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Geologic Map of the Saint Helens Quadrangle, Columbia County, Oregon, and Clark and Cowlitz Counties, Washington

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INTRODUCTION

GEOGRAPHIC AND GEOLOGIC SETTING

The Saint Helens 7.5' quadrangle is situated in the Puget-Willamette Lowland approximately 35 km north of Portland, Oregon (fig. 1). The lowland, which extends from Puget Sound into west-central Oregon, is a complex structural and topographic trough that lies between the Coast Range and the Cascade Range. Since late Eocene time, the Cascade Range has been the locus of a discontinuously active volcanic arc associated with underthrusting of oceanic lithosphere beneath the North American continent along the Cascadia Subduction Zone. The Coast Range occupies the forearc position within the Cascadia arc-trench system and consists of a complex assemblage of Eocene to Miocene volcanic and marine sedimentary rocks.

The Saint Helens quadrangle lies in the northern part of the Portland Basin, a roughly 2000-km^2 topographic and structural depression. It is the northernmost of several sediment-filled structural basins that collectively constitute the Willamette Valley segment of the Puget-Willamette Lowland (Beeson and others, 1989; Swanson and others, 1993; Yeats and others, 1996). The rhomboidal basin is approximately 70 km long and 30 km wide, with its long dimension oriented northwest. The Columbia River flows west and north through the Portland Basin at an elevation near sea level and exits through a confined bedrock valley less than 2.5 km wide about 16 km north of Saint Helens. The flanks of the basin consist of Eocene through Miocene volcanic and sedimentary rocks that rise to elevations exceeding 2000 ft (610 m). Seismic-reflection profiles (L.M. Liberty, written commun., 2003) and lithologic logs of water wells (Swanson and others, 1993; Mabey and Madin, 1995) indicate that as much as 550 m of late Miocene and younger sediments have accumulated in the deepest part of the basin near Vancouver. Most of this basin-fill material was carried in from the east by the Columbia River but contributions from streams draining the adjacent highlands are locally important.

The Portland Basin has been interpreted as a pull-apart basin located in the releasing stepover between two en echelon, northwest-striking, right-lateral fault zones (Beeson and others, 1985, 1989; Beeson and Tolan, 1990; Yelin and Patton, 1991; Blakely and others, 1995). These fault zones are thought to reflect regional transpression and dextral shear within the forearc in response to oblique subduction along the Cascadia Subduction Zone (Pezzopane and Weldon, 1993; Wells and others, 1998). The southwestern margin of the Portland Basin is a well-defined topographic break along the base of the Tualatin Mountains, an asymmetric anticlinal ridge that is bounded on its northeast flank by the Portland Hills Fault Zone (Balsillie and Benson, 1971; Beeson and others, 1989; Blakely and others, 1995), which is probably an active structure (Wong and others, 2001; Liberty and others, 2003). The nature of the corresponding northeastern margin of the basin is less clear, but a poorly defined and partially buried dextral extensional fault zone has been hypothesized from topography, microseismicity, potential field-anomalies, and reconnaissance geologic mapping (Beeson and others, 1989; Beeson and Tolan, 1990; Yelin and Patton, 1991; Blakely and others, 1995). Another dextral structure, the Kalama Structural Zone of Evarts (2002), may underlie the north-northwest-trending reach of the Columbia River north of Woodland (Blakely and others, 1995).

This map is a contribution to a U.S. Geological Survey (USGS) program designed to improve the geologic database for the Portland Basin region of the Pacific Northwest urban corridor, the populated forearc region of western Washington and Oregon. Better and more detailed information on the bedrock and surficial geology of the basin and its surrounding area is needed to refine assessments of seismic risk (Yelin and Patton, 1991; Bott and Wong, 1993), ground-failure hazards (Madin and Wang, 1999; Wegmann and Walsh, 2001) and resource availability in this rapidly growing region. The digital database for this publication is available on the World Wide Web at http://pubs.usgs.gov/sim/2004/2834.

PREVIOUS GEOLOGIC INVESTIGATIONS

Previous geologic mapping in the Saint Helens area, generally carried out as part of broad regional reconnaissance investigations, established the basic stratigraphic framework and distribution of geologic units in the quadrangle. The geology of the Saint Helens 7.5' quadrangle was first mapped and described by Wilkinson and others (1946) in their report on the Saint Helens 15' quadrangle. Their representation of the geology at a scale of 1:62,500 portrays the general distribution of the major geologic units of the area: Miocene basalt flows of the Columbia River Basalt Group, Miocene and Pliocene basin-fill sediments of the Troutdale Formation, and post-

Troutdale unconsolidated deposits. Geologic structures were discussed in an accompanying text but not shown on the map.

Phillips (1987a) compiled a geologic map of the Vancouver 30'x60' sheet, which includes the Saint Helens 7.5' quadrangle, at 1:100,000 scale as part of the state geologic map program of the Washington Division of Geology and Earth Resources (Walsh and others, 1987). His portrayal of the geology in the area of the Saint Helens quadrangle is essentially unmodified from that of Wilkinson and others (1946) but he did recognize the outcrop of Grande Ronde Basalt in the Middle Lands area.

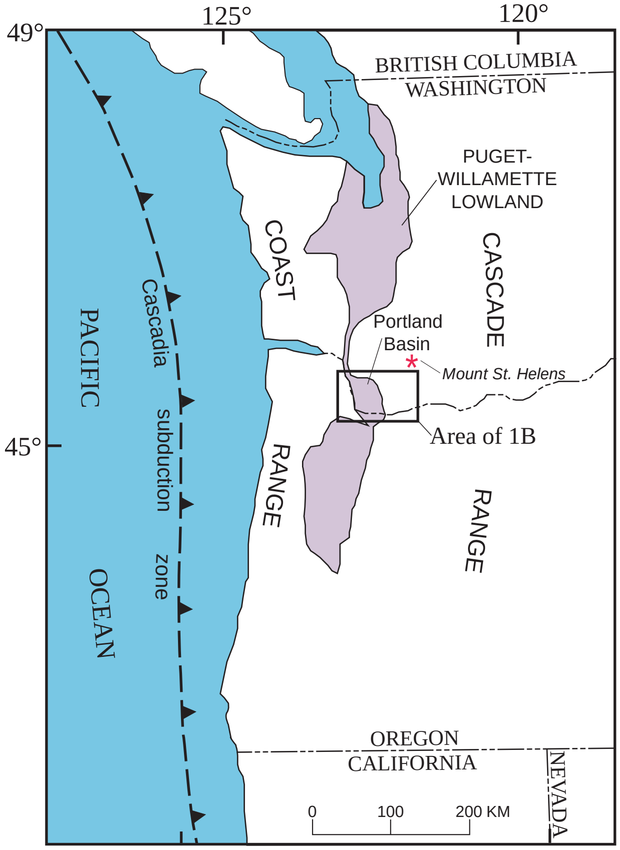

Figure 1A. Regional setting of the Saint Helens quadrangle showing major tectonic and physiographic features of the Pacific Northwest.

Mundorff (1964) undertook a systematic hydrogeologic investigation of Clark County, Washington, and published a 1:48,000-scale map. Swanson and others (1993) updated Mundorff's (1964) Clark County work as part of an investigation of ground-water resources throughout the Portland Basin. Their work focused on the basin-fill units, and their map shows hydrogeologic rather than lithostratigraphic units, although there is substantial equivalence between the two. They analyzed lithologic logs of 1500 field-located water wells to produce a set of maps that show the elevations and thicknesses of hydrogeologic units throughout the basin, thus constructing 3-dimensional view of the subsurface stratigraphy of the basin fill.

Several topical investigations of regional extent also provide information on the geology of the Saint Helens quadrangle and adjacent areas. These include the reports of Yancey and Geer (1940) on coal, Libbey and others (1945) on ferruginous bauxite, Lowry and Baldwin (1952) on late Cenozoic deposits, and Mundorff (1964) and Swanson and others (1993) on water resources.

