High Lava Plains

Landscape of the High Lava Plains

The geologically young High Lava Plains is an elevated desert plateau 50 miles wide and 150 miles long. Centrally located in Oregon, it borders five other regions. The Blue Mountains lie to the north, the Basin and Range and Owyhee Uplands to the south and southeast, and the Cascade Range is to the west. The northwestern corner shares a small boundary with the Deschutes-Umatilla province.

The overall topography is smooth with moderate relief, averaging just over one mile above sea level. Elevations range from a high of 7,984 feet at Paulina Peak, within the Newberry Volcano center, to 4,080 feet in Harney Basin. Between these two features, the level plain is broken sporadically by low rounded domes and steep-sided, flat-topped ridges.

Annual rainfall amounts are modest, and because of the xeric climate, juniper, sagebrush, and grasses predominate. Deeply eroded topography is lacking, and most tributary streams are seasonal, without well-defined channels. Water in the largest two lakes in Malheur and Harney basins is supplied by precipitation and snowmelt and from the Donner and Blitzen River, Silver Creek, and Silvies River. With its headwaters on Steens Mountain, the Donner and Blitzen drains around 200 square miles. Silver Creek and Silvies River both originate in the Blue Mountains. The watershed of Silver Creek is small, but Silvies River drains close to 950 square miles.

Past and Present

With the exception of Israel Russell's 1905 reconnaissance of central Oregon that included an extensive look at both the geology and water resources, early reports on the High Lava Plains concentrated on Harney Basin or Newberry Volcano. Arthur Piper and others of the U.S.G.S. published on the Harney Basin in 1939, followed by the works of George Walker during the 1960s. Howel Williams reported on Newberry Volcano in 1935 at the same time that Phil Brogan's many articles on the geology began to draw attention to the province.

Few did more to popularize the natural history of central Oregon than Phil Brogan, who contributed hundreds of articles to the *Bend Bulletin* and Portland *Oregonian* during his thirty-year-career. His book *East of the Cascades* remains a standard source for regional information. Born at The Dalles in 1896, Brogan attended school in an old sheep cabin before studying journalism and geology at the University of Oregon. During his years in eastern Oregon, he worked with geologists throughout the northwest. Retiring, Brogan and his wife Louise moved to Denver, where he died in 1983. (Photo courtesy Condon Collection)

Norman Peterson's numerous technical and popular articles and field trip guides on the volcanic terrain make him a major contributor to the investigation of eastern Oregon's geology. Co-authored with private geologist Ed Groh, his papers describe such highlights as Crack-in-the-Ground, Diamond Craters, and Fort Rock. Receiving his degree from the University of Oregon in 1957, Peterson took a position with the Oregon Department of Geology and Mineral Industries (DOGAMI), where his career spanned 25 years. He directed the Grants Pass office until retirement in 1982. In conjunction with his work, Peterson produced mineral evaluations and maps of Harney and Malheur counties and assessments of volcanic hazards, culminating in his editing of the Lunar Geological Field Conference Guidebook. Peterson died in 1994. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Raymond Hatton, who taught at Central Oregon Community College in Bend until retirement in the mid 1990s, has written several books that included the geology and natural history of the high desert. Teaching geology locally for many years, Lawrence Chitwood, with the Deschutes National Forest, also contributed articles on aspects of volcanism. Overview papers on the tectonic and volcanic development of the High Lava Plains by Martin Streck at Portland State University, Anita Grunder at Oregon State University, and Brennan Jordan at the University of South Dakota bring together earlier research and present a current perspective. Robert Jensen's 2006 roadside guide gives a detailed look at the events surrounding Newberry Volcano.

Overview

The High Lava Plains province offers a remarkable variety of exceptionally young lava flows, cones, and buttes which punctuate the otherwise subdued topography. Volcanism that began in the Miocene and continued into the Holocene is often bimodal in composition—lavas vary from rhyolitic to basaltic in composition. Additionally, the locus of rhyolitic activity moved progressively across the province from southeast in the Harney basin to Newberry Crater in the northwest. By contrast, the basaltic lavas were not age progressive, but often spread widely as lava fields, and most vents are located near Bend.

Volcanism didn't cease with the onset of Pleistocene glacial conditions, and the violent interaction of magma and water in pluvial lakes created unusual eruptive features such as circular pits and tuff rings. Similar to those in the Basin and Range, Ice Age lakes in the Fort Rock and Christmas Lake valleys were ephemeral and diminished with post-glacial warming. The broad lacustrine expanses drew mammals and birds to the habitat.

Norm MacLeod together with George Walker completed the first comprehensive *Geologic Map of Oregon* in 1991. MacLeod was born in Victoria, British Columbia, but moved to the United States at a young age, where he grew up, for the most part, in southern California. His graduate work in the University of California system culminated with a PhD from Santa Barbara in 1970. After 25 years with the U.S.G.S., MacLeod retired in 1986 to live along the Nisqually River in the Washington Cascades. (Photo courtesy N. MacLeod)

The diversity of eruptive features on the High Lava Plains is its greatest resource. Lava tubes, acres of pahoehoe and aa flows, domes, and the immense Newberry stratocone and its surrounding complex are among the most outstanding sights in the Pacific Northwest.

Geology

Cenozoic

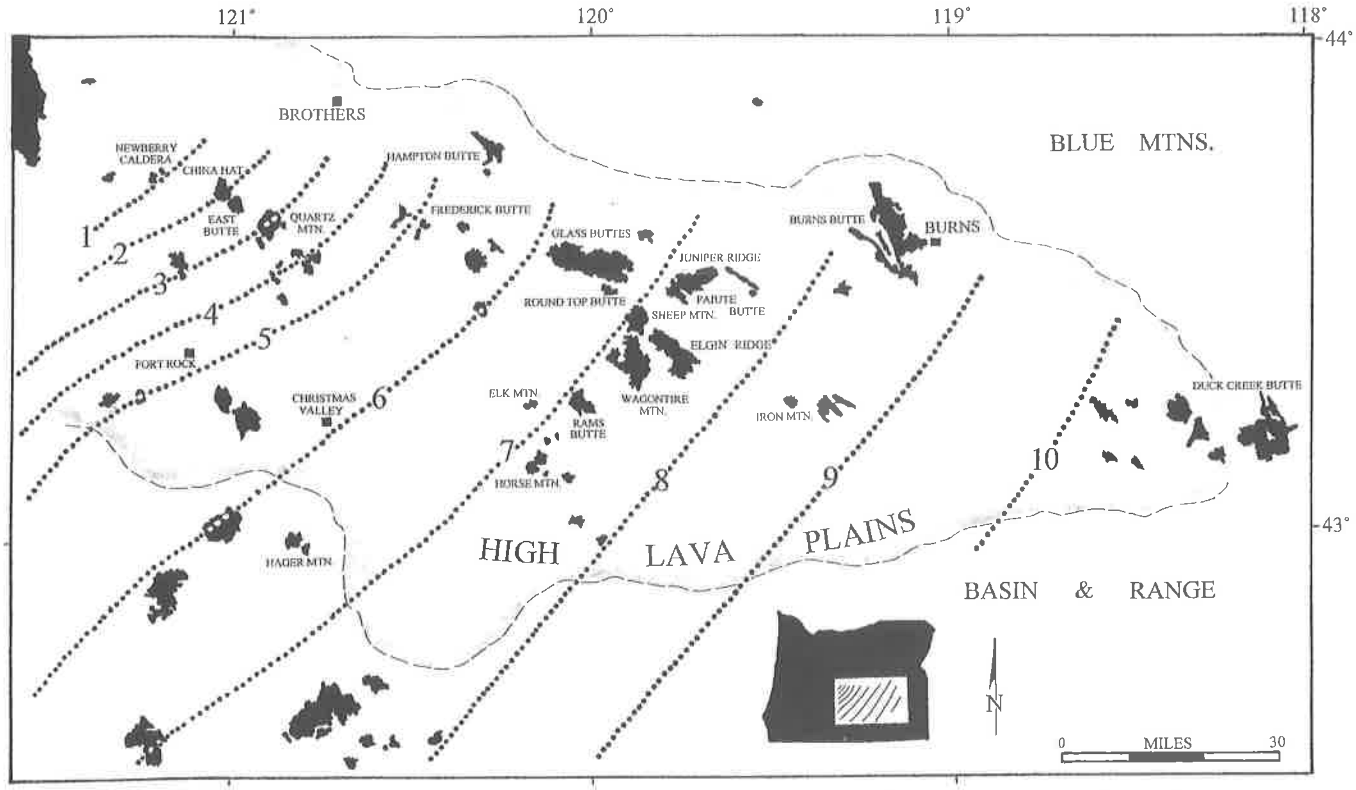
The oldest rocks in the High Lava Plains are Miocene lavas and tuffs, although Paleozoic and Mesozoic terranes, present in the adjacent Blue Mountains, are presumed to be buried beneath the younger volcanic layers. A veneer of late Miocene to Holocene lavas, obsidian flows, and ash from numerous volcanic vents is widespread.

