Basin and Range

Landscape of the Basin and Range

The Basin and Range across southcentral Oregon is only a small northern portion of a vast region that covers parts of Utah, Nevada, Idaho, Oregon, Arizona, California, New Mexico, and Mexico, encompassing an area of 300,000 square miles. The Oregon Basin and Range is bordered on the west by the Cascade Mountains, on the north by the High Lava Plains, and to the east by the Owyhee Uplands.

As the name implies, the Basin and Range is made up of long, narrow, north-south mountains alternating with broad valleys. From west to east, the most prominent geographic features are Klamath Lake, bordered by Modoc Rim and Hogback Mountain, the Summer Lake and Lake Abert basins, enclosed by Winter Rim and Abert Rim, Warner Valley and Hart Mountain, and the easternmost Catlow Valley, Steens Mountain, and Alvord basin. Steens Mountain is the highest in the province at 9,670 feet, followed by Warner Peak at 8,065 feet, while Hart Mountain is slightly lower at 7,724 feet. Overall, the elevation averages 4,000 feet.

The basins themselves vary in size as do the lakes filling the lowest portions. Klamath Lake is the longest at 50 miles as compared with Summer Lake at 20 miles. Both are about 10 miles wide. Some of the older dry lakebeds are grassy meadows that become shallow lakes during wet years.

A distinguishing feature of the province is that almost all of the streams have reduced watersheds which empty toward the interior. The Chewaucan River drains 620 square miles, Thomas Creek covers 325 square miles, and the Ana River, just six miles long, is fed by springs. Only the Klamath River indirectly reaches the Pacific Ocean. From a beginning in Upper Klamath Lake, it follows a torturous route through northern California to enter the ocean south of Crescent City. Its watershed encompasses 12,000 square miles, and it is augmented to a considerable extent by its tributaries the Wood, the Williamson, and the Sprague.

Past and Present

The Great Basin remained largely unknown until the 1840s when engineer and surveyor John C. Fremont explored and named the province, describing the topography and recognizing that its drainage was internal. Some thirty years later, G.K. Gilbert, a geologist with the U.S.G.S., whose work was primarily in Utah and Nevada, applied the names *Basin and Range* and *Basin Ranges*.

Overview

The Basin and Range is a tectonically youthful, regionally uplifted province with a thin crust and high heat flow. This area in Oregon is distinguished by the multiple processes of crustal extension, faulting, and accompanying phases of volcanism. East-west stretching, that began in the Miocene, is in concert with the movement of tectonic plates along the western margin of North America.

Extension of the crust led to faulting and volcanism. As the crust stretched and thinned, it fractured, allowing lavas to break through. Within the past 10 million years, complex zones of both northwest- and north-northeast-trending faults developed in response to extensional processes. A broad belt of Miocene strike-slip faults cut northwest, while Quaternary north-northeast normal faults give the province its distinctive physiography of high escarpments and intervening basins.

Volcanism began with eruptions of the 17-million-year-old flood basalts at Steens Mountain, triggered by the movement of the North American

Israel Russell, who accompanied G.K. Gilbert, went on to a career with the Survey. Russell's interests were glacial geology, geomorphology, and hydrology, and in central Oregon he published on pluvial and present-day lakes and water resources. Born in 1852, Russell received a civil engineering degree in 1872 from the University of the City of New York and taught for a time at the School of Mines, Columbia College, even later becoming a professor of geology at the University of Michigan. His *Lakes of North America* is one of the first works to describe the geology of lake basins. Russell died in 1906. (In the 1890 photo, Russell is standing third from the left with a U.S.G.S. group on the Alaskan Malaspina glacier moraine; courtesy U.S. Geological Survey)

