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GEOLOGIC MAP OF THE SILVER LAKE QUADRANGLE, COWLITZ COUNTY, WASHINGTON

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INTRODUCTION

The Silver Lake 7.5' quadrangle is situated in the westernmost foothills of the southern Washington Cascade Range near the physiographic boundary between the Cascades and the Coast Range (fig. 1). Regionally, these two mountain ranges are separated by the Puget-Willamette Lowland, a complex structural and topographic trough that extends from Puget Sound to west-central Oregon. The Cascade Range consists of a diverse assemblage of volcanic, volcaniclastic, and plutonic rocks of Eocene to Holocene age, the products 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 structurally complex assemblage of Eocene to Miocene volcanic and marine sedimentary rocks. Along most of its length, the Puget-Willamette Lowland consists of broad basins filled with late Cenozoic sediments, but in southwestern Washington, it narrows to a valley only 2-3 kilometers wide. The Silver Lake quadrangle is located near the northern end of this narrow segment of the Lowland.

The Silver Lake quadrangle is characterized by relatively low relief, with a maximum elevation near 1200 ft (365 m) in the southwestern part. The lowest elevation is about 80 ft where the Toutle River exits the quadrangle to the west. The Toutle River traverses the northern part of the Silver Lake quadrangle and joins the Cowlitz River about 3 km west of the quadrangle boundary (see index map on map sheet). The Toutle drains the north and west flanks of Mount St. Helens and has been severely impacted by eruptions of the volcano, most recently in 1980 when lahars destroyed the Tower Road bridge. Silver Lake itself is a product of Mount St. Helens, having formed about 2,500 years ago when several huge lahars moved down the Toutle River and dammed the mouth of a tributary, Outlet Creek (Scott, 1988a, 1989).

Historically, silviculture has formed the economic base of the local area, and land use in the Silver Lake quadrangle is dominated by corporate and family tree farms. Important additional activities include agriculture, production of industrial minerals, and tourism. In the past decade, population growth within the Seattle-Portland corridor has resulted in significant expansion of residential and associated commercial development within the Cowlitz floodplain and in the adjacent foothills. This rapid development raises important planning issues that can be adequately addressed only with reliable earth-science information. Such development increases the demand for basic geologic resources such as crushed rock, sand, and gravel while simultaneously reducing the areas available for resource extraction. Detailed hydrogeologic information is essential for a region that draws nearly all of its water from local groundwater sources. Greater development also increases vulnerability to substantial economic losses from earthquakes, landslides, and lahars (Rogers and others, 1996; Harp and others, 1997; Wolfe and Pierson, 1995). Essential utility routes, including a petroleum pipeline and fiber-optic communications cables, pass near the west edge of the quadrangle; thus, local geologic hazards in the Silver Lake quadrangle are of regional concern.

This map is a contribution to a program designed to improve the geologic database for the Pacific Northwest urban corridor. 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 and ground-failure hazards and resource availability in this rapidly growing region. For example, the risk posed by earthquakes generated in the shallow crust of southwestern Washington is widely recognized but difficult to quantify because mapped faults are few and seismicity is diffusely distributed (Stanley and others, 1996). Geologic mapping that leads to a better understanding of the regional structure can help to anticipate the types, sizes, and frequency of earthquakes. Likewise, knowledge of the location of past landslides and of the distribution of landslide-prone geologic materials can be used to guide

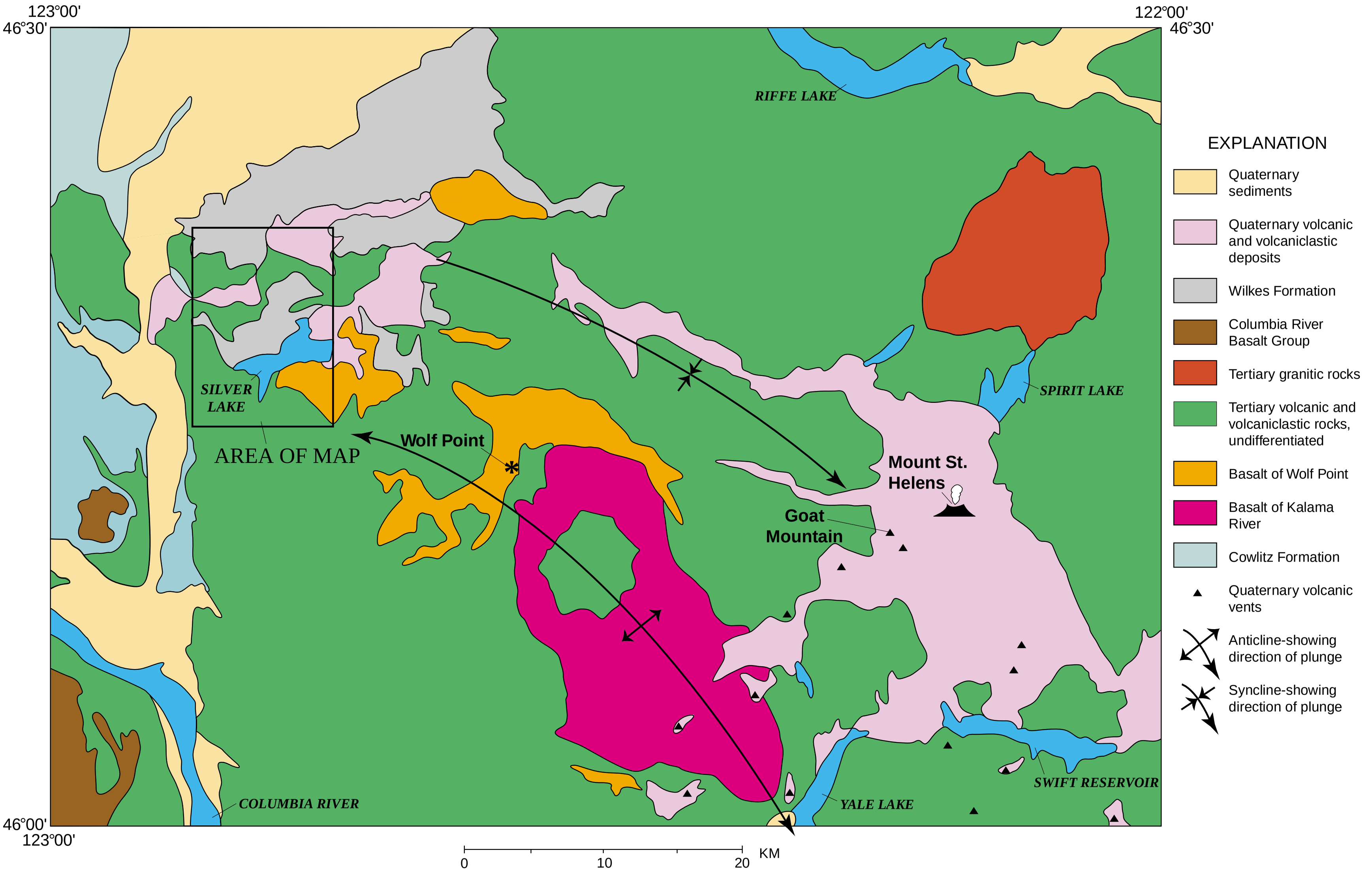

Figure 1. Simplified geologic map of the Mount St. Helens 30' x 60' quadrangle, modified from Phillips (1987.)

development and avoid ground-failure disasters such as those suffered by the Aldercrest neighborhood in Kelso, Washington, 13 km south of the map area (Burns, 1999).

PREVIOUS GEOLOGIC INVESTIGATIONS

Most previous investigations of the geology of the Silver Lake area were focused on the region's coal and clay resources. The existence of potentially exploitable coal beds in the lower Cowlitz River valley was known in the early nineteenth century but no significant mining occurred until the early 1890's (Roberts, 1958). Most of the coal was determined to be lignite of low value, and mining had largely ceased by the time of the first published descriptions of the general geology of the Castle Rock area and its coal deposits by Collier (1911) and Culver (1919). The only notable deposit within the Silver Lake quadrangle was the Leavell Mine developed in the Cowlitz Formation near the southwest corner of the quadrangle. The Leavell coal was a relatively high-value subbituminous to bituminous product but the deposit played out when the coal seam terminated against a fault; attempts to locate the offset extension of the seam by drilling failed.

Deposits of high-alumina clay were discovered on the hill east of lower Cline Creek in 1935 and exploited shortly thereafter (Glover, 1941; Popoff, 1955). In 1942-43, the U.S. Geological Survey and U.S. Bureau of Mines jointly evaluated the Cowlitz clay deposits as a potential source of aluminum (Nichols, 1943; Popoff, 1955). During this investigation, the geology of much of the area north of the Toutle River was mapped and 67 shallow exploratory holes were drilled. The work established that the economic clay deposits occur within a gently warped sequence of early Tertiary sedimentary rocks, that porphyritic and vesicular aphyric volcanic rocks locally overlie the sedimentary rocks, and that a younger section of weakly consolidated clayey sediments mantles much of the area.

Roberts (1958) conducted a comprehensive investigation of the geology of the Castle Rock/Toledo coal district and mapped, at a scale of 1:62,500, an area that includes the Silver Lake 7.5' quadrangle as well as contiguous quadrangles to the east, north, and west. He described the stratigraphy in considerable detail and named three Tertiary lithostratigraphic units: the Hatchet Mountain, Toutle, and Wilkes Formations. He assigned most of the volcanic rocks in the Silver Lake quadrangle to the Eocene Hatchet Mountain Formation, which overlies nearshore marine and nonmarine arkosic sandstones of the Cowlitz Formation. These rocks constitute the earliest manifestation of Cascade arc volcanism in this area. Roberts (1958) divided the Hatchet Mountain Formation into three lithologically distinct members (called "sequences"), which he described but did not portray on his map. According to his descriptions, only two of these members, the lowermost porphyritic basalt sequence and the uppermost olivine basalt sequence, crop out in the Silver Lake quadrangle; to the east these two are separated by a porphyritic andesite sequence. According to Roberts (1958), the Hatchet Mountain Formation is overlain by a section of volcaniclastic strata, including the economic clay deposits, which he named the Toutle Formation. The Toutle, to which Roberts assigned a late Eocene to early Oligocene age based on molluscan and plant fossils, is unconformably overlain by unnamed lava flows that Roberts (1958) inferred to be of Miocene age. North of Silver Lake, all of these units are covered by a dissected mantle of deeply weathered, poorly consolidated, fine-grained tuffaceous and arkosic sediments that Roberts (1958) named the Wilkes Formation for exposures in the Wilkes Hills. Plant fossils suggest that the Wilkes Formation was deposited in late Miocene and Pliocene time (Roberts, 1958).

The Toutle Formation in the Cline Creek area was restudied in detail by May (1980), who divided the unit into a dominantly marine lower member and a nonmarine upper member. He concurred with Roberts (1958) on the late Eocene and early Oligocene age of the formation.

Phillips (1987) compiled the geology of the Mount St. Helens 30 x 60-minute quadrangle, which includes the Silver Lake quadrangle, at 1:100,000-scale as part of a Washington Division of Geology and Earth Resources project to update the state geologic map (Walsh and others, 1987). Based on his own reconnaissance mapping and K-Ar dating results, Phillips made several revisions to Roberts' (1958) stratigraphy. Because Phillips and Kaler (1985) were able to trace volcanic rocks continuously from the Hatchet Mountain Formation as mapped by Roberts (1958) southward into the type area of the late Eocene to early Oligocene Goble Volcanic Series of Wilkinson and others (1946) near Kelso, Phillips (1987) considered the two units equivalent. Consequently he dropped Hatchet Mountain in favor of the older name. In addition, Phillips (1987) divided his Goble Volcanics into a lower member of predominantly volcaniclastic rocks and an upper member dominated by mafic lava flows. He included most of the rocks in the Silver Lake quadrangle that had been mapped as Hatchet Mountain Formation by Roberts (1958) into the lower, volcaniclastic-dominated member of the Goble Volcanics. A younger volcanic section that Roberts believed was probably Miocene in age was shown on the basis of K-Ar dates to be late Eocene by Phillips (1987), who therefore assigned these rocks to his upper member of the Goble Volcanics. Phillips (1987) accepted the Toutle Formation as mapped by Roberts (1958) without modification but was unable to trace it as a coherent stratigraphic unit beyond its type area. Phillips' (1987) map also showed the distribution of deposits derived from ancestral Mount St. Helens along the Toutle River, which Roberts (1958) had not recognized.

The more detailed work described herein requires revisions to both Roberts' (1958) formal and Phillips' (1987) informal lithostratigraphic schemes for the Silver Lake quadrangle. The results show that the distribution of lithologic units in the Silver Lake quadrangle as portrayed by Roberts (1958) is essentially correct, although stratigraphic relations are more complex than he believed. The present work does not support Phillips' (1987) subdivision of his Goble Volcanics, but does confirm his age assignments.

ACKNOWLEDGMENTS

Access graciously provided by the many landowners in the Silver Lake quadrangle was essential to completing the work presented here. Especially critical was permission from Weyerhaeuser Corporation (through Ross Graham and Dorothy Yount) and Longview Fibre Co. (through Dennis Mohan) to work on their timberlands and use their extensive road networks. Several U.S. Geological Survey colleagues provided essential data: David Siems (analytical chemistry), Jonathan Hagstrum (paleomagnetic measurements), Richard Blakely (aeromagnetic maps), and Robert Fleck (^{40}Ar/^{39}Ar ages). Bradley Reid provided able field and laboratory assistance in 1998. Andrei Sarna-Wojcicki, Kenneth Bishop, Judith Fierstein, and Michael Clynne made available essential laboratory facilities. Debra Hunemuller and Stephanie Abraham of the Washington Department of Ecology Southwest Regional Office in Lacey, Wash. provided access to their files of water-well logs as well as space to examine them. Connie Manson, librarian at the Washington Division of Geology and Earth Resources in Olympia, Wash., has been a continuing source of information from that agency's files. Discussions with Roger Ashley, Paul Hammond, Samuel Johnson, Dave Norman, Grant Newport, Alan Niem, Charles Payne, William Phillips, Charles Powell, II, Kevin Scott, James G. Smith, Donald Swanson, Karl Wegmann, and Ray Wells helped hone my understanding of the local and regional geology. Reviews by Roger Ashley, Kevin Scott, and Karl Wegmann stimulated many improvements in the final map. Publication costs for this map were underwritten by a contribution from the Mineral Resources Group of Weyerhaeuser Company.

SYNOPSIS OF GEOLOGY

Bedrock of the Silver Lake quadrangle consists chiefly of middle and upper Eocene volcanic and volcaniclastic rocks that represent the earliest activity of the Cascade volcanic arc. The lava flows are mostly subaerially emplaced olivine-phyric basalts and plagioclase-phyric basaltic andesites. The volcaniclastic rocks are primarily fluvial and lacustrine sedimentary deposits but include local marine sandstones and minor mafic hyaloclastites and dacitic ash-flow tuffs. Along the west edge of the quadrangle, the volcanic rocks rest unconformably on nearshore and nonmarine micaceous arkosic sandstones of the Cowlitz Formation. The near-absence of intrusive rocks indicates that the volcanics were erupted from vents outside the quadrangle, presumably located to the east near the axis of the arc. Except near the west edge of the quadrangle, where easterly dips of 15°-25° prevail, the Paleogene strata appear to be nearly flat lying, and measured structural attitudes show no coherent pattern. Mapped faults strike predominately northwest with inferred normal and strike-slip offsets; no fault was observed to cut Neogene units and none appears to be a major structure. A few erosional remnants of Grande Ronde Basalt in and east of the valley of Cline Creek indicate that at least one Columbia River Basalt Group flow reached into the area in middle Miocene time. North of Silver Lake, the Paleogene strata and Grande Ronde Basalt are partially buried by an extensive cover of Neogene deposits that include fine-grained clayey sediments of the Wilkes Formation (Roberts, 1958), probable early or middle Pleistocene glacial outwash, and dacitic debris washed downstream from Mount St. Helens.

A relatively mild, wet climate has prevailed in the western Pacific Northwest throughout most of the Cenozoic era (Wolfe and Hopkins, 1967; Wolfe, 1978; R.W. Brown, cited in Roberts, 1958), promoting intense chemical weathering of geologic units of the region. Mountain glaciers moved down the Toutle drainage during Pleistocene time but never reached as far as Silver Lake quadrangle (Crandell and Miller, 1974; Crandell, 1987). As a result of the long exposure to weathering processes, saprolitic soil horizons as much as 4 m thick have developed on Paleogene bedrock, and even deeper weathering is common in permeable Neogene surficial deposits. This deep weathering makes identification of some geologic units challenging. This problem is particularly severe in the area north of the Toutle River where it was difficult to distinguish the Wilkes Formation from clayey Eocene sedimentary strata and glacial outwash from weathered Eocene gravels. Because of the intense weathering, as well as the dense vegetation of the region, natural outcrops are generally limited to steep cliff faces, landslide scarps, and streambeds. However, the extensive network of logging roads, as well as many rockpits and quarries, in the quadrangle provided excellent access and, together, the artificial and natural outcrops are sufficient to allow the stratigraphy and structure of the bedrock to be mapped in considerable detail. The field information was supplemented with subsurface data obtained from water-well logs archived by the Washington Department of Ecology; well locations were taken from the reports and were not field checked.

PALEOGENE BEDROCK

The Paleogene bedrock of the Silver Lake quadrangle consists chiefly of a diverse assortment of subaerially erupted lava flows and volcaniclastic rocks broadly typical of the strata that underlie much of the western slopes of the Cascade Range in southern Washington (Evarts and others, 1987; Smith, 1993; Evarts and Swanson, 1994). Regional stratigraphic relationships and age determinations show that the rocks in this quadrangle include some of the earliest products of the Cascade volcanic arc and were emplaced during late middle and late Eocene time, about 39 to 35 Ma. The base of the Cascade arc sequence is well exposed here and in the adjacent Castle Rock quadrangle, where the volcanic rocks rest unconformably on nonvolcanic arkosic sandstones of the Cowlitz Formation.

