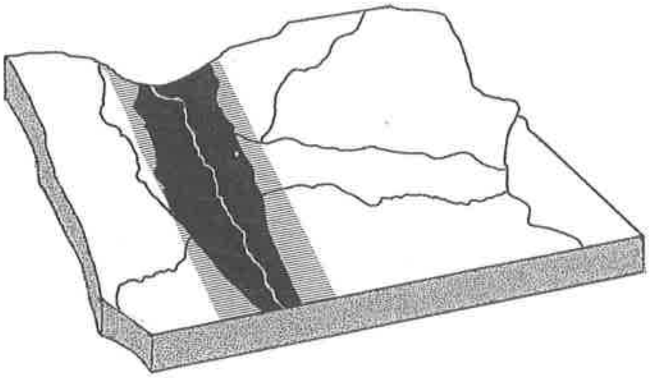
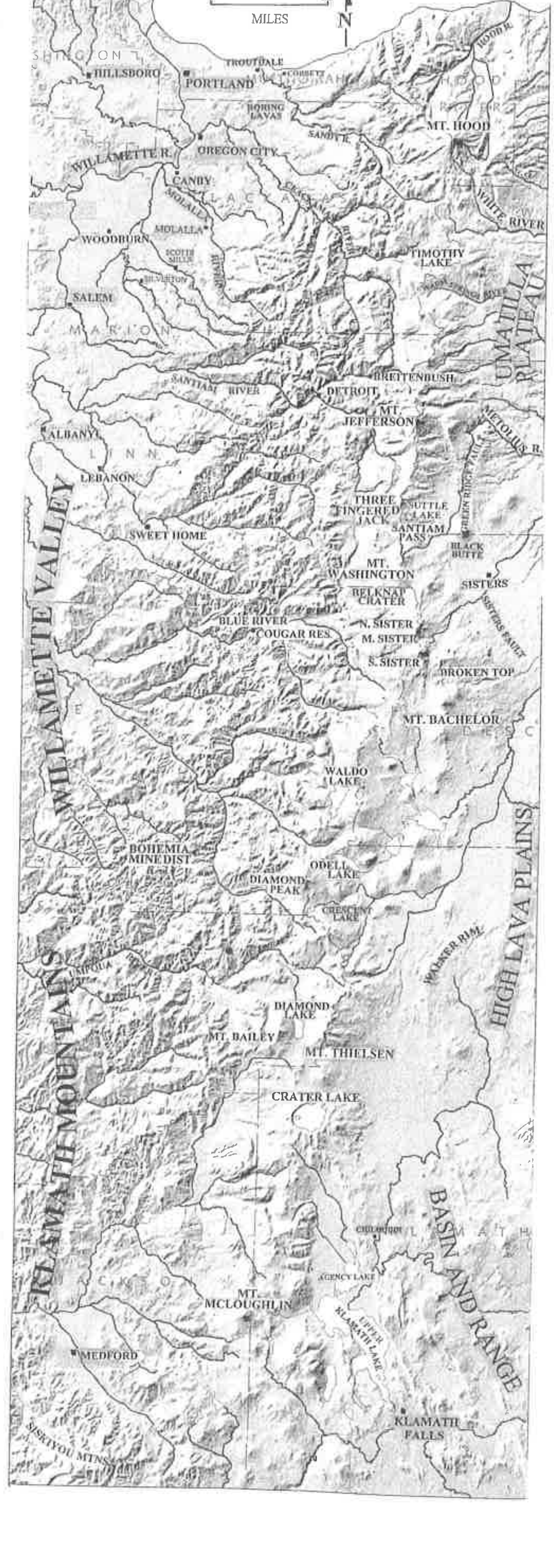




Physiographic map (After Loy, et al., eds., 2001)

Cascade Mountains

Landscape of the Cascade Mountains

The 600-mile-long Cascade Mountains from northern California through Oregon, Washington, and British Columbia provide some of the Pacific Northwest's most dramatic scenery. Touching all other provinces in Oregon except for the Blue Mountains and the Owyhee plateau, the Cascades lie east of the Willamette Valley. The Deschutes-Umatilla plateau is toward the northeast, the High Lava Plains is directly eastward, with the Basin and Range and the Klamath Mountains to the south. A small boundary is shared with the Coast Range.

In Oregon, the range is divided into the older, deeply eroded Western Cascades and the sharply contrasting snow-covered High Cascade peaks. With heights from 1,700 to 5,800 feet, the Western Cascades are only half the elevation of the younger summits, which reach in excess of 11,000 feet. This north-south volcanic chain divides the state into two distinct climate zones. Mild temperatures, high rainfall, thick soils, and heavy vegetation characterize the western slope, but on the east side the climate is warmer and drier, and the vegetation more sparse.

The major waterways drain westward. The Clackamas, Molalla, Santiam, and McKenzie rivers all wind their way from headwaters in the Cascade range to merge with the Willamette River system. Draining from the Calapooya Mountains of the Western Cascades, the Umpqua crosses the Coast Range to the Pacific Ocean at Reedsport, a distance of 112 miles. By flowing west then turning toward the north at Roseburg, the entire route of the Umpqua lies within Douglas County.

Eastward-flowing streams originating in the Cascades are comparatively small. With an average length of 30 to 35 miles, the White, the Warm Springs, and the Metolius all enter the Deschutes waterway. The Columbia, which is the demarcation between Oregon and Washington, is the only river that completely traverses the mountains from east to west.

Past and Present

In the 1930s Edwin Hodge from Oregon State University, Howel Williams from the University of California, and others addressed specific aspects of Cascade geology. Twenty years later a cooperative effort between Dallas Peck of the U.S.G.S. and the Oregon Department of Geology and Mineral Industries (DOGAMI) produced the first large-scale reconnaissance of the stratigraphy, structure, and lithology of 7,500 square miles of the central and northern Western Cascades. During the 1960s into the 1980s, papers by Paul Hammond from Portland State University and Edward Taylor at Oregon State University filled in details of the geology.

Born in 1898 in Liverpool, England, Howel Williams' undergraduate emphasis was on geography, archaeology, and geology, but he began to concentrate more on geology after his twin brother entered that field. Williams' PhD in 1928 from the University of Liverpool was awarded after his appointment to the University of California, Berkeley. In addition to providing some of the first geologic overviews of selected High Cascade peaks, Williams is, perhaps, best known for his recognition of Crater Lake as a collapse caldera, and for his compilations of volcanic data worldwide. Meticulous pen and ink drawings and field sketches illustrate his many publications. Williams died in 1980. (Photo courtesy Geology Department, University of Oregon)

A professor of Geology at Oregon State University, Edward Taylor encountered many students in his 33-year career of teaching mineralogy, crystallography, and field geology. Growing up in Corvallis, Taylor completed a PhD from Washington State University in 1967. His early research focused on the ages and evolution of volcanic activity in the central High Cascades with publications on individual peaks. He named and developed a stratigraphic sequence for the many ash-flow sequences west of Bend. An emeritus professor, Taylor lives in Corvallis. (In the photo, Collier Cone and North Sister are in the background; courtesy E. Taylor)

The careers of both Margaret Steere and Beverly Vogt at DOGAMI involved the roles of geologist, editor, and consultant. Originally from Michigan, Steere moved to Oregon to become the resident state paleontologist, identifying fossils, leading field trips, and giving talks. Editing articles for the book *Fossils in Oregon*, Steere retired in 1977 and died unexpectedly in 1995.

Beverly Vogt joined DOGAMI in 1977 where she produced *Oregon Geology* magazine, set up conferences, and conducted public outreach. Also from the Midwest, Vogt finished her graduate degree at Portland State University while still accomplishing the many aspects of her work in the department. After twenty years of service, Vogt retired in 1997 and currently lives in Portland. (Photos courtesy Oregon Department of Geology and Mineral Industries; and B. Vogt)

In light of plate tectonics, current researchers are attempting to clarify different aspects of Cascade volcanism. Among these, George Priest at DOGAMI and Richard Conrey at Washington State University are proposing several ideas to explain the complexities of arc evolution. Maps and reports by William Scott, David Sherrod, and James Smith at the U.S.G.S. refine the geology of individual stratovolcanoes.

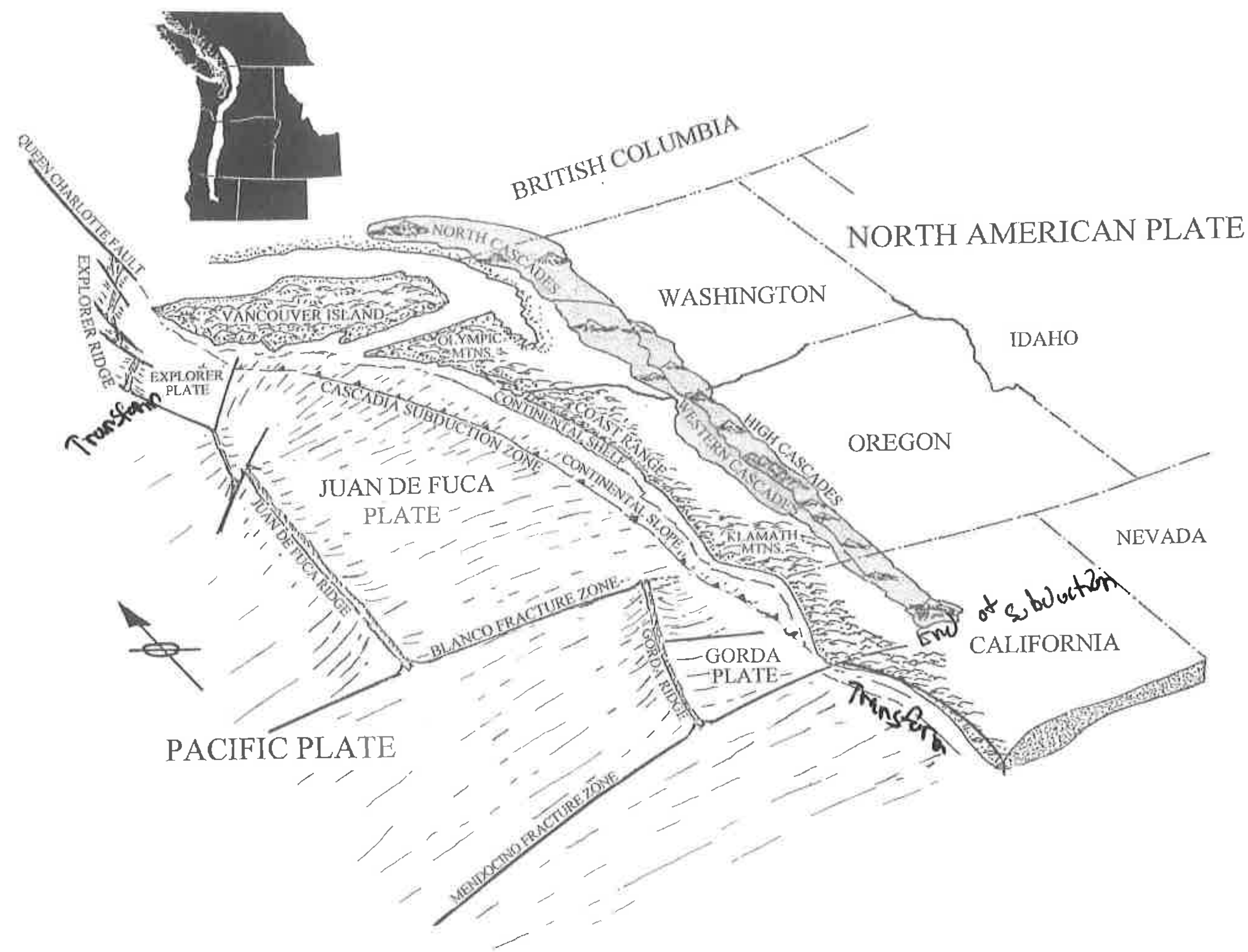
Overview

It is curious that the Cascade Range is regarded as the backbone of the state, yet it is one of Oregon's youngest geologic provinces. The Cascades began during the Eocene Epoch with outpourings of ash and lava from a line of cones parallel and adjacent to the Pacific Ocean. Fed by the subduction of the Farallon oceanic plate beneath North America, the lengthy volcanic arc erupted thick deposits that built the foundation of the Western Cascades. An interval of tilting and folding 5 million years ago brought a cessation to the activity and accelerated stream erosion.

The eruptive centers migrated steadily eastward between the late Miocene and Quaternary to erect the High Cascade peaks. Interspersed between the High Cascade stratovolcanoes and shield cones, black cindery fields erupted from hundreds of sites just a few thousand years in the past. An overprint of faults and the development of a High Cascade trough or graben, which extends most of the length of the state, represent crustal failure on a grand scale.

Cascade lavas exhibit a diversity of timing, spacing, and composition, and several models have been proposed to explain the differences. Most are related to subduction and crustal extension. Additionally, the volcanic arc has been divided into segments based on the location of the vents, and the individual centers have been grouped by the eruptive frequency or chemistry of the lavas.

During the late Pleistocene, less than 100,000 years ago, ice modified the Cascade landscape even as lava erupted above and beneath glacial sheets. The size of lahars, fast moving muddy slurries of ash, water, and rock, was increased by the addition of glacial melt-water and rubble, which choked channels downstream. On the mountain tops, glaciers enlarged valleys, filled lakes, and eroded sharp crests.



Reaching northward across three states and into British Columbia, the Cascade volcanic arc is a by-product of the collision and subduction of three tectonic plates and the North America continent.

Since the onset of High Cascade volcanism just over 7 million years ago, stratocones have continued to be active into historic times. European settlers witnessed smoke from Mount Hood, and most recently the Pacific Northwest saw the eruption of Mount St. Helens and the slow bulge in the Three Sisters area. Increased public awareness and government monitoring programs for potential volcanic activity may help to mitigate potential disasters.

Geology

Cenozoic

Beginning in the Eocene, around 40 million years ago, a volcanic arc was constructed parallel to the continental margin and well to the east of the Pacific Ocean shoreline. Volcanism was generated by convergence of the Farallon and North American plates. As the Farallon plate plunged beneath North America, partial melting of the mantle at depths of 60 to 75 miles created magma chambers that rose through the crust to feed the volcanoes.

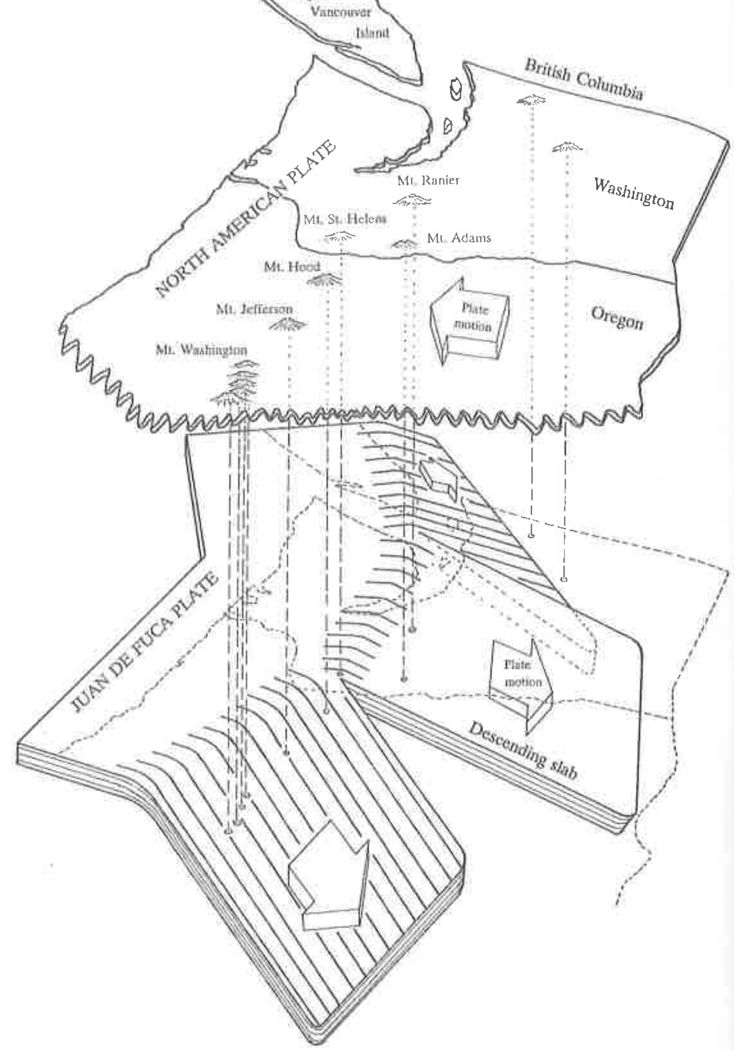
Lavas and ash from numerous volcanoes in the chain built the Western Cascade range, but tectonic adjustments brought a profound reduction in the amount of eruptive material, a narrowing of the arc, and limited periods of activity in the late Miocene Epoch around 7.5 million years ago. As the volcanic front shifted eastward, eruptions of the High Cascades commenced. Differences in the nature of the High Cascade regime relate to distance between the subduction trench and the volcanic arc, to the temperature, buoyancy, and rate of plate movement, and to the angle of the subducting slab.