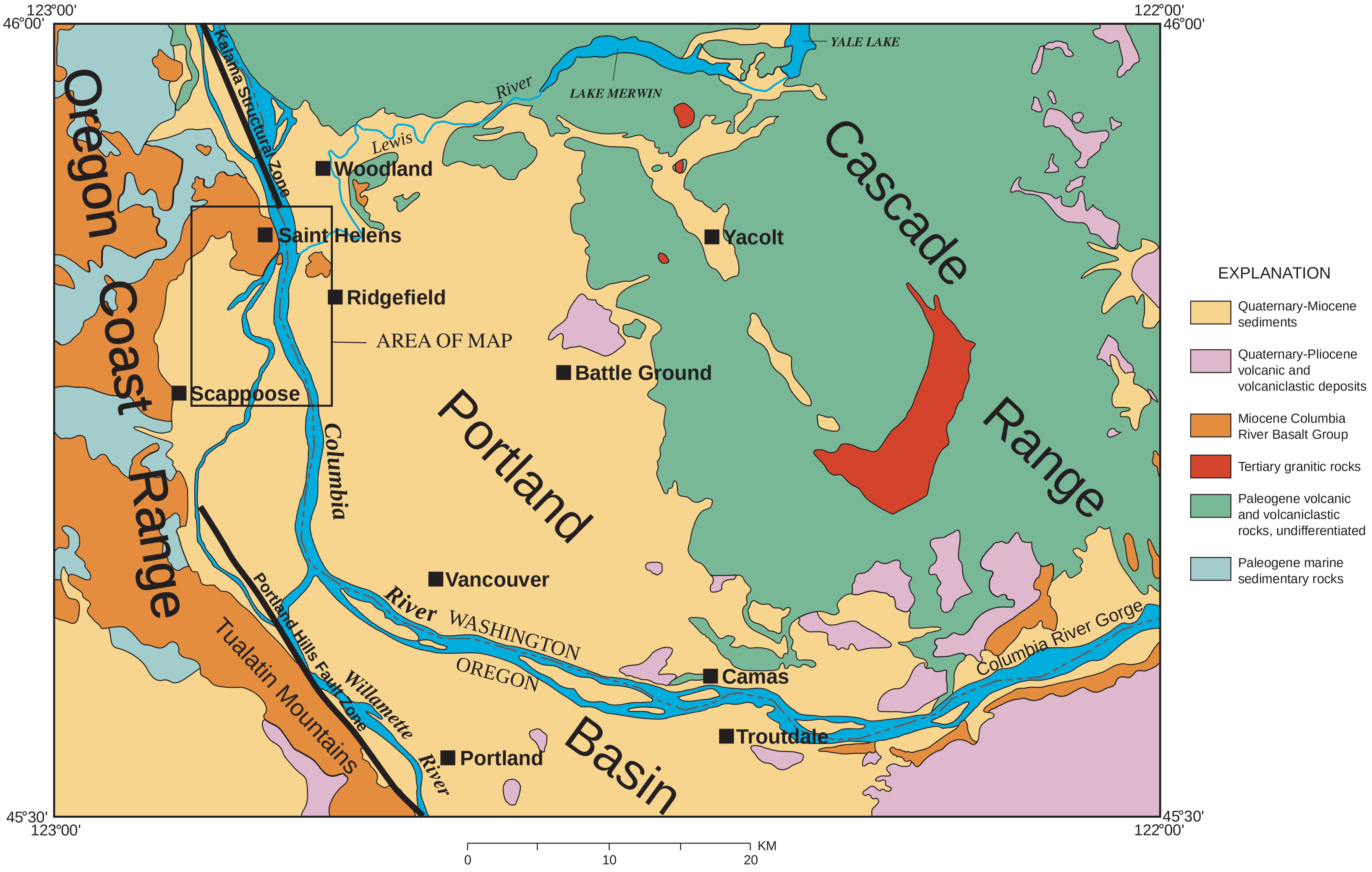

Figure 1B. Simplified geologic map of the Vancouver 30' x 60' quadrangle, modified from Phillips (1987a).

ACKNOWLEDGMENTS

Access granted by landowners was essential for mapping in the Saint Helens quadrangle. Managers Randy Baker of the Columbia Road and Driveway quarry west of Saint Helens, Brian Gray of the Morse Brothers quarry in Columbia City, Mark Tougas of the Glacier Northwest gravel pit in Scappoose, and Rhidian Morgan of the Plas Newydd Farm at Middle Lands provided unrestricted access to their properties for chemical and paleomagnetic sampling. Jonathan Hagstrum (USGS) provided paleomagnetic data and Diane Johnson (Washington State University) performed chemical analyses necessary for interpreting local stratigraphy in the Columbia River Basalt Group. Aeromagnetic maps compiled by Richard Blakely (USGS) were used to interpret buried structures. Andrei Sarna-Wojcicki, Kenneth Bishop, Judith Fierstein, and Michael Clynne provided laboratory facilities. Drillers' reports for water wells in Oregon were obtained from the Oregon Department of Water Resources website (http://stamp.wrd.state.or.us/apps/gw/well_log/php). Connie Manson, librarian at the Washington Division of Geology and Earth Resources in Olympia, Wash., aided in obtaining information from that agency's files. I have benefited from discussions with Marvin Beeson, Terry Tolan, Keith Howard, Lee Liberty, Alan Niem, Jim O'Connor, Stephen Reidel, and Ray Wells on various aspects of the regional stratigraphy and structure of the Portland Basin. Field visits by land and sea by O'Connor (USGS) were invaluable in clarifying relations among the late Cenozoic sedimentary deposits; he also provided maps showing the distribution of post-1880 alluvium and fill. Detailed and constructive reviews by O'Connor and Ian Madin (Oregon Department of Geology and Mineral Industries) resulted in substantial improvements in the map and interpretations.

SYNOPSIS OF GEOLOGY

All geologic units exposed at the surface in the Saint Helens quadrangle are Neogene or younger. In the subsurface these units rest unconformably on Paleogene volcanic and sedimentary rocks that crop out in adjacent quadrangles to the north and west (Wilkinson and others, 1946; Evarts, 2002). A broad aeromagnetic high in the northern part of the quadrangle (Snyder and others, 1993) is interpreted by Blakely and others (2000) to reflect the presence of Eocene basalt at depth. The oldest rocks exposed at the surface of the quadrangle are middle Miocene lava flows of the Grande Ronde Basalt, part of the Columbia River Basalt Group. The basalt is unconformably overlain by weakly lithified to unconsolidated fluvial sediment that accumulated in the Portland Basin as it subsided during Neogene and Quaternary time.

Evidence from surrounding areas indicates that the Paleogene bedrock units formed a terrain of low relief prior to inundation by the voluminous mafic lava flows of the Columbia River Basalt Group. These lavas erupted from fissures in eastern Washington and Oregon, traversed the Cascade Range by way of a broad structural lowland, and spread out to cover large areas of the Coast Range province (Beeson and others, 1989). After the basaltic eruptions ceased, fluvial deposits of Columbia River provenance (Troutdale Formation and Sandy River Mudstone) were deposited on the surface of the flows within and adjacent to the subsiding Portland Basin. Owing partly to late Cenozoic regional uplift, the Columbia River has locally cut through the Miocene sediments into the subjacent basalt. In addition to alluvial sediment, the fill of the Portland Basin includes deposits of colossal late Pleistocene jökulhlaups that originated from Glacial Lake Missoula in Idaho and western Montana. Inset into the Pleistocene and older deposits are up to 70 m of latest Pleistocene and Holocene alluvium deposited by the Columbia River and its tributaries as sea level rose from its last-glacial lowstand.

The relatively mild and wet climate prevailing in the western Pacific Northwest throughout most of the Cenozoic era (Wolfe and Hopkins, 1967; Wolfe, 1978) promoted intense chemical weathering of geologic deposits of the region and development of saprolitic soil horizons, locally as thick as 10 m, on the older Neogene deposits. Flows of the Columbia River Basalt Group have locally been converted to laterites in which all primary rock textures have been destroyed, and thoroughly weathered fine-grained sedimentary rocks are commonly difficult to distinguish from laterized basalt. Because of this intense weathering and the dense vegetation of the region, natural outcrops are generally limited to steep cliff faces, landslide scarps, and streambeds; most exposures are in roadcuts and quarries. Surface information was supplemented with lithologic data obtained from several hundred water-well logs provided by the Oregon Department of Water Resources and the Washington Department of Ecology; well locations were taken as described in the drillers' reports and not field checked.

COLUMBIA RIVER BASALT GROUP

In Miocene time, between 16.5 and 6 Ma, huge volumes of tholeiitic flood basalts erupted from fissures in southeastern Washington and adjacent regions of Oregon and Idaho, forming the Columbia River Basalt Group. Some of the largest flows crossed the Cascade Range through a broad lowland and ultimately reached the Pacific Ocean (Snavely and others, 1973; Tolan and others, 1989; Wells and others, 1989). West of the Cascade Range, thick sequences of lava flows buried large parts of low-relief terrain in the areas of the present Coast Range and Willamette Valley (Beeson and others, 1989). Dissected remnants of these flows underlie upland areas west of the Columbia River in the Saint Helens and adjacent quadrangles (Wilkinson and others, 1946). The majority of the flood-basalt flows erupted during a brief period between 16.5 and 15.6 Ma and constitute the voluminous Grande Ronde Basalt (Tolan and others, 1989; Reidel and others, 1989). All Miocene basalt exposed in the Saint Helens quadrangle belongs to this formation. Grande Ronde Basalt flows are medium-potassium tholeiitic basaltic andesites (fig. 2) that can be distinguished from other Columbia River Basalt Group units by their relatively low TiO_2 contents (Swanson and others, 1979; Mangan and others, 1986; Beeson and others, 1989; Reidel and others, 1989; Hooper, 2000).

The Grande Ronde Basalt crops out only in the northern part of the Saint Helens quadrangle, where it may be as much as 200 m thick. In the highlands of the northwestern part of the map area, the upper 30 m or more of basalt is deeply weathered to reddish-brown laterite, and natural outcrops of fresh rock are found only in the beds of Milton Creek and its tributaries. Latest Pleistocene glacier-outburst floods stripped unconsolidated deposits and soil from the Grande Ronde below elevations of 200 ft (65 m) and scoured a complex, scabland-style topography (Bretz, 1923) into the basalt at Saint Helens and in the Middle Lands area. Pronounced topographic breaks at Saint Helens mark contacts between three thick, gently south-dipping, flow units.