Bimodal Volcanism

Bimodal volcanism and age progression of the eruptions characterize the geology of the High Lava Plains. With bimodal volcanism, lavas are distinctly different in composition, varying from dark-colored fluid basalt to light-colored viscous rhyolites. Basaltic lavas tend to have a deeper source in the mantle, are extremely hot, and erupt as runny flows. The lower temperature rhyolites originate from shallow depths and erupt with explosive force. The association between basalts and rhyolites is not common and usually occurs where the earth's crust thins due to tension and stretching. Basalts elsewhere appear during an early stage of eruption, whereas rhyolites emerge late in the cycle. But in this province, the rhyolitic eruptions are older, although the younger basaltic lavas are greater in volume.

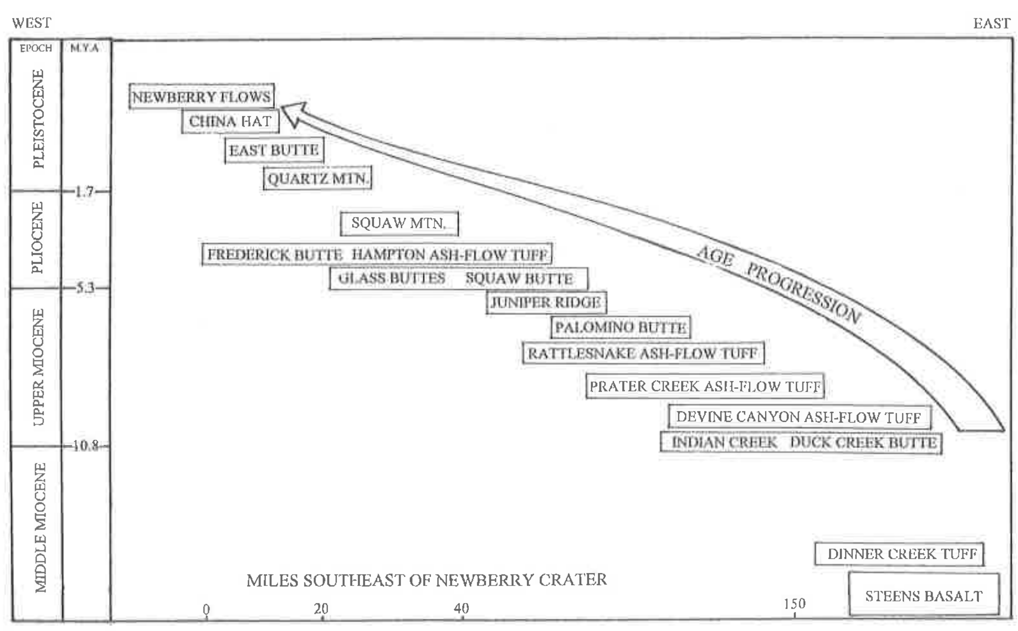
Age Progression of Volcanic Eruptions

One of the most striking aspects of volcanism here is the geographical age progression of the rhyolitic eruptions, first recognized in the 1970s by Norm MacLeod, George Walker, and Ed McKee. Lavas from a broad belt of approximately 100 centers became



Eruptive centers moved progressively from the late Miocene rhyolites in the southeast to the Pleistocene and Holocene flows and ash in the northwest. Contoured (dotted) lines show the movement of volcanic activity from east to west in millions of years. (After Jordan, Streck, and Grunder, 2002; MacLeod, Walker, and McKee, 1975; Walker and Nolf, 1981)

younger westward from the Owyhee Uplands and across the Lava Plains toward the Cascades. The uniform decrease in age prograded at 20 miles every million years between 10.5 to 5 million years ago, then slowed to 9 to 18 miles after that. The oldest lavas at Duck Creek Butte east of Harney Basin date back over 10 million years, while the most westerly Newberry complex erupted as recently as 1,300 years ago. A wide zone of silica-rich rhyolitic domes in the Basin and Range between Beatys Butte and Yamsay Mountain displays a similar east to west progression.



Tertiary stratigraphy of the High Lava Plains. (After Johnson and Grunder, 2000; Jordan, Streck, and Grunder, 2002; MacLeod, Walker, and McKee, 1975; MacLeod, et al., 1995; Sherrod, et al., 2004; Walker, 1979)

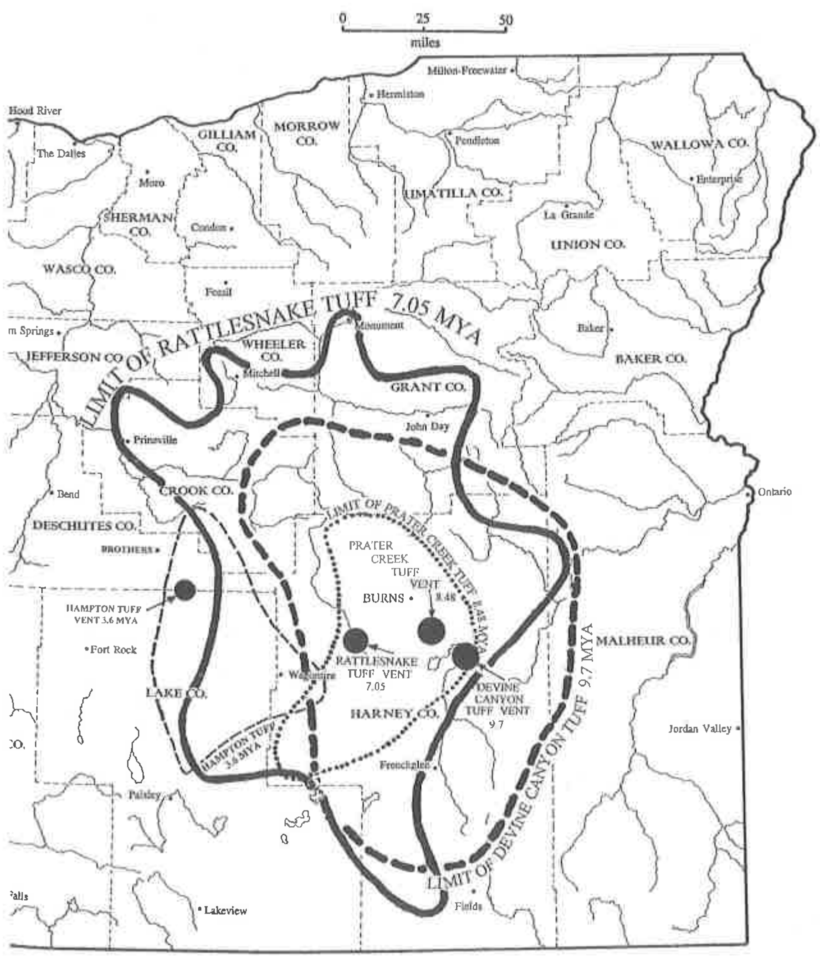
A number of theories address the progressive nature of the eruptions. Whereas earlier ideas focused on the movement of tectonic plates, subplate geometry, and crustal thinning, current research favors the activity of a hot spot. Around 17 million years ago, a hot spot or mantle plume (Yellowstone), centered at the junction of Oregon, Nevada, and Idaho, melted crustal rocks which reached the surface as flood basalts. The heat source for mantle plumes is not well understood, but when the balloon-like head of the Yellowstone hot spot encountered the edge of the North American continent, it began to flatten and divide before being sheared off. One of the tongues migrated northward from Steens Mountain into the Columbia plateau, and a second spread westward across central Oregon, triggering the age progression on the High Lava Plains and Basin and Range. In 2004, Camp and Ross proposed that a third tongue projected south across Nevada as a rift zone of volcanics, while the severed stem left a track across southern Idaho as the Snake River Plain.

