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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-size 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 andestic 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 about 2200-2800 cal yr B.P., and two others occurred 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 (Figure 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 (Figure 1).

The trip follows the historical path of the White River from the foothills near the volcano to the Duwamish River delta. The White 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 (Figure 1). As recently as 1907, the White River continued northwards to Seattle, joining the Green and Black Rivers along the way. The combined waterway, named the Duwamish River, is now fed only by the Green. Human modifications diverted the other tributary rivers, including the White, which now flows south and then west to Tacoma (Figure 1).

The broad shoulders of Mount Rainier rise above folded volcanic and volcaniclastic 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) probably represent early products of the modern volcano (Crandell, 1963; Mattinson, 1977). The present volcanic cone, chiefly andesitic in composition, began forming about 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 1840's, produced only scattered deposits of pumice (Mullineaux, 1974; Sisson, 1995). Greater volumes of tephra erupted 2200-2600 ^{14}C yr B.P. (about 2200-2800 cal yr B.P.) and around 1000 ^{14}C yr B.P. (about 1000 cal yr B.P.) (Vallance and Donoghue, 2000). Because these voluminous tephra layers contain charcoalized twigs, pyroclastic flows probably accompanied their eruption.

DEFINITIONS

A *lahar* is a gravity-driven, mixture of sediment and water that originates from a volcano (Vallance, 2000). Lahars are common occurrences at many volcanoes, particularly during eruptions. Because lahars can travel many tens of kilometers from their source, some have resulted in great loss of life and property. For example, a 1985 eruption at the Columbian volcano Nevado del Ruiz 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 diamictic deposits. Clay-poor lahars (also called non-cohesive lahars), generally consisting of gravel- and sand-size 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 pyroclastic flows (Eppler, 1987; Scott, 1988; Major and Newhall, 1989).

A lahar can vary in character with time and distance downstream. It may comprise one or more flow phases, which include debris-flow phase, transitional- or hyperconcentrated-flow phase, and streamflow phase (Vallance, 2000). In a *debris-flow phase* the solid and liquid fractions of the lahar have about equal volume and the two fractions move approximately in unison in a vertical section. In a *streamflow 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 streamflow. In a transitional phase, a lahar carries higher sediment loads than does streamflow, but it vertically sorts solids 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 factors 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 kilometers 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 (*^{14}C 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 eruption. 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 km^3 (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 1990's, 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 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 (Figure 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, Figure 2). The oldest of the three episodes coincided with volcanism of Summerland age (about 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 about 1350-1700 cal yr B.P. (range of 3 ages on detrital wood and charcoal from deposits along White River). The youngest, provisionally called the Fryingpan Creek episode, occurred about 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 (Figure 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, about 35 km north of Auburn (Figure 2). That 35-km distance implies post-Osceola sedimentation resulted in progradation at an average long-term rate of about 7 m/year 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 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; Figure 2).

Our findings also clarify downstream changes in the geomorphic setting and sedimentary facies of lahar and lahar-derived deposits (Figure 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 (Figure 2) occupy terraces and valley walls as much as 60 m above the current river. Where at river level, the deposits 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, to a lesser extent, downstream along the White River drainage. 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 assigned set Y an approximate age of 3000-3900 calendric years ago.). Next, from Mount Rainier itself, is set C, which dates to the interval between 1530-2690 and 1900-2780 cal yr B.P. (Mullineaux: about 2200 years ago). Pumice from set C appears not only at Mount Rainier but also, recycled, in andesitic deposits as far downstream 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 at about 1500 cal yr. B.P. A chunk of charred tree found in a deposit about 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 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 (Figure 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 andestic sand and gravel. From this point, laharic debris has traveled both northward towards Seattle and southward towards 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 to about 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 though through a narrow bedrock gap and then continues northward into a widening valley that leads to Puget Sound (Figure 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 sub-glacial 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 fresh water 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 (Figure 2). By Fryingpan Creek time (about 1100 cal yr. B.P.), it had crossed the Seattle fault and probably came to within a few km of the site of downtown Seattle. Then or soon afterwards 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 3 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 about 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 about 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 about 50 km downstream of Mount Rainier (Figure 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.

Directions.

0.0 (0.0)	On I-5 South out of Seattle, set odometer to 0.0 at mile post 165.
23.0 (37.0)	Exit right to Highway 18 east (Exit 142A).
27.5 (44.3)	Exit right onto 164 east (Auburn Way/Enumclaw).
42.4 (68.2)	Turn left at the stoplight onto 410 east.
54.8 (88.2)	Turn right down small gravel road and drive through Weyerhaeuser gate #54). Just beyond gate, turn left onto gravel road.
55.4 (89.1)	Turn right onto small dirt road.
55.5 (89.4)	Arrive at quarry.

