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Pleistocene tephrostratigraphy and paleogeography of southern Puget Sound near Olympia, Washington

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ABSTRACT

Our detailed mapping in the south Puget Sound basin has identified two tephras that are tentatively correlated to tephras from Mount St. Helens and Mount Rainier dated ca. 100–200 ka and 200 ka, respectively. This, plus the observation that fluvial and lacustrine sediments immediately underlying the Vashon Drift of latest Wisconsin age are nearly everywhere radiocarbon infinite, suggests that glacial and nonglacial sediments of more than the past five oxygen-isotope stages are exposed above sea level. Distal lacustrine advance outwash equivalent to the Lawton Clay in the Seattle area is conspicuously absent. Instead, a thick (>120 ft) glaciolacustrine silt below the Vashon sediments contains dropstones and is radiocarbon infinite. Elsewhere, coarse-grained advance Vashon outwash rests unconformably on radiocarbon-infinite nonglacial sediments. These relationships may imply that late Pleistocene tectonic activity has modified the paleotopography and stratigraphy of the south Puget Sound area.

Keywords: Quaternary stratigraphy, tephrochronolgy, Puget Lowland, glacial geology.

INTRODUCTION

Late Wisconsinan-age Vashon Drift covers most of the southern Puget Lowland. Pre-Vashon units are generally exposed only along coastal bluffs, where mass wasting is common. Landslides and colluvium disrupt and obscure the continuity of exposures so that pre-Vashon geologic history is not easily deciphered. In the south Puget Lowland (south of Tacoma), all finite radiocarbon ages reported before 1966 are suspect due to laboratory contamination (Dorn et al., 1962; Fairhall et al., 1966). Stratigraphic assignments based on these invalid radiocarbon ages are now questionable and need to be re-evaluated. In addition, radiocarbon dating of the Salmon Springs Glaciation, which is subjacent to the Vashon Drift in the Puyallup Valley (southeast of Tacoma; Fig. 1; Table 1) ca. 70 ka has been shown to be incorrect. The Salmon Springs has since been shown to be ca. 0.8–1 Ma on the basis of K-Ar dating of included tephra and reverse magnetization, suggesting deposition during the Matuyama Reversed Chron (Blunt et al., 1987; Westgate et al., 1987; Easterbrook, 1994). However, older geologic mapping has shown the drift below the Vashon to be Salmon Springs on the basis of stratigraphic position alone. Recent mapping and paleomagnetic analysis (Hagstrum et al., 2002) has demonstrated that this unconformity is probably due to the presence of an anticline that has been growing through at least the latter half of the Quaternary Period. Elsewhere in the Puget Lowland, particularly in the north, Easterbrook (1986, 1994) has demonstrated that glacial and nonglacial deposits of oxygen-isotope stage (OIS) 4-6,

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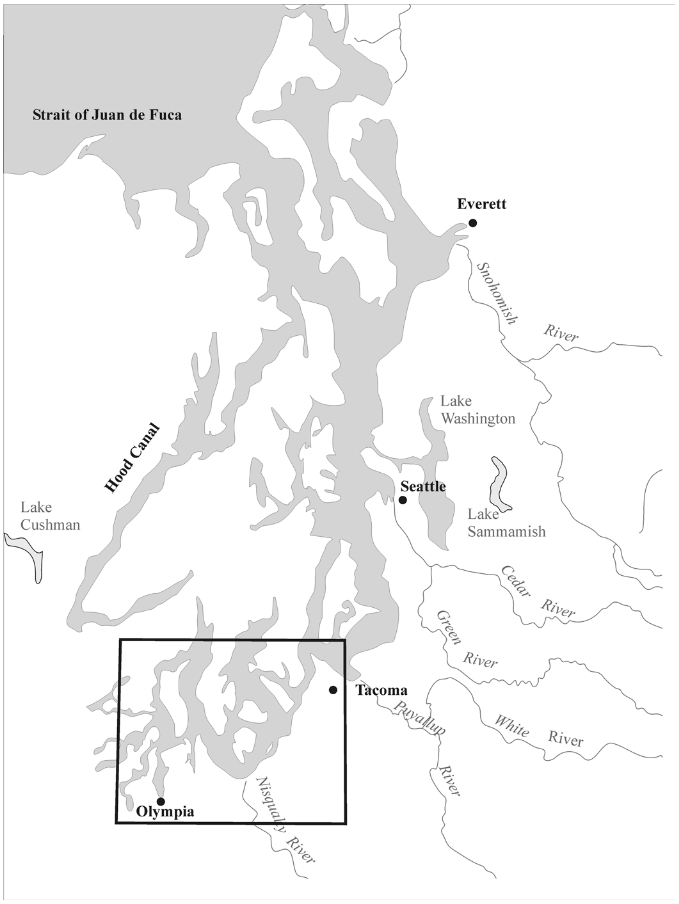

Figure 1. Location map for south Puget Sound field trip. Box shows area of trip, shown in detail in Figure 3.

called Possession Drift, Whidbey Formation, and Double Bluff Drift respectively, are exposed above sea level. For these reasons, previous mapping of Salmon Springs in the south Puget Sound is almost certainly in error. We have also shown (Logan et al., 2003; Walsh et al., 2003) that deposits previously mapped as Salmon Springs (Noble and Wallace, 1966; Walters and Kimmel, 1968) in the Nisqually River valley were deposited by alpine glaciers from the south Cascade Mountains.

We have systematically sampled all datable material from nonglacial sediments subjacent to the Vashon Drift and found them to be older than previously reported. With a few exceptions, these sediments have been beyond the range of radiocarbon dating.

The antiquity of the pre-Vashon units causes radiocarbon dating to be of little help for making correlations, and abrupt facies changes within glacial and nonglacial units also render correlations tenuous. We have augmented radiocarbon dating with paleomagnetic analyses (J.T. Hagstrum, 2000, personal commun.) and chemical analyses of tephra (Table 2) to reconstruct the stratigraphy of south Puget Sound, although much remains to be done. Despite these difficulties, we have developed a conceptual model for the more recent pre-Vashon geologic history that is consistent with our observations but by no means compelling.