Rhyolitic Volcanic Centers

Duck Creek Butte and Harney Basin

The oldest rhyolitic eruptions across the High Lava Plains began near the extreme southeastern border at Duck Creek Butte 10.4 million years ago. In contrast to the silica-rich rhyolitic cones which dominate the western segment of the vents, the Duck Creek Butte lavas were more andesitic and dacitic in composition. From the Basin and Range, the north-northeast-striking Steens Mountain fault cuts into Duck Creek Butte as do faults within the Brothers system.

Intersected by the Brothers fault zone, Harney Basin was the next in the progressive sequence to be impacted by eruptions. Volcanic and sedimentary deposits in the 3,000-square-mile basin reflect environmental changes that took place 17 million years ago with the onset of Miocene basalts from Steens Mountain. But as volcanism shifted westward, the region was overwhelmed with outpourings the Devine Canyon, Prater Creek, and



Source vents for the Hampton, Devine Canyon, Prater Creek, and Rattlesnake tuffs are situated in the Harney Basin southwest of Burns. It has been estimated that a huge caldera with a diameter of some 12 miles across would have been necessary for the erupted volume of the Rattlesnake Tuff. For its size, the Rattlesnake is one of the most far-travelled ignimbrites known, reaching 100 miles from the Harney Basin to John Day and Prineville. (After Rytuba, et al., 1990; Streck and Ferns, 2004; Streck and Grunder, 1997; Walker and Robinson, 1990)

Rattlesnake tuffs, representing the greatest volume of rhyolites on the High Lava Plains. Derived from local vents, air-borne pyroclastics and ash-flows of the Devine Canyon Tuff, dated at 9.7 million years ago, the overlying Prater Creek Tuff, and the capping 7-million-year-old Rattlesnake Tuff were originally lumped together as the Danforth Formation. Today, the three distinctive stratigraphic layers are recognized over vast regions of southeast and central Oregon. The greenish-gray Devine Canyon Tuff has been traced from Steens Mountain to Paulina Valley, an area of 7,000 square miles, whereas the Prater Creek ash-flow tuff is limited almost completely to exposures in the Harney Basin.

Palomino Buttes, Juniper Ridge, Squaw Butte, and Glass Buttes

Palomino Buttes at 6.29 million years of age, Juniper Ridge dated around 5.75, and Squaw and Glass buttes at 5 million years ago continue the northwestward-trending line of younger rhyolitic centers. Issuing from clusters of vents, Glass Butte, Little Glass Butte, eastern Glass Buttes, and Roundtop Butte are low domes, aligned in a west-northwest direction for about 12 miles. The domes were constructed during an eruptive phase that may have lasted over a million years. Significant amounts of obsidian at Glass Butte give the complex its name. Besides the common black obsidian, there are mixtures of red and black as well as iridescent silver. Obsidian or volcanic glass has no internal crystalline structure, and its failure to form crystals is due to the rapid cooling of the lavas. Small amounts of quicksilver have been mined from the volcanics of the buttes.

Hampton Butte, Dry Butte, Frederick Butte, Quartz Mountain

Rhyolites from vents near Hampton and Dry buttes erupted close to 8 million years ago. These lie along the northern margin of the High Lava Plains and the most northerly faults in the Brothers zone. A second period of volcanism around 3.8 million years ago produced the Hampton Tuff, an ignimbrite originating from Frederick Butte. Thin layers of this ignimbrite are readily distinguished by the abundance of dark pumice fragments. Frederick Butte is a semi-circular caldera, in which older eruptions may have built a dome before the center collapsed. Subsequently, the pit filled with lava from dikes along Last Chance Ridge.

Situated west of Frederick Butte and approximately 3 million years younger in age, Quartz Mountain consists of two domes. Exposures of the rhyolite flows display streaked layers of dark brown to black obsidian and fresh glassy surfaces.

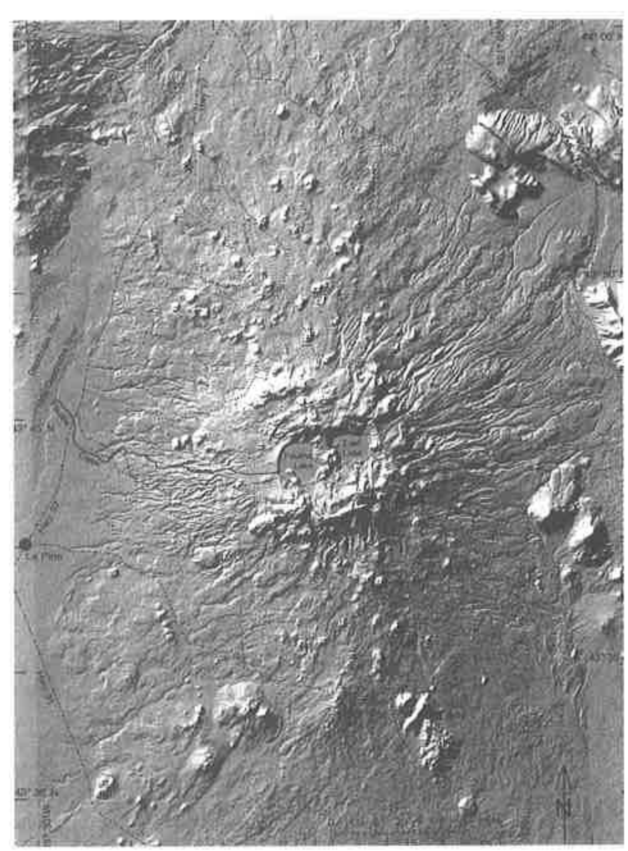
East of Newberry, the 800,000-year-old China Hat is a rhyolitic dome that erupted near the western end of the province. (Photo courtesy J. Mooney)

At the westward termination of the age progression, Newberry caldera is a stratovolcano with an eruptive life that began with voluminous flows 300,000 years ago. Successions of silica-rich rhyolitic lavas interspersed with andesitic flows and tuffs erected the summit 80,000 years ago, after which collapse produced a caldera similar to that at Crater Lake. More than a dozen postglacial eruptions are interlayered with the distinctive 7,700-year-old pumice and ash from Mt. Mazama to the southwest. (Shaded relief image from 10 meter digital elevation model; Jensen and Donnelly-Nolan, 2009)

Newberry Volcano

Located on the western edge of the High Lava Plains, eruptions from Newberry Volcano are the youngest in the age-progressive cycle. The long outer slopes of Newberry are sprinkled with over 400 parasitic cinder cones, aligned in a 20-mile–long northwest rift zone toward Bend. The most northerly is Lava Butte, whose flows 7,000 years ago entered the Deschutes River channel, damming and diverting the water. A two-mile-long east rim system of 19 rhyolitic domes, flows, and small explosion craters, arranged in a radial pattern around the central Newberry Crater, are blanketed by a thin veneer of Mt. Mazama ash.

Because of Newberry's position east of the Cascade volcanic arc and because of its history of both rhyolitic and basaltic lavas, the nature of its eruptive cycle has been difficult to characterize. In comparing Newberry with the similar Medicine Lake volcano in northern California, Julie Donnelly-Nolan at the U.S.G.S. has concluded that both are rear-arc Cascade volcanoes related to subduction in a region of extensional tectonics.