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 flood-plain facies described by Scott (1988) for modern lahars in the Toutle-Cowlitz river system of Mt. 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 (Figure 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 upwards 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., Table 1; and Pringle, 2000). 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

Directions.

55.5 (89.4)	Return to small dirt road that led to the quarry.
55.7 (89.6)	Turn left onto gravel road.
56.3 (90.5)	Turn right and proceed through Weyerhaueser gate #54.
63.6 (102.4)	Turn left onto Mud Mountain Dam Road.
64.3 (103.5)	Turn left into gravel parking area and park.

On foot, follow trail south out of parking area. After about 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 miles (0.8 km) from the parking lot. Continue down the road for an additional 0.4 miles (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.

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 about 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-size 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). 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 towards 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 flood plain 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 large "rip-up" clasts (up to 0.5 m) that float in the sand matrix (Figure 4). The composition of clasts resembles that of laminated icesheet 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

Directions.

64.3 (103.5) Turn left out of the parking area onto Mud Mountain Dam Road.

65.8 (105.9) Arrive at Mud Mountain Dam Recreation Area.

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 1800's and early 1900's, 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 northwards 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 years. The estimated volume of (3.8 km^3) of the Osceola Mudflow, a singular post-glacial event, is roughly 30 times that of the dam's storage capacity.

Stop 4 – Golden Valley terrace sequence

Directions.

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

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 (Figure 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 (Figure 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 (Figure 5B and 6) yielded an age of 2370-2770 cal yr B.P., similar to that of the Summerland eruptive episode. The middle unit (about 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 (about 1 m thick) is massive, and also primarily comprised 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 to 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

Directions

82.3 (132.4) Turn around and return to the drive which leads out of Golden Valley.
82.7 (133.0) Turn left onto Buckley-Tapps Highway.

84.0 (135.2) Turn right onto Sumner-Buckley Highway.
86.1 (138.6) Take left at stoplight onto 214th Avenue East.
86.9 (139.9) Take a right at the stoplight onto highway 410 west.
93.4 (150.3) Take the exit for highway167 north (Seattle).
112.8 (181.5) Take the exit for I-405 south.
115.1 (185.2) Take the exit for I-5 north (Seattle).
123.3 (198.4) Take the exit for West Seattle Bridge, Columbian Way (exit 163). Follow signs for West Seattle Bridge.
125.6 (202.1) 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.
126.8 (204.1) Turn left at Edmunds St. into the Duwamish Public Access Area and park.

Highlights. Peels of sediment slices 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 (Figure 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 post-glacial history of this part of Duwamish valley (cross section A-A' in Figure 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, 2000-2340, and 2000-2340 cal yr B.P.; Table 1, Figure 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', Figure 6). At 4th Avenue South, 0.9 km east of Stop 5, a twig in andesitic sand about 13 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 (Figure 6). Twigs and a stick higher in the andesitic sand gave ages of 1470-1820, 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 predates 1020-1050 cal yr B.P. because it contains burrows at elevations at or above modern high tides. Uplift along the Seattle fault about A.D. 900-930 (Bucknam et al., 1992; Atwater, 1999) raised this burrowed sand about 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 1520-1810, 1700-1960, and 1810-2120 cal yr B.P. (Table 1). Marsh deposits inset into the andesitic sand began forming by 780-930 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 (Figure 7) suggest energetic flow. Sand dikes and convoluted laminae perhaps resulted from the earthquake of A.D. 900-930.

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 (about 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 about 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 Figures 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 (5490-5600 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.; Figure 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.Figure 6). The distance between these sites is 7 km, for an average delta progradation rate 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 laharic episodes that began in Summerland time.