The OIS 4 glaciation, called the Possession Glaciation, in the northern Puget Lowland was mild relative to stages 2 and 6 (Mix, 1987; Fig. 2), which are represented in the Puget Lowland by the Vashon and Double Bluff Drifts, respectively. The Possession Ice Sheet probably did not extend far south of Seattle (Lea, 1984; Troost, 1999). Because the ice sheet blocked drainage out of Puget Sound to the Strait of Juan de Fuca, a proglacial lake was impounded in most of the southern Puget Lowland. Streams flowing into this lake, such as the Nisqually, Puyallup, and Skokomish Rivers, formed an alluvial plain and deltas grading to lake level. These nonglacial sediments, deposited during stage 4, are all radiocarbon infinite and overlie and interfinger with Possession outwash deposits. Once Possession ice no longer impounded the lake (but sea level was still significantly below modern sea level), existing drainages, such as the Nisqually and Puyallup Rivers, deeply and rapidly incised into their former alluvial plains and became entrenched. At least initially, stage 3, called the Olympia Interglaciation (Armstrong et al., 1965), was characterized by downcutting and erosion. As sea level began to rise, most deposition was confined to the entrenched channels. Because stage 3 sea level was probably ~100 ft lower than modern sea level (Ludwig et al., 1996, and references therein), stage 3 deposits were areally restricted. As Vashon ice advanced and sea level fell again at the beginning of stage 2, these rivers preferentially downcut in the same channels, eroding the late Olympia deposits so that finite-aged Olympia deposits would be rare above sea level.

As Vashon ice moved southward and grounded across the Strait of Juan de Fuca during stage 2, it dammed the northern outlet of the Puget Sound basin. Proglacial streams carried fluvial sediments southward into the Puget Lowland, filling proglacial lakes and eventually the Puget Sound basin, first with silts, then with sands and gravels. These sediments form the "great lowland fill" of Booth (1994). Ice overrode these sediments, covering most of them with till, or scoured them away to deposit till directly onto pre-Vashon sediments. Subglacial channels were subsequently eroded into the fill. Proglacial lakes became impounded in these channels at different elevations above today's sea level as ice impinged on divides. The former lakebeds are presently the southernmost inlets of Puget Sound. (For a more thorough discussion of the subglacial channel network, see Booth [1994] and Booth and Goldstein [1994].) As these proglacial lakes spilled into lower-elevation basins and channels near the end of the Pleistocene, they deposited coarse, steeply dipping deltaic gravels along the margins of the channels and basins. Some of these deposits can be found near Steilacoom and Fort Lewis.

Much of the drainage originating from the ice sheet flowed southward and southwestward toward the Chehalis River. Some of the drainage probably occurred as glacial-lake outburst floods as valley-blocking ice dams breached during ice retreat. Deep

TABLE 1. PUGET LOWLAND STRATIGRAPHIC NOMENCLATURE

		Age* (ka)	Puget Lowland Willis (1898), Bretz (1913)	Southeast Puget Lowland Crandell et al. (1958)	Central and northern Puget Lowland Armstrong et al. (1965), Mullineaux et al. (1965)	^{14}C age (ka)	Tacoma area Walters and Kimmel (1968)	Puget Lowland Easterbrook (1986), Blunt et al. (1987), Easterbrook (1994), Troost (1999)	Southern Puget Lowland This report	Age (ka)
RECENT		10			Fraser Glaciation					
PLEISTOCENE	LATE				Sumas Stade	9–11				
					Everson Interstade (glaciomarine)	11–13.5				
			Vashon Glaciation	Vashon Drift	Vashon Stade	13.5–25	Vashon Drift	Vashon Drift	Tumwater Sand	
							Steilacoom Gravel	Steilacoom Gravel	Steilacoom Gravel	
					Vashon till		Vashon till	Vashon till	Vashon till	
					Esperance Sand		Colvos Sand	Esperance Sand	Colvos Sand	
					Lawton Clay			Lawton Clay	Lawton Clay?	
					Evans Creek Stade (alpine)	15–25				
			Puyallup Interglaciation	Unnamed erosional/ nonglacial interval	Olympia Interglaciation	15–35	Kitsap Formation	Olympia beds	alpine drift? Olympia beds	15–60
								Possession Drift		60–80
			Admiralty Glaciation					Whidbey Formation	reversely magnetized sediments	ca. 100
								Double Bluff Drift		100–250
	MID	300							Unnamed beds on Ketron Island; alpine drifts from Mount Rainier?	60–500?
	EARLY	800		Salmon Springs Drift	Salmon Springs Glaciation		Salmon Springs Drift	Salmon Springs Glaciation		800
				Puyallup Formation	Puyallup Interglaciation		Puyallup Formation	Puyallup Interglaciation		>1000
				Stuck Drift	Stuck Glaciation		Stuck Drift	Stuck Glaciation		ca. 1600
				Alderton Formation	Alderton Interglaciation		Alderton Formation	Alderton Interglaciation		>1600
				Orting Drift	Orting Glaciation		Orting Drift	Orting Glaciation		>1600
		1800								

*Not to scale. Modified from Borden and Troost (2001).