The Cascade Range can be divided into a northern segment from British Columbia to Snoqualmie Pass, Washington, and a southern portion from Snoqualmie Pass into California. The southern section has been broken into the older dissected Western Cascades, which consists of Eocene to Miocene volcanic debris, intrusives, and marine sediments, and the High Cascade peaks that include late Miocene to Holocene ash and lava. Because of deep erosion and burial by younger lavas, traces of the volcanoes and landforms of the Western Cascades were obscured, and in Washington exposures of batholiths are the only evidence of early activity. High Cascade volcanism differs in Washington, where stratovolcanoes are isolated edifices, in contrast to Oregon and California. where large composite peaks are surrounded by fields of cinder cones, shield volcanoes, and recent flows.

Western Cascade Volcanism and Sedimentation

Because the 10,000-to-20,000-foot-thick sedimentary and volcanic underpinnings of the Western Cascades are limited in areal extent and not well defined, the individual layers are arranged by stratigraphic position and composition. Andesites, basaltic andesites, and dacites of the early Western Cascades from 35 to 17 million years ago were followed by a second late Western Cascade episode of flows and ash between 17 and 7.5 years ago. Volcanic output was highest during the first period, but declined thereafter.

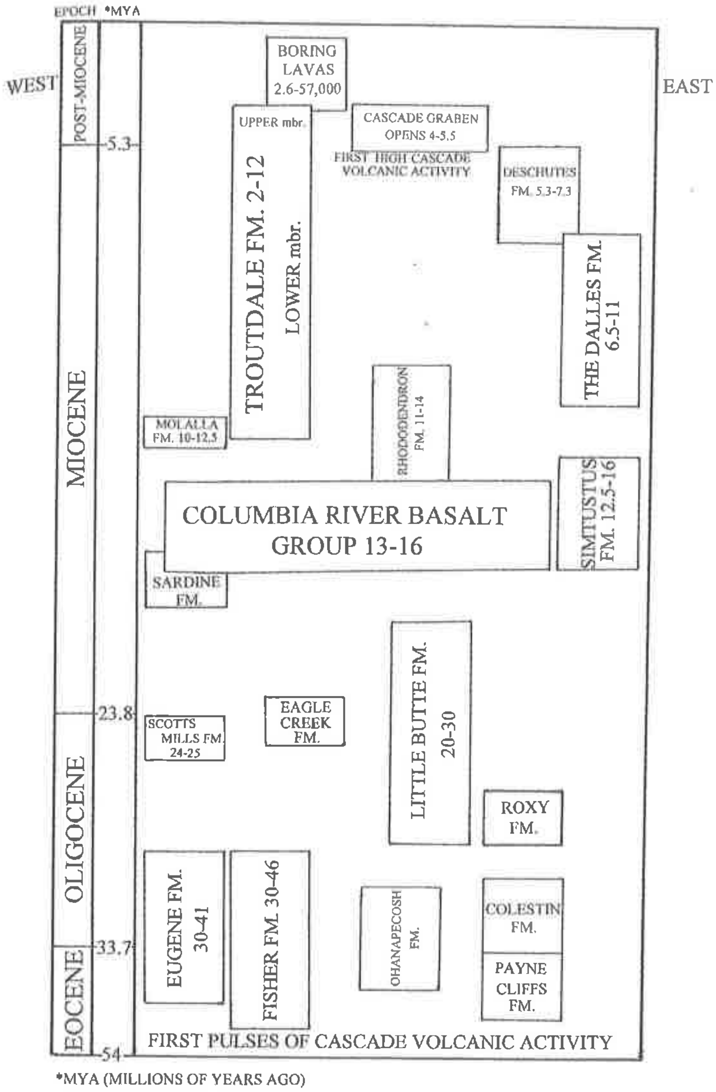
Deposited along the ocean shoreline, which paralleled the eastern border of what is now the Willamette Valley, marine and nearshore sands and volcanic tuffs of the Eugene and Fisher formations denote the earliest sediments of the central Western Cascades. Outcrops near Eugene preserve molluscs and leaf imprints. Overlying the Fisher, the Little Butte flows and tuffs erupted from some 30 vents irregularly spaced from Roseburg in Douglas County to the North Santiam River in Marion County. Near Molalla, the Little Butte is adjacent to or interfingers with the late Oligocene Scotts Mills Formation along the eastern marine strand. To the north, it is overlain by the Columbia River basalts and the Sardine lavas. Mudflows and ash of the Little Butte preserve wood, leaves, and pollen in



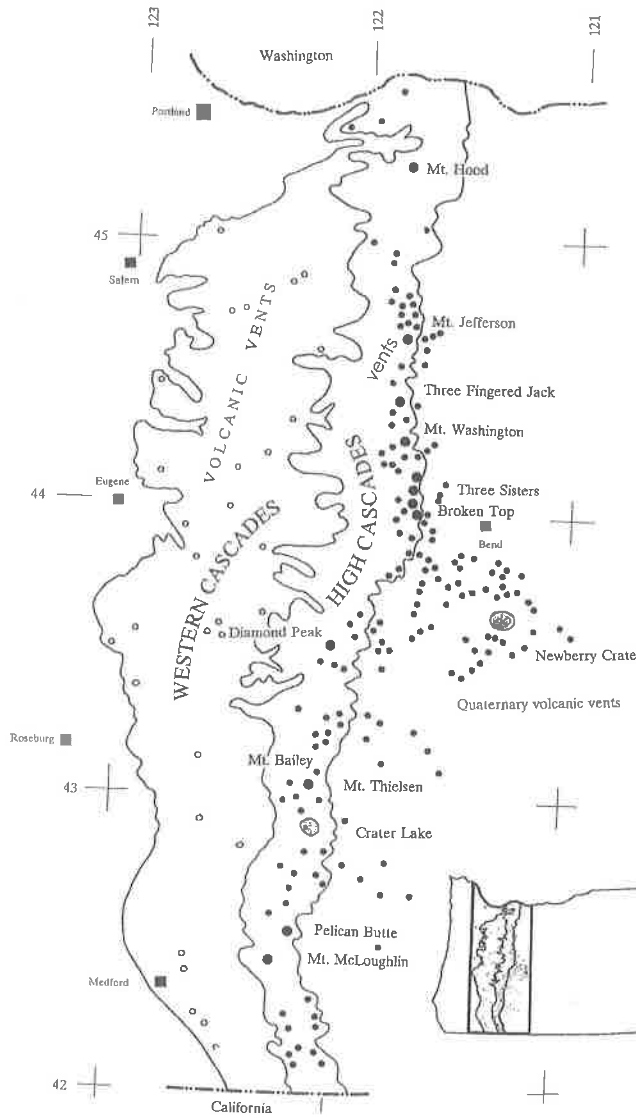
As the Juan de Fuca plate is subducted beneath Oregon and Washington, it splits into smaller tongues. Because the leading edge of the plate is tattered and uneven, the volcanic peaks in the Cascade chain are not aligned. (After Michaelson and Weaver, 1986; Duncan and Kulm, 1989)

Clackamas County and near Eagle Creek in Multnomah County.

At Siskiyou Pass in southern Oregon, Little Butte eruptives cover the Payne Cliffs and Colestin formations. Lavas, pyroclastic flows, ash, and lahars (mudflows) of the Eocene Payne Cliffs and the Oligocene Colestin formations record some of the earliest volcanic pulses of the Western Cascades. Delineated to the north by the Siskiyou Summit fault, a slowly subsiding graben filled with Colestin detritus carried by streams from Cascade slopes. Sediments of the Colestin, rich with plant remains, reflect mild coastal conditions. Petrified wood of



Stratigraphic chart of Cascade volcanic activity in Oregon. (After Bestland, 1987; Hammond, 1989; McKnight, 1984; Peck, et al., 1964; Priest, 1990; Priest and Vogt, 1983; Sherrod and Smith, 2000; Smith, 1993)



This map shows the contrast between the frequency and spacing between the older Western Cascade vents and the High Cascade volcanic cones. (After Peck, et al., 1964)

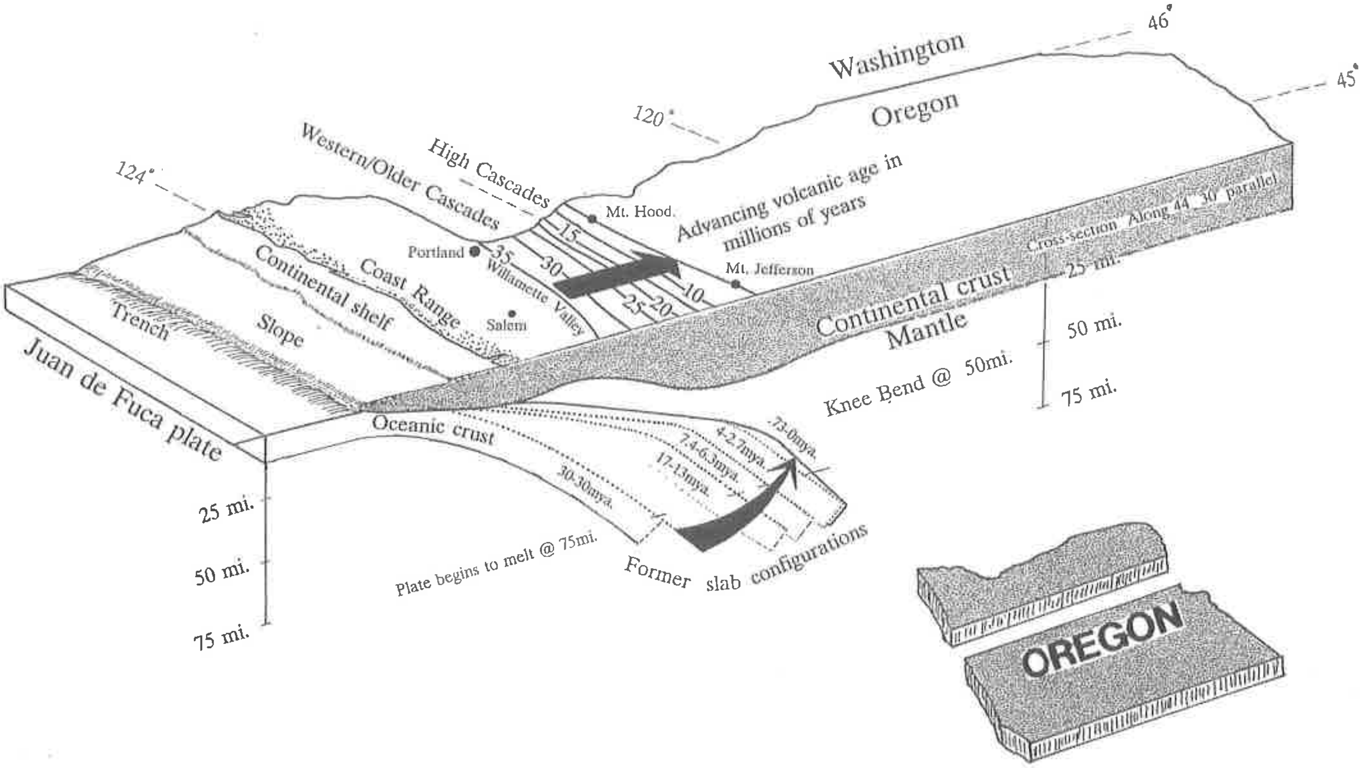
tropical tree ferns (*Cibotium*) and palm (*Palmoxylon*) mark a profound climatic shift from tropical to temperate by the early Miocene, a change also reflected by fossil plants in central Oregon.

A decline in central Western Cascade activity coincided with the onset of the Columbia River basalt eruptions from vents further east. But following this decrease, a late Western Cascade episode began around 17 million years ago with andesitic, basaltic andesite, and dacitic lavas of the Sardine Formation. Mapped by Dallas Peck, about a dozen vents of the Sardine are spaced from the McKenzie River in Lane County to Breitenbush Hot Springs in Marion County. Successions of Sardine Formation lavas cover much of the northern Cascades with thicknesses reaching 3,000 feet.

The Western Cascades were elevated in the early Pliocene, around 5 million years ago, contemporaneous with faulting and formation of High Cascade grabens. Entrenched streams and narrow canyons attest to the rapid erosion initiated by the uplift.

High Cascade Volcanism

Shifting eastward between the late Miocene and Pliocene epochs, the Cascade volcanic arc became increasingly narrow, signaling the onset of High Cascade eruptions and the renewal of volcanism after a period of low output. Composed of basaltic



During the late Tertiary, the active Cascade volcanic arc migrated eastward and became increasing narrow, as the volume of lavas diminished. One synthesis for these phenomena calls for a knee-bend in the subducting slab as it swung upward. (After Duncan and Kulm, 1989; Priest, 1990; Verplanck and Duncan, 1987)

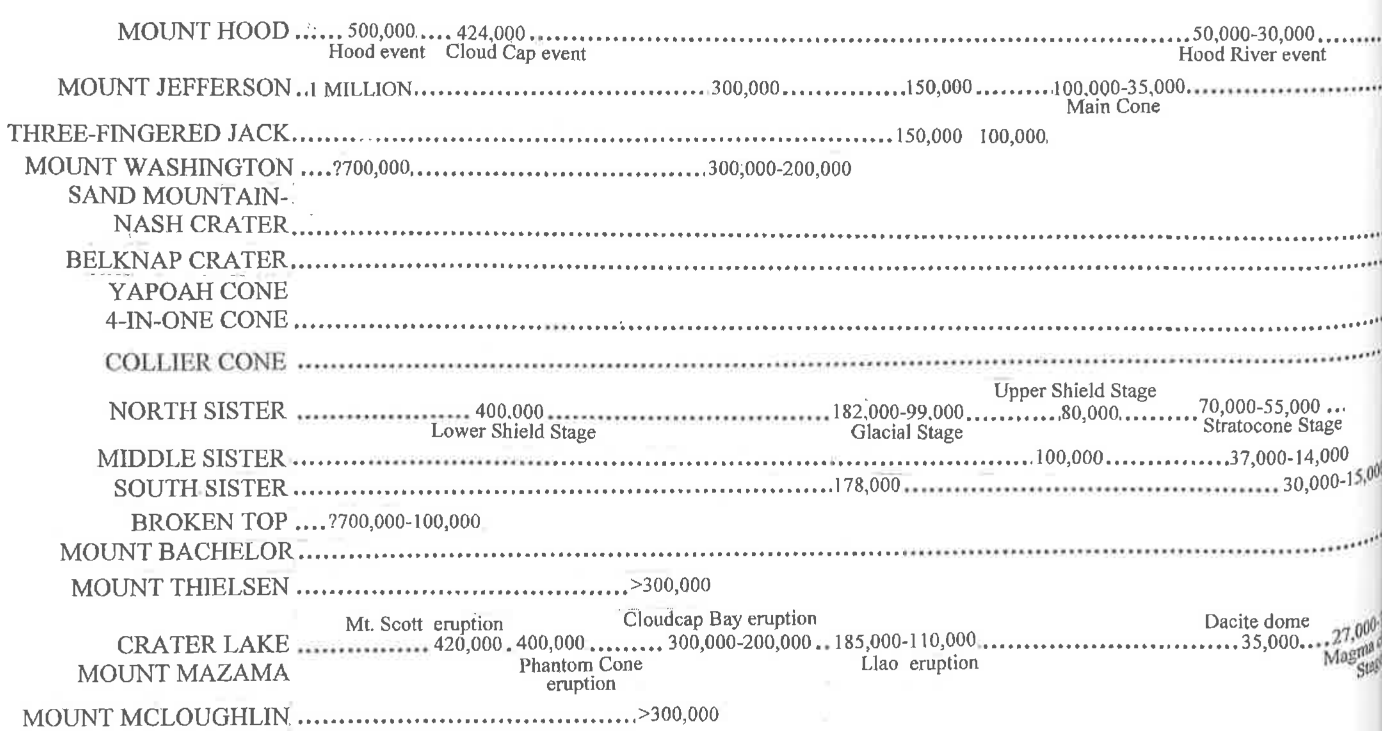
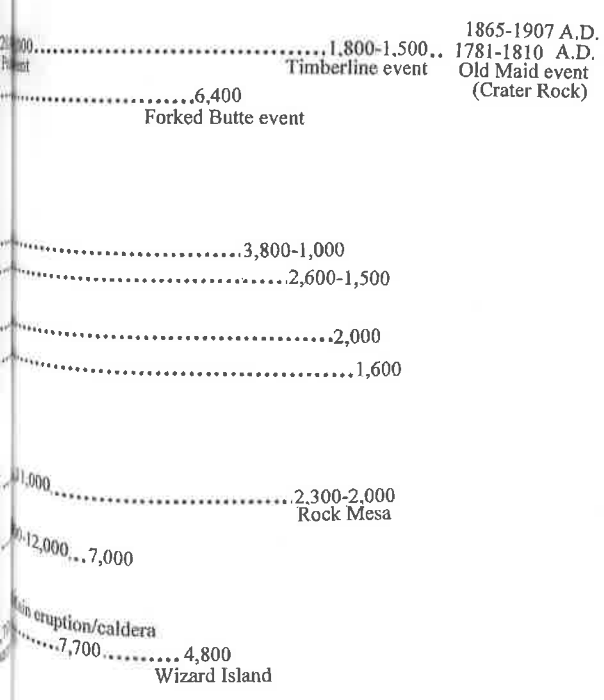


Chart of Cascade eruptive periods in Oregon during the past 700,000 years. (After Bacon and Lanphere, 2006; Conrey, et al., 2002; Harris, 2005; Schmidt and Grunder, 2009; Scott, 1990; Sherrod, et al., 1996; Wood and Kienle, 1990) and basaltic andesite, lavas from both strato-and-shield volcanoes built today's familiar snow-capped High Cascades.