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TABLE 1. RADIOCARBON AGES FROM THIS STUDY AND APPLICABLE AGES FROM PREVIOUS STUDIES

Lab ID	Age (14C yr B.P.)	Age* (cal yr B.P.)	Location	Deposit	Sample name or reference	Sample material
Non-laharic deposits						
CAMS 88808	750 ± 40	570 - 710	White River	overbank	RC-S85-1	charcoal
Beta 146056	920 ± 40	740 - 930	Seatte	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
Frying Pan Creek episode						
CAMS 88809	1090 ± 40	930 - 1170	Kent/Auburn	runout sand	RC-MC3-S14	wood
Beta 106603	1290 ± 60	1070 - 1300	Seattle	runout sand	Vallance and Pringle, unpub.	twig
N.A.[#]	1120 ± 80	800 - 1260	White River	lahar	Scott et al. (1995)	wood
N.A.	1255 ± 130	930 - 1410	White River	lahar	Scott et al. (1995)	stump
Twin Creek episode						
WW3353	1560 ± 40	1350 - 1530	White River	lahar	RC-1	charcoal
Beta 169386	1560 ± 60	1320 - 1560	Kent/Auburn	runout sand	RC 277-4	buried tree
WW3782	1615 ± 35	1410 - 1610	White River	lahar	RC-2	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	1308[†] - 1565[†]	Kent/Auburn	runout sand	755-A	inner rings detrital tree
WW3797	1783 ± 40	1371[†] - 1624[†]	Kent/Auburn	runout sand	755-B	inner rings detrital tree
WW3798	1773 ± 41	1420[†] - 1671[†]	Kent/Auburn	runout sand	755-C	inner rings detrital tree
WW3799	1561 ± 44	1250[†] - 1438[†]	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. (1999) and are years before 1950.

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

[#]N.A. indicates no data available.

FIGURE CAPTIONS

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 DEM at upper left is the approximate location of former Duwamish embayment as it existed at the time of the Osceola mudflow 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 about 45 km northward to Seattle. Shown is pre-1900 course of White River.

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).

Figure 3. Dish structures exposed in the quarry wall at stop 1.

Figure 4. Rip-up clasts in a lahar deposit exposed in walls of the river-cut exposure at Stop 2b. Pencil shows scale.

Figure 5. Location of backhoe trench at stop 3. Box on inset map shows area of DEM. Note prominent terraces along White River which are covered with lahar deposits. Trench log (B) and photo (C) showing three individual lahar deposits (I, II, and III). Sedimentology of the deposits suggests deposition in a hyperconcentrated-flow facies. The age is from a sample collected in a trench 150 m to the southeast that showed identical stratigraphy.

Figure 6. Map showing lower Duwamish Valley (Figure 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 calibrated years 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.

Figure 7. Photo-mosaic of geoslicer peel 9, sketch showing major features and fabric revealed in sample.

Figure 1.

