Road. Go 1.2 miles and turn left on Lusted Road (at stop sign). Go 0.25 mile and turn right on Hosner Road. Go 0.5 mile to 3-way stop sign and continue straight on Oxbow Parkway, which descends steeply into the Sandy River valley.
80.2	12:10	Arrive at entrance to Oxbow Regional Park, Stop 3. We will eat lunch here at Group Picnic Area A and visit 4, possibly 5, sites within the park. There are public restrooms in several locations within the park. Duration of stop = 3.0 hours.

Stop 3. Oxbow Park: Evidence of Eruption-Induced Rapid Channel Aggradation and Buried "Ghost Forests"

Oxbow Park lies within the upper response reach of the Sandy River, and it offers exposures of a variety of deposit types, sedimentary textures and features, and large-scale geomorphic features. Terraces preserving the record of aggradation and degradation are particularly well preserved in this park (Figs. 12 and 13). At 4 or 5 sites within the park (depending on time), we will examine:

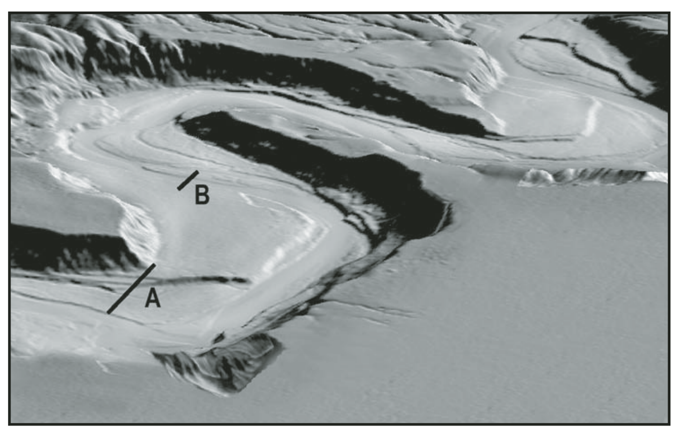

Figure 12. Oblique LiDAR image draped on 2 m digital elevation model of the upper part of the Sandy River response reach from River Mile 12.8 (lower left) to River Mile 8.6 (upper right). See Figure 4 for locations. View is downstream, and the two low, broad, alluvial terrace sets are in Oxbow Park. Sections A and B in Figure 13 are shown.

- Aggradational deposits from a November 2008 flood on the modern floodplain. The sediment pulse responsible for this aggradation came from rapid erosion of deposits that had been stored behind Marmot Dam, ~20 km upstream. The dam was removed on 19 October 2007.
- Multiple levels of Old Maid degradation terraces and the deposits composing them.
- "Ghost forests" of trees that had been buried by rapid deposition by lahars and floods during the Timberline and Old Maid eruptive periods.
- The complete sequence of aggradational deposits deposited over about a decade during and following the Old Maid eruption, exposed in ~20-m-high bluffs. The base of the sequence begins with fine-grained overbank deposits lying on forest duff (Fig. 14).
- Fine-grained backwater flood deposits laid down by flood waters surging nearly 20 km upstream during the huge Missoula Floods between 12 ka and 17 ka.

Directions to Stop 4

Cumulative Mileage	*Time*	*Route*
83.0	15:10	Depart Stop 3. Backtrack up Oxbow Parkway to the 3-way stop. Turn right on SE Oxbow Drive, which becomes SE Division Drive. Continue straight through the 4-way stop and road becomes NE Division Street. At first traffic light you