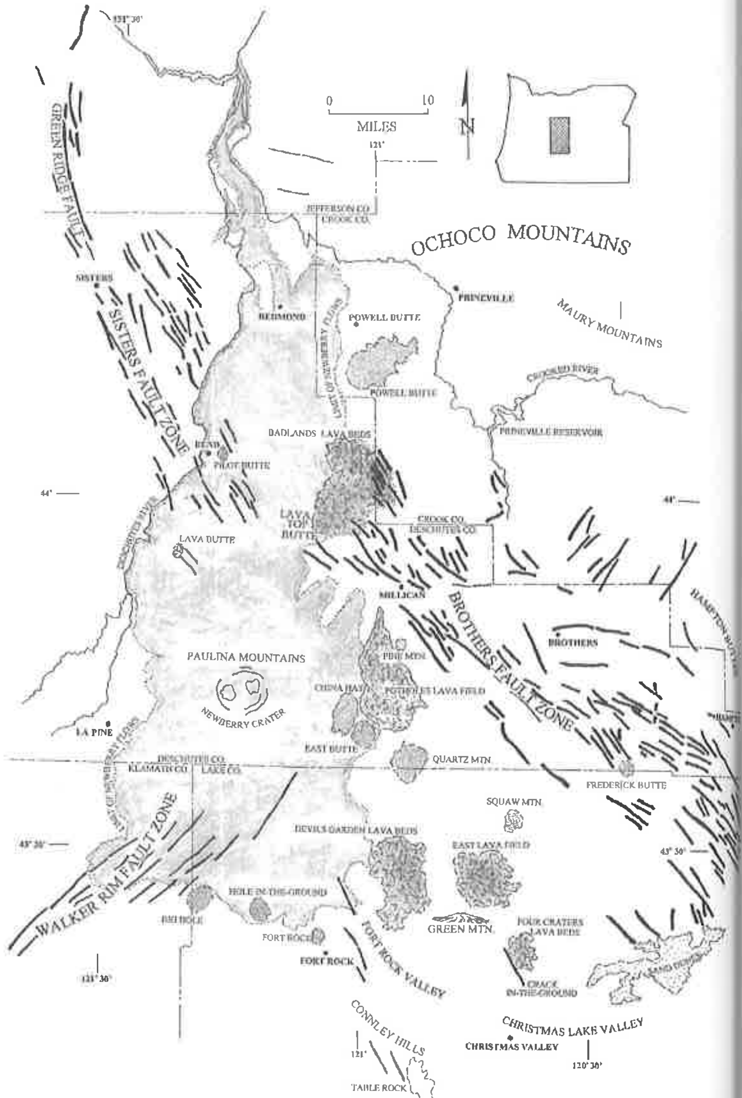


Basalt Volcanic Centers

Miocene to Holocene basalts punctuate the relatively flat surface of the High Lava Plains with distinctive structures and landforms. Eruptions of the fluid basalts are not age progressive like the rhyolites, and most originate from a central vent or from an aligned vent system. The older exposures are found along escarpments, whereas the Quaternary flows, with thicknesses up to 15 feet, cover wide areas that range in size from the Devils Garden at 45 square miles, the Potholes and Badlands close to 25 square miles, and the smaller Four Craters at 12 square miles.

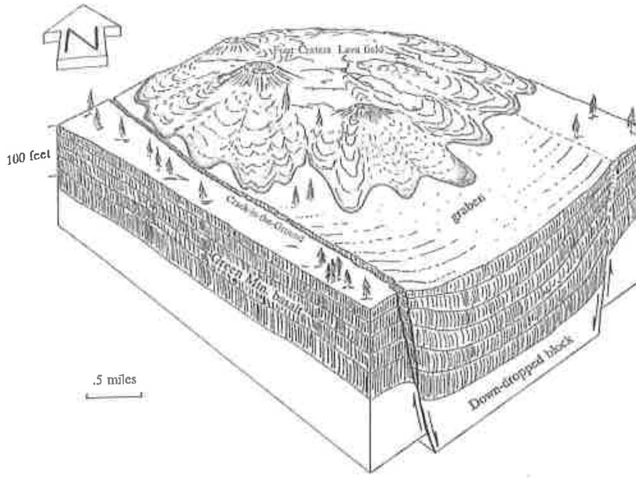
Basalt fields share a number of features such as the alignment of fissures, the age of the eruptions, and the composition of the lavas. Four Craters, East Lava field, Devils Garden, and the Potholes originated from northwest-trending fissures. Vents in the Four Craters field also extend northwestward toward craters in the Lava Mountain shield volcano complex, which produced the East Lava field. Devils Garden and the Potholes are both similar in composition and age, erupting around 50,000 years ago, whereas the Badlands, built by Lava Top Butte, is slightly older at 74,000 years. The 1,000 year date for the Four Craters eruption has been inferred by assessing the vegetation cover and surface erosion.

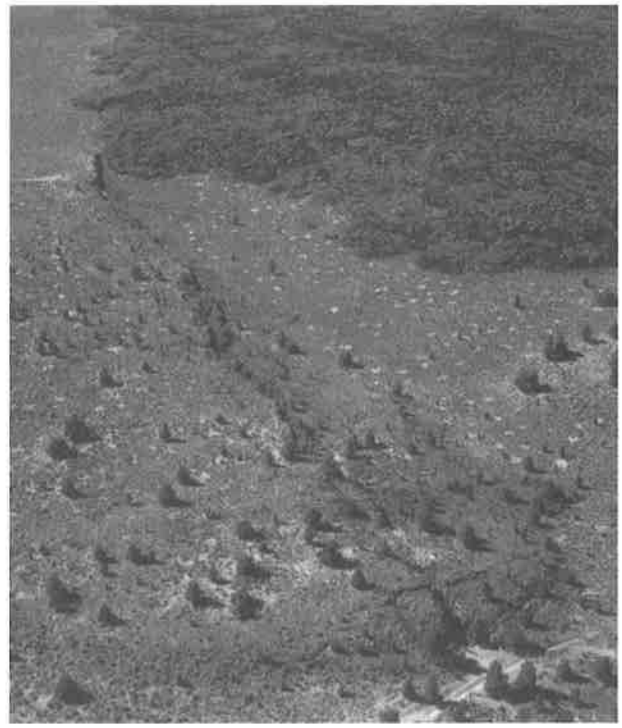
Some distance from the basalt layers at Bend, Diamond Craters lies at the east edge of Harney Basin. Dated at 17,000 years old, the complex encompasses over 30 cinder cones within a six-mile circular



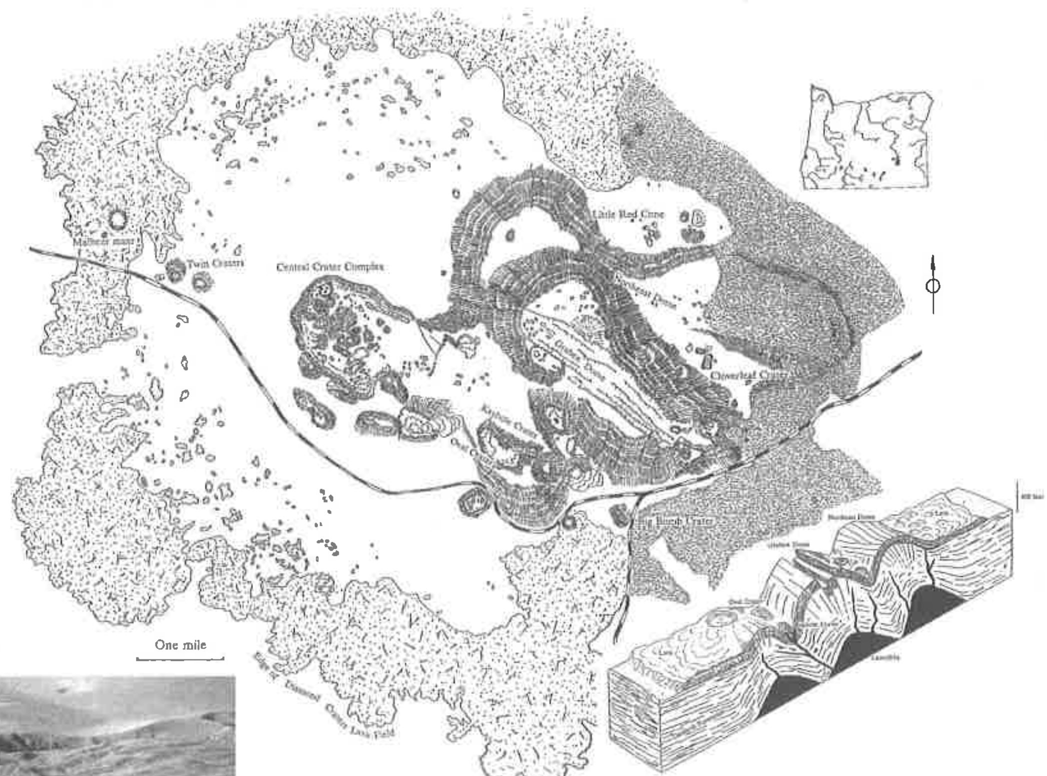
On the western High Lava Plains, the majority of Miocene to Holocene basaltic centers are clustered southeastward from Bend at the Badlands, the Potholes, the Devils Garden, the East Lava field, and the Four Craters. (After Jensen, et al., 2009; Jordan, Streck, and Grunder, 2002; Meigs, et al., 2009)

