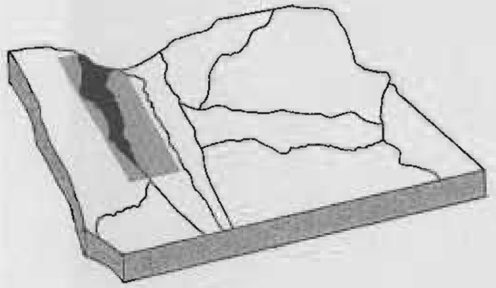
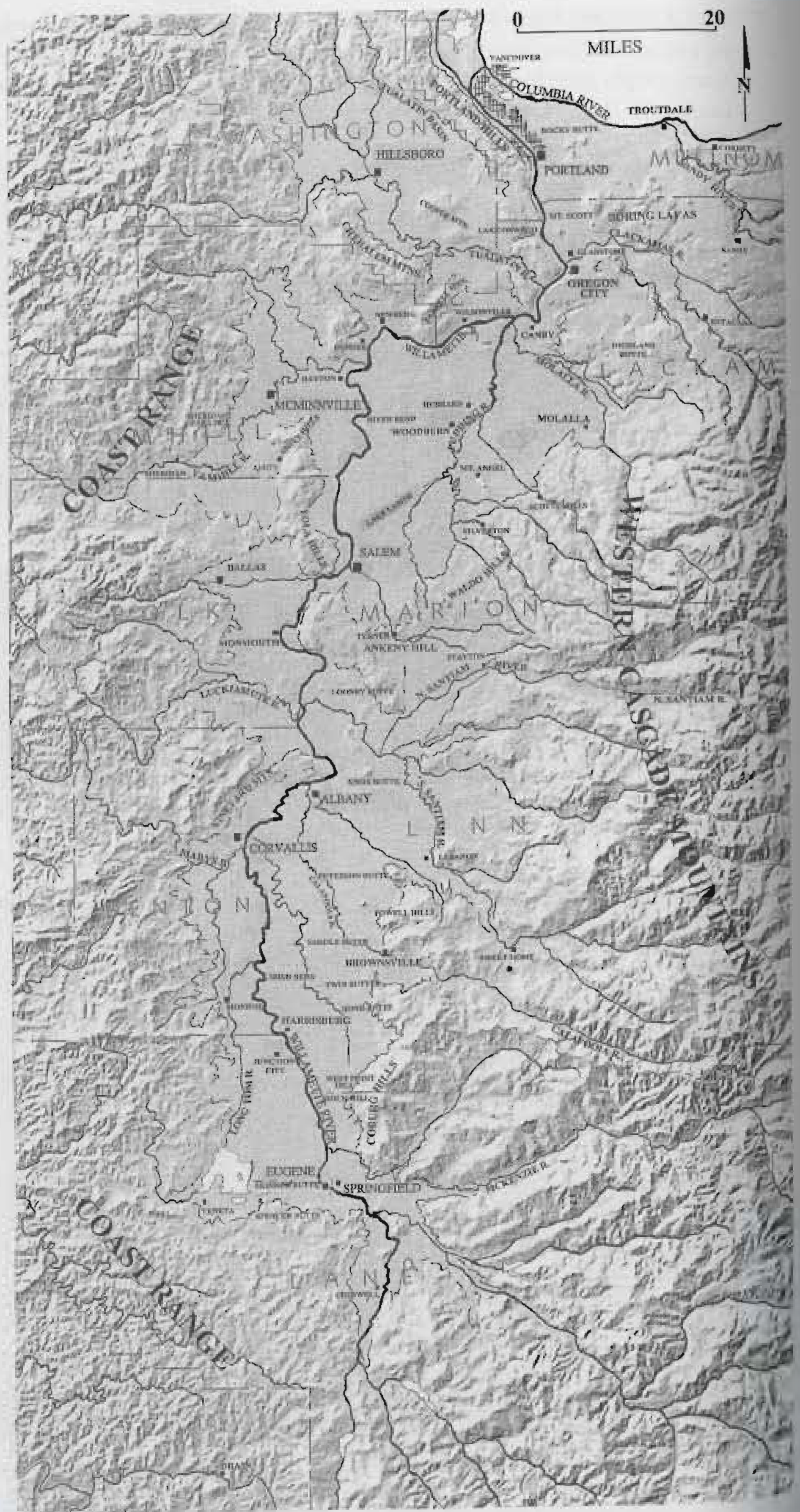




Physiographic map (After Loy, et al., eds., 2001)

Willamette Valley

Landscape of the Willamette Valley

The Willamette Valley and Puget Sound lowland stretches from Cottage Grove, Oregon, to British Columbia in Canada. In Oregon, the Willamette Valley is an elongate basin which narrows at either end before pinching out. Enclosed on the west by the Coast Range, on the east by the Cascade Mountains, and to the north by the Columbia River, the basin is approximately 130 miles long and up to 40 miles wide. From an elevation of 400 feet at Eugene, the surface drops close to sea level at Portland, an average gradient of only four feet per mile.

Contrasting topography divides the Willamette Valley into northern and southern regions at Salem. For the most part, the southern portion is nearly featureless, distinct from the hilly terrain in the north. Near Salem, the Eola Hills lie to the west, the Ankeny Hills are to the south, and the Waldo Hills to the east. The Tualatin basin is separated from Portland by the Portland Hills and from the Willamette Valley by the Chehalem Mountains. Smaller topographic projections on the valley floor include volcanic cones and buttes around Portland and Oregon City and from Brownsville to Eugene. Near the center of the province, the 45th parallel, halfway between the equator and the North Pole, passes close to Salem.

The Willamette Valley is a lengthy alluvial plain of the river, whose watershed drains 11,200 square miles. Originating at the junction of its Coast and Middle forks near Eugene, the Willamette River meanders toward the north to enter the larger Columbia system at Portland. The overall gradient is northward and not from the margins toward the center, making it one of the few rivers in the United States to flow in that direction.

South of Albany, tributary streams parallel the main Willamette channel for a distance before merging. The McKenzie, Calapooia, North and South Santiam, Pudding, Molalla, and Clackamas rivers have their headwaters in the Cascade Mountains, while the Long Tom, Marys, Luckiamute, Yamhill, and Tualatin rivers drain the Coast Range.

Although comparatively small, the Willamette Valley is the economic and cultural heart of Oregon. Supporting 70 percent of Oregon's population, a preponderance of the industry, and a varied agriculture, the province boasts fertile soils, generous rainfall, and a mild climate.

Past and Present

In conjunction with westward explorations, an examination of Pacific Northwest geology began indirectly with the Lewis and Clark expedition, commissioned by President Thomas Jefferson in 1803. With the purpose of furthering that knowledge, fifty years later the U.S. Congress authorized railroad surveying parties that included mineralogists and geologists. After the Civil War, the newly created U.S. Geological Survey initiated the westward search for mineral and fuel resources.

In the mid 1800s, Thomas Condon began an informal study of the regional geology and paleontology while stationed at The Dalles as a missionary. His interest and collections from the John Day fossil beds of central Oregon caught the attention of nationally known paleontologists. After his appointment as state geologist and later as professor at the University of Oregon in 1876, along with his book *The Two Islands*, Condon led the development of the science in the state. He died in 1907 at Eugene.

Chairman of the Geology Department at the University of Oregon from 1914 until 1947, Warren D. Smith participated in the early growth of geology in the state for 33 years. He saw the department through the emotional transfer of the sciences to Oregon State College (University) at Corvallis in the 1930s and experienced the turmoil that World War II brought to education. Because much of Oregon's geology was largely unknown when he arrived, Smith was called on to participate in many aspects of land-use, mineral identification, and paleontology. In addition to popularizing the state's scenic geology, he felt that one of his primary jobs was to provide the public with accurate information on geologic issues which surfaced. Politically active, Smith assisted in creation of the Oregon Department of Geology and Mineral Industries. He died in Eugene in 1950, three years after retirement. (Photo taken around 1930; courtesy Condon Collection)

Edwin T. Hodge also had to deal with much of Oregon that was still unmapped territory in the 1920s and 1930s. In that role, he was a consultant for government agencies on regional projects such as placement of the Bonneville Dam. His diverse interests included mineral resources and stratigraphy of the lower Columbia River and Cascades. Teaching at all three major institutions in the state at various times, Hodge, along with Ira Allison and William Wilkinson, was one of the initial faculty members of the new Geology Department at Oregon State College (later University) in 1923. As an outgrowth of his classes, he organized the Geological Society of the Oregon Country in 1935. Hodge died in 1970 at 81 years of age. (Photo taken in 1942; courtesy Geological Society of the Oregon Country)

Overview

The Willamette Valley and Coast Range had their beginnings as part of a wide continental shelf along the western margin of North America, where the two provinces shared closely related environments and sediments. The older foundation rocks are part of a volcanic island terrane, Siletzia, that developed in the Pacific Ocean basin. Colliding and accreting with the continental landmass, Siletzia subsequently subsided and was blanketed with layers of fossil-rich sediments from the late Eocene through the Oligocene. Uplift and tilting of the Coast Range in the late Cenozoic accompanied subsidence of the Willamette Valley into a lengthy structural trough, in which ocean waters shallowed and gradually retreated northward. By the middle Miocene, the Columbia River lavas, which spilled across from eastern Oregon, invaded the valley as far south as Salem.

The face of the valley was thoroughly reworked by events of the Pleistocene Epoch. A setting of tranquil lakes, meandering streams, and swamplands shifted to a more turbulent environment as torrential melt waters of the ancestral Columbia River and Cascade streams built great alluvial fans and gravel terraces atop the older bedrock. In the Willamette basin, thick silts were left by catastrophic floods, which originated from ice-dammed lakes in Montana. Once the ice blockage was breached, rushing flood waters cascaded across Idaho, southeastern Washington, and through the Columbia gorge, backing up into the Willamette Valley and forming the temporary Lake Allison. The multiple floods ceased when the climate warmed.

Lacking significant mineral wealth, the Willamette Valley boasts a plentiful supply of ground and surface water as its most valuable asset. This resource, the Willamette aquifer, has fostered the province's rapid growth and population. On the other hand, the basin experiences its share of natural geologic hazards. A surplus of rainfall brings flooding and landslides, while movement along the many faults intersecting the valley results in damaging earthquakes. Though not well understood, seismic activity originating along the offshore Cascadia subduction zone could prove even more destructive.

Geology

Cenozoic

Paleocene to Eocene

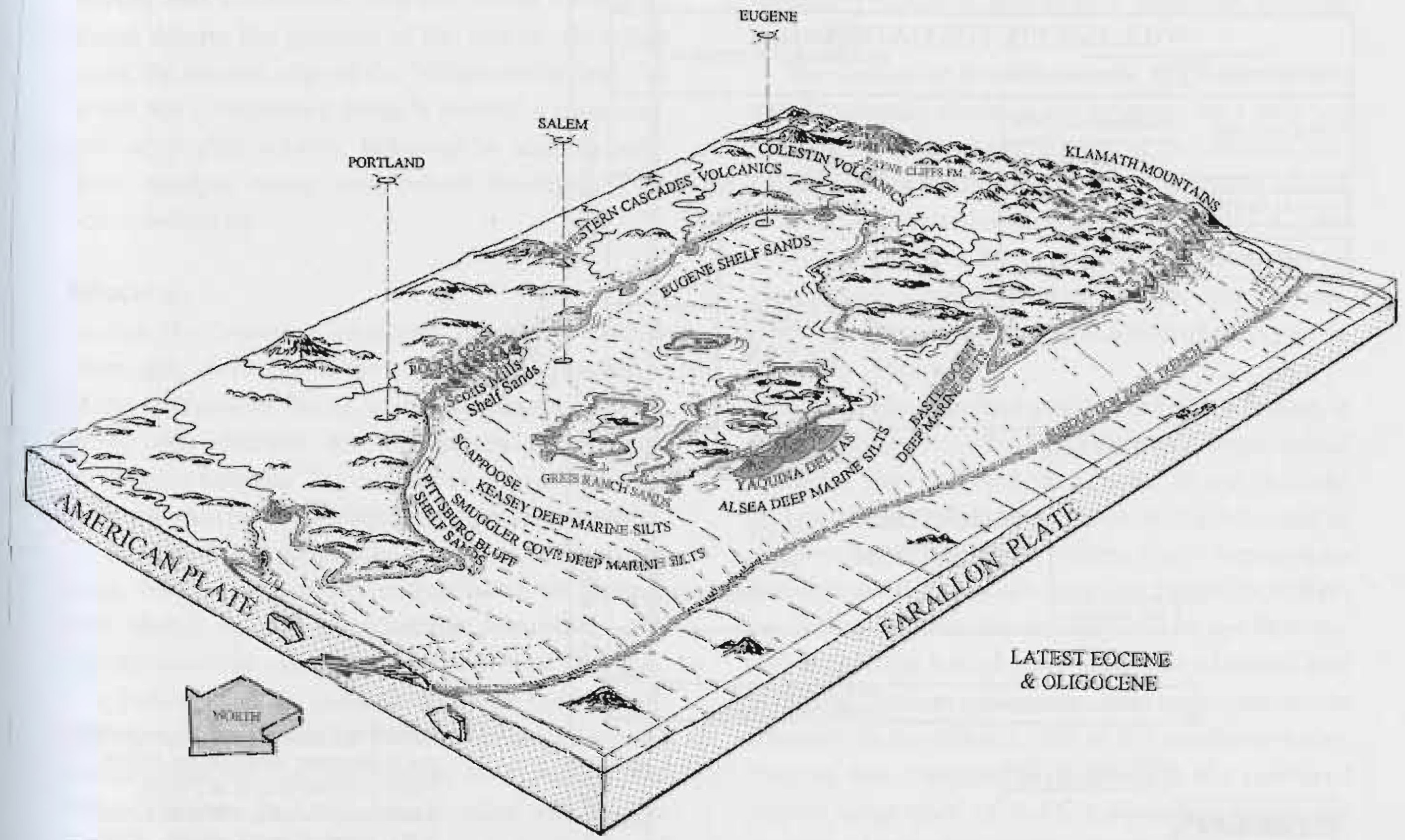
The Willamette Valley has played a somewhat passive role against the backdrop of moving tectonic plates. During the Paleocene to early Eocene, 60 million years ago, a chain of volcanic seamounts (Siletzia) carried atop the Farallon plate, were accreted to western North America. After the docking or initial contact, the Siletzia terrane began to slide beneath the continent and rotate into position, subsiding into a marine forearc trough west of the emerging Cascade volcanoes.