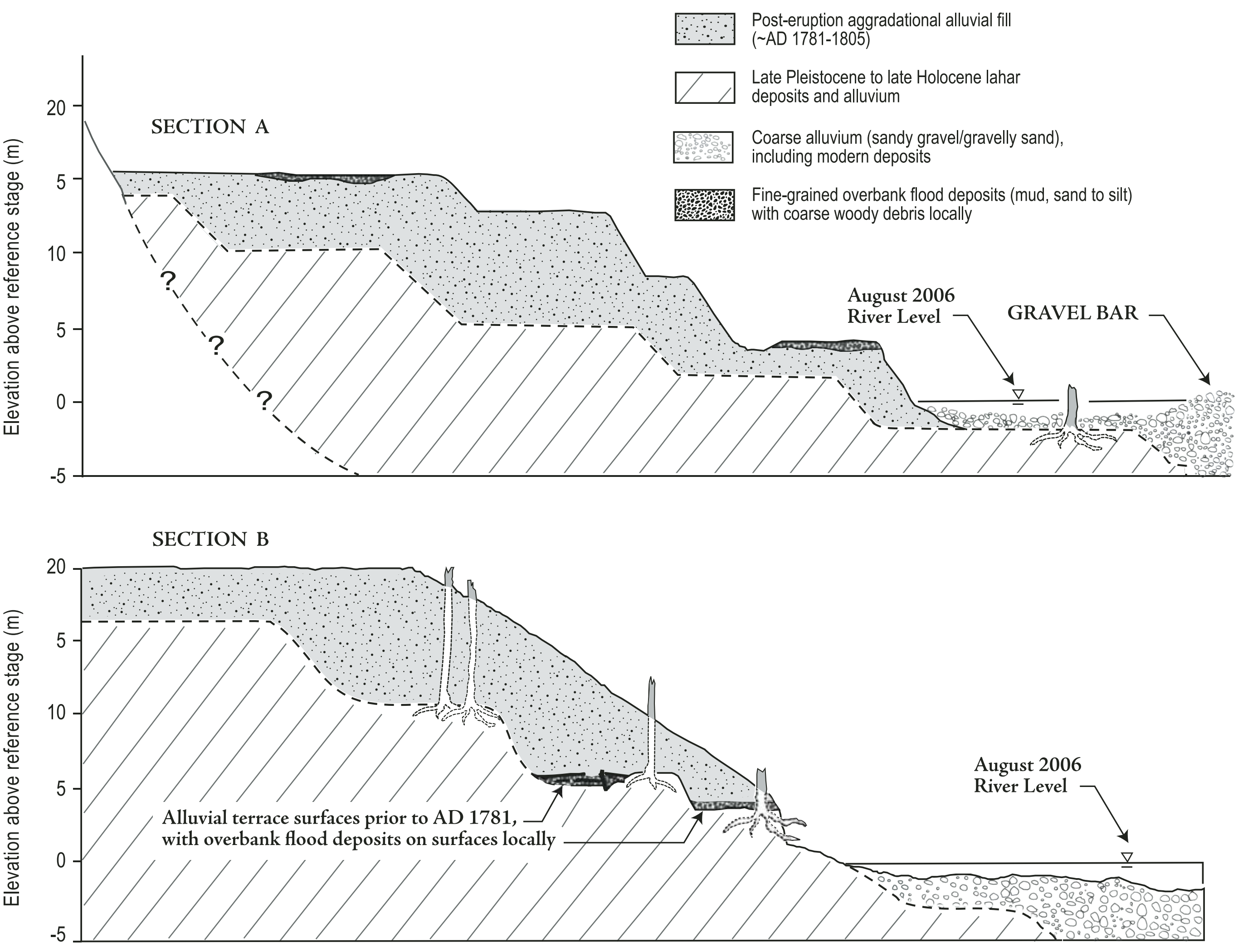

Figure 13. Stratigraphic sections in the response reach of the Sandy River in Oxbow Park at River Mile 12.8 (section A) and at River Mile 11.7 (section B). See Figure 4 for locations.

		come to, turn right on 257th Drive/Kane Drive and continue north down the hill into Troutdale. Go straight through traffic light at bottom of hill (Halsey Street), cross over the railway overpass and continue north under the I-84 underpass. Take an immediate right turn on NE Graham Road. Go about 0.25 mile and turn right on NE Harlow Place (dead end). Park at second to last pull-off area on left on the top of the bluff overlooking the river. Disembark vans and take trail down onto the side of the bluff.
93.1	15:30	Arrive at Sandy delta apex exposure, Stop 4. No restrooms at this site, although they are available at restaurant on NE Graham Road. Duration of stop = 1 hour.
93.1	16:30	Depart Stop 4. Backtracking on Graham Road, turn right at traffic light and continue straight on to the I-84 onramp. Backtrack on I-84 to the OCC in Portland.
108.5	17:00	Arrive at OCC.