Working at Fossil and Summer lakes in 1936, Ira Allison's pursuits in the Basin came some years after those of Russell. One of the first staff members in the newly established Geology Department at Oregon State University, Allison's focus on geology and education kept him at Corvallis for 62 years. Born near Chicago in 1895, he obtained his PhD in 1924 from the University of Minnesota. His main interest was the Pleistocene Epoch, and he completed classic works on Fossil Lake, Lake Chewaucan, and Fort Rock Lake. Publications on the significance of glacial erratic dropstones in the Willamette Valley gave additional evidence to the theory of remarkable Ice Age floods. In 1988 a geomorphology professorship was established in Allison's name at Oregon State University shortly before he died. (Photo courtesy Oregon State University, Archives)

plate across a mantle plume or hot spot. The plume sent eruptions northward as far as the Columbia plateau and activated explosive rhyolitic eruptions that prograded across the Oregon Basin and Range and High Lava Plains.

During the Pleistocene Epoch, a cooling climate and increased rainfall filled the lowlands with vast pluvial lakes and brought glaciers to Steens Mountain. The ephemeral lakes attracted migratory birds and herds of mammals, whose abundant fossil remains litter the sandy flat valleys.

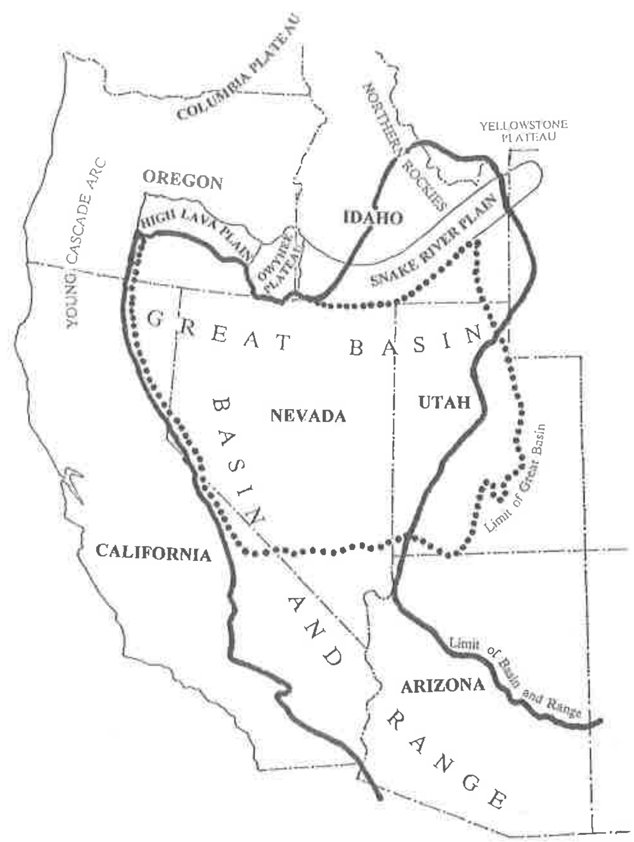
While mineral resources in the province are sparse, mercury and uranium have been extracted in Lake County, as have sunstones and opals.

Geology

Paleozoic-Mesozoic

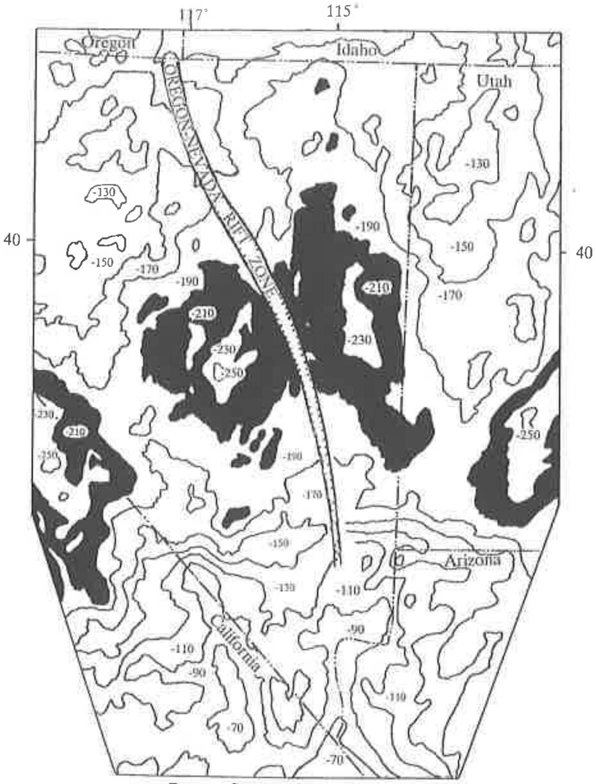
In southcentral Oregon, the foundation or basement rocks lie buried beneath layers of younger volcanics and sediments. Late Paleozoic and Mesozoic terranes, enormous slabs of rock that were moved on continental plates and accreted to the West Coast, are obscured by a mantle of late Tertiary sediments and volcanic debris.