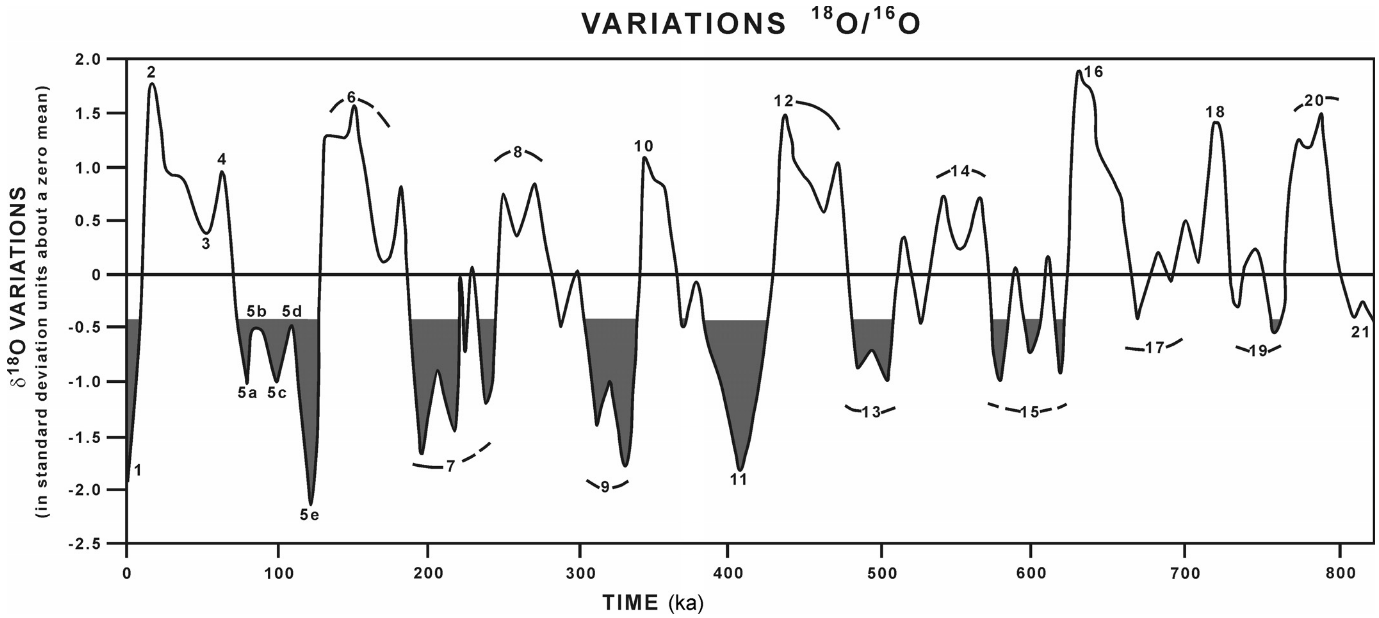

Figure 2. Marine oxygen-isotope stages (from Morrison, 1991). The numbers within the graph are stage numbers; the even-numbered peaks (at top) are glacial maxima, and the odd-numbered troughs (at bottom) are interglacial minima. The blue areas indicate interglacial episodes, based on a cutoff at –0.5 $\delta^{18}O$ oxygen-isotope values (equivalent to Holocene interglacial values).

troughs were carved out of the fill by subglacial fluvial erosion, and extensive and complex terraces and braided channels were formed. As the ice receded, northward-flowing streams near Olympia filled the deep troughs with sandy sediments characterized by northward-directed paleocurrent indicators. These sediments provide evidence that drainage reorganized to flow northward through the recently formed outwash plain. The thickness of these sediments varies substantially throughout the area, reaching more than 400 ft at the Port of Olympia.

In the waning stages of the Fraser Glaciation, Glacial Lake Russell covered a large area of the southern Puget Lowland and deposited a relatively thin layer (1–10 ft) of fine-grained varved sediments to an elevation of ~140 ft. These lacustrine silts (and rare clays and peats) usually overlie Vashon till, but rarely may overlie Vashon outwash. The latest Vashon sand is important because it is widespread throughout the populous South Sound area and appears to behave differently from the rest of the Vashon Drift during earthquakes (Palmer et al., 1999a, 1999b; Bodle, 1992; King et al., 1990).

The OIS 6 glaciation, called the Double Bluff Glaciation, in northern Puget Sound was probably as extensive as, or locally more extensive than, the stage 2 or Vashon Stade of the Fraser Glaciation (Mix, 1987; Lea, 1984). The end moraines of this glaciation lie a short distance beyond the inferred limit of the Vashon ice in the vicinity of Tenino (Lea, 1984). Subglacial erosion was probably similar to the erosion that Booth (1994) documented beneath Vashon ice and would have left more accommodation space for deposition during the interglacial time of OIS 5. For pre-Vashon nonglacial deposits that are radiocarbon infinite, therefore, it is difficult to distinguish deposits of OIS 3 from deposits of OIS 5 or OIS 7.

In some outcrops, however, tephras are present that provide a tool for geochemical correlation to known eruptions of nearby Cascade stratovolcanoes. Tephra analyses from numerous sites (F.F. Foit, Jr.; A.M. Sarna-Wojcicki; and T.W. Sisson, 2000–2002, personal communs.) have begun to form a framework that will help to enable more precise correlations of similar lithofacies in south Puget Sound.

BOAT LOG

Leave Steilacoom floating dock (1 on Fig. 3) and travel southwest ~1.25 mi (2 km) to the north end of Ketron Island, and travel southward along the east shore. At the north end of the island, lodgment till of the Vashon Drift is exposed at sea level, making a wave-cut platform, and forms the surface of the island. As the surface elevation of the island increases to the south, the lower contact of the till can be seen to rise in the bluff approximately parallel to the surface. Exposures are spotty and change with sloughing of the bluff and vegetation, but Vashon till can be seen truncating alternating deposits of oxidized pebble-to-cobble gravel and fluvial sand with interbedded silt. Just south of the ferry terminal, a sand channel trending east-west can be seen near the top of the bluff. There are angular blocks of silt up to ~2 ft across that also conform to the margins of the sand channel. Detrital carbon from this channel is radiocarbon infinite. We interpret this as a subglacial channel below Vashon ice reworking older deposits.

Continue south to southern tip of Ketron Island.

TABLE 2. MICROPROBE ANALYSES OF TEPHRAS DISCUSSED IN TEXT

Sample #	Location	Analyst	n	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	SO_3	Orig. total
93RW96	SA	S	16	74.81	0.30	13.58	1.51*	0.02	0.29	1.35	3.96	4.02	0.05	0.15	0.02	94.29
19-1E-11-73E-1	KI	S	26	74.13	0.32	13.76	1.79*	0.05	0.32	1.50	4.14	3.82	0.05	0.15	0.01	96.18
19-1E-11-73E-2	KI	S	21	74.82	0.30	13.54	1.50*	0.06	0.27	1.38	4.02	3.95	0.04	0.14	0.01	94.73
19-1E-11-73E-3	KI	S	15	74.59	0.39	13.56	1.55*	0.01	0.33	1.43	4.03	3.94	0.03	0.15	0.01	94.27
19-1E-11.73C	KI	F	16	75.04	0.29	13.42	1.68		0.30	1.41	3.71	3.91		0.17		
19-1E-11.73D	KI	F	17	75.05	0.29	13.56	1.71		0.30	1.43	3.63	3.84		0.16		
19-1E-11.73E	KI	F	16	74.85	0.31	13.65	1.74		0.31	1.42	3.69	3.83		0.17		
PLW8-11-01P4 T483-7	KI	F	16	75.27	0.28	13.54	1.66	0.04	0.27	1.28	3.79	3.87				90.34
19N-1W-23.85A	BC	F	16	76.59	0.11	14.27	1.07		0.33	1.80	3.45	2.26		0.09		
19N-1W-23.85A	BC	S	25	76.10	0.14	14.13	1.07*	0.05	0.35	1.77	3.93	2.29	0.05	0.08	0.02	94.32
PLW8/11/01P1 T483-8	BC mode 1	SW	9	76.14	0.09	14.37	1.07	0.02	0.35	1.82	4.03	2.10				86.54
PLW8/11/01P1 T483-8	BC mode 2	SW	2	73.47	0.19	15.00	1.75	0.05	0.36	1.48	4.63	3.07				94.77
19-1E-17.41A	AIS	F	15	76.43	0.12	14.17	1.11		0.35	1.84	3.65	2.21		0.09		
PLW8/11/01_P3 T487-4	AIS	SW	10	76.55	0.09	14.19	1.02	0.04	0.34	1.79	3.90	2.07				91.37
19/1E-18.94	AISW bulk	F	18	71.87	0.60	14.26	2.97		0.64	2.13	3.94	3.42		0.14		
19/1E-18.94	AISW glass 1	F	1	63.24	1.43	15.41	7.08		1.87	4.60	4.05	2.22		0.08		
19/1E-18.94	AISW glass 2	F	9	70.27	0.74	14.59	3.54		0.77	2.42	4.26	3.23		0.15		
19/1E-18.94	AISW glass 3	F	7	75.13	0.30	13.68	1.64		0.31	1.40	3.53	3.84		0.14		
19-1W-2.68	DH bulk	F	20	75.40	0.24	13.69	1.55		0.31	1.53	3.62	3.48		0.15		
19-1W-2.68	DH glass 1	F	5	76.50	0.11	13.98	1.10		0.33	1.80	3.74	2.33		0.08		
19-1W-2.68	DH glass 2	F	15	75.04	0.29	13.59	1.70		0.31	1.43	3.58	3.86		0.17		
PLW8/11/01P2ASH T487-3	DH mode 1	SW	8	75.23	0.30	13.81	1.63	0.02	0.29	1.38	3.82	3.54				92.63
PLW8/11/01P2ASH T487-3	DH mode 2	SW	4	74.43	0.32	14.01	1.86	0.03	0.46	1.59	3.97	3.35				95.42
19-2W-4.28B	TI bulk	F	20	72.16	0.59	14.21	2.90		0.62	2.09	3.79	3.45		0.16		
19-2W-4.28B	TI glass 1	F	2	64.83	1.24	15.44	6.12		1.54	4.21	4.07	2.41		0.11		
19-2W-4.28B	T I glass 2	F	9	70.55	0.74	14.61	3.49		0.75	2.37	4.06	3.24		0.16		
19-2W-4.28B	TI glass 3	F	9	75.42	0.29	13.53	1.60		0.29	1.34	3.45	3.88		0.17		

