



Geologic Map of the Lacamas Creek Quadrangle, Clark County, Washington

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INTRODUCTION

GEOGRAPHIC AND GEOLOGIC SETTING

The Lacamas Creek 7.5' quadrangle is in southwestern Washington, approximately 25 km northeast of Portland, Oregon, along the eastern margin of the Portland Basin, which is part of the Puget-Willamette Lowland that separates the Cascade Range from the Oregon Coast Range (fig. 1). Since late Eocene time, the Cascade Range has been the locus of an episodically active volcanic arc associated with underthrusting of oceanic lithosphere beneath the North American continent along the Cascadia Subduction Zone. Lava flows that erupted early in the history of the arc underlie the eastern half of the Lacamas Creek quadrangle, forming a dissected terrain, with elevations as high as 2050 ft (625 m), that slopes irregularly but steeply to the southwest. Weakly to moderately consolidated sediments that accumulated in the Neogene Portland Basin unconformably lap onto the bedrock terrain.

The Portland Basin has been interpreted as a pull-apart basin located in the releasing stepover between two en echelon, northwest-striking, right-lateral fault zones (Beeson and others, 1985, 1989; Yelin and Patton, 1991; Blakely and others, 1995). These fault zones are thought to reflect regional transpression and dextral shear within the forearc in response to oblique subduction of the Pacific plate along the Cascadia Subduction Zone (Pezzopane and Weldon, 1993; Wells and others, 1998). The southwestern margin of the Portland Basin (fig. 1B) is a well-defined topographic break along the base of the Tualatin Mountains, which form an asymmetric anticlinal ridge bounded on its northeast flank by the Portland Hills Fault Zone (Balsillie and Benson, 1971; Beeson and others, 1989; Blakely and others, 1995). This fault zone is believed to be an active structure (Wong and others, 2001; Liberty and others, 2003). The nature of the corresponding northeastern margin of the basin is less clear, but a poorly defined and partially buried dextral extensional structure has been hypothesized from topography, microseismicity, potential-field anomalies, and reconnaissance geologic mapping (Yelin and Patton, 1991; Beeson and others, 1989; Blakely and others, 1995).

This map is a contribution to a program designed to improve the geologic database for the Portland Basin region of the Pacific Northwest urban corridor, the densely populated Cascadia forearc region of western Washington and Oregon. Better and more detailed information on the bedrock and surficial geology of the basin and its surrounding area is needed to refine assessments of seismic risk (Yelin and Patton, 1991; Bott and Wong, 1993; Palmer and others, 2004), ground-failure hazards (Wegmann and Walsh, 2001), and resource availability in this rapidly growing region.

PREVIOUS GEOLOGIC INVESTIGATIONS

Previous geologic mapping in the Lacamas Creek area, generally carried out as part of broad regional reconnaissance investigations, established the basic stratigraphic framework and distribution of geologic units in the quadrangle. Trimble (1963) mapped and described the geology of the map area at a scale of 1:62,500 as part of a general geologic investigation of the Portland metropolitan area. Working simultaneously but independently, Mundorff (1964) mapped the area of the Lacamas Creek quadrangle for a water-resources evaluation of Clark County. He published a 1:48,000-scale geologic map and provided detailed descriptions of the basin-fill deposits.

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

Fiksdal (1975) mapped several inactive landslides in the map area.

ACKNOWLEDGMENTS

Access granted by the many landowners was essential for mapping in the Lacamas Creek quadrangle. Robert Ross and Dennis Mohan of the Longview Fibre Co. and Brian Poehlein of the Washington Division of Natural Resources permitted work on timberlands in the eastern half of the quadrangle. Thomas Curcio and Steven Hartung of the U.S. Army arranged access to restricted lands at Camp Bonneville Military Reservation. Diane M. Johnson of Washington State University performed chemical analyses. Robert J. Fleck and Jonathan T. Hagstrum of the U.S. Geological Survey (USGS) provided $^{40}\text{Ar}/^{39}\text{Ar}$ ages and paleomagnetic data, respectively. Andrei Sarna-Wojcicki, Kenneth Bishop, and Judith Fierstein of the USGS made available essential laboratory facilities. I obtained water-well drillers' logs from the Washington Department of Ecology website (<http://apps.ecy.wa.gov/welllog/>). Connie Manson and Lee Walkling aided in extracting information from the Washington Division of Geology and Earth Resources Library in Olympia, Washington, and Carol Edwards helped me obtain the unpublished field notes and map sheets of Donald E. Trimble

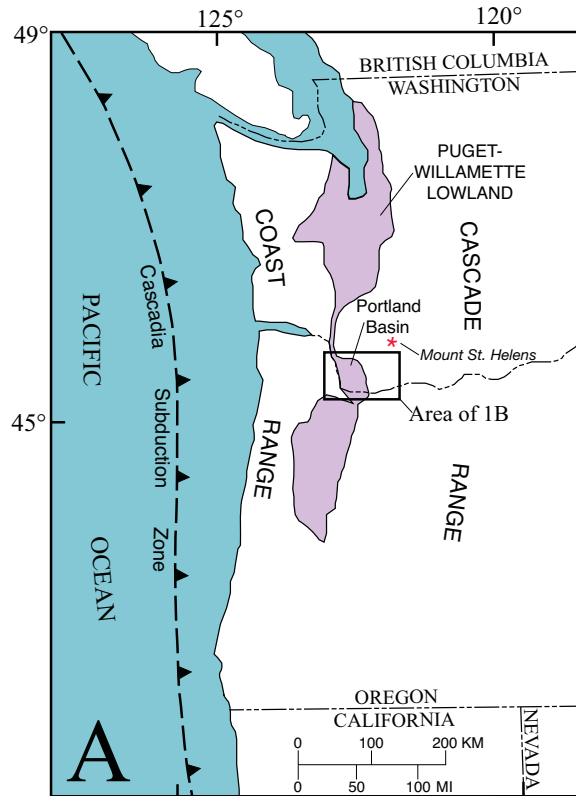


Figure 1A. Regional setting of the Lacamas Creek quadrangle showing major tectonic and physiographic features of the Pacific Northwest.

from the USGS Field Records Library in Denver, Colo. I have benefited immensely from discussions on various aspects of the regional stratigraphy, structure, and geologic history of southwestern Washington with Roger Ashley, Michael Clynne, Paul Hammond, Keith Howard, Alan Niem, Jim O'Connor, William Phillips, William Scott, James Smith, Donald Swanson, Rodney Swanson, Terry Tolan, Karl Wegmann, and Ray Wells. Roland Tabor and Jim O'Connor reviewed the map and offered many helpful suggestions.

SYNOPSIS OF GEOLOGY

Bedrock exposed in the Lacamas Creek quadrangle consists entirely of basalt and basaltic andesite flows erupted in early Oligocene time from one or more vents located outside the map area. The flows dip gently (less than 5°) west to southwest. In the western part of the map area bedrock is buried beneath middle Miocene to early Pleistocene(?) sediments that accumulated as the Portland Basin subsided. These sediments consist mostly of detritus

carried into the Portland Basin by the ancestral Columbia River. Northwest-striking faults offset the Paleogene basin floor as well as the lower part of the basin fill. In middle Pleistocene time, basalt and basaltic andesite erupted from three small volcanoes in the southern half of the map area. These vents are in the northern part of the Boring volcanic field, which comprises several dozen late Pliocene and younger monogenetic volcanoes scattered throughout the greater Portland region (Trimble, 1963; Allen, 1975; Fleck and others, 2002). In latest Pleistocene time, the Missoula floods of glacial-outburst origin inundated the Portland Basin. The floods deposited poorly sorted gravels in the southwestern part of the Lacamas Creek quadrangle that grade northward into finer grained sediments (Trimble, 1963).

Because of extensive dense vegetation, natural outcrops in the map area are generally limited to steep cliff faces, landslide scarps, and streambeds; many exposures are in roadcuts and quarries. The surface information was supplemented with lithologic data obtained from several hundred water-well reports in the files of the Washington Department of Ecology; well locations were taken as described in



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

the reports and were not field checked; only wells considered reliably located were used to infer the distribution and thicknesses of units in the subsurface.

BEDROCK

Trimble (1963) mapped all Paleogene rocks in eastern Clark County as the Skamania Volcanic Series. I have not adopted this name because regional mapping has shown the term to have limited utility. Neither the top nor the base of the unit were adequately defined, and as used by Trimble the term is essentially a synonym for Tertiary volcanic rocks of the southern Washington Cascade Range. Equivalent strata elsewhere in the region have been given other names (Wilkinson and others, 1946; Roberts, 1958; Wise, 1970; Hammond, 1980; Phillips, 1987a, b) and no reliable criteria have been found for mapping contacts between these various units. Therefore, I employ strictly lithologic units or, where appropriate, as on this map, informal lithostratigraphic units.