Using lithologic, chemical and paleomagnetic criteria, Reidel and others (1989) divided the Grande Ronde Basalt on the Columbia Plateau into several informal named members. Beeson and others (1989) and Wells and others (1989) traced some of these members into the Portland Basin and westward into the Coast Range. Chemical and laboratory paleomagnetic data from outcrops of basalt flows in the Saint Helens quadrangle allows their assignment to three of the informal members of the Grande Ronde Basalt defined by Reidel and others (1989).[1]

The youngest and most widespread informal member in the map area is the member of Sentinel Bluffs, which is also the youngest member of the Grande Ronde Basalt on the Columbia Plateau. It is distinguished by relatively high MgO contents (3.9 to 4.9 wt percent; tables 1, 2) and normal magnetic polarity. The member is well exposed by quarry operations in and near Saint Helens, where it typically displays a blocky to columnar jointing pattern. It also crops out near Warrior Point on Sauvie Island, and constitutes nearly all outcrops in the Middle Lands area between the Lewis and Lake Rivers in Washington. Two chemically distinguishable flows (table 1; fig. 2D) of the member of Sentinel Bluffs are present in the map area. The flow displaying lower MgO and higher TiO_2 contents is younger and crops out only in the Middle Lands area. Its MgO concentration is relatively low for the member of Sentinel Bluffs, overlapping those of low-MgO Grande Ronde flows (Reidel and others, 1989; Beeson and Tolan, 1990), but its relatively high CaO and Cr contents (fig. 2E) indicate an affinity with high-MgO chemical types (M.H. Beeson and T.L. Tolan, oral commun., 2001).

Two basalt flows with distinctly lower MgO contents (tables 1, 2) and normal magnetic polarity underlie the member of Sentinel Bluffs at Saint Helens. The upper flow ranges between 20 and 40m thick and exhibits a colonnade/entablature jointing pattern. It contains sparse phenocrysts and glomerocrysts of plagioclase, has MgO contents of 3.6 to 3.9 wt percent, and records a distinctive shallow northwest paleomagnetic direction that contrasts with the steep northeast directions that typify most Grande Ronde Basalt flows (table 2). Based on these characteristics, this flow is tentatively assigned to the member of Winter Water (Winter Water unit of Reidel and others, 1989), although its TiO_2 content of 2.03 to 2.10 wt percent is lower than reported for that unit elsewhere (Reidel and others, 1989; Beeson and others, 1989).

The lowermost Grande Ronde Basalt flow exposed in the map area is aphyric. About 25 m of this flow unit crop out in Saint Helens but it is at least 60 m thick directly north in the Deer Island quadrangle (Evarts, 2002). It is

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[1] Comparison of chemical analyses obtained for this report with older data in the literature (Reidel and others, 1989; Beeson and others, 1989), all of which were performed in the same laboratory at Washington State University, suggested that systematic biases were present. Re-analysis of a suite of 38 Columbia River Basalt Group samples, originally analyzed in 1983, confirmed this suspicion. The reasons for the discrepancies are unclear but probably relate to a change in instrumentation in the laboratory in 1986 (D.M. Johnson, written commun., 2001). Among the elements most useful in discriminating between Grande Ronde Basalt flows, the newer data exhibit consistently higher contents of TiO_2 (3.5%) and P_2O_5 (8.0%) and lower MgO (2.5%)(percentages are average relative differences between the datasets). These differences were taken into account in evaluating the data for correlation purposes.

a low-MgO flow chemically similar to the overlying member of Winter Water but contains slightly less MgO (3.5 to 3.6 wt percent) and CaO and more K_2O than the Winter Water flow (table 2). It exhibits a steep northeast paleomagnetic direction. These features indicate it belongs to the member of Ortley (Reidel and others, 1989; Wells and others, 1989; Reidel, 1998).

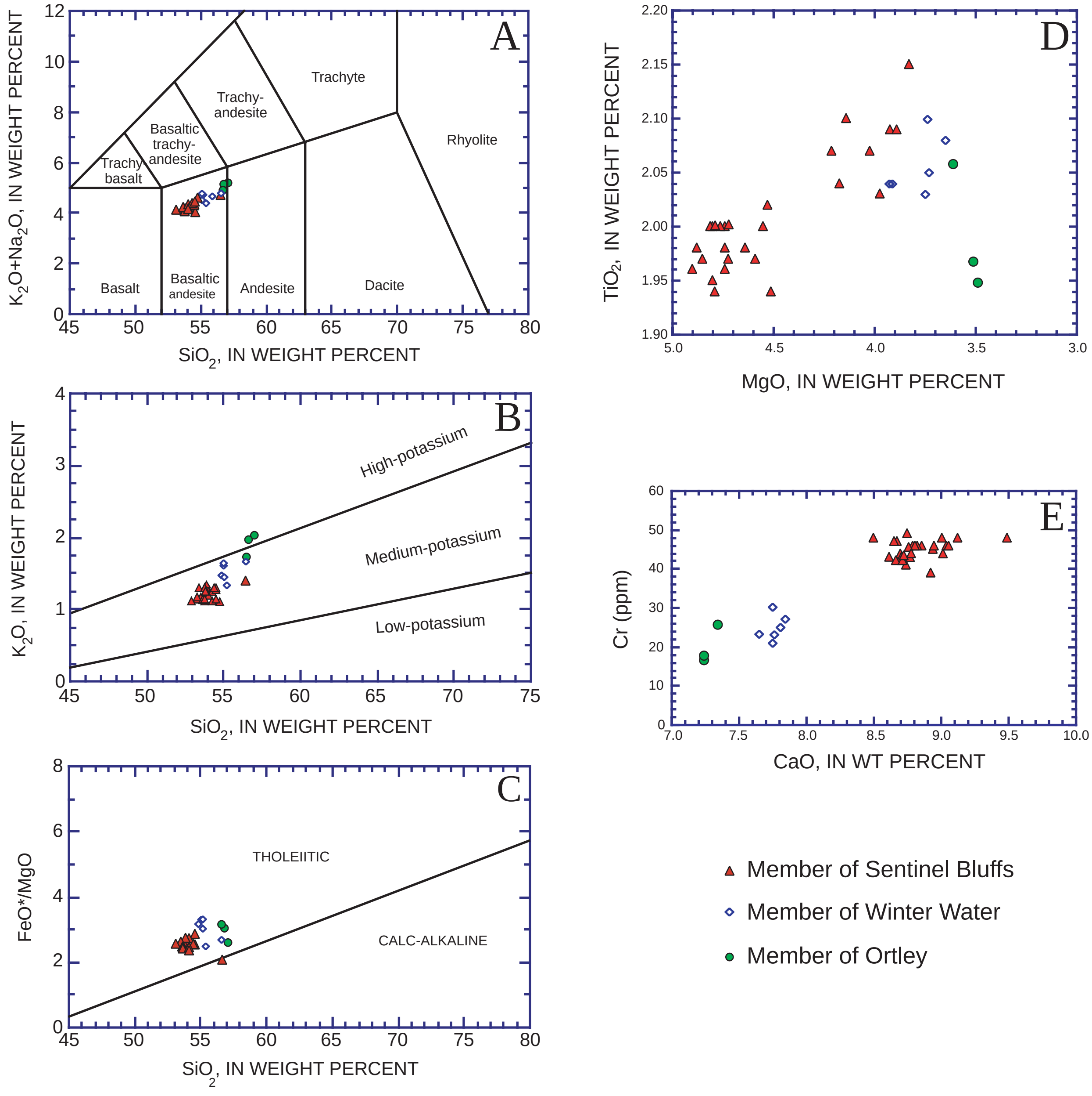

Figure 2. Chemical characteristics of Grande Ronde Basalt in the Saint Helens 7.5' quadrangle (analyses recalculated volatile-free). *A*, K_2O+ Na_2O versus SiO_2, showing IUGS classification (Le Maitre, 2002); *B*, K_2O versus SiO_2, showing low-, medium-, and high-potassium fields extrapolated from Gill (1981, p. 6); *C*, FeO*/MgO versus SiO_2, showing classification into tholeiitic and calc-alkaline rocks according to Miyashiro (1974). FeO*, total Fe as FeO; *D*, TiO_2 versus MgO; *E*, Cr versus CaO.

