Postglacial Influence of Volcanism on the Landscape and Environmental History of the Puget Lowland, Washington: A Review of Geologic Literature and Recent Discoveries, with Emphasis on the Landscape Disturbances Associated with Lahars, Lahar Runouts, and Associated Flooding

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Abstract
Geologic and geotechnical studies during the last several decades have shown that the environmental history of several major river systems of the Puget Lowland includes periodic severe geomorphic and environmental disturbances from lahars (volcanic debris flows), lahar runouts, and associated flooding. Episodic lahars and post-laharic sedimentation have significantly aggraded the Nisqually, Puyallup, White, Skagit, Duwamish, Stilliquamish, and Nooksack Rivers, caused delta progradation that has dramatically altered the coastline of the Puget Lowland, and, for extremely large events, triggered stream piracy, as exemplified by that in the Stillaguamish/Skagit River, Fraser/Nooksack, and White/Puyallup River systems respectively. These volcanic disturbances buried extensive landscapes including mature, old-growth forests and destroyed and/or severely disrupted pre-Euro-American-settlement human communities. Geologists have identified two main types of lahars, cohesive (>3% matrix clay) and noncohesive (<3% matrix clay), each of which has distinctive flowage and depositional characteristics. The recognition of flow transformations in noncohesive lahars now allows geologists to better identify lahar runout and laharic flood deposits in downstream areas. Collectively, the recent and ongoing studies of volcanic history in the Puget Sound drainage basin have greatly improved our understanding of the magnitude and frequency of the associated landscape disturbances. This history of past volcanism and landscape change—including a consistent trend of downstream aggradation, or landscape burial, and the inevitability of future eruptions and lahars have profound implications for a wide spectrum of environmental-, and hazards-related concerns that relate to aquifers, ecologic systems (including human), seismicity, land use, and future risk.

Introduction

Washington State's "active" volcanoes
Washington is home to five major composite volcanoes or stratovolcanoes: Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams. These volcanoes and nearby Mount Hood are part of the Cascade Range, a volcanic arc that stretches from southwestern British Columbia to Northern California. Although there are thousands of small basaltic or basaltic-andesite volcanoes in the Cascade Range, the 13 major composite volcanic centers in the U.S. part of the range have been the focus of most hazards concerns and studies. During the past 12,000 years, these volcanoes have produced more than 200 eruptions that have generated tephra (ejected material), lava flows, and lahars, and debris avalanches (Miller 1990). Earthquakes, intrusions of magma, or steam explosions may have caused some enormous debris avalanches and lahars whose deposits apparently do not correlate with major tephra layers.

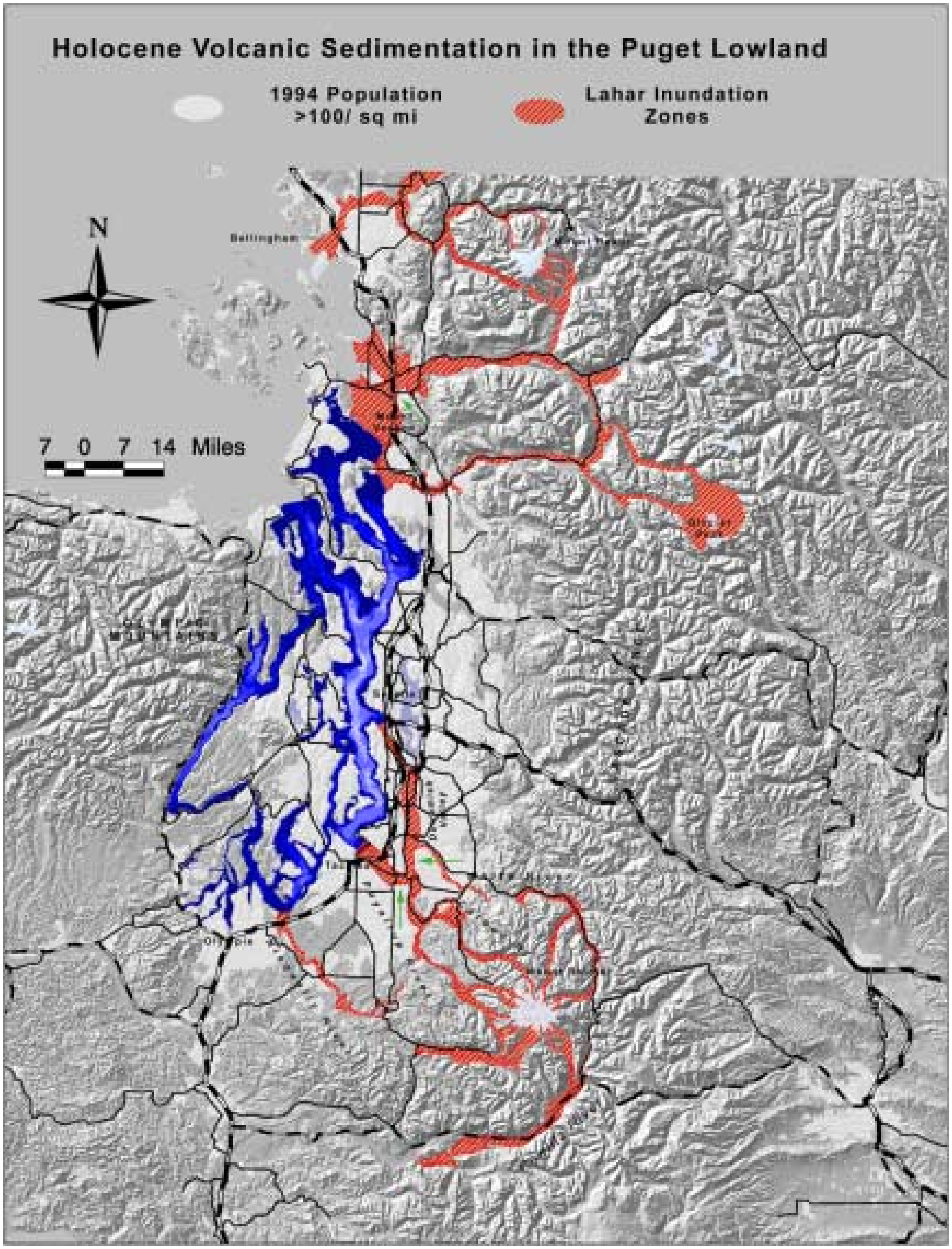

Figure 1 Shaded relief image (30 m DEM) showing approximate locations of Holocene lahar inundation areas based on US Geological Survey reports noted in text. Small green arrows show locations of shorelines about 5,500 yr ago in Puyallup, Duwamish, and Skagit River valleys, as interpreted by Luzier (1969) and Dragovich and others (1994; 2000). We include the Fraser-Nooksack lowland as part of the Puget Lowland as in Jones (1999). Only the blue-shaded bathymetry for Puget Sound is shown.