BASALTIC ANDESITE OF ELKHORN MOUNTAIN

Paleogene bedrock in the Lacamas Creek quadrangle consists of a monotonous sequence of subaerially erupted tholeiitic basaltic andesite and basalt flows informally named the basaltic andesite of Elkhorn Mountain. This package of flows has a maximum thickness of at least 800 m and extends from near Amboy, about 19 km north of Hockinson, to Camas, about 5 km south of the southern edge of the map area (Evarts, 2005; R.C. Evarts, unpub. mapping). Individual flows are typically 4 to 10 m thick but locally reach 70 m thick. They are characterized by blocky, platy, or columnar-jointed interiors that commonly grade into upper and lower flow breccia zones. The upper zones typically contain abundant zeolite-, quartz-, and clay-filled vesicles and have been oxidized to reddish-orange during cooling. All flows were apparently emplaced subaerially; many rest on red paleosols developed on previously emplaced flows or on thin sedimentary intervals, with no pillow lavas or other indications of subaqueous environments.

Structural attitudes of Paleogene rocks in the map area are difficult to ascertain because the unit lacks mappable sedimentary interbeds, and the commonly well developed platy parting within flows tends to vary erratically over short distances. The distribution of individual flows can be mapped locally, however, and indicates the section dips generally to the southwest at less than 5°.

No dikes were found in the map area. The thick sequence of flows probably represents part of a large mafic shield volcano centered east of the map area. Outcrops of bright red scoria about 3 km northwest of Little Elkhorn may be the remains of a parasitic cinder cone constructed on the flank of this large edifice.

Flows in the Elkhorn Mountain unit range from aphyric to highly porphyritic. Aphyric and sparsely aphyric flows commonly exhibit a closely spaced platy parting that is parallel to the alignment of feldspar microlites observed in thin section. Seriate to porphyritic flows contain phenocrysts of plagioclase and olivine, with or without augite, in an intergranular to trachytic groundmass. Extremely porphyritic to glomeroporphyritic basalts are scattered throughout the basaltic andesite of Elkhorn Mountain, some so packed with coarse blocky plagioclase phenocrysts (as much as 52 percent) that they macroscopically resemble phaneritic intrusive rocks. Widely spaced rectilinear joints typify these flows, which tend to weather into spheroids 1 to 3 m across. Plagioclase phenocrysts in these rocks are larger than 5 mm and commonly larger than 1 cm across, and are weakly zoned; many are anhedral and appear broken or partly resorbed. Groundmass textures indicate the basalts cooled rapidly; their coarse-grained appearance reflects pre-eruptive accumulation and concentration of feldspar crystals in a subvolcanic magma chamber rather than slow cooling at depth.

The lava flows of Elkhorn Mountain vary from basalt to mafic andesite, but most are basaltic andesite; they are uniformly tholeiitic, with low to medium potassium contents (fig. 2). The densely plagioclase-phyric basalts exhibit exceptionally high Al_2O_3 contents (as high as 21 wt percent) that correlate with the abundance of plagioclase phenocrysts (fig. 3a). Rocks with more than about 18 percent Al_2O_3 almost certainly accumulated plagioclase crystals prior to eruption, and most basalts in the unit were actually basaltic andesite magmas that contained excess feldspar crystals (fig. 3b). Compared to mafic flows elsewhere in the southern Washington Cascade Range (Evarts and Ashley, 1990a,b, 1991, 1992; Evarts and Bishop, 1994; Evarts and Swanson, 1994; Evarts, 2001, 2002, 2004a, b, c, 2005, 2006; R.C. Evarts, unpub. data), the Elkhorn Mountain flows are unusually rich in Fe (about 9.3 to 12.5 wt percent FeO^* in flows without excess feldspar; fig. 3c) and poor in Sr (generally less than 320 ppm Sr in flows without excess feldspar; fig. 3d). Incompatible-element ratios such as Ba/Nb (about 20), Ba/Zr (about 1.5), and Zr/Nb (about 13.5) are constant throughout the suite (Evarts, 2006), suggesting that the lavas are related primarily by fractional crystallization processes.

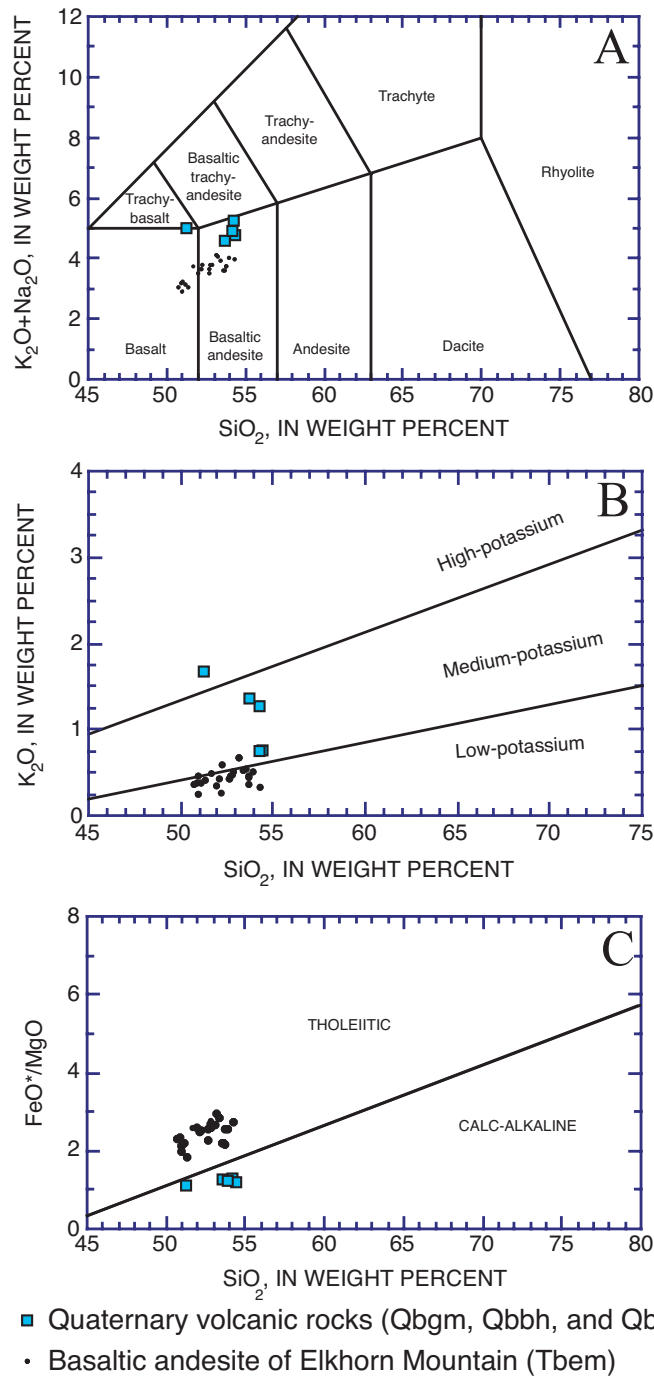


Figure 2. Chemical characteristics of volcanic rocks from the Lacamas Creek 7.5' quadrangle (analyses recalculated volatile-free). A, K₂O+ Na₂O versus SiO₂, showing IUGS classification (Le Maitre, 2002); B, K₂O versus SiO₂, showing low-, medium-, and high-potassium fields extrapolated from Gill (1981, p. 6); C, FeO*/MgO versus SiO₂, showing classification into tholeiitic and calc-alkaline rocks according to Miyashiro (1974). FeO*, total Fe as FeO.

Incremental-heating $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations in the adjacent Yacolt quadrangle (Evarts, 2006) indicate that the basaltic andesite of Elkhorn Mountain is about 26 to 27 million years old.

METAMORPHISM AND HYDROTHERMAL ALTERATION

The basaltic andesite of Elkhorn Mountain has been subjected to zeolite-facies regional metamorphism, the general character of which is similar to 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-wide

metamorphism reflects burial of the early Oligocene rocks by younger volcanic rocks within the relatively high-heat-flow environment of an active volcanic arc. The primary effect of very-low-grade metamorphism in the mafic flows of the map area is the nearly universal development of clay minerals and zeolites replacing labile interstitial glass, filling vesicles, and deposited on joint surfaces. Feldspar phenocrysts typically display partial alteration to clay minerals and (or) zeolites along fractures and cleavage planes. Olivine phenocrysts in the basalts and basaltic andesites are totally replaced by smectite with or without hematite and calcite. Primary augite and Fe-Ti oxides are largely unaffected by the zeolite-facies metamorphism.