Stop 4. Sandy River Delta Apex Exposure: Long-Runout, Fine-Grained Lahar Deposits

This bluff exposes mostly lahar and fluvial deposits of Timberline age (approximately AD 300–600), confirmed by several radiocarbon dates in the lowermost coarse volcanic sediments, which except where noted, are reported in Rapp (2005) and Evarts and O'Connor (2008). The Timberline sediments overlie a micaceous clayey silt (Columbia River overbank flood deposits) that has an age similar to those of the lowermost Timberline volcanics. A calibrated radiocarbon date on detrital wood in this unit gives a split 2σ calibrated age range of AD 261–280 (0.06), AD 323–473 (0.82), or AD 477–532 (0.12). The fractions in parentheses give probabilities for dates occurring in those splits (from probability density functions). The overlying Timberline volcanic sequence begins with two firm, well-compacted pebbly DF lahar deposits. Detrital wood samples from within the lower lahar unit have yielded calibrated 2σ age ranges of AD 256–305 (0.16) or AD 316–441 (0.80), AD 410–590 (T.C. Pierson, unpublished data), and AD 420–810 (T.C. Pierson, unpublished data). Density function intersections suggest a probable date for this initial Timberline lahar in the early 400s. Wood in a debris layer between these two lahar units gives a 2σ calibrated age range of AD 400–580. Their stratigraphic juxtaposition and the lack of any weathering on the surface of the lower unit suggest that the two lahars were relatively closely spaced in time. Following these two lahars, a period of fluvial aggradation ensued, and the resulting fluvial sands are capped by a third Timberline lahar unit that had hyperconcentrated phases (Figs. 6A, 6B, and 6C) sandwiching an apparent debris-flow phase (Fig. 5B). This suggests that the lahar was in the process of transforming from a debris flow to a hyperconcentrated flow when deposited. A detrital charcoal sample from this unit yielded a 2σ calibrated age range of AD 230–410 (Rapp, 2005). The possibly older date for this overlying unit could be explained by incorporation of "old charcoal" from a soil, where charcoal from wildfires can persist for many centuries.

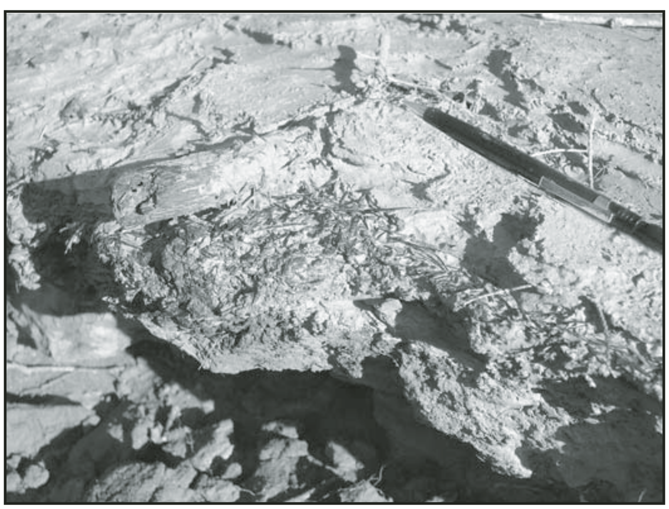

Figure 14. Surface of the AD 1781 forest floor (fir needles, fallen branches, etc.) on the surface of a paleoterrace that was buried by fine-grained overbank flood deposits at the beginning of channel aggradation triggered by Old Maid eruptive activity. Pencil is resting on ± horizontal surface. This material composes a duff layer, which is the O horizon of the paleosol on the paleoterraces tread. An underlying B horizon is well developed. U.S. Geological Survey photo by T. Pierson, 2008.

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