From the Eocene to the late Oligocene, copious sediments spread over the Siletzia volcanic plateau, which was to become the Willamette Valley and Coast Range. Consequently, rocks of the valley are continuous with those of the coastal province. The oldest are 15-mile thicknesses of submarine Siletz River Volcanics, which are covered by deep-water mica-rich sandstones and siltstones of the Tyee Formation. Tyee strata form a shallow delta at the southern end of the shelf near Roseburg and a larger deep-sea fan toward Salem. Although the Klamath Mountains supplied much of the sediment, there is evidence that an additional source lay well to the east.

Muds, sands, and silts of the Yamhill Formation, named by Ewart Baldwin, mixed with ash from the Western Cascades and were carried into the shallow seaway to overlap the Tyee. Within the Yamhill, shoals around offshore banks of the Rickreall and Buell limestones in Polk County hosted warm-water mollusks, foraminifera, and plants. These fossils, along with plant fragments, confirm a shelf setting close to a wave-washed beach.

Westward from Benton, Polk, and Lane counties, deep-water contrasts with the shallow marine and shoreline Yamhill conditions. In this environment, mollusks in sandstones of the Spencer Formation trace a flat, open continental shelf some distance from the shore. These strata are covered by nonmarine volcanic tuffs, sands, and conglomerates of the Fisher Formation. Plant imprints, preserved in the Fisher near Cottage Grove, reflect a warm, moist tropical climate where *Cinnamomum* (camphorwood), *Ficus* (fig), *Ocotea* (lancewood), and the broad-leafed *Aralia* grew adjacent to a coastal plain or a lakeside setting. Fisher deposits are overlain by the Little Butte volcanics.

Beneath the community of Eugene and northward toward Salem, almost a mile thickness of upper Eocene to Oligocene shallow marine and nonmarine sandstones and siltstones of the Eugene Formation entomb a varied assemblage of mollusks, crabs, sharks, and plants. The interpretation of this formation has evolved through multiple revisions in age and environments, but in the 2000s Donald

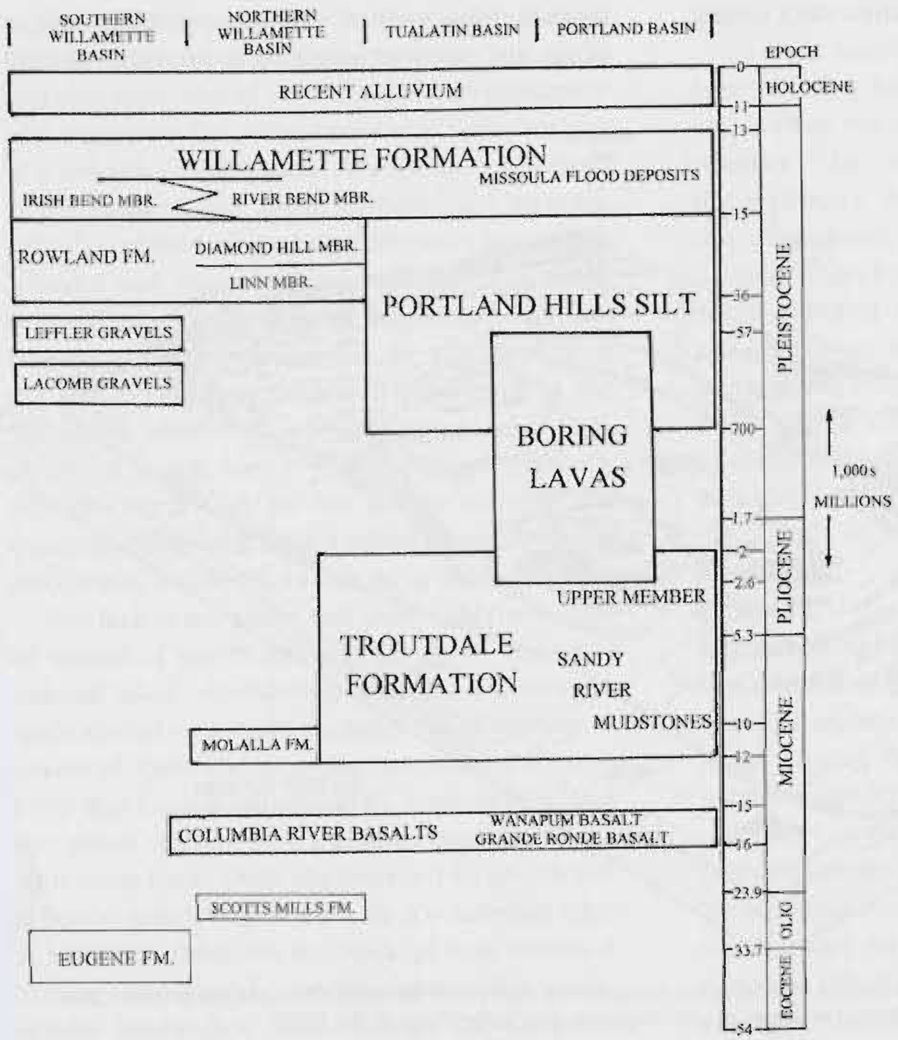


From the late Eocene to early Oligocene, a shallow tropical ocean occupied the southern Willamette Valley and the present Coast Range, before it was replaced by cooler climate conditions of late Oligocene time. (after Orr and Orr, 2009)

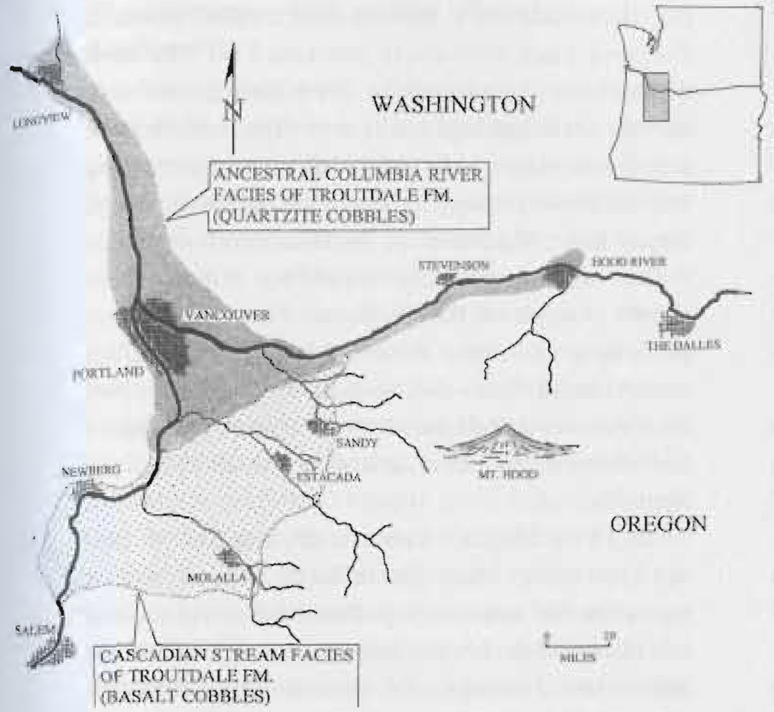
Prothero at Occidental College examined and revised many of the Pacific Northwest rocks using magnetic stratigraphy and biostratigraphy. Focusing on the timing of extinctions and the accompanying paleo-climatic changes on land and in the ocean, paleontologists at the 1999 Penrose Conference moved the Eocene-Oligocene boundary upward almost 4 million years from 38 to 33.7 million years ago. Their conclusions were published in the book *From Greenhouse to Icehouse*, edited by Prothero, who continues to adjust ages and rock correlations locally as well as internationally when new techniques emerge.

Oligocene

A gradual shift from a tropical to cool-temperate climate worldwide brought the demise of many species at the end of the Eocene. Locally the extinction of plants reached 60 percent with a corresponding 32 percent for marine invertebrates. Coinciding with cooling, the warm subtropical flora was replaced by temperate Oligocene plants while invertebrates continued to decline as the ocean withdrew from the valley. The faunal changes were noted as far back as 1968 by University of California paleontologist Carole Hickman, and in 2003 she concluded that in Oregon the climate alteration matched the onset of Cascade volcanism. A later overview paper by Greg Retallack at the University of Oregon, which also examines extinction rates and paleoclimates, recorded a similar loss of diversity for invertebrates and plants of the Eugene Formation by the early Oligocene, attributing it to long-term processes such as coastal uplift and shifting ocean temperatures rather than to meteorite impacts or volcanic eruptions.



Tertiary to Quaternary stratigraphy of the Willamette Valley. (After Allison, 1953; Armentrout, et al., 1983; Balster and Parsons, 1969; Beaulieu, 1971; Gannett and Caldwell, 1998; Glenn, 1965; Mc Dowell, 1991; O'Connor, et al., 2001; Roberts, 1984)



Terry Tolan, Marvin Beeson, and Beverly Vogt recognized two facies of the Troutdale Formation, each reflecting variable sources. Pebbles and cobbles of quartzite, schist, and granite transported by the ancestral Columbia River from the northern Rockies have origins in the Precambrian Belt series, whereas the high-alumina basalt sands and gravels of the Cascadian layer were derived locally from the Cascades and Boring lavas. The photograph is a close-up of the exotic quartzite conglomerate cobbles. (After Tolan, Beeson, and Vogt, 1984; Trimble, 1963; Wilson, 1998; photo courtesy Oregon Department of Geology and Mineral Industries)

Regional uplift by the late Oligocene caused the ocean to retreat. In the vicinity of Silverton in Marion and Clackamas counties, Scotts Mills sediments denote the position of the marine shoreline along the eastern edge of the Willamette Valley. The Scotts Mills Formation initially records a transgressive advancing seaway, followed by storm conditions, shallow water, and coastal swamps as the ocean withdrew.

Miocene

During the Miocene, between 23 and 5 million years ago, elevation of the coast range, subsidence of the Willamette Valley, and the invasion by lavas profoundly changed the topography and climate of western Oregon. The ocean continued to recede until the shoreline was close to its present position.

Sheets of dark Columbia River basalts, pouring from fissures and vents in northeastern Oregon and Idaho, crossed the Cascade Mountains and spread over the valley floor to depths of 600 feet. The basalts underlie most of Portland, the Tualatin Valley, and the northern Willamette basin, as well as mantling the uplifted Waldo, Eola, Amity, and Salem hills, the Red Hills near Dundee, and the Tualatin highlands. Near Portland the layers produced a monotonous flat surface with only the highest peaks projecting above the flows. In western Oregon's wet climate, the basalts began to decompose rapidly, yielding a thoroughly dissected volcanic landscape.

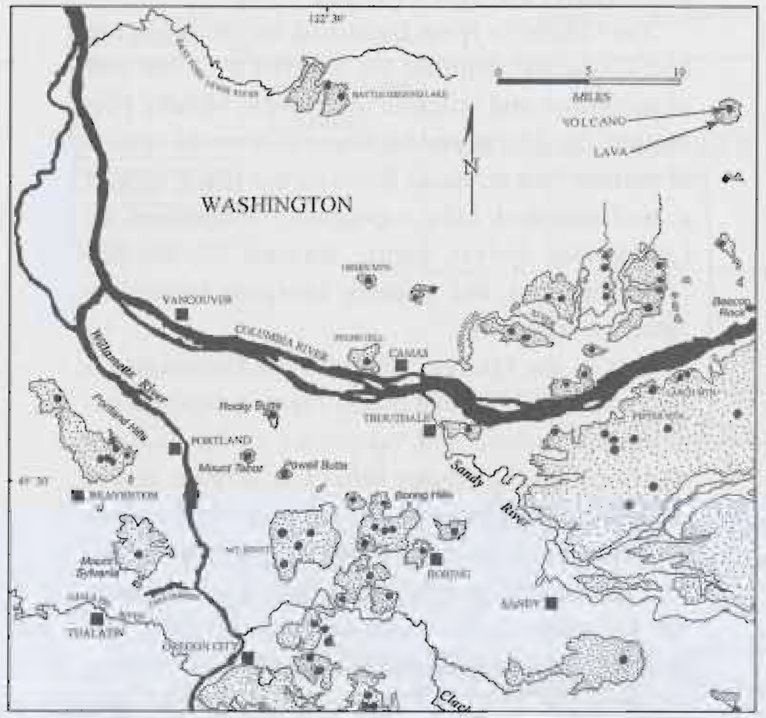
The Columbia River Basalts in northern Marion and Clackamas counties are covered by 1,000 feet of mudflows and volcanic tuffs of the Molalla Formation, the first terrestrial deposits after the retreat of marine waters. Fossil floras in the strata suggest a well-dissected hilly topography dominated by *Liquidambar* (sweet gum), *Platanus* (sycamore), *Carya* (hickory), and swampy lowlands favored by *Taxodium* (cypress).