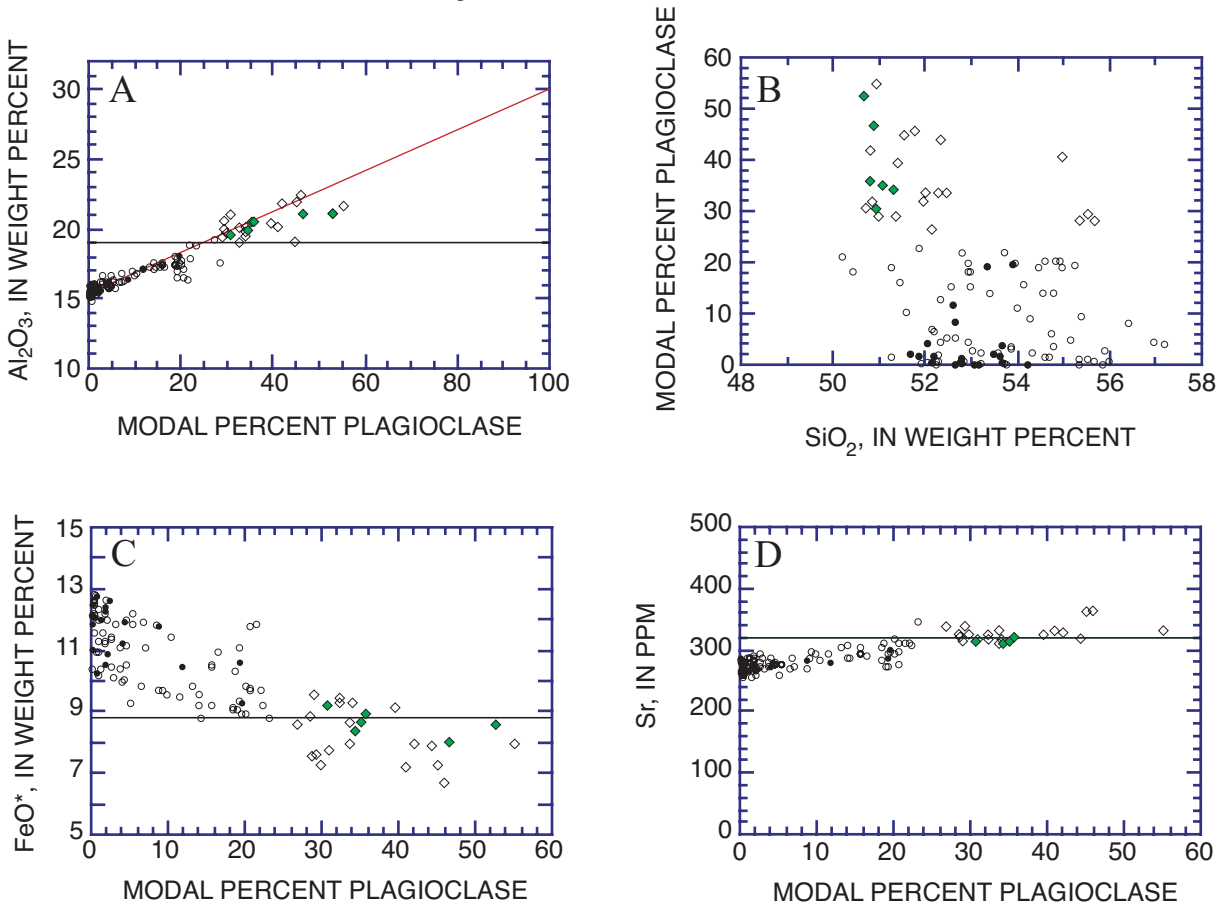


Figure 3. Chemical characteristics of lavas in the basaltic andesite of Elkhorn Mountain, illustrating the effects of plagioclase accumulation. Filled symbols designate samples from Lacamas Creek quadrangle, unfilled symbols designate samples from adjacent areas; strongly plagioclase-accumulative samples, shown as diamonds, contain more than 25 percent plagioclase phenocrysts. A, Al_2O_3 versus abundance of plagioclase phenocrysts, showing that the lavas plot along a plagioclase-accumulation line (shown in red) that projects to the composition of a calcic labradorite (about 30 wt percent Al_2O_3); B, SiO_2 versus abundance of plagioclase phenocrysts, showing that many basalts (SiO_2 less than 52 percent) are strongly plagioclase-accumulative lavas; C, FeO^* versus abundance of plagioclase phenocrysts, showing that FeO^* contents of most non-accumulative lavas are greater than 8.8 percent; FeO^* , total Fe as FeO ; D, Sr versus abundance of plagioclase phenocrysts, showing that Sr contents of non-plagioclase accumulative lavas are mostly less than 320 ppm.

BASIN-FILL DEPOSITS

As the Portland Basin subsided during the late Miocene and Pliocene, it filled with continental fluvial and lacustrine sediments that were transported through the Cascade Range by the ancestral Columbia River as well as with locally derived detritus carried in by tributaries draining the surrounding highlands. Surface exposures and numerous water-well logs indicate that these Neogene sedimentary rocks rest on an eroded bedrock surface of considerable relief. The bedrock-altitude map of Swanson and others (1993) indicates that the buried Paleogene bedrock surface slopes irregularly westward in the Lacamas Creek quadrangle and is deeper than 1000 ft (305 m) below sea level in the southwest corner of the quadrangle.

Most workers (Wilkinson and others, 1946; Lowry and Baldwin, 1952; Livingston, 1966; Trimble, 1957, 1963; Mundorff, 1964; Tolan and Beeson, 1984; Phillips, 1987a, b; Howard, 2002) assigned the Neogene nonmarine sedimentary beds of the Portland Basin to the Troutdale Formation of Hodge (1938). In its type area near the west end of the Columbia River Gorge, the Troutdale Formation is composed of three characteristic rock types: basalt-clast conglomerate, arkosic sandstone, and basaltic hyaloclastic (vitric) sandstone. The conglomerate consists chiefly of well-rounded pebbles and cobbles eroded from flows of the Columbia River Basalt Group, but its most distinctive components are well-rounded clasts of coarse-grained granitic and foliated metamorphic rocks and light-colored, commonly iron-stained, quartzite. These rock types are foreign to western Oregon and southwestern Washington and must have been transported by the ancestral Columbia River from terranes composed of pre-Tertiary granitic and metamorphic rocks in northeastern Washington, Idaho, and British Columbia. The arkosic sandstone consists largely of quartz, plagioclase, potassium feldspar, and felsic rock fragments and contains minor but conspicuous muscovite and biotite. Its composition, like that of the conglomerate, points to source terranes east of the Cascade Range. The vitric sandstone consists of poorly sorted, relatively coarse-grained, variably palagonitized hyaloclastic debris. The petrography and chemistry of the vitric clasts resemble those of olivine-bearing, high-alumina basalt and basaltic andesite flows erupted from volcanic centers flanking the Columbia River in the Cascade Range during Pliocene time (Tolan and Beeson, 1984; Swanson, 1986). Near the margins of the Portland Basin, the Troutdale Formation contains debris eroded from adjacent volcanic highlands. Tolan and Beeson (1984) refer to these locally derived deposits as the Cascadian stream facies of the Troutdale Formation,

which they distinguish from the more typical ancestral-Columbia River facies.

Scattered outcrops and abundant subsurface data from water-well drillers' logs show that, in much of the Portland Basin, a conglomeratic section as much as 120 m thick overlies a sequence of finer grained strata. This observation prompted Trimble (1957) and Mundorff (1964) to divide the Troutdale Formation into informal upper and lower members based on the pronounced difference in grain size. Trimble (1963) later formally named the lower, fine-grained member the Sandy River Mudstone. More recently, mapping in the northern Portland Basin by Howard (2002) and Evarts (2002, 2004a, c) showed that coarse-grained deposits that were previously mapped as Troutdale Formation consist of two lithologically similar deposits separated by an erosional unconformity.