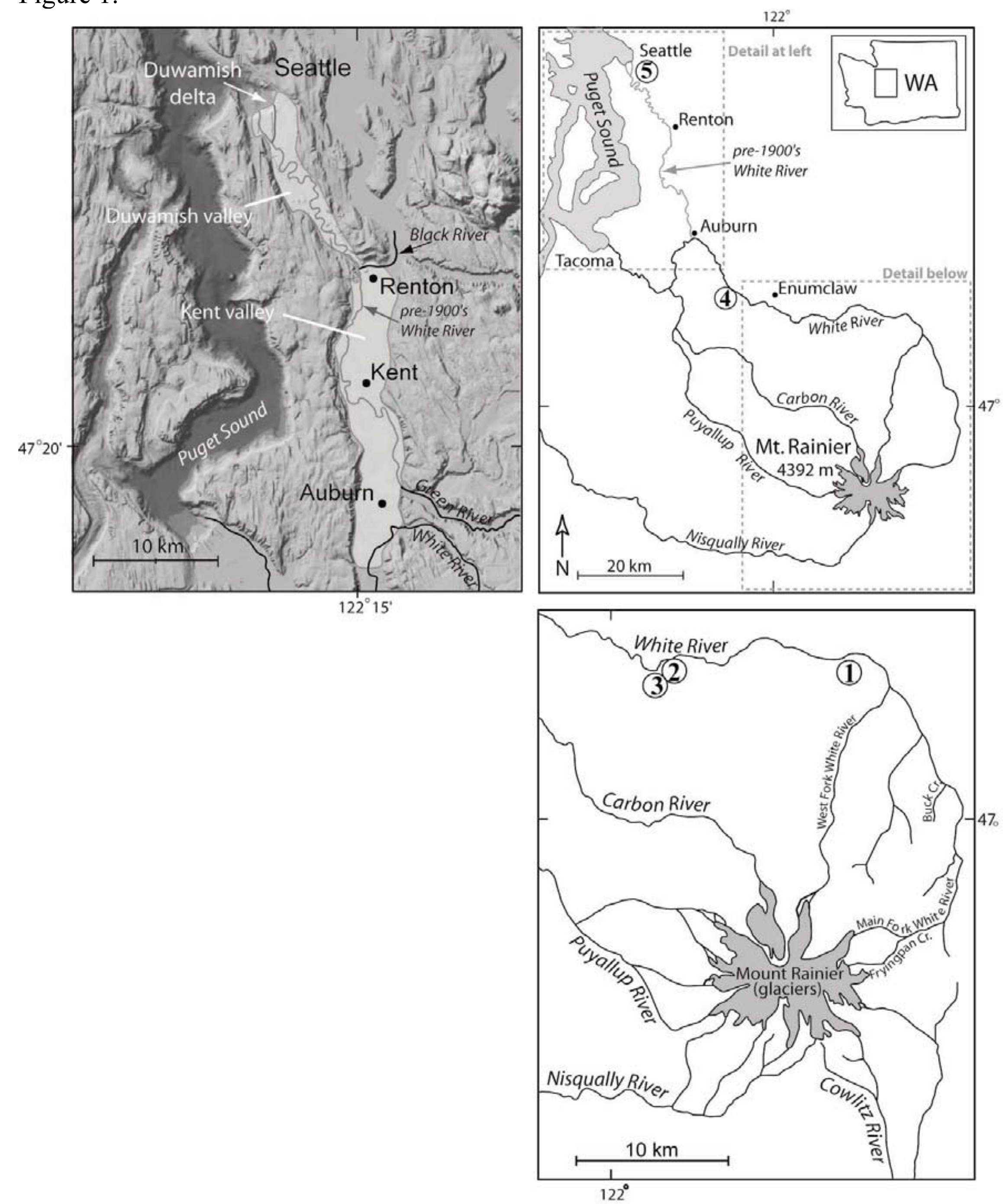
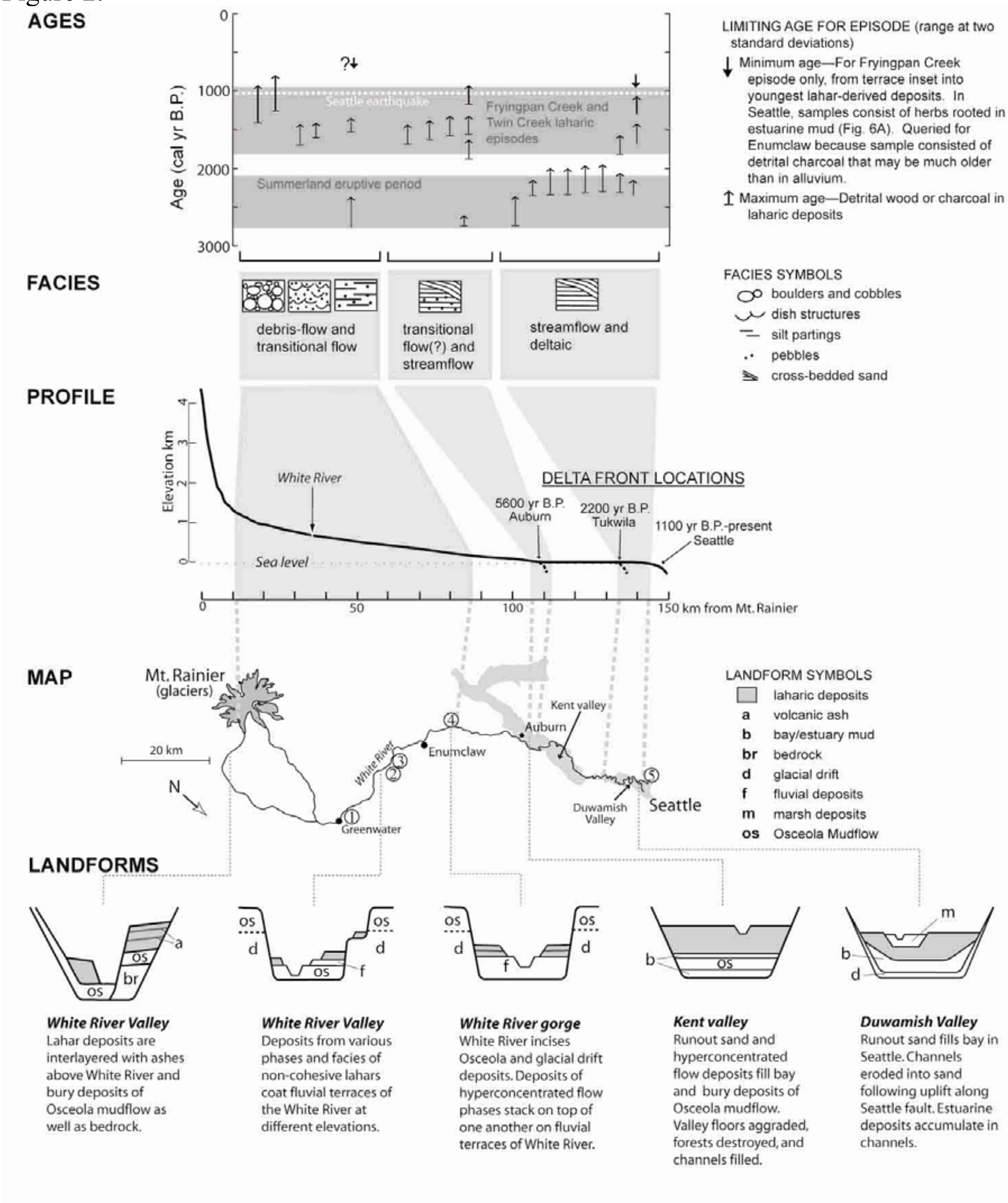