Late in the Miocene and into the Pleistocene, a series of fault-bounded blocks created depositional basins at Portland and Vancouver, in the Tualatin and northern Willamette valleys, at Stayton, and in the southern Willamette Valley. These depressions are separated from each other by ridges underlain by Columbia River basalt. Because of the barriers, the individual basins have different histories and multiple sediment sources, making correlations between them difficult. Fill in the southern valley may be one continuous unit, but in the northern region sequences of thick nonmarine strata are present. Here the Sandy River Mudstone and gravels of the Troutdale Formation reach depths of 1,000 to 1,500 feet atop the Columbia River Basalts.

The Sandy River Mudstone and Troutdale Formation were thoroughly eroded by streams, before being perforated and covered by Boring lavas and late Pleistocene silts and sands. In 1933 Edwin Hodge named the combined strata as the Troutdale Formation, but in his classic 1963 publication on the geology of Portland Donald Trimble of the U.S.G.S. assigned the Pliocene conglomerates in the upper portion to the Troutdale and the underlying fine-grained Miocene to Pliocene layers to the Sandy River. Exposures of the mudstones along the Sandy and Clackamas rivers have been traced south to Estacada and Oregon City. Originally interpreted as a lake setting, the sediments are now regarded as predominantly fluvial in origin.

Cores drilled at Tualatin in Washington County and near Monroe in Benton County yielded lake sediments dating back to the middle Tertiary. Because of its population density and geographic position, the Tualatin basin has received considerable attention. In 1967 Herb Schlicker published on the sedimentary history, and Doyle Wilson at Portland State University presented an overview of its geologic evolution in 1998. He reported that the surrounding highlands were the main source for the Tualatin Valley fill, informally renaming the previously mapped Troutdale Formation and Sandy River Mudstone as the Hillsboro Formation. Pollen of Cupressaceae (cypress), which make up 45 percent of the Hillsboro flora, with lesser percentages of *Pinus*, *Alnus* (alder), *Salix* (willow), and *Abies* (fir), in conjunction with the diatoms *Aulacosira* and *Melosira* allowed Wilson to assign a late Miocene to Pliocene age to the alkaline lake deposits.

In 1976, Michael Roberts, then at Simon Fraser University, identified a large lake of similar age after he examined pollen from conifers and broad-leafed deciduous trees recovered from cores drilled into a terrace near Monroe. The oldest unit encountered was the Eocene Spencer Formation, overlain by an organic-rich clay that may correlate with the Sandy River Mudstone, and an uppermost Pleistocene gravel.



Between 2.6 million and 50,000 years ago, a volcanic field of Boring lavas enveloped Portland and vicinity. Named for a small town in Multnomah Co... the flows extend westward to the Portland-Vancouver metropolitan area, south to Highland Butte, and southwest to Mount Sylvania near Beaverton. Among the most prominent are Rocky Butte, Mount Tabor, Powell Butte, and Mount Scott. Battle Ground Lake, filling a pronounced depression north of Vancouver, is an intact maar that formed from a violent explosion when rising magma encountered cooler groundwater. In the map on the right, the buttes are east of Portland (After Allen, 1975; Evarts, et al., 2009; Peck, et al., 1964; Trimble, 1963; photo courtesy University of Oregon)

Pleistocene—Volcanism, Floods, and Sediments

Because of continued subduction of the Juan de Fuca plate, uplift and gentle folding of the coastal mountains, and subsidence in the Willamette Valley during the Pliocene and Pleistocene, the province emerged as a separate physiographic region, no longer part of a wide coastal plain.

Volcanism in the Portland-Vancouver metropolitan area commenced 2.6 million years ago with eruptions from over 80 small cones, vents, and shield volcanoes. Merging to the east with the High Cascades, the Boring lava field is located in the forearc region. Its unique positioning with relation to the Cascades and the origin of the eruptions, while still unclear, indirectly relate to the mechanics of plate subduction. Following a hiatus lasting almost a million years, activity was resumed as the Boring lavas became widely dispersed, were more variable in composition, and were roughly continuous until 50,000 years ago. The youngest cones are in the north part of the field, and the oldest toward the south. The fine-grained texture and fracture pattern of the lavas, which weather into large blocks, readily distinguish them from the much older Miocene Columbia River basalts, in which small columns are common. In a 2009 paper, Russell Evarts of the U.S.G.S. addresses the possibility of future eruptions from the Boring cones, which he considers to be very low.

Portland Hills Silt

Interfingering with the Boring lavas around Portland and Tualatin, the gritty, fine, yellowish-brown Portland Hills silt was deposited from 700,000 to 15,000 years in the past. Commonly 25 to 100 feet thick, the silts cover much of the higher elevations from the Tualatin and Chehalem mountains all the way to Gresham and Boring. Microscopically, the silt is remarkably uniform, and its physical characteristics match the wind-blown (loess) Palouse sediments of southeast Washington. During dry interglacial periods, fine rock flour, ground up by the crushing and milling action of ice, was carried aloft in enormous clouds and distributed across the Columbia River basin by strong winds. Four different loess intervals mark interglacials, while soil horizons separating the silts indicate times of glacial advance.

River Deposits

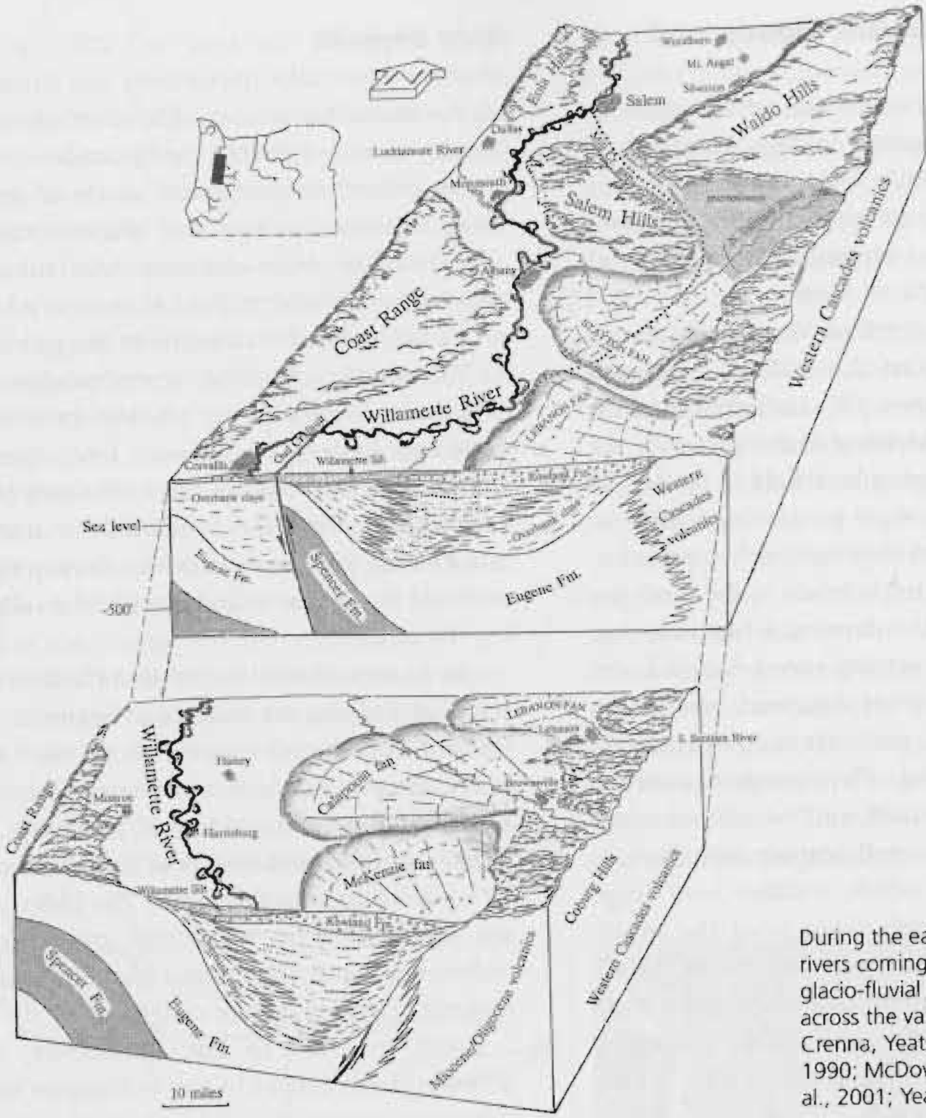
Shallow-water lake (lacustrine) and stream (fluvial) environments in the Willamette lowlands were heavily modified during the Pleistocene when the rivers and tributaries spread sheets of gravel and sand, constructing fans and terraces throughout the area. The older deposits were subsequently covered by Willamette Formation silts, which were deposited by flood waters late in the epoch.

The stratigraphy and geomorphology of the Willamette Valley were studied extensively by early researchers Ira Allison, Jerry Glenn, and Donald Trimble, while in the 1990s and 2000s Jim O'Connor of the U.S.G.S. revised the stratigraphy and Patricia McDowell at the University of Oregon outlined the problems and complexities of correlating the units.

An examination of the earliest Pleistocene landscape underlying the valley was begun in 1969 by Clifford Balster and Roger Parsons with the U.S. Soil Conservation Service to determine the relationship between the older soil and rocks and the overlying fluvial debris. These authors recognized 15 separate geomorphic units. The oldest surfaces are represented by weathered gravel and mud pediments, signifying various phases in the development of ancestral river systems.

From the mid to late Pleistocene, massive sediment loads carried by the Willamette River and tributaries constructed high glacio-fluvial terraces that today are preserved around the margins of the basin and along river channels. In his landmark 1953 publication on the Albany Quadrangle, Ira Allison produced a definitive stratigraphy of the units, dividing them from oldest (highest) to youngest (lowest)—the Lacomb, the Leffler, and the Linn. Composed of sediments from the Cascades to the east and the Coast Range on the west, gravels and muds of the Lacomb and Leffler terraces stand 100 to 300 feet above the valley floor. Extensively eroded or obscured by later deposits, only small exposures of these terraces remain.

Tectonic subsidence and renewed downcutting by the Willamette River preceded deposition of the 200-foot-thick Linn gravels, which occupy much of the valley floor. Representing glacial outwash, the Linn was flushed from the Cascades and distributed as a complex series of coalescing alluvial



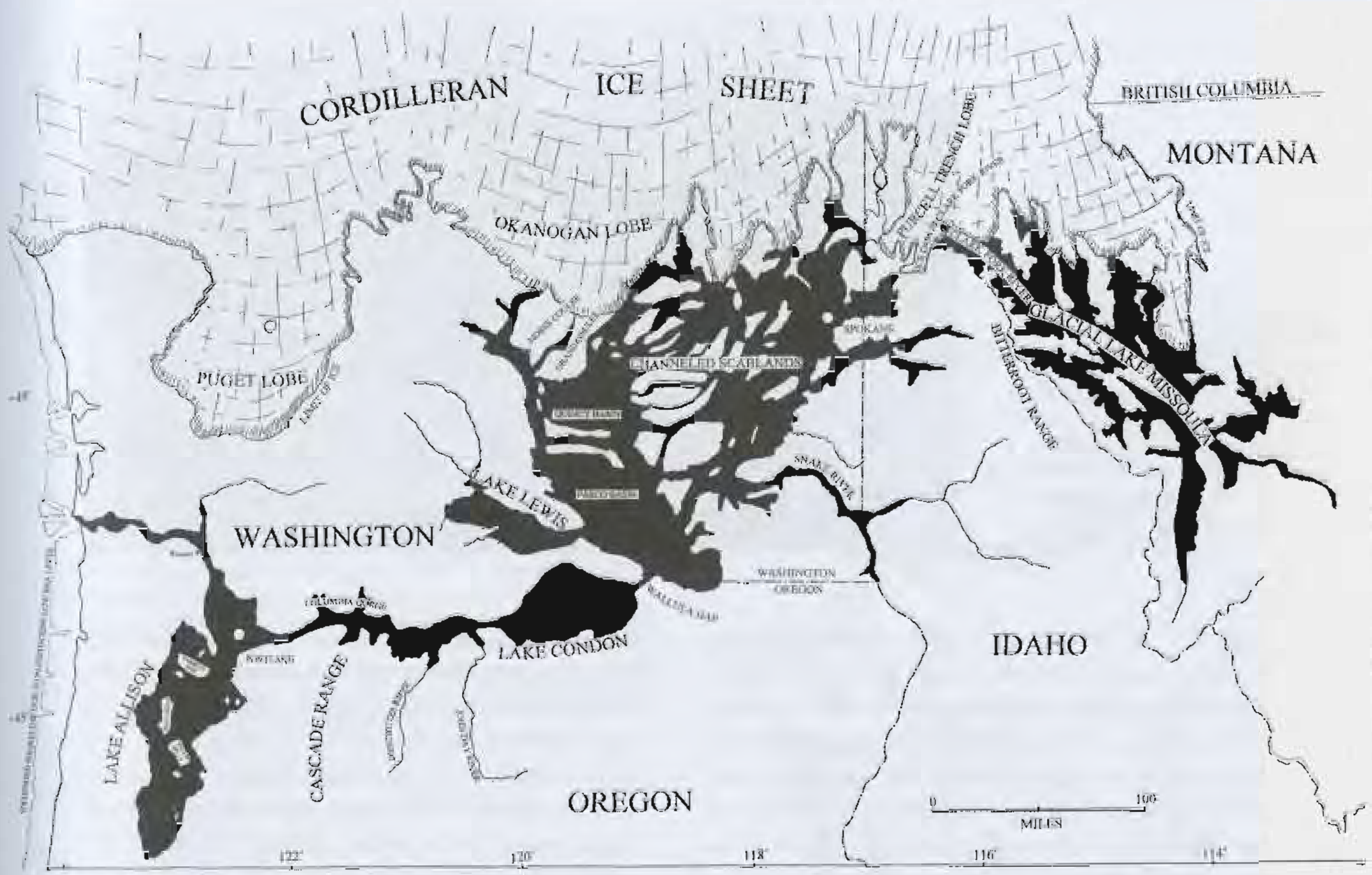
During the early to middle Pleistocene, rivers coming off the Cascades spread glacio-fluvial sand and gravel fans across the valley. (After Allison, 1953; Crenna, Yeats, and Levi, 1994; Graven, 1990; McDowell, 1991; O'Connor, et al., 2001; Yeats et al., 1991)

fans. These, in turn, pushed the Willamette River channel over to the west.

