**Holocene lahars and their by-products along the historical path of the White River between Mount Rainier and Seattle**

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**ABSTRACT**

Clay-poor lahars of late Holocene age from Mount Rainier change down the White River drainage into lahar-derived fluvial and deltaic deposits that filled an arm of Puget Sound between the sites of Auburn and Seattle, 110–150 km downvalley from the volcano’s summit. Lahars in the debris-flow phase left cobbly and bouldery deposits on the walls of valleys within 70 km of the summit. At distances of 80–110 km, transitional (hyperconcentrated) flows deposited pebbles and sand that coat terraces in a gorge incised into glacial drift and the mid-Holocene Osceola Mudflow. On the broad, level floor of the Kent Valley at 110–130 km, lahars in the runout or streamflow phase deposited mostly sand-sized particles that locally include the trunks of trees probably entrained by the flows. Beyond 130 km, in the Duwamish Valley of Tukwila and Seattle, laminated andesitic sand derived from Mount Rainier built a delta northward across the Seattle fault. This distal facies, warped during an earthquake in A.D. 900–930, rests on estuarine mud at depths as great as 20 m.

The deltaic filling occurred in episodes that appear to overlap in time with the lahars. As judged from radiocarbon ages of twigs and logs, at least three episodes of distal deposition postdate the Osceola Mudflow. One of these episodes occurred ca. 2200–2800 cal. yr B.P., and two others occurred ca. 1700–1000 cal. yr B.P. The most recent episode ended by about the time of the earthquake of A.D. 900–930. The delta’s northward march to Seattle averaged between 6 and 14 m/yr in the late Holocene.

**Keywords:** lahar, delta, Holocene, Mount Rainier, Seattle.

**INTRODUCTION**

This field trip guide describes natural and man-made exposures of lahar deposits along the White River. Its focus is on clay-poor lahar deposits that postdate the Osceola Mudflow of middle Holocene age and which change downstream into fluvial and deltaic facies. The itinerary highlights preliminary results of work intended to flesh out the history of post-Osceola lahars and to explore volcanic hazards of the valley floor between Auburn and Seattle.

GEOLOGIC SETTING

At 4392 m, Mount Rainier is the tallest volcano in the Cascade Range. On sunny days the mountain looms over Seattle, 90 km to the northwest (Fig. 1). Its glacial ice amounts to 4.4 km$^3$ (Driedger and Kennard, 1986). Valleys that head on the volcano’s flanks convey meltwater and debris flows toward the Puget Sound lowland and the Columbia River, via the Puyallup, Carbon, Nisqually, White, and Cowlitz Rivers. All but the Cowlitz flow into Puget Sound (Fig. 1).

The trip follows the historical path of the White River from the foothills near the volcano to the Duwamish River delta. The White River drains the northern and northeastern side of the mountain, then turns westward toward Auburn, where it exits a gorge and flows onto a broad, flat valley bottom (Fig. 1). As recently as 1907, the White River continued northward to Seattle.

Figure 1. Locations of field-trip stops (numbers in circles) with respect to Mount Rainier, major rivers, cities, and Puget Sound. Plotted in light gray on the digital elevation model at upper left is the approximate location of former Duwamish embayment as it existed at the time of the Osceola Mudflow ca. 5490–5600 cal. yr B.P. (Dragovich et al., 1994). Sedimentation since that time has filled the embayment and pushed the shoreline of Puget Sound ~45 km northward to Seattle. Shown is pre-1900 course of White River.
joining the Green and Black Rivers along the way. The combined
waterway, named the Duwamish River, is now fed only by the
Green River. Human modifications diverted the other tributary
rivers, including the White River, which now flows south and
then west to Tacoma (Fig. 1).

The broad shoulders of Mount Rainier rise above folded
volcanic and volcanoclastic rocks of Eocene and Miocene age
(Fiske et al., 1963). After dike intrusion and volcanic eruptions as
early as 26 Ma, these rocks were intruded by the Tatoosh pluton
14–18 Ma (Swanson et al., 1989). Eroded remnants of the Lily
Creek Formation (1.2 and 1.3 Ma; Sisson and Lanphere, 2000)
probable represent early products of the modern volcano (Cran-
dell, 1963; Mattinson, 1977). The present volcanic cone, chiefly
andesitic in composition, began forming ca. 0.5 Ma (Sisson and
Lanphere, 2000).

At least 11 tephra-producing eruptions occurred at Mount
Rainier during the Holocene (Mullineaux, 1974). The most
recent eruption, in the 1840s, produced only scattered deposits
of pumice (Mullineaux, 1974; Sisson, 1995). Greater volumes
of tephra erupted 2200–2600 14C yr B.P. (ca. 2200–2800 cal. yr
B.P.) and ca. 1000 14C yr B.P. (ca. 1000 cal. yr B.P.) (Vallance
and Donoghue, 2000). Because these voluminous tephra layers
contain charcoalized twigs, pyroclastic flows probably accom-
panied their eruption.

DEFINITIONS

A “lahar” is a gravity-driven mixture of sediment and water
that originates from a volcano (Vallance, 2000). Lahars are com-
mon occurrences at many volcanoes, particularly during eruptions.
Because lahars can travel many tens of kilometers from their
sources, some have resulted in great loss of life and property. For
example, a 1985 eruption at the Colombian volcano Nevado del
Ruíz generated a lahar that devastated the town of Armero, killing
more than 23,000 people.

As observed at Mount St. Helens (Scott, 1988), lahars can
be divided into those that are rich in clay (clay-rich lahars) and
those with little clay (clay-poor lahars). Clay-rich lahars typically
initiate as flank failures and leave diamicitic deposits. Clay-poor
lahars (also called “non-cohesive lahars”), generally consisting of
gravel- and sand-sized clasts, originate as water floods that entrain
material. Flood waters leading to the formation of clay-poor lahars
have been produced during lake breakout (Pierson, 1999; Pringle
and Cameron, 1999), intense rainfall (Rodolfo and Arguden, 1991;
Hodgson and Manville, 1999; Lavigne et al., 2000; Lavigne and
Thouret, 2003), and from melting of snow and ice by hot pyroclas-
tic flows (Eppler, 1987; Scott, 1988; Major and Newhall, 1989).