Note: Location abbreviations are SA—Sunset Amphitheater on Mount Rainier; KI—Ketron Island; BC—Butterball Cove; AIS—Anderson Island South at Thompson Cove; AISW—Anderson Island Southwest; DH—Devil's Head; TI—Totten Inlet. Analysts are S—Thomas W. Sisson, U.S. Geological Survey; F—Franklin F. Foit, Jr., Washington State University; SW—Andrei M. Sarna-Wojcicki, U.S. Geological Survey. All analyses recalculated to 100%.

*(reported as FeO).

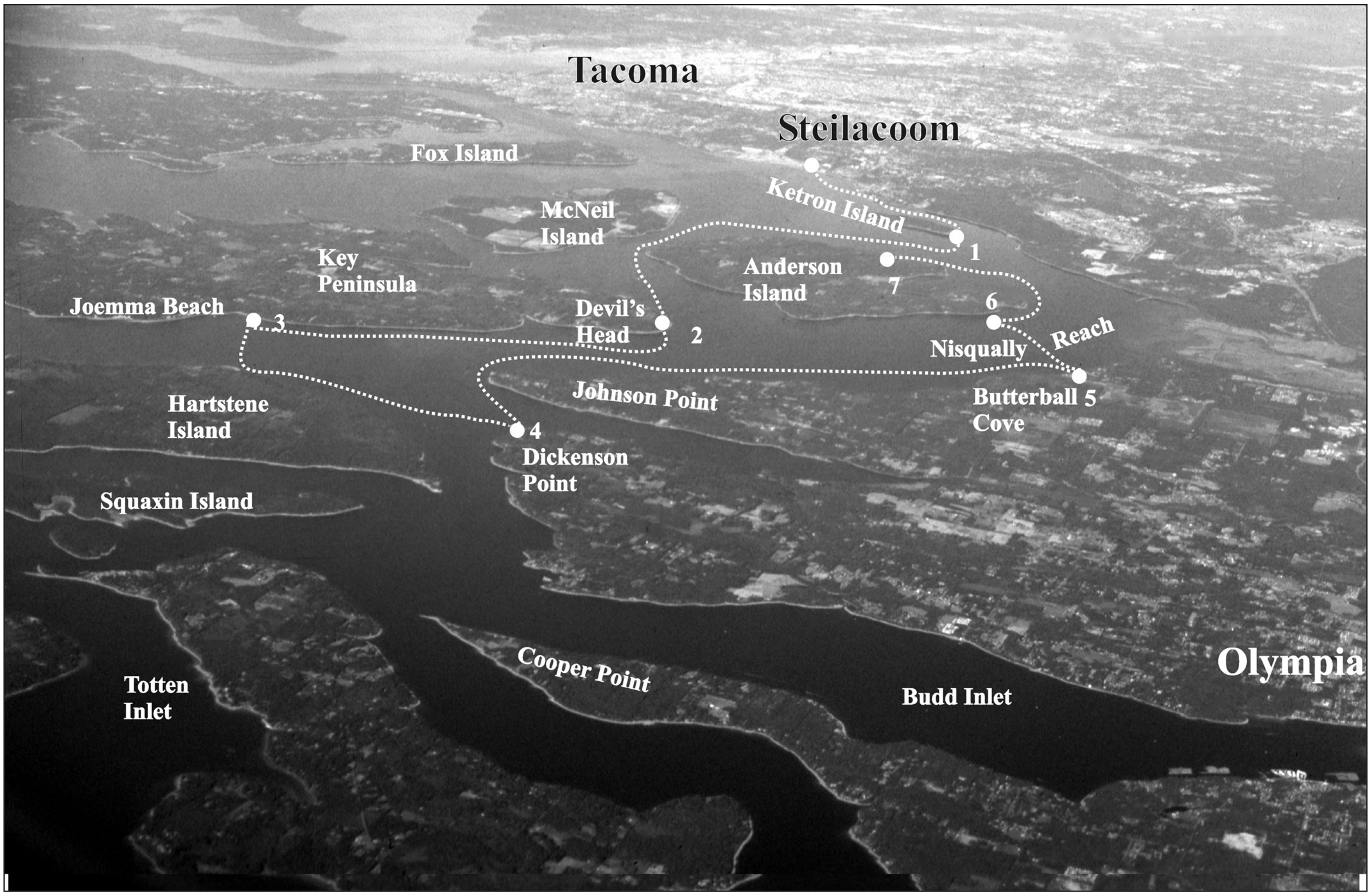

Figure 3. Field trip itinerary, looking east-northeast. At bottom are the peninsulas and inlets of the Olympia area. The Nisqually Delta is at the right middle. Scale variable.