Stratigraphic terminology on this map follows that of Evarts (2002, 2004a, c; fig. 4). The older conglomeratic deposits are assigned to the Troutdale Formation (Ttfc) and the younger deposits are designated as an unnamed conglomerate unit (QTc). Both units overlie fine-grained strata of the Sandy River Mudstone along erosional disconformities. Coarse sandstone and conglomerate composed largely of basaltic hyaloclastic debris crop out near Lacamas Lake. These beds are correlative with compositionally similar strata in the type area of the Troutdale Formation along the lower Sandy River (Hodge, 1938; Trimble, 1963; Tolan and Beeson, 1984) and are mapped here as an informal hyaloclastic sandstone member of the Troutdale (Ttth). Pleistocene volcanic rocks that overlie the unnamed conglomerate are included with the basin-fill strata.

SANDY RIVER MUDSTONE

Hundreds of water-well logs record clayey siltstone and sandstone, assigned to the Sandy River Mudstone, in the subsurface throughout the map area west of the Cascade foothills. Well logs indicate that this formation is present at the surface at Camp Killpack and east of Brunner Hill, although exposures are absent in those areas. These deposits thicken to the west and locally exceed 300 m thick. Outcrops in areas to the northwest of the quadrangle show that the formation consists of well-bedded sandstone, siltstone, and mudstone that typically display graded bedding, planar and trough crossbeds, and cut and fill structures indicative of a fluvial depositional setting (Mundorff, 1964; Howard, 2002; Evarts, 2004a, c). Most of the sandy beds are micaceous lithic and arkosic sandstones, but claystone beds, commonly carbonaceous and tuffaceous in part, increase in abundance down-

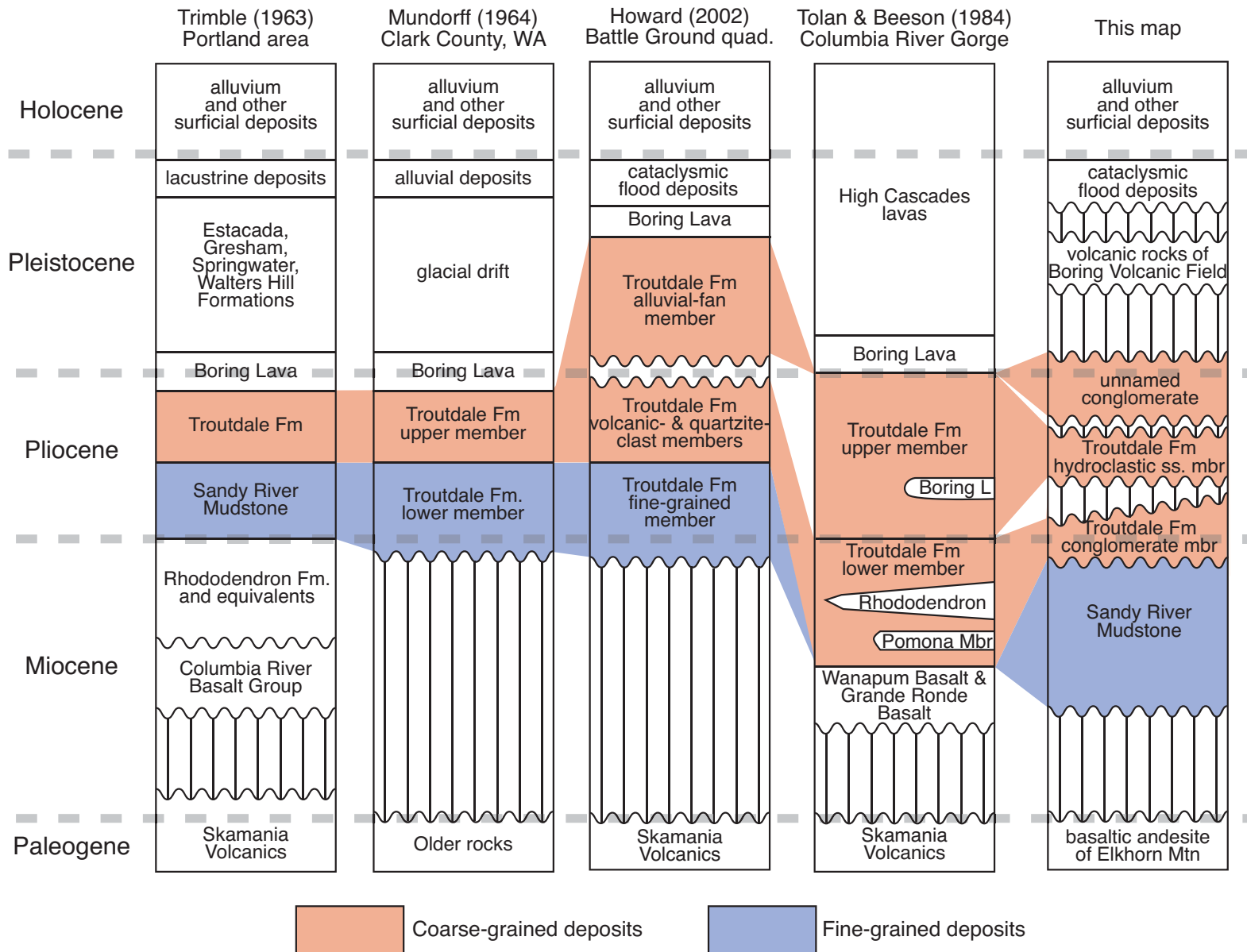


Figure 4. Comparison of stratigraphic nomenclature and age assignments for Neogene basin-fill units of the Portland Basin and vicinity.

section and a few interbeds of pebbly conglomerate are present locally. The upper contact with the Troutdale Formation is generally abrupt and probably disconformable.

TROUTDALE FORMATION

The Troutdale Formation of the map area is mapped as two lithologically distinct informal members (Tffc and Ttfh) that are separated by an unconformity. The older member (Tffc) consists of quartzite-bearing conglomerate and arkosic sandstone. The younger member (Ttfh) is composed largely of hyaloclastic basaltic debris. These two members correspond generally to the informal upper and lower members of the Troutdale mapped by Tolan and Beeson (1984) in the western Columbia River Gorge.

Conglomerate member

The older member (Tffc) underlies a flat to gently southwest-sloping and dissected surface, mostly below 600 ft (180 m) elevation, between Hockinson and Camp Bonneville that Mundorff (1964) called the Troutdale bench. It consists chiefly of deeply weathered conglomerate that stratigraphically overlies the Sandy River Mudstone (Tsr). Similar gravelly deposits are present at Green Mountain and east of Brunner Hill. In the map area, the conglomerate member (Tffc) is generally less than 80 m thick, although Swanson and others (1993) infer a thickness greater than 120 m at Green Mountain. Good exposures are uncommon owing to intense weathering; in many locations only residual quartzite clasts remain. Well rounded quartzite clasts are widely distributed on Paleogene bedrock near and south of Camp Bonneville indicating that the Troutdale Formation originally buried all of the terrain below about 700 ft (215 m) elevation. Scattered exposures show that the Troutdale Formation conglomerate member consists of weakly to moderately cemented pebble and cobble conglomerate and lenses of coarse sandstone. Well rounded pebbles and cobbles eroded from the Columbia River Basalt Group are the most abundant constituent of the conglomerate; the remainder includes light-colored granitic and quartzofeldspathic metamorphic rocks, Fe-oxide stained quartzite, and minor amounts of volcanic rocks eroded from the Cascade Range. The interbedded sandstone ranges in composition from basaltic to muscovite-bearing arkosic and quartzose, and is lithologically similar to the sandy matrix of the conglomerate. Significantly, the conglomerate member of the Troutdale Formation (Tffc) lacks clasts of Pliocene and younger basalts like those that dominate the basaltic hyaloclastic sandstone member (Ttfh). Sedimentological

characteristics of the conglomerate, such as the massive to crudely stratified beds, clast-support, moderate to good sorting, and clast imbrication, are consistent with deposition during flood stage in a gravelly braided river system (Miall, 1977, 1996; Rust, 1978).

Hyaloclastic sandstone member

The basaltic hyaloclastic sediment member of the Troutdale Formation (Ttfh) crops out along Lacamas Lake and lower Lacamas Creek; it is much more extensively exposed south of the map area (Trimble, 1963; Mundorff, 1964; Swanson and others, 1993; R.C. Evarts and J.E. O'Connor, unpub. mapping). This member is characterized by distinctive yellow-brown, palagonite-cemented, coarse to very coarse sandstone with dispersed conglomeratic lenses. The dominant clasts in the sandy and gritty beds are angular to rounded fragments of generally nonvesicular and variably palagonitized basaltic glass containing olivine and plagioclase microlites. The conglomerate lenses contain subrounded clasts of variably vesicular olivine- and plagioclase-phyric basalt similar to Pliocene volcanic rocks exposed in the Columbia River Gorge (Tolan and Beeson, 1984). The vitric clasts were probably generated by rapid chilling and quench fragmentation during interaction of basaltic lava with water. The sandstones exhibit cross-stratification, interbedding with conglomerate, and mixing with nonvolcanic debris, which indicate deposition in a fluvial environment, but the textural immaturity and monolithologic character of many beds suggest short transport distances. Following Trimble (1963) and Tolan and Beeson (1984), these beds are interpreted as hyaloclastic debris that was generated when late Pliocene basalt flows entered the Columbia River east of the map area. This debris was almost immediately transported downstream and deposited in the eastern Portland Basin. Swanson (1986) showed that the vitric clasts in deposits near Troutdale are almost all low-potassium tholeiites, and suggested they are derived from compositionally similar basalt flows exposed between Hood River and Bull Run, Oregon, about 40 km east of the map area.