Geologic age		Group		Formation	Series	Age (Ma)	Magnetic Polarity
Miocene	**Late**	**Columbia River Basalt Group**	**Yakima Basalt Subgroup of Swanson and others (1979)**	**Saddle Mountains Basalt**	**Lower Monumental Member**	6	N
					Erosional Unconformity		
					Ice Harbor Member	8.5	
					Basalt of Goose Island		N
					Basalt of Martindale		R
					Basalt of Basin City		N
					Erosional Unconformity		
					Buford Member		
	Middle				**Elephant Mountain Member**	10.5	N, T
					Erosional Unconformity		
					Pomona Member	12	R
					Erosional Unconformity		
					Esquatzel Member		N
					Erosional Unconformity		
					Weissenfels Ridge Member		
					Basalt of Slippery Creek		N
					Basalt of Tenmile Creek		N
					Basalt of Lewiston Orchards		N
					Basalt of Cloverland		N
					Asotin Member	13	
					Basalt of Huntzinger		N
					Local Erosional Unconformity		
					Wilbur Creek Member		
					Basalt of Lapwai		N
					Basalt of Wahluke		N
					Local Erosional Unconformity		
					Umatilla Member		
					Basalt of Sillusi		N
					Basalt of Umatilla		N
					Local Erosional Unconformity		
				Wanapum Basalt	**Priest Rapids Member**	14.5	
					Basalt of Lolo		R
					Basalt of Rosalia		R
					Local Erosional Unconformity		
					Roza Member		T, R
					Frenchman Springs Member		
					Basalt of Lyons Ferry		N
					Basalt of Sentinel Gap		N
					Basalt of Sand Hollow	15.3	N
					Basalt of Silver Falls		N, E
					Basalt of Ginkgo	15.6	E
					Basalt of Palouse Falls		E
					Eckler Mountain Member		
					Basalt of Shumaker Creek		N
					Basalt of Dodge		N
					Basalt of Robinette Mountain		N
					Local Erosional Unconformity		
				Grande Ronde Basalt	***Member of Sentinel Bluffs***	15.6	N_2
					Member of Slack Canyon		
					Member of Fields Spring		
					Member of Winter Water		
	Early				**Member of Umtanum**		
					Member of Ortley		
					Member of Armstrong Canyon		
					Member of Meyer Ridge		R_2
					Member of Grouse Creek		
					Member of Wapshilla Ridge		
					Member of Mt. Horrible		
					Member of China Creek		N_1
					Member of Downy Gulch		
					Member of Center Creek		R_1
					Member of Rogersburg		
					Teepee Butte Member		
					Member of Buckhorn Springs	16.5	
				Imnaha Basalt			R_1
							T
							N_0
						17.5	R_0

Figure 3. Stratigraphic nomenclature of the Columbia River Basalt Group and related units, after Tolan and others (1989). Terminology for informal members of the Grande Ronde Basalt described by Reidel and others (1989) is that of Reidel (1998). Magnetic polarity designations are N, normal; R, reversed; T, transitional; E, excursional; subscripts refer to magnetostratigraphic units of Swanson and others (1979). Time scale of Berggren and others (1995). Units present in the Saint Helens 7.5' quadrangle are shown in bold italics.

NEOGENE SEDIMENTARY ROCKS

Development of the Portland Basin probably began in late early Miocene time, shortly before emplacement of the Grande Ronde Basalt (Beeson and others, 1989; Beeson and Tolan, 1990). As the basin continued to subside during the late Miocene and Pliocene, it filled with continental fluvial and lacustrine sediments fed through the Cascade Range by the ancestral Columbia River as well as with locally derived detritus carried in by tributaries draining the surrounding highlands. These deposits have been mapped from the Columbia River Gorge west and north along the Columbia River to Kelso, Washington, about 25 km north of the map area (Wilkinson and others, 1946; Lowry and Baldwin, 1952; Livingston, 1966; Trimble, 1957, 1963; Mundorff, 1964; Tolan and Beeson, 1984; Phillips, 1987a, b). Most workers have assigned these post-Grande Ronde Basalt nonmarine sedimentary beds to the Troutdale Formation of Hodge (1938). In its type area near the west end of the Columbia River Gorge, the Troutdale Formation is composed of three characteristic rock types: basalt-clast conglomerate, arkosic sandstone, and vitric sandstone. The conglomerate consists chiefly of well-rounded pebbles and cobbles eroded from flows of the Columbia River Basalt Group, but its most distinctive components are well-rounded, light-colored but commonly iron-stained pebbles of quartzite, granite and schistose metamorphic rocks. These rock types are foreign to western Oregon and Washington and must have been transported from pre-Tertiary terranes east of the Cascade Range by an ancestral Columbia River. The arkosic sandstone consists largely of quartz, plagioclase, potassium feldspar, and felsic lithic clasts, and contains minor but ubiquitous muscovite and biotite. Its composition, like that of the conglomerate, indicates source terranes in eastern Washington and Idaho. The vitric sandstone consists of poorly sorted, sandy to pebbly, variably palagonitized hyaloclastic debris. The petrography and chemistry of the vitric sandstone resemble those of olivine-phyric, high-alumina basalt and basaltic andesite flows erupted from volcanic centers flanking the Columbia River in the Cascade Range during Pliocene time (Tolan and Beeson, 1984; Swanson, 1986). Near the margins of the Portland Basin, the Troutdale Formation contains debris eroded from adjacent volcanic highlands. Tolan and Beeson (1984) call these locally derived deposits as the Cascadian stream facies of the Troutdale Formation, which they distinguish from the more typical ancestral Columbia River facies.

Scattered outcrops and abundant subsurface data from water-well drillers’ logs show that a conglomeratic section as much as 120 m thick overlies a sequence of finer grained strata throughout most of the Portland Basin. This observation prompted Trimble (1957) and Mundorff (1964) to divide the Troutdale into informal upper and lower members based on the pronounced difference in grain size. Trimble (1963) later formally named the lower, fine-grained, member the Sandy River Mudstone.

In the Columbia River Gorge east of the Portland Basin, Tolan and Beeson (1984) mapped as Troutdale Formation a thick section of conglomerate and sandstone above (and locally beneath) the approximately 12-Ma Pomona flow of the Columbia River Basalt Group. They informally divided the Troutdale into a lower member characterized by quartzite-bearing conglomerate and arkosic sandstone and an upper member dominated by basaltic vitric sandstone and conglomerate that contains clasts of distinctive, olivine-phyric, high-alumina basalt. From the presence of early Pliocene fossil floras near the base of their upper member, Tolan and Beeson (1984) inferred the contact between their two members to have an age near the Miocene-Pliocene boundary (5.32 Ma; Berggren and others, 1995). Trimble (1963) placed these fossil localities near the base of the Troutdale Formation, about 30 m above the contact with the Sandy River Mudstone. Therefore, Tolan and Beeson’s (1984) Troutdale upper member corresponds to Trimble’s (1963) Troutdale Formation, and their Troutdale lower member is a coarse-grained correlative of the Sandy River Mudstone.

More recently, Howard (2002) mapped the Battle Ground quadrangle to the east of the Saint Helens quadrangle and employed lithologic and geomorphic criteria to subdivide Mundorff’s (1964) Troutdale Formation. He noted that some of the coarse-grained deposits mapped as Troutdale Formation by Mundorff are younger and were derived primarily from the adjacent Cascade Range rather than from the Columbia River Basin. Howard (2002) mapped these deposits as an informal alluvial-fan member of the Troutdale Formation, and suggested that they may include early Pleistocene outwash.

On this map, sedimentary deposits previously assigned to the Troutdale Formation (Mundorff, 1964; Phillips, 1987a) are divided by lithology and stratigraphic position into two units. The fine-grained sedimentary rocks, equivalent to the informal lower member of the Troutdale Formation of Mundorff (1964) are assigned to the Sandy River Mudstone (Tsr). In the Saint Helens quadrangle, these rocks are exposed only in the Perry Creek area, resting unconformably on weathered Grande Ronde Basalt but water-well data indicate that fine-grained strata interpreted as Sandy River Mudstone are present in the subsurface. The conglomeratic deposits that overlie the

Sandy River Mudstone in the map area correspond to the younger of the two coarse-grained units recognized by Howard (2002) and Evarts (2004) and are mapped as unnamed conglomerate (unit QTc).

SANDY RIVER MUDSTONE

Highly weathered mudstone, siltstone, and minor basalt-pebble conglomerate exposed in a quarry adjacent to Perry Creek are assigned to the Sandy River Mudstone. These sediments occupy a small channel cut into laterized basalt of the member of Sentinel Bluffs of the Grande Ronde Basalt. The rocks are tuffaceous, contain fragments of carbonized wood, and are intensely weathered to clay; limonite stains and cements the beds and forms veins about 1 cm wide along bedding planes. Only 3 m of strata are exposed in the quarry but the section is likely thicker because drillers' logs from the Perry Creek area report as much as 75 m of clay above basalt bedrock. Some of this clay may be laterized basalt, but the some logs record gray, blue, and light-brown clays, in contrast to the reddish-brown to yellow clays typical of weathered basalt, suggesting the wells intersected sedimentary beds. Judging from the the well logs and the elevations of basalt-sediment contacts in quarry walls, there may be as much as 50 m of fine-grained sedimentary rocks above the basalt. These are overlain by 1 to 2 m of massive, light-brown micaceous silt, which was included in the Troutdale Formation by Wilkinson and others (1946) but is actually Pleistocene loess (Lentz, 1981).

The age of strata mapped as Sandy River Mudstone in the map area is uncertain. They overlie the 16.5-Ma member of Sentinel Bluffs, so might correlate with the informally named Vantage interbeds, fluvial and lacustrine sediments between Grande Ronde Basalt and 14.5-Ma Wanapum Basalt (Beeson and others, 1985; 1989; Beeson and Tolan, 1990). The sedimentary section near Perry Creek, however, is thicker than Vantage interbeds elswhere in western Oregon, and the unconformable basal contact suggests that much time elapsed between emplacement of the basalt and deposition of the overlying deposits. Fossil floras from the Sandy River Mudstone in the southern Portland Basin indicate the unit is most likely of middle to late Miocene age (Wilkinson and others, 1946; Trimble, 1963; Mundorff, 1964). Similar strata in the Coast Range to the west have been assigned to the Miocene Scappoose Formation as redefined by Van Atta and Kelty (1985).