The phenomenon of inflated lava is well-illustrated by the basalt fields near Bend. As described by Larry Chitwood, inflation is an upward swelling or doming, known as a tumulus, that results after the initial thin lava flow, some eight to ten inches thick, has spread out, then slowed beneath a hardened outer crust. When molten material continues to move through the structure, the surface rises or inflates to thicknesses from 5 to 60 feet before cracking to produce a very rough topography. Ridges, pits, or raised, broken and tilted basaltic slabs, and caves are signs of internal swelling and inflation. (Photo courtesy Condon Collection)





Crack-in-the Ground is a northwest trending 15-foot-wide, 2-mile-long rift that opened in 740,000-year-old basalts from the Green Mountain shield volcano. The crack extends to the Four Craters field where the flow entered the north end. Later subsidence of the Green Mountain basalts produced a lengthening of the crack toward Fort Rock basin. Silvio Pezzopane and Ray Weldon suggest that the fracture coincides with the normal northwest fault pattern in the Basin and Range. (Diagram after Peterson and Groh, 1964; photo courtesy Oregon Department of Geology and Mineral Industries)



At Diamond Craters, the middle and most notable of the large cones is the Central Crater field (above), a moonscape of undulating pahoehoe and pits. (After Peterson and Groh, 1964; Photo courtesy Oregon Department of Geology and Mineral Industries) area, where magma welled up from an alignment of vents, and intrusions bowed the ground into three low domes. After the doming, violent eruptions expelled showers of football-shaped bombs that range from pea-sized to as much as two feet in diameter. The debris was briefly airborne, then fell, encircling the crater, which fractured and collapsed.

Structure and Faulting

Three discontinuous fault zones—the Brothers, the Sisters, and the Walker Rim—intersect the High Lava Plains. The east end of the lengthy Brothers fault system emerges from the Steens Mountain escarpment and terminates near Newberry Crater. As with the Sisters and Walker Rim faults, the westerly end point is buried beneath Pleistocene lavas.

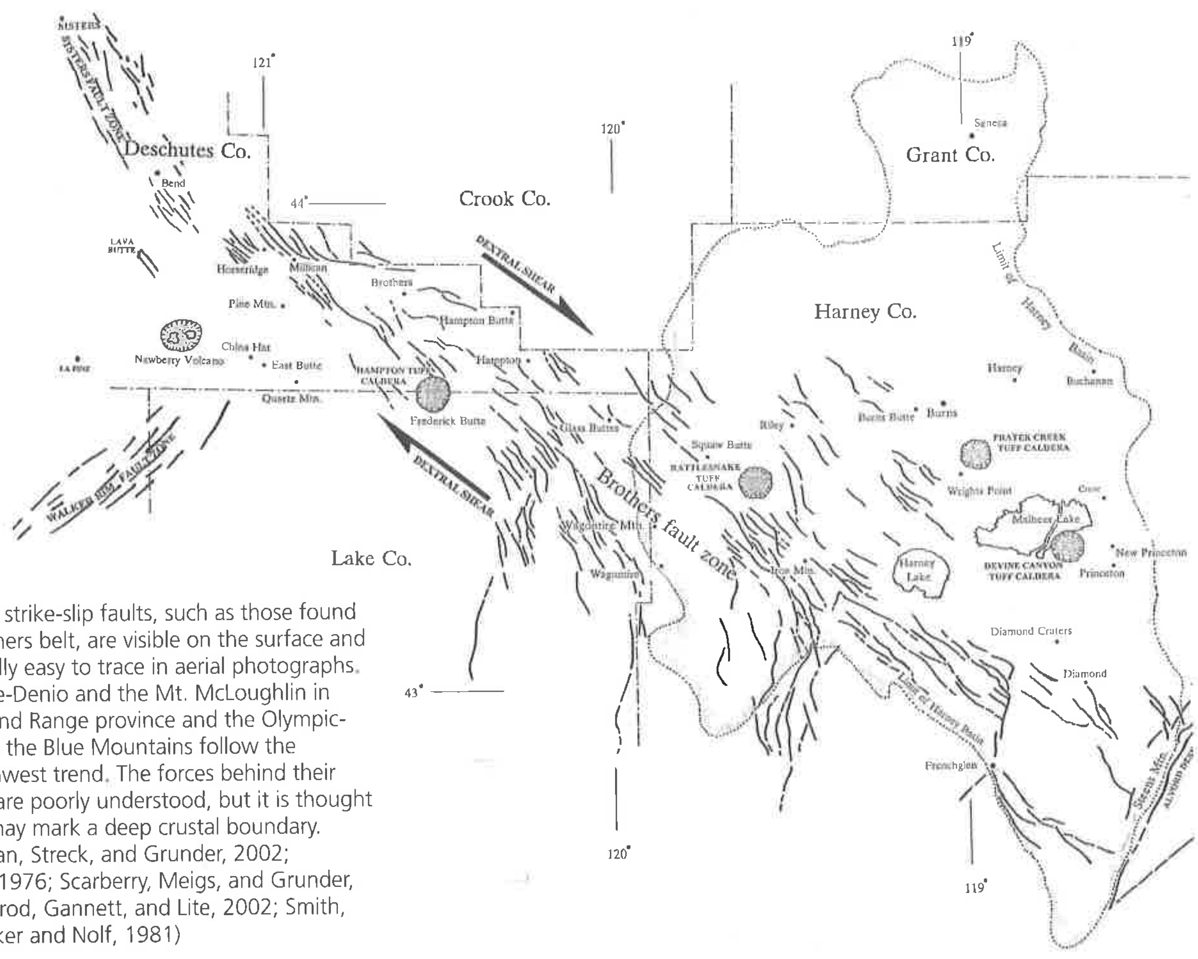
The Brothers strike-slip faults have been interpreted as the surface expression of the boundary between the thinner crust of the Basin and Range and the thicker crust of the Blue Mountains. Individual faults are irregularly spaced at quarter-to-two-mile intervals with displacements of less than 50 feet.

Projecting from Black Butte in the Cascades toward Bend, almost 50 separate faults occur within the Sisters zone. This system is around 10 miles wide and 40 miles long, and the most extensive thread is the 30-mile-long Tumalo fault.

Pleistocene Precipitation and Pluvial Lakes

The Pleistocene Epoch, which ended some 10,000 years ago, was a time of continuing volcanism as the climate cooled and continental ice masses moved southward out of Canada. Evidence of glacial erosion in the High Lava Plains was thought to be lacking; however, Robert Jensen, retired from the U.S. Forest Service, and Julie Donnelly-Nolan document glacial features within the Newberry Volcano system. Erratics some distance from the caldera rim, meltwater channels on the east and west slopes, and lava flows interlayered with glacial debris suggest the crater underwent modifications during the Ice Ages.