Strata lithologically similar to the basaltic hyaloclastic member (Ttfh) constitute most of the Troutdale Formation in the type area designated by Hodge (1938). Tolan and Beeson (1984) traced these deposits eastward from the type area into the Columbia River Gorge, where they overlie a thick section of quartzite-bearing conglomerate similar to that mapped as the conglomerate member of the Troutdale Formation (Tffc) in the Lacamas Creek quadrangle. Tolan and Beeson (1984) interpreted the contact between the upper and lower members as conformable. In the Lacamas Creek area, however,

the hyaloclastic sandstone member crops out at lower elevations than the quartzite-bearing conglomerate, so must have filled a valley incised into the older deposits.

UNNAMED CONGLOMERATE

An unnamed conglomerate unit (QTc), included in the Troutdale Formation by previous workers, unconformably overlies the conglomerate and hyaloclastic sandstone members of the Troutdale (Tffc and Tffh). These younger beds, like the older fluvial deposits, are deeply weathered and rarely exposed, but are more poorly sorted than those of the older unit and contain much higher proportions of Cascadian volcanic clasts. In addition, the volcanic clasts tend to be less rounded than the basalt and quartzite clasts of the older deposit.

The unnamed conglomerate overlies the basaltic hyaloclastic sandstone member of the Troutdale Formation, of inferred late Pliocene age, and is overlain by basalts (Qbbh, Qbmc) erupted about 600-700 ka. The stratigraphic position of unit QTc is comparable to that of the Springwater Formation mapped southeast of Portland by Trimble (1963) and Madin (1994).

VOLCANIC ROCKS

Three small Quaternary volcanoes are located in the southern part of the map area at Green Mountain, Brunner Hill, and along upper Matney Creek. They represent the northern part of the late Pliocene to Quaternary Boring Volcanic Field (Fleck and others, 2002), which consists of several dozen monogenetic vents scattered throughout the greater Portland area (Treasher, 1942; Trimble, 1963; Allen, 1975).

The conical hill at the west end of Green Mountain marks the vent for a lava flow of olivine-phyric basaltic andesite (Qbgm) that extends about 1 km to the northwest. Nonscoriaceous, platy lava crops out at the summit, presumably filling the vent. Sparse but persistent quartzite pebbles, derived from the underlying gravels, lie scattered on the slopes and occur in the lava at the summit. An $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 575 ± 7 ka was obtained for a sample from the lava flow west of Green Mountain (table 2). The flow has normal magnetic polarity (J.T. Hagstrum, written commun., 1999), and a low-amplitude aeromagnetic high is centered on Green Mountain (Snyder and others, 1993).

Brunner Hill is a cinder cone that marks the vent of a short lava flow (Qbbh). This flow is an olivine- and clinopyroxene-phyric, high-potassium (about 1.7 wt percent K_2O), calc-alkaline basalt (fig. 2) with very high Ba and Sr contents (table 1, nos.

27, 28). An $^{40}\text{Ar}/^{39}\text{Ar}$ age of 627 ± 9 ka (table 2) was obtained for this flow.

Another vent is marked by a small hill about 1.5 km northeast of Brunner Hill, which is the apparent source for a flow that runs along the south bank of upper Matney Creek (Qbmc). This flow is a basaltic andesite that is petrographically and chemically similar to the Brunner Hill flow (Qbbh) but is slightly higher in K_2O , Ba, and Zr (table 1, no. 26). This flow has not been dated but its proximity and chemical similarity to the Brunner Hill flow suggests that the basalt of Matney Creek is derived from the same magmatic source and is thus about the same age. A modest aeromagnetic high in the area of the Brunner Hill and Matney Creek cones (Snyder and others, 1993) may reflect the presence of the solidified shallow magma body that fed both centers.

Several water wells in the map area penetrate intervals of rock that are believed to be flows or shallow intrusions of Quaternary basalt interbedded with the Neogene sediments. Rocks intersected in wells near Green Mountain and Brunner Hill may be intrusive offshoots from those centers, as portrayed on cross section B-B'. A separate, unexposed, magmatic center may be located about 2 km east of the mouth of Shanghai Creek, where a cluster of wells penetrate rocks described in the well logs as black rock or basalt that overlies gravel.

SURFICIAL DEPOSITS

CATACLYSMIC FLOOD DEPOSITS

During the last glacial maximum in late Pleistocene time, an ice dam impounded Glacial Lake Missoula in western Montana. It failed repeatedly, releasing floods that coursed down the Columbia River and into the Portland Basin (Bretz, 1925, 1959; Bretz and others, 1956; Trimble, 1963; Allison, 1978; Baker and Bunker, 1985; Waitt, 1985, 1994, 1996; O'Connor and Baker, 1992; Benito and O'Connor, 2003). The sediment-laden floodwaters, confined within the walls of the Columbia River Gorge to the east, decelerated rapidly upon entering the Portland Basin. Downstream, floodwaters entering the relatively narrow Columbia River valley at the north end of the Portland Basin were hydraulically dammed. This produced temporary ponding in the basin and tributary valleys to elevations as high as 400 ft (120 m). Radiocarbon ages, paleomagnetic measurements, and tephrochronologic data indicate that these floods occurred chiefly between about 17 and 12 ka (Waitt, 1994; Clague and others, 2003), although evidence is accumulating for episodes of cataclysmic flooding earlier in the Quaternary

(McDonald and Busacca, 1988; Zuffa and others, 2000; Bjornstad and others, 2001).

The cataclysmic floods deposited two lithologically distinct facies in the Portland Basin. Decelerating floodwaters emerging from the Columbia River Gorge deposited a huge fan of bouldery gravel (Qfg) in the central Portland Basin, named the Portland delta by Bretz (1925). The grain size of these deposits decreases progressively away from the fan apex near Troutdale, about 12 km south of the map area (fig. 1B). Smaller gravel fans were formed downstream of distributary flood channels such as the one occupied by Lacamas Lake (Allison, 1978; Waitt, 1996). Also, during each flood event, suspended load fine sand and silt settled out of the temporarily ponded floodwaters, building up deposits of laminated slack-water sediment (Qfs) as thick as 30 m in parts of the Portland Basin.

Mill Plain, near the southwest corner of the map area, is the surface of a huge bar deposited by the floods in the lee of Prune Hill at Camas, 3.5 km south of the map area (fig. 1B) (Allison, 1978; Waitt, 1994). The bar consists of unconsolidated, poorly sorted, foreset-bedded cobble gravels with outsize clasts as large as 2.5 m across (Trimble, 1963; Mundorff, 1964). These deposits, as thick as 40 m or more, were apparently deposited by multiple floods (Waitt, 1996). Similar gravel accumulated as a fan west of Proebstel, where floodwaters discharged northwestward through the trough now occupied by Lacamas Lake, (Trimble, 1963; Waitt, 1994). Before the floods, Lacamas Creek probably flowed westward to Burnt Bridge Creek but was diverted sharply southeastward to Lacamas Lake by the fan near Proebstel. Well logs indicate that the gravel grades northward to predominantly sand near Hockinson.

Slack-water deposits (Qfs) underlie the low-relief terrain below about 300 ft (90 m) elevation north of Fifth Plain Creek, where they overlie sand and gravel (Qfg) of the Lacamas Lake fan. They are rarely exposed, however, and their thickness (up to 15 m) and distribution are inferred largely from water-well logs.

ALLUVIAL AND MASS-WASTAGE DEPOSITS

Thin alluvial deposits (Qa) underlie floodplains along Lacamas, Shanghai, Fifth Plain, and Morgan Creeks as well as the Little Washougal River. Well-rounded quartzite pebbles recycled from the Troutdale Formation are abundant in all of these deposits. The broad trough of lower Lacamas Creek northwest of Lacamas Lake was swept free of alluvium by the Missoula floods. That area is now underlain by a thin (< 5 m thick) sequence of organic-rich mud (Ql) and peat (Qp) deposited in a shallow closed depression on the surface of the Missoula-flood deposits.