Allison's divisions have since been revised. Balster and Parsons renamed the Linn as the Rowland Formation and subdivided it into the upper Diamond Hill and the lower Linn members. Wood fragments from the Diamond Hill have been dated between 23,000 to 20,000 years old. In 2001, O'Connor delineated four Quaternary stages in the Willamette Valley—the oldest gravels and sands from 2.5 million to 0.5 million years ago correspond to Allison's Lacomb and Leffler; lake and stream fill going back at least 420,000 years is equivalent to Allison's Linn gravel; Missoula flood deposits are dated from 15,000 to 13,000 years in the past, and Willamette River sediments are younger than 12,000 years.

Missoula Floods

Thick, uniformly laminated Willamette silts, over the Linn gravels and older bedrock, originated from episodes of catastrophic floods that swept from Montana, across Idaho and Washington, and through the Columbia River gorge to Oregon. When the notion of colossal flooding was first proposed in the 1920s by J. Harlen Bretz, a professor at the University of Chicago, the evidence was compelling, but the geologic community was slow to accept the idea without a source for such a huge volume of water. Richard Flint at Yale University, Ira Allison, and Edwin Hodge appealed to landslides, ice dams, glaciers, and streams, or a combination of these to substantiate alternate theories and to explain the erosion and deposition. Strong opinions prevailed



Deposits from four large lakes and the Columbia River gorge trace the source and pathway of catastrophic glacial floods. (After Allen, 1986; Allen, Burns, and Burns, 2009; Allison, 1953; Baker, 1973; O'Connor and Burns, 2009; Waitt, Denlinger, and O'Connor, 2009)

on all sides. The discovery of an ice-dammed Pleistocene lake in Montana by Joseph Pardee at the U.S.G.S. was the final puzzle piece required for the flooding theory to be accepted.

In the 1970s and 1980s, Richard Waitt of the U.S.G.S. and Victor Baker from the University of Arizona examined various aspects of the deposits and chronology of events, supplying new data on their magnitude and frequency. The story of the cataclysms and the controversy surrounding them is related particularly well in John Allen's book, recently updated by Marjorie Burns and Scott Burns, and by Waitt's 2009 field guide that compares early flood hypotheses, summarizing the hydraulics, discharge rates, and geomorphology.

Beginning about 15,000 years ago and continuing for a period of 2,000 to 3,000 years, the lower Columbia River drainage experienced a succession of devastating floods when the Clark Fork River in northern Idaho was dammed by the Purcell lobe of the Canadian ice sheet, backing up enormous Lake Missoula across much of western Montana. As the dam was breached, over 500 cubic miles of glacial ice, water, and debris poured out, traveling from an elevation over 4,200 feet to sea level. Flushing through the Idaho panhandle and scouring the area now known as the channeled scablands of southeast Washington, the deluge ponded briefly into the 1,000 foot deep Lake Lewis at the narrows of Wallula Gap, then a second time at The Dalles to create Lake Condon before coursing westward, scouring the canyon of the Columbia River. Water moving at the rate of 9.5 cubic miles an hour would have taken three days before draining the lake.

Geologists long ago concluded that separate layers along the route suggested many floods, but exposures of the Touchet Beds at Burlingame Canyon near Walla Walla in 1926 provided indisputable

Filling the Willamette Valley, Lake Allison covered Portland with 400 feet of water, and Lake Oswego, Beaverton, Hillsboro, and Forest Grove would have been submerged between 100 to 200 feet. (Image courtesy S. Burns)

evidence after water accidentally released from an irrigation canal revealed numerous distinct beds. Representing individual events, each unit is several inches thick, grading upward into the classic finer flood sequences. Since the 1920s, the number of proposed floods has steadily increased. The figures initially proposed ranged from seven, eight, or even to 35 or 40 deluges, but the consensus at present is there were 90 to 100 occurrences.

When flood debris choked the narrow Columbia River channel downstream from Portland at Kalama, Washington, the muddy water backed up into the Willamette Valley as the temporary Lake Allison. Corresponding in large part to Thomas Condon's designated Willamette Sound, the turbid freshwater body extended to Eugene. Repeated surging and ebbing as additional water entered through the gaps at Oregon City and Lake Oswego kept the level constantly fluctuating. After a brief interval of a week or two, Lake Allison drained back into the Columbia River and the Pacific Ocean, leaving innumerable layers of lacustrine silts, sands, and clays over the older gravels.

Willamette Formation (Silt)

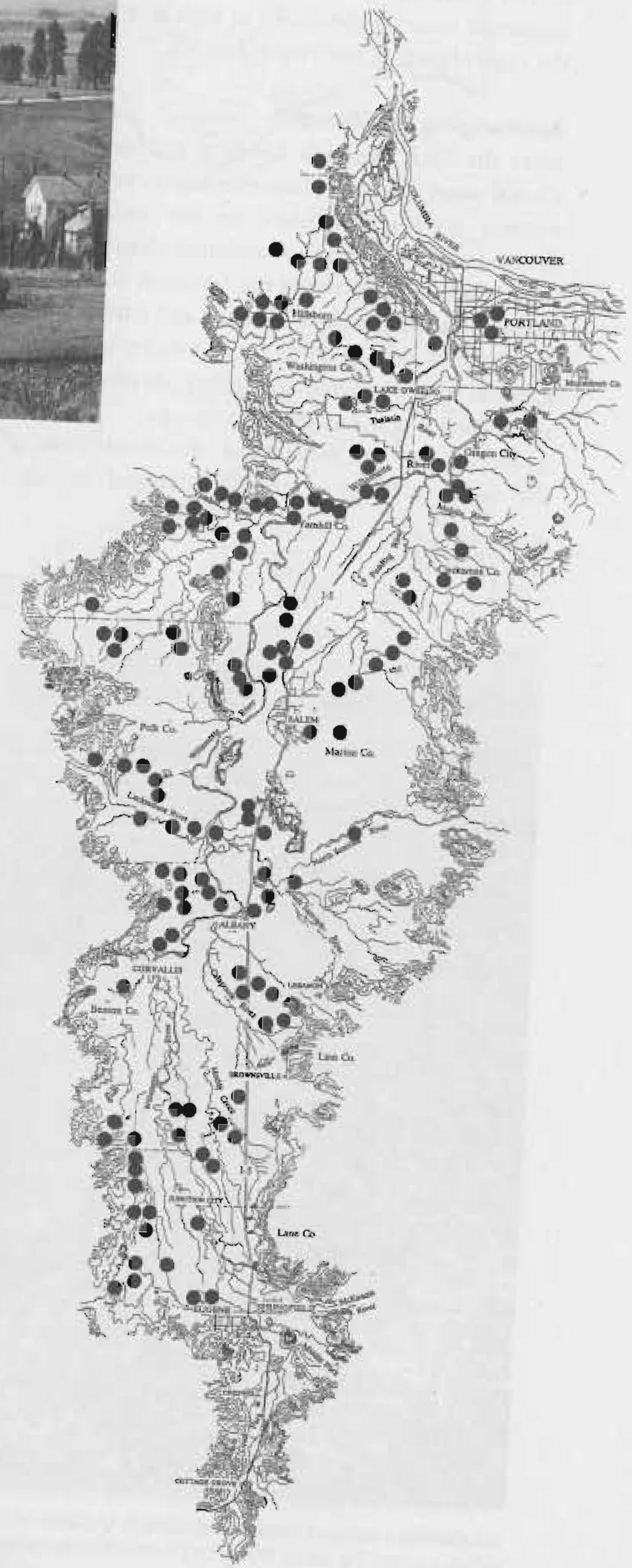
Ira Allison was the first to suggest that late fine-grained Pleistocene sediments in the Willamette Valley were deposited by glacial floods, and after his examination of the nine-to-twelve-foot-thick section at Irish Bend south of Corvallis, he described and named them the Willamette Silt. He concluded that they originated from a backwater lake, which resulted from countless glacial floods, but his theory was modified in 1965 by Jerry Glenn in his PhD from Oregon State University. Glenn worked out the stratigraphy of a section south of Dayton at River Bend, where the facies was similar to that at Irish Bend. His hypothesis fixed the number of floods at 40 with a single much larger climactic event.

In 1969, the Willamette Silts were redesignated as the Willamette Formation and subdivided into four members by Balster and Parsons. The oldest Wyatt layer represents river channel fill, the thick Irish Bend silt and fine sand mantled a wide central area, while the younger Malpass and Greenback covered the lowlands and foothills.

The flood torrents that spilled into the valley carried icebergs laden with erratics, which were dropped over a wide area when the ice melted. There are 300 recorded occurrences, but thousands more are still unrecognized. Whereas over 40 boulders exceeding three feet in diameter have been located, numerous smaller stones have been uncovered in fields, along roadcuts, and in old river terraces. Varying in composition, the erratics are clearly foreign to the Willamette Valley and more typical of rocks in western Montana. Their exotic nature makes it possible to trace the flood pathways down the Columbia River channel and through Wallula Gap to The Dalles, where they are found up

Large stones, called erratics, brought into the Willamette Valley atop ice floes, are scattered from Eugene to Portland. In this map the localities of over 300 erratics are based on work by Ira Allison. Of these, the largest known is the Sheridan erratic (photo) between McMinnville and Sheridan in Yamhill County. Composed of the metamorphic rock argillite, the stone originally weighed about 160 tons, but almost half has been removed by collectors. The site has been designated as a state park to protect and preserve the specimen. (After Allison, 1935; Photo courtesy Oregon State Highway Department)

Perhaps the most famous Oregon erratic is the Willamette meteorite (photo), which was apparently rafted by ice from Montana to a site later acquired by the Oregon Iron and Steel Company at Lake Oswego. Surreptitiously but strenuously moved by Ellis Hughes to his own property, the 31,107 pound behemoth became the focus of a court battle about ownership. The company won the judgment, and the rock was ultimately purchased in 1902 and donated to the American Museum of Natural History in New York. (Photo courtesy Oregon Department of Geology and Mineral Industries)



to 1,000 feet above sea level. In the valley, erratic fragments occur at elevations as high as 400 feet in the upper layers of the Willamette Silt.