Increased Pleistocene rainfall filled pluvial lakes at Fort Rock, Christmas Lake, and Malheur Lake. The largest of these, prehistoric Fort Rock Lake, occupied



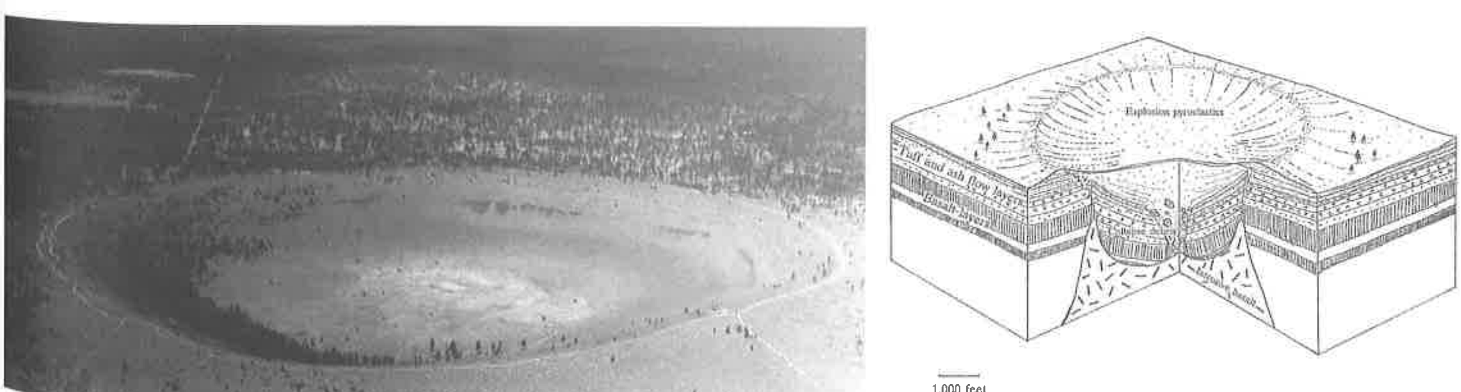
Large-scale strike-slip faults, such as those found in the Brothers belt, are visible on the surface and are especially easy to trace in aerial photographs. The Eugene-Denio and the Mt. McLoughlin in the Basin and Range province and the Olympic-Wallowa in the Blue Mountains follow the same northwest trend. The forces behind their formation are poorly understood, but it is thought that they may mark a deep crustal boundary. (After Jordan, Streck, and Grunder, 2002; Lawrence, 1976; Scarberry, Meigs, and Grunder, 2010; Sherrod, Gannett, and Lite, 2002; Smith, 1986; Walker and Nolf, 1981)

In Lake County, tuff rings and maars are striking volcanic features, formed when magma and groundwater interacted. The Fort Rock tuff ring lies within a shallow Pleistocene lake basin. The wide breach in the south rim is due to wave action breaking the thin volcanic walls. (After Peterson and Groh, 1963; Photo courtesy Condon Collection)

an irregular basin that was 40 miles wide, and only Malheur Lake rivaled it in size. During times of high water, the separate lakes became interconnected, often reaching depths in excess of 350 feet. During dry intervals, rocks, projecting as islands, became peninsulas, and arms of the lake became bays, until only isolated marshes and swamps remained. Sediments of the paleo-lakes preserve an outstanding record of Ice Age mammals, birds, and fish, as well as yielding artifacts by early man. Fossil bones in the lake sands are a distinctive shiny black color.

Except where obscured by younger lavas in the vicinity of the Devils Garden, the 30,000-year-old shorelines of Fort Rock Lake are well marked by gravel bars and beach deposits. At one point the water body included the now dry Silver and Fossil lakes. Bones of the anadromous salmon and the presence of the fresh-water snail, *Limnaea*, found at Fossil Lake, are known only in the Columbia River drainage and are evidence that the lake may have drained through a northern route to the sea.

Prehistoric Malheur Lake occupied an area from the present-day basin southwestward across Mud Lake and into Harney Lake, where the oldest fluvial sediments, which covered the ignimbrites, have been dated at 70,000 years. Paleo-shorelines of the pluvial lake trace Quaternary variations in the water levels that reached a maximum elevation around 4,000 feet. Lake Malheur began to dry by 7,500 years ago, draining into the South Fork of the Malheur River and from there to the Snake River, before the outlets near Princeton and Crane were dammed by lava. Ultimately, the lake shrank in size to small playas, marshes, and saline puddles.



Hole-in-the-Ground is a maar of remarkable symmetry, which exploded between 100,000 to 50,000 years ago when rising magma from Newberry Volcano encountered groundwater. The pit is close to a mile in diameter, and the floor is over 300 feet below the regional ground surface. Massive collapse blocks have slumped from the rim and are overlain by layers of ash and tuff. (After Peterson and Groh, 1961; Photo courtesy Oregon Department of Geology and Mineral Industries)

Pleistocene Volcanism and Groundwater

The presence of tuff rings, maars, and other hydrovolcanic features, clustered in the Fort Rock basin, demonstrate the catastrophic relationship between magma and Ice Age conditions at a time when fluctuating lakes covered hundreds of square miles. Symmetrical craters, maars and tuff rings result when rising magma encounters groundwater (phreatomagmatic). The resulting steam explosion throws rocks and ash high into the air. Settling close to the crater, the debris builds a rim or tuff ring. Saucer-shaped maars are formed by the same process but in shallower water. The craters are often fed from below by a diatreme, or funnel-like vent, which ultimately fills or is blocked with angular pieces of debris. These landforms are frequently obscured by vegetation or are badly eroded. Four tuff rings and maars located in Lake County are Fort Rock, Hole-in-the-Ground, Big Hole, and Table Mountain.

Resembling a castle, Fort Rock is an outstanding example of a crescent-shaped tuff ring, three-quarters of a mile in diameter, projecting 180 feet above the floor of the paleo-lake. Shattered rock, ash, and tuffs that make up the crater walls are a testimony to the violence of the event. After the initial eruptive stage, much of the ash fell back within the ring where the yellowish and brown tuffs dip inward toward the center.

An elongate oval at the edge of the Fort Rock basin, the Table Rock complex includes two overlapping tuff rings, one filled with rubble and the other capped by basalt. Several dikes exposed on the flanks between the two fed the flows. The large tuff cone was the first to erupt during a deep-water interval in contrast to the second surge when the magma encountered groundwater. Dates of the eruptions are uncertain.

A little over a mile in diameter, Big Hole is a circular maar created by a catastrophic phreatic (steam) explosion. A wide ledge within the basin may be the top of a large block that dropped into the depression during the eruption. Unlike Fort Rock and Hole-in-the-Ground, Big Hole is heavily forested. The trees and its immense size make this volcanic feature difficult to visualize from ground level.

Geologic Hazards

The potential for volcanic eruptions and flooding in this province has not been examined in great detail, but a case has been made by Daniele Mckay at the University of Oregon for future activity along the northwest fracture system, which extends from Newberry Crater toward Bend. Renewed volcanism from this structure might produce columns

The floor of Fort Rock Lake can be seen through a huge cleft in the wall. A cave in the wall here is famous as the locality where a 9,500-year-old sandal and other artifacts were discovered. (Photo courtesy Oregon Highway Department) of tephra and ash. Earlier eruptions blocked the Deschutes River, and such an occurrence today would find the community of Bend especially vulnerable.

In spite of the low rainfall, there are wet intervals when flood waters cover agricultural lands near the shallow Malheur, Harney, and Mud lakes. During El Niño years, the three lakes double or triple in size, even merging into one body. The water level in Malheur Lake is controlled by the Narrows. When it reaches 4093 feet in elevation, the water flows through the Narrows into Mud Lake, which, in turn, may discharge through Sand Gap into Harney Lake. In the early Holocene, Malheur Lake topped the ridge at The Narrows into Harney Lake several times, and record rainfall between 1981 to 1986 caused the three lakes, normally covering 100 square miles, to more than double. During the dry 1990s, only Malheur Lake had a residue of water in the low spots.

The alternating size of the lakes during dry and wet intervals can have serious legal consequences. In 1897, after years of drought, both grain growers and cattle ranchers claimed ownership of the exposed marshy bed of what had been Malheur Lake. The conflict ended in court after the murder of a prominent rancher, French Pete.

In 1934, Malheur, Harney, and Mud lakes were designated as the federal Malheur National Wildlife Refuge, a home for thousands of birds, native plants, and mammals.

Natural Resources

Geothermal Energy

Percolating from deep within the crust through cracks and fractures, heated water reaches the surface as warm or even hot springs. In the eastern High Lava Plains, thermal waters issue from perennial springs near Hines, in the Warm Springs valley, and around Harney and Mud Lakes. Some of the highest temperatures occur southwest of Harney Lake, where the 90° to 154° Fahrenheit waters indicate the proximity of a thermal source. Popular since the late 1800s, commercial facilities have been developed at many of the sites.