COWLITZ FORMATION

The Cowlitz Formation is the oldest stratigraphic unit exposed in the Silver Lake quadrangle. The name was applied by Weaver (1912, 1937) to middle and late Eocene nearshore marine and nonmarine sandstone and siltstone exposed in the banks of the Cowlitz River and one of its tributaries, Olequa Creek, north of the town of Vader. The type locality is about 8 km northwest of the Silver Lake quadrangle. Henriksen (1956) expanded the formation to include an underlying section of fine-grained marine rocks, but Wells (1981) and Niem and Niem (1985) restrict the name to the micaceous, arkosic, sandstone-dominated strata of middle to late Eocene age that typify Weaver's original type section. Similar sandstones underlie volcanic rocks along the lower valley walls of a small tributary of Salmon Creek near the southwest corner of the Silver Lake quadrangle. The Cowlitz Formation is widespread in the adjacent Castle Rock quadrangle, however, and its upper contact with mafic volcanic and volcaniclastic rocks (units Tk, Tba and Tmt) is located immediately west of and roughly parallels the quadrangle boundary (Roberts, 1958). Typical Cowlitz sandstones are medium- to fine-grained, friable, moderately to well sorted, lithic and arkosic arenites that contain conspicuous muscovite flakes. In fresh exposures Cowlitz sandstones are bluish gray but they rapidly weather to light yellowish gray. Many of the sandstone beds are uncemented and thus extremely friable; others originally possessed sparry calcite cement, but the carbonate is readily leached in the wet modern climate, so most outcrops rapidly disintegrate into loose sand. Some beds have been impregnated with limonite and are more durable. Locally intercalated with the arkoses are mafic volcaniclastic sandstones, fine-grained silicic tuffs, carbonaceous siltstones, and seams of subbituminous coal and lignite. Sedimentary facies indicate deposition in fluvial and delta-plain settings that graded westward into estuarine and nearshore marine deltaic environments (Roberts, 1958; Payne, 1998).

The Cowlitz Formation and correlative units in southern Washington and northern Oregon record deposition along the continental margin prior to full establishment of the Cascade volcanic arc (Buckovic, 1979, Armentrout, 1987; Vance and others, 1987; Heller and others, 1987; Johnson and Stanley, 1995). The framework of Cowlitz Formation sandstones is dominated by angular to subangular grains of quartz, plagioclase, potassium-feldspar, and fine-grained granitic and schistose metamorphic rocks. Most beds contain significant amounts of muscovite, biotite, and hornblende. This composition points to largely nonvolcanic sources, most likely pre-Tertiary terranes in Idaho and northern Washington (Heller and others, 1987; Brandon and Vance, 1992). The presence of detrital kyanite in Cowlitz Formation arkoses suggests that the Chiwaukum Schist of the northern Washington Cascades was a major contributor (Vance, 1989).

EOCENE VOLCANIC, VOLCANICLASTIC, AND INTRUSIVE ROCKS

Basalt of Kalama River

Coarsely porphyritic, olivine + plagioclase ± augite-phyric tholeiitic basalts that chemically resemble mid-ocean ridge basalts crop out locally near the western edge of the Silver Lake quadrangle south of the Spirit Lake Highway (State Route 504). The petrography, chemistry, and stratigraphic position of these rocks indicates that they are correlative with the basalt of Kalama River, a thick pile of Eocene lava flows mapped about 20 km west of Mount St. Helens by Evarts and Ashley (1990a; 1991; 1992). The basalt of Kalama River is one of the most distinctive Tertiary units in the southern Washington Cascade Range (Evarts and Swanson, 1994). It underlies an area in excess of 150 km^2, apparently forming the west flank of a single huge shield volcano. Dikes compositionally similar to the basalts have not been found, so the location of the source vent for the flows is unknown. However, southeastward thickening of the basalt pile suggests that it probably lies beneath younger arc strata south of Mount St. Helens. The few flows that crop out in the Silver Lake quadrangle are interpreted as the distal ends of lavas that erupted from this volcano and moved westward beyond the flank of the shield nearly to the Eocene strandline. The basalts here are found at or near the base of the Cascade volcanic-arc section, commonly resting directly on Cowlitz Formation sandstones.

The basalt of Kalama River is a petrographically and chemically unique unit in southern Washington. Most flows are conspicuously plagioclase-phyric, containing abundant phenocrysts and glomerocrysts of weakly zoned feldspar as large as 1 cm across. Olivine is present in most flows and is the sole phenocryst phase in many, whereas augite phenocrysts are relatively uncommon. Groundmass textures range from intergranular to ophitic and are commonly diktytaxitic but rarely foliated; a unique feature is the nearly ubiquitous presence of groundmass olivine. Chemically, the basalt of Kalama River constitutes a low- to medium-K_2O tholeiite series (figs. 2, 3, 4), with limited variation in SiO_2 (47-52 wt percent) but extensive ranges in Mg# (71-43), FeO* (9.0-12.5 wt percent), and TiO_2 (1.00-2.55 wt percent). The one analysis from this quadrangle (table 1, Map no. 1) is

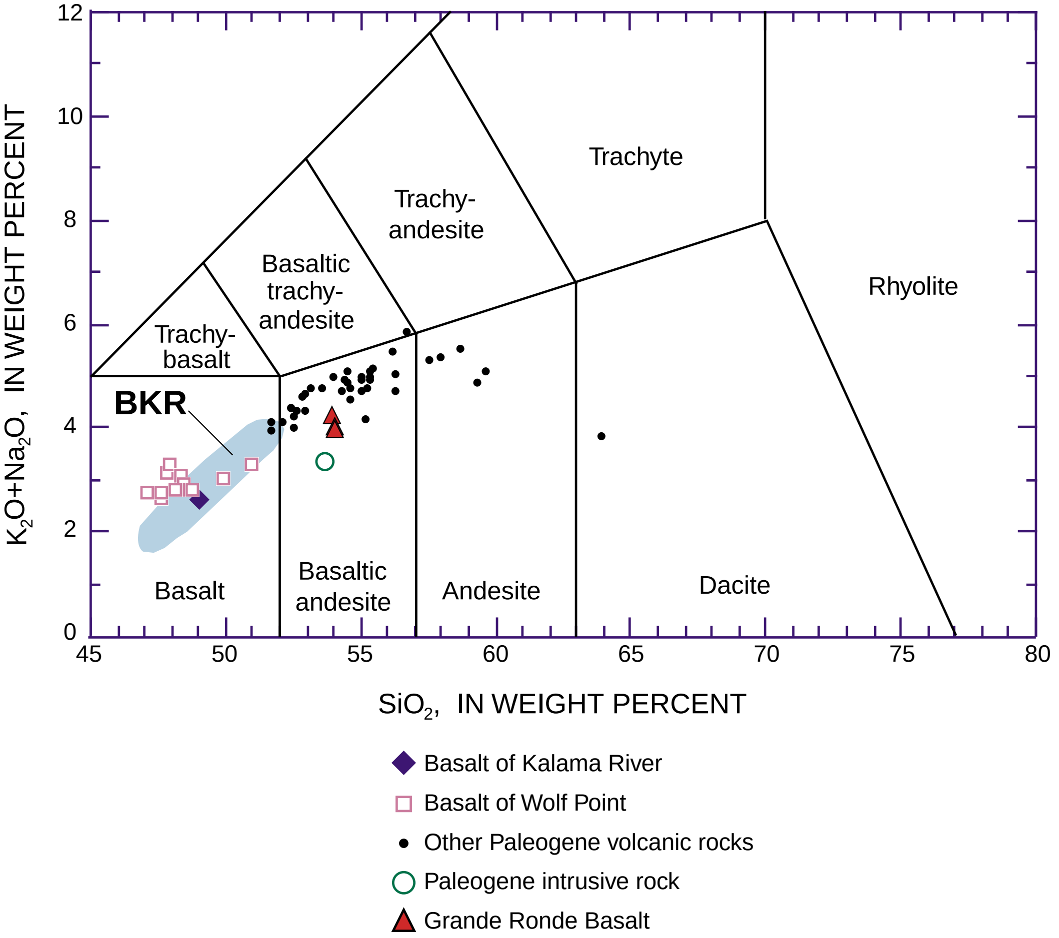

Figure 2. K_2O+Na_2O versus SiO_2 (recalculated volatile-free) for volcanic and intrusive rocks from Silver Lake 7.5' quadrangle showing IUGS classification (Le Bas and Streckeisen, 1991). Shaded area labeled BKR is compositional field for basalt of Kalama River (Tk) from Evarts and Ashley (1990a, 1991, 1992) and R.C. Evarts (unpub. data).

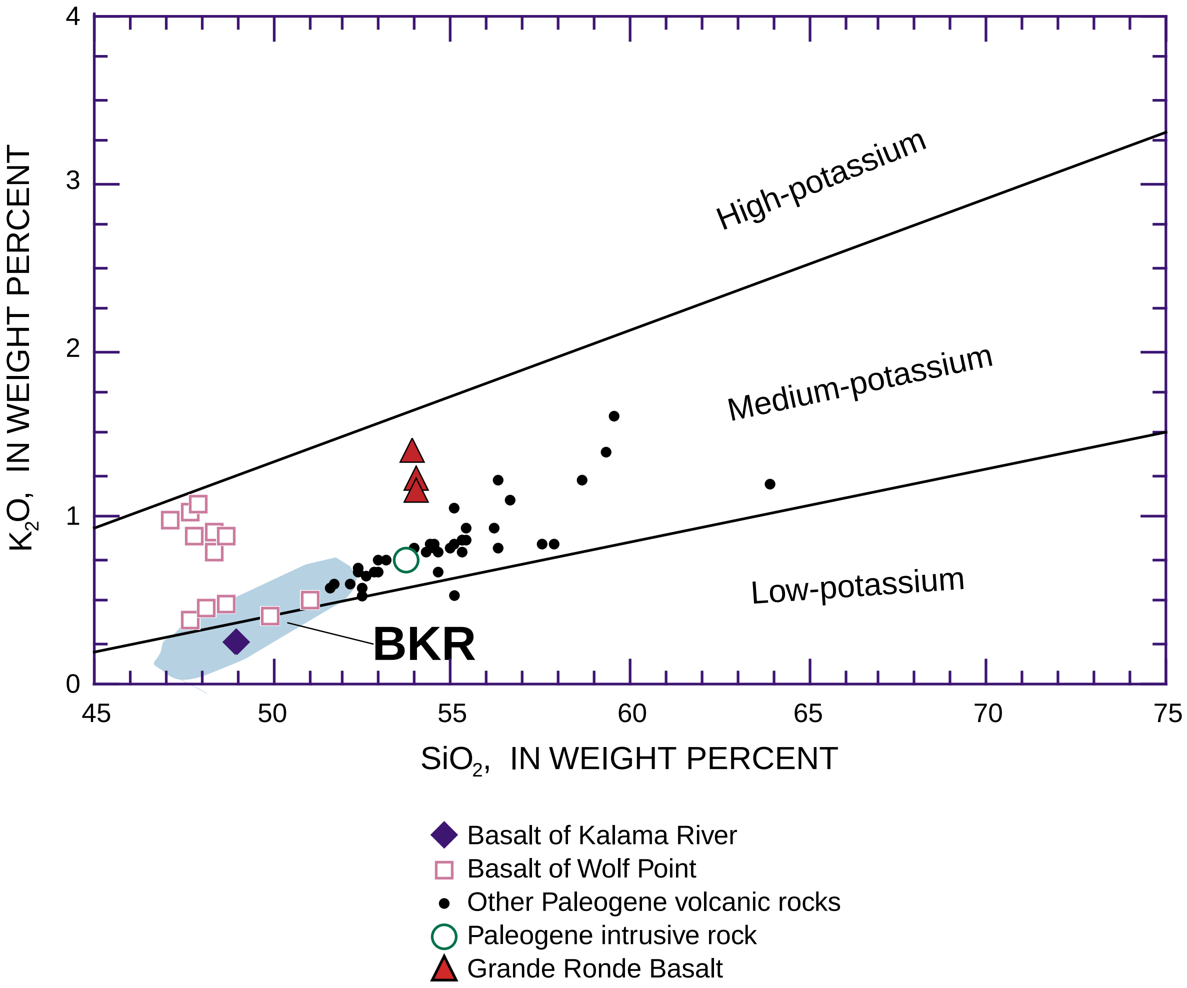

Figure 3. K_2O versus SiO_2 (recalculated volatile-free) for volcanic and intrusive rocks from the Silver Lake 7.5' quadrangle. Low-, medium-, and high-potassium fields from Gill (1981, p. 6). Shaded area labeled BKR is compositional field for basalt of Kalama River (Tk) from Evarts and Ashley (1990a, 1991, 1992) and R.C. Evarts (unpub. data).

typical. The unit's major- and trace-element chemistry closely resembles that of so-called enriched mid-ocean ridge basalts (Evarts, 1991; Evarts and Swanson, 1994). Uniformly low Sr contents of 200-300 ppm effectively discriminate the basalt of Kalama River from virtually all other Tertiary mafic lavas in the southern Washington Cascades (fig. 5).

Basaltic andesite, andesite, and mafic tuff

Flows and flow-breccia of basaltic andesite and minor andesite and basalt underlie most of the southwest part of the Silver Lake quadrangle. Isolated basaltic andesite flows are also found within the Toutle Formation. These flows and the associated volcaniclastic rocks are the earliest manifestations of voluminous Cascade arc volcanism in this area. Most of the flows are sparsely to moderately porphyritic rocks that contain phenocrysts of plagioclase and augite; many contain olivine as well. As a group, the basaltic andesites in this quadrangle are relatively titaniferous tholeiites (unit Tba, table 1) unlike Tertiary basaltic andesites elsewhere in the southern Washington Cascade Range (for example, Evarts and Ashley, 1990b, 1991). Their TiO_2 contents (1.8-2.6 weight percent TiO_2; fig. 6) are atypically high compared to most volcanic arc lavas (Gill, 1981); in this as well as certain other geochemical characteristics, such as low Ba/Nb (12-20), they more closely resemble oceanic island however, from the very high-TiO_2 tholeiitic basalts (the volcanic rocks of Grays River

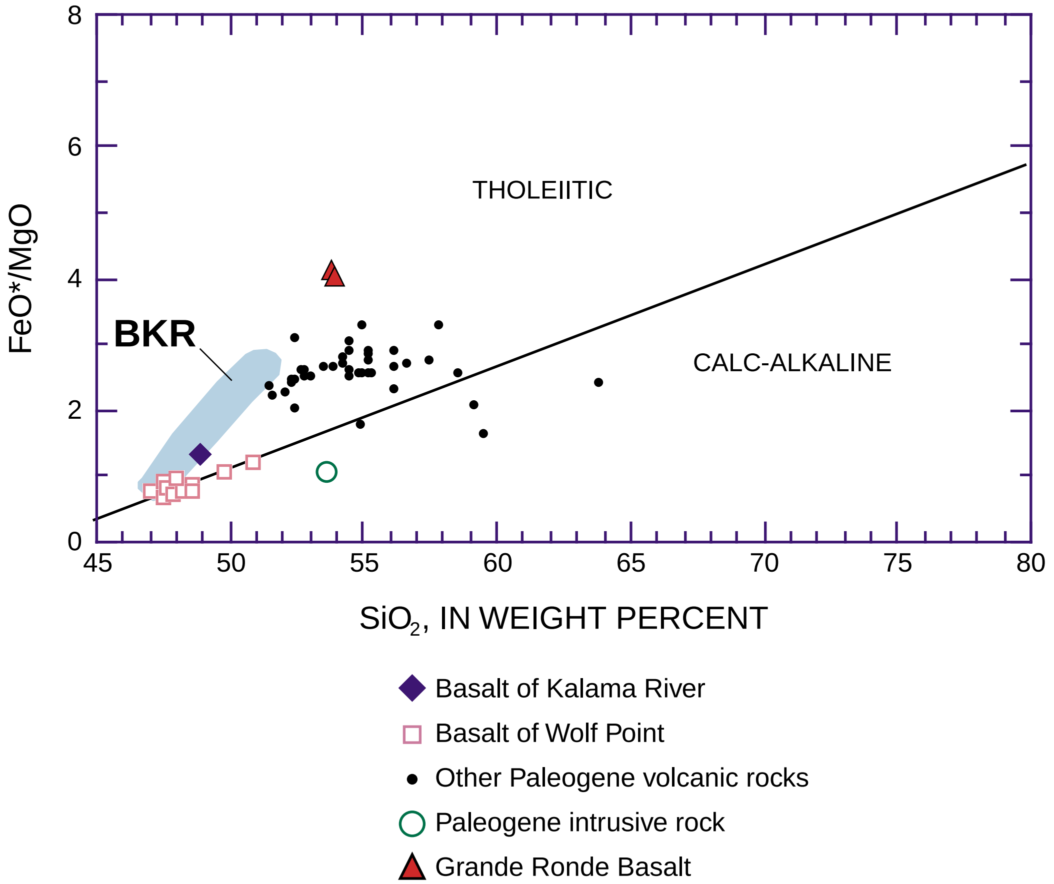

Figure 4. FeO*/MgO versus SiO_2 (recalculated volatile-free) for volcanic and intrusive rocks from the Silver Lake 7.5' quadrangle showing classification into tholeiitic and calc-alkaline rocks according to Miyashiro (1974). FeO*, total Fe as FeO. Shaded area labeled BKR is compositional field for basalt of Kalama River (Tk) from Evarts and Ashley (1990a, 1991, 1992) and R.C. Evarts (unpub. data).

of Phillips and others, 1989) that overlie the Cowlitz Formation west of the Cowlitz River (Phillips, 1987; Payne, 1998).

Although the basal basaltic andesite flows locally rest directly on arkosic sandstones of the Cowlitz Formation, in most places the lowest flows overlie or interfinger with distinctive mafic tuff and lapilli tuff beds. The massive to well-bedded, poorly sorted, mafic tuffs typically consist of angular, commonly scoriaceous basalt clasts cemented by abundant zeolites and yellowish clays. Most of the tuffs are thought to be hyaloclastites generated by phreatomagmatic eruptions. Nearly ubiquitous traces of quartz, muscovite, and hornblende in these tuffs indicate mixing with Cowlitz sands occurred during these explosive events. In some localities the clastic beds appear to grade upward into massive basaltic andesite flows, suggesting that the phreatomagmatic eruptions were triggered when subaerially erupted lavas flowed over water-saturated sands, probably near or at the late Eocene shoreline.