Several large landslide complexes mantle the steep bedrock terrain of the eastern part of the Lacamas Creek quadrangle. These slides appear to be generated by failure of weathered, clay-rich, flow-breccia zones or thin volcanoclastic interbeds. Small slides, including some too small to map, are widespread along steep slopes underlain by weakly consolidated parts of the Troutdale Formation.

STRUCTURAL FEATURES

Reliable bedding indicators are absent in the Oligocene strata of the Lacamas Creek quadrangle, but tracing of individual flows indicates that they dip to the west or southwest at less than 5°. The dissected west-sloping bedrock surface thus approximates a dip slope, and the exposed stratigraphic section in the map area is relatively thin, about 250 m.

Four subparallel northwest-striking faults are shown on the map although direct evidence for their existence is sparse. The northernmost structure, west of Elkhorn Mountain, is a probable right-lateral fault projected from a zone of disrupted and altered bedrock in the Yacolt quadrangle to the north (Evarts 2006). Two faults in the southern part of the map area define a northwest-trending, gravel-filled graben. The fault along Matney Creek, previously recognized by Swanson and others (1993), is inferred from water-well logs that suggest the top of the Sandy River Mudstone is downdropped at least 65 m to the southwest. To the southwest, a fault with the opposite sense of offset is interpreted from the logs of wells between Green Mountain and the north end of Lacamas Lake; these logs show an abrupt change in the elevation of Paleogene bedrock basement from near sea level on the southwest to 200 m below sea level on the northeast. This fault projects northwestward toward a steep, southwest-side-up reverse(?) fault mapped by Evarts (2004c) near Ridgefield, about 20 km northwest of the map area (fig. 1B). The southernmost mapped fault in the Lacamas Creek quadrangle is the Lacamas Lake Fault, which is projected northwest from Lacamas Lake in the adjacent Camas quadrangle. The lake occupies a linear basin that most previous workers suggest is controlled by a dextral strike-slip or southwest-side-down normal fault (Mundorff, 1964, Davis, 1987; Beeson and others, 1989; Tolan and Reidel, 1989; Beeson and Tolan, 1990; Swanson and others, 1993, Blakely and others, 1995). This is consistent with well logs south of Lacamas Campground that show a westward drop in the elevation of the buried bedrock surface.

The northwest-striking faults break the bedrock basement into several blocks, a configuration that is generally consistent with that interpreted by Davis (1987) from a gravity profile extending

southwest from the common intersection of Sections 28, 29, 32, and 33, T. 3 N., R. 3 E. Although most of the faults are mapped as dip-slip structures, each may have a significant dextral strike-slip component, similar to that exhibited by many northwest-striking faults in the Portland Basin and northern Willamette Valley (Blakely and others, 2000). Such lateral offset is impossible to detect from well logs.

It is not known if any faults in the map area experienced Quaternary movement. All appear to offset the Sandy River Mudstone (Tsr) and the older part of the Troutdale Formation (Ttfc), hence they were active during Pliocene time. Exposures in the map area are insufficient, however, to determine whether any displace the hyaloclastic sandstone member of the Troutdale Formation.

GEOLOGIC EVOLUTION

Paleogene volcanic bedrock in the Lacamas Creek quadrangle comprises lava flows of tholeiitic basaltic andesite and basalt that make up the basaltic andesite of Elkhorn Mountain. These flows form a chemically related suite and were probably emplaced on the middle to lower flanks of large shield volcano. Neither dikes nor hydrothermal alteration are present in the map area, indicating that the vent for this volcano is located outside the quadrangle, probably to the east. Age determinations in this and adjacent quadrangles (table 2; Evarts, 2005, 2006; R.J. Fleck, written commun., 2002, 2003, 2004, 2005) show that this volcano was active in Oligocene time, at about 27 Ma. The Oligocene rocks exhibit minor but pervasive zeolite-facies metamorphism, most likely caused by shallow burial. The low westward dip of the strata may reflect primary dips on the slopes of the shield volcano or may record mild deformation related to middle Miocene regional folding (Evarts and Swanson, 1994) or to subsidence of the Portland Basin (Beeson and others, 1989; Beeson and Tolan, 1990).

By late Miocene time, the Portland Basin was subsiding and accumulating fine-grained sediments of the ancestral Columbia River. These sediments, mapped as the Sandy River Mudstone, were deposited in a low-energy fluvial environment, probably near sea level. Maintenance of this setting throughout Sandy River time and onlap of these sediments against eroded Oligocene bedrock indicate that subsidence and accumulation rates were approximately the same. Normal or oblique-slip on the northwest-striking faults may have started at this time and continued into the Pliocene.

During latest Miocene or early Pliocene time, the sedimentary regime in the Portland Basin changed dramatically. The low-energy environment that is recorded by the Sandy River Mudstone was

superceded by progradation of a gravelly braid-plain across the basin. Clast compositions in these Troutdale Formation gravels indicate transport from terranes east of Cascades by an ancestral Columbia River. This pronounced change in the Columbia River sedimentary regime may record regional uplift to the east and initial incision of the Columbia River Gorge. Continued rise of the Cascade Range during Pliocene time raised and tilted the east side of the Portland Basin. As a result, the Columbia River incised its older floodplain and eroded the Troutdale Formation gravels from much of the basin, leaving remnants preserved only on its uplifted eastern flank.

In late Pliocene time, about 3–4 Ma, voluminous basaltic lava flows erupted in the Cascade Range east of the map area (Tolan and Beeson, 1984; Conrey and others, 1996). Some of these lavas entered the Columbia River and interacted violently with river water to produce large volumes of hyaloclastic sediment. The river may have been temporarily dammed by the flows but, if so, such dams were probably short-lived and the hyaloclastic debris was rapidly flushed downriver and deposited in an large alluvial fan in the eastern Portland Basin (Tolan and Beeson, 1984).

The unnamed conglomerate unit (QTc) represents a younger episode of gravel deposition in the Portland Basin in latest Pliocene or early Pleistocene time. Compared to the Troutdale Formation, this unit contains a higher proportion of volcanic clasts derived from the adjacent uplifted Cascade Range.

Beginning about 2.5 Ma, mafic volcanic activity spread westward from the Cascade Range into the Portland Basin to form the Boring Volcanic Field (Treasher, 1942; Trimble, 1963; Allen, 1975; Conrey and others, 1996; Fleck and others, 2002). The map area is near the northern edge of the volcanic field and contains three centers that erupted between 600 and 650 ka, one at Green Mountain and two in the Brunner Hill-Matney Creek area. The Brunner Hill and Matney Creek vents produced chemically similar lava flows that are probably products of a single magmatic system, and may have erupted more or less simultaneously.

The Lacamas Creek quadrangle lies beyond the limits of Pleistocene glaciers emanating from the southern Washington Cascade Range (Mundorff, 1984; Evarts, 2006). However, elevations below about 400 ft (120 m) were inundated by the latest Pleistocene glacier-outburst floods from Glacial Lake Missoula (Bretz, 1925; Trimble, 1963; Waitt, 1994, 1996). Floodwaters exiting the Columbia River Gorge spread out into the Portland Basin, spilling through and eroding the trough now occupied by Lacamas Lake. Bouldery bedload debris was dumped in a fan at the northwest end of the lake basin formed the large Mill Plain bar in the lee of Prune Hill.

Hydraulic damming downriver resulted in temporary ponding of floodwaters in the basin, and suspended fine sand and silt settled out, mantling topography below about 300 ft (100 m) elevation.

GEOLOGIC RESOURCES

Known geologic resources available in the Lacamas Creek quadrangle are limited to nonmetallic industrial materials, chiefly aggregate for road construction and similar purposes (Johnson and others, 2005). Paleogene and Quaternary volcanic rocks are quarried locally for crushed aggregate used primarily as base and surface layers for logging roads. Unconsolidated sandy gravel (Qfg) of the Mill Plain bar has been quarried for many years from large pits with an aggregate area exceeding 2 km².