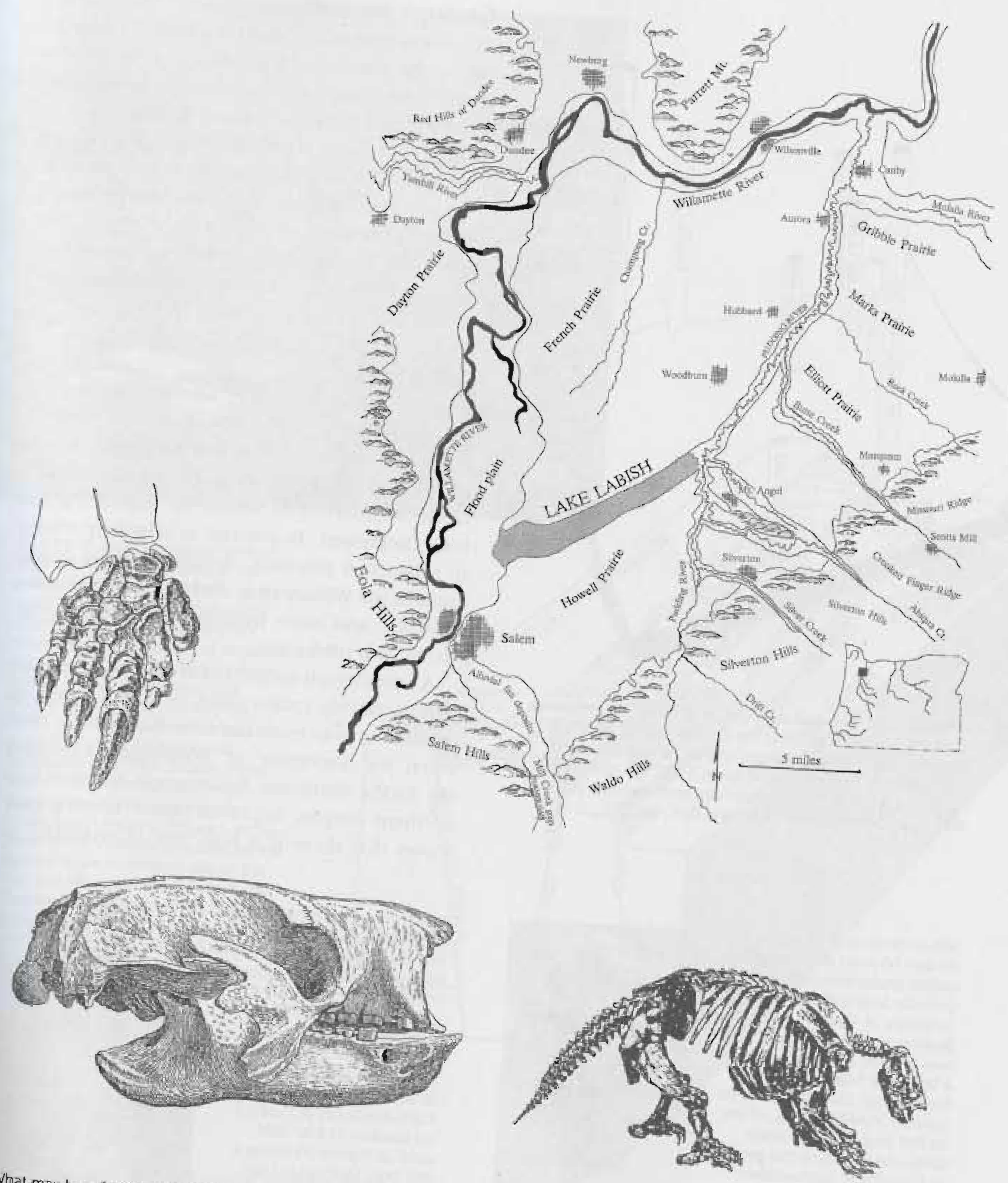
Rearranging the Rivers

After the final Missoula flooding episode around 13,000 years ago, the Willamette River and Cascade streams were reestablished on the valley floor. Braided river networks, abandoned channels, and oxbow lakes characterized the lowlands during this period. Post-Missoula flood sands and gravels up to 60 feet thick fanned out in broad swaths where the Cascade rivers entered the valley, displacing and redirecting the meandering pathways.

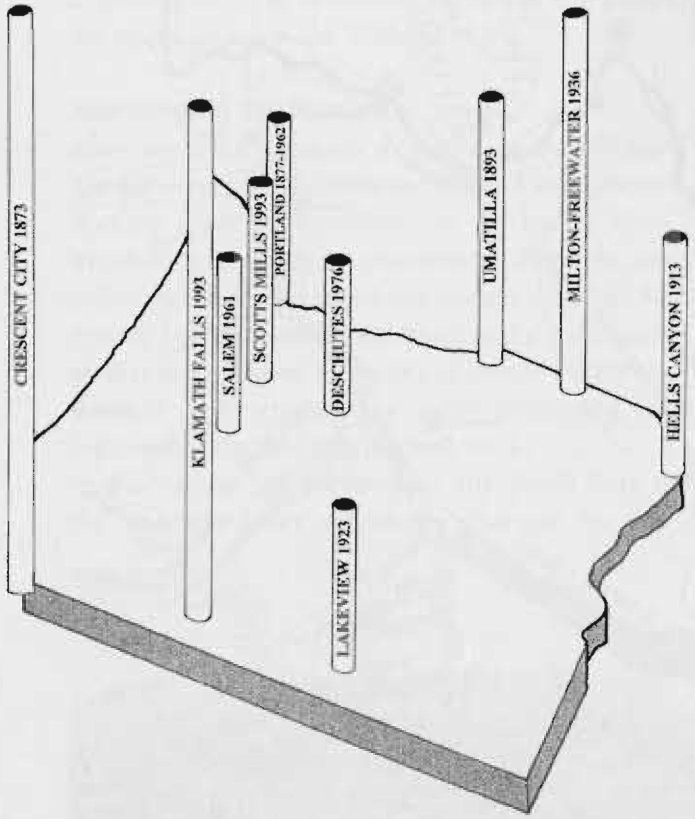
During the late Pleistocene, the North Fork of the Santiam River repeatedly changed its confluence point with the Willamette. Transporting fine Cascade glacial deposits of the Missoula flood, it followed a course northward from the Stayton basin through the narrow pass at Turner (Mill Creek) Gap to join the Willamette River at Salem instead of merging at its present-day junction north of Albany.

In the northern Willamette basin, the channel of the Willamette River may have been pushed westward by gravels of the Troutdale Formation, by heavy Cascade glacio-fluvial sediments, or even by lavas from the Boring field. Establishing its present route some 11,000 years ago, the river cut the prominent cliffs and falls through the Columbia River basalts at Oregon City.

Lake Oswego occupies a channel scoured by the Missoula floods. The Cascade Mountains and Mount Hood can be seen in the distance across the valley. (Photo by Delano Photographics; courtesy Condon Collection)



What may be a former route of the Willamette River, Lake Labish extends in a straight strip for almost 10 miles northeast from Salem. The river was blocked by a flux of sediments from Silver, Abiqua, Drift, and Butte creeks, and the resulting shallow lake slowly converted into a peat-rich marsh. Dated around 14,000 years ago, the bones of Ice Age mammals such as mammoths, mastodon, giant sloth (claw, skull, and skeleton), and bison are frequently exposed during farming operations. Unlike the LaBrea tar pits of Los Angeles, the animals were probably not mired in the bog, but the carcasses were washed in and covered, allowing the remains to be preserved in the oxygen-poor setting away from the attention of scavengers. Today the fertile lakebed soils support a thriving vegetable industry. (After Glenn, 1962; Orr and Orr, 2009; Schlicker and Deacon, 1967)



A look at large earthquakes in Oregon shows most measured VI on the Mercalli scale. Only the Crescent City (California), Klamath Falls, Milton-Freewater, and Portland quakes were stronger at VII. (After Berg and Baker, 1963; Byerly, 1952; Madin and Mabey, 1996; Niewendorp and Neuhaus, 2003; Townley and Allen, 1939; Wong and Bott, 1995)

Geologic Hazards

In western Oregon, and especially in the Willamette Valley, the increase in population, the decrease in available land, and inadequate land-use evaluations have led inhabitants to situate themselves, their structures, or their activities on floodplains, atop unstable soils, or near seismically active regions. As a consequence, work on geohazards has become of primary importance, with concerted efforts by state and federal agencies to make information on risks available through seminars, newspapers, maps, and reports.

Earthquakes

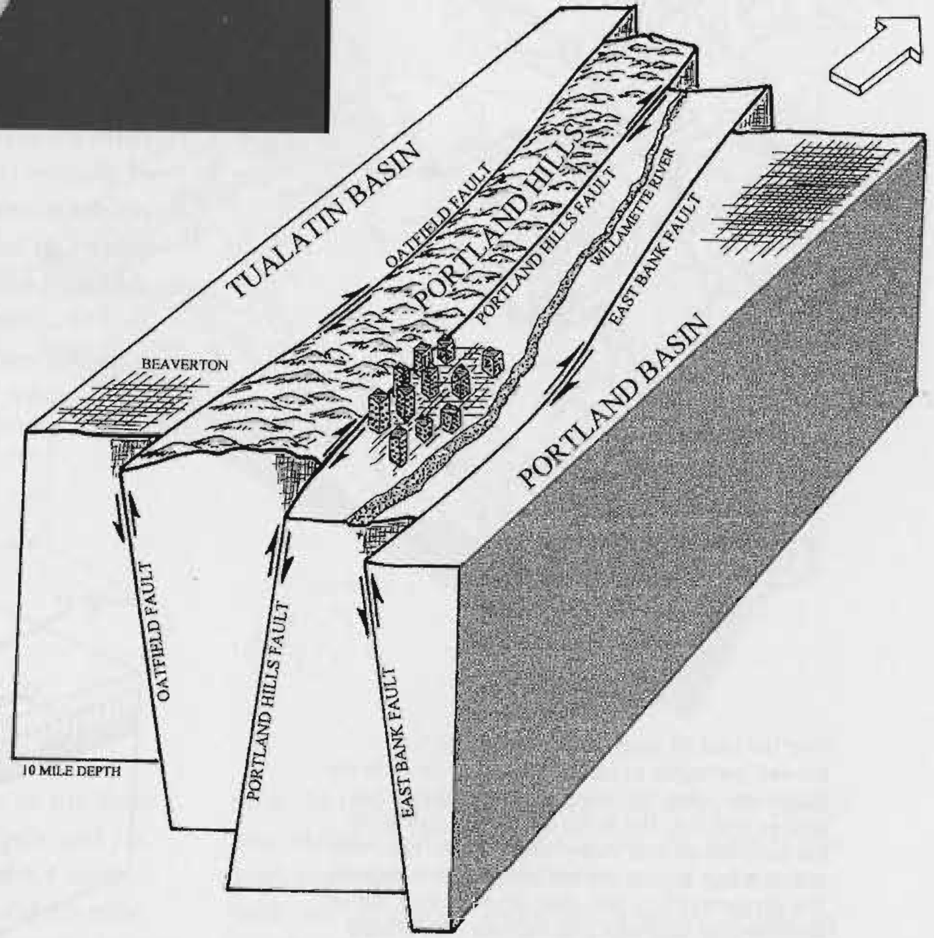
Situated inland from the Cascadia subduction zone and adjacent to the Cascade volcanic arc, the Willamette Valley is vulnerable to seismicity from crustal faults, from the subduction zone (megathrusts), or from events within the subducting slab itself (intraplate). In contrast to seismicity related to subduction processes, movement along crustal faults in the Willamette is shallow, at 6 to 12 miles in depth, and more frequent than activity connected with subduction.

A seismograph station at Corvallis has been part of a worldwide system since 1963, but improved monitoring was established for Portland in 1980 when the University of Washington expanded the Pacific Northwest Seismograph Network into northern Oregon. Improved record keeping now shows that there is a high rate of seismicity in the Willamette Valley. Ground shaking from a 6.8 magnitude rupture of the Portland Hills crustal fault could exceed even the damage produced by a Cascadia subduction zone event. Ground motion maps also measure the distance from the epicenter and the susceptibility of the soils to liquefaction.

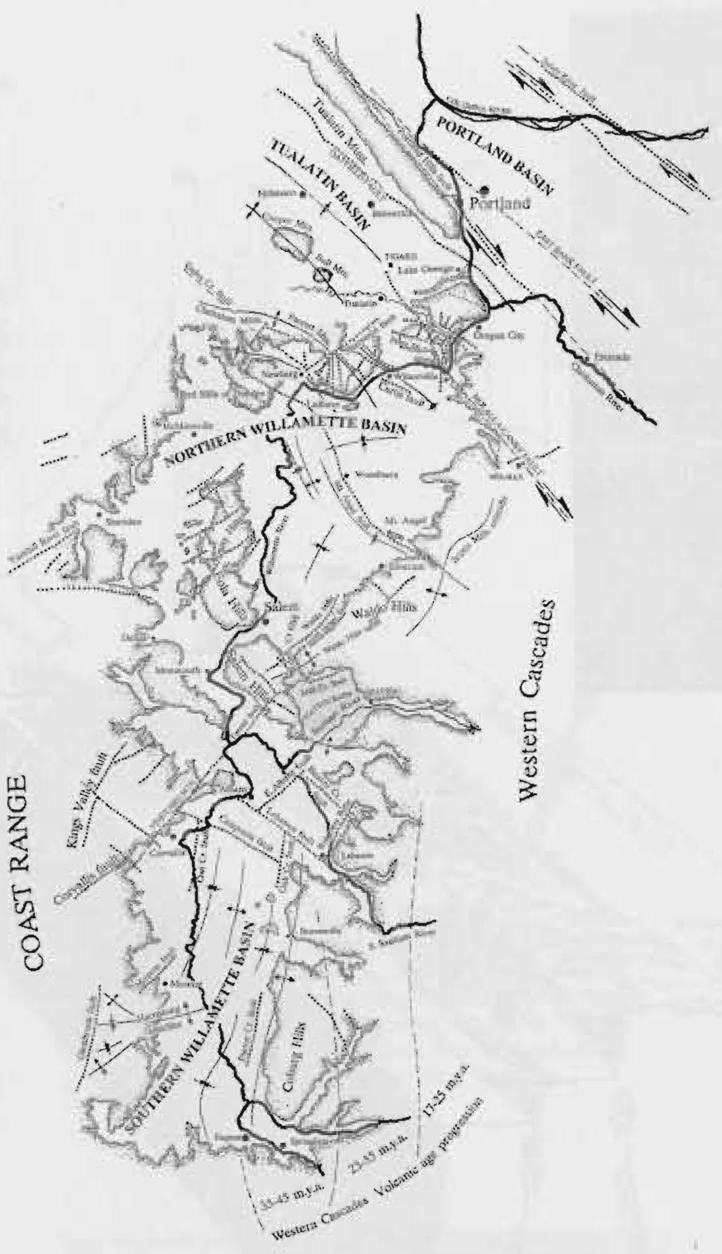
When saturated with heavy rainfall, the soft loose Willamette Silts, that fill the Portland basin, might liquefy if shaken. Somewhat like Jell-O, they would continue to shake after the event had stopped, then begin to flow, thus accentuating the destructive effects.