UNNAMED CONGLOMERATE

Weakly to moderately consolidated cobbly conglomerate mapped here as unit QTc forms a 15-m-high ridge that extends about 6 km north-northeast from Scappoose and underlies adjacent parts of the Columbia River floodplain. The deposit is well exposed in several large active gravel pits. It consists of massive to thick-bedded, crudely stratified, poorly sorted to moderately well sorted conglomerate with rare lenticular interbeds less than 20 cm thick of micaceous sand. In the upper 4 to 5 m of conglomerate, the silty to gritty matrix is weathered to limonite and clay; the deposit is capped by about 5 cm of dark-brown soil. Tabular foreset bedding and pronounced clast imbrication indicates transport to the north. Clasts in the gravel are predominantly well-rounded pebbles and cobbles derived from the Columbia River Basalt Group, but the deposit includes rare quartzite pebbles and subangular clasts of Pliocene or Quaternary olivine-bearing basalt. Its sedimentology indicates deposition in a gravelly braided stream setting (Miall, 1977, 1996; Rust, 1978; Ramos and Sopeña, 1983).

Similar conglomerate underlies an isolated terrace at Deer Island to the north (Evarts, 2002) and a 20-m-high ridge on Sauvie Island to the south (Gates, 1994; J.E. O'Connor, written commun., 1993). It is widespread to the east and southeast of the quadrangle, where it unconformably overlies the Sandy River Mudstone and forms a sheetlike deposit traceable into the type area of the Troutdale Formation (Trimble, 1963; Mundorff, 1964; Swanson and others, 1993). These dispersed conglomerate outcrops were probably contiguous prior to incision by the Columbia River.

Previous workers suggested that the conglomerate exposed near Scappoose, at Deer Island, and on Sauvie Island were latest Pleistocene or Holocene in age because the surfaces of these deposits are free of the slack-water silt deposited throughout the Portland Basin by late Pleistocene glacier-outburst floods (Lowry and Baldwin, 1952; Swanson and others, 1993; Gates, 1994). Intense weathering and soil development, however, indicate these conglomeratic beds must be much older. The absence of slack-water silt more likely reflects nondeposition or subsequent erosion, as inferred from field relations at Deer Island and near Ridgefield, Washington, directly east of the map area (Evarts, 2002; R.C. Evarts, unpub. mapping). Evidence supporting an older age for the conglomerate near Scappoose comes from the chemistry of glass shards dispersed in a sandstone interbed (A.W. Sarna-Wojcicki, written commun., 2000). The shards were presumably transported with other framework grains from sources in eastern Washington by the ancestral Columbia River. All of the shards exhibit chemical compositions indicative of Miocene and Pliocene sources in the Snake River Plain region. They resemble neither Quaternary tephras erupted from the Cascade Range nor widespread late Pliocene and younger (about 2.06 Ma; Lanphere and others, 2002) tephra beds erupted from the Yellowstone region. This suggests that the conglomerate near Scappoose is most likely a Pliocene deposit.

QUATERNARY DEPOSITS

DEPOSITS OF THE COLUMBIA RIVER VALLEY

The major influences on sedimentation in the lower Columbia River valley during Quaternary time were glacially-induced changes in sea level (Warne and Stanley, 1995) and episodic colossal floods (Bretz, 1925, Trimble, 1963; Allison, 1978; Waitt, 1985, 1994, 1996; McDonald and Busacca, 1988; Zuffa and others, 2000; Bjornstad and others, 2001; Benito and O'Connor, 2003). Pre-Holocene alluvium underlies the Columbia River floodplain in the Saint Helens quadrangle but the subsurface stratigraphy is poorly known because most wells bottom in gravelly deposits at depths less than 50 m. Swanson and others (1993) infer that the thickness of basin-fill deposits increases from zero near Warrior Rock to about 400 m beneath Guiles Lake, and that unconsolidated Quaternary alluvium constitutes as much as 100 m of this section.

Cataclysmic Flood Deposits

During the last glacial maximum in late Pleistocene time, an ice dam impounded Glacial Lake Missoula in western Montana. It failed repeatedly, releasing floods that coursed down the Columbia River and into the Portland Basin (Bretz, 1925, 1959; Bretz and others, 1956; Trimble, 1963; Allison, 1978; Baker and Bunker, 1985; Waitt, 1985, 1994, 1996; O'Connor and Baker, 1992; Benito and O'Connor, 2003). The sediment-laden floodwaters were hydraulically constricted by the narrow reach of the Columbia River valley north of (downstream from) the Saint Helens quadrangle. The constriction caused temporary ponding in the Portland Basin and tributary valleys to levels as high as 400 ft (120 m). Radiocarbon ages, paleomagnetic measurements, and tephrochronologic data indicate that the last-glacial episode of floods occurred chiefly between about 17,000 and 13,000 ^{14}C years B.P. (Waitt, 1985,1994; Atwater, 1986; Clague and others, 2003). Similar episodes of cataclysmic flooding probably occurred earlier in the Quaternary (McDonald and Busacca, 1988; Zuffa and others, 2000; Bjornstad and others, 2001).

During each flood, the suspended load of fine sand and silt settled out of the temporarily ponded floodwaters. In the northern Portland Basin, multiple floods (Waitt, 1994, 1996) collectively built up deposits of laminated micaceous silts as thick as 30 m. These slack-water deposits (Qfs) now mantle surfaces between 200 and 250 ft (60 and 75 m) west of the Columbia River floodplain. Local unmapped patches of micaceous silt are found at elevations up to 350 ft (105 m). An exotic, presumably ice-rafted, boulder of coarse-grained gneiss lies on top of flood deposits at about 300 ft (95 m) elevation on a ridge south of Milton Creek. The laminated character of the flood deposits is obvious only in fresh slump-scarp outcrops; oxidation colors exposures light brown and obscures bedding. They are dominated by grains of quartz and feldspars and contain conspicuous muscovite, which confirms their Columbia River provenance.

Holocene Alluvial Deposits

Holocene alluvium (Qa) of the Columbia River floodplain consists largely of silt and fine sand with local concentrations of organic debris. The sand is dominated by quartz, feldspar, and lithic fragments eroded from pre-Tertiary nonvolcanic terranes east of the Cascade Range (Whetten and others, 1969; Gates, 1994), but near the northeast corner of the quadrangle it contains a substantial proportion of pumice and other volcanic clasts derived from Mount St. Helens and carried to the Columbia River floodplain by the Lewis River.

At the latest Pleistocene glacial maximum, about 20 ka, sea level was about 120 m lower than at present (Warne and Stanley, 1995; Clark and Mix, 2002) and the Columbia River had cut a narrow valley through Neogene fluvial deposits into and possibly below the Grande Ronde Basalt. The floor of this paleovalley passes through the Saint Helens quadrangle about 75 m below the floodplain and approximately coincides with the present course of the river (Gates, 1994). During the subsequent rapid marine transgression, aggradation in the lower Columbia valley generally kept pace with the rise in sea level, filling the ice-age valley with fluvial silt and fine sand (Gates, 1994).

The floodplain has been modified locally by construction of levees and deposition of dredge spoils. Large, historic floods, such as those of 1984, and 1948, achieved stages of 28 to 31 feet (9 m) above sea level at Saint Helens (U.S. Army Corps of Engineers, 1968), inundating most of the area of unit Qa flanking the Columbia River. Comparison of the topographic base with 1880–1882 Coast and Geodetic Survey maps (J.E. O'Connor, written commun., 2003) shows that several areas along the Columbia have experienced post-1880 sedimentation; although some of these deposits consist of dredge spoils, most appear to be natural.

LOESS

Most of the relatively gentle upland surface west of the Columbia River is covered by up to several meters of massive, light-brown micaceous silt, which was not mapped. This surface-mantling deposit is quartzofeldspathic, similar to the Missoula Flood deposits, but is found at higher elevations. It resembles some beds in the Troutdale Formation and was considered an upper silty phase of the Troutdale by Wilkinson and others (1946) and Lowry and Baldwin (1952), who named it the Portland Hills Silt Member of the Troutdale Formation. Lentz (1981) showed that the unit is loess composed of material blown off the Columbia River floodplain during Pleistocene glacial episodes.

LANDSLIDE DEPOSITS

Because of the gentle topography, landslides are uncommon in the Saint Helens quadrangle, and the risk of seismogenic landslides in most of the map area is considered low (Madin and Wang, 1999). Slides in the northwest part of the quadrangle formed by failure of clay-rich laterized basalt and sedimentary deposits, probably caused by undercutting of steep creekbanks. The landslide east of Perry Creek is located directly above bedrock scoured by the Missoula Floods and may have been triggered by flood-induced undercutting.

STRUCTURAL FEATURES

Lava flows of the Columbia River Basalt Group are widespread units with originally near-horizontal surfaces and thus constitute excellent marker beds for detecting post-15 Ma deformation (Beeson and Tolan, 1990). In this quadrangle and the Deer Island quadrangle to the north (Evarts, 2002), Grande Ronde Basalt flows dip uniformly south at less than 2° before disappearing beneath surficial deposits south of Saint Helens. In the Chapman quadrangle about 2 km northwest of Scappoose, it dips north at about 3° (Wilkinson and others, 1946). The distribution and attitudes of these flows delimit a subtle, southeast-plunging synclinal axis between Saint Helens and Scappoose (see also Wilkinson and others, 1946; Phillips, 1987a). The syncline projects along the axis of the Portland Basin (Swanson and others, 1993; L.M. Liberty, written commun., 2003) and parallels several northwest-trending folds in the Coast Range to the west (Beeson and others, 1989; Beeson and Tolan, 1990).