Although evident in the Blue Mountains, exposures of underlying terrane rocks are limited to the fringes of the Basin and Range in Oregon, and it is necessary to step over into Nevada to make comparisons and conclusions about the pre-Cenozoic history. In the Pueblo and Trout Creek mountains that straddle the Oregon-Nevada border, metamorphic rocks and granitic intrusions have been

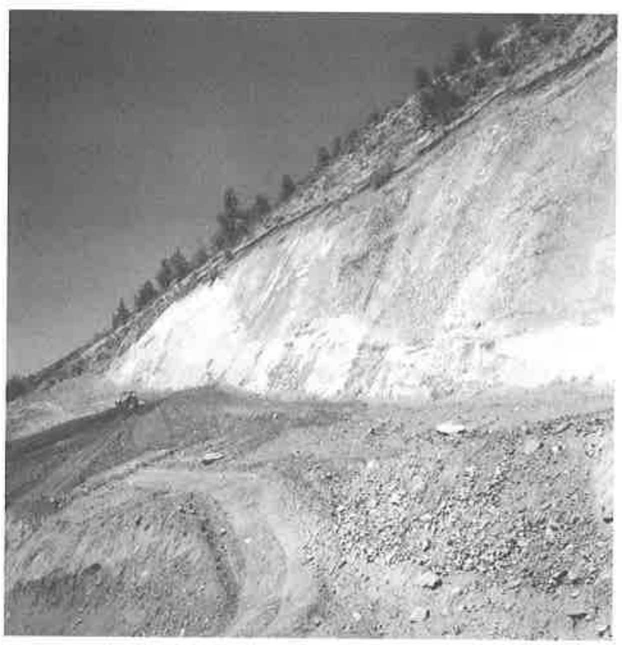


The Basin and Range is a vast region across the southwestern United States covering portions of Nevada, California, Idaho, Oregon, Arizona, Utah, and New Mexico, extending into Mexico. The Great Basin, which takes in only the northwestern portion of that area, is characterized by internal drainage and north-south mountains separated by broad structural valleys.

assigned to the Jurassic or older periods. Nearly identical rocks in Nevada have been dated with some confidence as Paleozoic to late Triassic, suggesting that terrane rocks may form the basement



Stretching in this province is reflected by a distinctive pattern of gravity anomalies in Nevada and Oregon. Over a low (dark areas), there is less gravitational attraction as compared to that over a gravity high (light areas). The gravity map for the basin shows remarkably similar images east and west of the of the 117° meridian, which denotes the northern end of the Nevada rift zone where it enters Oregon. (after Eaton, et al., 1978)



North of Klamath Falls the shear flat face of a rock quarry displays slickenslides and striae characteristic of movement along a fault. (Photo courtesy Oregon State Highway Dept.)

here. On the other hand, geophysical work suggests that the crust beneath the Cascades thins toward central Oregon but thickens again beneath the Owyhee Plateau, indicating that the Miocene volcanics underlying the Oregon Basin and Range may, in fact, constitute the oldest strata.