The High Cascade volcanoes differ from each other to some degree, and for that reason there are various parameters for classification. Based on age, George Priest broke the eruptions into an early interval from 7.4 to 4 million years ago and a late period from 3.9 million years ago to the present. Additionally, the High Cascade regime has been separated into steep-sided composite or stratovolcanoes that are long-lived and active over hundreds of thousands of years and shield cones that are broad, gently sloping structures of ephemeral but persistent activity. From north to south, eight of the Oregon composite peaks are Mount Hood, Mount Jefferson, Mount Washington, Three-Fingered Jack, the South and Middle Sisters, Broken Top, and Crater Lake. Belknap Crater, the North Sister, Mount Bachelor, Mount Thielsen, and Mount McLoughlin are shield volcanoes.



Of the 13 stratocones within the entire Cascade Range, few have erupted during the past 5,000 years, and in Oregon only Mount Hood, the South Sister, and Crater Lake fall within that time frame. Mount Hood and the South Sister are identified today as having the highest potential for activity. Along the length of the volcanic regime, the last recorded flows from Mount Lassen were in 1917, and Mount Baker produced steam in 1975. The explosive episodes that began in 1980 at Mount St. Helens saw dome construction and as late as 2005.

Evolution of Individual High Cascade Peaks

Northern Cascades At the northern end of the province in Oregon, Mount Hood and Mount Jefferson are both andesitic in composition, but they have different histories. Lavas erected a platform at Mount Hood 1.5 million years ago, but construction of the central cone began at 500,000 years. Although a volcanic field has existed in the vicinity of Mount Jefferson as far back as 4 million years, the stratocone dates back only 1 million years. After a dome-building phase, Mount Hood experienced several eruptive periods and continued to emit gas, smoke, and pumice as late as 1907, attesting to the proximity of an active magma source below the summit. Even today steam plumes rise near Crater Rock. By contrast, activity at Mount Jefferson ended around 20,000 years ago. The total output of lava and ash for the long-lived Mount Hood edifice is estimated at over 12 cubic miles, whereas the volume from Mount Jefferson was considerably smaller, even though a large eruption caused ash to fall in southeast Idaho.

Attempts to decipher Mount Hood's past began with observations in the early 1900s by Harry F. Reid, professor at Johns Hopkins University. From the 1940s to the 1970s, the geology and petrology were examined by William Wise of the University of California, whereas U.S.G.S. geologist Dwight Crandell recounted the eruptive history and potential future hazards. One of the best sources is the overview and fieldtrip guidebook by William Scott and others.

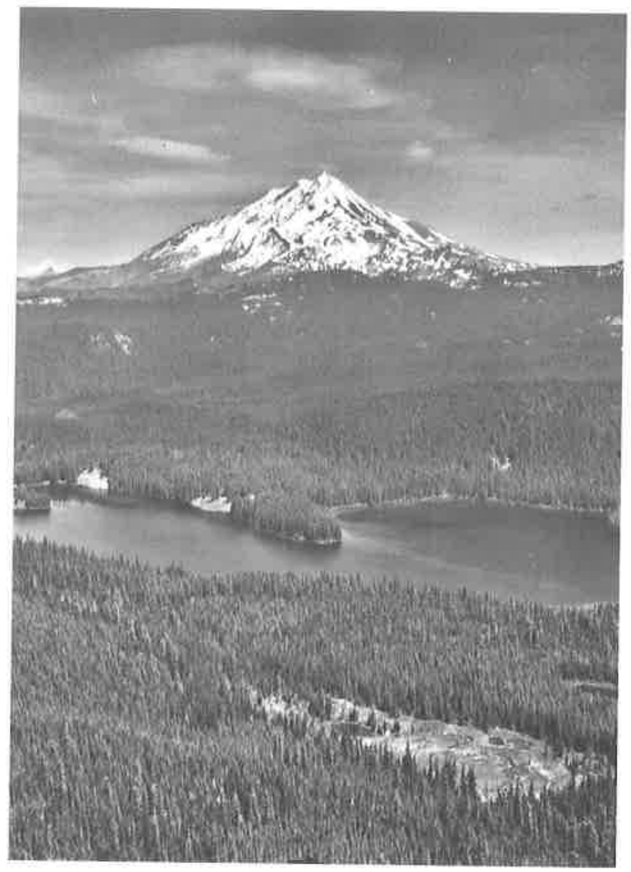
While the older vents at Mount Hood are obscured by younger lavas, they probably lay close to the main edifice, which was built from extensive Hood River and Cloud Cap lavas. The eruptive

Lava flows and dome construction during the last 20,000 years account for many of Mount Hood's surface features. Looking north in this photograph, Crater Rock and Illumination Ridge can be seen on the upper left skyline (west). Illumination Rock was eroded from a thick, 121,000-year-old andesitic flow, and Crater Rock is the remnant of the central dome emplaced in the Old Maid period. During the Polallie interval, Steel Cliff, on the upper right (east) near the summit, sent pyroclastics and lahars toward White River and Mount Hood Meadows. Forests of pines and fir blanket the lower slopes. (Photo courtesy Oregon State Highway Department)

events began with the dome-building Polallie from 20,000 to 13,000 years ago, the Timberline from 1,800 to 1,500 in the past, the Zigzag from 600 to 400, and the Old Maid from 1781 to 1810 A.D. The domes emplaced during the Timberline and Old Maid periods subsided into avalanches of ash, lavas, and snowmelt. The partial collapse of Crater Rock that deposited pyroclastics along the White River took place as recently as 200 years ago.

Central Cascades Edwin Hodge summarized volcanic events in the central Cascades after surveying Broken Top, the Husband, the Three Sisters, and other peaks in 1924, concluding that they were once part of a single large volcano, which had exploded and collapsed. He named the vanished structure Mount Multnomah, and his hypothesis gained wide acceptance until a reexamination by Howel Williams demonstrated that such an edifice never existed.

The South and Middle Sisters and Broken Top are major composite volcanoes that experienced long eruptive periods, in contrast to North Sister and Belknap shield cones, which have had shorter cycles. Within this group, the North Sister is the oldest at almost half a million years, and Belknap Crater is the most recent at 1,500 years ago. The Three Sisters history included at least four early pyroclastic flows, but most episodes, which built the Middle and South peaks, occurred from single



Sitting in a deep graben, Mount Jefferson has had a long eruptive history that includes a cluster of numerous domes and small shield-like volcanoes. Richard Conrey showed that the early wide expanse of eruptive sites was the consequence of crustal extension which allowed magma to spread over a broad area, whereas late Quaternary volcanism focused on a single stratocone. Lying in a deep glacially-scoured basin, Marion Lake is in the foreground. (Photo courtesy Oregon State Highway Department)

Viewed from the southwest, Mount Bachelor is a remarkably symmetrical shield cone. Broken Top is on the left, Lucky Lake is in the foreground, Lava Lake is directly behind, and Little Lava Lake is to the right. These are typical of the mountain lakes dammed by basalt. Cascade Lakes Highway (Highway 46) is the white line between the lakes. (Photo courtesy Oregon State Highway Department)

conduits during the past 100,000 years. On the northwest margin of North Sister, Collier Cone covered an extensive region with lava, cinders, and bombs (blobs of airborne lava) around 1,600 years ago, blocking and backing up the McKenzie River drainage into Spring Lake and Linton Lake.

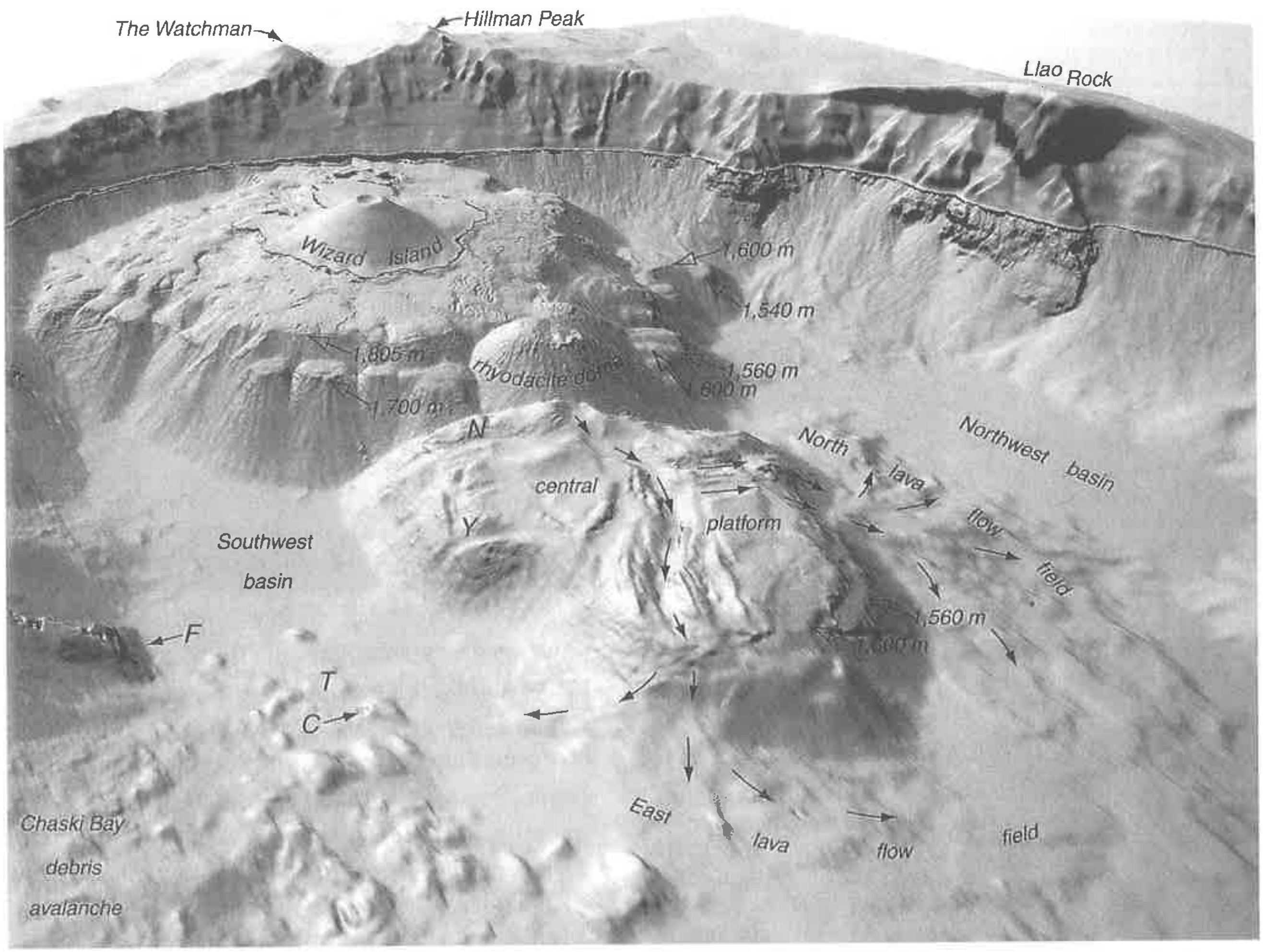
Projecting as vertical walls above the surrounding lava fields, parallel dike swarms are characteristic along the flanks of the Three Sisters. The seven-mile-long Matthieu Lakes fissure that extends northwest from North Sister is the largest in the Cascades. Erupting through ice fields about 75,000 years ago, lava from the Matthieu Lakes vents ponded into thick platforms. This was the final overprinting after which the magma supply shifted away from the main center.

South of the Three Sisters, the Mount Bachelor cone has seen little glaciation, whereas the sharply eroded spines of Mount Thielsen, and Mount McLoughlin are all that remain of the once larger volcanoes. The 15-mile-long Mount Bachelor complex is composed of cones, flows, and three shield volcanoes, Sheridan Mountain, Kwolh Butte, and Mount Bachelor. Between 18,000 and 7,000 years ago, volcanic activity moved northward from the oldest lavas at Sheridan Mountain, to those at Kwolh Butte, to Mount Bachelor. Papers by William Scott and Cynthia Gardner discuss the eruptive history of Mount Bachelor and in particular the interaction between the lava and Pleistocene glaciers.

Southern Cascades Mount Thielsen and Mount McLoughlin are shield volcanoes that were probably active over 300,000 years in the past. Studies of Mount Thielsen began with Joseph Diller in 1902 and continued with Howel Williams in 1933. The summit of Mount Thielsen was built of pyroclastic debris and thin lava flows before two volcanic plugs intruded the central core.

Little was known of the geology of Mount McLoughlin until Leroy Maynard's field mapping for his Masters degree from the University of Oregon in 1974. Severe glacial erosion, which has carved out a distinct semi-circular basin or cirque on the northeast slope, suggests this mountain is probably one of the older High Cascade peaks, although the exact periods and sequence of activity have yet to be clarified. Multiple eruptions built the cone and surrounding blocky lavas, and in the final Pleistocene stages andesites oozed from fissures low on the western side to construct North and South Squaw Tips.

The geology of Crater Lake was first described in detail by Joseph Diller and Horace Patton of the U.S.G.S. in 1902. Diller questioned whether the caldera resulted from volcanic subsidence or from explosive eruption, an idea favored by many geologists. Some 40 years later, Howel Williams wrote a dramatic account of the growth and eruption of the volcano, and from the 1980s to the present Charles Bacon of the U.S.G.S. has employed several



In recent explorations of the floor of Crater Lake, Charles Bacon used submersibles and underwater cameras to reveal many bathymetric features such as lava flows and volcanic domes, landslides, and older shorelines from varying water levels. In this perspective looking toward the west, the slopes of Wizard Island cone and the central platform edifice record past lake levels. (U.S.G.S. digital image; courtesy Bacon, et al., 2002).

techniques to reveal additional details of the eruptive cycle and features of the crater wall and floor.

The construction of Mount Mazama began over 400,000 years ago with overlapping shield and stratovolcanos from successive andesite and dacite lavas that ultimately erected the foundation. The earliest eruptions from Mount Scott, Phantom Cone, and Cloudcap Bay continued until about 170,000 years ago, after which new vents at Llao Bay sent out sheets of andesites. Immediately before the main eruption, The Watchman, Redcloud Cliff, and Steel Bay domes were emplaced, and flows from Llao Bay shield cone and Cleetwood Cove were still fresh when the entire mountain exploded.

Erection of a central dome and large magma chamber around 30,000 years ago was followed by an intermediate dormant period, which ended with climactic violence from a single vent on the northeast side of Mount Mazama dated at 7,700 years. The slopes and surrounding valleys were covered with avalanches of pyroclastics to depths of 300 feet, while an incandescent ash cloud, over 30 miles high, darkened much of the Pacific Northwest. Bacon determined that the eruption took place over three days during a warm dry interval when ice would have been restricted to the highest regions. Once the immense quantities of rhyodacite magma had been evacuated from the chamber, the roof collapsed.

The caldera filled rapidly with water to its present levels within the first few hundred years, even as vents on the central and western crater floor produced lavas beneath the rising lake. It was during this period that Wizard Island and Merriam Cone erupted. Only the crest of Wizard Island rises above the water, and Merriam Cone, submerged close to the northern rim, is a mile across at the base and projects 1,320 feet from the caldera floor. The last known lavas from vents at the base of Wizard Island constructed a central platform around 4,800 years before the present.

Future violent explosions are unlikely, but smaller eruptions on the floor could propel rocks or ash beyond the rim, and submarine landslides might produce small waves.

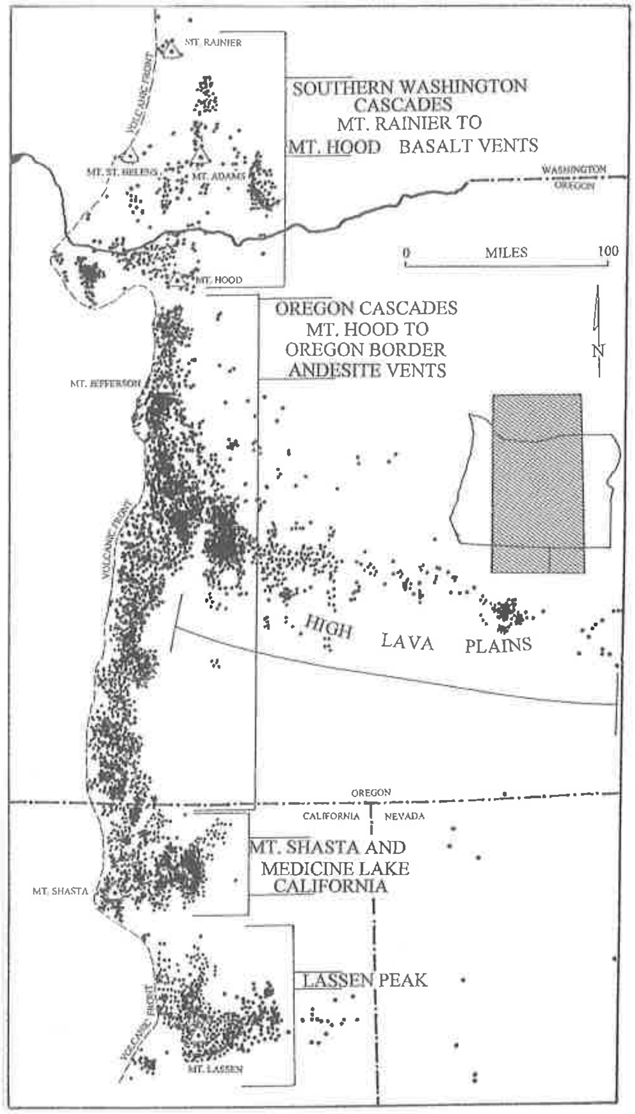
The cold bright blue lake waters that occupy the caldera are remarkably clear because algal growth is limited to thick belts of moss on the walls where light penetrates. By dating lake sediments with pollen and diatoms from core and dredge samples, Bacon established a post-collapse chronology for the crater.