A lahar can vary in character with time and distance down-
stream. It may comprise one or more flow phases, which include
debris-flow phase, transitional- or hyperconcentrated-flow phase,
and stream-flow phase (Vallance, 2000). In a debris-flow phase
the solid and liquid fractions of the lahar have about equal vol-
ume and the two fractions move approximately in unison in a
vertical section. In a stream-flow phase, water transports the
lahar’s fine-grained sediment in suspension (suspended load)
and moves its coarse-grained sediment along the bed at discrete
intervals (bed load). A transitional flow phase, commonly known
as “hyperconcentrated flow,” is intermediate between debris flow
and stream-flow. In a transitional phase, a lahar carries higher
sediment loads than does stream-flow, but it vertically sorts sol-
ids by size and density more than does a debris flow. Although
the literature distinguishes the hyperconcentrated-flow phase
from more dilute and more concentrated phases in terms of solids
fraction, transitions are gradational and dependent on other fac-
tors like sediment-size distribution and energy of the flow. Thus,
flow-phase transitions cannot be precisely defined.

The height above the channel bottom of the flowing lahar
is the stage. A lahar commonly has an initial rising or waxing
stage, a peak-inundation stage, and a relatively prolonged falling
or waning stage.

In proximal or medial reaches, clay-poor lahars commonly
leave poorly sorted, massive or crudely stratified deposits. Such
deposits can be inversely graded. In distal reaches, the flows
leave voluminous, sandy deposits that may extend tens of kilo-
meters beyond the main body of the lahar (Scott, 1988). These
distal facies are commonly referred to as “lahar-runout” deposits.
They commonly exhibit bedding and better sorting than that of
the proximal or medial deposits.

Radiocarbon ages in this guide are reported in radiocarbon
years before A.D. 1950 (14C yr B.P.), in calibrated years before
A.D. 1950 (cal. yr B.P.), or both. For an age in cal. yr B.P.,
we report the range at two standard deviations, computed with
the INTCAL98 calibration data of Stuiver et al. (1998) and an
error multiplier of 1.0. Most of the ranges are treated as limiting
maximum ages because they were measured on detrital wood or
charcoal that predates the time of deposition. In cases where the
outer preserved rings of a detrital tree were dated, the resulting
age may approximate the time when the tree was knocked down,
entrained, and deposited during a laharic episode.

PREVIOUS WORK

Lahars of Mount Rainier

Mount Rainier readily generates lahars. It has an enormous
volume of snow and ice available for melting during an erup-
tion. It also stores water beneath its glaciers, which sometimes
release outburst floods. Its huge mass of hydrothermally altered
rock weakens the edifice and contributed to the enormity of the
Osceola Mudflow, which had a volume of 3.8 km³ (Crandell,
1971; Vallance and Scott, 1997).

Lahars are thought to represent the greatest hazard from
Mount Rainier (Driedger and Scott, 2002). Several hundred
thousand people live in lowland areas underlain by Holocene
lahars or laharic deposits derived from the volcano. In the 1990s,
the U.S. Geological Survey installed a monitoring system in the
Carbon and Puyallup Valleys that is intended to detect and warn
residents of the impending arrival of a lahar.
Concern about future lahars on Mount Rainier spurred the mapping and dating of the volcano’s Holocene lahar deposits (Crandell, 1971; Scott et al., 1995). This work shows that Mount Rainier produced both clay-rich and clay-poor flows during the Holocene. The largest of these was the clay-rich Osceola Mudflow, which flowed down the White River drainage ca. 5490–5600 cal. yr B.P. (Vallance and Scott, 1997). Lesser, mainly post-Osceola lahars were catalogued by Crandell (1971) and Scott et al. (1995), who used radiocarbon ages and constraining ash layers to place them in time. They identified at least five clay-poor lahar deposits in the White River drainage, deposited since the time of the Osceola Mudflow. The largest of these flows, found as much as 60 m above present river level, form part of a unit named the Deadman Flat lahar assemblage (Scott et al., 1995). Wood from within a deposit of the assemblage near the confluence of Fryingpan Creek and the White River (Fig. 1) gave an age of 800–1260 cal. yr B.P. (Scott et al., 1995).

Deposits younger than the Osceola Mudflow define at least three episodes of clay-poor lahars in the White River drainage. This inferred history is based on previous work by Crandell (1971), Scott et al. (1995), and Pringle (2000), and on new results from our study (Table 1, Fig. 2). The oldest of the three episodes coincided with volcanism of Summerland age (ca. 2200–2600 \(^{14}C\) yr B.P. or 2200–2800 cal. yr B.P.), when as many as five eruptions may have occurred (Vallance and Donoghue, 2000). Next came two episodes that correspond to the Deadman Flat assemblage of Scott et al. (1995). The oldest of these, provisionally called the Twin Creek episode, dates to ca. 1350–1700 cal. yr B.P. (range of three ages on detrital wood and charcoal from deposits along White River). The youngest, provisionally called the Fryingpan Creek episode, occurred ca. 800–1260 cal. yr B.P. (wood in lahar deposit; Scott et al., 1995).

**Lahar Deposits Downstream from Auburn**

Most of the foregoing history has been inferred from deposits exposed on valley walls on or near the mountain. Farther downstream, exposures of lahar deposits are rare because stream gradients are low and river incision shallow. However, runout of large clay-poor lahars from Mount Rainier reached the Puget Sound lowland (Scott et al., 1995; Pringle, 2000; Pringle and Scott, 2001). Examples include valley-floor deposits of andesitic sand (informally called “black sand”) between Auburn and Seattle that were probably derived from lahars in the White River drainage (Cisternas, 2000; Pringle et al., 1997; Pringle, 2000; Pringle and Scott, 2001).