Soils engineer and geologist Herbert Schlicker was one of the earliest proponents to regard geohazardous and environment conditions as restraints on development. Schlicker was born in 1920 and grew up on a farm near Salem. Graduating from Oregon State University, he joined DOGAMI in 1955, where his first study on the Tualatin Valley and his last on the geology and hazards of northwestern Clackamas County bracket 25 years with the state. Providing expertise for many boards and government agencies, Schlicker also was instrumental in initiating registration for geologists in Oregon, and, as the first, he was assigned the number One. He died in Clackamas in 1992. (Photo courtesy Oregon Department of Geology and Mineral Industries)

During his career, John Beaulieu also emphasized the need for land-use planning that would take geohazards into account. Born during World War II to parents who worked on the Manhattan project, Beaulieu and his twin brother grew up near the Hanford Nuclear facility in Washington. Finding mastodon bones at Hanford led Beaulieu to later field work on the site. Finishing a PhD from Stanford in 1969, he began with DOGAMI shortly afterward, where, as director he frequently worked with the legislature to create environmental awareness and goals. Beaulieu retired in 2003 and currently lives in Portland, where he works on selected geologic projects. (Photo courtesy J. Beaulieu)



Swarms of small to medium tremors during July, 1991, centered at the north end of the Portland Hills fault, were noticed in many communities of western Oregon, and the 2001 discovery of up to six feet of displaced flood deposits beneath Rowe Middle School in Milwaukie shows that activity is continuing. On April 24, 2003, a 3.6 earthquake near Kelly Butte Park shook Portland and Vancouver, nine miles distant. There were no damages or injuries, but this was one of the largest quakes locally within the past 35 years. In the photograph, Portland is located on the down-thrown (northeast) side of the Portland Hills fault, which follows the Tualatin Mountains (upper left). (After Blakely, et al., 1995, 2000; Wang, et al., 2001; Photo courtesy Delano Photographics)

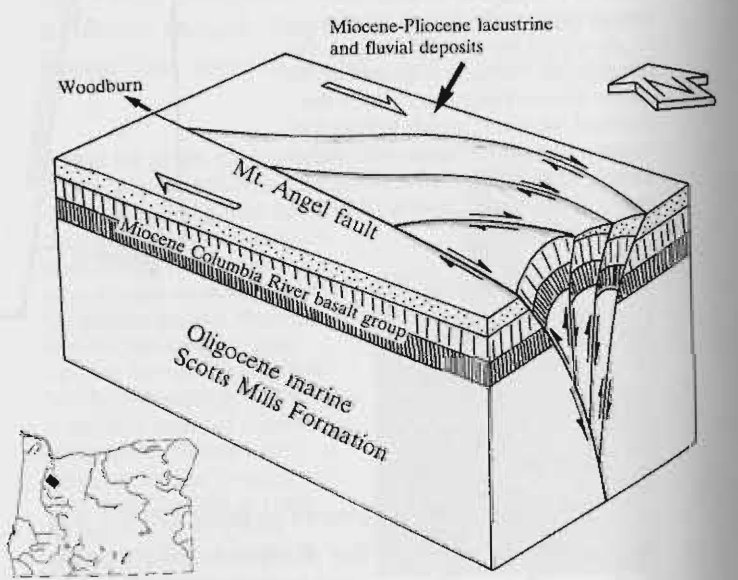


Over the past 20 years, detailed mapping has allowed geologists to connect disparate faults in the Willamette Valley that were originally regarded as isolated features. The faults of greatest concern in the north Willamette Valley follow the Portland Hills anticline that date to the late Miocene and Pliocene. The Portland Hills system, over 40 miles long, trends northwest by southeast and includes the Portland Hills, the Oatfield, the East Bank, and the Frontal (Sandy River) faults. Aeromagnetic surveys flown in 1992 show that Portland Hills faults, which parallel the Willamette River in the downtown area, are concealed beneath Quaternary sediments and may join the Clackamas River fault belt to the south. This alignment of surface fractures traverses all the way to the Steens Mountains as part of the Brothers Fault zone. (After Blakely, et al., 1995, 2000; Crenna, Yeats, and Levi, 1994; Gannett and Caldwell, 1998; Graven, 1990; Werner, 1990)

Accounts of historic earthquakes in the Pacific Northwest have been extensively re-evaluated in order to anticipate future high-magnitude episodes. In 1993, private consultants Jacqueline Bott and Ivan Wong chronicled the crustal earthquake record for the Portland area, revealing at least 17 shocks of magnitude 4.0 or larger on the Richter Scale since the late 1800s. Brick buildings swayed, windows rattled, and inhabitants rushed into the streets during the tremor of February 3, 1892, although there was minimal damage. In 1961 and 1962 and again in 1968 magnitude 4.7 and 5.2 quakes struck Portland from epicenters on the eastern edge of the city, causing some structural problems. Richard Blakely with the U.S.G.S. notes that the strongest 1962 quake occurred between the Portland Hills and Frontal (Sandy River) fault zones.

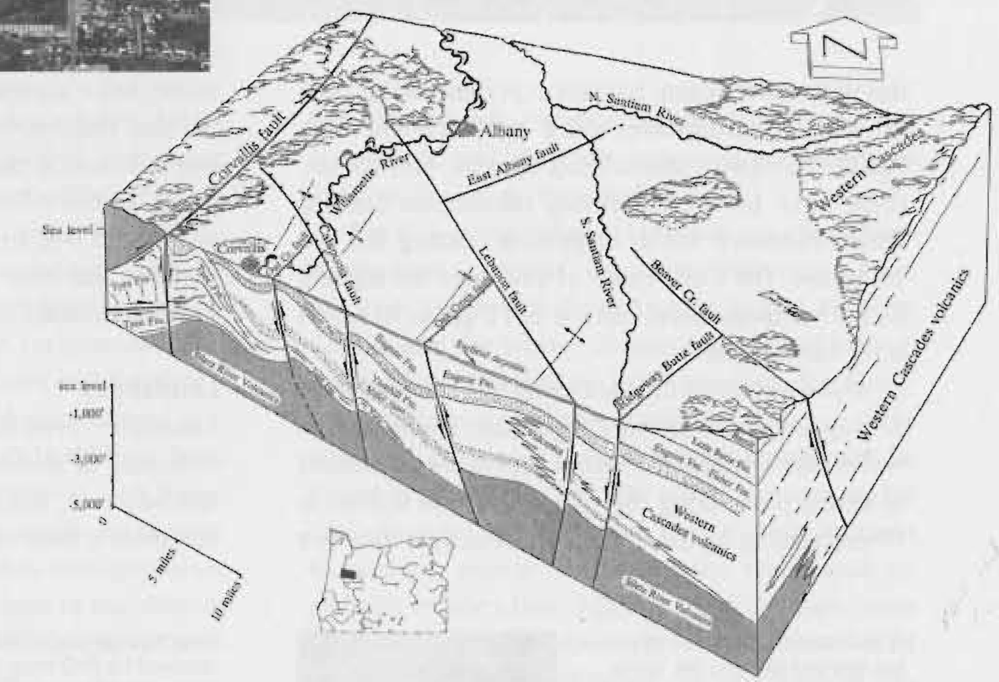
Elsewhere in the Willamette Valley seismic records are scant, although there have been a number of shallow crustal quakes. On November 16, 1957, residents near Salem described a shaking that registered an intensity of 4.5 but with no damage, although a similar occurrence at Albany and Lebanon in 1961 toppled chimneys, broke windows, and knocked over signs. The more recent Scotts Mills 1993 quake, centered 25 miles northeast of Salem, caused considerable structural damage to the State Capitol, as well as to buildings in Molalla and Mt. Angel at a cost of $28 million. Rated at 5.6 magnitude, it was triggered by motion along the 35-mile-long Mt. Angel fault. The Mt. Angel structure is on the southeast end of a fault complex that trends northwestward beneath Woodburn to project into the Gales Creek fault zone from the Coast Range and southeastward into the Waldo Hills front range system.

In 2000, Richard Blakely described the previously unrecognized Canby-Molalla lineament, which runs 40 miles through the communities of Canby and Molalla in Clackamas County. He regards this fault as similar to the parallel Mt. Angel zone in that both are extensive strike-slip features displacing significant sections of the upper crust.



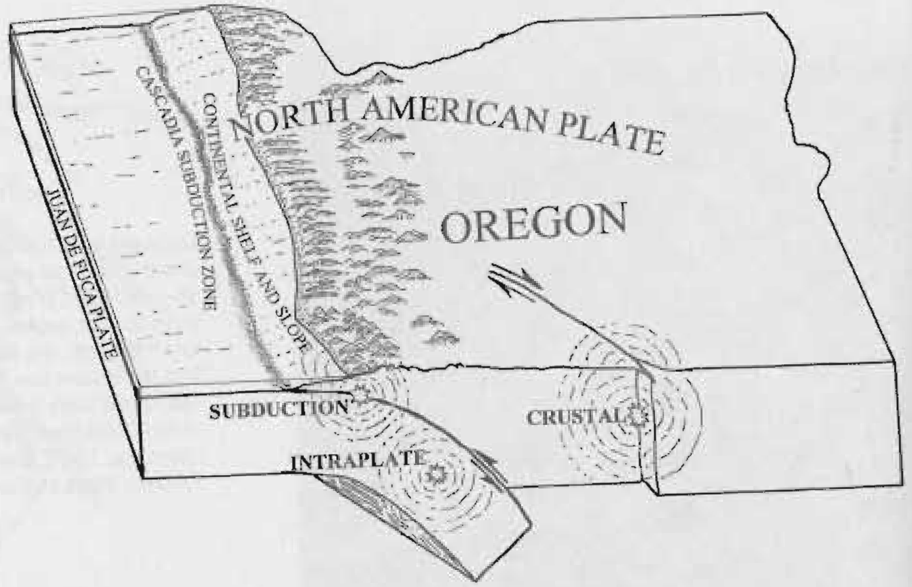
The butte at Mt. Angel, where the Abbey sits, forms what is called a fault "pop-up" in which rocks, caught and squeezed between a series of intersecting fault blocks, are slowly extruded to the surface. (After Werner, et al., 1992)

Eastward from Corvallis, a criss-crossing network of normal and thrust faults extends to the Western Cascades. The 30-mile-long Corvallis fault has been identified as the source of three to four quakes of 3.0 to 5.0 intensity. In the photograph looking north, the fault passes diagonally between the city and the distant low Vineyard Mountain at the edge of the McDonald State Forest. Marys River is in the foreground. (After Goldfinger, 1990; Graven, 1990; Kienle, Nelson, and Lawrence, 1981; Werner, 1990; Yeats, et al., 1991; Photo by Western Ways of Corvallis; courtesy Condon Collection)



Subduction—Intraplate Earthquakes

Marking the boundary between the Juan de Fuca and North American plates, the Cascadia subduction zone lies roughly 100 miles west of the Willamette basin. Subduction earthquakes are generated along the interface between the two plates, but historically



The chance of a subduction quake in the Pacific Northwest is more probable than for an intraplate episode, which is associated with deformation, temperature, and pressure changes within the Juan de Fuca plate itself. However, there are exceptions. A 1949 mid-plate quake in Olympia, Washington, registered 7.1 magnitude, one near Tacoma-Seattle in 1965 recorded 6.5, and in 2001 Nisqually, Washington, experienced a 6.8 magnitude shaking. (After Hofmeister, Wang, and Keefer, 2000)

the Willamette region has not experienced this type of massive earthquakes since establishment of a Pacific Northwest monitoring system. Worldwide, there have been eight strong subduction quakes, which exceeded 9.0 in magnitude, during the last 100 years. The Chile event of 1960 was the highest with a 9.5 magnitude, and the 2011 quake in Japan is the most recent.

Many estimates for the timing and damage from earthquakes in western Oregon are based on the worst-case scenarios, where ruptures are postulated as taking place along the entire length of a fault or where activity in the Cascadia subduction zone is a factor. Since a great deal of uncertainty exists about the size and location of earthquakes, crustal faults, and subduction plate motion, the calculations vary widely from a 5.5 magnitude quake every 100 to 150 years to a 7.0 or an 8.5 event every 475 years. Blakely, Yeats, and other seismologists urge caution before drawing detailed conclusions for future predictions.

Landslides

Landslides involve the downslope movement of rock, soil, or related debris in response to gravity. In this province, slides are rare on the valley floor but common in hilly topography, where weathering and

In recent years, Scott Burns has worked to bring the issues and problems connected with landslides to the public's attention. His book *Environmental, Groundwater, and Engineering Geology* provides invaluable information on geohazards and is a critical tool for responsible planning. Burns' varied research includes engineering and environmental geology, soils, and geomorphology. Completing degrees at Stanford and the University of Colorado, he began a teaching career that took him abroad as well as elsewhere in the United States. A sixth-generation Oregon native who grew up in Beaverton, Burns returned to the state in 1970, when he joined the staff at Portland State University. (In the 1996 photograph Burns is inspecting the Newell Creek Canyon slide at Oregon City; Photo courtesy S. Burns).