All Washington volcanoes except for Mount Adams have erupted since the birth of the United States in 1776, and all of them, as well as Mount Hood, have active seismicity and/or geothermal activity. Scott (1990) provides a compilation of eruptive histories and hazards from major Cascade peaks in Washington and Oregon. This article will focus mainly on the volcanic processes associated with the three northernmost Washington volcanoes, Mounts Baker and Rainier, and Glacier Peak, because they are the sources of major rivers that flow into Puget Sound. However, a major eruption from a volcano in the Canadian Cordillera could have adverse regional effects and contribute to sedimentation in the adjacent Strait of Georgia and northernmost Puget Sound (Fig. 1).

A growing environmental and geologic history

As noted above, geologic investigations during the latter half of the 1900s provided growing evidence that some of the major river systems that discharge into the Puget Lowland are dominated by periodic disturbances from lahars and laharic flooding. While other disturbances include those caused by tephra deposition, meteorologic flooding, mass wasting, and earthquakes (as well as fires and human activity), those related to laharic sedimentation and to such secondary effects as episodic post-laharic sedimentation and erosion, and the catastrophic breakouts of lahar-, pyroclastic-flow-, and volcanic-landslide-dammed lakes have had the greatest impacts on the fluvial systems that are tributary to Puget Sound.

The Nisqually, Puyallup, White, Skagit, and Nooksack Rivers, all of which drain active volcanoes (Mounts Rainier and Baker, and Glacier Peak), have aggraded significantly in postglacial times, with some of the sedimentation events being so enormous that they dramatically altered the present Puget Sound coastline and geography and caused major stream piracy in the Stillaguamish/Skagit River system (Vance 1957; Beget 1982), Fraser/Nooksack (Cameron 1989), and White/Puyallup (Crandell 1963; Luzier 1969; Dragovich and others 1994). These volcanic disturbances have buried extensive forests and ecosystems (Pringle and others 1997; Pringle 2000; Vallance and Scott 1997), have undoubtedly destroyed pre-Euro-American-settlement human communities (e.g. Hedlund 1972; Williams 1973; Ballard 1929; Clark 1953), and have caused long-term aggradation in lowlands.

Post-Mount St. Helens studies of lahars and lahar-related flows and disturbances have identified two major types of laharic flows based on clay content (Scott 1988; 1989). The recognition of flow transformation processes in one of these types, the noncohesive (low clay content) lahars (Pierson and Scott 1985), has allowed identification of previously unrecognized lahar-runout deposits in downstream reaches of the drainages (Scott and others 1995; Palmer and others 1991; Pringle and Palmer 1992; Dragovich and others 2000). The characteristics of these lahar types will be discussed in more detail below.

One of the reasons that lahars are so significant as agents of landscape change and can be so hazardous is their potential for great size—flow depths of the largest lahars can be as deep as several hundred meters at the volcanic edifice and tens of meters as far as 50 km flow distance from the volcano. This significance of scale is why geologist Kelvin Rodolfo (1991; 2000) has suggested that volcanologists continue to use the term “lahar,” to distinguish this uniquely large and distinctive debris flow process from other debris flows and “mudflows”—such as those generated by meteorological events and which are commonly thought of by the general public to be much smaller in scale. The large size, energy, and thick consistency of lahars commonly trigger large-scale “cascade” effects, such as the blocking of tributary valleys, widespread bank erosion, and resultant catastrophic flooding. (See chapters 2 and 3 in Chorley and others 1984). These processes, combined with the range of landscape-altering effects associated with volcanism, such as tephra fallout and destruction of vegetation, commonly alter geomorphic thresholds, such as base level, stream gradient or valley geometry, or bed roughness. The complex geomorphic responses that may result can radically change the equilibrium of a drainage basin and allow increased rates of erosion for periods of decades after a volcanic disturbance. Some examples of these secondary effects will be discussed below.

Finally, a wealth of new information from subsurface geotechnical studies of volcanogenic deposits has proven integral to better reconstructions of paleogeography and geologic history (e.g. Dragovich and others 1994; Palmer 2001) of the Puget Sound landscape as well as to a better understanding of the geotechnical qualities of the valley-filling materials. Continued study and sound use of this new information will help mitigate future losses from hazardous geological processes; this includes reducing the environmental impacts of seismic activity in the valleys (e.g. 1995; Palmer and others 1994b, 1995). Indeed, the character of interbedded volcanic deposits in valleys downstream of stratovolcanoes has profound implications for aquifers, volcanic hazards, seismic hazards—including liquefaction susceptibility in the lowland (Palmer and others 1994a), and for delta stability (Barnhardt and others 1998; 2000), as well as for specialized land uses such as agriculture.

The primary focus of this overview and literature review will be on landscape changes related to lahars, lahar runouts, and associated flooding in Washington Rivers that are tributary to Puget Sound. (Note: “yr B.P.” signifies the number of uncalibrated radiocarbon years before present, where “present” = AD 1950. This uncalibrated age may differ by as much as several centuries from the calibrated age, particularly for older samples).

Volcanic Processes and Hazards

Parts of the following overview of volcanic processes and hazards in Washington are revised from Pringle (1994). For a more complete discussion of this topic, chapter 2 in Tilling (1989) is an excellent reference; Fisher and Schmincke (1984), Cas and Wright (1987), and Decker and Decker (1988) are among other informative texts. Generally, composite volcanoes (stratovolcanoes), which are the main focus in this paper, are associated with subduction zones. Consequently, they are found around the Pacific Rim ("Ring of Fire") and in the Mediterranean-Himalayan Belt. Composite volcanoes are mainly characterized by the following processes, features, or aspects:

Lava domes and flows

Lavas of higher viscosity tend to pile up and form domes because they cannot flow as readily as those having a lower viscosity (such as Hawaiian basaltic lavas). The new Lava Dome at Mount St. Helens was constructed during 17 episodes of activity from 1980 to 1986 that included both intrusion of new magma into the dome and extrusion of lobes of lava onto the dome’s surface and flanks. Crater Rock at Mount Hood is the remnant of a dome that was constructed by eruptions during the last 1,800 years. Hazards from lava domes include explosions and collapses. Dome collapse can produce pyroclastic flows and surges, lahars, and floods.