Variations in Cascade Volcanism

Patterns in the evolution of High Cascade volcanoes differ considerably, and several models account for the contradictory amounts of extruded material, for the spacing between volcanic vents, for the composition of lavas, and for the style (composite vs. shield, vs. cinder cone). Volcanologists have attributed most of these to interaction between tectonic plates and the effects of crustal extension.

With modifications of the subducting slab, the eruptive volumes dropped, and the Cascade arc diminished to a strip only eight miles wider than at present. By averaging mapped thicknesses and quantities of rocks in Oregon, George Priest was able to demonstrate that the total volume in the early High Cascades was 1,200 cubic miles as opposed to 960 in the late High Cascades. Greater rates characterize the Three Sisters area, but obvious decreases are evident south of Crater Lake and north of Mount Jefferson. A more specific approach by David Sherrod and James Smith calculated the rate of output per edifice for the entire Cascade chain. The relatively brief but explosive Crater Lake event had substantially greater production than is the case for the range in general.

Recent theories to explain the spacing and eruptive style of the Cascades have subdivided the arc into structural segments, ranging from three to six increments, each with a set of unique characteristics. There is presently little agreement on the various parameters, but it appears that no one section is representative of the entire range. Ed Taylor summarized the problems related to spacing and organization of High Cascade composite volcanoes

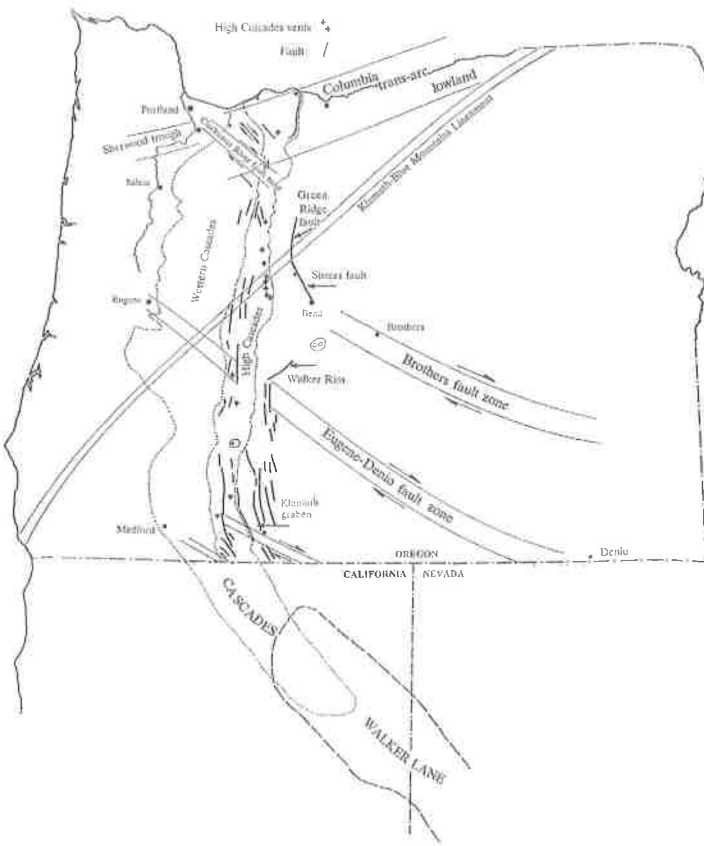


In their 1988 paper, Marianne Guffanti and Craig Weaver of the U.S.G.S. turned their attention to the late Tertiary in the Pacific Northwest. Studying the spacing of 2,821 separate vents, active since the Pliocene, they divided the Cascade range into six regions, five of which are in the Cascades and the sixth toward the High Lava Plains. The most northerly segment is from British Columbia to Mount Rainier. From Mount Rainier to Mount Hood the vents are primarily basaltic, but segment three from Mount Hood to the California border includes a dense cluster of andesitic eruptive centers. The fourth and fifth segments are Mount Shasta, Medicine Lake, and Lassen Peak in California. (After Blakely and Jachens, 1990; Christiansen and Yeats, 1992; Guffanti and Weaver, 1988; Hughes, Stoiber, and Carr, 1980; Peck, et al., 1964; Riddihough, 1984) noting that they are not widely distributed but instead are clustered in a few areas, they appear to be randomly placed, and they vary considerably in age.

By compiling data on 3,000 volcanic centers in the High Cascades, Paul Hammond showed that the areal distribution and concentration of centers increase between Mount Rainier and Mount Hood but diminish in numbers between Mount Hood and Mount Jefferson and in northern California. Examining the spacing of basaltic cones, Richard Conrey concluded that they average 12 miles apart while stratocones are consistently almost four times that. Since stratocones and shield volcanoes evolve separately (one is not parent to the other), two styles of volcanism in the north-central Oregon Cascades are responsible for the spacing. The incidence of long-lived stratovolcanoes is controlled by processes in the mantle or in the lithosphere (crust), while ephemeral but persistent basaltic cones are the product of extension along the arc or from bending of the subducting Juan de Fuca plate.

In the central section of the High Cascade province, the majority of cones and shield volcanoes produced basaltic (mafic) lava. During the late Quaternary, the volcanic pattern progressed southward from the oldest 3,850-year-old eruptions at Nash Crater and Sand Mountain near Santiam Pass to the Belknap, Yapoah, and Collier cones along the McKenzie Highway dated at 1,500 years, reflecting an underlying fracture zone.

Impinging on the Sand Mountain field, eruptions from Belknap Crater, Yapoah, and the Four-in-One complex were the most recent and widespread. The youngest shield volcano in the Cascades, Belknap has two summit craters, the largest of which is 250 feet deep and 1,000 feet wide. Belknap's repeated eruptions impacted 40 square miles, immersing trees and filling the McKenzie River channel. Cylindrical molds from one to five feet in diameter, as well as 35-foot-long trenches, are the remains of tree trunks consumed by lavas, which cooled and hardened around them. Where the McKenzie disappears into the porous Belknap field, it percolates underground to reemerge at Tamolitch Falls.



Crossing the state diagonally, the north-northwest-trending McLoughlin, Eugene-Denio, and Brothers fault zones extend from the Basin and Range and High Lava Plains into and through the Cascades. The Clackamas River belt of faults, which projects northwesterly to merge with the Portland Hills, may be an extension of the Brothers fault system, and Walker Lane, at the northern reach of the eastern California shear zone, may extend into the Cascades. (After Dokka and Travis, 1990; Faulds, Henry, and Hinz, 2005; Priest and Vogt, 1983; Venkatakrishnan, Bond, and Kauffman, 1980)

Faulting, Volcanics, and Sediments

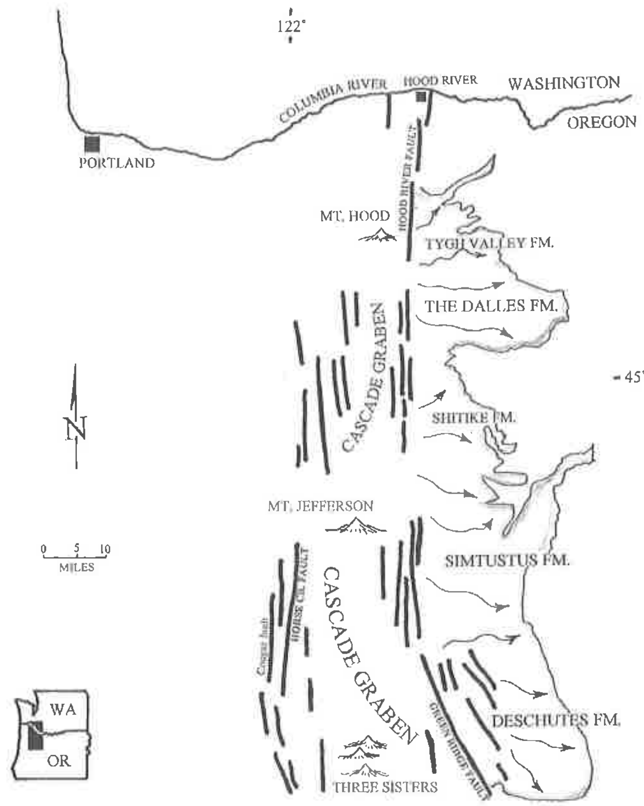
The late Tertiary shield volcanoes and subsidence of the High Cascades into a deep intra-arc graben are associated with extensional tectonics. The word *graben*, from the German *grave*, refers to the sunken trough above a collapsed block. Structurally a graben is a depression between two faults.

As early as 1938, Eugene Callaghan and Harold Buddenhagen of DOGAMI suggested that a series of faults ran the length of the Oregon High Cascades, and considerable documentation since the 1980s has confirmed the presence of an intra-arc graben. Paralleling the axis of the Cascades between the Three Sisters and Mount Jefferson, the east side of the graben is well-defined by the steep Green Ridge scarp and the west by the Horse Creek fault. In the central section, the graben lies along the upper Clackamas River, and in the north it follows the Hood River fault.

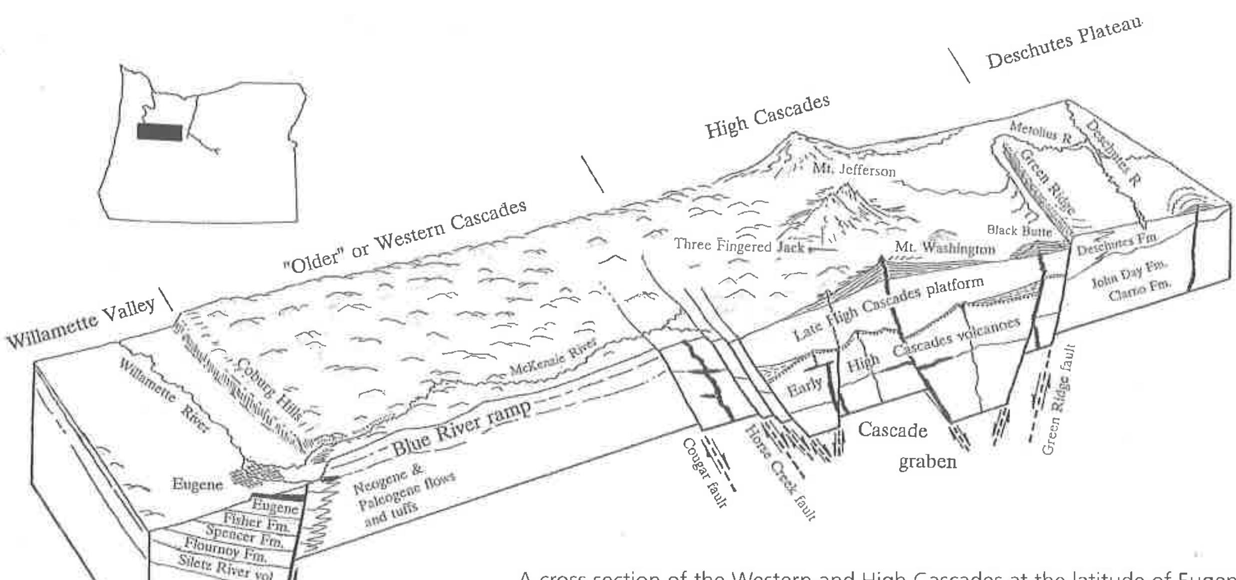
After field mapping in 2004, Richard Conrey at Washington State University and Ed Taylor proposed a segmented time-propagating rift beginning as far back as 8 million years. Opening like a zipper from the south, a lengthy intra-arc graben began to develop, subsiding as deep as two miles in the south to less than a mile in the center. Lavas, emerging with the rifting, closely resemble mid-ocean ridge basalts (MORB).

Thick layers of lava, pyroclastics and ash from High Cascade volcanoes were discharged both east and west along the intra-arc rift. In basins to the west, explosive eruptions of breccias, tuffs, and flows of the Rhododendron Formation are intermixed with or overlain by basaltic and andesitic cobbles of the Troutdale Formation. The Troutdale is composed of sediments transported along the ancestral Columbia River canyon and spread laterally into tributary stream valleys. Above the Troutdale, the Pliocene–Pleistocene Boring lavas erupted from the many buttes and smaller hills in and around Portland and Vancouver, Washington.

Eastward, the late Western Cascades and High Cascades contributed muds, silts, and volcanic debris to the Simtustus, The Dalles, and the Deschutes formations in basins atop the Columbia River basalts. Conrey concluded that each structural portion



A northward propagating rift along the Cascade arc has been divided into three segments, whose boundaries line up with the stratovolcanoes. The youngest portion from the Columbia River to Hood River valley and Mount Hood is a half graben with a broken western hinge. The central segment between Mount Hood and Mount Jefferson lies along the upper Clackamas River and is a complete graben bounded by faults, while the oldest southern part from Mount Jefferson to the Three Sisters is between the Green Ridge escarpment and Horse Creek fault. (After Allen, 1966; Callaghan and Buddington, 1938; Conrey, Grunder, and Schmidt, 2004; Conrey, et al., 2002)



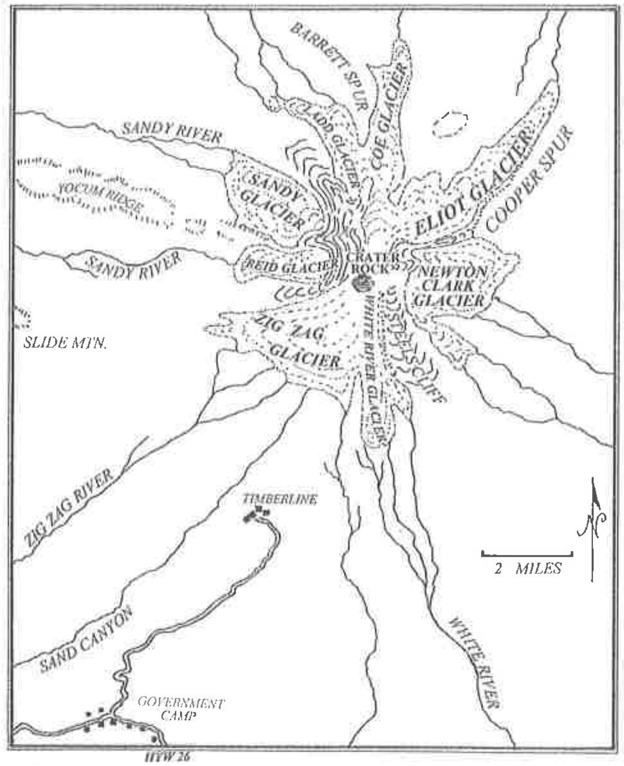
A cross section of the Western and High Cascades at the latitude of Eugene shows the Blue River ramp, the High Cascade Graben, and the Green Ridge fault. (After Gandera, 1977; Taylor, 1990; Vokes, Snavely, and Myers, 1951) of the intra-arc rift is associated with the three eastside basins, and the eruption of late Miocene to Pliocene lavas and tuffs began immediately prior to rifting During the early Pliocene, sedimentation ceased when the source was cut off by the wall of the Green Ridge scarp as the High Cascades subsided into a graben.

Pleistocene—Ice and Lava

In the High Cascades 2 million years ago, snow and advancing ice sheets, interacting with lava and ash, sent lahars (mudflows) down the mountain sides. Subglacial lava flows were sometimes flattened beneath the ice (tuya).

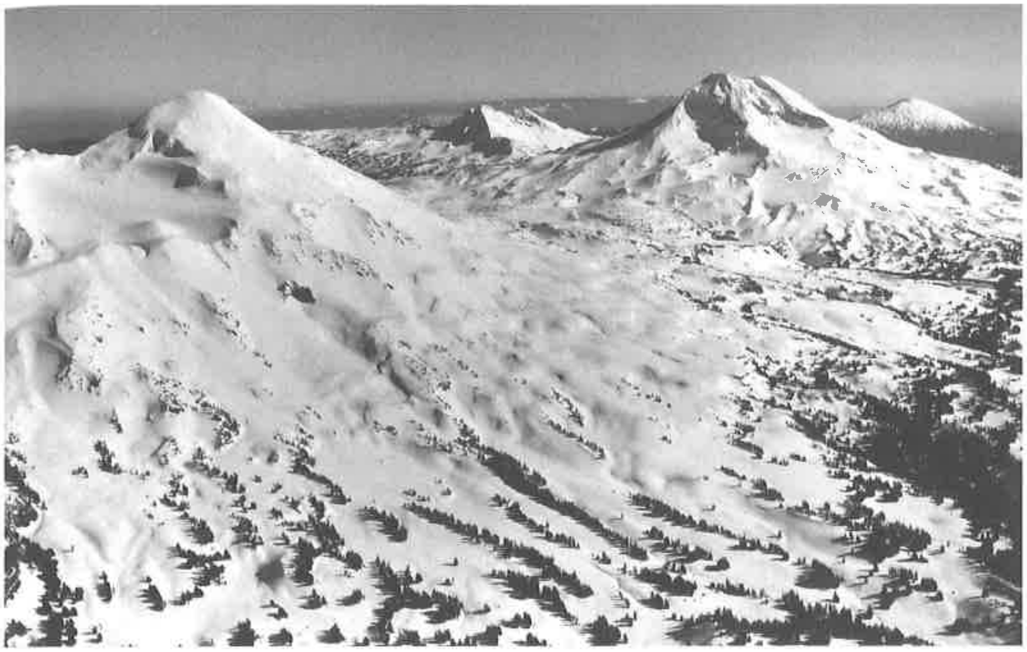
While northern Washington experienced continental glaciers, a nearly continuous ice field capped the Oregon Cascades, and sizeable ice masses in the lower canyons advanced and retreated. Many of the naturally occurring lakes in the Cascades owe their origin to moraines of gravel, sand, silt, and clay which blocked streams. Semi-circular basins (cirques) hold smaller lakes (tarns).