Structural geologist Bob Yeats received his PhD from the University of Washington in 1958, then worked a time for Shell Oil Company before teaching at Ohio University. His research focused on mapping earthquake faults in three dimensions using subsurface data. In 1977 he transferred to Oregon State University to take over the chairmanship of the geology department. Through his numerous papers, including *Tectonics of the Willamette Valley* and his several books—notably *Living with Earthquakes in the Pacific Northwest*—and his many students, Bob has been a major player in unraveling Oregon's geology. Living in Corvallis, he is currently working on an international project to create a worldwide active fault database. (Photo courtesy A. Yeats)

The February, 1996, storm, now known as a 100-year event, fostered landslides and flooding throughout the state. The Portland metropolitan area alone suffered $10 million in losses. The highest cost was to private residences, since few homeowners were prepared or had insurance. Inspecting over 400 sites, Burns observed that Portland became the "City of Plastic" as owners futilely attempted to prevent further sliding with slope coverings. Most of the moderate to small earthflows and slumps were in Portland Hills loess that mantles the West Hills. (This photo was taken near S.W. Montgomery Drive and Elm Street; photo courtesy S. Burns)

erosion have over-steepened the gradients. Heavy rainfall, removal of the vegetation cover, excavating, poor drainage, and loading all destabilize the slope. In the northern Willamette basin, winter mass movements at multiple locations happen almost annually.

While predicting volcanic eruptions and earthquakes with any precision is not yet possible, forecasting the occurrences of landslides and flooding is more certain. For some time geologists such as William Burns and Ian Madin at DOGAMI have been working with LIDAR (Light Detection and Ranging), which effectively sees through vegetation, to map and define unstable slopes with precision. Burns estimates that there are close to one-fifth of a million landslides in Oregon and that about one-tenth of these have been mapped.

In the Portland, Vancouver, and Tualatin basins, landslides develop where the Boring lavas cover the Troutdale Formation and Sandy River Mudstone or within layers of the Portland Hills silt. Over half of all identified landslides in the Willamette Valley are comparatively moderate in size, and geologists surmise that the larger prehistoric ones may have been induced by Cascadia subduction zone earthquakes.

In 2002 Jon Hofmeister, formerly at DOGAMI, completed a number of site specific maps for landslide-prone areas in 19 western Oregon counties. Politicians and government officials, however, felt that the maps labeled too much of the area as hazardous, and since economic growth might be affected, the maps were withdrawn.

The 125-acre Highlands landslide is perhaps Portland's most notorious, involving Washington Park, the zoo, residential housing, the World Forestry Center, and the former Oregon Museum of Science and Industry (OMSI). Up to 90 feet deep, the block-and-earth flow of Portland Hills silt above a shear zone of decomposed Columbia River basalts may be traced as far back as 700,000 years. Excavations for city reservoirs in Washington Park in 1894 initiated movement, which has since been reactivated by periodic construction. After years of difficulty with an unstable building foundation, OMSI abandoned the site for a new facility on the east bank of the Willamette River.

Close to Oregon City, the Troutdale Formation has been responsible for the great concentration of ongoing slides within the 600 acres of Newell Canyon. In 1993 Scott Burns and his students mapped the canyon, which is bisected by Highway 213, recording 53 landslides. Of the seventeen new earthflows and slumps discovered in 1996, the largest was approximately 200 cubic yards in size. However, it was enlarged to a 15,000-cubic-yard debris flow by the rains of 1996.

Landslides fostered by the 1996 storm were not restricted to Portland. Lane County had the largest number with 2,264. Douglas County was second with 1,084, followed by Linn County with 913 and Clackamas with 880. A state of emergency was declared, and the effects were compared to the high waters of 1964. Destruction was most pronounced on federal forest lands, where logging roads were washed out and blanketed with rocks and mud. The Eugene district of the Bureau of Land Management suffered some $2.5 million in losses as over 20 miles of roadways, along with campgrounds, bridges, and boat ramps were destroyed.

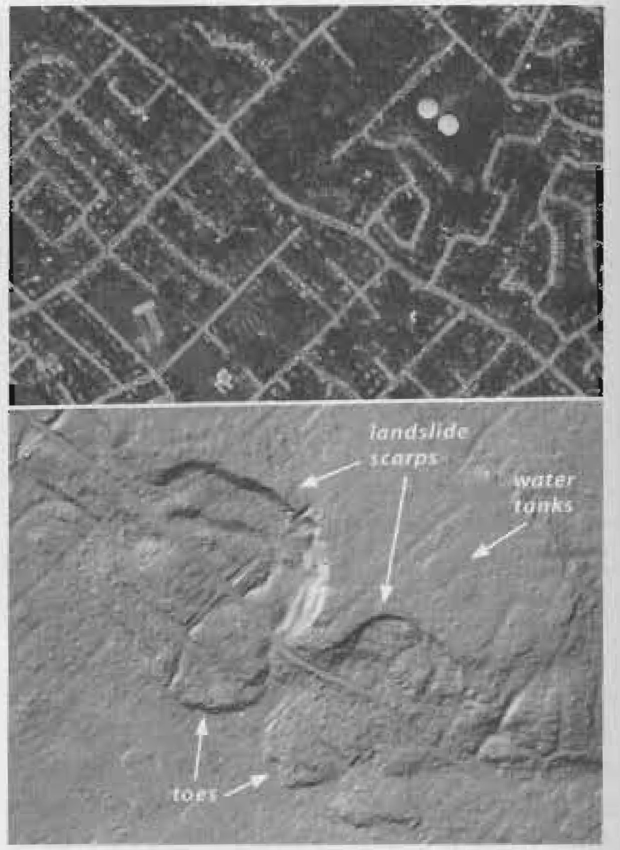
Calling them *giant* landslides in the Coburg Hills, Ian Madin and Robert Murray of DOGAMI mapped the quadrangle north of Eugene in 2004, recognizing a series of major slides along 2,500-foot-high escarpments. They identified decomposed Little Butte basalts covering the Eugene and Fisher formations as responsible for a prehistoric debris avalanche, which continues to move. Although the Coburg Hills offer spectacular views of the valley and coastal mountains, such existing hazardous conditions would necessitate extensive study before any development on the steep slopes.

The use of LIDAR by the Oregon Department of Geology has revealed hundreds of broad, shallow depressions, approximately 100 feet across and 5 to 10 feet deep, on the Willamette Valley floor. One suggestion as to the origin of these intriguing "pits of mystery" is that they may be sites where huge Missoula flood icebergs grounded and slowly melted to create a divot in the soft silt layers.

Flooding

Flooding on low-lying lands throughout Oregon was recognized by the first Europeans, who attempted to control high waters with drainage ditches, dams, or levees. Since these early endeavors in the 19th Century, agriculture and towns have steadily expanded onto floodplains and wetlands, where they are vulnerable to inundation by waters rising from a combination of melting snow and heavy rainfall. Floods can occur at any season of the year, but they are most frequent during late winter or early spring, and today they have become almost yearly occurrences.

Over one million acres of recognizable floodplains in Oregon—areas where river bars, banks, and terraces were overtopped—had been mapped



Beginning in 2005, a cooperative five-year LIDAR (Light Detection and Ranging) project between DOGAMI, Portland State University, and the U.S.G.S. hoped to identify areas at risk from landslides along the immediate coastline and in the Willamette Valley. LIDAR provides clear images of surface geomorphology to show features associated with slides. (In this 2005 digital image, the toes and scarps of active slides along Oatfield Road in Gladstone are clearly visible; courtesy Oregon Department of Geology and Mineral Industries)

by the 1970s; however, as noted by consultant Frank Reckendorf, even with this knowledge, hazard prone regions continued to be developed. Reliance on inadequate federal and state maps, guidelines, and monitoring, which failed to account for channel constrictions and fill, for the encroachment of buildings, or for the natural stream geomorphology, contributed to the $200 million damage caused by the 1996 floods. Throughout the valley, cities became islands, while individual houses and businesses were isolated in the middle of lakes. Minimal oversight by Oregon state as well as federal agencies still exacerbates flooding problems.

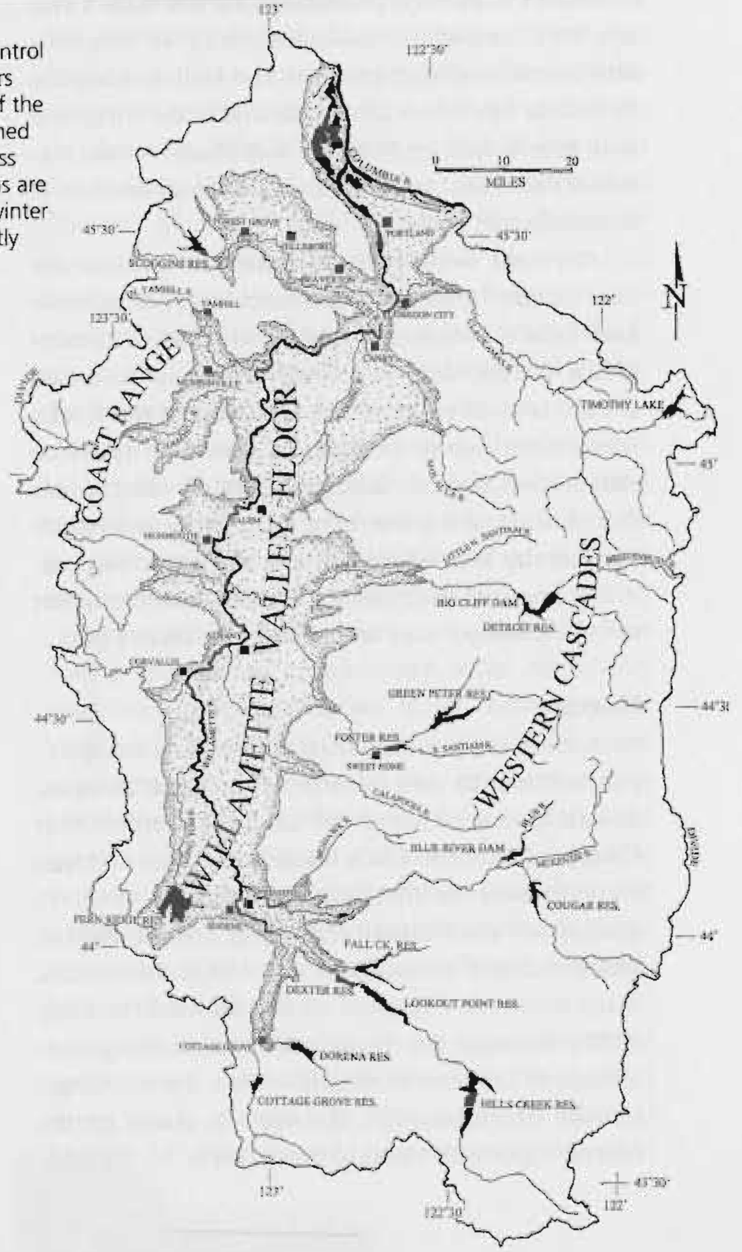
Oregon's most disastrous flood overwhelmed the community of Vanport on May 30, 1948, in the area now occupied by Portland's Delta Park. Many accounts detail the events, in which the

In what has become known as the first "great flood" of December, 1861, a prolonged warm rain and snow melt inundated many towns the length of the Willamette Valley. Intermittent episodes over the next century were punctuated by the record-breaking storms when intense rains caused destructive landslides and overflowing rivers. In February, 1890, the second largest flood on the Willamette River took out virtually every large bridge in the valley, shifted the river channel, and inundated Salem (above). (Photo courtesy Oregon State Archives)

In the Willamette Valley, the construction of large dams for flood control began in the 1940s, and today there are 13 Army Corps of Engineers storage projects. The five earliest facilities are in the southern part of the valley near Cottage Grove and Eugene, and the other eight are aligned toward the north along the east side. The final one was placed across Blue River in Lane County in 1968. Because they are aging, the dams are facing repairs. Anticipating a high chance of valley flooding in the winter of 2011, the Army Corps announced that about 42 spillways urgently needed attention.

ill-conceived federal housing project for workers at the Kaiser Company shipyards was destroyed and 15 people killed. Situated on the floodplain of the Columbia River, the two square miles of Vanport village were protected from the river by narrow dikes maintained by the Army Corps of Engineers. Even as the water reached the top of the levees, 13 feet over river flood stage, the populace was assured there was no danger. Rainfall and runoff from late snow-melt over-topped the dike and opened a six-foot-wide break, allowing the surge to enter the housing area.

As noted by John Beaulieu, one of the unexpected consequences of dam construction is that changes in the meandering patterns of larger rivers lengthen the period of flooding. Prior to dam construction, floods peaked over short periods of time and inundated wider areas, whereas, with dams in place, the duration of high water, channel changes, and erosion can be more extensive. During the 1996 flooding, high water persisted in Portland for two weeks.



Natural Resources

Bauxite and Iron

Where surfaces of the Columbia River basalts are deeply weathered, residual ores of aluminum and iron develop in swampy areas. With rock decomposition, soluble chemicals are leached out leaving a clay soil with the insoluble bauxite enriched with aluminum and iron. In the northern Willamette Valley, the thickest deposits are in Washington and Columbia counties.