Deep weathering of bedrock and thick cover of young sediment obscures evidence of faulting in the Saint Helens quadrangle, and undetected faults almost certainly exist beneath the Quaternary fill. The northwest-striking fault northeast of Middle Lands is projected from an outcrop in the adjoining Ridgefield quadrangle where slightly warped Sandy River Mudstone on the north is juxtaposed against Grande Ronde Basalt to the south. This structure follows a conspicuous aeromagnetic anomaly and is interpreted as oblique-slip reverse fault (Evarts and others, 2002; R.C. Evarts, unpub. mapping). It appears to continue north-northwestward beneath the Columbia River into the Deer Island quadrangle, where it probably merges with the right-lateral Kalama Structural Zone of Evarts (2002).

Paleomagnetic declinations measured at several sites within a member of Sentinel Bluffs flow in the Saint Helens and Middle Lands area are oriented clockwise relative to areas to the east and west, which Evarts and others (2002) ascribed to rotation of crustal microblocks caught in a dextral shear couple, presumably a continuation of the Kalama Structural Zone. The fault northeast of Middle Lands may form the eastern boundary of the rotated zone, and a northeast-striking fault that offsets flow units of the Grande Ronde Basalt is presumably a subsidiary structure accommodating rotation, but the locations of other faults within the zone or bounding its west side are unconstrained.

GEOLOGIC EVOLUTION

The Portland Basin and its bounding structures have a long and complex tectonic history (Beeson and others, 1989; Blakely and others, 1995; Yeats and others, 1996). Beeson and Tolan (1990) suggest that development of the structure that evolved into the present basin began in middle Miocene time, shortly before eruptions of the Grande Ronde Basalt. Considerable evidence also exists for older regional deformation (Snavely and Wells, 1996; Niem and others, 1992, 1994).

In early to middle Miocene time, when the Portland Basin began to form (Beeson and Tolan, 1990; Beeson and others, 1989), western Washington and Oregon constituted a terrain of modest relief eroded into mildly deformed Paleogene volcanic and sedimentary rocks (Wilkinson and others, 1946; Beeson and others, 1989). Wilkinson and others (1946) infer pre-basalt surface relief of about 150–180 m in the area of the Saint Helens quadrangle. Largely nonmarine fine-grained sedimentary deposits that rest unconformably on Paleogene bedrock throughout western Oregon and Washington (Van Atta and Kelty, 1985; Beeson and others, 1989; Tolan and Beeson, 1999; Evarts 2004) reflect deposition in low-energy fluvial, lacustrine, paludal, estuarine, and shallow-marine environments. The absence of coarse-grained volcaniclastic debris signifies that the middle Miocene Cascade arc was low in elevation and volcanically quiescent compared to earlier times.

Starting about 16.5 Ma, flood-basalt flows of the Grande Ronde Basalt entered the incipient Portland Basin and spread widely throughout the region (Beeson and others, 1989). The ancestral river was displaced repeatedly by late Grande Ronde Basalt flows, which filled the valley and covered much of the adjacent, topographically subdued terrain.

A period of northeast-southwest-directed compression accompanied and followed emplacement of the Columbia River Basalt Group in the Saint Helens area, producing the gentle southeast-plunging syncline whose axis passes near Warren. Similarly oriented folds are present in the western Cascade Range east of this quadrangle (Phillips, 1987a, b; Evarts and Swanson, 1994) and west of Portland (Beeson and others, 1989; Beeson and Tolan, 1990), suggesting this compressive event was regionwide. The timing and duration of folding in the Saint Helens quadrangle are uncertain. Involvement of the member of Sentinel Bluffs demonstrates post-15.6 Ma-deformation, but folding may have begun before its emplacement. Folding in the southern Washington Cascade Range was largely confined to the late early to middle Miocene, about 15–20 Ma (Evarts and Swanson, 1994), whereas development of northwest-striking folds and associated faults in northwestern Oregon apparently occurred discontinuously throughout the Neogene (Beeson and others, 1989; Beeson and Tolan, 1990).

By late Miocene time an area of localized northwest-southeast extension within a broad, northwest-trending zone of dextral shear evolved into a major structure, the Portland Basin (Beeson and others, 1989; Beeson and Tolan, 1990). The basin apparently controlled the course of the lower Columbia River during late Neogene time, and at least 440 m of fluvial and lacustrine sediment of the Sandy River Mudstone and Troutdale Formation accumulated within it (Swanson and others, 1993; Mabey and Madin, 1995). Regional uplift during the Pliocene triggered downcutting by the ancestral Columbia, which removed much of the Troutdale Formation and the upper part of the Sandy River Mudstone. Later, in latest Pliocene or early Pleistocene time, gravel deposition (QTc) prograded northward across the basin floor, burying the eroded surface of the Sandy River Mudstone.

During the Quaternary, largely in response to climatic fluctuations and related sea level changes, the lower Columbia River experienced repeated cycles of erosion and sedimentation. The Pliocene to late Pleistocene gravel was incised, leaving the ridge east of Scappoose as a terrace, and the Columbia became localized near its present course. Near the end of the Pleistocene, floods from ice-dammed Lake Missoula repeatedly inundated the Portland Basin. The Missoula Floods eroded surficial deposits below about 300 feet (90 m) elevation and left behind silty slack-water deposits that mantle land surfaces as high as 400 ft (120 m) throughout the basin. In the Saint Helens quadrangle, flood deposits between Scappoose and Saint Helens exhibit a pronounced north-trending ridge and swale topography. The origin of this fluted landscape is unknown; it may reflect scouring of the slack-water deposits by later floods or by wind, or the silt may simply veneer an older surface sculpted in subjacent gravels. Similar fluting in the Battle Ground quadrangle about 6 km east of the Saint Helens quadrangle was interpreted by Howard (2002) as a cataclysmic-flood erosion feature.

Sea level near the end of the Pleistocene was about 120–135 m lower than at present (Warne and Stanley, 1995; Clark and Mix, 2002), and the Columbia River had a correspondingly lower base level. During the subsequent rapid marine transgression, aggradation in the lower Columbia valley generally kept pace with the rise in sea level, filling the latest Pleistocene channel with fine-grained sediment (Gates, 1994).

Evidence in the Saint Helens quadrangle for specific structures to account for Pliocene and younger deformation is scant. No faults have been observed to cut the basin-fill strata, and fault scarps in the unconsolidated deposits are unlikely to have survived the high sediment loads and constant reworking of valley-bottom sediments that typified the Quaternary Columbia River fluvial regime. Ryan and Stephenson (1995) collected high-resolution seismic reflection data at several locations along the Columbia River, seeking evidence for recent faulting. They detected no offset of the river bottom but did record dipping and truncated reflectors in the shallow subsurface north of Saint Helens that may reflect disruption of young basin-fill deposits. This locality is along the trend of the fault inferred by Evarts and others (2002) to run northwest of Middle Lands.

GEOLOGIC RESOURCES

Geologic resources available in the Saint Helens quadrangle are largely limited to nonmetallic industrial materials; no metallic deposits or significant hydrothermal alteration associated with such deposits have been found. Coarse aggregate extracted from flows of the Columbia River Basalt Group possess desirable engineering properties for many uses, and several operations currently quarry the Grande Ronde Basalt in and near Saint Helens (see Gray and others, 1978). Abundant unconsolidated alluvial deposits throughout the quadrangle provide sources for sand, and the ridge of older conglomerate (QTc) north of Scappoose sustains several gravel pits.

Intense weathering under warm humid conditions produced weathering profiles more than 40 m thick on the Grande Ronde Basalt. Typical profiles consists of a lower saprolitic horizon, wherein the basalt has been totally replaced by kaolinite, halloysite, and goethite, overlain by massive red-brown laterite largely leached of alkalies and silica. The residual laterite consists largely of gibbsite and goethite, forming ferruginous bauxite deposits (Libbey and others, 1945; Wilkinson and others, 1946; Lowry and Baldwin, 1952; Trimble, 1963; Livingston, 1966). Libbey and others (1945) describe three occurrence of ferruginous bauxite near the northwest corner of the quadrangle that are shown on the map of Wilkinson and others (1946).