Although the final cold phase ended around 11,000 years ago, glaciers persist on Mount Hood today. The total volume of 12 billion cubic feet of ice and snow on the slopes, if melted, would provide enough water to enable the Columbia River to sustain its normal flow for 18 hours. The amount of ice above Crater Rock at Mount Hood is estimated at 47 million cubic feet.

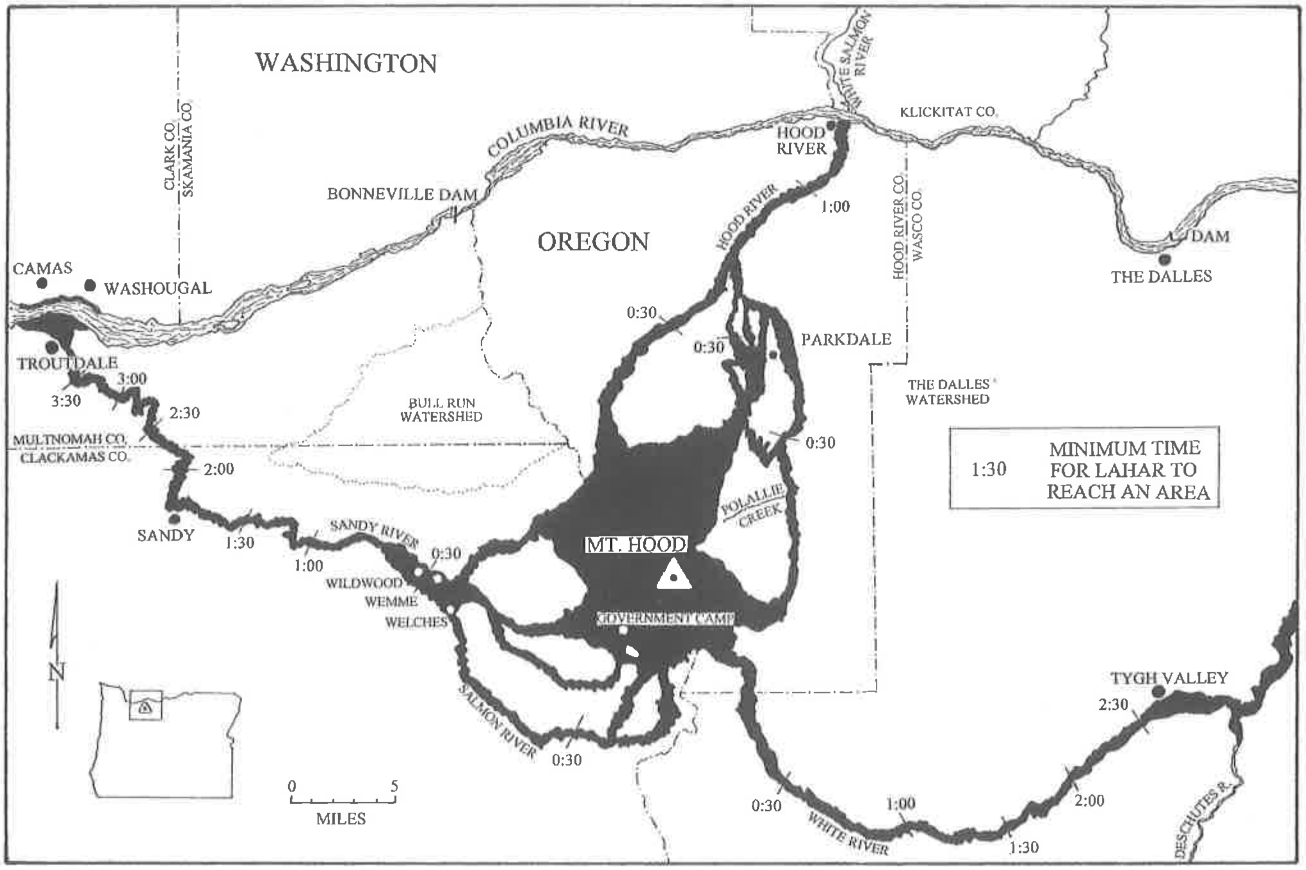


Radiating outward from Mount Hood, glaciers shaped the peak, cutting deep crevices to leave sharp spurs and ridges projecting between ice fields. Meltwater, rocks, and mud combined as lahars moving down the river valleys and depositing broad fans of volcanic debris. (After Crandell, 1980; Williams, 1912)

Once central Oregon's lava fields cooled, fluvial and glacial erosion began to wear away at the tall Cascade peaks. The older volcanoes, which ceased activity over 100,000 years ago, were reduced by Pleistocene glaciation to craggy amphitheaters and ragged ridges as seen at Broken Top (above). In the foreground, a snow-covered lava field appears to be flowing. (Photo courtesy Oregon State Highway Department)



The steep eastern face of the Middle Sister is covered by the Hayden and Diller glaciers, while Collier Glacier extends from the north slope of the Middle Sister across to the base of the North Sister. The largest of the five ice fields on the Three Sisters today, Collier Glacier covers 200 acres, a decrease of over 50 percent during the past 80 years. Since the last ice advance in 1700 A.D., all of Oregon's glaciers have been shrinking at a rapid rate. (In this view looking south, the Three Sisters are in the foreground, Broken Top is back center, and Mount Bachelor is behind right; Photo courtesy Delano Photographics)



Hazard zonation maps, such as this one of Mount Hood's historic eruptions, are drawn to depict possible routes, intensity, and times of future events. (After Cameron and Pringle, 1986; Pierson, et al., 2009; Scott, et al., 1997; Scott et al., 1977a. Photo courtesy U.S. Geological Survey)

Geologic Hazards

Its tectonic position, topography, and stratigraphy make the Cascade province especially vulnerable to earthquakes, landslides, and volcanism. Vastly improved imagery and mapping is now available through the use of LIDAR (Light Detection and Ranging), a technology that literally sees through the vegetation cover to provide details of the bare land surface and expose ancient and modern features beneath. This tool enables geologists to identify potentially risky conditions.

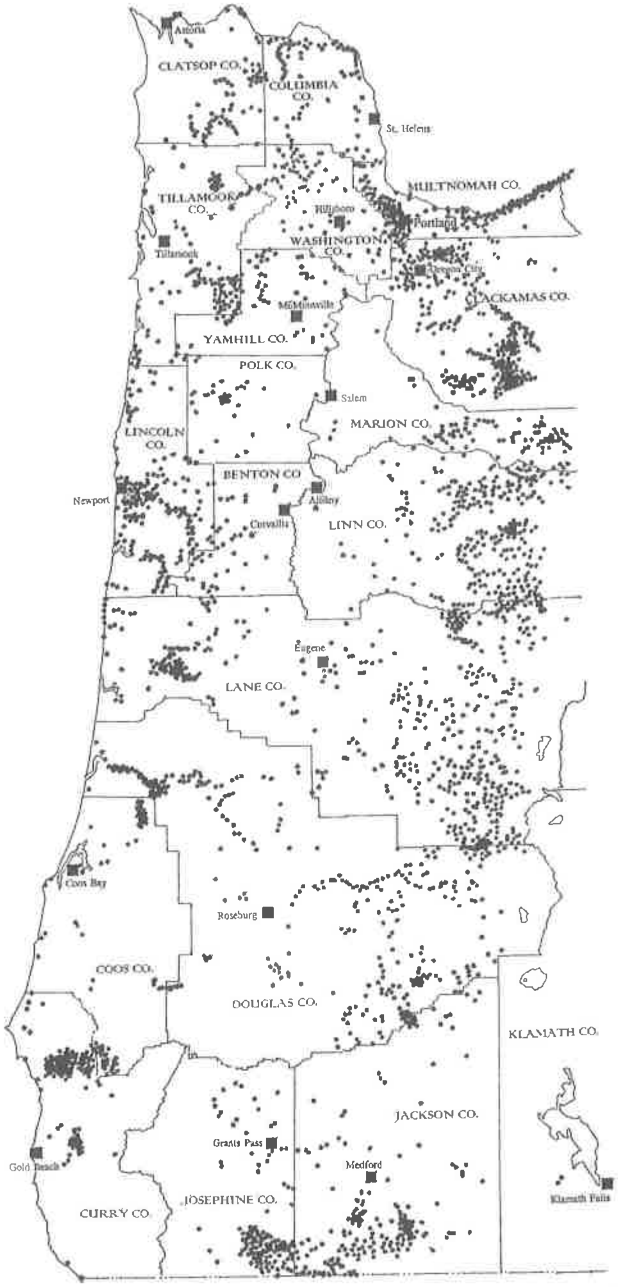
Earthquakes

The U.S.G.S., the University of Washington's Pacific Northwest Seismograph Network, and other cooperating groups have been monitoring the Cascades for close to 20 years. Mount Hood experiences small swarms annually, each involving over one hundred individual events. In 2011, by the use of LIDAR, Ian Madin discovered a fault scarp that stretched for several miles on the north flank of Mount Hood. Madin estimates that the fault was generated by a 6 to 9 magnitude quake. Because of its location and potential for causing damage, Mount Hood is closely watched.

Landslides

When the Cascades and Columbia River gorge experience prolonged heavy rains, loosely consolidated rocks and soils move in mass on steep hillsides. An understanding of the intricate relationship between supersaturated soils, denuded slopes, and stratigraphy is crucial to assessing the potential for hazards.

No area of the Cascades has been more heavily studied than the H.J. Andrews Experimental Forest in the upper Blue River and Lookout Creek watersheds, where ecosystem research by the U.S. Forest Service and Oregon State University has been ongoing since 1948. In conjunction with other forest service personnel, Fred Swanson has documented local streamflow, landslides, and slope processes, relating them to the dynamics of clearcutting. Not surprisingly, he found that the removal of trees on slopes composed of the Sardine Formation and Little Butte lavas increased the annual streamflow by 40 percent, a condition that persisted longer at the upper elevations. Sediment load, flooding, and stream transport were dramatically higher where the terrain was cut over or where the placement of roads created instability. When combined with severe storms, as in the winters of 1964 and 1996, slumping, rock avalanches, and degradation of water quality and stream habitat ensued. Additionally, damage to campgrounds, roads, hiking trails, and boat launching ramps was extensive.



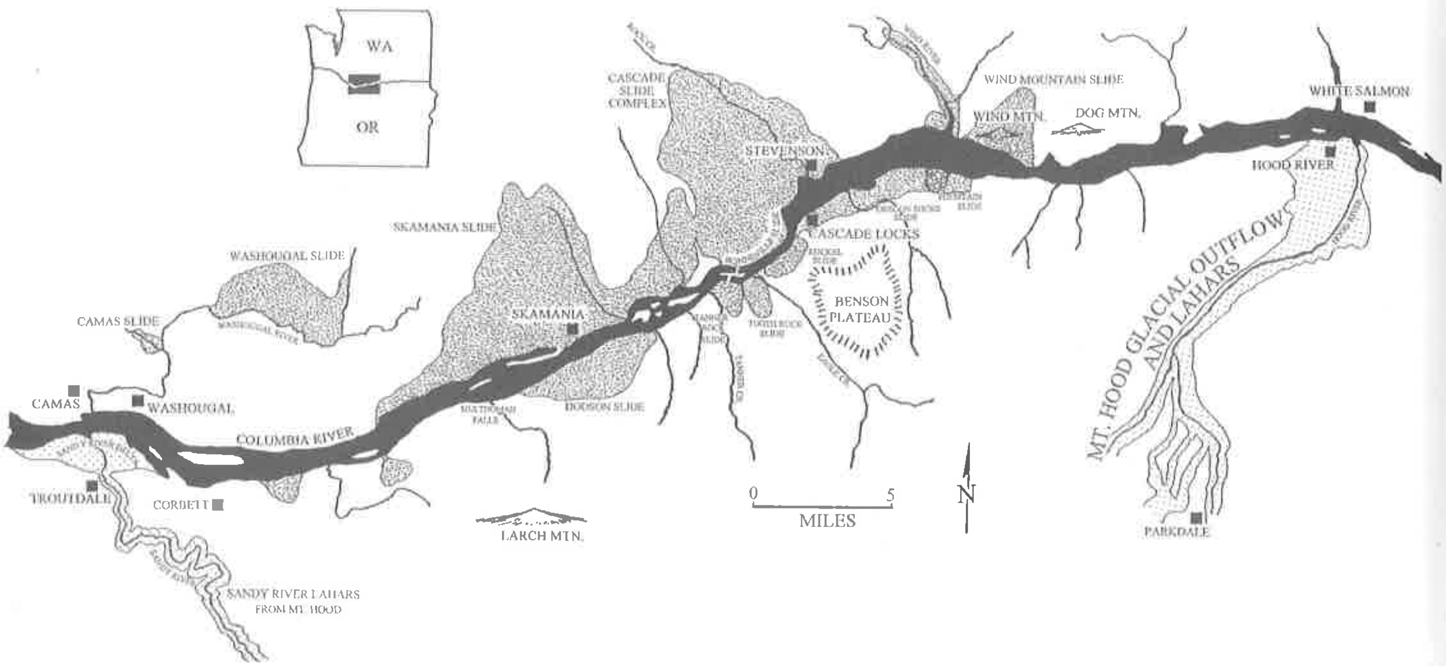
Oregon experienced exceptionally heavy rainfall in February, 1996, a landmark time for flooding and slides, which DOGAMI designated as an 100-year event. The 1996 to 1997 landslide occurrences in western Oregon are indicated by the dots on this map. (Map courtesy University of Oregon; after Hofmeister, 2002)

Similar conclusions were reached in studies of the Mount Hood National Forest following the floods of November, 1995, and February, 1996. Surveys by the U.S. Forest Service in the upper Clackamas River drainage near Estacada revealed over 250 landslides in logged over areas or where roadways had been sited. A more focused look at conditions on Fish Creek and Roaring River confirmed these findings. Because of steep slopes and soft, easily eroded rocks of the Rhododendron Formation, the intensely managed Fish Creek watershed experienced a tenfold increase of landsliding in areas of timber harvest. Roughly 75 percent of the slides in Fish Creek were associated with clear-cutting, in contrast to the Roaring River area where minimal logging activated only two percent of the slides.

The slopes of the High Cascade peaks have often been subjected to free-flowing mixtures of mud, ice, water, and trees after winter and spring rains. Triggered by precipitation around Christmas, 1980, the Polallie Creek avalanche was one of the largest on record. After the slumping of a headwall along the creek on the northeast flank of Mount Hood, the debris traveled up to 35 miles an hour to enter the East Fork of Hood River. Over 100,000 cubic yards of material temporarily dammed the water to form a lake, which, in turn, failed sending a second wave carrying whole trees, enormous boulders, sections of bridges, and pavement slabs across Highway 35 just south of the community of Hood River. One person was killed, and property damage was $13 million.

In September, 1998, and again in November, 2006, debris flows, resembling a watery cement-like mixture, pushed large boulders and gravel down the White River channel on the south side of Mount Hood. Triggered by melting ice and ponding water, the surge is estimated to have traveled at 10 to 15 miles an hour. Since then, high gradient streams, easily eroded deposits, and melting ice continue to deliver sediments to the fan in the lower channel at roughly five-to-ten-year intervals.

The bridge on Oregon Route 35, crossing the White River below Mount Hood, was blocked by debris in November, 2006 (lower photo). The White River channel is frequently impacted by flow surges, and 2 to 14 feet of deposits layer the floor. New channels have been scoured by glacial melt water (upper photo). (Photos courtesy T. DeRoo, C. Hedeen, D.Jones)



The map illustrates the location of landslides and lahars on the Columbia River between The Dalles and Portland, and the digital images pinpoint the strip near Bonneville dam and Cascade Locks where innumerable slides have taken place. (After O'Connor and Burns, 2009; Loy, et al., eds., 2001; Wang, et al., 2002; photo courtesy University of Oregon)

In the Columbia River gorge, large slides, up to 20 square miles in extent, originate predominantly from the Washington side, because the rocks along the river are sloping (dip) toward the south. For the same reason, most of the waterfalls are on the Oregon side. Typically, the slides are fostered by thick clays derived from the decomposed Ohanapecosh Formation lying beneath the Eagle Creek Formation and the Columbia River Basalts. As Aaron Waters observed in 1973, once they become saturated with water, the clays act as a "well greased skidboard."