Formerly an arm of Puget Sound, the valley floor near Auburn and Kent was successively filled by the Osceola Mudflow, deltaic and fluvial deposits, and andesitic sand (Dragovich et al., 1994). The Osceola Mudflow flowed onto the floor of Puget Sound from Auburn to Renton (Fig. 1) (Luzier, 1969; Mullineaux, 1970; Dragovich et al., 1994). The thickness of post-Osceola deposits in this area affords estimates of average rates of sedimentation and delta-front migration for the past 5490–5600 cal. yr. Today, the Duwamish River delta lies within the city limits 2 km southwest of downtown Seattle, ~35 km north of Auburn (Fig. 2). Estimated using that 35 km distance, post-Osceola sedimentation resulted in progradation at an average long-term rate of ~7 m/yr during the late Holocene (Dragovich et al., 1994). Higher rates can now be estimated for laharic episodes, as discussed below in the section on Stop 5.

**NEW WORK**

To further explore the history of lahars and lahar-derived deposits from the White River drainage basin, we are examining deposits along a profile that extends from the flanks of Mount Rainier to Puget Sound. Close to the volcano, we are studying the sedimentology and age of debris-flow and transitional facies of lahars. Far from the volcano, we are making parallel studies of fluvial and deltaic facies of andesitic deposits, as well as materials stratigraphically beneath them, as sampled in engineering borings and exposed in excavations. To clarify lahar hazards, we hope to identify which deposits represent lahars or their runout and which resulted from later fluvial recycling of lahar-derived sediment.

Our new ages show that andesitic sand accumulated in the Kent and Duwamish Valleys around the times of the Summerland, Twin Creek, and Fryingpan Creek episodes of clay-poor lahars in the White River drainage. Twigs, as well as detrital and buried trees, sampled from within sand units have yielded ages similar to those for upstream lahar deposits (Table 1, Fig. 2).

Our findings also clarify downstream changes in the geomorphic setting and sedimentary facies of lahar and lahar-derived deposits (Fig. 2). Close to the volcano, lahar deposits plaster steep valley walls incised into the flanks of the volcano and into older bedrock. At the margin of the Puget Sound lowland, lahar deposits coat fluvial terraces situated in a gorge carved into late Pleistocene glacial drift and Holocene mudflow deposits. In distal areas, lahar-derived deposits comprise the floors of broad valleys once filled with marine waters.

Like the field-trip route, our discussion of lahar-related deposits now moves downstream from Mount Rainier to Puget Sound—from the White River valley, through White River gorge and Kent Valley, to the Duwamish Valley.

**White River Valley**

Post-Osceola lahar deposits in the White River valley between Mount Rainier and Enumclaw (Fig. 2) occupy terraces and valley walls as much as 60 m above the current river. Deposits exposed near river level are clast supported and extremely poorly sorted, consisting of boulders (up to 2 m diameter) and cobbles in a matrix of pebbles and sand. Deposits high on valley walls and near the back edges of terraces are finer grained and better sorted, mostly composed of pebble- and sand-sized particles. Deposits upstream from Enumclaw were probably left by lahars in the debris-flow phase.

Tephra layers provide ways to estimate relative and numerical ages of deposits at Mount Rainier (Mullineaux, 1974) and,
Holocene lahars and their by-products

Among widespread tephra layers from post-Osceola time is Mount St. Helens tephra set Y, which erupted in the centuries between 2470–3700 and 3640–4240 cal. yr B.P. (each of these ranges represents a bounding radiocarbon age; calibrating these ages with data available in the early 1970s, Mullineaux (1974) assigned set Y an approximate age of 3000–3900 cal. yr B.P.). Next, from Mount Rainier itself, is set C, which dates to the interval between 1530–2690 and 1900–2780 cal. yr B.P. (Mullineaux (1974): ca. 2.2 ka). Pumice from set C appears not only at Mount

| TABLE 1. RADIOCARBON AGES FROM THIS STUDY AND APPLICABLE AGES FROM PREVIOUS STUDY |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Lab ID          | Age (14C yr B.P.) | Age* (cal. yr B.P.) | Location        | Deposit          | Sample name     | Sample material |
| Non-laharic deposits |
| CAMS 88808      | 750 ± 40         | 570 – 710         | White River     | overbank         | RC-S85-1         | charcoal         |
| Beta 146056     | 920 ± 40         | 740 – 930         | Seattle         | marsh            | Q23A             | herbaceous stem  |
| Beta 146057     | 1120 ± 40        | 950 – 1140        | Seattle         | marsh            | Q23B             | herbaceous stem  |
| Beta 146058     | 890 ± 50         | 690 – 930         | Seattle         | marsh            | Q23C             | herbaceous stem  |
| Beta 146059     | 990 ± 40         | 790 – 960         | Seattle         | marsh            | Q23D             | herbaceous stem  |
| Beta 145728     | 1890 ± 60        | 1700 – 1960       | Seattle         | bay mud          | Q15F             | charcoal         |
| Beta 145729     | 1730 ± 60        | 1520 – 1810       | Seattle         | bay mud          | Q17B             | wood             |
| Beta 145730     | 1990 ± 70        | 1810 – 2120       | Seattle         | bay mud          | Q15G             | wood             |
| Fryingpan Creek episode |
| CAMS 88809      | 1090 ± 40        | 930 – 1170        | Kent/Auburn     | runout sand      | RC-MC3-S14       | wood             |
| Beta 106603     | 1280 ± 60        | 1070 – 1300       | Seattle         | runout sand      | N.A.             | twig             |
| N.A.            | 1120 ± 80        | 800 – 1260        | White River     | lahar            | N.A.             | wood             |
| N.A.            | 1255 ± 130       | 930 – 1410        | White River     | lahar            | N.A.             | stump on lahar deposit |
| Twin Creek episode |
| WW3353          | 1560 ± 40        | 1350 – 1530       | White River     | lahar            | N.A.             | charcoal         |
| Beta 169386     | 1560 ± 60        | 1320 – 1560       | Kent/Auburn     | runout sand      | RC 277-4         | buried tree      |
| WW3782          | 1615 ± 35        | 1410 – 1610       | Kent/Auburn     | lahar            | N.A.             | charcoal         |
| CAMS 88805      | 1655 ± 30        | 1420 – 1690       | Seattle         | runout sand      | DGS-6A            | twig             |
| Beta 171509     | 1670 ± 50        | 1430 – 1700       | White River     | lahar            | RC-S132-A        | charred wood     |
| CAMS 88806      | 1790 ± 40        | 1570 – 1820       | Seattle         | runout sand      | DGS-6B            | twig             |
| CAMS 88801      | 1850 ± 45        | 1630 – 1880       | Kent/Auburn     | runout sand      | RC-MC6-S10       | wood             |
| WW3796          | 1761 ± 39        | 1308¹ – 1565⁵     | Kent/Auburn     | runout sand      | 755-A             | inner rings detrital tree |
| WW3797          | 1783 ± 40        | 1371¹ – 1624¹     | Kent/Auburn     | runout sand      | 755-B             | inner rings detrital tree |
| WW3798          | 1773 ± 41        | 1420¹ – 1671¹     | Kent/Auburn     | runout sand      | 755-C             | inner rings detrital tree |
| WW3799          | 1561 ± 44        | 1250¹ – 1438¹     | Kent/Auburn     | runout sand      | 755-D             | inner rings detrital tree |
| Summerland episode |
| Beta 169383     | 2110 ± 60        | 1970 – 2310       | Boeing Field    | runout sand      | MF 28B            | outer rings detrital tree |
| CAMS 88807      | 2115 ± 40        | 1950 – 2300       | South Park      | runout sand      | DGS-9M-1          | twig             |
| CAMS 91123      | 2170 ± 35        | 2060 – 2310       | South Park      | runout sand      | DGS-9N            | twig             |
| Beta 169384     | 2180 ± 60        | 2000 – 2340       | Boeing Field    | runout sand      | MF 29A1           | outer rings detrital tree |
| Beta 169385     | 2180 ± 60        | 2000 – 2340       | Boeing Field    | runout sand      | MF 29B4           | outer rings detrital tree |
| CAMS 88800      | 2260 ± 50        | 2150 – 2350       | Boeing Field    | runout sand      | B410              | twig             |
| CAMS 88799      | 2265 ± 40        | 2150 – 2350       | Seattle         | runout sand      | RC-H14            | twig             |
| CAMS 88804      | 2500 ± 40        | 2360 – 2740       | Boeing Field    | runout sand      | B407              | twig             |
| CAMS 88803      | 2510 ± 40        | 2610 – 2740       | Kent/Auburn     | runout sand      | RC-B5-S10         | wood             |
| Beta 172998     | 2540 ± 60        | 2370 – 2770       | White River     | lahar            | RC-S115-1         | charcoal         |