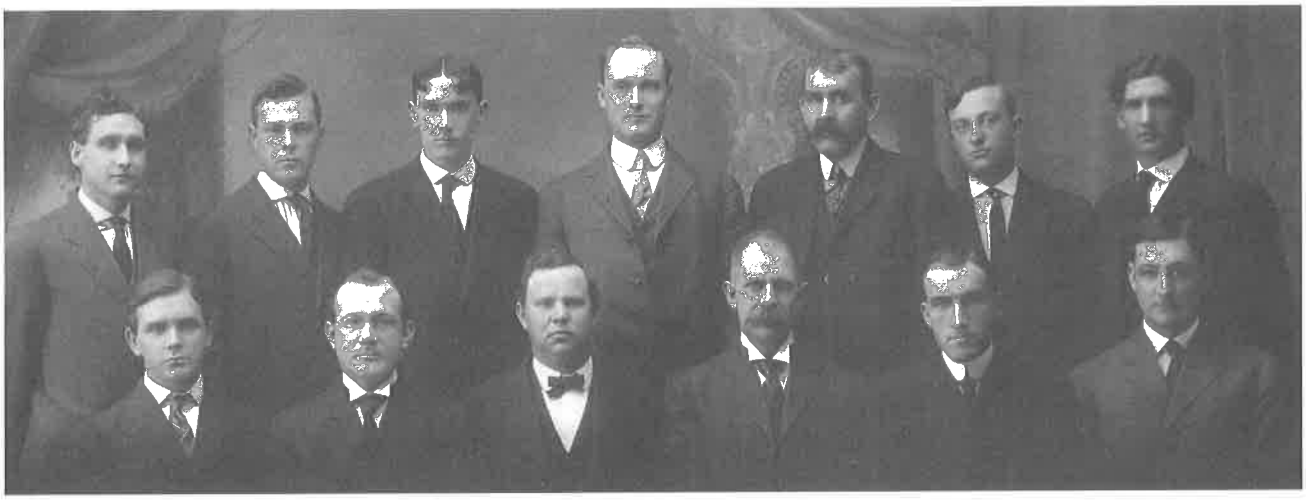
Because it is rated as Oregon's top potential geothermal site, Newberry Volcano has been the focus of intensive investigations over the past decade, but the establishment of the Newberry Volcanic National Monument in 1990 limited exploration to the flanks. Drilling encountered both near-surface and deeper hydrothermal systems that recorded temperatures at high as 500° Fahrenheit, however, water in the wells was very limited.

Surface and Groundwater

The High Lava Plains is a desert environment in which the available water supply varies widely. Evaporation is high and rainfall low. Precipitation, which ranges annually from less than eight inches in the valleys to 30 inches at the higher elevations can temporarily fill the streams, pond in shallow basins, or percolate into the ground. During dry years, the streambeds can be farmed, while in wet intervals thousands of acres of land might be flooded for months at a time.

Shallow groundwater levels exist in both alluvial and lakebed deposits and in volcanic rocks. The near-surface water table makes the aquifers susceptible to degradation from saline water at or beneath the playas, as well as from sewage and agricultural chemicals. Prior to the 1970s, less than 20,000-acre-feet was pumped annually with no long-term effects, but water levels have decreased steadily since the Oregon Water Resources Department began to issue 60,000 permits on low-interest federal and state-sponsored farm loans in the 1960s. The water table fell when withdrawal reached 80,000-acre-feet annually. It wasn't until 1986 that new appropriations were restricted, but then only after the aquifer had become critically depleted. Today irrigators vie with households for the resource.

Settlement, ranching, and farming in southcentral Oregon are dependent on adequate water, and at one time it was thought that a bountiful lake lay beneath the ground, but the perception did not match the reality. In 1921 the state legislature funded the drilling of four test wells in the Fort Rock basin to assess the situation. As the precursor to the state department of geology, the Oregon Bureau of Mines and Geology, founded in 1911, was to conduct the study. The Bureau was the logical choice because at that time it was based in the School of Mines at Oregon Agricultural College (later Oregon State University) in Corvallis, which offered courses to students interested in geology. It



Henry M. Parks was appointed Dean of the School of Mines as well as head of the Oregon Bureau of Mines. Parks, who had taken a degree in mining engineering from Iowa State College in 1909, moved to Oregon three years later. The legislature dissolved the Bureau in 1923, at which time Parks purchased land in the Fort Rock valley, where exploratory water wells were to be sited. The drilling program was declared a success, with wells producing 700 to 1,000 gallons a minute. But farmers still had to contend with leaky wooden flumes and water draining away into the lavas or evaporating. For the next 20 years Parks advocated pump irrigation, but it still had not become a reality when he died in 1945. (In the 1910 photo of the faculty at the School of Engineering and Mechanical Arts, Oregon State College, the mustached Parks is 3rd from the right in the back row.; courtesy Oregon State University, Archives)

wasn't until 1932 that the School of Science and a Geology Department were established.

Geologic Highlights

A drive eastward through the High Lava Plains gives an exceptional perspective on Cenozoic volcanism from the imposing Newberry Volcano to Harney basin. Sparsely vegetated lava fields, rounded cones, shrinking lakes, and expansive plains give way to flat-topped ridges and sheets of ash flow tuffs and lavas.

Volcanic Cones, Craters, and Flows

Quaternary volcanism and faulting on the High Lava Plains have erected some of Oregon's most extraordinary landmarks within the past 100,000 years. Preserved in the dry eastern Oregon climate, these features would have been eroded or obscured

South of Bend, Newberry Volcano is a cluster of lava flows, domes, lakes, and craters. Newberry National Volcanic Monument, dedicated in 1990 by President George Bush, includes the caldera, Lava Butte, Lava River Cave, and the Lava Cast Forest. Looking west in the photo, the central crater and East and Paulina lakes are enclosed by the five-mile-wide rim. Paulina Creek flows westward from Paulina Lake, dropping 100 feet as Paulina Falls to flow into the Deschutes River. Toward the south rim of the caldera, the summit of Paulina Peak at 7,984 feet above sea level affords an outstanding view. (Photo courtesy Condon Collection)

Spreading one and one-half miles from its vent, the Big Obsidian flow was Newberry's final and largest eruption 1,300 years ago. (Photo courtesy Condon Collection)

by vegetation in an environment with a higher rainfall.

Within the city limits of Bend, Pilot Butte served as a visible landmark for pioneers traveling to the Willamette Valley. At 600 feet in height, the lone cinder cone offers an impressive panorama of the Cascades and High Lava Plains with glimpses of the winding Deschutes River canyon. Discharged from a fissure 7,000 years ago, cinders and ash settled to build the symmetrical cone. Pilot Butte has been a state park since 1928.

Named for John Newberry, geologist with the Corps of Topographic Engineers in 1855, Newberry Volcano is the most exceptional volcanic feature of the province, and it is among the largest Quaternary stratovolcanoes in the United States. The caldera is an oval 30 miles long and 20 miles wide with a surrounding lava field encompassing 500 square miles. The oldest rhyolitic lavas formed the summit caldera 80,000 years ago, while obsidian flows and basalt cones that line the flanks and floor of the edifice are dated as recently as 1,300 years.

Placed at the northernmost end of a rift zone extending from Newberry Crater, Lava Butte cinder cone erupted close to 6,700 years ago. The event built the 5020-foot-high summit and sent lava over an area of 95 square miles, blocking the Deschutes River. Atop the cone, the newly remodeled Lava Lands Visitor Center has added the Lawrence Chitwood Exhibit Hall in honor of the popular lecturer, forester, and geologist who died unexpectedly in 2008 while hiking Pilot Butte. (Photo courtesy Condon Collection).