The Cascade group, incorporating multiple separate slides near Cascade Locks, extends over five miles from Table Mountain, Greenleaf Peak, and Red Bluffs in Washington to the Oregon shore, an area of 14 square miles. Rapids in the channel here, which constitute evidence of mass movements, have been the subject of speculation since first

Heavy rain and a slurry of mud washing through Dodson were harbingers of the 1996 debris flow that would destroy the Royse home. On February 7, 1996, Carol Royse heard a loud rumbling and felt the ground vibrating just before she looked out to see a wall of mud, trees, and rocks moving in her direction. The Royses, their horses, and cat escaped, but their two-story home was lifted off its foundation before being immersed in 15 feet of rocky debris. The flow continued across the highway and railroad to the Columbia River. (Photos courtesy C. Royse)

observed by Indians and explorers. In 1887 Reverend Gustavus Hines wrote that the river dropped "in continued rapids for three miles, not less than fifty feet." A few years later, government geologists such as Clarence Dutton and G. K. Gilbert also took notice of the blockage.

The most recent of the Cascade landslides, the Bonneville rubble, which temporarily dammed the Columbia channel around 500 years ago, may be the origin of the legend of the Bridge of the Gods. As related by Indians, the story describes a bridge arching over the river that crashed down to form the rapids. Rising waters behind the natural dam submerged trees upstream as far as The Dalles until the river cut through the rubble to create the whitewater in the channel. Using radiocarbon to date the drowned trees, Jim O'Connor with the U.S.G.S. and Scott Burns place the Bonneville slide between 1425 to 1450 A.D.

To enhance ship navigation at Bonneville, the U.S. Army Corps of Engineers built a system of locks and canals around the rapids in 1896, but their 1937 dam submerged most of those features. The footings of the dam itself are anchored into the toe of the Bonneville slide.

Land movements originating on the Oregon side of the Columbia River tend to be of limited extent. West of Bonneville Dam, recurring debris flows near Dodson are of impressive size, while east of the dam the Tooth Rock, Ruckel, and Fountain slides only cover one square mile each. An article by Yumei Wang DOGAMI, as well as a 2009 guide by O'Connor and Burns, provide an excellent overview of gorge landslides.

The Dodson-Royse-Warrendale-Tumalt Creek slides all fall within the informally-designated Dodson fan that has been accumulating fluvial sediments since the late Pleistocene. The Columbia River basalt, the Troutdale Formation, and the Boring lavas supply most of the debris for the fan, and when sections of the rock upstream slump off, as happened in 1996 and again in 2001, housing, Interstate 84, and the railroad tracks were covered. During the same day in February, 1996, boulders and gravel of Boring lavas came loose along Tumalt Creek east of the Royse property to pond water in the upper reaches. When the obstruction broke, the mud, rock, and water moved at 30 miles an hour, hitting trucks and train cars, already halted because of the Royse slide, and pushing them into the Columbia River channel.

Adjacent to the Bonneville Dam, Tooth Rock is an ancient slide that was studied extensively in the 1980s by the Army Corps of Engineers before they pinned a Bonneville navigation lock into the slump block. The large block had been rotated 40°, however, engineers concluded that further movement was unlikely because the slab had been stabilized by bedrock that projected into the toe. No motion has been reported since construction.

Even during emplacement of a railroad portage at Ruckel Creek in 1924, the crew described the moving slope as a "glacier." Although dormant at present, the landslide involves the Eagle Creek Formation lying beneath the Columbia River basalt. Similar in composition, the Fountain is an older slide that was mobilized by highway construction in 1952. Heavy rainfall along with the widening of Interstate 84 in 1966 has contributed to the present-day movement.

Volcanic Eruptions

A close examination of historic and current volcanic activity is crucial to anticipating future risks from the potentially explosive Cascades. While many of the stratocones from British Columbia to northern California appear to be dormant, earthquakes, evidence of hydrothermal fluids, steam eruptions, and fumaroles are clear signs that they are still active. Risks from an eruption involve more than flowing lavas, which rarely extend over ten miles from their source. Rapidly moving clouds of incandescent ash, cinders, and chunks of rock can cover great distances at speeds well over 100 miles an hour, and lahars can travel up to 30 miles an hour, stretching tens of miles from their sources.

Typically, the volcanic history of Mount Hood has been one in which lavas, ash, and water combine in a soupy mixture to move as destructive lahars. In his guidebook, William Scott documents some of the most notable. The oldest lahar, dated at 38,000 years ago, swept into the Hood River valley. Of impressive size, it overwhelmed the site of present day Hood River before crossing the Columbia River and moving up the White Salmon River into Washington, where the deposits piled 350 feet high. Starting 500 years ago, numerous lahars spread down the Zigzag and Sandy rivers toward the Columbia and down the White River to the Deschutes, depositing coarse rubble. As recently as the 1800s, during Mount Hood's Old Maid eruptive period, mud and ash flooded the White and Sandy river beds to reach the Columbia.

Over the past 2,000 years, coniferous forests almost 50 miles from Mount Hood have been overwhelmed by lahars, then later exhumed by erosion. Of these, the best known is the Stadter forest on the south side of Illumination Ridge below Zigzag Glacier. Named by Edwin Hodge in 1931, the Stadter was described in 1991 by Kenneth Cameron, formerly of the U.S.G.S., and Patrick Pringle of the Washington State Department of Natural Resources. They compiled the glacial and volcanic history of the Stadter and six similar sites from the Timberline and Old Maid periods.

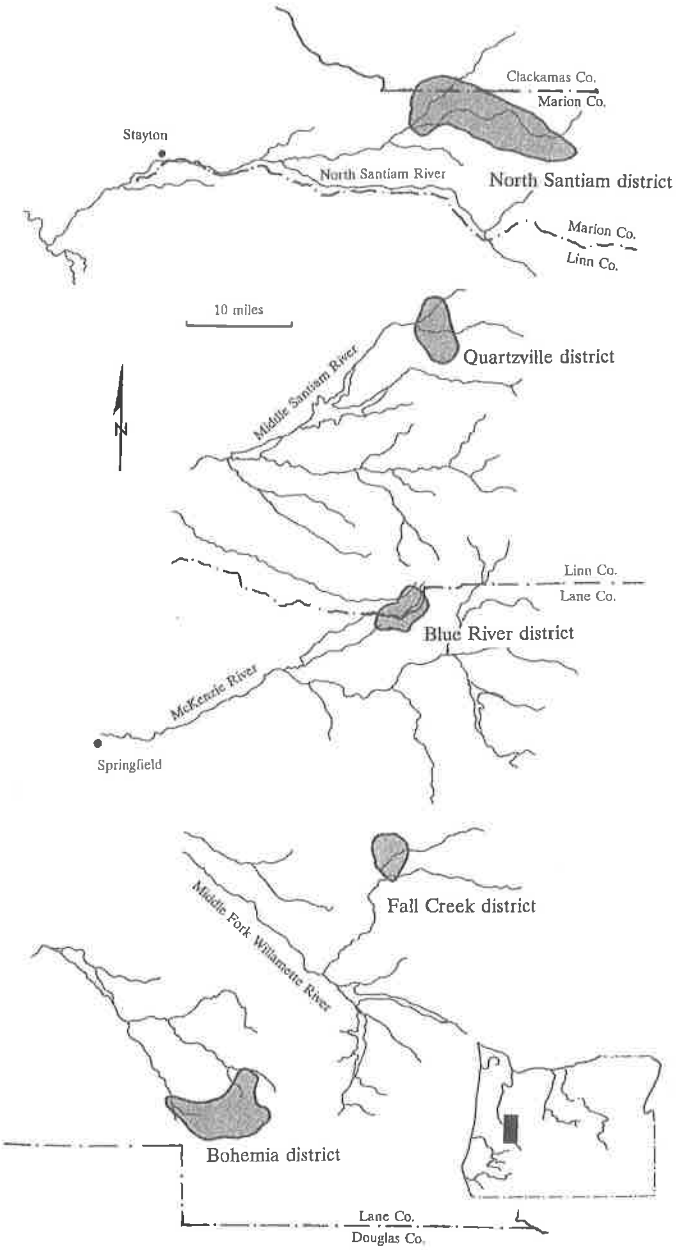
Eruptions of ash and lava are not unknown along the central Cascades, and around 2,300 years ago Rock Mesa was built on the flanks of South Sister. Historically, one of the Three Sisters was viewed belching forth dense volumes of smoke from its summit. In 1996, calculations by Charles Wicks of the U.S.G.S. revealed an area three miles west of the South Sister that was doming upward. The cause was thought to be an accumulation of magma at a depth of about four miles. Three years later, when an earthquake swarm was centered near the uplift, geologists began to monitor the bulge closely, but by 2007 it had diminished in size. Studying what came to be called the South Sister bubble, Wicks suggested that major subduction earthquakes might even trigger an eruptive cycle in the Cascade arc. The idea that a quake of such magnitude might accompany volcanic activity brings to mind an almost unimaginable calamity.

Natural Resources

Erosion removed much of the overlying Western Cascade rocks during the past 5 million years, exposing mineralized zones along valley floors. Mineralization is associated with granodiorite intrusions that developed during separate phases of volcanism, and thus the ore bodies are not interrelated. Where veins of shattered breccias were invaded by hydrothermal fluids at temperatures of 250° to 350° Fahrenheit, minerals precipitated in the host rocks.

Gold and Silver

Bohemia Mountain south of Cottage Grove has been the most productive and versatile in this province, although mineralization is confined to only nine square miles. Discovery of placer gold on Sharps Creek in 1858 came shortly before that of lode veins by James Johnson, who had traveled north to the "extreemly wild and untenanted wilderness." Since Johnson was from Bohemia in eastern Europe, the region was named for him. The Champion, Helena,



Five mining districts, the North Santiam in Clackamas and Marion counties, the Quartzville, the Blue River, the Fall Creek, and the Bohemia in Linn and Lane counties all lie within a 25-to-30-mile-wide belt of the Western Cascades. Even though yields were small in comparison to other areas of Oregon, there was a surprising variety of gold, silver, and other ores. (After Brooks and Ramp, 1968)

Musick, and Noonday mines dominated the Bohemia district, generating a combined total of about $1 million from both gold and silver.

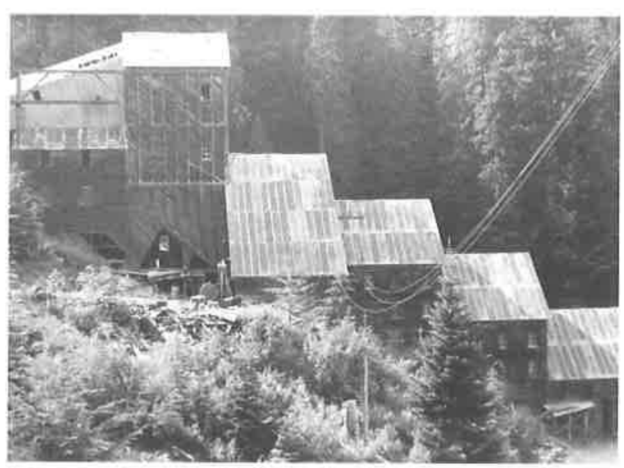
Dorena Lake, a U.S. Army Corps of Engineers flood control reservoir, is being contaminated by high levels of mercury leaching from the Bohemia Mine. A mercury amalgamation process was used to extract the gold.

Revenue from the Quartzville and Blue River districts was marginal. At Quartzville, gold-bearing veins were located in 1864, and the complete output amounted to $181,000. Somewhat less was removed in later years, when the mines only operated intermittently. In 1984 the Quartzville Recreation Corridor was set aside for panning.

About 45 miles east of Eugene in Lane County, the Blue River district was largely confined to the Lucky Boy Mine, located in 1887. Practically all of its operations ceased by 1913, when the vein was exhausted. Production figures for gold and silver have been estimated at $175,000. Gold ores at the Fall Creek mines in Lane County are of comparatively low grade, and mining has been limited.

Along with the Bohemia Mountain area, the North Santiam district yielded a variety of copper, zinc, lead, silver, and gold since it opened in the 1860s. Most activity focused on the Ruth vein where ores of zinc and lead have been mined periodically. The quantity of gold and silver is low in comparison with that of other minerals, and the total for all ores was $25,000. The most recent exploration involved surveying and drilling for copper by the Shiny Rock Mining Company, which holds a large block of claims. The claims were subsequently leased in 1980 to Amoco Minerals Company.

While production figures for all Cascade minerals can only be estimated because the records are lacking, the revenue since 1858 is $1.5 million, keeping in mind that the price of gold was well below $35 an ounce before 1960.



At the sophisticated Champion Mill, a 100 ton selective flotation plant processed ore in the Bohemia area. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Geothermal Energy

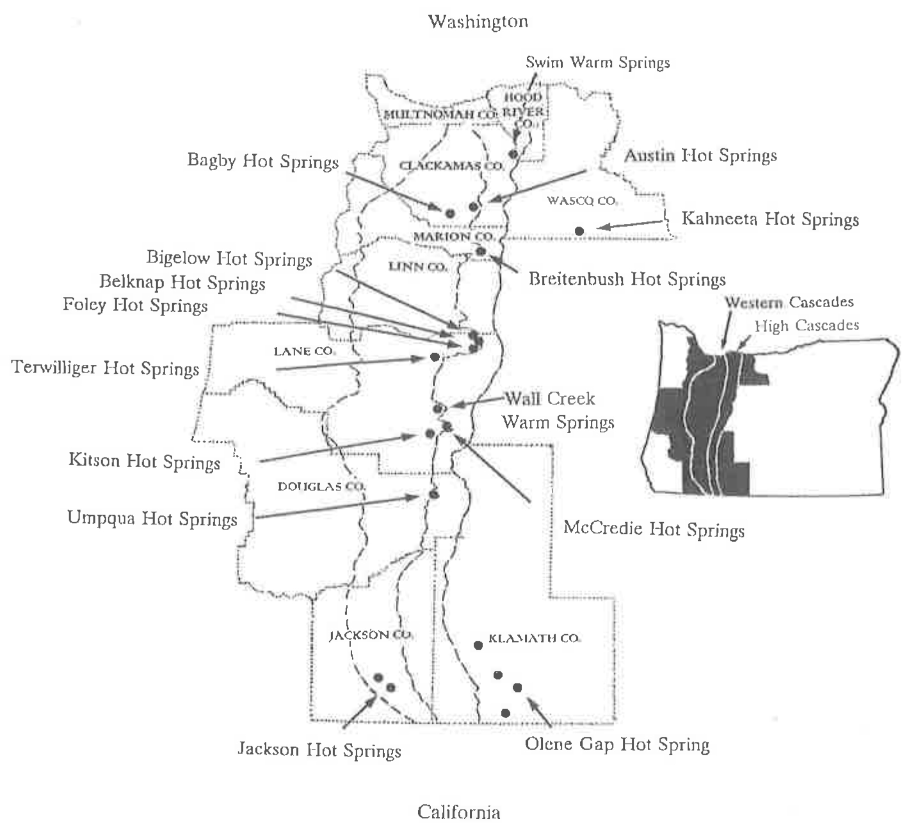
Between the High and Western Cascade mountains, an irregular north-south belt of hot springs, narrowing to less than 12 miles in width, marks a major thermal boundary or heat flow change. Low temperature gradients in the Willamette Valley and adjacent Western Cascades increase toward the High Cascades. Many of the thermal springs are located along faults, where superheated waters migrate through fractures to reach the surface. A 1983 monograph edited by George Priest and Beverly Vogt summarizes the geology of the central Cascades and reviews heat flow patterns.

A combination of warm groundwater and partially molten material beneath the younger volcanic rocks is responsible for the thermal springs. A decade of examining gravity anomalies (variations) and heat flow near the Three Sisters led David Blackwell at Southern Methodist University to conclude that the source was a large magma chamber or wide thermal zone at a depth of six miles (midcrust).

However, William Stanley and Steven Ingebritsen at the U.S.G.S. reached an alternate hypothesis. They surmised that a narrow zone of high heat flow along the axis of the High Cascades is caused by groundwater moving laterally though porous Quaternary rocks. Based on drill holes reaching depths of several hundred feet, they considered the area of crustal melt to be smaller than that postulated by Blackwell, and, because the volcanic rocks were permeable, the heat flow was shallow.

Thermal waters discharge at an average rate of 80 gallons per second from the Cascades in California, Oregon, and Washington in comparison to hot springs at the Yellowstone caldera, which release 800 gallons per second. Austin Hot Springs in Clackamas County has the highest thermal discharge of any in Oregon at 30 gallons a second.

Even though the geothermal potential is only modest, the Cascades has been rated as a Known Geothermal Resource Area by the U.S.G.S. At present, DOGAMI is working with the Oregon Department of Energy to inventory Oregon's geothermal systems, most of which are located on federal lands. Since the 1970s, these agencies have drilled exploratory wells to pinpoint heat flow on Mount Hood. The volcanic history of the mountain implies significant hydrothermal systems, but the results were



A north-south belt of hot springs marks a thermal boundary between the Western and High Cascades. Springs in the northcentral portion of the Western Cascades have higher water temperatures than those at either end. Jackson Hot Springs is the most southerly in the Oregon system, while the warm springs at the old town of Swim in Clackamas County are at the northern end. Temperatures average between 90° to 190° Fahrenheit. (after Black, Blackwell, and Steele, 1983; Blackwell, et al., 1978; Blakely, 1994; Blakely and Jachens, 1990; Ingebritsen, Mariner, and Sherrod, 1994; Mariner, et al., 1990; Priest and Vogt, 1983) inconclusive, and there was little evidence of high temperature waters circulating near the surface or even in deep-seated magmas. As with Newberry Volcano and Crater Lake, the recreational value must be considered.