Volcaniclastic sedimentary rocks

Exposures of Paleogene volcaniclastic sedimentary rocks are scattered throughout the Silver Lake quadrangle, but only in the north half and near the southwest corner of the map area are they sufficiently abundant to form mappable units. Roberts (1958) assigned most of the volcaniclastic rocks in the quadrangle to the Toutle Formation. The type area of the Toutle Formation as designated by Roberts (1958) encompasses several geographically isolated exposures of diverse volcaniclastic rocks in

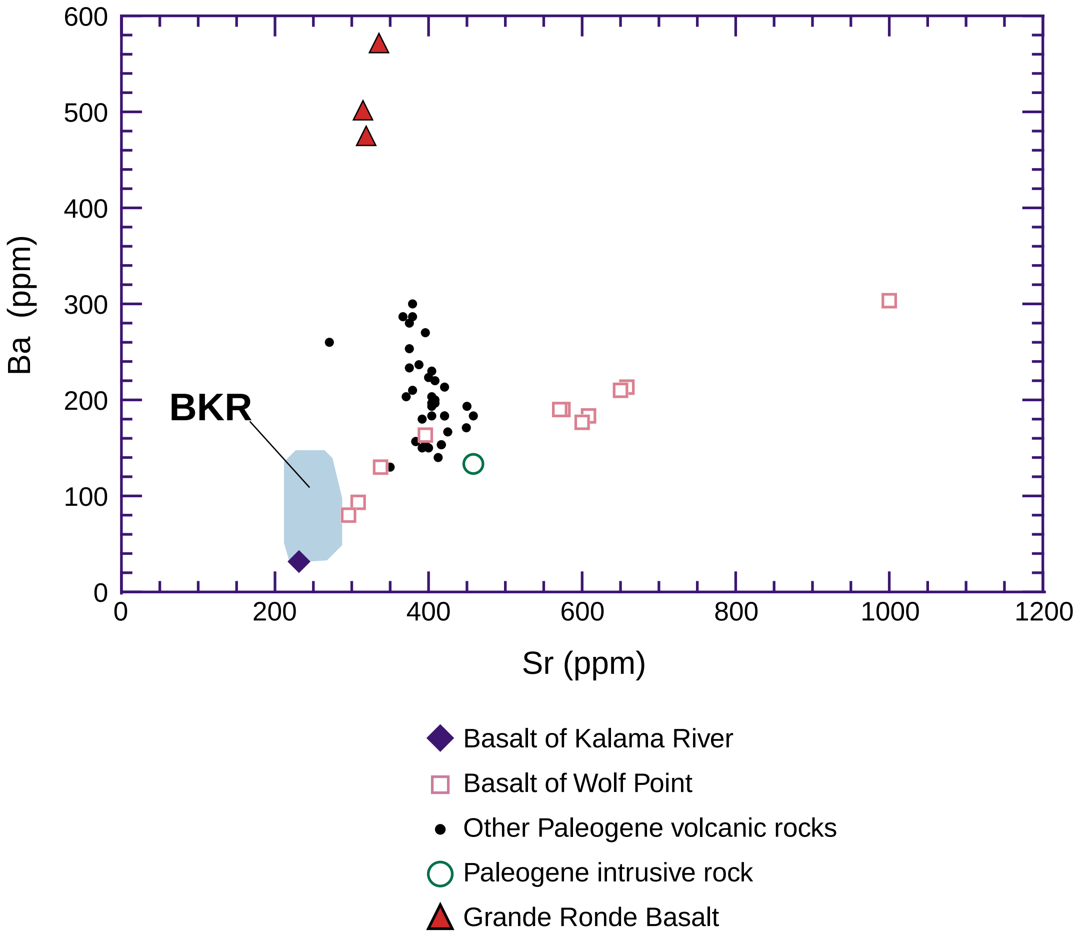

Figure 5. Ba versus Sr for volcanic and intrusive rocks from the Silver Lake 7.5' quadrangle. Shaded area labeled BKR is compositional field for basalt of Kalama River (Tk) from Evarts and Ashley (1990a, 1991, 1992) and R.C. Evarts (unpub. data).

the Silver Lake and adjacent quadrangles. Although not specified as such by Roberts (1958), a 175-m-thick section exposed in lower Cline Creek and on the hill immediately to the east was treated by him as the type section. This nearly flat-lying section rests depositionally on an irregular surface of olivine-basalt and basaltic andesite flows and is unconformably overlain by flows of porphyritic andesite and Grande Ronde Basalt.

May (1980) informally divided the Toutle Formation in lower Cline Creek valley into a lower, dominantly marine member and an upper continental member. The lower member, about 60 m thick, consists of dark green to brown, generally poorly sorted, volcanic sandstone and conglomerate, minor interbedded tuffaceous siltstone, and lithic-rich lapilli tuff and tuff breccia. The sandstones are composed chiefly of angular to subrounded grains of mafic and intermediate volcanic rocks, plagioclase, and Fe-Ti oxide. The conglomerates consist of subangular to well-rounded pebbles, cobbles, and small boulders (as large as 1 m) of basalt and andesite in a sandy to gritty matrix. Massive, green, lithic-rich lapilli tuff and tuff breccia constitute the lowest several meters of the section; they are well exposed along the banks of the Toutle River near the Tower Road bridge. Some of the sandstones contain traces of quartz, muscovite, biotite, and hornblende that indicate limited mixing of the volcanogenic debris with detritus derived from the same extrabasinal source that supplied the Cowlitz Formation. A few of the clastic beds contain a poorly preserved megafauna (Roberts, 1958; May, 1980) referable to the provincial Galvinian molluscan stage of late Eocene age (Armentrout, 1981). A paleoecological analysis of the fossil assemblages by May (1980) suggests deposition took place in a shallow marine environment, probably at water depths less than 40 m.

About 115 m of generally finer grained nonmarine beds overlie the marine sandstones and conglomerates east of lower Cline Creek (Roberts, 1958); these strata constitute the upper member of the Toutle Formation of May (1980). This sequence is dominated by tuffaceous and carbonaceous siltstone, claystone, sandstone, tuff, and lapilli tuff

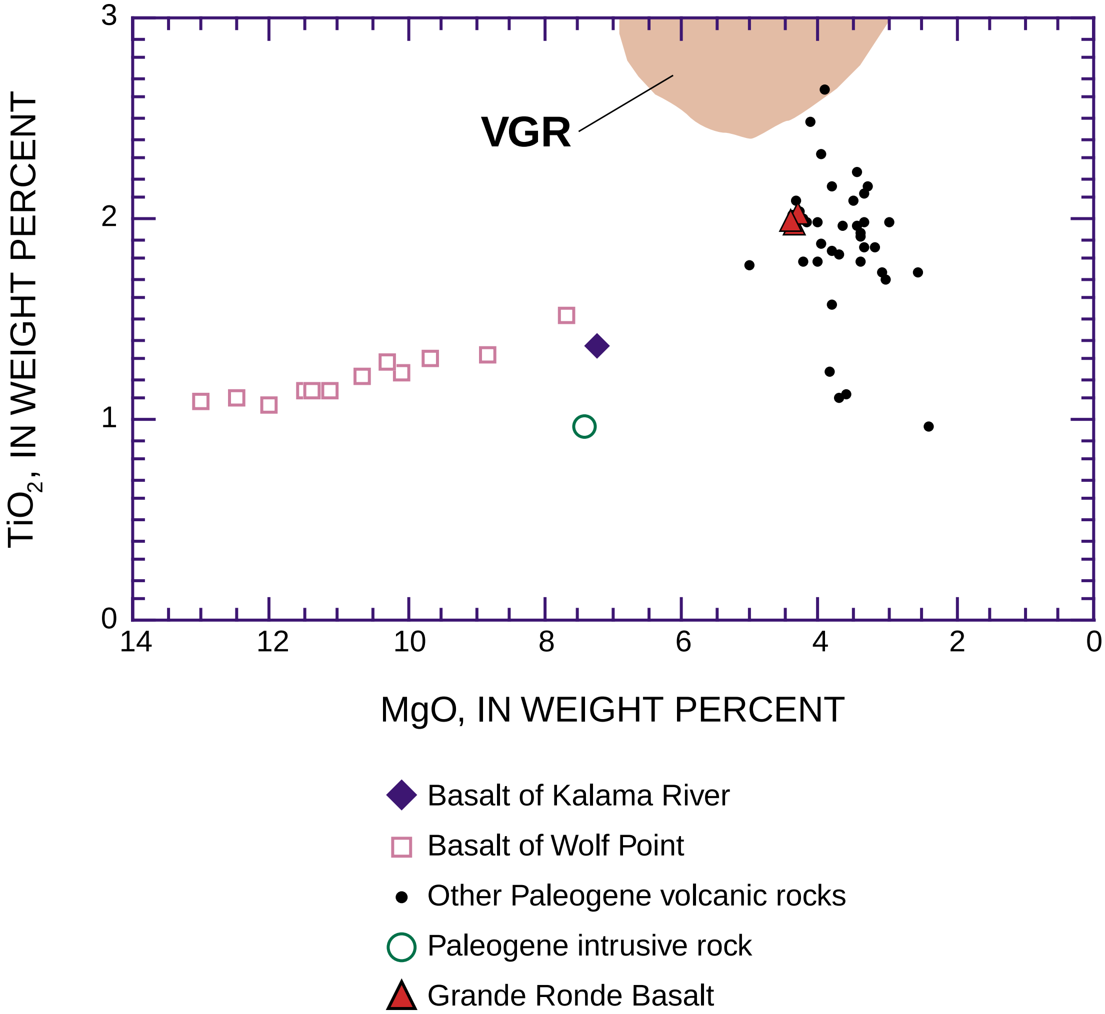

Figure 6. MgO versus TiO$_2$ (recalculated volatile-free) for volcanic and intrusive rocks from the Silver Lake 7.5' quadrangle. Shaded area labeled VGR is compositional field for volcanic rocks of Grays River from Phillips and others (1989) and R.C. Evarts (unpub. data). Note that some Wolf Point lavas contain more than 12 wt percent MgO and thus are picrites according to the revised IUGS classification (Le Bas, 2000).

but includes minor interbedded conglomerate, lignite, and a few intercalated basaltic andesite flows. The uppermost 50 m of the section includes two horizons containing beds of high-alumina clay intercalated with lignite seams (Glover, 1941; Popoff, 1955). The clay consists largely of kaolinite, gibbsite, and smectites; carbonaceous material and siderite concretions are common. Relict textures show that the clay beds are altered volcanic sandstones, siltstones, and pumiceous and lithic lapilli tuffs, some of which were tephra deposits (tonsteins). Well-preserved fossil leaves collected from continental beds of the Toutle Formation in the Silver Lake quadrangle and adjacent areas (Roberts, 1958) were assigned to the late Eocene Kummerian stage by Wolfe (1981). May (1980) inferred that the fine-grained upper part of the Toutle Formation near Cline Creek was deposited under fluvial, lacustrine, and paludal conditions on a low-relief coastal plain at the margin of the active Cascade volcanic arc.

A distinctive pumice-lapilli tuff herein designated the Cline Creek Tuff Member crops out east of Cline Creek. The tuff bed is the basal unit in May's (1980) upper member of the Toutle Formation, lying about 60 m stratigraphically above a basaltic andesite flow that defines the base of the formation and roughly 30 m above a horizon that yielded Galvinian mollusks (Roberts, 1958). The lapilli tuff is 16 m thick and consists chiefly of poorly sorted light gray to yellowish pumice and ash; a few dark angular lithic clasts are sparsely distributed through the unit and concentrated near the base. The tuff is nonwelded but indurated, forming a prominent light-colored cliff. The abundance, fresh appearance, and uncompacted nature of the vitric debris offer a striking contrast to the flaky, green, lithic-rich tuffs that are typical of the Tertiary Cascade section. Roberts (1958) describes the tuff as waterlain, but provides no evidence to support this interpretation. The massive appearance, very poor sorting, and angular nature of constituent pumice and lithic clasts are characteristic of subaerially emplaced pumice-flow deposits (Fisher and Schmincke, 1984). The tuff is dacitic (table 1, Map no. 51) and sparsely phyric; plagioclase phenocrysts 1-2 mm across constitute about 5 percent of the tuff, accompanied by about 1 percent each of augite and hypersthene. The plagioclase yielded an incremental-heating $^{40}Ar/^{39}Ar$ age of 37.4±0.2 Ma (table 2).

Roberts (1958) inferred an age range of late Eocene to early Oligocene for the Toutle Formation. However, an andesite that overlies and locally intrudes the Toutle Formation (unit Tahg) has been dated at about 35 Ma. This age and the age of the tuff of Cline Creek indicate the Toutle Formation is restricted to the Eocene epoch according to the timescale of Berggren and others (1995).

Correlation of isolated exposures of volcaniclastic beds elsewhere in the Silver Lake quadrangle with the putative type section of the Toutle Formation in Cline Creek is problematic because of the rapid facies changes that typify subaerial volcanic sequences (Cas and Wright, 1987; see discussion below of stratigraphic nomenclature). Scattered outcrops to the north of the type section consist predominantly of sandstone and conglomerate, whereas the semi-continuous exposures along the Toutle River east of Cline Creek are composed largely of well-bedded fine-grained strata. The distribution of facies suggests that the coarse-grained nearshore-marine sequence in Cline Creek grades eastward into finer-grained nonmarine beds. Poorly exposed volcaniclastic rocks in the southwestern part of the quadrangle include sandstone, conglomerate, and lapilli tuff. The stratigraphic position of these beds suggests they are older than those in the Cline Creek area. Because of their uncertain relationship with the type Toutle Formation, they are shown generically as volcaniclastic rocks (unit Tvs) on this map. Similarly, although the pumice-lapilli tuff of Sucker Creek closely resembles the Cline Creek Tuff Member, its stratigraphic position below olivine basalts of Roberts' (1958) Hatchet Mountain Formation demonstrates that it is an older deposit so it is excluded from the Toutle Formation.

Basalt of Wolf Point

The Hatchet Mountain Formation as originally described by Roberts (1958) consists of basalt, olivine basalt, and andesite. Of these, only the olivine-phyric basalt in the upper part of the unit is sufficiently distinctive lithologically and restricted stratigraphically to be useful for region-scale correlation. As discussed in detail below, the name Hatchet Mountain Formation is herein abandoned and the distinctive olivine-phyric basalt flows are informally named the basalt of Wolf Point. The unit is named for exposures on Wolf Point, a peak about 14 km southeast of the Silver Lake quadrangle (see fig. 1).

The olivine basalt is distinguished by the presence of conspicuous olivine as the dominant or sole phenocryst phase; the olivine almost invariably contains abundant minute octahedra of chromian spinel. Many flows contain anhedral to subhedral phenocrysts or crystal clots of augite as well. Plagioclase, however, which is a nearly universal phenocryst phase in Tertiary volcanic rocks of the Cascade Range, is typically restricted to the groundmass of these basalt flows. Where the flows do contain large plagioclase crystals, the feldspars are generally ridden with inclusions, partly resorbed or reversely zoned, and are probably xenocrysts; some of these same flows contain amoeboid quartz xenocrysts. Flows of the basalt of Wolf Point almost invariably exhibit a pronounced flow foliation. Many are diktytaxitic, with the interstitial voids filled with zeolites or greenish, iron-bearing smectite. The groundmass of some flows contains fine-grained phlogopite, whereas others contain hypersthene oikocrysts that enclose smaller plagioclase and pyroxene grains.

Chemically, the basalt of Wolf Point constitutes a medium-K_2O suite (R.C. Evarts, unpub. data) with relatively low TiO_2 contents (<1.5 wt percent TiO_2; fig. 6) that characterize volcanic-arc basalts (Perfit and others, 1980; Gill, 1981). Analyzed flows from the Silver Lake quadrangle (table 1; figs. 2, 3, 4) are typical of the formation as a whole except that xenocrystic basaltic andesites are not found here. Most flows are relatively primitive basalts, with FeO*/MgO less than 1, and some are picritic, containing nearly 15 percent olivine phenocrysts and having MgO contents as high as 13 wt percent (fig. 6). A characteristic feature of the basalt of Wolf Point is the large variation in concentrations of large-ion lithophile elements, even among samples with similar FeO*/MgO. K_2O contents in basalts from the Silver Lake quadrangle range from 0.4 to 1.1 wt percent; variations in Ba (80-300 ppm) and Sr (295-1000 ppm) are even more pronounced (table 1; fig. 5).

Regionally, the basalt of Wolf Point appears to occupy a relatively restricted stratigraphic range. However, it exhibits significant along-strike variations in thickness, interfingers with other volcanic rocks, and locally pinches out entirely (Evarts and Ashley, 1991; 1992; R.C. Evarts, unpub. mapping). The thickness variations probably reflect both the original form of volcanic cones and the accumulation of flows in canyons eroded into older volcanic rocks. A basalt of Wolf Point flow south of Silver Lake yielded a whole-rock incremental-heating $^{40}Ar/^{39}Ar$ age of 38.8±0.3 Ma (R.J. Fleck, oral commun., 1999).

Andesite of Hollywood Gorge

Massive, dark gray to black, strikingly porphyritic pyroxene andesite unconformably overlies and (or) intrudes volcaniclastic rocks in the northern part of the quadrangle. The andesite is well exposed in the Hollywood Gorge of the Toutle River where it appears to constitute a single body at least 60 m thick. Local exposures at river level along Hollywood Gorge reveal massive andesite in sharp conformable contact with flat-lying sedimentary rocks of the Toutle Formation. The absence of flow breccia zones, as well as the coarse, crudely columnar jointing pattern, suggests that the andesite is an invasive flow that burrowed into unconsolidated sediments to form a shallow sill. Probable invasive-flow relations were observed along the upper contact of the andesite in a quarry just west of Hollywood Gorge and in natural exposures near Coalbank Rapids in the adjacent Toutle quadrangle.