The main hazard from lava flows is damage or total destruction by burying, crushing, or burning of everything in their paths. (However, higher viscosity lava flows do not generally flow far from the volcano.) Lava flows can melt snow and ice, but they commonly do not produce major floods and lahars because they generally do not mix turbulently with snow and ice. They can, however, melt large quantities of glacial ice that can be released as “jokulhlaups.”

Pyroclastic density currents

Pyroclastic density current is a general name for various types of flows of hot gas and rock down the slopes of a volcano. These include pyroclastic flows, pyroclastic surges, and directed blasts (sometimes called “lateral blasts” or “directed blasts”). Based on flow characteristics inferred from deposits, typical pyroclastic density flows have two components: (1) a ground-hugging, dense basal portion (the “flow”), and (2) a turbulent ash-cloud surge (the “surge”) that extends out from the flow and can move across the landscape over topographic barriers.

Pyroclastic flows are masses of hot (300°->800° C), dry rock debris and gases that move rapidly along the ground surface at velocities ranging from 10 to several hundred meters per second. Direct hazards of pyroclastic flows are asphyxiation, burial, incineration, and impact. Pyroclastic flows also can generate lahars and floods by quickly melting snow and ice (Pierson 1999), can dam tributary valleys, and can start fires. Pyroclastic flows are strongly controlled by topography and are likely to be restricted to valley floors. Most pyroclastic flows are limited to within 9 to 15 mi (15 to 25 km) of a volcano.

Unlike pyroclastic flows, hot *pyroclastic surges*, because they are less concentrated and less dense than pyroclastic flows, are not necessarily confined to valleys and can affect more extensive areas many tens of kilometers from the volcano. Pyroclastic surges can generate secondary pyroclastic flows. Surges are responsible for many catastrophes, including 30,000 deaths at Mount Pelee (1902) and 2,000 at El Chich∴n (1982) and can also trigger devastating lahars, such as that at volcano Nevado del Ruiz in 1995 that killed more than 23,000 people (Wright and Pierson 1992). Cold, or base, surges typically result from explosive interactions with magma and water, such as that witnessed at Kilauea, Hawaii in May 1924, and, on a smaller scale, by the post-1980 phreatic (steam) explosions on the Pumice Plain and in the crater at Mount St. Helens.

Directed blasts are very powerful, laterally directed explosions such as that at Mount St. Helens in 1980 and at Bezymianny, Kamchatka, in 1956. Blasts can affect large areas (230 mi^2 or 600 km^2 at Mount St. Helens). Evidence for large and aerially extensive, such as the 1980 Mount St. Helens event, have been found, however, most Holocene examples in the Cascades were considerably less energetic and extensive than the Mount St. Helens blast—examples are found at Mount Rainier (F and S tephra layers) and the 1,200-yr B.P. “Sugar Bowl” explosion, and March 1982, February 1983, and May 1984 small explosive events at St. Helens.

Lahars, lahar-runout flows, floods

Lahars are volcanic debris flows ("mudflows"), or rapidly flowing mixtures of rock debris that are mobilized by water and that originate on the slopes of a volcano—typically they are restricted to stream valleys. (See Vallance 2000). Although lahars can originate in several ways (Scott and others 1986), two major flow types—based on sedimentary characteristics that relate to origin and flow behavior—have been noted by Scott (1988): cohesive and non-cohesive (Fig. 2). Scott’s classification scheme has been very useful, not only for interpreting the genesis and flow processes of ancient lahars from the sedimentary characteristics of their deposits, but also for recognizing their downstream transformations, so that correlative deposits now can be identified in distal areas (e.g. Palmer and others 1991; Pringle and Palmer 1992). The two deposit types, and by inference the flows that yielded those deposits, may also be referred to as “muddy” (cohesive) and “granular” (noncohesive) for those concerned with engineering implications of the terms as applied to flows. We emphasize that the terminology used herein is based on the deposits of lahars.

Figure 2 A geologist examines the cohesive (“muddy”, or clay-rich) Round Pass lahar deposit from Mount Rainier near the town of National, about 20 km flow distance from Mount Rainier. Overlying it the noncohesive (“granular”, or clay-poor) National lahar deposit. Both of these flows may have traveled along the Nisqually River as far as Puget Sound.

Noncohesive lahars have relatively low matrix clay content (<3%); these flows typically begin as a flood surge that incorporates sediment and becomes a debris flow as it travels. The debris flow then rapidly transforms downstream to more diluted flow types (lahar-runout flows and floods; see Fig. 3) because of sediment deposition (particularly the coarser fraction) and/or incorporation of water. The many causes of these clay-poor lahars include:

- Interaction of a pyroclastic density current with snow and ice.

- Meteorologically induced erosion of tephra (or other fragmental debris) from the slopes of a volcano (rainstorm or rain-on-snow events).
- Failure of a landslide-dammed lake.
- Glacial outburst flood or jokulhlaup.

Cohesive lahars are relatively clay-rich (>3%) and typically begin as volcanic landslides. The largest landslides from volcanoes, described as *sector collapses*, commonly remove the summit of the volcano leaving a characteristic horseshoe-shaped crater and have a volume of 1 km^3 or more. Sector collapses are nearly always associated with an eruption or with hydrovolcanic activity (magma-water interactions) such as steam explosions. Consequently, precursory volcanic activity should provide a degree of pre-event warning. Reid (1995) has suggested that hydrothermal pressurization may be a destabilizing factor for such collapses by providing high pore-fluid pressures that contribute to large-scale collapse.