*Dates calibrated using CALIB program of Stuiver et al. (1998) and are calibrated years before 1950 (cal. yr B.P.).

†Dates were adjusted after calibration by subtracting number of rings between sample and outer rings of tree. Error expanded to account for uncertainty in ring counts (± 3 years).

§N.A. indicates no data available.

to a lesser extent, downstream along the White River drainage.
Figure 2. Geometry and generalized interpretations of lahar and lahar-runout deposits in the White River system of Mount Rainier and the Duwamish Valley. Ages for laharic and non-laharic sediments (from Table 1) in the White River and Duwamish Valleys. Age of sample 277-D omitted because it is discordant with three other ages on logs from same deposit (277-A, B, C; Table 1).
Rainier but also, recycled, in andesitic deposits as far down-stream as Seattle. Tephra set W, which erupted from Mount St. Helens and blanketed much of Mount Rainier, is unrecognized around Puget Sound. The largest of the set W eruptions occurred in A.D. 1479 (Fiacco et al., 1993).

Radiocarbon ages from woody debris within lahar deposits suggest that a previously unrecognized lahar, or lahar episode (Twin Creek), occurred ca. 1500 cal. yr B.P. A chunk of charred tree found in a deposit ~30 m above the White River near the confluence with Buck Creek yielded an age of 1320–1560 cal. yr B.P. Charcoal from a lahar deposit near the town of Greenwater gave ages of 1350–1520 and 1410–1610 cal. yr B.P. (Table 1).

White River Gorge

Just east of the present location of Enumclaw, the Osceola Mudflow left the confines of bedrock valleys and spread out over the rolling surface of the Puget Sound lowland. The White River has since cut a gorge 40 m deep by incising through deposits of the Osceola Mudflow and into the underlying glacial drift. Terraces formed during the incision provided platforms for subsequent lahar deposits. Lahar deposits found here occur as much as 30 m above current river level.

At least three lahars successively covered terraces in the gorge. Charred wood in the oldest of the three yielded an age of 2370–2770 cal. yr B.P. (Table 1). The deposits are granular and poorly sorted, with mean grain sizes in the sand-size range. While sand-sized particles are predominantly andesitic, pebble-sized clasts vary in lithologic composition and may be granitic, metamorphic, or andesitic. Deposits are mostly massive; however, in some places they are normally graded at their tops and inversely graded at their bottoms. Each of the deposits resembles those left by transitional flows, a resemblance that suggests dilution of the lahars as they descended the gorge.

As with deposits seen in the White River valley, lahar deposits near river level in the gorge are substantially coarser than those flanking terraces. The deposits attain thicknesses up to 3 m and contain abundant clasts up to 20 cm in diameter, with occasional boulders up to 1 m in diameter. The matrix, which is comprised of pebble- and sand-sized clasts, resembles material observed in deposits on the terraces.

Kent Valley

At the city of Auburn, the White River exits the post-Osceola gorge and spills onto the valley bottom of the White and Green Rivers (Fig. 1). For simplicity, we refer to this portion of the valley between Auburn and Renton as the Kent Valley.

The Osceola Mudflow in the vicinity of Auburn, as identified in geotechnical borings, underlies as much as 80 m of deltaic and laharic deposits (Dragovich et al., 1994). The White River’s post-Osceola incision of the drift plain east of the Kent Valley by the White River delivered sediment to the delta at Auburn while forming the gorge. Lahars flowing through the White River gorge buried the deltaic sediments with andesitic sand and gravel. From this point, laharic debris has traveled both northward toward Seattle and southward toward Tacoma.