Duwamish delta
Seattle
Duwamish valley
Black River
Renton
Kent valley
pre-1900's White River
Kent
Puget Sound
47°20'
Auburn
Green River
White River
10 km
122° 15'
122°
Seattle
5
Detail at left
WA
Puget Sound
Renton
pre-1900's White River
Auburn
Tacoma
Detail below
4
Enumclaw
White River
Carbon River
47°
Puyallup River
Mt. Rainier
4392 m
N
20 km
Nisqually River
White River
2
3
1
West Fork White River
Buck Cr.
Carbon River
47°
Main Fork White River
Fryingpan Cr.
Puyallup River
Mount Rainier (glaciers)
Nisqually River
Cowlitz River
10 km
122°

Figure 2.



AGES
Age (cal yr B.P.)
0
1000
2000
3000
Seattle earthquake
Fryingpan Creek and Twin Creek laharic episodes
Summerland eruptive period
LIMITING AGE FOR EPISODE (range at two standard deviations)
Minimum age—For Fryingpan Creek episode only, from terrace inset into youngest lahar-derived deposits. In Seattle, samples consist of herbs rooted in estuarine mud (Fig. 6A). Queried for Enumclaw because sample consisted of detrital charcoal that may be much older than in alluvium.
Maximum age—Detrital wood or charcoal in laharic deposits
FACIES
debris-flow and transitional flow
transitional flow(?) and streamflow
streamflow and deltaic
FACIES SYMBOLS
boulders and cobbles
dish structures
silt partings
pebbles
cross-bedded sand
PROFILE
Elevation km
White River
DELTA FRONT LOCATIONS
5600 yr B.P. Auburn
2200 yr B.P. Tukwila
1100 yr B.P.-present Seattle
Sea level
0
50
100
150 km from Mt. Rainier
MAP
Mt. Rainier (glaciers)
20 km
N
White River
Greenwater
Enumclaw
Auburn
Kent valley
Duwamish Valley
Seattle
LANDFORM SYMBOLS
laharic deposits
a volcanic ash
b bay/estuary mud
br bedrock
d glacial drift
f fluvial deposits
m marsh deposits
os Osceola Mudflow
LANDFORMS
White River Valley
Lahar deposits are interlayered with ashes above White River and bury deposits of Osceola mudflow as well as bedrock.
White River Valley
Deposits from various phases and facies of non-cohesive lahars coat fluvial terraces of the White River at different elevations.
White River gorge
White River incises Osceola and glacial drift deposits. Deposits of hyperconcentrated flow phases stack on top of one another on fluvial terraces of White River.
Kent valley
Runout sand and hyperconcentrated flow deposits fill bay and bury deposits of Osceola mudflow. Valley floors aggraded, forests destroyed, and channels filled.
Duwamish Valley
Runout sand fills bay in Seattle. Channels eroded into sand following uplift along Seattle fault. Estuarine deposits accumulate in channels.

Figure 3.

Figure 4.

Figure 5.