Smaller landslides that do not involve the summit of the edifice are called "flank collapses" (Scott and others 2001) and may also yield cohesive lahars that inundate areas well beyond 50 km from the source volcano. Flank collapses have a variety of triggers, including eruptions, intrusions, magmatic activity that destabilizes the edifice (i.e. hydrothermal alteration or , earthquakes, phreatic (steam) activity), or simply gravity. (See Swanson and others 1995). From a hazards perspective, although there is no guarantee of an effective pre-event warning that will lead to evacuation of large populations potentially at risk long distances from a volcano, lahars can be detected close to there sources because of their characteristic vibrations in the range of 30 Hz to 80 Hz (LaHusen 1998). Thus, the USGS has installed an array of 10 Acoustic Flow Monitors in two drainages of Mount Rainier to provide an "event warning" (a lahar is occurring)(Murray and others 2000).

Cohesive lahars can have enormous volumes and flow great distances. The Electron, Round Pass, Paradise, and Osceola mudflows at Mount Rainier, and Middle Fork Nooksack flow at Mount Baker are noteworthy local examples. The volume of the Electron Mudflow has been estimated at more than 300 million yds^3 (0.25 km^3)(Crandell 1971; Scott and others 1995) and the volume of the Osceola Mudflow at about 1 mi^3 ($4km^3$)(Dragovich and others 1994; Vallance and Scott 1997), making it one of the world’s largest mass wasting events from a volcano.

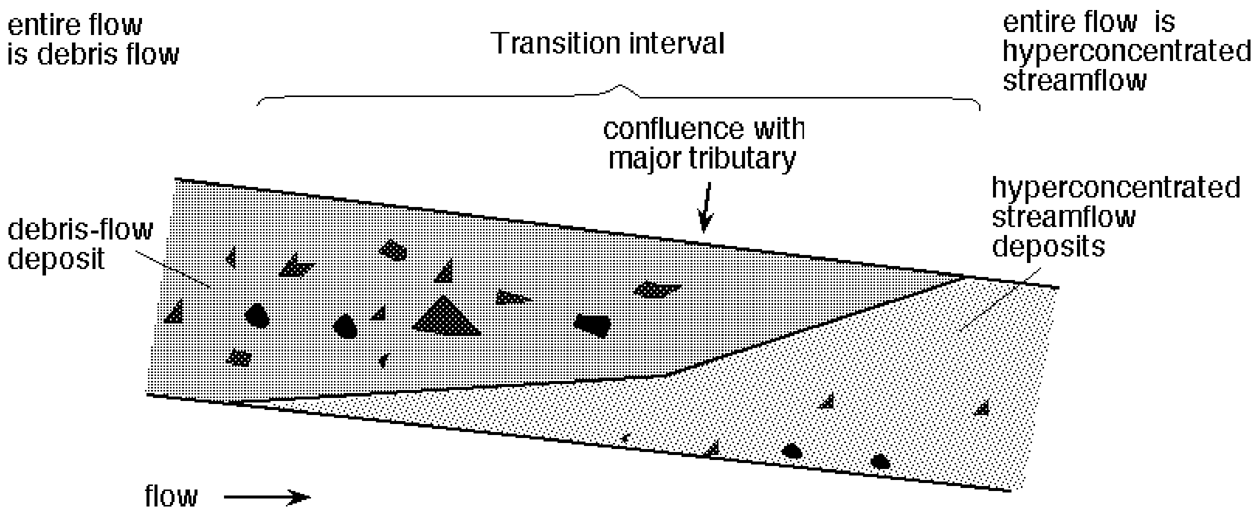

Figure 3 Diagrammatic transformation of a granular lahar (noncohesive or low clay content) to a more diluted hyperconcentrated flow, from Scott (1985). These observations of textural changes has allowed geologist to recognize downstream deposits that are correlative with lahar deposits in proximal areas. Inundation height, runout length, velocity, and duration of flood wave for lahars can vary widely. Spacing between events, amount of available sediment for bulking, and other factors can change the scale of hazards and of the sedimentation and landscape effects from lahars.

Debris avalanches

Volcanic *debris avalanches* are a type of volcanic landslide—specifically a flowing mixture of rock, soil, and miscellaneous debris, with or without water, that moves away from a volcano at high speed under the influence of gravity (e.g. Pierson and Costa 1987). Debris avalanches are an end member of a continuum of mass-wasting processes at composite volcanoes—as noted above, some large lahars at some highly hydrothermally altered volcanoes, such as Mount Rainier, have undoubtedly transformed directly from such volcanic landslides. Since the 1980 eruption of Mount St. Helens, hummocky debris avalanche deposits have been recognized at several hundred volcanoes around the world (Siebert 1996). The deposits of a debris avalanche can reach a great thickness, in excess of 200 m at Mount St. Helens (Glicken 1986, 1998). Therefore, even if a debris avalanche does not transform into a lahar or flow more than 10 or 15 km from a volcano, they can cause drastic, long-term environmental changes throughout the affected drainage basins by altering the equilibrium of stream systems and providing a source of sediment and small scale landslides as well as temporary lakes (discussed below)—the impacts can include severe sedimentation in downstream areas for decades. (See Major and others 2000). Some debris avalanches have been caused by earthquakes, such as that at Mount Ontake, Japan in 1984 (Yanase and others 1985; Nagaoka 1987).

The nature of the hazard from debris avalanches and its relation to hydrothermal alteration and destabilization of a volcanic cone also indicate that sector-collapse events (very large debris avalanches) can affect any drainage heading on a volcano, although they may be more likely in sectors where alteration is at a more advanced stage (Zimbelman; 1996; 2000; Finn and others 2001). The stratigraphic record of enormous megathrust earthquakes in the Cascadia subduction zone as well as our increasing recognition of shallow-crustal fault zones in the Puget-Willamette Lowland and along the Cascade Range and their possible triggering of landslides by seismic shaking (e.g. Pringle and others 2000) amplifies the need for further study of this major slope-stability process at composite volcanoes.

Secondary Effects of Eruptions

The secondary effects of the 1980 Mount St. Helens eruption serve as a reminder that landscape disturbances caused by volcanoes (and therefore volcanic hazards) can persist long after initial eruptive activity has ceased. At Mount St. Helens, dramatic post-eruption erosion and sedimentation and the ongoing potential of floods from lakes that had been impounded by the 1980 debris avalanche presented costly problems. Nearly $1 billion was spent during the first 10 years after the eruption to mitigate the downstream flood hazards.