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Table 1. Chemical analyses of volcanic rocks, Lacamas Creek 7.5' quadrangle

[X-ray fluorescence analyses. Rock-type names assigned in accordance with IUGS system (Le Maitre, 2002) applied to recalculated analyses. LOI, loss on ignition. Mg#, atomic ratio 100Mg/(Mg+Fe²⁺) with Fe²⁺ set to 0.85x Fe^{total}. Modal analyses, secondary minerals counted as primary mineral replaced. -, not present. X-ray fluorescence analyses by D.M. Johnson at GeoAnalytical Laboratory of Washington State University using methods described in Johnson and others (1999)]

Map No.	1	2	3	4	5	6	7	8	9
Field sample No.	02CM-T98	02CM-T99	02CM-T138	02CM-T118A	02CM-T121	02CM-T120	03CM-T226	00CM-T14B	02CM-T144
Latitude (N)	45°42.93'	45°42.66'	45°42.23'	45°42.77'	45°42.11'	45°42.51'	45°40.67'	45°44.70'	45°40.10'
Longitude (W)	122°26.69'	122°26.54'	122°23.59'	122°25.42'	122°26.57'	122°25.99'	122°24.13'	122°22.72'	122°24.50'
Map unit	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem
Rock type	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Basaltic andesite
Analyses as reported (wt percent)									
SiO ₂	50.43	50.71	50.69	50.78	50.72	51.08	51.71	51.98	51.73
TiO ₂	1.14	1.19	1.11	1.34	1.19	1.08	1.95	2.00	1.77
Al ₂ O ₃	21.00	20.55	21.04	19.62	20.44	19.93	15.71	15.62	16.15
FeO*	8.56	8.93	8.00	9.20	8.57	8.34	12.66	12.53	11.77
MnO	0.16	0.17	0.16	0.17	0.16	0.16	0.21	0.24	0.22
MgO	3.73	3.82	4.06	4.32	3.86	4.51	4.85	4.82	4.73
CaO	11.34	11.17	11.50	10.92	11.10	11.28	9.09	9.39	9.13
Na ₂ O	2.71	2.83	2.70	2.81	2.79	2.66	3.31	3.22	3.23
K ₂ O	0.35	0.36	0.23	0.44	0.37	0.40	0.48	0.33	0.42
P ₂ O ₅	0.11	0.11	0.10	0.12	0.11	0.10	0.19	0.18	0.17
Total	99.53	99.83	99.59	99.72	99.31	99.55	100.15	100.32	99.32
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO ₂	50.65	50.79	50.88	50.91	51.04	51.29	51.64	51.84	52.04
TiO ₂	1.14	1.19	1.11	1.35	1.20	1.08	1.95	1.99	1.78
Al ₂ O ₃	21.09	20.58	21.12	19.67	20.57	20.01	15.69	15.58	16.25
FeO*	8.64	8.95	8.06	9.25	8.68	8.42	12.62	12.46	11.92
MnO	0.16	0.17	0.16	0.17	0.17	0.16	0.21	0.24	0.22
MgO	3.75	3.83	4.08	4.33	3.88	4.53	4.84	4.81	4.76
CaO	11.39	11.19	11.54	10.95	11.17	11.33	9.08	9.36	9.18
Na ₂ O	2.72	2.83	2.71	2.82	2.81	2.67	3.31	3.21	3.25
K ₂ O	0.35	0.36	0.23	0.44	0.37	0.40	0.48	0.33	0.42
P ₂ O ₅	0.11	0.11	0.10	0.12	0.11	0.10	0.19	0.18	0.17
Mg#	47.6	47.3	51.5	49.6	48.4	53.0	44.6	44.7	45.6
Modes (volume percent)									
Plagioclase	52.6	35.7	46.5	30.6	35.1	34.3	2.2	1.8	4.1
Clinopyroxene	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	1.4	0.4	0.6	0.8	0.7	1.5	0.1	0.1	0.3
Fe-Ti Oxide	-	-	-	-	-	-	trace	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Biotite	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	46.0	63.9	52.9	68.6	64.2	64.2	97.7	98.1	95.6
No. points counted	810	810	800	810	800	810	810	800	812
Texture (rock/ groundmass)	porphyritic/ intergranular	porphyritic/ intergranular	porphyritic/ intergranular	porphyritic/ intergranular	porphyritic/ subophitic	porphyritic/ intergranular	sparsely phyric/ trachytic	sparsely phyric/ intergranular	porphyritic/ trachytic
Trace element analyses (ppm)									
Ba	98	111	84	117	112	99	152	131	143
Rb	7	8	3	10	7	9	8	2	6
Sr	326	323	328	316	315	314	272	277	283
Y	19	19	18	22	19	18	31	32	26
Zr	60	62	57	70	61	61	97	91	87
Nb	4.0	5.3	5.1	6.1	4.8	4.7	5.1	7.8	7.8
Ni	10	11	14	21	12	18	8	7	17
Cu	141	139	141	176	142	91	238	175	222
Zn	71	77	76	83	76	73	115	109	109
Cr	25	24	33	47	23	51	27	42	38

Table 1. Chemical analyses of volcanic rocks, Lamas Creek 7.5' quadrangle—Continued

Map No.	10	11	12	13	14	15	16	17	18
Field sample No.	03CM-T176	02CM-T133	02CM-T115	02CM-T88	00CM-T14A	02CM-T140	03CM-T222A	02CM-T112	02CM-T124
Latitude (N)	45°42.95'	45°42.46'	45°43.77'	45°43.50'	45°44.71'	45°39.89'	45°40.84'	45°44.76'	45°40.43'
Longitude (W)	122°23.98'	122°24.94'	122°24.45'	122°25.24'	122°22.62'	122°22.92'	122°24.76'	122°25.67'	122°24.25'
Map unit	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported (wt percent)									
SiO ₂	52.19	51.84	52.21	52.30	52.80	52.38	52.79	52.62	52.87
TiO ₂	1.82	1.83	1.60	1.76	1.70	1.79	1.69	1.94	2.05
Al ₂ O ₃	15.82	15.42	17.13	15.50	15.40	15.65	16.48	15.78	15.09
FeO*	12.11	12.12	10.37	12.00	12.82	11.87	11.92	11.69	12.34
MnO	0.24	0.22	0.22	0.24	0.23	0.24	0.20	0.21	0.23
MgO	4.77	4.81	4.57	4.71	4.64	4.58	4.40	4.35	4.16
CaO	9.34	9.15	9.50	8.97	8.44	8.72	8.87	8.11	8.43
Na ₂ O	3.40	3.19	3.08	3.22	3.41	3.30	3.40	3.43	3.41
K ₂ O	0.26	0.58	0.41	0.44	0.46	0.50	0.41	0.66	0.66
P ₂ O ₅	0.16	0.17	0.15	0.17	0.16	0.18	0.16	0.25	0.22
Total	100.11	99.33	99.23	99.31	100.06	99.20	100.33	99.04	99.46
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO ₂	52.14	52.15	52.57	52.62	52.77	52.75	52.64	53.07	53.12
TiO ₂	1.82	1.84	1.61	1.77	1.70	1.80	1.69	1.96	2.06
Al ₂ O ₃	15.80	15.51	17.25	15.59	15.39	15.76	16.43	15.91	15.16
FeO*	12.09	12.27	10.52	12.16	12.80	12.05	11.84	11.90	12.47
MnO	0.24	0.22	0.22	0.24	0.23	0.24	0.20	0.21	0.23
MgO	4.77	4.84	4.60	4.74	4.63	4.61	4.39	4.39	4.18
CaO	9.33	9.20	9.57	9.02	8.44	8.78	8.84	8.18	8.47
Na ₂ O	3.40	3.21	3.10	3.24	3.41	3.32	3.39	3.46	3.43
K ₂ O	0.26	0.58	0.41	0.44	0.46	0.50	0.41	0.67	0.66
P ₂ O ₅	0.16	0.17	0.15	0.17	0.16	0.18	0.16	0.25	0.22
Mg#	45.3	45.3	47.9	45.0	43.2	44.5	43.7	43.6	41.3
Modes (volume percent)									
Plagioclase	0.4	1.6	11.6	trace	0.6	1.1	8.5	0.1	trace
Clinopyroxene	-	0.1	-	-	trace	-	-	-	trace
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	-	trace	0.4	-	trace	0.1	0.7	trace	trace
Fe-Ti Oxide	trace	-	-	-	trace	-	trace	-	trace
Hornblende	-	-	-	-	-	-	-	-	-
Biotite	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	99.6	98.3	88.0	100.0	99.4	98.8	90.8	99.9	100.0
No. points counted	800	810	800	800	800	810	810	800	800
Texture (rock/ groundmass)	~aphyric/ trachytic	sparsely phyric/ microphyric	porphyritic/ trachytic	aphyric/ intergranular	~aphyric/ trachytic	sparsely phyric/ trachytic	seriate/ trachytic	~aphyric/ intergranular	aphyric/ intergranular
Trace element analyses (ppm)									
Ba	131	156	134	154	148	155	141	192	183
Rb	4	13	4	5	7	11	6	13	14
Sr	275	270	283	266	265	267	285	287	265
Y	27	30	27	30	28	28	26	32	33
Zr	87	95	83	89	92	90	90	137	114
Nb	5.1	6.9	6.8	6.2	5.5	7.5	5	10.7	8.7
Ni	6	15	11	10	4	13	9	†18	7
Cu	206	217	198	208	214	129	241	282	257
Zn	114	107	108	114	111	112	111	113	119
Cr	16	52	25	25	14	36	15	21	12