The process of extracting aluminum from bauxite ore requires considerable electric power, and Oregon's readily available inexpensive hydroelectric resources made the state attractive to the industry even before the demands of World War II. A global increase in the use of aluminum in 1987 was reflected in expanded production by the state's two smelters, Reynolds Metals Company at Troutdale and Northwest Aluminum at The Dalles. After the Reynolds operation closed in 2002, the structure was demolished, and the site was placed on the National Priorities List for remedial cleanup because of contaminated soils.

Attempts were made to mine and process the iron oxide mineral, limonite, near Scappoose and Lake Oswego from 1867 to 1894. Furnaces of the Oregon Iron and Steel Company produced 83,400 tons of pig iron, the first west of the Rocky Mountains, before being shut down by financial difficulties. Several thousand feet of old tunnels still existing under the Lake Oswego Country Club and nearby Iron Mountain are of historic interest. A furnace used for smelting, located near the outlet of Lake Oswego, may still be seen in the city park.

Mercury

In western Oregon cinnabar, an ore of mercury, occurs within a 20-mile-wide belt from Lane, Douglas, and Jackson counties to the California border. Near Cottage Grove, the Black Butte and Bonanza mines were responsible for about one-half of Oregon's quicksilver production, exploiting Eocene marine sediments and volcanics of the Fisher Formation. Black Butte was operated off and on until the early 1970s. Because the waste piles are leaching contaminants into creeks that flow into the municipal Cottage Grove reservoir, the site was placed on the federal superfund cleanup list in 2010.

Cinnabar at the Bonanza Quicksilver Mine in Douglas County was discovered in the 1860s. Eventually ranked as the state's highest producer, the mine peaked between 1940 and 1943, after which output dwindled, and it was closed in 1960.

Oil and Gas

Along with the search for minerals, the hunt for oil has captured the imagination of many since the early 1900s. The western region of the state, in particular, has seen ongoing exploration, both fraudulent and legitimate. Warren D. Smith, among other geologists, wrote letters to newspapers and answered enquiries about possible claims, warning the public against deceptive get-rich-quick schemes. In spite of these efforts, however, investors continued to lose money to fast-talking entrepreneurs.

Oregon laws, which date back to 1923, require that oil and gas operations be regulated by the state. In 1949 and again in 1953 the statutes were modified, authorizing DOGAMI to oversee the drilling, abandonment, and reclamation of sites, as well as the storage of well cuttings and cores. A record of the repository samples and cores is available to the public. Over 500 gas and oil wells have been authorized since the program began, but most were drilled prior to World War II, and few penetrated deeper than a mile. Except for the Mist gas field in Columbia County, exploratory wells have not been successful, although a gas well near Lebanon did produce economic amounts for six months during the mid-1980s.

Surface and Groundwater

The lowland, that extends from the southern Willamette basin into Clark County, Washington, is recognized for its surface and groundwater resources. No part of the basin can be classified as arid, but it experiences rainless periods lasting up to two or more months, during which the supply becomes greatly diminished. Although the state Water Code decrees that Oregon's water belongs to the public, its availability is complicated by that fact that almost all has already been appropriated or allocated.

Surface and groundwater in this province are maintained by the 30 to 60 inches of snowmelt and precipitation that percolates through volcanic rocks of the Cascades to feed the rivers coming off the western slopes. Little is lost during the wet months,

The state Water Resources Department has designated 22 regions throughout Oregon as areas where the amount of groundwater is depleted. Of these, 17 draw from the interbeds of the Columbia River Basalt Group in the northern Willamette basin (shown in pattern), and the remainder are located in eastern Oregon. The department can impose restrictions on future use where drawdown from the aquifer exceeds the estimated natural long-term recharge rate. (After Bastasch, 1997; Burt, et al., 2009; Oregon Water Resources Department, 1984, 1992; Orr and Orr, 2005).

but from August through September discharge occurs by evapo-transpiration through vegetation, with supplying surface streams, and through pumping for agricultural, industrial, or public use. Recharge is slow if the area is small or if the flow is impeded by clay or bedrock.

The groundwater system that underlies 3,700 square miles of the Willamette lowland was divided into separate hydrogeologic units by Marshall Gannett and Rodney Caldwell of the U.S.G.S. The oldest are Eocene to Oligocene marine sedimentary and volcanic rocks, which are occasionally saline and have low permeability. Above these, interbeds between flows of the Miocene Columbia River basalts can produce large quantities of water locally, but they tend to draw down rapidly and recover slowly. A 2009 paper by consultant Walter Burt and coauthors summarizes the hydrology of the basalts in the northern Willamette Valley.

The Willamette aquifer is the principal groundwater repository for the province. Restricted to the coarse-grained Pleistocene alluvial fans and deposits on the valley floor, the sands and gravels of the aquifer range in thickness from 200 to over 400 feet. In the Portland basin, the alluvium was laid down by the ancestral Columbia and Clackamas rivers, and southward it was spread by the Molalla, Santiam, Calapooia, and McKenzie rivers that debouch from the Cascades. The Willamette aquifer is absent in the Tualatin Valley, a region that relies on modest amounts from the Willamette Silt, the Troutdale Formation, or the deeper Columbia River basalts. Comparing the long-term rates of recharge and discharge, Dennis Woodward and others of the U.S.G.S. concluded that on a regional basis the annual level of the Willamette aquifer shows little variation.

The Willamette Silt overlies the aquifer. Deposited by Missoula floods, it is 130 feet thick in the central valley but thins to 10 feet toward the south. The silt provides only a moderate amount of groundwater and is generally used for domestic wells.

Although in recent years some municipalities have begun to tap groundwater wells, historically most have relied on surface water. Exploiting the Willamette River since 2002, the Wilsonville water treatment plant processes the flow and markets it to customers as potable. The state's three largest urban regions, Portland, Salem, and Eugene, are fortunate in that their supplies from Bull Run Lake, from the North Santiam River, and from the McKenzie River are protected by legislation from pollution, contamination, and depletion.

In light of probable global warming and increased water usage, monitoring the western United States snowpack is essential. A 2009 paper by Michael Strobel of the Natural Resources Conservation

Service in Portland stresses the need to compile annual snowpack data as a critical component of the regional water supply for populated areas of the Willamette Valley. In this province at least 50 to 80 percent of the water needs are provided by snowmelt.

Geologic Highlights

Hills, Buttes, and Volcanoes

During the Eocene Epoch, the ocean shoreline along the eastern border of the Willamette Valley was punctuated by volcanic vents that are visible today as topographic features projecting above the floor. Aligned from Salem to Eugene, 14 isolated buttes are composed of 30-to-35-million-year-old basalts. The origin of the buttes varies, but their mineral and chemical composition and age suggest that they are substantially older than the Miocene Columbia River basalts. In the past they have been interpreted as lava flows, but most are now seen as ancient volcanic plugs or sills, where magma invaded the sedimentary layers. Visible from Interstate 5, Hale Butte, Hardscrabble Butte, and Knox Butte are composed of Little Butte volcanics. Once the surrounding ash layers were eroded, the hard basalt was exposed as small rounded hills.

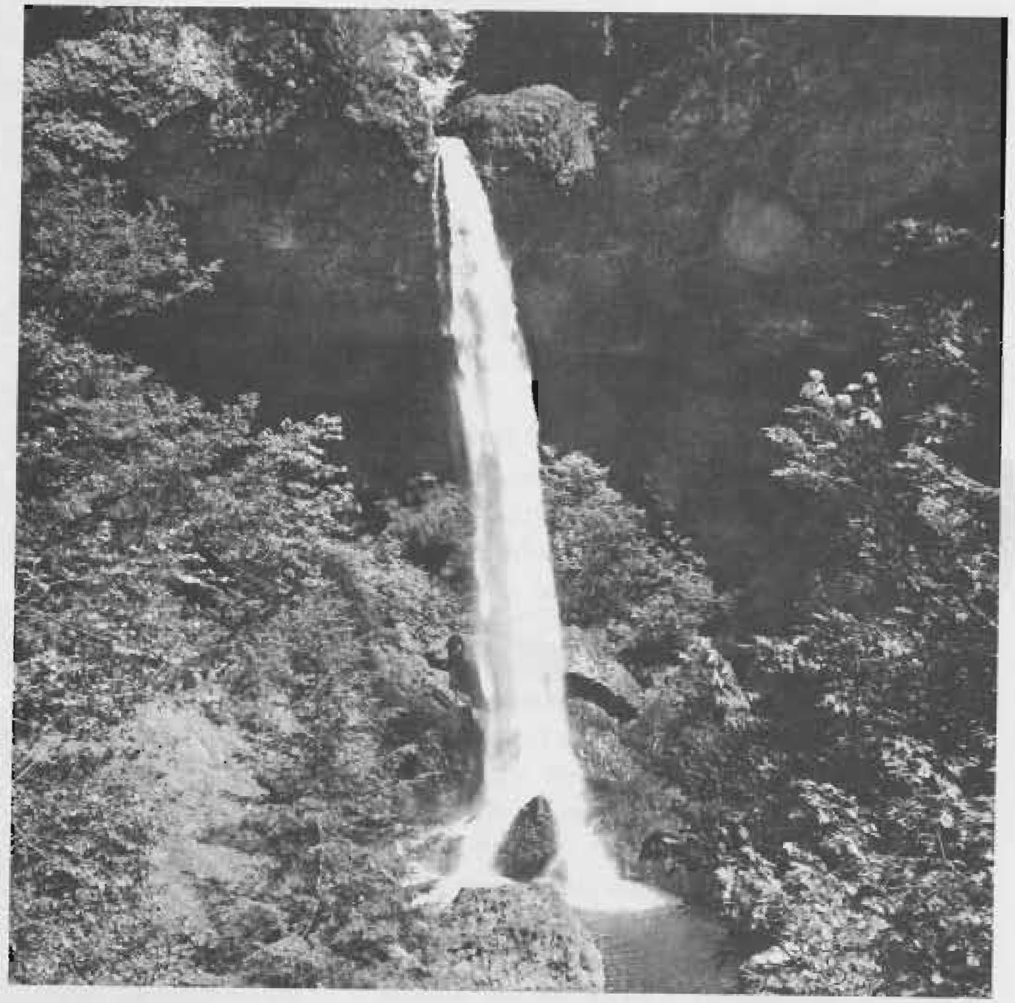
Near Albany, Knox Butte is the most northerly of these, rising 634 feet above the valley floor, while Peterson Butte, with the highest elevation at 1,434 feet, has 12 dikes radiating from the cone. Southward to the Coburg Hills, the buttes average just over 600 feet high. West Point Hill, Rock Hill, and Lenon Hill are spurs of resistant rock from Western Cascade eruptions that extend into the valley.

Silver Falls

Silver Falls was set aside as a state park near Silverton in 1933. It is the largest in Oregon, covering 9,000 acres. Of the 15 cataracts in the park, South Falls drops 177 feet into a beautiful, deep plunge pool, while the North Falls, at 136 feet, has worn away a 300-foot amphitheater in the softer fossiliferous sandstones behind the tumbling water. Chimney-like holes in the overhang are molds where lava surrounded and engulfed standing trees. When the flow cooled, only the shape of the trunks remained.

Thirty million years ago, the region around Silver Falls lay at the edge of a shallow Oligocene ocean. Once the seaway had receded, flows of middle Miocene Columbia River basalts covered the area only to be enveloped by ash and lavas from Cascade volcanoes. Streams began to work their way down through the layers, selectively removing the softer ash beds. Where the large streams easily cut through the basalts, eroding deep canyons, the smaller creeks with less volume wear away at the rock more slowly. Consequently a lip of basalt remains, which allows the water to spill over.

In Eugene, the face of Skinner Butte, rising 682 feet, displays jointed columnar basalt as does the 602 foot high Gillespie Butte across the river. Spencer Butte dominates south Eugene at 2,065 feet. Both Skinner and Spencer buttes are Tertiary sills that intruded the Eugene Formation. (Photo taken by James G. Houser; courtesy Condon Collection)



North Falls at Silver Falls State Park drops over an edge of Miocene Columbia River basalt into a plunge pool cut into Oligocene marine rocks of the Scotts Mills Formation. (Photo courtesy Oregon State Highway Department)

Table Rock

About 35 miles east of Salem, Table Rock is visible on the skyline of the Western Cascades. Shaped like a cardinal's hat, the distinctive summit and surrounding 5,500 acres are overseen by the Bureau of Land Management, which dedicated the wilderness area in 1984. Access to the crest of the monolith is provided by a moderately strenuous hiking trail through a dense forest that begins on the north face and winds almost completely around the edifice to ascend from the south.

A dissected remnant of late Western Cascades lava flows, Table Rock is capped by isolated exposures of resistant basalt. Columnar fractures in the lava and scattered outcrops on surrounding peaks attest to its volcanic nature.

Urban Geology

There are numerous fieldtrip, hiking, and roadside guidebooks to geology for those traveling far-flung distances by automobile, but few offer walking or biking excursions centered on compact metropolitan areas. One of the earliest proponents of urban geology, Ralph Mason provided an unusual look at the stone facings on Portland's buildings in his several publications. A mining engineer with DOGAMI, Mason's descriptions of structures which have since been altered or torn down make his accounts of particular historic interest. Also with DOGAMI, Ian Madin's 2009 overview and guide to Portland is well-illustrated and thorough.

Local colleges and geologic societies frequently offer tours and talks on urban sites. Formerly at Portland State University, Leonard Palmer's 1973 urban environmental guide to Portland focuses on geohazards.