Stop 1. Southern Tip of Ketron Island: Outcrop of Pumiceous Sands and Older Glacial Gravels of Probable OIS Stages 7 and 8

Vashon till and advance outwash cap the slope and can be accessed from above. Much of the section below is inaccessible here because of the unstable slope, but appears to be largely silt and fine sand. The lowest 75 ft of the section here is accessible from the beach. The unit at beach level is made up of sand, silt, and peat. The peat is radiocarbon infinite and the silt is normally magnetized (J.T. Hagstrum, 2000, personal commun.). Above this lower unit is gravel of mixed provenance, which we infer to be deposits of the Cordilleran Ice Sheet. Above the gravel (Figs. 4, 5) is a richly pumiceous sand with large amplitude cross-beds that imply transport toward the west and northwest. The pumice has been analyzed at three different labs and correlates strongly with the pumice at Sunset Amphitheater (Figs. 6, 7, 8; Table 2) on Mount Rainier, which is visible from here on a clear day. Lanphere and Sisson (unpublished data) have dated this pumice at Sunset Amphitheater (sample 93RW96, $^{40}Ar/^{39}Ar$ on plagioclase, plateau age 194 ± 12 ka [2-sigma], isochron age 184 ± 54 ka) to probable OIS 7 (Fig. 3). Above this is the inaccessible section. The presence of fluvial deposits from Mount Rainier shows that Ketron Island was not an island during OIS 7, and that, while the present-day configuration of islands, peninsulas, and channels may be a useful analogue for the nonglacial paleotopography, the present channel configuration was probably formed in Late Wisconsinan time and does not necessarily mimic any prior paleobathymetry and paleotopography.

From Ketron Island, travel north-northwest. Anderson Island is to the west. Exposures along the bluff are mostly blue-gray glaciolacustrine silt and fluvial fining upward sequences of sand, silt, and peat. At about the ferry terminal, the Vashon Drift becomes visible in the bluff. As on Ketron Island, the Vashon surface slopes to the north and Vashon Drift cuts out the older section. As we pass westward, north of Anderson Island, through Balch Passage, we travel between the small Eagle Island on the south and McNeil Island on the north. On Eagle Island, Vashon till makes up the wave-cut platform and forms the surface of the island. On McNeil Island, Vashon Drift forms the upper surface and older glacial and nonglacial sediments are exposed in the bluff below. Near the prison, to the west, Vashon till can be seen

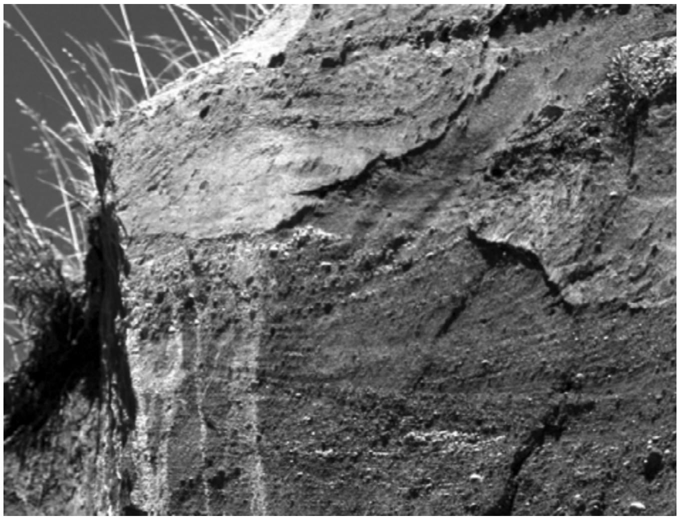

Figure 4. Cross-bedded sand bearing the tephra correlated with the tephra of Sunset Amphitheater from Mount Rainier. The crossbeds here imply a paleocurrent direction to the west-northwest, implying that Cormorant Passage to the east of here was filled at the time of deposition of this tephra.

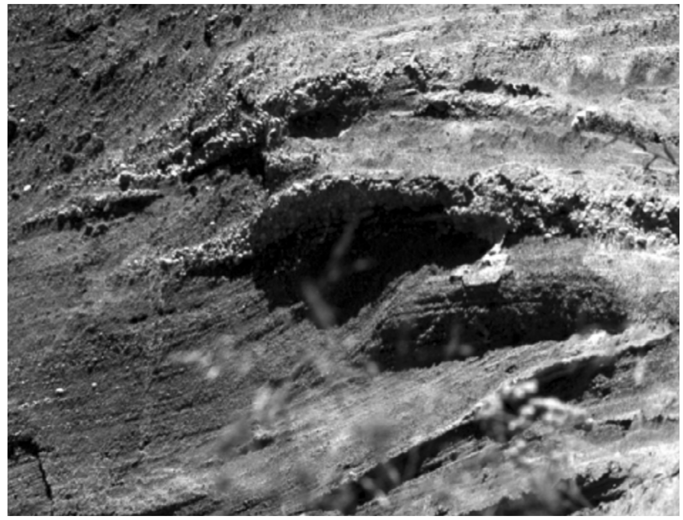

Figure 5. Close-up of outcrop adjacent to Figure 4, showing the high concentration of pumice clasts in this deposit as well as the high concentration of tephra making up the sand matrix.