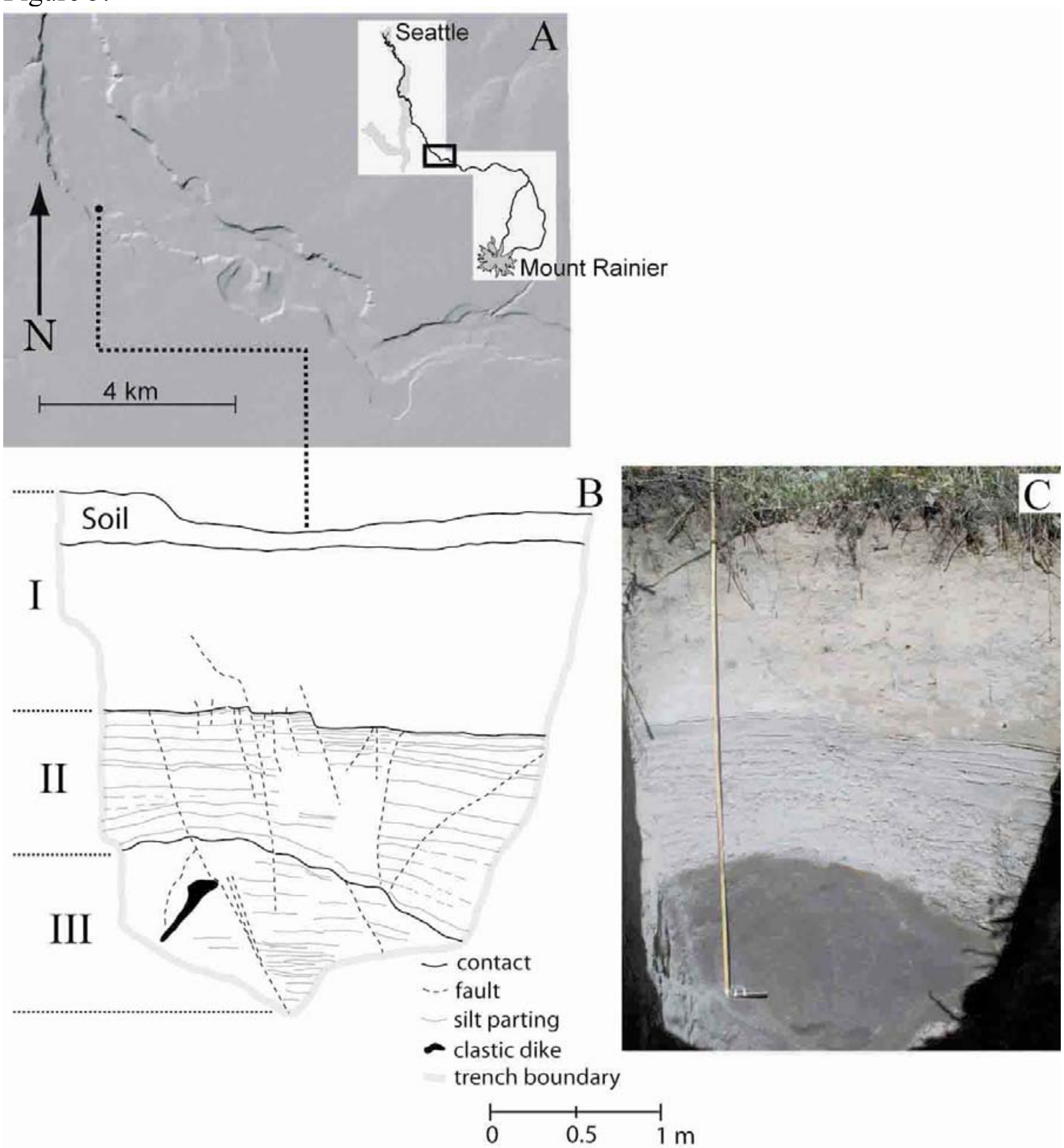

Seattle
A
Mount Rainier
N
4 km
B
Soil
I
II
III
contact
fault
silt parting
clastic dike
trench boundary
0
0.5
1 m
C

Figure 6.