Private companies, seeking to explore Crater Lake for geothermal resources, have been opposed by environmental groups, fearing that drilling, even a distance from the lake, might interfere with plumbing conduits. Ongoing assessments by Charles Bacon confirmed the presence of discharging thermal vents on the floor of Crater Lake as well as on the south and east flanks in the Wood River Valley. Evidence from drill holes led him to conclude that the springs are associated with heat from the final eruption. However, their flow has diminished since early in the lake history. Temperatures in the Crater Lake hydrothermal system reach a maximum of over 200° with an average of 55° Fahrenheit.

Surface and Groundwater

When moisture-laden air masses from the Pacific Ocean encounter the Coast Range and Cascades, rain soaks Oregon's western region, but much of it is blocked by the mountains from reaching the drier eastern part of the state. As a result, annual precipitation in the Western Cascades averages from 70 to over 150 inches, contrasting to the approximately 12 inches on the east slopes of the High Cascades, most of which falls in the wintertime. Thus the north-south Cascade physiographic division has shaped the climate of the state since the Miocene.

A mature soil cover and high gradient streams in the Western Cascades absorb rainfall rapidly after a dry fall, quickly become saturated, and have little storage capacity. These characteristics lead to winter and spring flooding and a diminished summer flow. In the High Cascades, a 2004 investigation examined the relationship between the aquifers, lavas, and topography. Anne Jefferson and coauthors from Oregon State University found that along the upper McKenzie River the movement of shallow groundwater is controlled by the geographic limits of the volcanic fields, by the high permeability of the lavas, and by the rate of recharge. As rainfall percolates through young High Cascades lavas it supplements the groundwater and emerges downslope as springs.

There have been periodic attempts to divert what is perceived as Oregon's abundance of water. The Columbia River has been a prime target for schemes to pipe water out of state to the dry southwest, and the 2008 "discovery" of reservoirs in volcanic rocks of the Cascades was characterized in the *Oregonian* newspaper as "a secret stockpile of water." U.S. Forest Service and Oregon State University staff viewed the aquifers as unused and a potential supply for future needs, focusing on the economic value. This notion played to the popular but falsely held belief in an unlimited underground reservoir waiting to be discovered and tapped. Hydrogeologists were quick to point out the importance of this already well-known supply to basins on both sides of the range, where it is has been utilized for decades. They noted that the Cascade aquifers periodically suffer from drought and do not constitute a hidden resource.

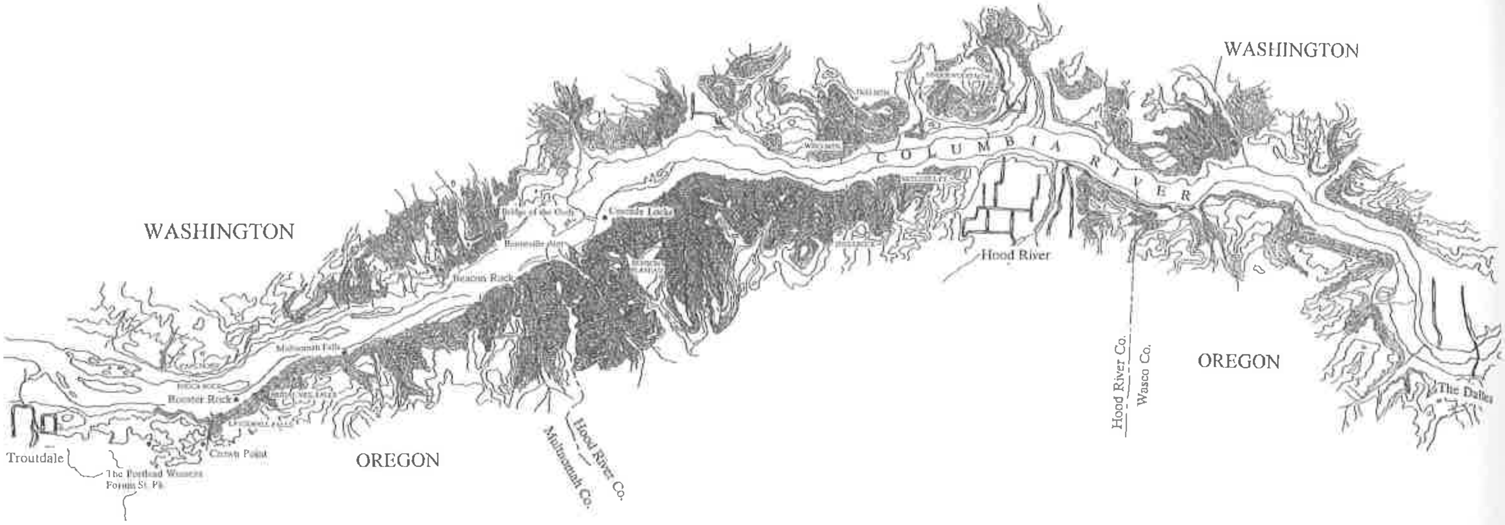
Geologic Highlights

Columbia River Gorge

The best perspective on the inner workings of the Cascade Range can be found in the Columbia River gorge, which cuts through the mountains. Laid bare and swept clean by Ice Age floods, the strata and the multiple ancient channels are revealed.

The gorge comprises 75 miles of geologically spectacular scenery along the Columbia River from the narrows at The Dalles to Portland. Following this route, the Columbia River Highway opened in July, 1915, and was dedicated one year later. The deterioration and abandonment of many portions of the route by the 1940s were rectified in 1986 with the acknowledgment of its historic and picturesque value. Through the efforts of a number of people, the 292,615-acre Columbia River Gorge National Scenic Area was dedicated. One stipulation of the partnership between government agencies was to preserve and restore parts of the original highway for public use.

An early account of the geology by Ira Williams in 1916, was not updated until John Allen's 1984 guidebook *The Magnificent Gateway*. Terry Tolan, Marvin Beeson, and Beverly Vogt offer a Tertiary overview, while 2009 articles by Jim O'Connor and Scott Burns integrate the geology of many sites with impacts of the Missoula floods.



From The Dalles to Portland, the Columbia River is entrenched in a 75-mile-long gorge, famous for its exceptional array of geologic highlights. (After Allen, 1984; Williams, 1916)

Viewpoints Overlooking the River

Formerly named Chanticleer, the promontory at Womens Forum State Park near Corbett rises 925 feet above the river and gives a view of adjacent Rooster Rock and Crown Point to the east, of Mount Zion and Cape Horn directly across the river, and of Beacon Rock a distance upriver.

Observations from Vista House and the cliff at 725-foot-high Crown Point are even more impressive. On the windswept height once known as Thor's Crown, Vista House was the site of the opening ceremony dedicating the Columbia River Highway. The English Tudor-style stone building rests directly on the Priest Rapids intra-canyon flow, the youngest member of the Wanapum Formation (Columbia River basalts), which invaded the gorge some 14 million years ago. The blocky jointed basalt that makes up the cliff is 500 feet thick, covering over 200 feet of older volcanic layers that had filled the channel. Floodwaters from Pleistocene Lake Missoula, cresting at Crown Point, would have enveloped Vista House.

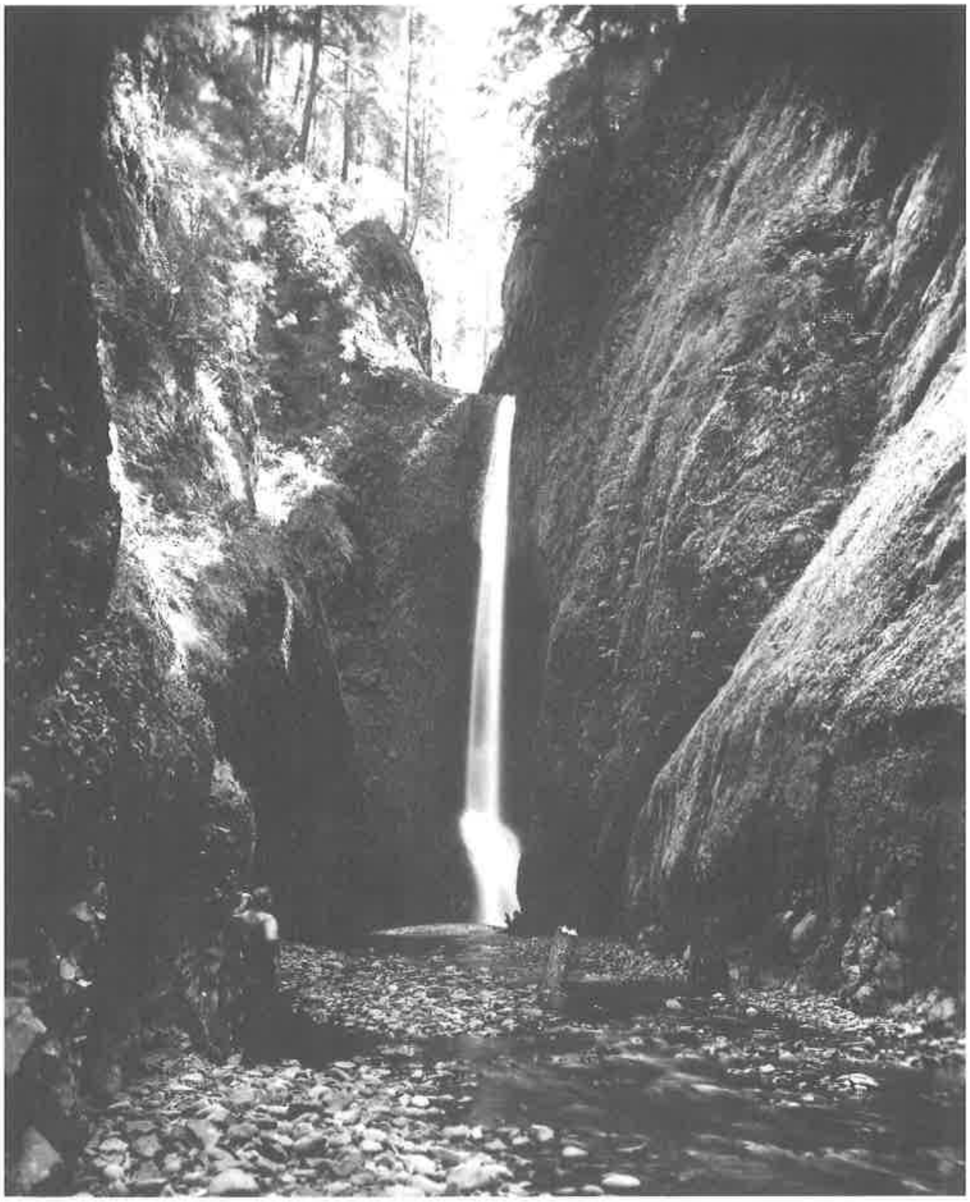
Exposures of the Priest Rapids flow are also prominent at Womens Forum State Park and Shepperds Dell. Pepper Mountain, Larch Mountain, Mount Pleasant, and Mount Zion, cinder cones and volcanic plugs of the Pliocene Boring lavas, are visible for many miles in both directions. Larch Mountain is a low-profile shield volcano.

Born in Seattle, Washington, in 1908, John E. Allen grew up in Eugene where he attended the University of Oregon as a journalism major. Influenced by Edwin Hodge and Warren D. Smith, he completed a Masters on the geology of the Columbia River Gorge before taking a PhD at the University of California, Berkeley, in 1944. His initial job involved field mapping with DOGAMI in the Baker City office. Years of professorships in geology at several institutions led him to Portland State University in the 1950s, where he remained until retirement. His two books on the Columbia gorge are now classics. Allen died in 1996. (Photo taken in 1942; courtesy Geologic Society of the Oregon Country)

Waterfalls

The Columbia River is lined with 71 waterfalls, 11 of which drop over 100 feet. Of these, Multnomah Falls, which is the fourth highest in the United States, is actually two falls, precipitating a distance of 620 feet from a projecting ledge of the Grande Ronde basalts. Elowah Falls at 289 feet, Latourell at 250, Wahkeena at 242, and Oneonta Falls at 221 feet are the next highest.

Waterfalls tend to be temporary, and most of those in the gorge originated during glacial floods between 18,000 to 15,000 years ago. As surging waters stripped away hundreds of feet of basalt from the canyon walls, the streams were left to plunge over the sheer face. Falls most often occur when the lavas are flat-lying, and, after erosion removes



Oneonta Falls, typical of those along the the Oregon side of the Columbia River, is fed by snowfields of the High Cascades. (Photo courtesy Oregon State Highway Department)

the less resistant material between the basalt, the lip gradually retreats. Amphitheater-shaped grottos below form when mist and splashing water penetrate the blocky jointing to freeze and expand, splitting the rock.

Four separate layers of the Columbia River basalts, each with differing erosional properties, have created Multnomah Falls. The steep slopes are not without incident. A fire in 1991 removed the vegetation above the bridge, and a few years later a bus-sized chunk of rock fell, breaking loose a shower of pieces, and injuring 20 people. The U.S. Forest Service has since erected cable nets to protect the public.

Pinnacles and Promontories

Upriver, sharp pinnacles and cliffs project at Rocky Butte, Rooster Rock, and Phoca Rock. Now within the city limits of Portland, Rocky Butte is the core of a late Pleistocene volcano that discharged Boring lavas. The Federal Works Progress Administration built a park on top of Rocky Butte in the 1930s, and the Multnomah County jail was constructed at its base some 10 years later with rock quarried from the east side.

On the north bank near Skamania, Washington, the vertical 850-foot-high column of Beacon Rock is the andesitic basalt plug of an ancient volcano that erupted the Boring lavas only 57,000 years ago.

The layers surrounding the plug were carried away by Missoula floods, exposing the pillar midstream. When Bonneville slide debris engulfed the monolith, the shoreline shifted, and Beacon Rock was effectively transferred to Washington. During the construction of jetties at the entrance to the Columbia River in the early 1900s, the U.S. Army Corps of Engineers proposed quarrying Beacon Rock for use. To that end, they drilled holes into the monolith preparing to dynamite it for the needed stone, before a private investor purchased the landmark.

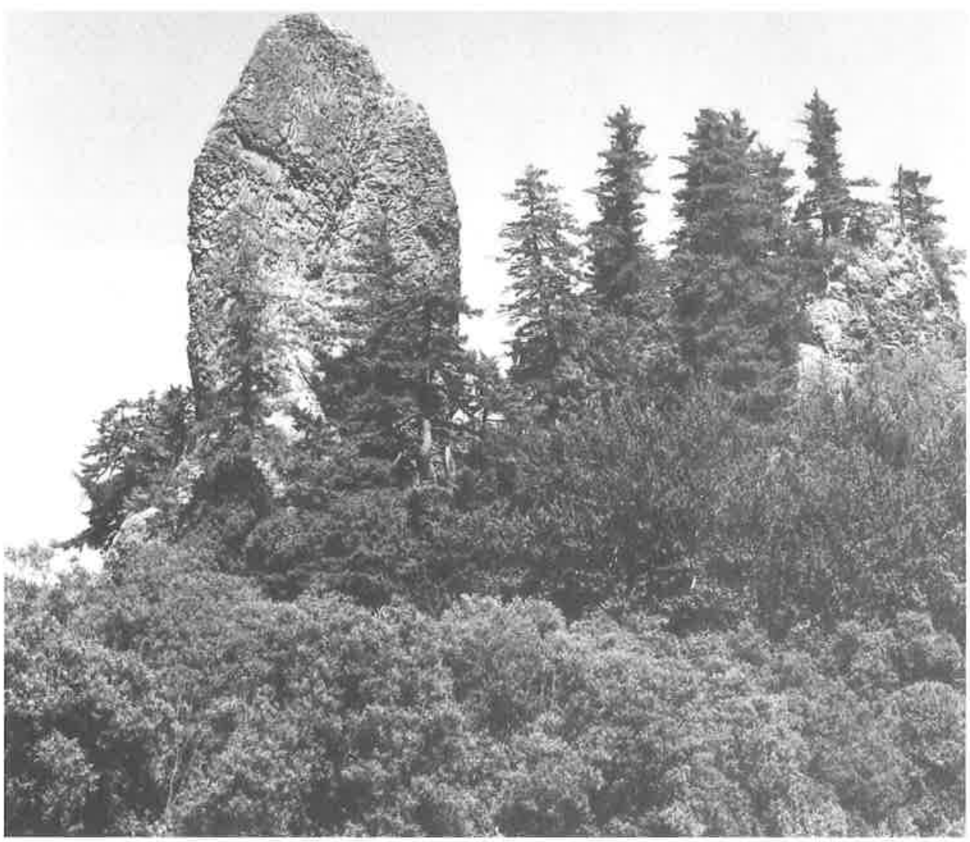
The proposal to demolish Beacon Rock was not unusual, and many of the pinnacles and projections have been removed or modified to make way for highways and railroads. The Pillars of Hercules, two sharp upright columns of basalt between Bridal Veil and Latourell falls, were cut away when the highway was constructed. On the Washington side, Cape Horn, a steep promontory near Mount Zion, was destroyed to make way for the highway and railroad tunnel. Tunnels were bored through the Tooth Rock landslide block at Eagle Creek as well as through the overhanging Mitchell Point basalt cliff west of Hood River.