Shallow deposits near Auburn are composed chiefly of laharic sediment, as judged from boreholes logs, borehole samples, and excavations from engineering projects. Construction projects and cross sections drawn from lines of geotechnical borings provide views of these deposits and means for sampling dateable material and sediment. Uninterrupted layers of andesitic, moderately to poorly sorted sand and gravel are as much as 10 m thick and are overlain by overbank silt deposits up to 6 m thick. Buried logs, common near the tops of sand deposits, yield ages similar to that of the lahar dated ca. 1300–1600 cal. yr B.P. in the White River valley. Wood fragments found low in two, separate sand deposits gave ages of 930–1170 and 2610–2740 cal. yr B.P. (Table 1), similar to the ages of the Fryingpan Creek episode and Summerland eruptive period, respectively.

Duwamish Valley

West of Renton, below the former confluence of the White River with the Black River, the Duwamish River flows through a narrow bedrock gap and then continues northward into a widening valley that leads to Puget Sound (Fig. 1).

To study andesitic deposits in the Duwamish Valley, we are using geotechnical borings, construction site excavations, and peels made from vertical slices (geoslices). The slices, 0.5 m wide and up to 8 m long, were peeled with hydrophilic grout that reveals sedimentary structures and liquefaction features (Atwater et al., 2001).

Ice-sheet cover and retreat, marine inundation, and the arrival of sediment from lahars produced a diverse array of subsurface sedimentologic units observed in borings from this area. The Duwamish Valley itself was carved by subglacial meltwater streams during the Last Glacial Maximum (Crandell, 1963; Booth 1994). During recession, glacial ice dammed marine waters at the Strait of Juan de Fuca, flooding much of the area that is now Puget Sound with freshwater lakes, where silt and clay accumulated (Bretz, 1913; Thorson, 1989). Continued ice retreat eventually opened the strait, allowing marine waters to invade the region. In the Duwamish Valley, the resulting embayment produced tens of meters of mud that contains marine shells. As laharic debris built northward through the valley from Auburn, the White River delta overrode this mud.

The delta reached Tukwila by Summerland time (Fig. 2). By Fryingpan Creek time (ca. 1100 cal. yr B.P.), it had crossed the Seattle fault and probably came to within a few kilometers of the site of downtown Seattle. Then, or soon afterward, the floodplain behind the delta front was warped by an earthquake on the Seattle fault, dated elsewhere to A.D. 900–930 (Bucknam et al., 1992; Atwater, 1999). As discussed at Stop 5, the Fryingpan Creek episode probably ended around the time of this earthquake, and no subsequent lahars in the White River drainage have managed to leave much if any stratigraphic record in Seattle since 780–930 cal. yr B.P.
SUMMARY

Ages for lahar deposits in the White River system suggest at least three episodes of post-Osceola clay-poor lahars. One episode was concurrent with volcanism of Summerland age (2200 to 2600 yr B.P. or 2200 to 2800 cal. yr B.P.; Vallance and Donoghue, 2000). The following episodes occurred ca. 1500 (Twin Creek) and 1100 cal. yr B.P. (Fryingpan Creek).

The timing of lahar and lahar-derived sand deposition in the Kent and Duwamish Valleys as far as the city of Seattle appears to coincide with the timing of clay-poor lahars in the White River system. Sand deposits correlative with the Summerland episode occur near the surface at Tukwila, suggesting that delta progradation had extended at least to that point by ca. 2200 cal. yr B.P. Deposits correlative with Twin Creek and Fryingpan Creek episodes occur throughout the length of the field area between Mount Rainier and Seattle and contributed to further delta progradation as well as floodplain aggradation.

ROAD LOG

The sequence of stops moves downstream along the White and Duwamish River valley areas beginning at a site ~50 km downstream of Mount Rainier (Fig. 1). Distances are given in miles and kilometers (in parentheses).

Stop 1. Weyerhaeuser Gravel Quarry

Note: The first stop is located on Weyerhaeuser land and advanced permission is required in order to gain access.

<table>
<thead>
<tr>
<th>Cumulative Miles (km)</th>
<th>Description</th>
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<tbody>
<tr>
<td>0.0 (0.0)</td>
<td>On Interstate 5 south out of Seattle set odometer to 0.0 at milepost 165.</td>
</tr>
<tr>
<td>23.0 (37.0)</td>
<td>Exit right to Highway 18 east (exit 142A).</td>
</tr>
<tr>
<td>27.5 (44.3)</td>
<td>Exit right onto State Route 164 east (Auburn Way/Enumclaw).</td>
</tr>
<tr>
<td>42.4 (68.2)</td>
<td>Turn left at the stoplight onto SR 410 east.</td>
</tr>
<tr>
<td>54.8 (88.2)</td>
<td>Turn right down small gravel road and drive through Weyerhaeuser gate #54. Just beyond gate, turn left onto gravel road.</td>
</tr>
<tr>
<td>55.4 (89.1)</td>
<td>Turn right onto small dirt road.</td>
</tr>
<tr>
<td>55.5 (89.4)</td>
<td>Arrive at quarry.</td>
</tr>
</tbody>
</table>

Highlights

Sedimentary structures of a clay-poor lahar exposed in quarry walls.

Description

As of July 2003, the walls of this active quarry formed a large (30 m diameter) horseshoe-shaped exposure made up entirely of a single lahar deposit, locally at least 3 m thick. The White River flows 300 m to the north and 13 m below, meandering around the deposit. The stop is 7 km downstream from the town of Greenwater and 50 km from the summit of Mount Rainier, as measured down the Main Fork of the White River.

The exposure provides excellent views of clay-poor lahar deposits. In grain size and sedimentary structures, the deposits closely resemble those of the lahar floodplain facies described by Scott (1988) for modern lahars in the Toutle-Cowlitz river system of Mount St. Helens. Overall, the portion of the deposit in view is normally graded and composed of sand- and pebble-sized material. The upper meter of the exposure contains more pumice lapilli (layer C) than does the rest of the section.

Especially striking are dish and pillar structures. These form chains of concave-upward silt partings commonly broken from one another at their ends (Fig. 3). The partings themselves are millimeters in thickness and are spaced tens of centimeters apart vertically. Although typically associated with subaqueous sediment gravity flows, these structures also occur in hyperconcentrated-flow deposits (Scott et al., 1995). They apparently begin to form soon after deposition as water is expelled upward out of the deposit (Lowe and LoPiccolo, 1974). Continued translocation of clay and silt enhances the structures (Scott et al., 1995).