Roberts (1958) interpreted the andesite of Hollywood Gorge to be a Miocene unit. He recognized that the Grande Ronde Basalt that unconformably overlies the Toutle Formation near Cline Creek was probably correlative with the middle Miocene Columbia River(?) Basalt of Snavely and others (1958) and apparently miscorrelated this flow with older aphanitic flows in the South Fork Toutle River to the east of the Silver Lake quadrangle. Near Signal Peak, these aphanitic flows are overlain by strikingly porphyritic andesites similar to those at Hollywood Gorge, so Roberts considered the andesite to be Miocene as well. However, Phillips and others (1986) obtained a conventional K-Ar age of 34.5±0.5 Ma on plagioclase separated from andesite collected near Hollywood Gorge. Subsequently, Phillips (1987) described regional stratigraphic relations that, together with chemical analyses and the K-Ar age, demonstrated that most of the rocks mapped as Miocene by Roberts (1958) were actually late Eocene. Plagioclase separated from an andesite outcrop above Coalbank Rapids, about 1.2 km east of the Silver Lake quadrangle, yielded an $^{40}Ar/^{39}Ar$ age of 35.2±0.3 Ma, confirming a late Eocene age for this unit (R.J. Fleck, oral commun., 1999).

Diorite

The only holocrystalline intrusion mapped in the Silver Lake quadrangle is a small body of medium-grained pyroxene diorite that crops out near the southwestern corner of the quadrangle. The body cannot have been a feeder for local flows because the chemistry of the diorite does not resemble that of any extrusive rock in the quadrangle (table 1; figs. 2, 4, 6).

ISSUES OF STRATIGRAPHIC NOMENCLATURE

The new detailed mapping in this and adjacent quadrangles necessitates revisions to the stratigraphic nomenclature previously employed in the Silver Lake quadrangle. The Hatchet Mountain Formation of Roberts (1958) is formally abandoned. Roberts' (1958) Toutle Formation is retained but is restricted to those strata that can be traced directly into the type section at Cline Creek. In addition, strata that Roberts (1958) inferred to be of Miocene age are shown to actually be late Eocene. Abandonment of the Hatchet Mountain Formation follows the suggestion of Phillips (1987), but his reassignment of these rocks to the Goble Volcanics, on the basis of lateral contiguity and priority, is not adopted. The detailed work in the Silver Lake and adjacent quadrangles demonstrates that stratigraphic relations are more complex than inferred by Roberts (1958) and Phillips (1987). Packages of volcanic and sedimentary strata that they considered to be bounded by disconformities can be shown to interfinger, and most rock types recur repeatedly throughout the stratigraphic section so that lithology has little stratigraphic significance.

As defined by Roberts (1958), the Hatchet Mountain Formation consists of "lava flows, flow breccias, pyroclastic rocks, and tuffaceous sedimentary rocks … typically exposed in the vicinity of Hatchet Mountain …" The Hatchet Mountain Formation depositionally overlies nonvolcanic arkosic sandstones of the Cowlitz Formation and is separated from overlying volcaniclastic rocks of the Toutle Formation by an erosional unconformity. According to Roberts (1958), "The Hatchet Mountain Formation consists of three relatively distinct petrologic groups of volcanic rocks separated either by thin sedimentary deposits or local erosional unconformities. In chronological order they are the porphyritic basalt sequence, the porphyritic andesite sequence, and the olivine basalt sequence." Roberts described the lithology and distribution of these sequences (equivalent to members) but did not portray them on his geologic map. As he noted, the porphyritic andesite sequence is absent from the area of this quadrangle, and his olivine basalt sequence lies unconformably on his porphyritic basalt sequence.

Most of the rocks in the Silver Lake quadrangle that Roberts (1958) mapped as the Hatchet Mountain Formation belong to his porphyritic basalt sequence. Their chemistry (table 1; fig. 2) indicates that they are mostly basaltic andesites and they are shown as such (unit Tba) on this map. Many of these flows exhibit relatively high TiO_2 contents compared to typical Tertiary basaltic andesites in the southern Washington Cascade Range. To the north, as much as 50 m of sandy to pebbly volcaniclastic sedimentary rocks are present at the base of the porphyritic basalt sequence, resting on and locally interfingering with the subjacent Cowlitz Formation, but correlative rocks (unit Tmt) are scarce in this quadrangle. Flows petrographically equivalent to Roberts' (1958) olivine basalt sequence (unit Twp on this map) underlie an area extending from Stankey Creek to near the southeast corner of the quadrangle (some of these basalts were mapped by Roberts as middle(?) Miocene volcanic rocks, apparently because he miscorrelated the pumice-lapilli tuff of Sucker Creek with the similar tuff in Cline Creek). Roberts (1958) assigned most volcaniclastic rocks in the Silver Lake and adjacent quadrangles to his Toutle Formation. The base and top of this formation are described as erosional unconformities that separate the clastic rocks from subjacent basalts of the Hatchet Mountain Formation and from superjacent basalt and andesite flows of inferred middle Miocene age (Roberts, 1958).

Observed stratigraphic relations within the Silver Lake quadrangle are generally consistent with Roberts' (1958) stratigraphy in that olivine-basalt flows appear to overlie basaltic andesite flows and, in at least two localities along the Toutle River, are overlain by volcaniclastic rocks of the Toutle Formation. In quadrangles to the south and east, however, stratigraphic relations among these rock types are not as simple (R.C. Evarts, unpub. mapping). In the Toutle quadrangle, high-TiO_2 basaltic andesite flows crop out at higher stratigraphic levels than the olivine basalt, and both rock types are interbedded with volcaniclastic rocks that Roberts (1958) mapped as Toutle Formation, producing apparently inverted stratigraphic successions. Similarly, the pumice-lapilli tuff of Sucker Creek, which Roberts (1958) mapped as the Toutle Formation, presumably because of its similarity to the pumice-lapilli tuff near Cline Creek, is overlain by basaltic andesite and olivine basalt that are indistinguishable from those in the supposedly subjacent Hatchet Mountain Formation; $^{40}Ar/^{39}Ar$ age determinations confirm that the two tuffs are not equivalent (R.J. Fleck, oral commun., 1999). Thus rock units that Roberts (1958) believed were deposited sequentially are in significant part coeval.

Phillips (1987) recognized these problems and attempted to address them in his compilation of the Mount St. Helens 30 x 60-minute quadrangle. Although he portrayed the Toutle Formation on his map, he was unable to trace it as a discrete stratigraphic unit beyond Roberts' (1958) map area. As noted above, even strata mapped as Toutle Formation by Roberts (1958) are not stratigraphically equivalent. A formation that cannot be traced beyond its type area serves little purpose. Thus abandonment of the Toutle Formation as a formal lithostratigraphic unit would seem appropriate. However, the Toutle Formation has become entrenched in the literature, being viewed as the continental correlative of the marine Lincoln Creek Formation of the Washington Coast Range, largely because of its well-known flora and molluscan fauna (Armentrout, 1981, 1987; Wolfe, 1981; Rau and Johnson, 1999). All of the reported fossil collections have come from the type section at Cline Creek or from strata that can be traced directly into it. Therefore, this map follows Phillips (1987) in retaining the Toutle Formation but restricting it to those strata that can be confidently correlated with those of the Cline Creek section.

Phillips (1987) did not show the Hatchet Mountain Formation on his regional map. Phillips and Kaler (1985) traced more-or-less continuous exposures of Tertiary volcanic rocks between the type areas of the Hatchet Mountain Formation of Roberts (1958) and the Goble Volcanics of Wilkinson and others (1946). Phillips (1987) therefore considered the two units to be equivalent and reassigned all these rocks to the Goble Volcanics, abandoning the Hatchet Mountain Formation on grounds of priority. This map follows Phillips (1987) in abandoning the Hatchet Mountain Formation. However, detailed regional mapping (R.C. Evarts, unpub. data) indicates that neither the Goble Volcanics as originally defined by Wilkinson and others (1946) nor the modifications proposed by Phillips (1987) provide workable solutions to stratigraphic nomenclature in the western Cascade Range.

These problems illustrate the difficulties of consistently applying formal stratigraphic nomenclature in ancient subaerial volcanic terranes such as the western Cascade Range. These terranes are characterized by rapid facies changes, numerous erosional unconformities, an absence of fossils, and the occurrence of lithologically similar rock types at multiple stratigraphic levels (Cas and Wright, 1987; Evarts and others, 1987). In such areas coherent lithologic units are typically of limited extent, and correlations between noncontiguous exposures based on lithology alone are suspect. Because of this, most of the Paleogene rocks are designated on this map simply by lithology; informal stratigraphic names are applied to strata that are distinctive locally. In general, few sections in the Tertiary volcanic sequence of the western Cascade Range are sufficiently unique in lithology and widespread in distribution to justify a status as formal stratigraphic units. The basalt of Kalama River and the basalt of Wolf Point, although treated informally here, are rare exceptions.

METAMORPHISM AND HYDROTHERMAL ALTERATION

The Paleogene rocks of the Silver Lake quadrangle have been subjected to zeolite-facies regional metamorphism, the general character of which is similar to but less intense than that described from other areas in the southern Washington Cascade Range (Fiske and others, 1963; Wise, 1970; Evarts and others, 1987; Evarts and Swanson, 1994). This region-scale metamorphism reflects burial of the late Eocene rocks by younger volcanics within the relatively high-heat-flow environment of an active volcanic arc. The low intensity of alteration in strata of this quadrangle compared to areas farther east presumably relates to their position on the west fringe of the Paleogene volcanic arc, as evidenced by the scarcity of intrusions, and to shallower burial depths. The extent of replacement of igneous minerals by secondary phases ranges from incipient to complete; glass-rich, permeable, silicic volcaniclastic rocks are the most susceptible. In lava flows, the primary effect of the very low grade metamorphism is the nearly universal development of clay minerals and zeolites replacing labile interstitial glass, filling vesicles, and deposited on joint surfaces. Vesicular flow-breccias are much more altered than associated flow interiors. Feldspar typically displays partial alteration to clay minerals and (or) zeolites along fractures and cleavage planes, although plagioclase in the massive andesite of Coalbank Rapids is virtually pristine. Olivine phenocrysts in most basaltic andesites are totally replaced by smectite with or without hematite and calcite; alteration of the abundant olivine in basalt of Wolf Point flows, however, is incomplete. Primary augite and Fe-Ti oxides are largely unaffected by the zeolite-facies metamorphism. Hypersthene phenocrysts in pyroxene andesite flows commonly exhibit minor replacement by dark brown smectite.

Pervasive alteration of permeable volcaniclastic rocks manifests itself in the extensive replacement of detrital grains by clay minerals and zeolites and the widespread development of clay and zeolite cements. The abundant vitric debris in tuffaceous beds is typically altered to green, iron-rich smectites. In contrast, the pumice-lapilli tuffs of Cline Creek and Sucker Creek appear virtually unaltered except for hydration of original glass (table 1, Map no. 50). The high-alumina Cowlitz clay deposits were produced by late Eocene weathering processes and do not reflect subsequent zeolite-facies conditions (Nichols, 1943; Allen and Nichols, 1946; Popoff, 1955).

Arkosic sedimentary rocks of the Cowlitz Formation exhibit relatively minor zeolitization. This stems from their paucity of reactive volcanic glass and abundance of chemically resistant quartz; furthermore, framework grains in some sandstone beds seem to have been protected from further alteration by early deposition of sparry calcite cements. Dissolution of the carbonate under the current weathering regime is responsible for the friable nature of Cowlitz sandstones.

The most common zeolites in the Silver Lake quadrangle are members of the heulandite-clinoptilolite series, which is indicative of metamorphic temperatures no higher than 180°C (Cho and others, 1987).

No significant areas of hydrothermal alteration were found in the Silver Lake quadrangle, which is consistent with the paucity of intrusive rocks. The only evidence for circulation of hydrothermal fluids is the localized development of kaolinite replacing crushed rock within fault zones.

COLUMBIA RIVER BASALT GROUP

In middle Miocene time, between 17 and 12 Ma, huge volumes of tholeiitic flood basalts erupted from fissures in southeastern Washington and adjacent regions of Oregon and Idaho. The largest flows moved down an ancestral Columbia River valley into the Portland basin (Tolan and others, 1989), and some of them exited the basin and flowed to the Pacific Ocean, taking a variety of paths to the coast (Snavely and others, 1973; Beeson and others, 1989). A few basalt flows evidently sent lobes northward into the Chehalis basin along a route roughly along the modern lower Cowlitz River valley. Post-Miocene erosion has stripped the basalt from most of this area, leaving only scattered remnants capping hills west of the river (Snavely and others, 1958; 1973; Livingston, 1966; Phillips, 1987). The four small outcrops in the Silver Lake quadrangle and another in the Castle Rock quadrangle (R.C. Evarts, unpub. mapping) are the only known occurrences of the Columbia River Basalt Group east of the Cowlitz River. As noted above, Roberts (1958) recognized the petrographic similarity of these rocks to the middle Miocene Columbia River(?) Basalt as mapped to the north by Snavely and others (1958). They are readily distinguished from the Paleogene volcanic rocks by their glass-rich, intersertal, microvesicular texture, general absence of alteration, and chemical composition, specifically their relatively low Al_2O_3 and high FeO*, K_2O, and Ba contents (table 1; figs. 3, 5). Analyses indicate that all of the Columbia River Basalt Group outcrops in this quadrangle belong to the relatively low TiO_2 Grande Ronde Basalt (Swanson and others, 1979; Mangan and others, 1986; Beeson and others, 1989; Reidel and others, 1989; Hooper, 2000). Although slight differences in composition among the outcrops are apparent (table 1, Map nos. 53-55), they are well within the normal intraflow variation of Grande Ronde Basalt flows (Mangan and others, 1986) so the scattered outcrops are probably remnants of a single flow. Because of its normal magnetic polarity (J.T. Hagstrum, written commun., 1999) and its relatively high MgO content of 4.4 wt percent (table 1), this flow is assigned to the member of Sentinel Bluffs, which is equivalent to the Sentinel Bluffs unit of Reidel and others (1989).

WILKES FORMATION

Roberts (1958) named the Wilkes Formation for a sequence of semiconsolidated, nonmarine, commonly carbonaceous claystone, siltstone, sandstone, and minor pebbly conglomerate, airfall tuff, and lignite that underlies the Wilkes Hills in the northwestern part of the Silver Lake quadrangle. The Wilkes Formation unconformably overlies Paleogene rocks and the Grande Ronde Basalt in the northern part of the quadrangle. It is as much as 230 m thick in its type area but thins southward. South of Silver Lake the formation is limited to isolated patches that are probably erosional remnants of a once-continuous mantle. Because it is poorly lithified and clay-rich, the Wilkes Formation is highly susceptible to erosion, and good exposures are largely restricted to recent roadcuts. In many localities the formation is recognized only as a deposit of dense, light-colored, semiplastic clay, some of which has likely been transported and redeposited on topographically flat or low-lying surfaces. North of Toutle River, the Wilkes Formation can be difficult to differentiate from lithologically similar Eocene strata. Distinguishing features of the Wilkes Formation include the presence of quartz, green hornblende, and biotite, which are rare to absent in the older beds, and the presence of relatively fresh feldspar even in otherwise thoroughly weathered clays.

Stratified volcanic sandstones and siltstones are the dominant lithologies in the Wilkes Formation. They consist primarily of volcanic lithic fragments, plagioclase, and magnetite, with lesser amounts of pumice, quartz, pyroxene, hornblende, and rare biotite. Silicic ash was probably a major component of many beds, but intense postdepositional weathering has reduced the vitric debris to mottled, limonite-stained, smectitic or kaolinitic clay. Plant debris is common, especially in the finer-grained beds, and woody lignite forms beds 1 to 2 ft thick. Locally interbedded with the volcaniclastic deposits are beds of friable micaceous arkose that resemble Cowlitz Formation sandstones, from which they may have been derived (some contain detrital garnet and kyanite). Thin beds and lenses of conglomerate contain well-rounded pebbles of aphyric and porphyritic intermediate and silicic volcanic rocks in a gritty to sandy matrix that compositionally resembles associated sandstones. Although water-borne and airfall ash constitutes a significant proportion of the Wilkes Formation, coarser tephra is scarce; however, beds composed of hornblende-dacite pumice lapilli have been found in Wilkes sections to the east in the Toutle quadrangle.

Sedimentologic features such as widespread crossbedding and scour-and-fill channels in sandstones and conglomerates, thin, varve-like bedding in finer-grained deposits, and woody lignite beds indicate that the Wilkes Formation records deposition in low-energy fluvial, lacustrine, and swampy environments. Interbedded tephra signifies contemporaneous silicic volcanism, but its fine grain size indicates that eruptive vents were located many kilometers from the Wilkes depositional basin. Leaf fossils collected from localities in the lower part of the formation north of the map area have been assigned a middle to late Miocene age (Roberts, 1958; Phillips, 1987).

GLACIAL AND ALLUVIAL DEPOSITS

LOGAN HILL FORMATION

The Logan Hill Formation was named by Snavely and others (1958) for surficial deposits of unconsolidated and deeply weathered gravel and sand near Chehalis, about 40 km north of the Silver Lake area. Because till-like diamicts are locally interbedded with Logan Hill Formation gravels, the formation is inferred to be of glaciofluvial origin (Snavely and others, 1958; Roberts, 1958; Easterbrook, 1986). Roberts (1958) mapped several large areas of Logan Hill Formation in the lower Cowlitz River valley west of the Silver Lake quadrangle. He interpreted these occurrences as erosional remnants of an early Pleistocene outwash fan deposited by the Cowlitz River system.

The deposits mapped as Logan Hill Formation in the Silver Lake quadrangle are pebbly and cobbly gravels similar in lithology and weathering characteristics to those that Roberts (1958) mapped as Logan Hill Formation. The small areas of Logan Hill Formation that cap ridgecrests in the Wilkes Hills are probably erosional outliers of the deposits mapped by Roberts (1958). More extensive gravel deposits underlie the dissected, low-relief surface bordering the Toutle River east of Stankey Creek. These may be distal deposits of a Cowlitz River outwash train or may be coeval outwash transported down the ancestral Toutle River. The topographic position and deep weathering of the Logan Hill Formation indicate it is probably a lower Pleistocene deposit possibly correlative with the Orting Drift, the oldest glacial unit in the Puget Sound area (Crandell and Miller, 1974; Easterbrook, 1986). The Orting Drift is believed to have been deposited between 1.87 and 2.48 Ma (Easterbrook, 1994). Some of deposits shown as Logan Hill Formation on this map may be younger and perhaps correlative with the middle Pleistocene Wingate Hill Drift of Crandell and Miller (1974).