At the Lava Cast Forest, flows engulfed pine forests, much like those living in this area today. Some trees remained upright while others fell to be buried by the molten material. Once enclosed, the trees burned inside the hardening crust, leaving a mold the size and shape of the trunk. As the flow receded, rough cylinders in black lava were left standing as the Lava Cast Forest. (Photo courtesy Oregon State Highway Department)

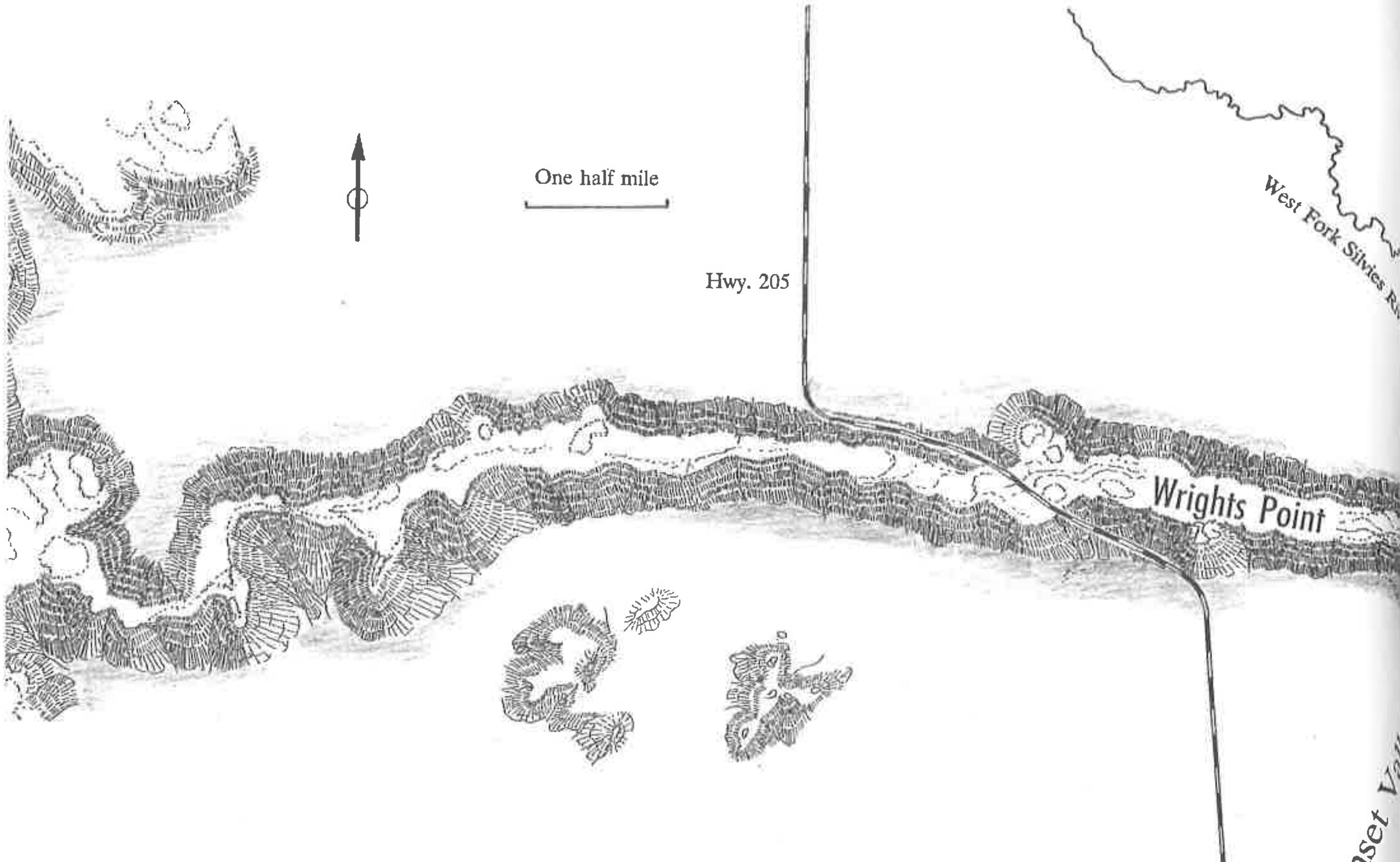
Part of the Newberry Volcano National Monument, Lava River Cave, formerly known as Dillman Cave, is one of the longest unbroken tubes in Oregon. Near the entrance, the roof has collapsed, and the main passageway is blocked by sand. Delicate formations, vertically stacked tubes, ledges marking the levels of lava flow, and the unusual sand castles of a miniature badlands carved by water make the cave of geologic interest. (Photo of the entrance from Williams, 1923)

Caves, Tubes, and Tunnels

Caves, intricate cavern systems, and tubes may develop when the outer crust of a lava flow cools and hardens over a still-moving basaltic stream. As the lava continues to flow within the crust, it drains away leaving an open cave or cavern. Lava tubes are most common in pahoehoe lava, and when the basalt fills a narrow valley a single tunnel or a series of stacked tubes result. Straight caves may follow faults and fractures, but more often the tunnels mark the meandering pathway of a prehistoric stream channel. Interconnected tubes may form when thick, syrupy lava moves in sheets. Once the roof of caves and tubes are attacked by weathering processes, they collapse into openings.

Typically, benches or ledges lining the wall give the cave a keyhole or skull shape in cross-section to show that the lava drained in stages. In one of these, Derrick Cave, the entrance is through an opening in the roof, which rises as high as 50 feet in places. Lava River Cave has a similar keyhole shape. At other times, the molten lava left a coating on the ceiling, which dripped to the floor as pinnacles or formed hanging lavacicles. At Lavacicle

Historically lava caves were used by early inhabitants for shelter, for chilling food, or for supplying ice. The Arnold tube runs northeasterly from Paulina Peak through basalt from fissures on the flanks of Newberry Volcano. In a number of places the roof has fallen in, breaking the tunnel into smaller sections. As part of this complex, Arnold Ice Cave maintains a steady temperature of 40° Fahrenheit. Where the cave intersects water, it cascades down and freezes into silent waterfalls. The entrance has been badly damaged and is unstable. Because of rising groundwater, ice now covers the stairway once in use, so that special climbing equipment is needed to enter safely. (In the photograph, ice is being harvested from Arnold ice cave; courtesy Condon Collection).



Wrights Point in Harney County traces the ancient channel of a meandering stream that had been filled in by basalt. Projecting 250 feet above the plain, the flat-topped sinuous ridge is six miles in length and averages 400 yards in width before it merges with a broad mesa at its western end. Fossilized fish bones and freshwater clams and snails, collected in the lower strata of Wrights Point, are evidence of the older stream environment.

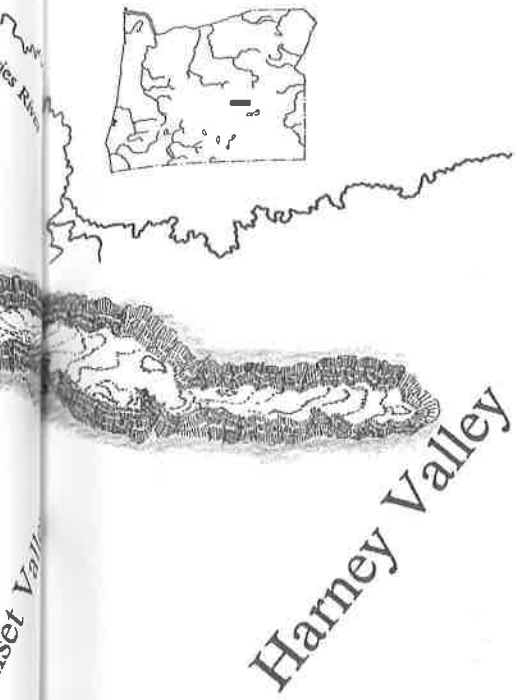
Cave south of Millican, the lavacicles are only a few inches long, but those rising from the floor are two to six feet high. Because of the fragile nature of the formations, the cave entrance is barred and permission to enter must be obtained from the U.S. Forest Service.

Lava caves in basalt terrains often served as conduits to carry the fluid material great distances underground. Robert Jensen notes that the basalt from Lava Top Butte spread northward some 10 miles through the Arnold Lava Cave system until it was blocked. At that point the lava emerged to cover the surface as the Badlands topography. What has been called the Badlands volcano is in actuality a rootless vent that was fed through the Arnold Cave passageway.

On the extreme eastern edge of the Lava Plains, the privately owned Malheur Cave is both obscure and difficult to explore. At least one-half of the cave is filled with water, creating a long underground lake where it intersects the groundwater table. The cave can only be traversed by canoe or raft, although the lake and configuration of the tunnel prevent passage after a certain point. Permission must be obtained to enter.

Wrights Point

As the softer layers of Pleistocene fluvial sands, conglomerates, and ignimbrites, which had invaded the Wrights Point paleo-valley, were stripped away with erosion, the streambed was left cast in lava as an excellent example of inverted topography. Because of the orientation of the lavas and stream deposits, Alan Niem suggests that they flowed from the west and that Palomino Butte was the possible source.



In this oblique aerial view looking westward, Wrights Point appears to wind along the ground. ((From Niem, 1974; photo courtesy Oregon Department of Geology and Mineral Industries)