Charcoal collected from within the deposit gave ages of 1350–1520 and 1410–1610 cal. yr B.P. The dates are similar to that of a lahar deposit near the confluence of the White River with Buck Creek (1320–1560 cal. yr B.P.; charred wood). The ages are also similar to those of logs in fluvial deposits near Kent (1320–1560 cal. yr B.P.; Pringle, 2000; Table 1). Thus far, no eruptive products that correlate with this lahar episode (Twin Creek) have been identified on Mount Rainier volcano itself.

Stops 2a and 2b. Mud Mountain Dam

<table>
<thead>
<tr>
<th>Cumulative Miles (km)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.5 (89.4)</td>
<td>Return to small dirt road that led to the quarry.</td>
</tr>
<tr>
<td>55.7 (89.6)</td>
<td>Turn left onto gravel road.</td>
</tr>
<tr>
<td>56.3 (90.5)</td>
<td>Turn right and proceed through Weyerhaeuser gate #54.</td>
</tr>
<tr>
<td>63.6 (102.4)</td>
<td>Turn left onto Mud Mountain Dam Road.</td>
</tr>
<tr>
<td>64.3 (103.5)</td>
<td>Turn left into gravel parking area and park.</td>
</tr>
</tbody>
</table>

On foot, follow trail south out of parking area. After ~100 m the trail will meet a gravel road. Follow the road past two metal gates and down the hill. Stop 2a is a small outcrop of lahar deposits on the left side of the road and is 0.5 mi (0.8 km) from the parking lot. Continue down the road for an additional 0.4 mi (0.6 km) to Stop 2b, a large outcrop of lahar deposits.

Highlights

Two more examples of clay-poor lahar deposits. Morphology of the White River valley.
Holocene lahars and their by-products

Description

On the right hand side of Mud Mountain Dam Road, as you leave the highway, is a patch of clear-cut land exposing several mounds, or hummocks. The surface here is underlain by deposits of the Osceola Mudflow, which flowed through this part of the White River valley at a width of ~3 km and maximum depth of 130 m (Scott and Vallance, 1995; Vallance and Scott, 1997). Most hummocks of the Osceola Mudflow consist of car- to house-sized pieces of the volcanic edifice that survived transport and deposition and became stranded along the margins of the flow as the flow waned (Scott et al., 1995; Vallance and Scott, 1997).

A clay-poor lahar deposit forms an exposure a few meters high at Stop 2a. Grain size ranges from fine sand to gravel. Although the deposit is undated, it contains pumice from layer C and therefore postdates 2200 yr B.P. (age from Mullineaux, 1974). Horizontal bands of brownish silt (millimeters in thickness) are also present in the outcrop. The bands appear genetically related to dish structures but lack their characteristic concavity. Using a hand auger, we bored 5 m beneath ground surface without reaching the base of the lahar deposit.

As the road descends out of the forest and toward Stop 2b, the White River valley comes into view. During rainy winter months, this part of the valley is often inundated by water impounded by Mud Mountain Dam, situated 1 km to the west. Downstream, the river flows through a narrow notch incised into bedrock.

Where the road begins to flatten on the modern floodplain of the White River, a clay-poor lahar deposit crops out in an exposure 30 m long and 3 m tall (Stop 2b). The deposit is made of andesitic sand and occasional pebble laminae. A particularly impressive feature of the exposure is the presence of large “rip-up” clasts (up to 0.5 m) that float in the sand matrix (Fig. 4). The composition of clasts resembles that of laminated ice-sheet drift exposed in nearby roadcuts. Suspended in the deposit are cobbles and even boulders up to 40 cm in diameter. The age of this deposit is uncertain, however, it is probably younger than the Osceola Mudflow, which it appears to overlie. Deposits of the Osceola Mudflow crop out near river level at this locality.

Stop 3. Mud Mountain Dam Recreational Facility

<table>
<thead>
<tr>
<th>Cumulative Miles (km)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.3 (103.5)</td>
<td>Turn left out of the parking area onto Mud Mountain Dam Road.</td>
</tr>
<tr>
<td>65.8 (105.9)</td>
<td>Arrive at Mud Mountain Dam Recreation Area.</td>
</tr>
</tbody>
</table>

Highlights

Lunch at the Chinook shelter. Public restrooms.

Description

Mud Mountain Dam was completed in 1949 with the purpose of reducing flood hazards on the valley floor between Auburn and Tacoma. During wet, winter months in the late 1800s and early 1900s, farmland in the lower White River valley in the vicinity of...
Auburn and Kent often flooded. During that period, local farmers feuded over the course of the flooding channel. Several clandestine attempts were made to redirect floodwaters by blowing up portions of the channel with dynamite. One such attempt backfired when explosions generated a landslide that redirected water in the direction of the demolitionists’ land, and completely dried up the original channel of the White River (Valley Daily News, June 9, 1991, p. 29–30). Today the White River, which used to flow northward to Seattle, instead flows southward to Tacoma.

While intended for flood control, Mud Mountain Dam might provide some defense against lahars traveling down the White River valley. The dam is composed of local, unconsolidated mudflow and glacial till deposits, sand and gravel, and an inner concrete wall. The total storage capacity of the dam, 130 million m$^3$, equals about half the volume of lahars that Scott et al. (1996) assigned an average recurrence interval of 500–1000 yr. The estimated volume (3.8 km$^3$) of the Osceola Mudflow, a singular postglacial event, is roughly 30 times that of the dam’s storage capacity.