During the first 3 years after 1980, an estimated 8 million tons of tephra were washed off hillslopes into the Toutle River system. While hillslope erosion eased somewhat after 1983, erosion of the debris avalanche and the subsequent widening and incision of this drainage system by the development of a stream network resulted in a huge sediment discharge to downstream areas. The post-eruption Toutle River became one of the most sediment-laden rivers in the world. Downstream water quality and aquatic habitat severely deteriorated, and increased downstream flooding due to sediment-filled river channels jeopardized homes and roads built near the river; large floods, including rain-on-snow events in the mid 1990s triggered the most significant sedimentation in the Toutle River downstream of the Mount St. Helens since the 1980 eruption (Major 2000). At Pinatubo volcano in the Philippines during 1991 (the year of the cataclysmic eruption), Janda and others (1996) measured post-eruption rates of sediment yield as high as 4×10^6 m^3 of sediment per square kilometer of watershed, and as high as 1,600 m^3 of sediment per square kilometer per millimeter of rainfall, an order of magnitude higher than at Mount St. Helens!

The 1980 Mount St. Helens debris-avalanche deposit dammed numerous tributary valleys of the North Fork Toutle River. The deposit dammed Spirit Lake >50 m higher than its pre-eruption level and dammed such tributaries as Coldwater Creek, Castle Creek, and Jackson Creek to form lakes. On at least five occasions from 1980 to 1982, the collapse of a dam released a small lake or pond adjacent to the debris avalanche and caused minor floods. However, public concern focused on Spirit, Coldwater, and Castle Lakes, the three largest lakes impounded by the debris avalanche. In the 1980s, geologists recognized that some lahar deposits represented enormous floods had resulted from the breakouts of lakes in similar settings at the volcano in ancient times (Scott; 1988; 1989). Scott noted that some of these ancient “lake-breakout” lahars had discharges > 250,000 m^3/s at ~30 km flow distance from the volcano—equivalent to the modern Amazon River in flood! Similar blockages no doubt occurred at Mounts Rainier and Baker, and at Glacier Peak in the past, and could likely recur in the future at these volcanoes.

Overview of the Postglacial Activity of Volcanoes that Drain into Puget Sound

Mount Rainier

Mount Rainier, known to the American Indians as Taco’ma, Tacobed, or Taho’ma is the highest and third most voluminous volcano in the Cascade Range. It is potentially the most dangerous volcano in the range because of the increasingly large population living along its lowland drainages. For example, more than 150,000 people live on areas that have been inundated by its lahars and volcanic floods during the past 6000 years (Sisson and others 2001). These riparian areas are at risk because of the mountain's great relief and the huge area and volume of ice and snow on the cone 35 mi^2 (92 x km^2) and ~1mi^3 (4.2 x km^3) respectively (Driedger and Kennard 1986) that could generate lahars during eruptions.

Geologists have discovered that enormous (>2×10^8 m^3) “sector collapses” of clay-rich, hydrothermally-altered debris from the cone have occurred at least 6 or 7 times since the Mount Mazama layer "O" ash was deposited (6,730 ±40 yr B.P., Hallet and others 1997)—examples include the Osceola, Round Pass, and Electron Mudflows. Mount Rainier's steep, glacially carved slopes, hydrothermally altered core, active hydrothermal system, bedding characteristics (thin lava flows and interbedded volcaniclastics on generally outward-facing dip planes), and exposure to pulses of tectonic and/or volcano-seismic energy impulses make all valleys surrounding Mount Rainier susceptible to future sector collapses (although those hazards are not homogeneous).

Most of the Holocene history of Mount Rainier has been pieced together through studies of its fragmental deposits, chiefly tephra, lahar, and glacial deposits—these include the pioneering work of Crandell, (1963b 1971), Mullineaux (1970; 1974), and Crandell and Miller (1974) and more recent work by Scott and others, (1992; 1995), Dragovich and others (1994), and Vallance and Scott (1997). Holocene explosive eruptions at Mount Rainier produced 11 major pumice or scoria beds (Mullineaux 1974) and at least 20 to 25 lithic tephra layers (Vallance and Donoghue 2000) totaling more than 0.5 km^3. Roughly 30 to 40% of this volume (eight layers) was erupted between 6,500 and 4,000 radiocarbon years B.P. Layer C was erupted during the "Summerland" eruptive period of Vallance (2000) and Sisson and others (2001). Tephra from this eruptive episode accounts for about 60% of the volume of postglacial tephras and is the most widespread, covering much of the eastern half of Mount Rainier National Park with 2-30 cm of lapilli, blocks, and bombs. It is also the coarsest of the Rainier tephras: 25-30 cm bombs can be found 8 km to the east of the summit. Columbia Crest, the 250-m-high summit cone, is younger than 2,300-yr-old layer C because that tephra unit does not occur on its snow-free parts (Mullineaux 1974). Lahars generated by eruptions during the Summerland eruptive period (circa 2,600 to 2,200 yr B.P.) traveled great distances along nearly all drainages and underlie the towns of Packwood, Orting, Sumner, Puyallup, Elbe, and McKenna as well as others. Palmer (1997) has dated wood debris at 2,670 yr B.P. from >60 ft below the surface at Black River (near Tukwila) that was likely transported along the White River during this eruptive period. This and future studies should better reveal the nature and dynamics of the episodic delta progradation in this valley in response to lahars from Mount Rainier.

Because volcanic deposits are vulnerable to both erosion and burial by subsequent flows or other geologic processes, they comprise an incomplete record of a volcano's history. At Mount Rainer, ongoing discoveries of subfossil buried forests (Fig. 4) and/or buried volcanic layers thus continue to provide valuable evidence of past eruptions, lahars, and laharic floods. For example, during investigations of liquefaction in the City of Puyallup, one of the liquefiable sand units was identified as a lahar runout or laharic flood from Mount Rainier (Palmer and others 1991; Pringle and Palmer 1992). The presence of Mount Rainier "C" tephra and ^{14}C age of 2,320 ± 120 yr B.P. from a twig found in the deposit correlated that unit with newly discovered lahar deposits in upper reaches of the Puyallup River and with block-and-ash flow deposits noted by Crandell (1971) on the west flank of Mount Rainier. Deposits from that eruptive episode had not previously been discovered as far downstream as Puyallup. We have recently observed lahar and lahar runout deposits along the Nisqually River as far downstream as the town of McKenna that were probably erupted during the Summerland eruptive period. Recent studies of subsurface deposits by US Geological Survey geologists and Steve Palmer of the WA Division of Geology and Earth Resources suggests that deposits of the Summerland-age laharic flows, as well as those of a sizeable flood that buried trees in a flood plain upstream of McKenna about 600 years ago, reached and partially core the modern Nisqually delta (Walter Barnhardt and Brian Sherrod written communication 2001).