Table 1. Chemical analyses of volcanic rocks, Lacamas Creek 7.5' quadrangle—Continued

Map No.	19	20	21	22	23	24	25	26	27
Field sample No.	00CM-T11	02CM-T116A	02CM-T90	02CM-T135	02CM-T110	02CM-T18	02CM-T125	02CM-T143	02CM-T131
Latitude (N)	45°44.14'	45°43.60'	45°43.44'	46°42.60'	46°44.52'	46°44.62'	46°40.71'	46°39.05'	46°38.64'
Longitude (W)	122°24.85'	122°23.94'	122°24.51'	122°24.48'	122°24.91'	122°24.45'	122°23.79'	122°24.24'	122°24.33'
Map unit	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Tbem	Qbmc	Qbbh
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basalt	Basaltic andesite
Analyses as reported (wt percent)									
SiO ₂	53.44	53.17	53.44	53.24	53.23	53.73	53.79	49.57	52.00
TiO ₂	1.63	1.53	1.59	1.58	1.62	1.46	1.83	1.39	1.30
Al ₂ O ₃	17.31	15.76	15.83	15.98	16.03	18.12	15.83	17.77	18.29
FeO*	10.70	10.76	10.51	10.15	11.05	9.29	10.84	7.89	7.76
MnO	0.21	0.22	0.22	0.21	0.22	0.20	0.22	0.13	0.12
MgO	3.77	4.85	4.81	4.70	4.29	3.61	3.93	7.01	6.18
CaO	9.06	9.34	9.46	9.43	8.79	9.15	8.49	7.34	6.11
Na ₂ O	3.43	3.11	3.29	3.29	3.31	3.53	3.67	3.21	3.17
K ₂ O	0.52	0.52	0.35	0.43	0.44	0.49	0.32	1.63	1.31
P ₂ O ₅	0.19	0.14	0.15	0.15	0.15	0.15	0.20	0.68	0.51
Total	100.25	99.41	99.64	99.16	99.13	99.73	99.12	96.62	96.75
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)									
SiO ₂	53.32	53.45	53.61	53.64	53.65	53.86	54.22	51.16	53.60
TiO ₂	1.62	1.54	1.59	1.60	1.63	1.47	1.84	1.43	1.34
Al ₂ O ₃	17.27	15.84	15.88	16.10	16.16	18.16	15.96	18.34	18.85
FeO*	10.65	10.88	10.58	10.31	11.23	9.33	11.02	8.43	8.27
MnO	0.21	0.22	0.22	0.21	0.22	0.20	0.23	0.13	0.13
MgO	3.76	4.88	4.83	4.74	4.32	3.62	3.96	7.23	6.37
CaO	9.04	9.39	9.49	9.50	8.86	9.17	8.56	7.58	6.30
Na ₂ O	3.42	3.13	3.30	3.31	3.3	3.5	3.7	3.3	3.3
K ₂ O	0.52	0.52	0.35	0.43	0.44	0.49	0.32	1.68	1.35
P ₂ O ₅	0.19	0.14	0.15	0.15	0.15	0.15	0.20	0.70	0.53
Mg#	42.6	48.4	48.9	49.1	44.7	44.9	43.0	64.3	61.8
Modes (volume percent)									
Plagioclase	19.1	1.9	1.6	0.5	3.8	19.5	0.1	trace	0.1
Clinopyroxene	trace	trace	0.1	0.1	0.2	trace	trace	2.2	2.2
Orthopyroxene	-	-	-	-	-	-	-	-	-
Olivine	0.1	trace	0.1	trace	0.8	0.1	trace	4.7	4.9
Fe-Ti Oxide	trace	-	-	-	trace	trace	trace	-	-
Hornblende	-	-	-	-	-	-	-	-	-
Biotite	-	-	-	-	-	-	-	-	-
Quartz	-	-	-	-	-	-	-	-	-
K-feldspar	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-
Groundmass	80.8	98.1	98.2	99.4	95.2	80.4	99.9	93.1	92.8
No. points counted	780	810	810	810	800	800	800	780	780
Texture (rock/ groundmass)	porphyritic/ intergranular	sparsely phyric/ intergranular	sparsely phyric/ trachytic	~aphyric/ trachytic	seriate/ trachytic	porphyritic/ intergranular	aphyric/ trachytic	porphyritic/ microphyric	porphyritic/ intergranular
Trace element analyses (ppm)									
Ba	143	144	133	159	124	128	141	1372	1063
Rb	10	13	5	3	7	11	6	7	8
Sr	290	267	279	278	275	302	280	1289	1092
Y	29	26	26	28	25	22	33	22	21
Zr	99	82	87	86	87	85	105	204	167
Nb	8.2	5.9	5.9	7.1	7.0	6.5	8.7	10.8	9.6
Ni	11	11	10	10	5	7	8	140	124
Cu	147	205	214	257	212	136	244	48	68
Zn	99	101	104	100	104	93	114	102	96
Cr	31	58	45	45	14	7	10	201	175

Table 1. Chemical analyses of volcanic rocks, Lamas Creek 7.5' quadrangle—Continued

Map No.	28	29	30
Field sample No.	02CM-T145	QV97-03	02CM-T123
Latitude (N)	46°38.40'	45°39.36'	46°39.29'
Longitude (W)	122°24.35'	122°28.04'	122°27.32'
Map unit	Qbbh	Qbgm	Qbgm
Rock type	Basaltic andesite	Basaltic andesite	Basaltic andesite
Analyses as reported (wt percent)			
SiO ₂	53.90	53.98	54.28
TiO ₂	1.19	1.27	1.26
Al ₂ O ₃	17.39	17.79	18.46
FeO*	7.19	7.75	7.16
MnO	0.12	0.12	0.13
MgO	5.88	5.89	5.77
CaO	8.11	7.76	7.89
Na ₂ O	3.96	4.07	4.06
K ₂ O	1.27	0.73	0.73
P ₂ O ₅	0.46	0.28	0.26
Total	99.47	99.36	100.00
Analyses recalculated volatile-free and normalized to 100% with all Fe as FeO (wt percent)			
SiO ₂	54.17	54.15	54.28
TiO ₂	1.20	1.27	1.26
Al ₂ O ₃	17.48	17.85	18.46
FeO*	7.26	7.82	7.16
MnO	0.12	0.12	0.13
MgO	5.91	5.91	5.77
CaO	8.15	7.78	7.89
Na ₂ O	4.0	4.08	4.06
K ₂ O	1.28	0.73	0.73
P ₂ O ₅	0.46	0.28	0.26
Mg#	63.1	61.3	62.8
Modes (volume percent)			
Plagioclase	0.3	-	-
Clinopyroxene	1.5	-	-
Orthopyroxene	-	-	-
Olivine	4.0	2.7	3.4
Fe-Ti Oxide	-	-	-
Hornblende	-	-	-
Biotite	-	-	-
Quartz	-	-	-
K-feldspar	-	-	-
Other	-	-	-
Groundmass	94.2	97.3	96.6
No. points counted	750	750	790
Texture (rock/ groundmass)	porphyritic/ trachytic	porphyritic/ intergranular	porphyritic/ trachytic
Trace element analyses (ppm)			
Ba	923	189	202
Rb	11	6	6
Sr	1449	581	582
Y	17	19	20
Zr	153	132	122
Nb	8.9	9.8	9.1
Ni	110	97	103
Cu	47	40	38
Zn	87	76	76
Cr	168	145	154

Table 2. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating age determinations, Lacamas Creek 7.5' quadrangle

Field sample no.	Location Latitude (N)	Location Longitude (W)	Map unit	Rock type	Material dated	Age ($\pm 1\sigma$ error)	Source
02CM-T145	45°38.40'	122°24.35'	Qbbh	Basalt	Groundmass	627±9 ka	R.J. Fleck, written commun., 2004
QV97-03	45°39.36'	122°28.04'	Qbgm	Basaltic andesite	Groundmass	575±7 ka	R.J. Fleck, written commun., 2006