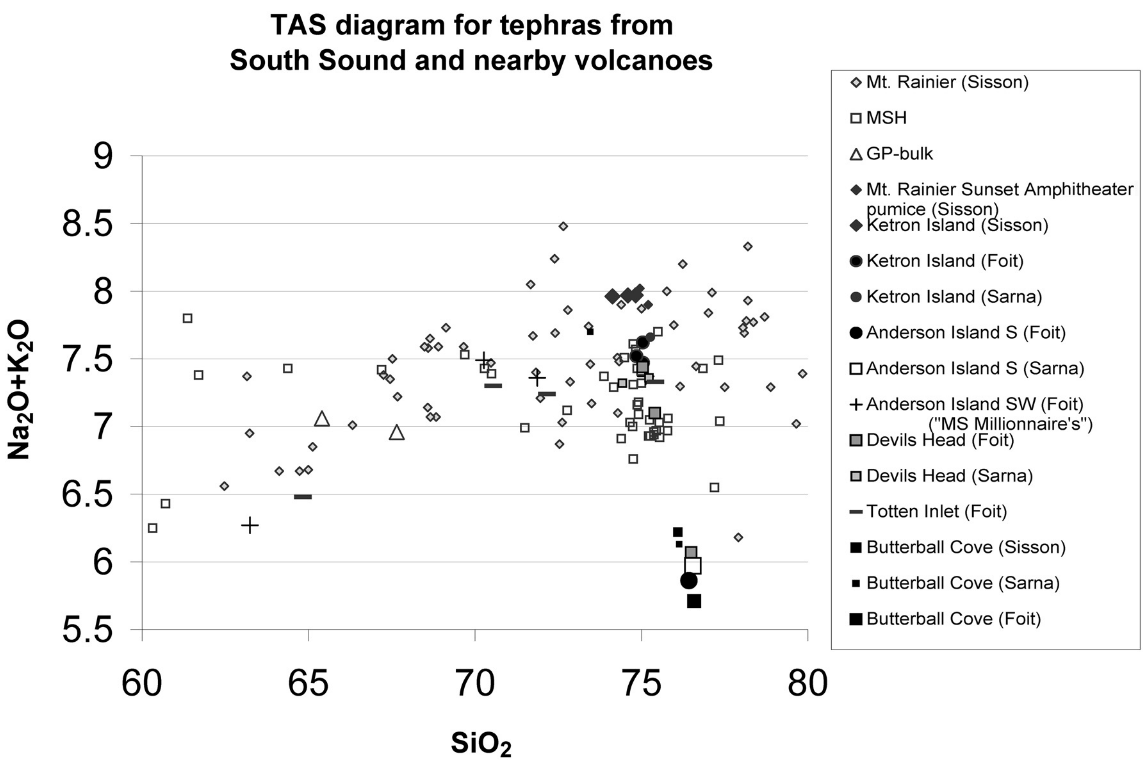

Figure 6. Plot of total alkalis vs. silica (TAS) for tephras from Mount Rainier, including Sunset Amphitheater, Mount St. Helens (MSH) and Glacier Peak (GP-bulk), the principal producers of late Pleistocene tephra in Washington. The other analyses plotted, with the analysts name in parentheses, are from this study.

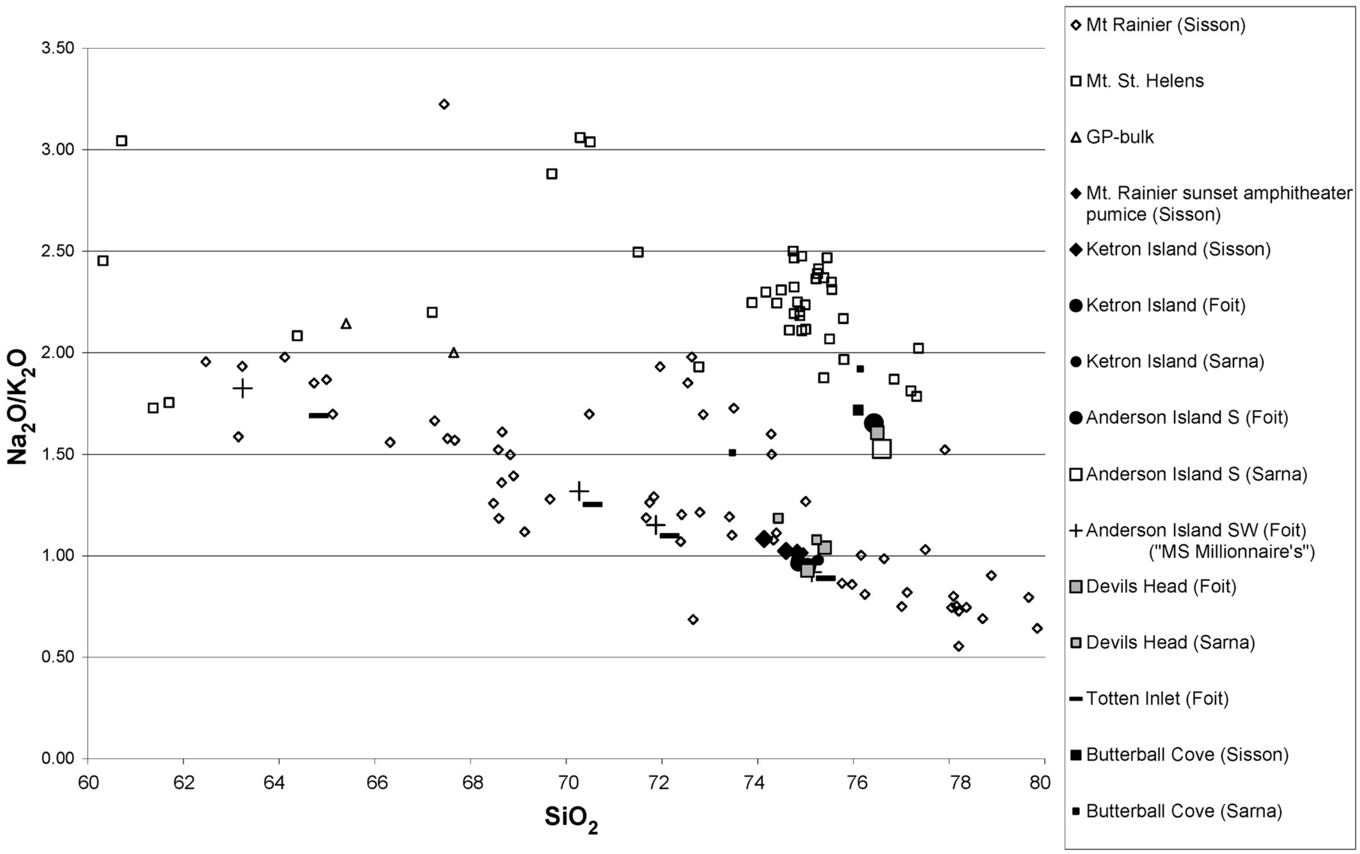

Figure 7. Plot of the ratio of sodium to potassium vs. silica for tephras from Mount Rainier, including Sunset Amphitheater, Mount St. Helens (MSH), and Glacier Peak (GP-bulk), the principal producers of late Pleistocene tephra in Washington. The other analyses plotted, with the analysts name in parentheses, are from this study.