Cenozoic Extension, Faulting, and Volcanism

The structure of the Basin and Range is characterized by extension, faulting, and magmatism that can be traced to the interaction of crustal plates. As the Farallon, Kula, and Pacific tectonic plates converged along the North American margin, the Farallon and Kula slabs slowly sank beneath the continental landmass and largely disappeared, while the Pacific plate expanded. Today the north-northwest motion of the Pacific plate at more than two inches a year with respect to North America can be linked to extension and right lateral strike-slip faulting (dextral shear) of the mainland.

Accommodating the motion between the two plates, a broad belt of concentrated strike-slip faults known as the eastern California shear zone was named in 1990 by Roy Dokka and Christopher Travis of Louisiana State University. They show that the belt may project east of the Sierra Nevada Mountains and into central Nevada and Oregon, where it is known as the Walker Lane zone. In a 2010 paper, Kaleb Scarberry and coauthors at Oregon State University speculate that the High Cascade graben may be the northern limit of the Walker Lane shear.

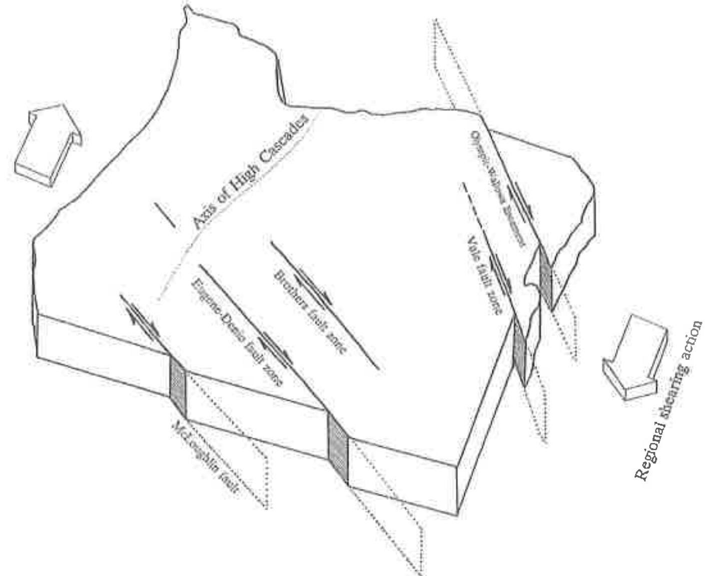
Extensional Tectonics

The most profound geologic event in the Basin and Range is the east-west stretching or extensional phenomenon, which thinned the crust and expanded the northernmost portion of this province by as much as 17 percent during the past 15 million years, 39 percent since 37 million years ago, and 72 percent since 50 million years ago. With extension, the crust was pulled apart and thinned until it began to fail. The resultant faults provided routes for mineral-laden hydrothermal fluids and lavas to reach the surface as hot springs and volcanic eruptions.