**Stop 4. Golden Valley Terrace Sequence**

<table>
<thead>
<tr>
<th>Cumulative Miles (km)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.8 (105.9)</td>
<td>Leave Mud Mountain Dam Recreation Area and follow Mud Mountain Dam Road back to SR 410.</td>
</tr>
<tr>
<td>68.0 (109.4)</td>
<td>Turn left onto SR 410.</td>
</tr>
<tr>
<td>76.5 (123.1)</td>
<td>At stoplight, turn right onto Park Avenue.</td>
</tr>
<tr>
<td>76.9 (123.8)</td>
<td>Road turns left and becomes Naches St.</td>
</tr>
<tr>
<td>77.2 (124.2)</td>
<td>Turn right at stop sign onto West Mason St.</td>
</tr>
<tr>
<td>78.6 (126.5)</td>
<td>Turn right at stop sign onto Sumner-Buckley Highway east.</td>
</tr>
<tr>
<td>81.0 (130.4)</td>
<td>Turn right onto Buckeye-Tapps Highway.</td>
</tr>
<tr>
<td>81.9 (131.8)</td>
<td>Turn right at sign for Golden Valley and follow the drive down a steep hill.</td>
</tr>
<tr>
<td>82.3 (132.4)</td>
<td>Arrive at Stop 4.</td>
</tr>
</tbody>
</table>

**Highlights**

Backhoe pit into as many as three successive lahar deposits.

**Description**

Now 17 km downstream from Mud Mountain Dam, we stand inside the margin of the Puget Sound lowland. At the sign to Golden Valley, we dropped off the plain of till-mantled outwash that dominates the lowland’s skyline (Booth, 1994). Below the sign, the White River has cut a gorge into the Osceola Mudflow and underlying Pleistocene glacial drift. Prominent terraces capped by younger lahar deposits are preserved in pockets on either side of the river (Fig. 5A).

Backhoe trenches and hand auguring reveal a sequence of at least three lahar deposits that may be traced between different terraces on either side of the White River (Fig. 5A). The lowermost deposit (at least 1 m thick) is dark gray in color and composed primarily of poorly sorted andesitic sand. Charcoal from this unit (Fig. 5B and 6) yielded an age of 2370–2770 cal. yr B.P., similar to that of the Summerland eruptive episode. The middle unit (~1 m thick) is the most poorly sorted in the section and contains mostly dark gray andesitic sand with abundant pebbles of varying lithologies. The coarsest material is concentrated in the middle 0.5 m of the unit. Also present are horizontal silt laminae similar to those observed at Stop 2a. The uppermost deposit (~1 m thick) is massive and also primarily composed of andesitic sand. A higher fraction of silt than underlying deposits gives it a distinct yellowish hue. Fragments of pumice (up to 1 cm) from layer C are also common in this unit. The two upper units must postdate 2370–2770 cal. yr B.P., and they predate 570–710 cal. yr B.P. if that is the approximate age of the next lowest terrace.

That terrace was built by ordinary fluvial deposits of the White River. Well-exposed in the modern river bank, these deposits consist of cobble gravel capped with 1–2 m of overbank silt. Charcoal from the base of the overbank deposits gave an age of 570–710 cal. yr B.P. If that charcoal is similar in age to its time of deposition, no large lahars have descended this part of the White River in the past six centuries.
Stop 5. Terminal 107, Seattle

<table>
<thead>
<tr>
<th>Cumulative Miles</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.3 (132.4)</td>
<td>Turn around and return to the drive, which leads out of Golden Valley.</td>
</tr>
<tr>
<td>82.7 (133.0)</td>
<td>Turn left onto Buckley-Tapps Highway.</td>
</tr>
<tr>
<td>84.0 (135.2)</td>
<td>Turn right onto Sunnner-Buckley Highway.</td>
</tr>
<tr>
<td>86.1 (138.6)</td>
<td>Take a left at stoplight onto 214th Avenue east.</td>
</tr>
<tr>
<td>86.9 (139.9)</td>
<td>Take a right at the stoplight onto Highway 410 west.</td>
</tr>
<tr>
<td>93.4 (150.3)</td>
<td>Take the exit for Highway 167 north (Seattle).</td>
</tr>
<tr>
<td>112.8 (181.5)</td>
<td>Take the exit for I-405 south.</td>
</tr>
<tr>
<td>115.1 (185.2)</td>
<td>Take the exit for I-5 north (Seattle).</td>
</tr>
<tr>
<td>123.3 (198.4)</td>
<td>Take the exit for West Seattle Bridge, Columbia Way (exit 163). Follow signs for West Seattle Bridge.</td>
</tr>
<tr>
<td>125.6 (202.1)</td>
<td>Take the exit for Port of Seattle terminals 5–115 (Delridge Way SW, South Seattle Community College, SW Spokane St.). At the bottom of the ramp, follow signs for West Marginal Way.</td>
</tr>
<tr>
<td>126.8 (204.1)</td>
<td>Turn left at Edmunds St. into the Duwamish Public Access Area and park.</td>
</tr>
</tbody>
</table>

Highlights

Peels of sediment slice into deltaic deposits probably derived from lahars of Mount Rainier.

Description

This site was recently made into a park as part of an effort to restore natural environments along the Duwamish waterway. The bottom of the waterway is a Superfund site. Lahar-derived sand, which underlies most of the rest of the valley floor, contains polluted groundwater.

The waterway originated in 1914 through hydraulic dredging across former meanders of the Duwamish River (Fig. 6). Some of the dredge spoils were pumped eastward to fill tide flats and marshes. The park itself occupies a natural terrace that the Port of Seattle had planned to make into a terminal. Discovery of an archaeological site led the Port to abandon that plan.

Cross section A–A′

Deposits above a bedrock surface record the postglacial history of this part of Duwamish Valley (cross section A–A′ in Fig. 6).

That history begins with glacial ice or subglacial streams that cut the bedrock surface and covered it with compact drift. The drift was then covered by clay that probably accumulated in the proglacial lake during retreat of the Puget lobe of the Cordilleran Ice Sheet. Shell-bearing deposits in the middle of the section were deposited after marine waters inundated the area when the ice sheet retreated beyond the Straight of Juan de Fuca. Those waters arrived before 11,280–11,940 cal. yr B.P., the age of a log in peat between two units of bay mud. Above this peat, shell-rich units of sand and gravel represent deep-water currents or a beach. These coarse-grained deposits were then covered by estuarine mud.

The uppermost part of section A–A′ records the arrival of the White River delta. Stratigraphic units containing intercalated mud and andesitic sand probably represent bottomset beds of the lahar-fed delta. Andesitic sand of the delta is 20 m thick across much of the section. The sand is capped by mud and peat as much as 5 m thick—probably the deposits of floodplains and marshes of the past two millennia. Radiocarbon ages of logs in the uppermost part of the sand near the eastern end of cross section A–A′ suggest that the delta built past this area in Summerland time (1970–2310 and 2000–2340 cal. yr B.P.; Table 1, Fig. 6). The samples came from sand less than 2 m below the mud cap.