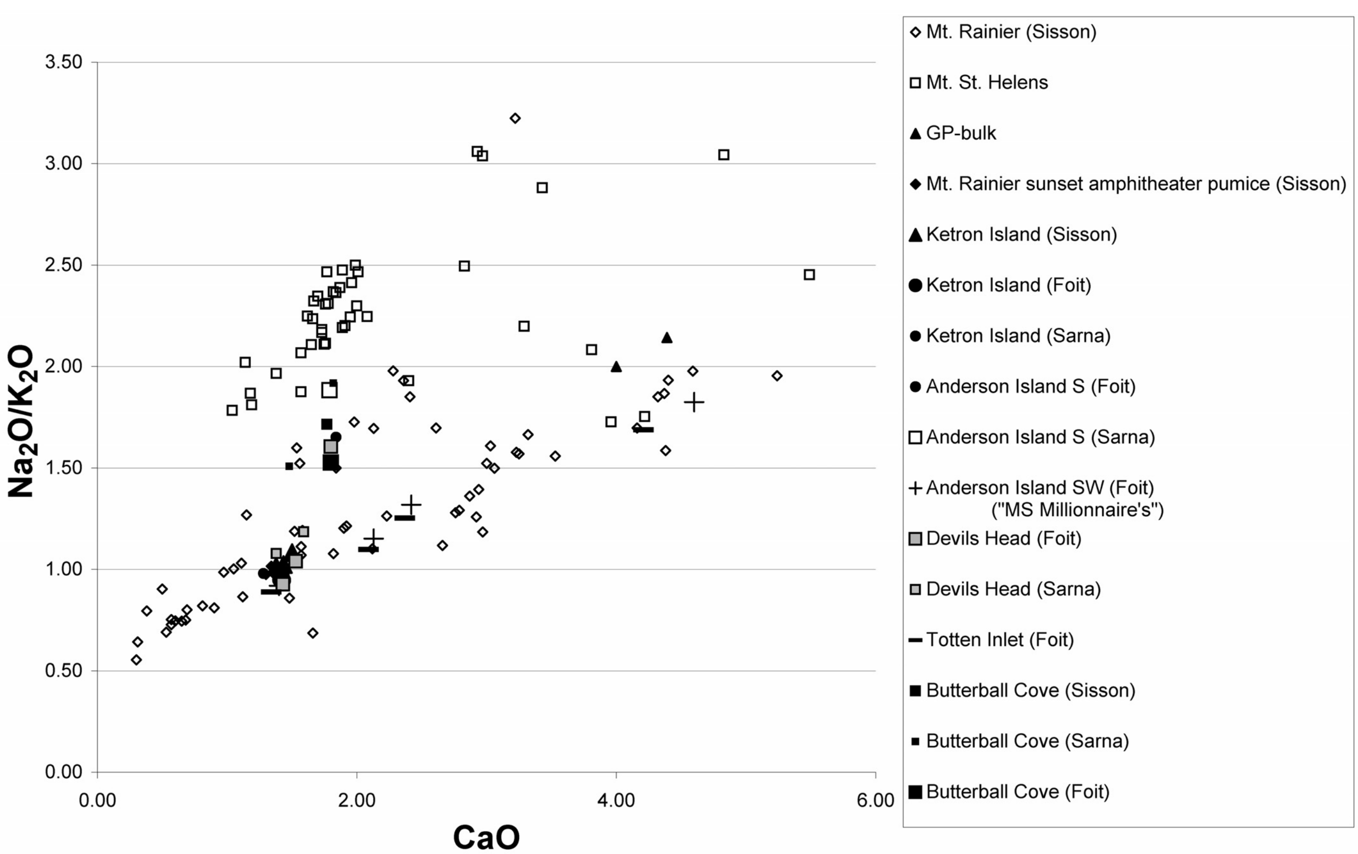

Figure 8. Plot of the ratio of sodium to potassium vs. calcium for tephras from Mount Rainier, including Sunset Amphitheater, Mount St. Helens (MSH), and Glacier Peak (GP-bulk), the principal producers of late Pleistocene tephra in Washington. The other analyses plotted, with the analyst's name in parentheses, are from this study.

Figure 9. Nonglacial beds at Devil's Head, showing the lowermost several fining-upward sequences overlying older glacial gravels. A radiocarbon date of 50,500 ka and a normally magnetized silt analysis are from the center-right of this photo.

Figure 10. Uppermost peaty soil in the sequence of Olympia beds at Devil's Head, from which an accelerator mass spectrometry radiocarbon age of 30,120 ± 250 ka was obtained.

cutting through the older section down to sea level at the prison dock. As we round the north end of Anderson Island and travel southwest, the Vashon Drift rises up the bluff again and exposes fluvial and lacustrine sediments with a prominent diatomite exposed at about midbluff. As we approach Devil's Head, the southernmost tip of the Key Peninsula, a large deep-seated landslide is visible in the southeast-facing bluff.

Continue around the point and land at Devil's Head.

Stop 2. Devil's Head: Low-Energy Fluvial Sequence Underlying Vashon Drift with Two Reworked Tephras

The base of the section is a pebble-to-cobble gravel of mixed provenance, inferred to be of Cordilleran glacier origin. Above the gravel, there are seven sequences of fine-to-medium sand fining upward to silt and peat or peaty soils (Fig. 9, 10). Near the bottom of this unit is a peat bed that was radiocarbon dated ca. 50,500 yr B.P. by Minze Stuiver, University of Washington (Walsh, 1987). Sand below this peat contains a concentrated layer of reworked tephra that contains two distinct modes (Figs. 6, 7, 8). One of the modes is the Sunset Amphitheater tephra of Mount Rainier. The other cannot be confidently matched to a well-characterized tephra, but bears a strong resemblance to Mount St. Helens set Cy of Mullineaux (1996) (F.F. Foit, 2000, personal commun.; A.M. Sarna-Wojcicki, 2003, personal commun.). Silt from approximately this horizon is normally magnetized (J.T. Hagstrum, 2000, personal commun.). The uppermost of the fining-upward sequences is capped by a peaty soil (Fig. 10), from which we obtained an accelerator mass spectrometry radiocarbon age of 30,120 ± 250 ka. This is one of the few sections that we can confidently assign to OIS 3 and consider to be Olympia beds (Table 1). Overlying this sequence and capping the bluff is the Vashon till overlying outwash sand and gravel, in turn overlying a diamicton that may be a flow till or that may imply a minor retreat and readvance of Vashon ice.

Travel north along west shore of Key Peninsula. The bluff all along here is capped by Vashon till. Underlying the till is advance outwash sand and gravel, which in turn overlies a thick sequence of Colvos Sand (Table 1). The Colvos is a distal advance outwash sand that correlates with the Esperance Sand. In the Seattle area, though, Esperance Sand overlies Lawton Clay, a distal glaciolacustrine silt deposited in the lake formed in Puget Sound when Vashon ice dammed the Strait of Juan de Fuca (Fig. 1). There is no equivalent of the Lawton Clay, however, below the Colvos. Rather, as along the coast of the Key peninsula, Colvos Sand either overlies a fluvial sequence similar to that exposed at Devil's Head or an older glaciolacustrine silt. We will see examples of these at Stops 3 and 7, respectively.

Continue north to Joemma Beach State Park.

Stop 3. Joemma Beach State Park: Colvos Sand Overlying Olympia Beds or Older Equivalent

Vashon Drift caps the bluff here. Advance outwash grades downward from sand and gravel to Colvos Sand, a fine-medium sand with low-amplitude sedimentary structures. These beds overlie fluvial sands, silts, and peat resembling those at Devil's Head, but which are radiocarbon infinite (Fig. 11).