Figure 4 A contractor examines a large 350-year-old Douglas fir stump rooted ~20 feet below the present valley bottom at Orting, Washington. It was buried by the Electron Mudflow, a cohesive (clay-rich) lahar from Mount Rainier, about AD 1400, and was preserved below the mean high groundwater table. At the time of the lahar, much of the valley bottom was covered by an old growth forest consisting mostly of Douglas firs. (Photo by Pat Pringle WADNR 1993. View is to the southwest, about one mile north of Orting.)

Postglacial deposits at Mount Rainier are dominated by lahars–more than 60 have been identified. Although, as has been noted, relations between some Holocene tephra and lahar deposits remain speculative, most lahars were probably eruption induced, such as the Paradise Lahar and Osceola Mudflow of Crandell (1971). The 5,000 yr B.P. Osceola Mudflow had a volume of more than 4 km^3, inundated at least 485 km^2, and flowed into Puget Sound more than 100 km channel distance Mount Rainier (Dragovich and others 1994). As interpreted from well logs (neglecting minor relative sea level changes), syn-, and post-Osceola sedimentation has pushed the shoreline seaward 25 and 50 km respectively in two Puget Sound embayments, the Puyallup and Duwamish, and added more than 400 km^2 of new land surface (Dragovich and others 1994). Palmer (1997) found evidence for rapid progradation of the Puyallup delta following deposition of the Osceola Mudflow.

Wood from trees buried in the Round Pass Mudflow has been dated at about 2,600 yr B.P. In the Puyallup River valley, this clay-rich deposit is characterized by great thickness (locally >250 m), hummocky surface, and megaclasts of lithologically homogeneous material. It probably began as a debris avalanche of hydrothermally altered material from high on the western slopes of Mount Rainier, although some of its hummocks are composed almost entirely of blocks of pre-Mount Rainier bedrock. Although most of the Round Pass Mudflow was deposited in the upper 20 km of the Puyallup River valley, a distributary of this lahar flowed along the Nisqually River at least as far as Yelm.

About 1,100 yr B.P., a lahar or lahars triggered by a moderately explosive eruption of Mount Rainier traveled as far as Auburn. Sand deposits correlative with this deposit have been discovered as far downstream as the Port of Seattle (Pringle and others 1997; Cisternas 2001). We have identified buried forests and probably correlative deposits at Kent, Fife, and Pacific.

Another clay-rich lahar, the Electron Mudflow, has been dated at about 530 yr B.P. This lahar, which evidently began as a failure of part of the western edifice, has not yet been correlated with any eruptive activity at Mount Rainier. The Electron Mudflow was very fluid and underwent minimal downstream attenuation of discharge. This behavior is demonstrated by the relatively high peak stage of the lahar about 30 km west of Mount Rainier and upstream of where the narrow canyon of the Puyallup River enters the Puget Lowland at Electron. There, the Electron Mudflow was more than 60 m deep as it neared the Cascade Mountain front and flowed onto the Puget Lowland. More than 60 trees have been exhumed from Electron deposits at the town of Orting since the summer of 1993, and these will provide clues to the exact age of the lahar as well as a record of local climate for the centuries preceding this event.

Debris flows that can be considered as lahars can result from collapse and incision of stagnant, debris-covered ice downstream of the receding distal termini of active glaciers. These debris flows, which have informally been known as “glacial outburst floods” or “jokuhlhaups,” have been especially pronounced at Mount Rainier where, as at all the Cascade Range volcanoes, glacier recession has occurred with the climate amelioration that has followed the end of the Little Ice Age about AD 1850 (Walder and Driedger 1993; 1994). The largest historic flow occurred in Kautz Creek on October 2, 1947. Approximately the lower mile (1.6 km) of the Kautz Glacier progressively collapsed in response to heavy rain, producing surges of debris flow that probably extended in the Nisqually River to the southwest boundary of the National Park (Richardson 1968; Crandell 1971). In addition, clusters of glacial-outburst floods from the active terminus of South Tahoma Glacier (the last cluster from 1986 to approximately 1993) have transformed and bulked to debris flows as the floods crossed and incised a large area of stagnant, debris-rich ice. The outburst floods from South Tahoma Glacier were triggered both by rainfall and by periods of unseasonably hot weather. Glacial outburst floods and debris flows have occurred in many other drainages, most notably Kautz Creek and Nisqually River during historical time (Driedger and Fountain 1989) and at Glacier Peak and Mount Baker.

A third glacier-related hazardous process is the possibility of debris flows produced by breakouts of moraine-dammed lakes. Terminal Neoglacial moraine dams have failed in numerous cases in the Oregon Cascades, but no significant historic examples have yet occurred at the five volcanoes in Washington. A lake impounded by the Neoglacial terminal moraine of the Emmons Glacier has enlarged significantly in recent years, and its level is being monitored by USGS and NPS scientists. Failure of the moraine dam could produce a debris flow large enough to put a large downstream campground at risk.

Many small lahars such as the aforementioned probably will not be preserved or recognized in the geologic record (e.g. Cameron and Pringle 1990). They do, however, cause localized ecological disturbances (Frenzen and others 1988) and hazards, and occur more frequently (on annual or decadal scales) than larger more infrequent flow types. The size and abundance of past lahars from Mount Rainier certainly indicates that future lahars and laharic aggradation pose the greatest risk to downstream populated areas, particularly on flood plains of the Nisqually and Puyallup River valleys and to sections of the White River valley, most notably those upstream of Mud Mountain Dam.