Owing to the deep weathering, exposures of Logan Hill Formation gravels are scarce; in most places the unit was identified from a lag deposit of resistant clasts such as felsic volcanics, granodiorite, hornfels, vein quartz, and tourmalinite. All these rock types are found upstream in the Cowlitz and Toutle River valleys, supporting a Cascadian source for the gravels. It consists essentially of fine-grained black schorl + quartz and was almost certainly eroded from areas of hydrothermal alteration associated with large Miocene granitic intrusions such as the Spirit Lake pluton north of Mount St. Helens (Evarts and Ashley, 1993). Roberts (1958) noted the difficulty of separating the Wilkes Formation from the younger Logan Hill Formation because of the deep weathering that has affected both units. However, the larger clast size and distinctive clast types of Logan Hill Formation gravels serve effectively to distinguish them from the Wilkes Formation.

DEPOSITS OF MOUNT ST. HELENS VOLCANO

Eruptive activity at the stratovolcano of Mount St. Helens, centered about 45 km east-southeast of Silver Lake, has profoundly influenced the depositional history of the Toutle River system (Scott, 1988a, b, 1989). Deposits exposed along the river in the Silver Lake quadrangle record some of the oldest eruptive activity at Mount St. Helens, as well as some of the youngest (fig. 7). They include deposits left by lahars that moved through the Toutle River system during major eruptive episodes at the volcano and alluvium that reflects aggradation in response to the huge influxes of volcanic debris produced by the eruptions.

Poorly exposed and moderately weathered sand and gravel form dissected terraces with surface elevations of 300 to 450 ft (90 to 140 m) on both sides of the Toutle River valley. These deposits are distinguished by the presence of sparse to abundant clasts of light-gray to white, coarsely and densely porphyritic, quartz- and biotite-phyric dacite. The only known sources for this rock type in the Toutle valley are Mount St. Helens and the neighboring older plug-dome of Goat Mountain (Evarts and Ashley, 1990b; M.A. Clynne, written commun., 2000). Voluminous quantities of biotite-bearing dacite were produced by Mount St. Helens early in its history, during the Ape Canyon eruptive stage of Crandell (1987), but no biotite-bearing dacite was erupted after about 36 ka. The deposits in the Silver Lake quadrangle that contain clasts of biotite-bearing dacite are considered remnants of an extensive valley fill of Ape Canyon age as described by Scott (1989). The distribution of this fill just north of the quadrangle indicates that, at times during the Ape Canyon eruptive stage, the Toutle River may have spilled northward into Salmon Creek rather than following its present course through Hollywood Gorge. Most of the sediments forming the Ape Canyon-age fill are probably alluvium, but poorly sorted beds exposed in roadcuts north of the Toutle River are composed almost exclusively of dacite and were likely deposited by lahars. Some of the alluvium, especially gravels that contain relatively few dacite clasts, is probably glacial outwash. The outwash is believed to be correlative with the Hayden Creek Drift, deposited during the penultimate glaciation in the southern Washington Cascade Range (Crandell and Miller, 1974).

Younger alluvial and lahar deposits underlie terrace surfaces along the Toutle River at elevations lower than the one of Ape Canyon age. They contain clasts of lithic and pumiceous gray and pink dacite bearing phenocrysts of hornblende, cummingtonite, and (or) pyroxene, but no biotite. These dacites are similar to those erupted from Mount St. Helens after Ape Canyon time. Although several large lahars moved through the Toutle River system during post-Ape Canyon time (Crandell, 1987; Scott, 1988b, 1989), not all left significant deposits in the Silver Lake quadrangle. Near the northeast corner of the Silver Lake quadrangle, an undissected terrace is inset against the Ape Canyon-age fill. Its surface lies approximately 25 m below the eroded top of the older deposits. Excellent cutbank exposures north of the Toutle River show that the terrace is constructed of lahars and lahar-runout deposits; the top of the sequence exhibits soil

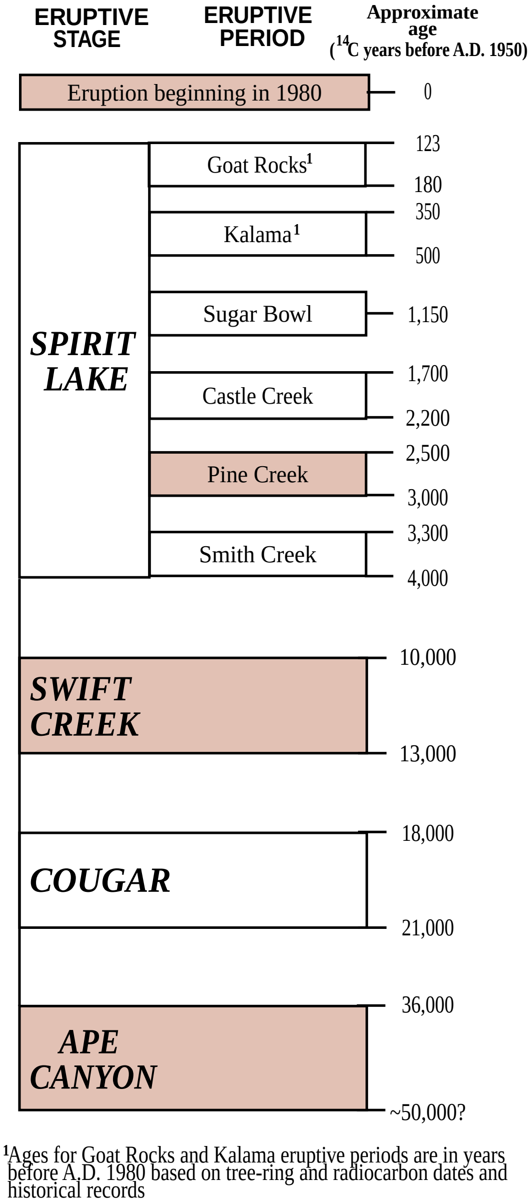

Figure 7. Diagram showing eruptive stages and periods of Mount St. Helens volcano, after Crandell (1987). Shaded boxes designate stages and periods corresponding to mapped deposits in the Silver Lake quadrangle; minor unmapped deposits of other ages, especially Cougar and Smith Creek, are probably present locally.

development to a depth of 1 m (Scott, 1989). The lahar deposits contain rare clasts of hypersthene- and hornblende-bearing dacitic pumice similar to tephra set J of Mullineaux (1996), which was erupted from Mount St. Helens about 10,500 and 12,000 radiocarbon years b.p. The extensive soil development and the presence of J tephra indicates these deposits were emplaced during the Swift Creek eruptive stage of Mount St. Helens (Scott, 1989). Downstream from Hollywood Gorge, poorly exposed sediments that contain Mount St. Helens-derived dacitic debris are mapped as Swift Creek-age deposits largely on the basis of their topographic position and relative dissection; they underlie surfaces lower than deposits containing biotite-bearing dacite of Ape Canyon age but higher than the prominent undissected terraces left by Pine Creek-age lahars. Large lahars also passed through the Toutle River system during the Cougar eruptive stage and the Smith Creek eruptive periods (Scott, 1989). Consequently, the areas shown as Swift Creek deposits on this map may include deposits left by these other lahars as well as younger and older alluvium.

The most dramatic changes in the Silver Lake quadrangle associated with eruptive activity at Mount St. Helens occurred during the Pine Creek eruptive period of Crandell (1987). As described by Scott (1988a, 1989), several huge lahars were triggered by repeated failure of a debris dam at Spirit Lake during a very short interval about 2,500 radiocarbon years b.p. The initial lake-breakout flood surges were transformed into lahars by incorporating alluvium from the streambed and riverbanks as they moved through the Toutle River system and into the Cowlitz River. The first of these lahars (PC 1) was the largest in the history of the Toutle River system; it attained an instantaneous peak discharge above Coalbank Rapids of 200,000 to 300,000 m^3/s, which is equal to that of the mid-course Amazon River at flood stage (Scott, 1989). The lahar backed up behind the constricted reach of the river at Coalbank Rapids and spread across the wide valley floor immediately upstream, leaving deposits that impounded a minor tributary, Outlet Creek, thus creating Silver Lake. The estimated peak discharge of PC 1 in the reach of the Toutle River that passes through the Silver Lake quadrangle was between 85,000 and 50,000 m^3/s, which was sufficient to clog the narrow Hollywood Gorge and inundate the wider valley bottom above. The deposits of this lahar and the three that followed in rapid succession are described in detail by Scott (1988a, b, 1989). About 15 m of Pine Creek-age lahar deposits accumulated in the broad area of aggradation above Hollywood Gorge. They consist primarily of very poorly sorted, matrix-supported, pebbly to cobbly deposits that typify the floodplain-facies of Scott (1988b). The deposits of PC 1 are distinguished by local zones of clast support (which thus resemble Scott's channel facies) and the presence of scattered megaclasts of hydrothermally altered dacite and black porphyritic andesite. The dacite is brecciated but otherwise similar to dacite domes at Mount St. Helens that predate the Pine Creek eruptive period; they are thought to have been eroded from the debris dam at Spirit Lake (Scott, 1988a). The andesite blocks, some more than 10 m across, were picked up by the lahar as it passed through the landslide complex at Coalbank Rapids. Downstream from Hollywood Gorge, the Pine Creek-age lahars incorporated progressively more river water and were transformed into lahar-runout (hyperconcentrated stream) flows (Scott, 1988a). The resultant sections are thinner and more heterogeneous than those upstream. They are dominated by massive to crudely stratified lahar-runout deposits, which are finer-grained and better sorted than the coeval lahar deposits, and intercalated alluvium.

Compared with many earlier events, the two lahars formed during the May 18, 1980 eruption of Mount St. Helens were small. In the Silver Lake quadrangle they were largely confined to the modern river channel and consequently deposited relatively little sediment. On this map, the distribution of these deposits is shown as of June 1980, the date of the aerial photographs used to compile the topographic base. Later stream action has thoroughly reworked and largely removed them. The first lahar, generated from pyroclastic flows in the headwaters of the South Fork Toutle River, had transformed into a lahar-runout flow by the time it reached Coalbank Rapids, leaving no more than 0.5 m of crudely stratified sand and granules along the river bank (Scott, 1988b). The second, larger, lahar was formed by dewatering of the debris-avalanche deposit in the North Fork Toutle River. It remained a debris flow as it passed through this quadrangle, depositing an unstratified, poorly sorted layer of sandy pebble gravel less than 2 m thick.

CATACLYSMIC FLOOD DEPOSITS

During the last glacial maximum in late Pleistocene time, an ice dam at Lake Missoula in Idaho and Montana failed repeatedly, each collapse generating enormous floods that coursed down the Columbia River to the sea (Bretz, 1925, 1969; Trimble, 1963; Allison, 1978; Baker and Bunker, 1985; Waitt, 1985, 1994; Allen and others, 1986; O'Connor and Baker, 1992). The floodwaters backed up into tributaries of the Columbia, such as the Cowlitz River, each flood depositing a layer of silt and fine sand. Multiple floods built up sequences of laminated silts as much as several tens of meters thick. Radiocarbon ages and tephrochronologic data indicate the floods occurred between about 15.5 and 12.7 ka (Waitt, 1994), although some evidence suggests that similar floods occurred in earlier times (McDonald and Busacca, 1988; McDowell, 1991; Zuffa and others, 2000).

Deposits of rhythmically bedded micaceous quartzofeldspathic silt and fine sand, similar to flood deposits elsewhere along the Columbia River, form terraces in the lower Cowlitz River valley between Kelso and Castle Rock (Phillips, 1987; Scott, 1989). The surfaces of these terraces are as high as 120 ft (40 m). Floodwaters deep enough to deposit these silts would have also extended into the lower Toutle River valley. Most fine-grained deposits left within the relatively narrow valley by the receding floodwaters have been flushed out by the river or buried beneath younger deposits such as the large Pine Creek-age lahars. However, a small remnant of micaceous silt in lower Stankey Creek provides compelling evidence that the glacial floodwaters did reach into the Toutle drainage, attaining an elevation of at least 230 ft (70 m).

ALLUVIAL, MASS WASTAGE, AND LAKE DEPOSITS

Terraces in the Toutle River valley record alternating periods of aggradation and downcutting that reflect the complex interplay between fluvial and volcanic processes. Most of the terrace deposits along the river consist of lahar and lahar-runout deposits that are the direct products of eruptive events at Mount St. Helens. Minor interbedded alluvium in terrace sections records reworking of the surface of the laharic deposits immediately after emplacement, but erosional regimes were probably quickly re-established. However, even eruptions that did not send lahars as far downstream as the Silver Lake quadrangle could have induced temporary aggradational episodes in the lower Toutle River owing to erosion and redeposition of sediment derived from laharic and pyroclastic flow deposits emplaced upstream. The terrace deposits now found 3 to 8 m above the active river may be products of such an event. They contain clasts of both Tertiary bedrock and Mount St. Helens volcanic rocks. The Mount St. Helens clast population includes basalt and andesite, which were erupted at the volcano only during the Castle Creek eruptive period, about 2,200 to 1,700 radiocarbon yrs b.p. (Crandell, 1987). Several lahars moved down the Toutle River system during the Castle Creek and Kalama (about A.D. 1480-1600) eruptive periods, but apparently none of them were large enough to reach the Silver Lake quadrangle (Scott, 1988b, 1989). Nevertheless, the influx of volcanic debris into the headwaters of the Toutle River could have triggered a short-lived period of aggradation downstream that constructed the low, subsequently incised terraces.

As noted above, the 1980 lahar deposits have since been extensively reworked by normal stream processes, and most of the areas shown as 1980 lahar deposits on the map are now underlain by active alluvium. Local accumulations of alluvial deposits also occupy low-gradient stretches of small active streams; these deposits typically consist of poorly to moderately sorted sand, silt, and fine-grained gravel composed of subrounded clasts of local bedrock.

All landslides shown on the map result from failure of weathered or poorly lithified Paleogene sedimentary rocks that underlie more resistant lava flows. The slides along the western quadrangle boundary south of the Spirit Lake Highway were generated by collapse of friable Cowlitz Formation sandstones that form the lower part of a westward-facing slope in the Castle Rock quadrangle. Slides elsewhere reflect failure of weathered, clayey volcaniclastic strata. The most conspicuous landslide in the map area, caused by slippage within subhorizontal beds of aluminous clay in the Toutle Formation, is located just west of Hollywood Gorge. Its well-developed hummocky surface is littered with angular blocks of Grande Ronde Basalt as large as 10 m across. Some field evidence suggests that the bedrock beneath this slide may be a large rotational slump block (K.W. Wegmann, written commun., 2001). Downslope transport is also widespread within areas underlain by poorly consolidated clays, silts, and sands of the Wilkes Formation, even where slope gradients are low. Movement of this cohesive, water-saturated, surficial unit is dominated by creep and minor slumping and flowage, so pronounced landslide morphology is rarely developed and rapidly destroyed by erosion.

Talus deposits have been mapped along the Toutle River and north of the eastern end of Silver Lake. In both locations the talus is composed of large angular blocks derived from the andesite of Hollywood Gorge where it overlies weathered, clayey volcaniclastic beds. The deposits near Silver Lake result from repeated slope collapse stemming from mechanical failure of the subjacent sedimentary rocks. The Toutle River accumulation formed as erosion of sedimentary rocks at stream level undercut the overlying andesite flow, causing blocks as large as 6 m across to topple into the stream.

Silver Lake, which was created about 2,500 years ago when the PC 1 lahar impounded Outlet Creek, sits in a small basin with only modest topographic relief. Although it covers more than 15 km^2, the lake is very shallow, little more than 3 m at its deepest, and contains vegetation-choked nearshore shallows fringed by marshes. The lake deposits comprise clay, silt, sand, and peat; the detrital components of the deposits consist of washed-in soil, clay-rich Wilkes Formation, and, in the eastern half of the lake, PC 1 deposits. The thickness of these deposits is unknown but probably no more than a few meters; like other lahar-impounded lakes, Silver Lake was probably never very deep (Scott, 1988a).

STRUCTURAL FEATURES

Except in local areas underlain by volcaniclastic rocks, measurable structural attitudes are sparse in the Silver Lake quadrangle. Most dips observed in Paleogene sedimentary rocks are low, commonly less than 10°, and strikes exhibit no consistent orientation. Platy parting recorded in flow-dominated sections shows greater variability but can be considered only a rough approximation of original horizontal. Gentle warping of beds is apparent in a few places, but most of these minor structures probably reflect primary dips or differential compaction. The overall impression is one of undulating subhorizontal Paleogene beds locally disrupted near faults. All bedding observed in the Miocene Wilkes Formation is essentially horizontal.

Roberts' (1958) geologic map shows the axis of a broad, gently north-northwest-plunging depression passing a few kilometers east of the Silver Lake quadrangle; he considered this fold to be the southern extension of the Napavine syncline that was mapped by Snavely and others (1958) near Chehalis, about 40 km to the north. He proposed that the structure grew continuously throughout most of the Tertiary and implied that the late Miocene and Pliocene Wilkes Formation accumulated within the gradually subsiding structural trough. During his regional reconnaissance work, Phillips (1987) traced a syncline in Tertiary volcanic rocks west-northwestward from near Mount St. Helens (fig. 1). He interpreted this structure as the continuation of the Napavine syncline of Roberts (1958). Detailed mapping at 1:24,000-scale (R.C. Evarts, unpub. mapping) confirms the existence of the fold mapped by Phillips. However, the limbs of this structure become progressively shallower to the west and the fold axis cannot be located with confidence east of the confluence of the forks of the Toutle River.