Travel west toward Hartstene Island. Sand, silt, and peat exposed along the base of the bluff are similar to those at Joemma Beach, and are also radiocarbon infinite. Silt in an exposure due west of Joemma Beach is reversely magnetized (J.T. Hagstrum, 2000, personal commun.). Reverse magnetization is generally thought to imply deposition during the Matuyama Reversed Chron, and for nonglacial sediments, this would suggest correlation with the Puyallup or Alderton Formations (Table 1). However, because the evidence from included tephras suggests deposition during OIS 5 and 7, we suspect that this magnetization represents a shorter reversed interval, such as the Blake Reversed Subchron, which occurs within OIS 5. These sediments are more or less continuously exposed along the southeast shore of Hartstene Island.

Continue southeast to Dickenson Point.

Stop 4. Dickenson Point: Optional Stop

Glacial deposits older than the Vashon in this area generally lack till. Sand and gravel deposits containing clasts exotic to the area, such as high-grade metamorphic rocks or granitics, particularly those bearing pink feldspar, suggest northern provenance. Thick (>50 ft) lacustrine deposits, commonly bearing dropstones, also suggest deposition during continental glaciations. Deposits of OIS 4, called Possession Drift, in the northern Puget Lowland (Table 1) are generally less extensive than the OIS 6 deposits (Double Bluff Drift in the northern Puget Lowland) and Possession ice may never have occupied this area and may be represented here only by outwash deposits. At this locality, though, there is an older till exposed within a landslide deposit. This outcrop also indicates another difficulty in previous mapping, that landslides dropping Vashon till below its general elevation may be misinterpreted as older till.

Figure 11. Colvos Sand exposure at Joemma Beach, grading upward to Vashon advance outwash sand and gravel. The sand overlies a sand and silt unit that may be the equivalent of the Olympia beds but are radiocarbon infinite.

Stop 5. Butterball Cove: Outcrop of Tephra Similar to Mount St. Helens Cy

At the top of this exposure are silts deposited in Glacial Lake Russell, which existed in Puget Sound during glacial retreat until an outlet to the Strait of Juan de Fuca was uncovered. These sediments are commonly found in south Puget Sound at elevations below ~140 ft, and are usually, as here, deposited directly on Vashon till. Underlying the till is 10 ft of Vashon advance outwash sand and gravel. The Vashon is underlain by ~50 ft of fluvial sediments. Peat in about the middle of these sediments, and wood from near the top are both radiocarbon infinite (Logan et al., 2003). The lower 5–10 ft of these fluvial sediments contain highly concentrated tephra that can be traced at low tide for ~200 ft along shore. The full extent of the tephra is unknown because the outcrop is covered by a landslide and retaining wall to the southeast and by bulkheads to the northwest. Chemical analysis (Figs. 6, 7, 8) does not precisely match this tephra with any known tephras, but it is almost certainly not from Mount Rainier, and it closely resembles Mount St. Helens set Cy (Mullineaux, 1996). According to A.M. Sarna-Wojcicki (2003, personal commun.), this tephra closely resembles other older Mount St. Helens tephras that he calls "proto-C tephra," such as at Carp Lake (Whitlock et al., 2000), which are probably 100–200 ka.

Travel north-northeast across Nisqually Reach to Thompson Cove (Figs. 12, 13).

Stop 6. Thompson Cove, Anderson Island: Optional Stop, Outcrop of Butterball Cove Tephra

The tephra here is equally concentrated as it is at Butterball Cove, but the sand here is interbedded with gravel. This outcrop was exposed by a slump caused by the M6.8 Nisqually earthquake. This sand and gravel can be traced more-or-less continuously to an outcrop labeled "MS millionaire's" on Figures 6, 7, and 8, although we have not found the tephra west of this outcrop. Tephra sampled there is ~25 ft higher in the section and correlates with tephra found to the southwest of here in Totten Inlet (lower left corner, Fig. 3). These tephras appear to be from Mount Rainier, but have not been correlated to any specific tephra there. Peat below the upper tephra there is radiocarbon infinite.

Travel east and then north around Lyle Point. Vashon till caps the bluff and cuts down to the west through the older sequence.

Figure 12. Tephritic sand overlying glacial gravel at Butterball Cove. At low tide, the tephra layer can be traced ~200' along shore, where it is cut off to the southeast by a landslide (and now a retaining wall), and to the northwest by bulkheads.

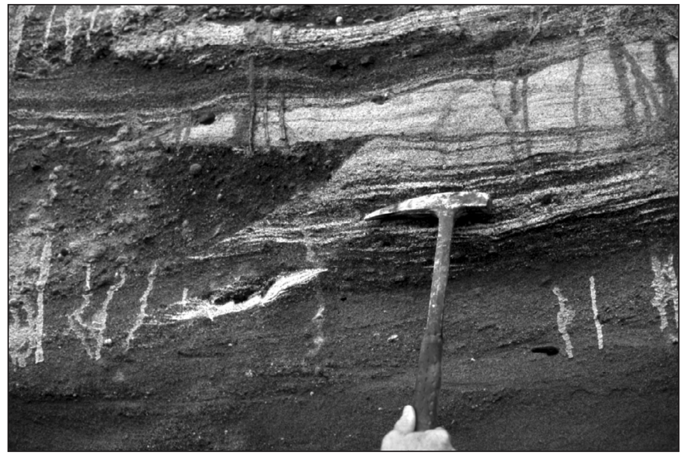

Figure 13. Close-up of Figure 12, showing abrupt truncation of lower part of tephra beds by gravelly sands. This bedding style is common here, showing abundant channel switching and high sediment loads. Paleocurrent indicators here are chaotic but generally have a northward component. This tephra is found at Thompson Cove on Anderson Island to the north-northwest of here in equally high concentration.

A thin silt near the top of the pre-Vashon section can be seen to thicken to the north and is exposed sporadically along the bluff to De Oro Bay, where Vashon till cuts down through the section to below sea level. At the north end of the bay, the till cuts upsection, again exposing thick silt along the bluff at Cole Point. Continue north to Country Club Beach.

Stop 7. Country Club Beach, Anderson Island: Thick Sequence of Pre-Vashon Glaciolacustrine Silt Overlying Older Till

This is the only in-place exposure of pre-Vashon till we have found in this area. It is overlain by gravel of mixed provenance, which is in turn overlain by a thick (>120 ft) sequence of blue-gray silt with dropstones. In the lower 20 ft of this silt there are abundant ptygmatic folds that are probably due to slumping caused by high sedimentation rates in a glacial lake. There is a thin sand capped by a paleosol about halfway up this section, overlain by another 60 ft of glaciolacustrine silt, suggesting that these may be two different glaciations. The upper unit is capped by small-scale channel deposits, sloping to the east and lined by layers of charcoal, which are radiocarbon infinite. We speculate that these may represent recessional glaciolacustrine deposits of Double Bluff (OIS 6) Drift overlain by advance glaciolacustrine deposits of Possession (OIS 4) Drift.

Return to Steilacoom. End of trip.

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