Glacier Peak

Glacier Peak is commonly not recognized as a volcano by many residents of the northwest (Mastin and Waitt 1995). Early investigations at Glacier Peak identified thick deposits from explosive eruptions that had blocked the Stillaguamish River and forced the Sauk River to flow into the Skagit (Vance 1957; Tabor and Crowder 1969). Later studies of its late-glacial and Holocene eruptive and flowage deposits by Beget (1982; 1983) have documented numerous eruptions. Beget found explosive Holocene eruptions during the intervals 5500-5100, 2800-1800, and 1800-1000 yr B.P. He also recognized that lahars that flowed as much as 100 km from the volcano and that the volcano had probably erupted within the past 200 years. More recently, Dragovich and others (2000) have traced lahar runouts of Beget's Kennedy Creek assemblage (~5500-5100 yr B.P.) as far downstream as Mount Vernon and have interpreted that correlative deposits underlie La Conner. Waitt and others (1995) revised the volcanic hazard assessment for Glacier Peak. However, scientists from the US Geological Survey and Washington Department of Natural Resources, Division of Geology continue to study Glacier Peak's lavas and fragmental deposits.

Figure 5 Lahar isopachs (thickness) of the inferred ~5,000 yr B.P. Glacier Peak laharic deposits in the subsurface near Mount Vernon, WA. From Dragovich and others (2001). Dragovich and others estimate the location of the Skagit delta front and mid-Holocene sea level to be near Mount Vernon;

Mount Baker

The American Indians called Mount Baker *Komo Kulshan*, which, according to Harris (1988) means, “shot at the point,” referring to the “wound” or smoking crater on the mountain’s flank. Hyde and Crandell (1978) provided an earlier overview of the postglacial volcanic history of Mount Baker volcano, however, until recently little was known about the chronology of eruptive activity because of a dearth of radiocarbon dates. One of us (Scott) is investigating the fragmental deposits at the volcano, and the accumulation of new radiocarbon and stratigraphic data will allow for a revised chronology of eruptive and flowage events (Scott and others 2000). These investigations coincide with those of Wes Hildreth (2000), also USGS, who is studying the lava flows and pre-Holocene fragmental deposits of Mount Baker. Gardner and others (1995) have revised the volcanic hazard assessment for Mount Baker.

Construction of the main edifice of Mount Baker was completed with tephra-producing eruptions as late as 10,000 to 11,000 yr B.P.. Subsequent periodic Holocene activity at the area of the active vent on the south side, Sherman Crater. Most notable was a closely related series of events during either an extremely brief eruptive period or a single major eruption about 5,900 yr B.P. These include, in order, (1.) Two cohesive lahars descending Park Creek and resulting from flank collapse of the southeast side of the volcano, from the area east of the Sherman Crater vent. (2.) A cohesive lahar from flank collapse of the southwest side of the edifice, from the area west of Sherman Crater. This flow extended past Deming reaching at least as far as the Sumas Valley in the Fraser Lowland, where we have identified it in geotechnical borings of the SR 504 bridge near Cedarville. (See cross section in Dragovich and others 1997, plate 1). (3.) A cohesive lahar of extremely altered material collapsed from the area at and immediately west of Sherman Crater. (4.) A mainly lithic phreatomagmatic tephra was erupted synchronously with the lahar from the area of Sherman Crater. (5.) A juvenile andesitic tephra extending at least as far as 30 km to the northeast. Additionally, Cameron (1989) identified a fan of coarse andesitic debris had prograded into the postglacial Sumas Valley until some time after the deposition of an ash layer that she interpreted to that of Mount Mazama (Fig. 6), thus demonstrating that the Nooksack River had, for a time, drained north into the Fraser during the Holocene.

Sherman Crater was also the site of phreatomagmatic activity from AD 1843 to approximately 1880-90. An initial phreatomagmatic eruption in 1843 created a local, mainly lithic tephra and the present configuration of the crater. Within months, the east side of the crater collapsed into Boulder and Park Creeks, creating a lahar that inundated the Baker River valley. In 1975, heat flux from Sherman Crater increased by an order of magnitude, leading to concerns of a possible eruption. However, no seismic activity accompanied the increased heat emission, levels of which subsequently declined to near pre-1975 levels. Investigations by Carolyn Driedger of the USGS using ice-penetrating radar suggest that the flat-topped summit of Mount Baker is underlain by an ice-filled crater >80 m deep.

A remarkable analog to the 1947 surges of debris flow from Kautz Glacier at Mount Rainier originated from the distal part of Deming Glacier at Mount Baker in June 1927. This event, recently noted from an archival account and confirmed by field investigations, also involved at least one large debris flow that had resulted from collapse of the terminal "one mile" (1.6 km) of the Deming Glacier. The resulting debris flow(s) and associated flooding traveled at least 12 km and removed 2 mi (3.2 km) of logging railroad in the Middle Fork Nooksack River. Research continues on defining the exact date of the collapse and thus the possible role, if any, of rainfall. Reports at the time linked the flow to a significant earthquake that was, however, not recorded at the existing seismic stations in Seattle and Victoria (Ludwin and Qamar 1995). One observer concluded that the earthquake was the ground tremor of the flow. However, USGS scientists conclude, from the descriptions of the earthquake and the distances at which it was reported, that such an explanation is unlikely, creating the possibility that the flow was triggered by a local earthquake.