Limited exposures and complex stratigraphy hamper mapping of faults. Most faults shown on the map are projected from structures observed in roadcut and rockpit outcrops. Others are inferred from apparent discontinuities in bedrock stratigraphy. Not all such discontinuities are due to faulting, however; some, such as the marked contrast between the thick sedimentary section east of Cline Creek and the flow-dominated section south of the Toutle River, probably reflect Paleogene topographic relief. Many undetected faults probably exist, especially in areas underlain by flow-dominated sequences and by weakly consolidated surficial deposits. The fault system is dominated by a set of northwest-striking, high-angle structures that exhibit both vertical and lateral offsets; subsidiary faults strike northeast. The orientations of these faults are consistent with the regional pattern observed in both the Coast Range (Wells, 1981; Wells and Coe, 1985) and the Cascade Range west of Mount St. Helens (Evarts and Ashley, 1991, 1992; Evarts and Swanson, 1994; R.C. Evarts, unpub. mapping). This fault pattern is thought to accommodate the paleomagnetically-recorded rotation of crustal blocks resulting from oblique convergence along the Cascadia subduction zone (Wells and Coe, 1985; Wells, 1989, 1990; Beck and Burr, 1979; Hagstrum and others, 1999). Aeromagnetic anomalies in the southwest Washington

Cascade Range (R.J. Blakely, written commun., 1997) exhibit a strong northwest grain that appears to reflect faulting of Tertiary strata. One such anomaly, defined by a steep magnetic gradient, extends into the quadrangle near the east end of Silver Lake and may mark the location of a buried fault.

GEOLOGIC EVOLUTION

Paleogeographic reconstructions for western Washington during middle Eocene time portray a broad, low-relief coastal plain lying to the south and west of highlands in what is now Idaho, northern Washington, and eastern Oregon (Buckovic, 1979; Armentrout and Suek, 1985; Heller and others, 1987; Vance and others, 1987; Flores and Johnson, 1995; Johnson and Stanley, 1995). Rivers meandering across this plain carried sediments eroded from pre-Tertiary crystalline rocks of the highlands and deposited them in fluvial and deltaic settings along the continental margin. These nonvolcanic micaceous arkosic sediments constitute the Cowlitz Formation and correlative units. During this time, predominantly calc-alkaline volcanic activity, referred to as the Challis episode by Armstrong (1978), occurred throughout the Pacific Northwest. Eruptions at Challis volcanic centers to the east are recorded by widespread beds of airfall tuff scattered throughout the Cowlitz Formation and equivalent units. Local coeval volcanism built basaltic islands in offshore areas. These basalts, the volcanic rocks of Grays River of Phillips and others (1989), possess chemical characteristics similar to those of basalts erupted at hotspot-related oceanic islands. Patterns of sedimentation and volcanism in the Pacific Northwest during middle Eocene time were strongly influenced by a complex system of right-lateral strike-slip and extensional faults apparently formed in response to strongly oblique subduction (Johnson, 1985; Johnson and Stanley, 1995). Multiple unconformities in the Cowlitz Formation (Armentrout, 1987; Payne, 1998) also attest to Eocene tectonic instability along the continental margin in southwestern Washington.

In late middle Eocene time, about 40 Ma, volcanic activity in the Pacific Northwest began to concentrate in a belt parallel to the continental margin, and the Cascade volcanic arc was born (Heller and others, 1987; Duncan and Kulm, 1989; Evarts and Swanson, 1994; Bestland and others, 1999). Initially, isolated volcanic centers appeared within the fluvial-deltaic system and diverted west-flowing rivers around them, but by the late Eocene, the arc had grown into a permanent topographic barrier that effectively cut off the coast from the inland sources of nonvolcanic sediment. The increased volcanic activity produced a massive influx of volcanogenic debris into forearc basins, where arkose of the Cowlitz Formation is overlain by fine-grained volcaniclastic strata of the Lincoln Creek Formation (Armentrout, 1987). Once established, Cascade magmatism in southern Washington was vigorously and continuously active for at least 20 m.y. (Smith, 1993) and built up a pile of subaerially erupted volcanic rocks at least 7 km thick (Evarts and Swanson, 1994). Arc volcanism in Washington appears to have declined sharply in middle Miocene time, coincident with the main outpourings of Columbia River Basalt Group flood basalts to the east, and remained at a relatively low level into the Pliocene. Major compressional deformation and uplift occurred during this interval (Evarts and Swanson, 1994). A modest renewal in volcanic activity began about 5 Ma (Guffanti and Weaver, 1988; Smith, 1993). It is manifested in stratovolcanoes such as Mount St. Helens and in widespread monogenetic basaltic centers, most of which are younger than 1 Ma.

Throughout the development of the Cascade volcanic arc, the area of the Silver Lake quadrangle has occupied a position west of the volcanic front. Although most strata in the map area were deposited subaerially, regional stratigraphic relationships (Armentrout and Suek, 1985; Armentrout, 1987) indicate that, during much of the Cenozoic, the Pacific Ocean shoreline was located in the vicinity of the quadrangle. Thin tuff beds in the uppermost Cowlitz Formation to the west (Irving and others, 1996; Payne, 1998) may constitute the earliest manifestations of volcanic activity along the axis of the nascent Cascade arc. Continuing activity gradually built a pile of volcanogenic rocks that prograded westward, burying the Cowlitz fluvial-deltaic system. In the Silver Lake quadrangle, the lowest part of the volcanic sequence consists of massive to columnar-jointed tholeiitic basaltic andesite flows and interbedded mafic tuffs. The compositions of the tuffs indicate they were produced by explosive mixing of basaltic andesite magma and water-saturated arkosic sediments. Locally observed flow-tuff intergradations suggest these phreatomagmatic eruptions were generated when subaerially erupted lavas entered the shallow sea. The absence of compositionally equivalent dikes also suggests the flows come from outside the map area, presumably from the east. In a few places, the basaltic andesites and mafic tuffs are interbedded with or underlain by chemically distinctive basalts. These are distal flows of the basalt of Kalama River, a thick accumulation of flows interpreted as the product of a huge Eocene shield volcano constructed within the Cascade volcanic arc (Evarts and Ashley, 1991, 1992; R.C. Evarts, unpub. mapping). West of Mount St. Helens, the basalt of Kalama River overlies a section at least 200 m thick of subaerially emplaced calc-alkaline volcanics, indicating that, although only arkosic sands were being deposited in the Silver Lake area at this time, arc development was already well underway.

Subsequent arc development continued to reflect the complexly evolving interplay between volcanism, erosion, and tectonism. Olivine-phyric flows of the basalt of Wolf Point erupted from scattered extrusive centers. The relatively restricted compositional range of the basalts in this quadrangle suggests they erupted from the same center. No dikes of olivine phyric basalt have been found in the Silver Lake or adjacent quadrangles, which implies that the basalt flows entered the area from distant source vents. The distribution of the basalt of Wolf Point indicates that it fills canyons eroded into the older basaltic andesite flows. To the east, however, the two rock types are interbedded, so their respective eruptive episodes overlapped and the local disconformity between them probably represents little time. Unlike the basalt of Kalama River and the titaniferous basaltic andesites, the basalt of Wolf Point Basalt displays calc-alkaline compositions typical of volcanic arc magmas. The near-simultaneous production of strikingly different basaltic magma types, including some with strongly oceanic affinities, within a relatively small area of southwestern Washington poses an intriguing petrologic and tectonic problem. Basalt of oceanic character was not erupted again in southern Washington during the remainder of the Tertiary. This suggests that its production was a function of some unusual conditions that existed during the tectonic transition from extension-associated Challis volcanism to subduction-related Cascade volcanism. Interestingly, petrologically similar rocks have reappeared in southern Washington during Quaternary time. This recent activity has been interpreted as reflecting northward-propagating rifting of the arc or the progressively younger age of subducting oceanic lithosphere (Leeman and others, 1990; Conrey and others, 1997).

The Toutle Formation and similar Tertiary volcaniclastic units consist largely of epiclastic debris eroded from contemporaneous mafic and intermediate volcanoes of the Cascade arc. Minor quartz and mica signify a nonvolcanic component in the lower part of the Toutle Formation, but the voluminous volcanic output soon overwhelmed the depositional system. Interbedded pumice-lapilli tuffs attest to explosive eruptions at silicic volcanic centers. The low elevation of Toutle strata compared to the older volcanic rocks south of the Toutle River suggests that the sediments were deposited on the northern flank of a volcanic highland. Shallow-marine fossils in the lower part of the Toutle Formation signify a coastal environment, but clasts in the poorly sorted sandstones and conglomerates were likely transported in rivers. Together, these features suggest a river mouth-shoreface depositional setting in which sand and gravel delivered to the sea by a river flowing out of the arc were locally redistributed within a deltaic system. Redistribution of gravel in this environment was probably limited but transport of sandy detritus into deeper water farther west is recorded by volcaniclastic interbeds in the upper part of the Cowlitz Formation (Payne, 1998). Gradually, the nature of sedimentation in this area changed to finer-grained deposits characteristic of subaerial overbank settings, perhaps reflecting progradation of the delta. The upper part of the Toutle Formation represents heavily vegetated interdistributary bogs, lakes, and swamps, which received periodic influxes of airfall and waterborne ash and lapilli. Numerous drill holes in the area (Allen and Nichols, 1946; Popoff, 1955) show that the lower clay horizon rests on the irregular surface of a volcanic breccia, and a trench at the Cowlitz clay mine in 1994 revealed subhorizontal beds of volcaniclastic rocks and coal lapping out against a weathered, poorly sorted, debris-flow deposit. These relations suggest that a large lahar may have filled and diverted the river channel and formed a barrier behind which upper Toutle Formation sediments accumulated in a setting analogous to modern Silver Lake.

Shortly thereafter, a canyon was eroded into the sedimentary section and subsequently occupied by the 35-Ma andesite of Hollywood Gorge. Possible invasive relations observed in the adjacent Toutle quadrangle indicate the sediments were still unconsolidated and probably water saturated when the andesite flow entered the area, suggesting that erosion resulted from breaching of the debris dam rather than tectonism.

The Cascade volcanic arc in southern Washington remained vigorously active throughout Oligocene and early Miocene time (Evarts and others, 1987, 1994; Phillips and others, 1986; Smith, 1993; Evarts and Swanson, 1994). However, no rocks of this age range are found in the Silver Lake quadrangle. Although some deformation and erosion of younger strata undoubtedly occurred, the very low grade of metamorphism and low rank of coal beds are inconsistent with deep burial and exhumation. The absence of Oligocene and early Miocene rocks indicates the map area was located at the west edge of the active arc. Regional relations suggest that the axis of the arc gradually subsided as the arc evolved, thus trapping much of the output of the arc in proximal locations to the east of the quadrangle (Evarts and Swanson, 1994). Substantial quantities of volcaniclastic debris were also deposited offshore to form the Lincoln Creek Formation (Snavely and others, 1958; Armentrout and Suek, 1985; Armentrout, 1987) but little was apparently retained in subaerial parts of the forearc.

Aside from the subsidence of the central part of the Cascade volcanic arc, regional Paleogene deformation seems to have been relatively minor. Roberts (1958) believed that the gentle folding in the map area was distributed throughout the Tertiary, but there is no compelling evidence to support this inference. Evarts and Swanson (1994) cite evidence in the Cascade Range to the east that regional folding was largely confined to the middle Miocene, about 15-20 Ma; quite likely, the observed modest tilting in the Silver Lake quadrangle also occurred at this time. The age of faulting is essentially unconstrained. However, the northwest-dominant fault pattern is characteristic of most of southern Washington, and evidence from the Coast Range indicates that it reflects long-term vertical-axis block rotations in response to oblique subduction along the continental margin (Wells and Coe, 1985; Wells, 1989, 1990; Snavely and Wells, 1996; Wells and others, 1989).

Beginning about 17 Ma, voluminous flood basalts of the Grande Ronde Basalt issued from fissures east of the arc and, following the ancestral Columbia River, passed through a gap in the Cascade Range and entered western Washington and Oregon (Snavely and others, 1973; Beeson and others, 1989; Tolan and others, 1989; Beeson and Tolan, 1990). A few of the last Grande Ronde Basalt flows reached the ocean via a route along what is now the lower Cowlitz River valley, just west of the Silver Lake quadrangle. The valley at that time was wider and probably shallower than it is now, because basalt outcrops are found many kilometers from the present river. Subsequent uplift and erosion has stripped away most of Grande Ronde Basalt, leaving remnants on upland surfaces both in this quadrangle and to the south near Kelso (Livingston, 1966).

At roughly the same time as the first outpourings of the Columbia River Basalt Group, the level of volcanic activity in the Washington segment of the Cascade arc appears to have precipitously declined (Smith, 1993; Evarts and Swanson, 1994). Relatively minor late Miocene and Pliocene volcanism is evidenced by scattered hypabyssal intrusions near the east margin of the Cascade Range and by tuffaceous deposits interbedded with basalt flows on the Columbia Plateau. These eruptions generally produced hornblende-phyric dacite, in marked contrast to the compositionally diverse and pyroxene-phyric magmas erupted earlier. Volcaniclastic debris derived from the dacitic volcanoes was transported westward to accumulate in fluvial, lacustrine, and swamp environments on low-relief terrain of eroded Paleogene rocks. These deposits, along with distal airfall ash beds and detritus eroded from Paleogene volcanogenic rocks and Cowlitz Formation arkosic sandstones, constitute the Wilkes Formation. The fine-grained sediments of the Wilkes Formation reflect a low-energy depositional system and indicate that the Cascade Range was not a major topographic feature at this time. The uplift that produced the modern range probably began in late Pliocene time (Tolan and Beeson, 1984).

Several times during the Pleistocene, ice sheets covered the Cascade Range and valley glaciers moved down all the major drainages including the Cowlitz and Toutle Rivers (Crandell and Miller, 1974). The glaciers never reached as far west as the map area but proglacial outwash trains covered much of its northern part. The most extensive deposits are those of the early(?) Pleistocene Logan Hill Formation (Snavely and others, 1958; Roberts, 1958). The Logan Hill Formation outwash filled the lower Cowlitz River valley and, in the Silver Lake area, merged with the outwash train of the Toutle River drainage. Post-Logan Hill outwash deposits in the quadrangle came entirely from the Toutle River system; the youngest contain clasts of early Mount St. Helens dacites. On several occasions near the end of the Pleistocene, glacier-outburst floodwaters moved down the Columbia River and inundated the lower Cowlitz River valley; at least one flood was large enough to deposit slackwater silts in the lower Toutle River valley.

The recent geologic history of the Silver Lake area has been strongly influenced by activity at the Mount St. Helens volcanic center. Eruptions began at least 50 ka and probably much earlier (Berger and Busacca, 1995; Whitlock and others, 2000; M.A. Clynne, oral commun., 1999). Several times the Toutle River valley was filled with lahar deposits and lahar-derived alluvium, then entrenched, and refilled with debris from later eruptive events. Perhaps the greatest impact on the landscape of the Silver Lake quadrangle resulted from the emplacement, about 2500 years ago, of four huge lahars that dammed a tributary of the Toutle River and created Silver Lake. The lahars in 1980, although comparatively small and leaving little evidence in the depositional record, destroyed the Tower Road bridge and forced the relocation of roadways, utilities, and structures in the north part of the quadrangle.

GEOLOGIC RESOURCES

Geologic resources of the Silver Lake quadrangle include energy and nonmetallic industrial materials; no metallic deposits or significant hydrothermal alteration associated with such deposits were found. Coal beds in the Cowlitz and Toutle Formations were recognized by the earliest European settlers in the 1830s. Several attempts have been made to exploit the coal, but the only reported production was in 1902-1906 from the Leavell Mine, near the southwest corner of the quadrangle; the quantity of coal extracted is not known but presumably small (Roberts, 1958). These workings are no longer visible but descriptions by Collier (1911), Culver (1919), and Roberts (1958) indicate that the coal occurred in two beds within a 1.5 m-thick interval in the Cowlitz Formation about 30 m below its contact with volcanic rocks (Tba). Excavation terminated where the coal-bearing horizon was truncated by a fault of unknown orientation, and subsequent drilling failed to locate the offset beds. An analyzed sample collected from the mine area was subbituminous B with a moisture content of 25% and an ash content of 7.1% (Roberts, 1958). Roberts (1958) calculated total reserves of 2.84 million tons of coal in this area (see also Beikman and others, 1961).

The other notable coal deposits in the Silver Lake quadrangle are beds of lignite in the Toutle Formation. The best-known deposits are those associated with high-alumina clay beds of in the Cowlitz clay mine east of Cline Creek (Roberts, 1958). A drilling program designed to evaluate the clay deposits as a source of aluminum (Popoff, 1955) revealed the existence of several beds of woody lignite ranging from 0.5 to 10 m thick. One of these beds may correlate with the Silver Lake coal bed exposed near the village of Toutle (Roberts, 1958), a sample of which had a moisture content of 32% and an ash content of 28%. Roberts (1958) estimated that total reserves of about 13 million tons of lignite existed in the vicinity of the Cowlitz clay mine, much of which lies beneath an overburden of Grande Ronde Basalt. He calculated reserves of approximately 17 million tons for the Silver Lake bed south of the Toutle River, most of which underlies the andesite of Hollywood Gorge. Given the low rank and high moisture and ash contents of the coals in the map area, commercial development of these relatively thin and discontinuous deposits is unlikely.

Johnson and others (1997) discuss the potential for undiscovered petroleum deposits in Washington. Although subaerial volcanogenic rocks like those exposed in the Silver Lake quadrangle are unsuitable for petroleum generation, more favorable nonvolcanic sedimentary rocks of the Cowlitz Formation are likely present at depth. The Silver Lake quadrangle lies within the southern part of Johnson and others' (1997) Cowlitz-Spencer conventional gas play, which includes the only gas field in the Pacific Northwest with significant production, at Mist, Oregon. Using the Mist field as a model, they considered that gas generated from Eocene marine shale and nonmarine shale and coal could migrate into fluvial-deltaic sandstones of the Cowlitz Formation and accumulate in small structural traps. In the same area, these authors also identified a western Washington-southern Puget Lowlands coal-bed gas play. Their analysis suggests a significant potential for relatively small gas accumulations within these plays, although the amount of gas that has been generated is limited because of the relatively low thermal maturity of organic matter in the potential source rocks.