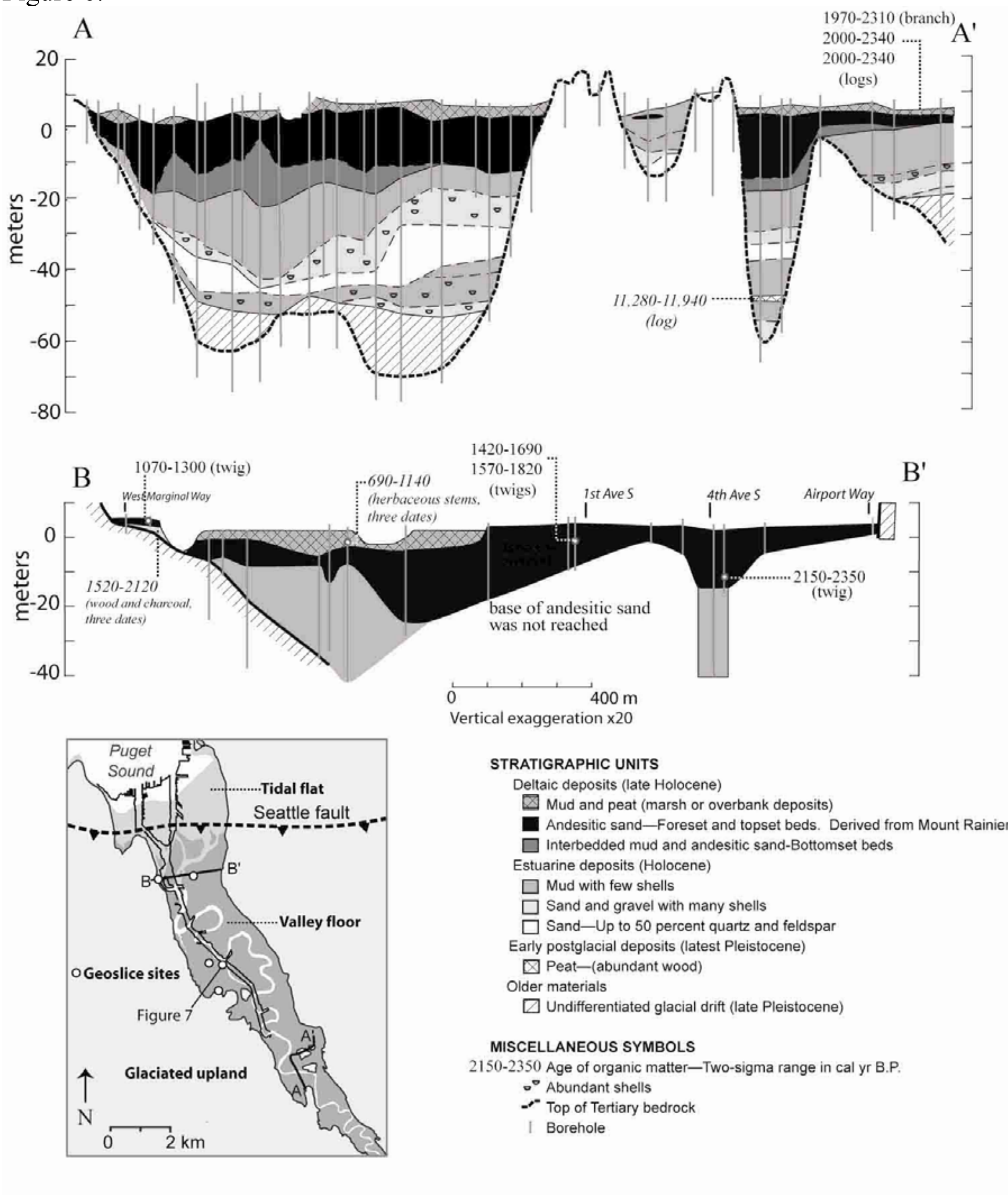
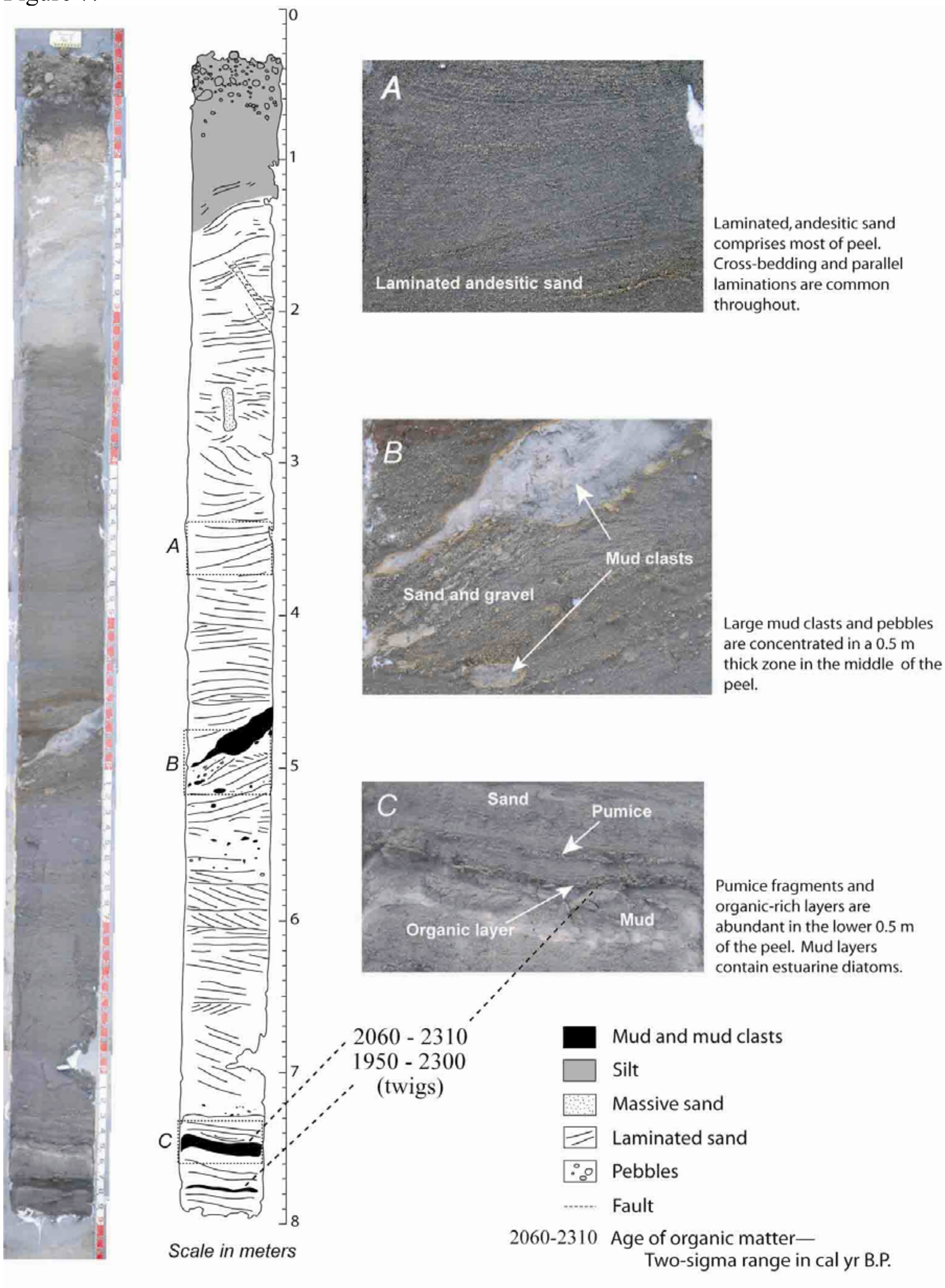