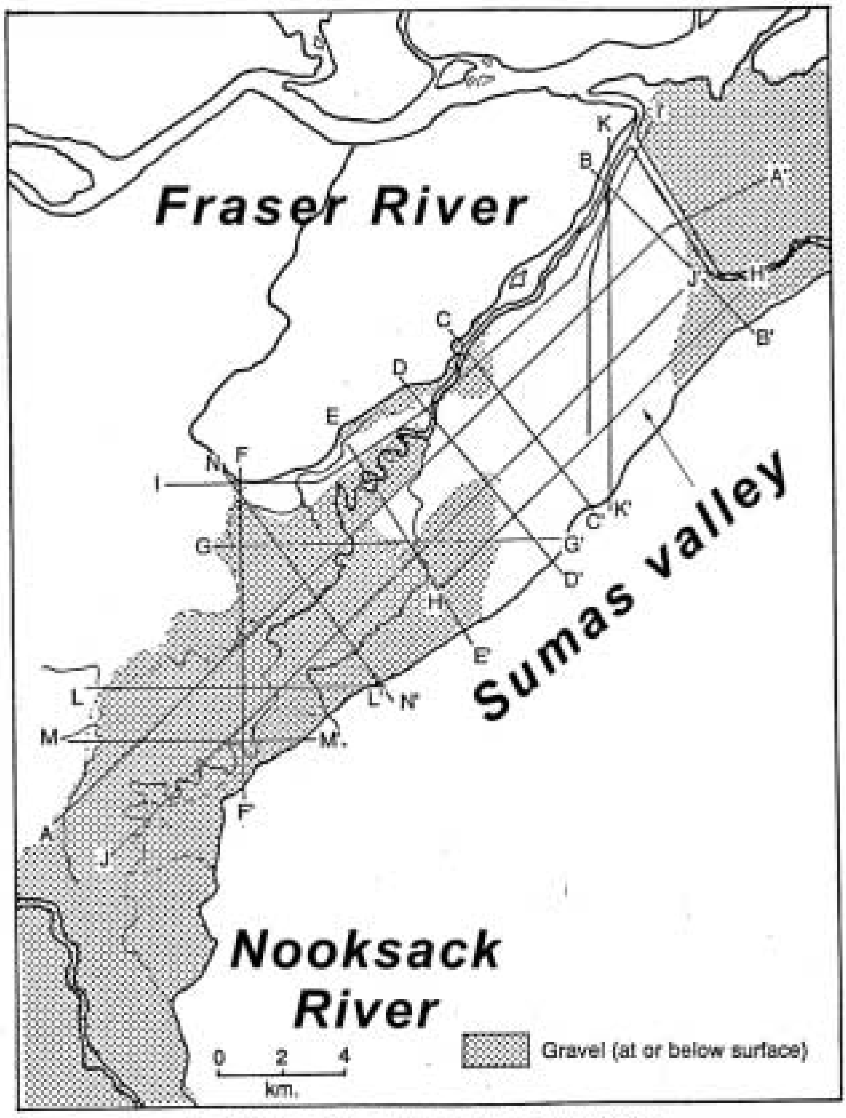

Fig. 3.17 Location of gravels in the Sumas Valley

Figure 6 Fig. Map, modified from Cameron (1989), of the Sumas Valley showing subsurface fans of coarse debris (stippling) that were constructed in the valley by the postglacial Nooksack (south fan) and Chilliwack Rivers (north fan).

Miscellaneous volcanic processes and effects on river systems

Tephra fallout also can have a major impact on river systems. Mullineaux (1974; 1996) and Crandell (1971) have noted the thickness and widespread distribution of Mount St. Helens pumice and ash in such localities as the Cowlitz River valley. As an example of the degree of environmental disturbance caused by the thick tephra fallout, archaeological surveys in that area have detected an apparent hiatus in settlements at locations having heavy fallout and a probable increase in settlements in nearby plateau areas away from the tephra fallout (north and east of the volcano) from about 3,600 to 1,600 yr B.P. (McClure 1992). Events like the damaging meteorologically induced debris flows at Sarno, Italy in 1998 (Pareschi and others 2000) show that, aside from their original impact on a landscape, thick tephra deposits in areas of moderate-to-high relief can create debris flow hazards for decades or even centuries. For example, US Geological Survey geologist Norm Banks identified ancient debris flow deposits in the Cowlitz River valley that were composed predominantly of Mount St. Helens' Yn pumice (erupted ~ 3,500 yr B.P.).

Riedel and others (2001) and Schuster and others (2000) have obtained a minimum radiocarbon age of about 7,030 yr B.P. on a large rock slide-debris avalanche that dammed the Skagit River about 16 km east-northeast of Marblemount near Damnation Creek. “Lake Ksnea” (named by the authors for a local Indian place name), which formed behind the landslide dam, was at least 14 km long by 1 km wide and was in existence at the time of the great Mazama eruption that produced Crater Lake about 6,740 yr B.P. (Bacon 1983; Hallet and others 1997), because a 2-cm fallout ash layer from that eruption can be identified in lake deposits. The lacustrine sediments and overlying Mount Mazama fallout ash are overlain by as much as 17 m of detrital Mazama ash that was carried into the lake when the Skagit River reworked the ash that was deposited throughout the basin! A large volume of these ashy deltaic deposits were later remobilized and carried farther downstream when the Skagit River breached the landslide dam.

Neotectonic uplift and submergence of the Puget Sound shoreline, such as that reported by Bucknam and others (1996) and Sherrod (1998; 1999; 2001), have no doubt also played a role in forcing changes to the geomorphic thresholds of the river systems that drain Mounts Baker and Rainier and Glacier Peak. Future investigations should help to locate fault structures and to define the nature and timing of uplift or of subsidence on them (e.g. Brocher and others 2001; Blakely and others 2001). Other factors that undoubtedly have influenced the equilibrium of these volcano-influenced fluvial systems, in concert with volcanism and neotectonic movements, include sea level changes (e.g Dragovich and others 1994; Palmer 1997, repr. 2001) and shifts in climate over various time scales (e.g. Mantua and others 1997; Hunt and Zheng 1999; Nigan and others 1999).

On a smaller scale, the character of the geologic materials and hydrology of the respective drainage basins also affect the chemistry and temperature of the rivers tributary to Puget Sound, particularly near volcanoes. (See Frank 1995 a, b; Frank and Realmuto 1995; Frank 2000; Mariner 2000). Many citations on the environmental and ecological aspects of volcanism as demonstrated at Mount St. Helens can be found in Keller and others (1985), Manson (2001), Manson and others (1987), and Frenzen and others (1994).

Summary

The environmental history of the major river systems of the Puget Lowland that drain active Cascade Range volcanoes includes periodic geologic disturbances from lahars (volcanic debris flows), lahar runouts, and associated flooding. The details and richness of this history has just begun to emerge over the past few decades. In many cases disturbance-forcing volcanic events occurred at catastrophic scales and were followed by years or decades of sedimentation that altered existing ecosystems by burial and episodic delta progradation. Future geomorphic changes in the valleys will likely follow similar patterns.

Acknowledgements

We would like to thank all the authors and researchers whose work we have tried to summarize and review here. Collectively, these investigations continue to shed light on the eruptive histories of the various volcanoes that drain to Puget Sound and on the profound landscape and environmental changes that resulted from these volcanic disturbances.

Selected Internet Resources

http://www.wa.gov/dnr/htdocs/ger/index.html
WA DNR Div. of Geology and Earth Resources
http://vulcan.wr.usgs.gov/
USGS Cascades Volcano Observatory
http://volcanoes.usgs.gov/
USGS Volcano Hazards Program
http://motion.wr.usgs.gov/
Animations of lahars from Mount Rainier

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