High-alumina clay deposits in the Toutle Formation east of Cline Creek have been worked intermittently since their discovery in 1935, most recently in 1999 (Derkey and Hamilton, 2000). The clay has been used chiefly for the production of refractory bricks and as an ingredient in cement (Glover, 1941; Popoff, 1955; Roberts, 1958; Derkey and Hamilton, 2000). During World War II, the U.S. Geological Survey and the U.S. Bureau of Mines evaluated the deposits as a potential source of aluminum metal (Nichols, 1943; Popoff, 1955). Geologic mapping and drilling undertaken by this program showed the presence of two clay-rich zones, each about 15-20 m thick, separated by about 30 m of volcaniclastic sedimentary rocks. Each zone contains seams of bluish-gray, white- to tan-weathering, carbonaceous clay between 0.5 and 3 m thick interbedded with woody lignite beds as much as 2 m thick. Concretions and wavy beds of orange siderite are common in the clay seams; they are considered a contaminant and removed from the clay before shipping. Most of the upper clay zone was eroded away prior to emplacement of the Grande Ronde Basalt flow. The clay is mineralogically simple, consisting of kaolinite and gibbsite with minor montmorillonite and nontronite-beidellite and traces of feldspar, quartz and mica (Allen and Nichols, 1946; Popoff, 1955). Locally the clay has become calcined by natural burning of interbedded lignite (Glover, 1941). Chemical analyses of samples from the lower clay bed show typical compositions of 30-35 wt percent Al_2O_3, 35-45 wt percent SiO_2, 5-11 wt percent Fe_2O_3, 2 wt percent TiO_2, and 15-20 wt percent H_2O and CO_2 (Popoff, 1955). The upper clay zone is less pure, and all clay mined to date has come from the lower zone. Nichols (1943) and Popoff (1955) believed that most of the clay was detrital but relict textures indicate that the clay seams were originally beds of volcanic sandstone, siltstone, grit and pumiceous and lithic lapilli tuff altered in situ. Some beds were probably of airfall origin and may properly be termed tonsteins (Bohor and Triplehorn, 1993). The clay seams were most likely formed by the same mechanism that forms tonsteins: reaction of volcanic debris with the reduced, acidic groundwater of coal-forming environments. Degradation of the organic matter in peat produces humic and fulvic acids that, in a hydrologically open system, leach alkaline and alkaline-earth elements from primary volcanic glass and minerals, leaving residual kaolinitic clay (Bohor and Triplehorn, 1993). Estimated total reserves of high-alumina (>20 wt percent Al_2O_3) clay in the Cline Creek area range from 25-35 million tons according to Popoff (1955).

The abundant igneous rocks of the Silver Lake quadrangle provide a convenient source of crushed rock for construction purposes and are used primarily for road metal on private logging roads and public highways. Engineering tests indicate that most of this rock is of relatively low quality (D. Norman, written commun., 2001), but the outcrops of Grande Ronde Basalt in the Cline Creek area represent a potential source of crushed rock of sufficiently high grade to justify transport to distant construction sites. The basalt possesses desirable engineering properties and large quarries have been developed in Grande Ronde flows to the south near Longview and Woodland, Washington and Saint Helens, Oregon, but none exist near Castle Rock. Most likely only the exposure east of Cline Creek is large enough to be developed economically. The basalt flow here evidently continues northward beneath Wilkes Formation, but a drilling program would be required to determine its extent. The andesite of Hollywood Gorge tends to break into large massive blocks and is a source of riprap (D. Norman, written commun., 2001). Sand and gravel for local use has been obtained from the Mount St. Helens deposits along the Toutle River, but larger sources are available closer to the populated areas of the lower Cowlitz valley west of the Silver Lake quadrangle.

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Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle

[Major-element oxides in weight percent; trace elements in parts per million. For modal analyses, secondary minerals counted as primary mineral replaced. Rock-type names assigned in accordance with IUGS system (Le Bas and Streckeisen, 1991) applied to recalculated analyses. Mg# is atomic ratio 100Mg/(Mg+Fe^{+}) with Fe^{2+} set to 0.85x Fe^{total}. X-ray fluorescence analyses by methods described in Taggart and others, (1987), Johnson and King (1987), and King and Lindsay (1990); analyst, D. Siems. Analyses marked by asterisks performed by GeoAnalytical Laboratory of Washington State University using methods described in Johnson and others (1999); analyst: D. Johnson. Data for sample numbers beginning with "BP" are from Phillips (1987). Texture: first term describes overall rock texture; second term (where appropriate) describes groundmass. -, not present. ---, no data]

Map no.	1	2	3	4	5	6	7	8	9
Field sample no.	93CR-F32	93CR-F62	98CR-F166	93CR-F64	93CR-F67	93CR-F59	97CR-F129	93CR-F61A	93CR-F58C
Latitude (N)	46°15.54'	46°17.16'	46°17.82'	46°16.74'	46°17.10'	46°17.22'	46°16.56'	46°16.74'	46°16.98'
Longitude (W)	122°51.06'	122°47.04'	122°47.46'	122°47.64'	122°45.42'	122°46.32'	122°46.32'	122°47.34'	122°45.96'
Map unit	Tk	Twp	Twp	Twp	Twp	Twp	Twp	Twp	Twp
Rock type	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt
Analyses as reported									
SiO_2	48.00	45.90	45.70	46.00	46.90	46.10	47.31	46.70	46.80
TiO_2	1.32	1.09	1.19	1.06	1.19	1.04	1.13	1.12	1.28
Al_2O_3	17.30	13.80	16.16	13.50	15.30	13.60	14.68	14.20	16.00
Fe_2O_3	2.35	4.18	10.24	2.95	3.32	3.94	9.84	9.76	3.65
FeO	7.25	5.66	---	5.95	6.11	4.99	---	---	6.26
MnO	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.17
MgO	7.09	12.20	9.78	12.60	10.50	11.60	11.01	11.20	9.43
CaO	11.90	11.60	10.98	11.40	11.50	11.40	11.18	11.00	11.10
Na_2O	2.30	1.69	2.16	1.65	2.20	2.09	2.25	1.95	2.26
K_2O	0.23	0.95	0.36	0.99	0.87	1.04	0.76	0.88	0.44
P_2O_5	0.13	0.57	0.22	0.55	0.45	0.57	0.47	0.50	0.21
H_2O^+	1.07	2.37	2.49	2.26	1.02	2.56	1.41	1.87	1.51
H_2O^-	0.46	0.25	---	0.15	0.10	0.25	---	---	0.36
CO_2	0.04	0.02	---	0.04	0.01	0.04	---	---	0.06
Total	99.60	100.44	99.44	99.26	99.63	99.38	100.20	99.34	99.53
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO									
SiO_2	49.08	47.13	47.64	47.66	47.78	47.95	48.37	48.40	48.13
TiO_2	1.35	1.12	1.24	1.10	1.21	1.08	1.16	1.16	1.32
Al_2O_3	17.69	14.17	16.85	13.99	15.59	14.15	15.01	14.72	16.46
FeO	9.58	9.67	9.61	8.92	9.27	8.88	9.06	9.10	9.82
MnO	0.16	0.16	0.17	0.17	0.16	0.17	0.16	0.17	0.17
MgO	7.25	12.53	10.19	13.06	10.70	12.07	11.26	11.61	9.70
CaO	12.17	11.91	11.45	11.81	11.71	11.86	11.43	11.40	11.42
Na_2O	2.35	1.74	2.25	1.71	2.24	2.17	2.30	2.02	2.32
K_2O	0.24	0.98	0.38	1.03	0.89	1.08	0.78	0.91	0.45
P_2O_5	0.13	0.59	0.23	0.57	0.46	0.59	0.48	0.52	0.22
Mg#	61.4	73.1	69.0	75.4	70.8	74.0	72.3	72.8	67.5
Modes									
Plagioclase	23.5	-	2.7	0.1	1.0	-	-	-	6.8
Clinopyroxene	1.7	0.3	0.2	-	6.0	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	3.7	13.1	13.3	12.9	11.2	14.2	10.0	10.6	8.6
Fe-Ti Oxide	-	-	-	-	-	---	-	-	-
Hornblende	-	-	-	-	-	---	-	-	-
Quartz	-	-	-	-	-	---	-	-	-
K-feldspar	-	-	-	-	-	---	-	-	-
Other	-	-	-	-	-	amygdules: 0.7	-	-	-
Groundmass	71.1	86.6	83.8	87.0	81.8	85.8	90.0	89.4	84.6
No. points counted	764	696	810	743	686	802	844	722	736
Texture	porphyritic/ intergranular	porphyritic/ intergranular	seriate/ intergranular	porphyritic/ intergranular	porphyritic/ intergranular	porphyritic/ intergranular	seriate/ intergranular	porphyritic/ intergranular	seriate/ intergranular
Trace element analyses									
Ba	30	215	114	184	210	305	189	176	95
Rb	<10	30	<10	28	29	34	28	27	<10
Sr	230	660	318	610	650	1000	576	600	310
Y	20	21	18	18	20	15	17	26	18
Zr	79	156	76	150	136	160	138	150	98
Nb	<10	12	<10	<10	15	<10	14	<10	10
Ni	78	265	155	280	210	250	213	220	186
Cu	110	118	115	120	104	85	136	122	104
Zn	68	71	63	71	69	66	77	66	60
Cr	144	630	---	720	445	710	---	550	280

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	10	11	12	13	14	15	16	17	18
Field sample no.	95CR-F115B	93CR-F45	93CR-F60	94CR-F78	98CR-F160	95CR-F126	94CR-F107	93CR-F72	93CR-F07A
Latitude (N)	46°15.60'	46°16.08'	46°16.92'	46°16.08'	46°16.44'	46°17.28'	46°18.30'	46°16.20'	46°19.98'
Longitude (W)	122°45.30'	122°46.02'	122°46.26'	122°45.42'	122°51.96'	122°51.48'	122°52.50'	122°49.02'	122°52.08'
Map unit	Twp	Twp	Twp	Twp	Tba	Tba	Tba	Tba	Tba
Rock type	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported									
SiO_2	47.10	46.60	48.70	49.60	50.22	50.15	50.90	51.10	51.60
TiO_2	1.25	1.11	1.29	1.48	1.76	1.75	1.81	1.99	1.96
Al_2O_3	15.45	14.20	15.90	15.80	17.89	17.81	18.40	16.10	15.70
Fe_2O_3	10.25	7.28	4.18	10.50	10.54	10.29	9.60	11.80	12.00
FeO	---	2.17	5.60	---	---	---	---	---	---
MnO	0.16	0.16	0.16	0.15	0.15	0.16	0.12	0.18	0.18
MgO	10.06	11.00	8.65	7.55	3.97	4.15	3.76	4.34	4.12
CaO	10.48	10.70	10.40	9.62	9.71	9.50	9.69	8.62	8.59
Na_2O	2.27	1.85	2.51	2.72	3.28	3.41	3.44	3.63	3.85
K_2O	0.47	0.84	0.41	0.50	0.57	0.58	0.60	0.66	0.65
P_2O_5	0.31	0.49	0.26	0.39	0.23	0.26	0.26	0.26	0.30
H_2O^+	2.39	3.12	1.20	1.65	1.37	1.73	1.21	1.12	0.80
H_2O^-	---	0.22	0.45	---	---	---	---	---	---
CO_2	---	0.04	0.03	---	---	---	---	---	---
Total	100.18	99.78	99.74	99.96	99.67	99.78	99.79	99.80	99.75
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO									
SiO_2	48.67	48.71	49.88	51.00	51.64	51.69	52.14	52.41	52.79
TiO_2	1.29	1.16	1.32	1.52	1.81	1.80	1.85	2.04	2.01
Al_2O_3	15.96	14.84	16.28	16.25	18.40	18.35	18.85	16.51	16.06
FeO	9.54	9.12	9.59	9.71	9.75	9.55	8.85	10.89	11.05
MnO	0.16	0.17	0.16	0.15	0.15	0.16	0.12	0.18	0.18
MgO	10.40	11.50	8.86	7.76	4.08	4.27	3.85	4.45	4.21
CaO	10.83	11.18	10.65	9.89	9.98	9.79	9.93	8.84	8.79
Na_2O	2.34	1.93	2.57	2.80	3.37	3.52	3.52	3.72	3.94
K_2O	0.48	0.88	0.42	0.51	0.58	0.60	0.61	0.68	0.66
P_2O_5	0.32	0.51	0.27	0.40	0.24	0.26	0.27	0.27	0.31
Mg#	69.6	72.6	66.0	62.6	46.7	48.4	47.7	46.2	44.5
Modes									
Plagioclase	-	-	-	-	23.5	17.0	17.3	5.9	1.3
Clinopyroxene	-	-	-	-	-	-	0.6	0.4	0.1
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	12.0	12.7	7.8	6.9	0.1	-	0.1	0.1	0.3
Fe-Ti Oxide	-	-	-	-	-	-	-	-	0.1
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	amygdules: 0.4	-	-	-	-	-	-	-
Groundmass	88.0	87.3	92.2	93.1	76.4	83.0	82.0	93.6	98.2
No. points counted	733	694	761	740	788	850	789	796	802
Texture	porphyritic/intergranular	porphyritic/intergranular	porphyritic/intergranular	seriate/intergranular	seriate/intergranular	porphyritic/intergranular	porphyritic/intergranular	seriate/intergranular	sparsely phyric/intergranular
Trace element analyses									
Ba	162	190	80	131	152	149	139	158	300
Rb	10	21	<10	<10	15	<10	10	10	14
Sr	396	570	295	339	415	399	411	385	380
Y	19	13	20	23	24	25	20	26	26
Zr	111	138	118	147	124	129	123	136	150
Nb	13	<10	11	17	11	14	14	10	11
Ni	226	245	152	144	29	24	23	20	16
Cu	120	106	104	74	140	178	79	176	176
Zn	76	69	65	85	64	76	73	84	86
Cr	---	530	285	---	---	---	---	31	30

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	19	20	21	22	23	23	24	25	26
Field sample no.	93CR-F29A	93CR-F28A	93CR-F19B	93CR-F70B	84CR-H01C	BP1004841	93CR-F06A	93CR-F65	93CR-F58A
Latitude (N)	46°16.08'	46°16.14'	46°16.92'	46°16.20'	46°18.27'	46°18.27'	46°19.88'	46°16.74'	46°16.95'
Longitude (W)	122°51.12'	122°51.60'	122°52.38'	122°48.84'	122°52.04'	122°52.04'	122°52.38'	122°48.06'	122°45.85'
Map unit	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Tba
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported									
SiO_2	51.30	51.50	51.70	51.50	52.20	52.25	52.10	52.50	53.00
TiO_2	2.05	1.97	1.74	1.76	1.99	1.98	2.00	2.44	2.29
Al_2O_3	16.20	16.60	15.80	18.20	15.90	15.69	15.90	15.40	15.50
Fe_2O_3	3.73	4.11	2.79	9.74	3.78	---	4.01	3.73	4.12
FeO	7.27	6.48	7.67	---	7.59	12.37	7.02	7.36	6.74
MnO	0.17	0.16	0.18	0.16	0.16	0.20	0.15	0.17	0.17
MgO	4.27	4.14	4.95	3.32	4.34	4.00	4.20	4.04	3.91
CaO	8.73	8.88	9.68	9.07	8.25	8.46	8.11	7.73	7.63
Na_2O	3.60	3.59	3.41	3.60	3.84	3.59	3.91	3.92	4.07
K_2O	0.68	0.64	0.51	0.65	0.73	0.58	0.73	0.74	0.80
P_2O_5	0.27	0.26	0.27	0.28	0.28	0.28	0.30	0.33	0.42
H_2O^+	0.49	1.16	0.58	1.17	0.49	---	1.13	1.00	0.88
H_2O^-	0.84	0.13	0.50	---	0.42	---	0.63	0.52	0.44
CO_2	0.17	0.01	0.01	---	0.01	---	0.01	<0.01	0.01
Total	99.77	99.63	99.79	99.45	99.98	99.40	100.20	99.88	99.98
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO									
SiO_2	52.40	52.59	52.53	52.93	52.90	52.56	53.15	53.58	53.95
TiO_2	2.09	2.01	1.77	1.81	2.02	1.99	2.04	2.49	2.33
Al_2O_3	16.55	16.95	16.05	18.70	16.11	15.78	16.22	15.72	15.78
FeO	10.85	10.39	10.34	9.01	11.14	12.45	10.84	10.94	10.63
MnO	0.17	0.16	0.18	0.16	0.16	0.20	0.15	0.17	0.17
MgO	4.36	4.23	5.03	3.41	4.40	4.02	4.28	4.12	3.98
CaO	8.92	9.07	9.84	9.32	8.36	8.51	8.27	7.89	7.77
Na_2O	3.68	3.67	3.46	3.70	3.89	3.61	3.99	4.00	4.14
K_2O	0.69	0.65	0.52	0.67	0.74	0.58	0.74	0.76	0.81
P_2O_5	0.28	0.27	0.27	0.29	0.28	0.28	0.31	0.34	0.43
Mg#	45.7	46.0	50.5	44.3	45.3	40.4	45.3	44.2	44.0
Modes									
Plagioclase	6.7	6.3	0.3	25.6	2.2	---	0.8	-	1.0
Clinopyroxene	0.7	0.4	trace	0.9	0.1	---	-	-	trace
Orthopyroxene	-	-	-	-	0.2	---	-	-	-
Olivine	0.4	0.6	-	0.4	-	---	-	-	trace
Fe-Ti Oxide	-	-	-	-	-	---	-	-	-
Hornblende	-	-	-	-	-	---	-	-	-
Quartz	-	-	-	-	-	---	-	-	-
K-feldspar	-	-	-	-	-	---	-	-	-
Other	-	-	-	-	-	---	-	-	-
Groundmass	92.2	92.7	99.7	73.1	97.5	---	99.2	100.0	99.0
No. points counted	766	766	750	752	790	---	750	-	747
Texture	seriate/ intergranular	seriate/ intergranular	~aphyric/ intergranular	porphyritic/ intergranular	sparsely phyric/ intergranular	---	seriate/ intergranular	aphyric/ intergranular	~aphyric/ intergranular
Trace element analyses									
Ba	158	152	130	168	150	---	180	182	198
Rb	11	11	12	12	14	---	11	18	14
Sr	385	395	350	425	390	---	390	420	410
Y	24	25	24	27	25	---	29	26	27
Zr	146	144	138	144	158	---	164	164	172
Nb	11	<10	10	11	<10	---	14	16	15
Ni	20	20	29	17	17	---	22	<10	13
Cu	142	174	156	164	170	---	184	48	35
Zn	68	75	82	72	72	---	81	66	94
Cr	42	42	60	22	36	---	41	26	35