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Table 1. Chemical analyses of volcanic rocks, Saint Helens 7.5' quadrangle

[X-ray fluorescence analyses. Rock-type names assigned in accordance with IUGS system (Le Maitre, 2002) applied to recalculated analyses. LOI, loss on ignition. Mg#, atomic ratio 100Mg/(Mg+Fe^{2+}) with Fe^{2+} set to 0.85x Fe^{total}. Modal analyses, secondary minerals counted as primary mineral replaced. -, not present. Analyses by D.M. Johnson at GeoAnalytical Laboratory of Washington State University using methods described in Johnson and others (1999)]

Map No.	1	2	3	4	5	6	7	8	9
Field sample No.	99SH-X96B	00SH-X112B	01SH-X119B	97SH-X48B	99SH-X96A	99SH-X97	01SH-X118	01SH-X119A	01SH-X129
Latitude (N)	45°52.47'	45°52.48'	45°52.17'	45°52.44'	45°52.40'	45°52.38'	45°51.98'	45°52.11'	45°51.32'
Longitude (W)	122°48.33'	122°47.89'	122°47.86'	122°48.75'	122°48.33'	122°48.70'	122°47.84'	122°47.86'	122°45.98'
Map unit	Tgo	Tgo	Tgo	Tgww	Tgww	Tgww	Tgww	Tgww	Tgww
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported reported (wt percent)									
SiO_2	56.74	56.12	56.28	54.49	54.70	54.25	56.24	54.58	55.27
TiO_2	1.95	2.03	1.96	2.02	2.04	2.02	2.08	2.01	2.06
Al_2O_3	13.94	14.00	13.74	13.61	13.43	13.54	14.05	13.51	13.68
FeO	10.86	9.72	11.27	11.79	12.48	12.49	10.17	12.59	11.52
MnO	0.19	0.19	0.19	0.21	0.21	0.21	0.21	0.21	0.30
MgO	3.48	3.55	3.49	3.88	3.69	3.87	3.71	3.72	3.61
CaO	7.23	7.21	7.19	7.66	7.58	7.72	7.77	7.68	7.68
Na_2O	3.13	3.08	3.16	3.24	3.04	3.08	3.10	3.01	2.99
K_2O	1.96	1.97	1.72	1.41	1.57	1.40	1.64	1.46	1.53
P_2O_5	0.33	0.34	0.33	0.32	0.32	0.31	0.32	0.31	0.32
Total	99.82	98.20	99.33	98.63	99.06	98.89	99.29	99.08	98.96
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO reported (wt percent)									
SiO_2	56.84	57.15	56.66	55.16	55.22	54.86	56.64	55.09	55.85
TiO_2	1.95	2.06	1.97	2.04	2.05	2.04	2.10	2.03	2.08
Al_2O_3	13.97	14.26	13.83	13.78	13.56	13.69	14.15	13.64	13.82
FeO	10.88	9.89	11.34	12.10	12.60	12.63	10.24	12.70	11.64
MnO	0.19	0.20	0.19	0.21	0.21	0.21	0.21	0.21	0.31
MgO	3.49	3.61	3.51	3.93	3.73	3.91	3.74	3.75	3.65
CaO	7.24	7.34	7.24	7.75	7.65	7.81	7.83	7.75	7.76
Na_2O	3.14	3.14	3.18	3.28	3.07	3.11	3.12	3.04	3.02
K_2O	1.96	2.01	1.73	1.43	1.58	1.42	1.65	1.47	1.55
P_2O_5	0.33	0.34	0.33	0.32	0.33	0.32	0.33	0.31	0.32
Mg#	40.2	43.4	39.4	40.5	38.3	39.4	43.3	38.3	39.7
Modes (volume percent)									
Plagioclase	-	-	-	trace	trace	trace	trace	trace	trace
Clinopyroxene	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	-	-	-	-	-	-	-	-	-
Fe-Ti Oxide	-	-	-	-	-	-	-	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Texture (rock/ groundmass)	aphyric/ intergranular	aphyric/ intersertal	aphyric/ intersertal	sparsely phyric/ intersertal	sparsely phyric/ intersertal	sparsely phyric/ intersertal	sparsely phyric/ intergranular	sparsely phyric/ intersertal	sparsely phyric/ intersertal
Trace element analyses (ppm)									
Ba	670	808	685	531	565	530	759	549	577
Rb	50	52	49	39	39	37	42	38	42
Sr	318	331	315	304	305	307	326	310	319
Y	38	38	36	33	36	36	43	37	37
Zr	191	187	180	166	172	166	179	171	171
Nb	16	12.5	14	13.6	14.0	12.8	14.9	13.5	12.6
Ni	5	4	7	0	5	3	4	5	1
Cu	4	13	8	11	13	15	3	6	2
Zn	118	127	119	120	125	115	127	116	119
Cr	18	26	17	30	23	25	27	21	23

Table 1. Chemical analyses of volcanic rocks, Saint Helens 7.5' quadrangle—Continued

Map No.	10	11	12	13	14	15	16	17	18
Field sample No.	97SH-X48A	97SH-X49A	97SH-X49B	99SH-X93B	99SH-X98	99SH-X99	00SH-X106	00SH-X107	00SH-X109
Latitude (N)	45°52.45'	45°52.309'	45°52.10'	45°50.88'	45°51.74'	45°50.49'	45°50.70'	45°50.39'	45°50.19'
Longitude (W)	122°48.83	122°50.1'	122°49.98'	122°45.41'	122°48.09'	122°49.83'	122°46.05'	122°45.88'	122°45.01'
Map unit	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported (wt percent)									
SiO_2	53.47	53.23	52.99	53.03	53.09	53.74	52.80	52.91	53.08
TiO_2	1.98	1.95	1.94	1.94	1.98	1.96	1.95	1.95	1.98
Al_2O_3	13.80	13.75	13.85	13.71	13.74	14.34	13.67	13.73	13.93
Fe_2O_3	11.32	11.87	12.07	11.76	12.18	11.19	11.83	11.89	11.10
MnO	0.21	0.21	0.21	0.23	0.21	0.22	0.22	0.21	0.31
MgO	4.74	4.80	4.85	4.64	4.68	4.56	4.80	4.55	4.45
CaO	8.57	8.56	8.64	8.63	8.62	8.87	8.71	8.53	8.78
Na_2O	3.05	2.99	2.93	2.85	2.82	2.87	2.88	2.98	2.92
K_2O	1.21	1.14	1.11	1.24	1.13	1.26	1.24	1.09	1.29
P_2O_5	0.33	0.33	0.32	0.32	0.33	0.31	0.32	0.31	0.33
Total	98.69	98.83	98.91	98.34	98.78	99.33	98.42	98.15	98.16
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO_2	54.10	53.78	53.57	53.93	53.75	54.11	53.65	53.91	54.07
TiO_2	2.00	1.97	1.96	1.97	2.00	1.97	1.98	1.98	2.02
Al_2O_3	13.96	13.89	14.00	13.94	13.91	14.44	13.89	13.99	14.19
FeO	11.61	12.13	12.20	11.96	12.33	11.27	12.02	12.12	11.31
MnO	0.22	0.21	0.21	0.23	0.21	0.23	0.22	0.21	0.31
MgO	4.80	4.85	4.90	4.72	4.74	4.59	4.88	4.64	4.53
CaO	8.67	8.65	8.74	8.78	8.73	8.93	8.85	8.69	8.94
Na_2O	3.09	3.02	2.96	2.90	2.85	2.89	2.93	3.04	2.97
K_2O	1.22	1.15	1.12	1.26	1.14	1.27	1.26	1.11	1.31
P_2O_5	0.33	0.33	0.32	0.32	0.34	0.32	0.33	0.32	0.33
Mg#	46.4	45.6	45.7	45.3	44.6	46.1	46.0	44.5	45.7
Modes (volume percent)									
Plagioclase	-	-	-	-	-	-	-	-	-
Clinopyroxene	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	-	-	-	-	-	-	-	-	-
Fe-Ti Oxide	-	-	-	-	-	-	-	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Texture (rock/ groundmass)	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intergranular
Trace element analyses (ppm)									
Ba	466	467	484	526	453	531	504	501	558
Rb	30	28	25	29	25	24	27	25	29
Sr	301	305	307	310	308	318	314	307	314
Y	33	34	38	36	36	37	35	35	38
Zr	160	158	159	160	159	157	161	159	157
Nb	13.7	12.7	12.1	11.1	12.6	13.0	11.5	11.9	11.7
Ni	8	8	12	10	10	10	12	10	11
Cu	27	30	28	23	28	31	30	26	29
Zn	116	116	119	112	117	114	120	121	116
Cr	47	47	49	46	41	45	46	44	46

Table 1. Chemical analyses of volcanic rocks, Saint Helens 7.5' quadrangle—Continued