A
A'
1970-2310 (branch)
2000-2340
2000-2340
(logs)
11,280-11,940
(log)
meters
B
B'
1070-1300 (twig)
West Marginal Way
690-1140
(herbaceous stems, three dates)
1420-1690
1570-1820
(twigs)
1st Ave S
4th Ave S
Airport Way
1520-2120
(wood and charcoal, three dates)
2150-2350
(twig)
base of andesitic sand
was not reached
0
400 m
Vertical exaggeration x20
Puget Sound
Tidal flat
Seattle fault
Valley floor
Geoslice sites
Figure 7
Glaciated upland
N
0
2 km
STRATIGRAPHIC UNITS
Deltaic deposits (late Holocene)
Mud and peat (marsh or overbank deposits)
Andesitic sand—Foreset and topset beds. Derived from Mount Rainier
Interbedded mud and andesitic sand-Bottomset beds
Estuarine deposits (Holocene)
Mud with few shells
Sand and gravel with many shells
Sand—Up to 50 percent quartz and feldspar
Early postglacial deposits (latest Pleistocene)
Peat—(abundant wood)
Older materials
Undifferentiated glacial drift (late Pleistocene)
MISCELLANEOUS SYMBOLS
2150-2350 Age of organic matter—Two-sigma range in cal yr B.P.
Abundant shells
Top of Tertiary bedrock
Borehole

Figure 7.



0
1
2
3
4
5
6
7
8
A
B
C
Scale in meters
2060 - 2310
1950 - 2300
(twigs)
A
Laminated andesitic sand
Laminated, andesitic sand comprises most of peel. Cross-bedding and parallel laminations are common throughout.
B
Mud clasts
Sand and gravel
Large mud clasts and pebbles are concentrated in a 0.5 m thick zone in the middle of the peel.
C
Sand
Pumice
Organic layer
Mud
Pumice fragments and organic-rich layers are abundant in the lower 0.5 m of the peel. Mud layers contain estuarine diatoms.
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.