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	27	28	29	30	31	32	33	34	35
Field sample no.	93CR-F08	95CR-F116B	93CR-F40	93CR-F39	93CR-F69	93CR-F37	93CR-F75A	93CR-F71	98CR-F146
Latitude (N)	46°20.34'	46°20.04'	46°15.36'	46°15.66'	46°15.48'	46°15.24'	46°16.68'	46°15.90'	46°19.56'
Longitude (W)	122°52.32'	122°51.72'	122°48.00'	122°48.24'	122°48.78'	122°47.58'	122°50.46'	122°49.32'	122°50.34'
Map unit	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Tba
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported									
SiO_2	52.70	53.18	53.30	53.80	53.70	52.40	53.50	53.80	53.67
TiO_2	2.20	1.86	1.94	1.90	2.61	1.78	1.79	1.90	1.92
Al_2O_3	16.20	15.89	16.50	16.10	15.50	16.60	16.20	16.10	16.35
Fe_2O_3	10.50	11.09	3.93	5.23	3.34	3.53	10.30	10.70	10.33
FeO	---	---	6.28	5.20	7.17	6.19	---	---	---
MnO	0.14	0.18	0.15	0.67	0.16	0.28	0.17	0.14	0.14
MgO	3.38	3.93	3.60	3.39	3.85	3.07	3.64	3.33	3.36
CaO	7.59	7.39	7.98	7.80	7.10	7.84	7.83	7.52	7.09
Na_2O	3.99	3.97	3.82	3.91	4.16	3.72	3.82	3.89	3.96
K_2O	0.82	0.80	0.77	0.77	0.84	0.64	0.79	0.76	0.85
P_2O_5	0.48	0.35	0.28	0.25	0.39	0.28	0.28	0.26	0.33
H_2O^+	1.63	1.44	0.40	0.33	0.69	0.68	1.14	1.15	1.88
H_2O^-	---	---	0.73	0.75	0.53	0.50	---	---	---
CO_2	---	---	0.02	0.01	<0.01	2.13	0.02	0.00	---
Total	99.63	100.08	99.70	100.11	100.04	99.64	99.48	99.55	99.86
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO									
SiO_2	54.36	54.53	54.30	54.62	54.53	54.60	54.99	55.28	55.36
TiO_2	2.27	1.90	1.98	1.93	2.65	1.85	1.84	1.95	1.98
Al_2O_3	16.71	16.29	16.81	16.35	15.74	17.30	16.65	16.54	16.86
FeO	9.75	10.24	10.00	10.06	10.33	9.76	9.53	9.89	9.59
MnO	0.14	0.19	0.15	0.68	0.16	0.29	0.17	0.14	0.14
MgO	3.49	4.03	3.67	3.44	3.91	3.20	3.74	3.42	3.47
CaO	7.83	7.58	8.13	7.92	7.21	8.17	8.05	7.73	7.31
Na_2O	4.12	4.07	3.89	3.97	4.22	3.88	3.93	4.00	4.08
K_2O	0.85	0.82	0.78	0.78	0.85	0.67	0.81	0.78	0.87
P_2O_5	0.50	0.35	0.29	0.25	0.40	0.29	0.29	0.27	0.34
Mg#	42.9	45.2	43.5	41.8	44.2	40.7	45.2	42.0	43.1
Modes									
Plagioclase	6.3	-	5.9	-	0.3	12.4	trace	-	0.1
Clinopyroxene	1.0	-	0.9	-	-	0.2	-	-	-
Orthopyroxene	-	-	trace	-	-	-	-	-	-
Olivine	0.5	-	trace	-	-	0.4	-	-	-
Fe-Ti Oxide	-	-	0.1	-	-	0.1	-	-	-
Hornblende	-	-	---	-	-	-	-	-	-
Quartz	-	-	---	-	-	-	-	-	-
K-feldspar	-	-	---	-	-	-	-	-	-
Other	-	-	---	-	-	-	-	-	-
Groundmass	92.2	100.0	93.1	100.0	99.7	86.9	100.0	100.0	99.9
No. points counted	766	-	784	-	627	768	-	-	724
Texture	sparsely phyric/ intergranular	aphyric/ intergranular	sparsely phyric/ intergranular	aphyric/ intergranular	aphyric/ intergranular	seriate/ intergranular	aphyric/ intergranular	aphyric/ intergranular	~aphyric/ intergranular
Trace element analyses									
Ba	213	209	184	154	200	198	194	182	223
Rb	16	12	13	17	14	17	16	17	16
Sr	423	381	405	415	410	410	405	420	402
Y	26	24	19	24	26	27	32	28	30
Zr	155	170	160	154	176	154	166	150	175
Nb	13	17	10	13	14	14	13	10	17
Ni	<10	20	10	20	<10	<10	13	<10	19
Cu	43	108	132	85	18	62	210	79	113
Zn	86	97	72	74	93	90	106	93	97
Cr	---	---	32	32	25	28	25	21	---

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	36	37	38	39	40	41	42	43	44
Field sample no.	98CR-F149	98CR-F151	93CR-F23	93CR-F36A	98CR-F133	98CR-F156	93CR-F22A	93CR-F31	94CR-F110
Latitude (N)	46°15.18'	46°18.12'	46°15.42'	46°15.30'	46°15.06'	46°16.68'	46°15.42'	46°15.78'	46°20.04'
Longitude (W)	122°51.00'	122°50.70'	122°52.32'	122°47.22'	122°50.10'	122°52.38'	122°51.72'	122°50.94'	122°50.64'
Map unit	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Tba	Ttob
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
					Analyses as reported				
SiO_2	53.84	53.67	53.80	53.80	54.51	54.51	55.40	55.20	53.10
TiO_2	2.06	2.12	2.12	1.94	1.55	1.81	2.14	2.08	1.94
Al_2O_3	16.19	15.50	15.40	16.10	16.21	15.94	15.50	15.54	16.20
Fe_2O_3	9.88	10.70	4.12	3.96	9.74	9.70	2.72	9.86	10.70
FeO	---	---	5.93	5.71	---	---	7.10	---	---
MnO	0.15	0.15	0.18	0.14	0.13	0.17	0.19	0.19	0.14
MgO	3.45	3.74	3.73	3.25	3.76	3.25	3.26	3.27	2.91
CaO	7.40	6.64	7.64	7.60	7.08	7.23	6.74	5.92	7.39
Na_2O	4.12	4.10	3.82	3.97	3.80	3.69	4.44	4.66	3.94
K_2O	0.85	0.91	1.04	0.84	0.80	1.19	0.93	1.07	0.82
P_2O_5	0.36	0.38	0.34	0.30	0.25	0.34	0.37	0.53	0.35
H_2O^+	1.26	1.56	0.79	0.38	1.76	1.94	0.68	1.58	2.23
H_2O^-	---	---	0.61	0.44	---	---	0.14	---	---
CO_2	---	---	<0.01	1.21	---	---	<0.01	---	---
	---	---	---	---	---	---	---	---	---
Total	99.56	99.47	99.52	99.64	99.58	99.77	99.61	99.92	99.72
			Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO						
SiO_2	55.33	55.42	55.06	55.34	56.28	56.28	56.23	56.70	55.07
TiO_2	2.11	2.19	2.17	2.00	1.60	1.87	2.17	2.14	2.01
Al_2O_3	16.64	16.01	15.76	16.56	16.74	16.46	15.73	15.96	16.80
FeO	9.14	9.94	9.86	9.54	9.05	9.01	9.69	9.12	9.99
MnO	0.16	0.15	0.18	0.14	0.13	0.18	0.19	0.20	0.15
MgO	3.54	3.86	3.82	3.34	3.88	3.36	3.31	3.36	3.02
CaO	7.60	6.86	7.82	7.82	7.31	7.46	6.84	6.08	7.66
Na_2O	4.23	4.24	3.91	4.08	3.93	3.81	4.51	4.78	4.09
K_2O	0.87	0.93	1.06	0.86	0.82	1.23	0.94	1.10	0.85
P_2O_5	0.37	0.39	0.35	0.31	0.26	0.35	0.38	0.55	0.36
Mg#	44.8	44.9	44.8	42.4	47.4	43.9	41.7	43.6	38.8
					Modes				
Plagioclase	2.6	trace	-	3.3	12.5	-	-	-	-
Clinopyroxene	trace	-	-	0.4	3.4	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	0.4	-	-	0.1	0.6	-	-	-	-
Fe-Ti Oxide	-	-	-	0.1	-	-	-	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	97.0	100.0	100.0	96.1	83.5	100.0	100.0	100.0	100.0
No. points counted	800	-	-	777	789	-	-	-	-
Texture	seriate/ intergranular	~aphyric/ intergranular	aphyric/ intergranular	seriate/ intergranular	seriate/ intergranular	aphyric/ intersertal	aphyric/ intersertal	aphyric/ intergranular	aphyric/ intergranular
					Trace element analyses				
Ba	238	234	205	205	198	229	255	269	220
Rb	14	17	24	15	16	22	14	17	13
Sr	388	376	370	405	404	404	375	394	408
Y	30	28	33	25	22	27	32	39	24
Zr	190	188	172	164	148	182	210	222	167
Nb	17	16	17	10	13	16	14	19	12
Ni	15	16	12	<10	22	11	<10	<10	19
Cu	48	93	142	93	214	57	150	14	113
Zn	92	99	114	71	98	94	84	98	79
Cr	---	---	34	30	---	---	30	---	---

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	45	46	47	48	49	50	51	52
Field sample no.	95CR-F117s*	93CR-F43A	93CR-F43B	94CR-F81	94CR-F84	BP1004842	93CR-F10A	93CR-F22B
Latitude (N) Longitude (W)	46°20.46' 122°51.60'	46°16.20' 122°46.74'	46°16.26' 122°46.80'	46°19.08' 122°49.44'	46°20.46' 122°48.84'	46°21.66' 122°48.58'	46°20.34' 122°51.06'	46°15.54' 122°51.72'
Map unit	Ttob	Ta	Ta	Ta	Tahg	Tahg	Ttoc	Tdi
Rock type	Basaltic andesite	Andesite	Andesite	Andesite	Pyroxene andesite	Pyroxene andesite	Dacitic pumice-lapilli tuff	Pyroxene diorite
Analyses as reported								
SiO_2	54.72	56.30	56.60	57.20	58.40	59.31	56.17	52.60
TiO_2	1.23	1.67	1.70	1.71	1.09	1.12	0.86	0.94
Al_2O_3	18.62	16.20	16.30	15.60	16.50	16.24	15.97	16.10
Fe_2O_3	---	3.81	5.48	8.70	6.77	7.55	5.83	4.24
FeO	7.17	4.91	3.39	---	---	---	---	---
MnO	0.12	0.16	0.14	0.17	0.12	0.14	0.06	0.13
MgO	3.80	3.00	2.51	3.04	3.68	3.63	2.15	7.28
CaO	9.42	6.62	6.46	6.09	6.90	6.95	3.93	9.72
Na_2O	3.46	4.34	4.44	4.20	3.42	3.43	2.32	2.55
K_2O	0.53	0.82	0.82	1.19	1.58	1.40	1.05	0.73
P_2O_5	0.27	0.42	0.43	0.46	0.24	0.22	0.15	0.15
H_2O^+	---	0.31	1.01	1.17	1.29	---	11.44	0.63
H_2O^-	---	0.75	0.19	---	---	---	---	0.97
CO_2	---	0.31	<0.01	---	---	---	---	<0.01
Total	99.35	99.62	99.47	99.53	99.99		99.90	99.96
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO								
SiO_2	55.08	57.53	57.92	58.67	59.58	59.31	63.92	53.71
TiO_2	1.24	1.71	1.74	1.75	1.11	1.12	0.97	0.96
Al_2O_3	18.74	16.55	16.68	16.00	16.84	16.24	18.17	16.44
FeO	7.22	8.52	8.51	8.03	6.21	7.55	5.97	7.90
MnO	0.12	0.16	0.14	0.17	0.12	0.14	0.06	0.13
MgO	3.82	3.07	2.57	3.82	3.75	3.63	2.44	7.43
CaO	9.48	6.76	6.61	6.25	7.04	6.95	4.47	9.92
Na_2O	3.48	4.43	4.54	4.31	3.49	3.43	2.64	2.60
K_2O	0.53	0.84	0.84	1.22	1.61	1.40	1.20	0.75
P_2O_5	0.27	0.43	0.44	0.47	0.24	0.22	0.16	0.15
Mg#	52.8	43.0	38.8	44.9	55.9	50.2	46.2	66.4
Modes								
Plagioclase	28.6	2.1	1.2	0.6	29.2	---	---	62.7
Clinopyroxene	0.8	0.4	0.2	0.4	7.5	---	---	19.7
Orthopyroxene	trace	---	---	---	5.9	---	---	8.7
Olivine	1.4	---	trace	0.3	---	---	---	---
Fe-Ti Oxide	---	trace	trace	trace	1.7	---	---	1.4
Hornblende	---	---	---	---	---	---	---	---
Quartz	---	---	---	---	---	---	---	---
K-feldspar	---	---	---	---	---	---	---	---
Other	---	---	---	---	---	---	---	clay: 7.5
Groundmass	69.2	97.5	98.6	98.7	55.7	---	---	---
No. points counted	812	777	771	801	810	---	---	726
Texture	seriate/ intergranular	sparsely phyric/ intergranular	seriate/ intergranular	sparsely phyric/ intergranular	porphyritic/ hyalopilitic	--- ---	sparsely phyric/ vitric	intergranular
Trace element analyses								
Ba	172	194	184	287	280	286	261	134
Rb	10	20	14	19	28	32	25	13
Sr	450	450	460	365	375	379	271	460
Y	24	23	23	31	24	25	28	13
Zr	159	152	156	228	213	207	302	89
Nb	16.1	12	12	20	13	13	21	<10
Ni	25	<10	<10	10	27	43	15	56
Cu	105	58	83	205	105	230	78	130
Zn	76	70	92	81	70	156	82	45
Cr	66	<20	22	---	---	62	---	186

Table 1. Chemical analyses of volcanic and intrusive rocks, Silver Lake 7.5' quadrangle—Continued

Map no.	53	53	53	54	54	55	55
Field sample no.	94CR-F90	94CR-F90	94CR-F90*	98CR-F137	98CR-F137*	98CR-F158	98CR-F158*
Latitude (N)	46°21.12'	46°21.12'	46°21.12'	46°21.48'	46°21.48'	46°21.24'	46°21.24'
Longitude (W)	122°49.92'	122°49.92'	122°49.92'	122°51.48'	122°51.48'	122°51.84'	122°51.84'
Map unit	Tgrs	Tgrs	Tgrs	Tgrs	Tgrs	Tgrs	Tgrs
Rock type	Basaltic Andesite	Basaltic Andesite	Basaltic Andesite	Basaltic Andesite	Basaltic Andesite	Basaltic Andesite	Dacitic Pumice-Lapilli Tuff
Analyses as reported							
SiO_2	52.90	52.97	53.59	52.70	52.74	52.68	53.84
TiO_2	1.95	1.93	1.97	1.99	2.022	1.97	2.00
Al_2O_3	13.60	13.66	13.65	14.00	13.99	13.88	13.93
Fe_2O_3	13.70	13.70	---	12.92	---	13.14	---
FeO	---	---	12.04	---	11.94	---	11.89
MnO	0.26	0.26	0.26	0.23	0.24	0.20	0.21
MgO	4.32	4.31	4.34	4.24	4.15	4.32	4.29
CaO	8.14	8.15	8.33	8.33	8.56	8.26	8.42
Na_2O	2.79	2.92	2.93	2.75	2.87	2.76	3.02
K_2O	1.35	1.35	1.37	1.19	1.22	1.13	1.16
P_2O_5	0.37	0.37	0.31	0.35	0.32	0.33	0.31
H_2O^+	0.93	0.86	---	1.02	---	0.89	---
H_2O^-	---	---	---	---	---	---	---
CO_2	---	---	---	---	---	---	---
Total	100.31	100.49	98.79	99.71	98.05	99.56	99.06
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO							
SiO_2	53.98	53.91	54.24	54.11	53.79	54.11	54.35
TiO_2	1.99	1.97	1.99	2.04	2.06	2.02	2.01
Al_2O_3	13.88	13.90	13.82	14.38	14.27	14.25	14.06
FeO	12.58	12.54	12.19	11.93	12.17	12.15	12.00
MnO	0.27	0.27	0.27	0.24	0.25	0.21	0.21
MgO	4.41	4.39	4.39	4.36	4.23	4.44	4.33
CaO	8.31	8.30	8.43	8.55	8.73	8.49	8.50
Na_2O	2.85	2.97	2.97	2.82	2.93	2.83	3.05
K_2O	1.38	1.38	1.39	1.22	1.24	1.16	1.17
P_2O_5	0.38	0.38	0.32	0.35	0.32	0.34	0.31
Mg#	42.4	42.3	43.0	43.4	43.4	43.4	43.1
Modes							
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
No. points counted	-	-	-	-	-	-	-
Texture	aphyric/ intergranular	aphyric/ intergranular	aphyric/ intergranular	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intersertal	microphyric/ intersertal
Trace element analyses							
Ba	473	476	468	569	597	501	467
Rb	32	32	33	28	26	24	29
Sr	323	307	306	336	327	316	314
Y	34	33	32	39	42	31	34
Zr	166	156	156	169	166	163	160
Nb	13	12.6	12.8	14	13.0	13	13.1
Ni	26	3	8	15	10	22	4
Cu	46	24	24	32	27	27	25
Zn	103	114	116	124	122	112	116
Cr	---	34	39	---	33	---	36

Table 2. Summary of isotopic age determinations, Silver Lake 7.5' quadrangle

Field sample no.	Location Latitude (N)	 Longitude (W)	Map unit	Rock type	Material dated	Method	Age (Ma) (±1σ error)	Source
93CR-F10A	46°20.36'	122°51.07'	Ttoc	Pumice-lapilli tuff	Plagioclase	$^{40}Ar/^{39}Ar$	37.4±0.2	R.J. Fleck, oral commun., 1999
93CR-F67	46°17.11'	122°45.39'	Twp	Olivine basalt	Whole rock	$^{40}Ar/^{39}Ar$	38.8±0.2	R.J. Fleck, oral commun., 1999
BP1004842	46°21.66'	122°48.58'	Tahg	Pyroxene andesite	Plagioclase	K-Ar	34.5±0.5	Phillips and others, 1986