Map No.	19	20	21	22	23	24	25	26	27
Field sample No.	00SH-X110	00SH-X111	01SH-X114	01SH-X115	01SH-X116	01SH-X122	01SH-X123	01SH-X126	01SH-X127
Latitude (N)	45°50.95'	45°51.06'	45°50.57'	45°50.42'	45°50.12'	45°50.83'	45°50.94'	45°50.93'	45°51.18'
Longitude (W)	122°47.26'	122°47.68'	122°45.22'	122°45.55'	122°45.97'	122°45.60'	122°45.21'	122°45.73'	122°45.99'
Map unit	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported (wt percent)									
SiO_2	52.77	52.33	53.39	53.55	54.14	53.74	53.72	53.34	53.42
TiO_2	1.97	1.97	1.93	1.95	1.94	1.96	1.94	1.92	1.98
Al_2O_3	13.79	13.82	13.91	13.92	13.95	13.89	13.95	13.85	13.90
Fe_2O_3	12.14	12.41	12.50	12.15	11.75	11.71	11.86	11.76	12.06
MnO	0.22	0.23	0.21	0.21	0.22	0.21	0.22	0.21	0.21
MgO	4.69	4.74	4.47	4.72	4.46	4.70	4.78	4.73	4.51
CaO	8.69	8.67	8.54	8.66	8.45	8.63	8.62	8.61	8.65
Na_2O	2.85	2.89	2.99	2.91	3.16	2.90	2.84	2.83	2.84
K_2O	1.11	1.08	0.95	1.11	1.10	1.17	1.26	1.27	1.12
P_2O_5	0.33	0.34	0.32	0.32	0.32	0.31	0.32	0.31	0.33
Total	98.55	98.47	99.21	99.49	99.49	99.23	99.50	98.84	99.02
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO_2	53.55	53.14	53.82	53.83	54.42	54.16	53.99	53.97	53.95
TiO_2	2.00	2.00	1.94	1.96	1.95	1.98	1.95	1.94	2.00
Al_2O_3	13.99	14.03	14.02	13.99	14.02	14.00	14.02	14.01	14.04
FeO	12.31	12.60	12.60	12.21	11.81	11.80	11.91	11.90	12.18
MnO	0.22	0.23	0.21	0.21	0.23	0.22	0.22	0.22	0.22
MgO	4.76	4.81	4.51	4.74	4.48	4.74	4.80	4.79	4.55
CaO	8.82	8.80	8.61	8.70	8.49	8.70	8.66	8.71	8.74
Na_2O	2.89	2.93	3.01	2.93	3.18	2.92	2.85	2.86	2.87
K_2O	1.13	1.10	0.96	1.12	1.11	1.18	1.27	1.28	1.13
P_2O_5	0.33	0.34	0.32	0.32	0.32	0.32	0.32	0.32	0.33
Mg#	44.8	44.5	42.9	44.9	44.3	45.7	45.8	45.8	44.0
Modes (volume percent)									
Plagioclase	-	-	-	-	-	-	-	-	-
Clinopyroxene	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	-	-	-	-	-	-	-	-	-
Fe-Ti Oxide	-	-	-	-	-	-	-	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Texture (rock/ groundmass)	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intergranular
Trace element analyses (ppm)									
Ba	489	495	507	489	490	484	485	486	485
Rb	24	26	21	26	26	27	28	26	25
Sr	310	312	311	311	305	307	308	308	312
Y	37	37	36	36	37	36	34	36	36
Zr	163	164	163	161	160	159	157	158	161
Nb	12.4	11.8	13.6	12.9	13.6	13.3	12.5	12.9	12.3
Ni	13	13	12	10	15	11	14	13	11
Cu	30	29	19	21	18	18	19	17	20
Zn	119	123	112	113	119	115	113	111	106
Cr	46	46	43	42	48	43	42	42	44

Table 1. Chemical analyses of volcanic rocks, Saint Helens 7.5' quadrangle—Continued

Map No.	28	29	30	31	32	33	34	35	36
Field sample No.	99SH-X92	99SH-X93A	00SH-X103	00SH-X105	01SH-X113	01SH-X124	01SH-X125	01SH-X128A	02SH-X130
Latitude (N)	45°51.25'	45°50.89'	45°51.91'	45°50.39'	45°50.70'	45°51.11'	45°51.21'	45°51.19'	45°52.02'
Longitude (W)	122°45.76'	122°45.43'	122°51.87'	122°45.17	122°45.03'	122°45.50'	122°45.68'	122°45.76'	122°49.20'
Map unit	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb	Tgsb
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported (wt percent)									
SiO_2	52.96	53.79	53.65	53.85	56.60	54.98	53.73	53.81	52.99
TiO_2	2.05	2.05	2.06	2.04	2.15	2.07	1.99	2.01	1.976
Al_2O_3	14.05	14.38	14.29	14.41	15.49	14.54	14.18	14.05	13.80
Fe_2O_3	10.88	10.76	10.63	10.44	7.99	9.76	11.34	11.01	11.95
MnO	0.29	0.26	0.22	0.29	0.19	0.37	0.21	0.30	0.211
MgO	3.84	4.16	4.06	3.96	3.83	3.86	3.90	4.12	4.72
CaO	9.28	8.92	8.84	8.99	8.72	8.93	8.77	8.94	8.59
Na_2O	2.94	2.96	2.87	3.05	3.26	3.01	2.79	2.92	2.84
K_2O	1.22	1.21	1.22	1.24	1.36	1.30	1.10	1.26	1.15
P_2O_5	0.34	0.35	0.34	0.34	0.35	0.34	0.33	0.34	0.330
Total	97.85	98.83	98.18	98.60	99.94	99.17	98.34	98.76	98.56
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO_2	54.13	54.42	54.64	54.62	56.64	55.44	54.64	54.49	53.76
TiO_2	2.09	2.07	2.10	2.07	2.15	2.09	2.03	2.04	2.00
Al_2O_3	14.36	14.55	14.55	14.62	15.50	14.66	14.42	14.23	14.00
FeO	11.12	10.88	10.83	10.58	8.00	9.84	11.53	11.14	12.13
MnO	0.30	0.26	0.23	0.29	0.19	0.37	0.21	0.30	0.21
MgO	3.92	4.21	4.14	4.02	3.83	3.89	3.97	4.17	4.79
CaO	9.48	9.03	9.00	9.12	8.73	9.01	8.92	9.05	8.72
Na_2O	3.00	2.99	2.92	3.09	3.26	3.04	2.84	2.96	2.88
K_2O	1.25	1.22	1.24	1.26	1.36	1.31	1.12	1.28	1.17
P_2O_5	0.35	0.35	0.35	0.34	0.35	0.34	0.33	0.35	0.33
Mg#	42.5	44.8	44.5	44.3	50.1	45.3	41.9	44.0	45.3
Modes (volume percent)									
Plagioclase	-	-	-	-	-	-	-	-	-
Clinopyroxene	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	-	-	-	-	-	-	-	-	-
Fe-Ti Oxide	-	-	-	-	-	-	-	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Texture (rock/ groundmass)	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intersertal	microphyric/ intergranular	microphyric/ intergranular
Trace element analyses (ppm)									
Ba	693	580	624	757	911	874	1019	598	484
Rb	28	25	29	30	33	30	30	27	28
Sr	338	323	335	333	359	329	351	321	305
Y	37	38	38	39	42	37	37	37	36
Zr	168	165	167	167	182	165	165	162	157
Nb	13.1	12.4	11	11	15	12.5	13.4	13.5	13.2
Ni	10	9	6	9	10	11	17	10	17
Cu	32	29	31	34	24	16	21	20	28
Zn	125	121	126	122	136	114	118	115	114
Cr	48	46	48	48	46	44	39	46	43

Table 1. Chemical analyses of volcanic rocks, Saint Helens 7.5' quadrangle—Continued

Map No.	37
Field sample No.	02SH-X131
Latitude (N)	45°51.88'
Longitude (W)	122°48.59'
Map unit	Tgsb
Rock type	Basaltic andesite
Analyses as reported (wt percent)	
SiO_2	53.10
TiO_2	1.99
Al_2O_3	13.83
Fe_2O_3	11.75
MnO	0.21
MgO	4.62
CaO	8.66
Na_2O	2.81
K_2O	1.18
P_2O_5	0.33
Total	98.49
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)	
SiO_2	53.92
TiO_2	2.02
Al_2O_3	14.04
FeO	11.93
MnO	0.22
MgO	4.69
CaO	8.79
Na_2O	2.85
K_2O	1.20
P_2O_5	0.34
Mg#	45.2
Modes (volume percent)	
Plagioclase	-
Clinopyroxene	-
Orthopyroxene	-
Olivine	-
Fe-Ti Oxide	-
Hornblende	-
Quartz	-
K-feldspar	-
Other	-
Groundmass	100.0
Texture (rock/ groundmass)	microphyric/ intersertal
Trace element analyses (ppm)	
Ba	472
Rb	26
Sr	310
Y	36
Zr	160
Nb	12.4
Ni	15
Cu	31
Zn	113
Cr	44

Table 2. Comparison of selected chemical and paleomagnetic characteristics of Grande Ronde Basalt flows in the Deer Island and Saint Helens quadrangles (Evarts, 2002; R.C. Evarts, unpub. data; J.T Hagstrum, written commun., 1999, 2000, 2001)

[Magnetic polarity: N, normal; R, reversed. Paleomagnetic directions determined by standard laboratory alternating-field demagnetization techniques; terminology is that of Wells and others (1989). Ranges in chemical composition based on analyses recalculated volatile-free and normalized to 100% with all Fe as FeO]

Member	Tgsb	Tgww	Tgo	Tgru*
Magnetic polarity	N	N	N	R
Paleomagnetic direction	north	northwest shallow	northeast	north
MgO (wt %)	3.83-4.90	3.65-3.93	3.46-3.61	4.13-4.77
TiO_2 (wt %)	1.94-2.15	2.03-2.10	1.95-2.07	1.96-2.14
P_2O_5 (wt %)	0.32-0.35	0.31-0.33	0.33-0.35	0.33-0.35
CaO (wt %)	8.41-9.48	7.65-7.83	7.05-7.34	8.74-9.02
K_2O (wt %)	0.96-1.36	1.42-1.67	1.73-2.01	1.34-1.42
Ba (ppm)	447-1019	530-759	668-838	447-582
Cr (ppm)	39-49	21-30	17-28	48-52

*not exposed in the Saint Helens quadrangle