Cross Section B–B′

Subsurface deposits in Seattle’s part of the Duwamish Valley show evidence for further progradation of the delta fed by lahars from Mount Rainier and for subsequent vertical displacement during an earthquake. A valley cross section drawn from geotechnical borings shows that andesitic sand deposits bury shell-bearing estuarine deposits to depths of 20 m or more (B–B′, Fig. 6). At 4th Avenue south, 0.9 km east of Stop 5, a twig in andesitic sand ~5 m below the top of the sand gave an age of 2150–2350 cal. yr B.P. (Table 1), in the range of the Summerland eruptive episode (Fig. 6). Twigs and a stick higher in the andesitic sand gave ages of 1700–1960, 1420–1690, and 1070–1300 cal. yr B.P. (Table 1). If these younger ages date deposition of the delta’s topset beds, an arm of Puget Sound persisted off the site of Terminal 107 through the Summerland eruptive period; the White River delta did not build past the site of Terminal 107 until the Twin Creek or Fryingpan Creek lahar episodes.

The andesitic sand along cross section B–B′ probably pre-dates 1020–1050 cal. yr B.P. because it contains burrows at elevations at or above modern high tides. Uplift along the Seattle fault ca. A.D. 900–930 (Bucknam et al., 1992; Atwater, 1999) raised this burrowed sand ~5 m, thereby forming a single valley-floor terrace that stood above the level of historical floods.

Non-laharic deposits in contact with the sand provide additional ages that limit the time when the White River delta built past the site of Terminal 107. At Terminal 107, the sand overlies shell-bearing bay deposits from which sticks have given ages of 1700–1810, 1690–2120, and 1810–2120 cal. yr B.P. (Table 1). Marsh deposits inset into the andesitic sand began forming by 1070–1300 cal. yr B.P. (Table 1). These deposits lack sand layers other than sand-blow lenses connected to feeder dikes. The marsh deposits thus imply that no sandy lahar runout has approached the site of Seattle in the past eight to ten centuries.

In fall of 2000, a team of Japanese, American, and Chilean scientists collected giant vertical slices (geoslices) of deltaic, andesitic sand in the lower Duwamish Valley. Peels made from these slices show cross-bedding and parallel lamination. Most of the sand in the peels is moderately well to moderately sorted, medium to coarse sand. Rip-up mud clasts and planar-laminated sand (Fig. 7) suggest energetic flow. Sand dikes and convoluted laminae perhaps resulted from the earthquake of A.D. 900–930.
Figure 6. Map showing lower Duwamish Valley (Fig. 1), general physiographic features, and the location of cross sections A–A′ and B–B′. Also shown are the former course of the Duwamish River (in white) and the present, straightened course (outlined in black). Cross sections A–A′ and B–B′ are drawn from geotechnical borings. All ages are cal. yr B.P. Italicized ages are from non-laharic deposits, shell-bearing mud from intertidal or subtidal bay-bottom deposits, and mud and peat from a tidal marsh.
Holocene lahars and their by-products

Mud and mud clasts
Silt
Massive sand
Laminated sand
Fault
Pebbles

Laminated, andesitic sand comprises most of peel. Cross-bedding and parallel laminations are common throughout.

Laminated andesitic sand

Large mud clasts and pebbles are concentrated in a 0.5 m thick zone in the middle of the peel.

Sand and gravel
Mud clasts

Pumice fragments and organic-rich layers are abundant in the lower 0.5 m of the peel. Mud layers contain estuarine diatoms.

Scale in meters

2060 - 2310
1950 - 2300
(twigs)

Mud and mud clasts
Silt
Massive sand
Laminated sand
Pebbles
Fault

2060-2310 Age of organic matter—Two-sigma range in cal yr B.P.

Figure 7. Photo-mosaic of geoslicer peel 9; sketch showing major features and fabric revealed in sample.
Delta Progradation Rates

The White River delta built northward from Auburn at an average rate of 6.9 m/yr in the late Holocene according to estimates by Dragovich et al. (1994). Dragovich and his coworkers assumed that the delta prograded 35 km since Osceola time, which they assigned to 5700 cal. yr B.P. Average progradation rates can now be computed for subdivisions of post-Osceola time, by means of new evidence reported in this field guide.

Between the time of the Osceola Mudflow and the approximate end of the Summerland episode (ca. 2200 cal. yr B.P.), rates of delta progradation between Auburn and Tukwila were similar to or slightly higher than the longer-term average calculated by Dragovich et al. (1994). At Tukwila, floodplain mud began to cover deltaic sand ca. 2000–2340 cal. yr B.P., as judged from the age of logs and a branch in the eastern part of cross section A–A′ (described above and plotted in Figs. 2 and 6). The delta thus prograded at least 26 km between the time of the Osceola Mudflow and the end of the Summerland episode. Calculated using the age range of the Osceola Mudflow (5400–5600 cal. yr B.P.; Vallance and Scott, 1997) and the age of the logs, the minimum long-term average delta progradation rate between Auburn and Tukwila in the intervening period was 7.2 to 8.3 m/yr.

The delta probably prograded at least this fast during the Twin Creek and Fryingpan Creek episodes, as the delta advanced to its present site in Seattle. As a starting point for this interval we use the age and location of the logs and branch on the eastern part of section A–A′ in Tukwila (2000–2340 cal. yr B.P.; Fig. 6). As a conservative end point, we use the age and location of a twig in andesitic sand on the terrace at Stop 5, on cross section B–B′ (1070–1300 cal. yr B.P.; Fig. 6). The distance between these sites is 7 km, for an average delta progradation rate of 5.5–10.0 m/yr. The rate was higher if during that time the delta built beyond Stop 5 to its present position, 3 km beyond Stop 5. In that case, the rate averaged 7.9–14.3 m/yr during the laharc episodes that began in Summerland time.

ACKNOWLEDGMENTS

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REFERENCES CITED