Mountain Peaks

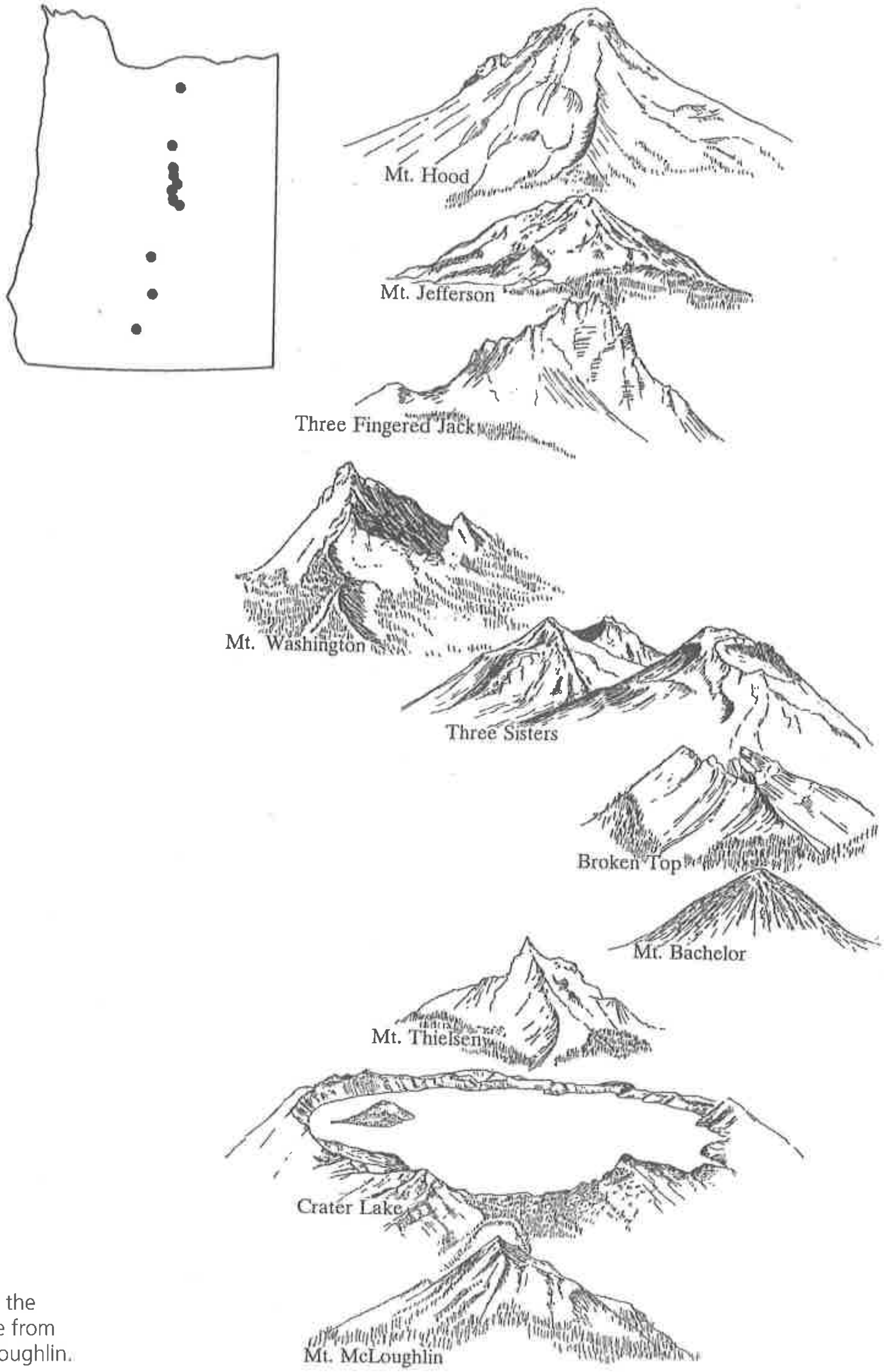
The High Cascades offer a variety of majestic peaks, dazzling glaciers and snowfields, forested slopes, cold streams, lakes, and waterfalls. While the crest of the range averages just over 5,000 feet in altitude, a number of conical summits, which rise considerably higher, are more conspicuous than the older eroded spires.

Stephen Harris's *Fire and Ice* provides an invaluable overview of all Cascade volcanoes from California to Canada, while Raymond Hatton's *Oregon's Sisters Country* gives a very readable account of the history and geology. Fieldtrip guides by Edward Taylor, Richard Conrey, and University of Oregon geologist Katharine Cashman examine different aspects of volcanic activity including the widespread Quaternary cover.

Most areas of the High Cascades attract climbers, but Mount Hood, with its proximity to Portland, has long presented a challenge. Joel Palmer, Territorial Commissioner of Indian Affairs, was the first reported to have scaled the south face in October, 1845, reaching around 9,000 feet before turning back. Three years later, newspaperman



The monoliths of Rooster Rock (left) and Phoca Rock are believed to have been moved by a large landslide activated when Missoula flood waters undercut cliffs along the Columbia River. Rising 200 hundred feet, Rooster Rock and the surrounding acreage were purchased for $10,000 as a state park in 1938. Lying nearby in the middle of the channel, Phoca Rock was so named because seals (phocids) rested here on their way upriver. (Photo courtesy Oregon State Highway Department)



Significant volcanic peaks of the Oregon High Cascade Range from Mount Hood to Mount McLoughlin.

Henry Pittock with a party of six placed a flag on the top. Many who ascend Mount Hood fail to heed weather conditions or take safety measures, and 20 lives have been lost over the last decade, although many others have been rescued.

Facing Mount Adams and Mount St. Helens across the Columbia River, Mount Hood was named for Samuel Hood, an officer in the British Royal Navy, who was stationed off the Northwest coast during the American Revolution. At 11,235 feet in elevation, it is the highest of Oregon's Cascade mountains, the prominent summit serving as a reminder to travelers that their epic journey to the Willamette Valley was coming to an end.

Named Faith, Hope, and Charity in the 1940s, the Three Sisters are pitted with small glacially cut

Mount Washington and Three-Fingered Jack both reach close to the same elevation at 7,800 feet, both are composite volcanoes, and both have been glacially carved into horns. Built on thin lava flows, the central conduit of Mount Washington was intruded by a large resistant plug that projects as a spire on the horizon. Looking toward the south in the photo, the saw-toothed ridgeline of Three-Fingered Jack, which consists of loose tephra covering a dike, is in the foreground with Mount Washington and the Three Sisters behind. Broken Top and Mount Bachelor are in the back on the left, and Mount Thielsen is in the background on the right. (Photo taken by D. Rohr; courtesy Condon Collection)

ravines, crevasses, and ridges. Within the Three Sisters volcanic cluster, the South cone is the highest at 10,354 feet, but the 10,182-foot-high North Sister is the oldest and most deeply eroded with no evidence of a central crater. The South Sister is the best preserved with a circular summit crater, in which snow-melt forms a small lake during the summer. Ice has been persistently cutting away at the Three Sisters, leaving sharpened crests and cirque valleys. Established in 1957, the Three Sisters

A series of flows and domes around the rim of Crater Lake reveal the different eruptive stages of Mount Mazama. Prior to the final explosion, the cone is estimated to have been between 10,000 and 12,000 feet above sea level, but today the caldera rim averages 8,000 feet in elevation. At 8,929 feet, Mount Scott is the highest point along the rim. (Acoustic backscatter map of Crater Lake, U.S.G.S., 10 m DEM, 2002)

Overshadowing Diamond Lake, Mount Thielsen is distinguished by its needle-like plug, evidence of the erosive force of ice that scalloped its north side. In this view looking to the east, Summit Rock is to the right, and the spire is to the left. Diamond Lake was constructed when lava from Mount Thielsen blocked a basin already deepened by Pleistocene ice. (Photo courtesy Oregon State Highway Department).

Wilderness covers 287,000 acres and is under federal protection.

Closest to Oregon's southern border, Mount Thielsen and Mount McLoughlin both average just over 9,000 feet in elevation. Mount McLoughlin, which is the highest between the Three Sisters and Mount Shasta, has had many designations in its past. Once called Snowy Butte or Big Butte, the peak became Mount Pit in 1842, a name derived from the many pits dug by Indians to trap game. It was subsequently named for John McLoughlin, director of the Hudson's Bay Company.

Mountain Lakes

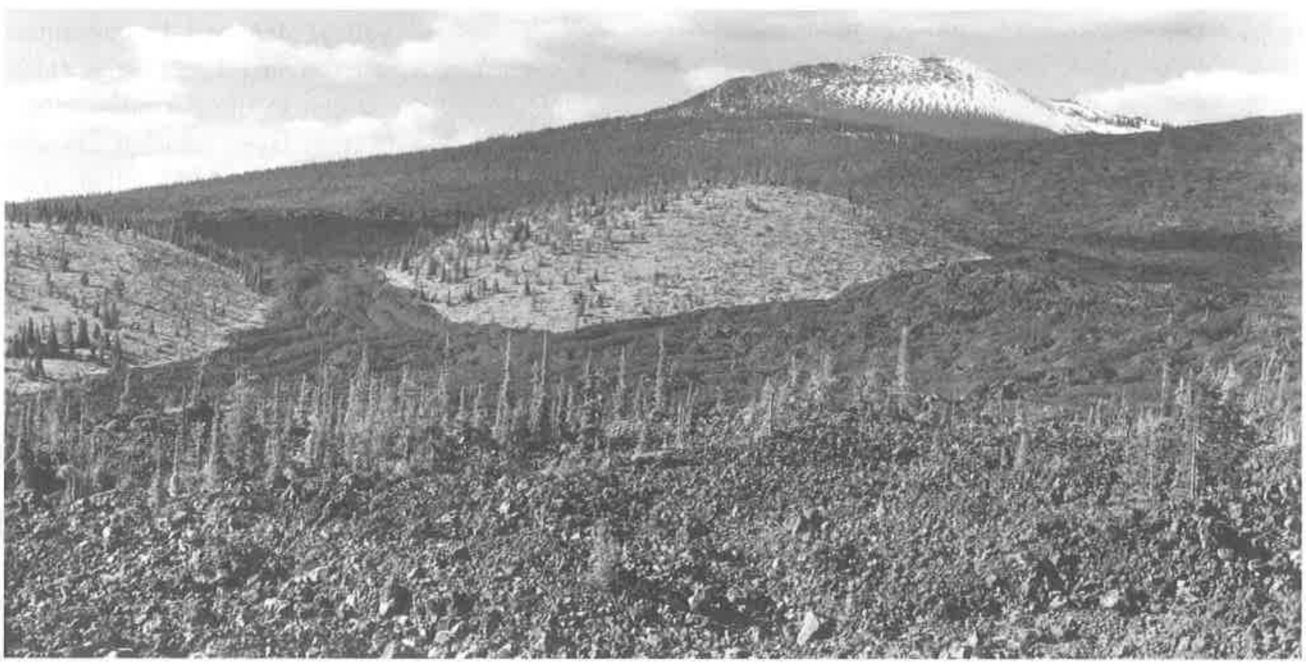
The wealth of lakes in the Cascade Mountains is the product of several geologic processes. Landslides, lava, or glacial till block and alter stream flows, while rainfall and snow melt may fill a basin or caldera. Lakes dammed by lava or glaciers are the most numerous in the Oregon Cascades, where volcanic eruptions and ice interacted during the Pleistocene.

Oregon's most celebrated is Crater Lake, a caldera that filled after the volcanic explosion and collapse of Mount Mazama 7,700 years ago. The symmetrical basin containing the lake today is five miles in diameter with a depth of one mile, making it the deepest fresh-water body in the United States and the second deepest in North America. The crater, lake, and surrounding 183,180 acres in Klamath County were dedicated as Crater Lake National Park in 1902.

North of Crater Lake, Diamond, Crescent, Odell, and Waldo lakes are among the many that lie in glacially scoured valleys dammed by moraines. With a surface area exceeding 3,582 acres, Odell Lake is one of the largest in the Cascades. When a terminal moraine from layers of High Cascade ice blocked Odell Creek, the basin filled with melt-water. The formation of Crescent Lake was similarly due to glacial activity. Lying in the same valley as Suttle Lake but of volcanic origin, Blue Lake is relatively small but one of Oregon's deepest at over 300 feet. The depth gives the water its unusual blue color. The lake resulted from a violent explosion when magma encountered groundwater around 3,500 years ago.

In the central portion of the range, the spread of basalt from the Sand Mountain-Nash Crater chain altered the flow of streams. This linear field of 23 cinder cones and 41 separate fissures and vents discharged nearly a cubic mile of lava and ash, blocking the McKenzie River to impound Lava Lake, Fish Lake, and Clear Lake. Sahalie and Koosah falls drop

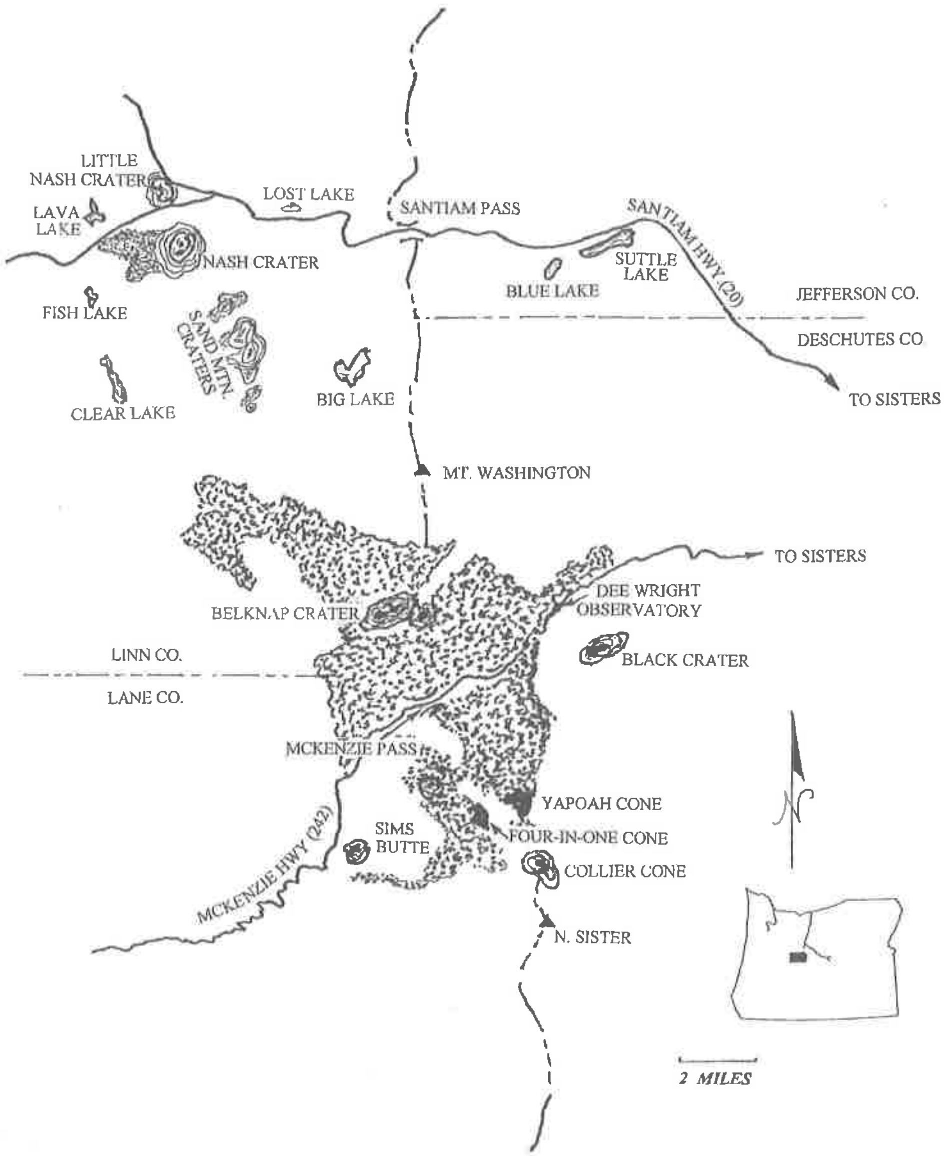
Near Highway 20, the popular Suttle Lake had its beginnings when glacial moraines of ice and rock impounded Lake Creek. The long, narrow outlines and depth of the lake reflect its origins in a glacially carved valley. The composite cone of Black Butte is in the background. (Photo courtesy Oregon State Highway Department)



In this view toward the west from Dee Wright Observatory, Belknap shield is on the horizon, and rubble from the Yapoah eruption is in the foreground. The stone observatory was built by the Civilian Conservation Corps in 1935 and named for the person who spent many years working there. (Photo courtesy Oregon State Highway Department) over a resistant lobe of the basalt. At Clear Lake, an entire forest was submerged. Radiocarbon dates from upright *ghost* trees, visible in the depths of the unusually clear water, have pinpointed the time at 2,750 years in the past. Successions of diatoms living in the lake deposited a snow-white layer on the bottom. Fed by cold springs, Clear Lake is the source for the McKenzie River.

Recent Volcanic Eruptions

The central High Cascade region is essentially a Quaternary volcanic platform of overlapping cones, flows, and volcanoes. Here an interval of very recent volcanism emplaced dark cindery fields between 3,850 to 1,500 years ago from the Sand Mountain-Nash Craters, Yapoah Crater, Collier Cone, Four-in-One vents, and Belknap shield cone.



Lava fields along the Santiam and McKenzie highways provide one of the best places in western Oregon to see a fresh volcanic cover. From the summit of McKenzie Pass at Dee Wright Observatory, the desolate landscape has been created by blocky Yapoah basalts, Belknap flows, and the Four-in-One vents. Reaching 500 feet above the surroundings, Yapoah Crater is mantled by red cinders. Nearby, the Four-in-One cones, aligned in a northwest-southeast direction, were initially active along a one-half mile fissure but subsequently concentrated at four conduits.