Faulting and Structure

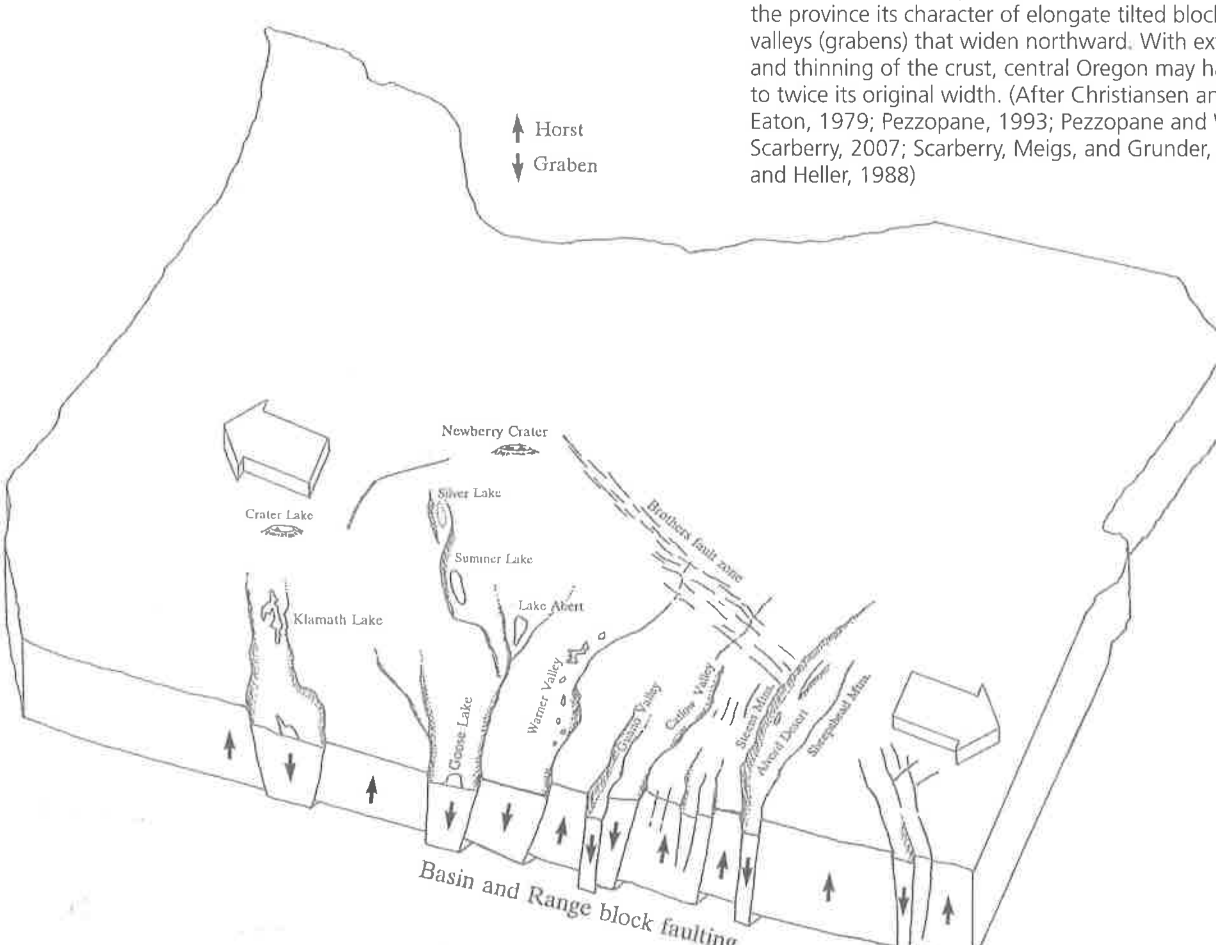
Extension and crustal thinning generated complex networks of faults and fractures in the Basin and Range, which were linked to a major rift system that included the Columbia River Basalt dike swarms, the Oregon-Nevada rift, and the opening of the Oregon-Idaho and western Snake River grabens. Beginning 12 million years ago, northwest strike slip faults and north-northeast normal faults modified the topography of the province.

Broad northwest-trending zones of strike-slip faults that run for hundreds of miles across the Great Basin and High Lava Plains were active as late as 7 to 8 million years ago. First named and described by George Walker and Robert Lawrence, then at Oregon State University, the McLoughlin, the Eugene-Denio, and the Brothers fault zones are enormous structural features that parallel the Olympic-Wallowa lineament. Each is composed of a network of smaller overlapping faults which show 150 feet of maximum displacement with spacing of about a mile between them. The poorly-understood



Crossing central Oregon in a northwesterly direction, the McLoughlin, the Eugene-Denio, and the Brothers faults are wide networks of smaller overlapping faults. (After Lawrence, 1976; Pezzopane, 1993; Walker, 1969, 1973)

Extensional tectonics produced north-northeast faults that give the province its character of elongate tilted blocks (horsts) and valleys (grabens) that widen northward. With extreme extension and thinning of the crust, central Oregon may have expanded to twice its original width. (After Christiansen and Yeats, 1992; Eaton, 1979; Pezzopane, 1993; Pezzopane and Weldon, 1993; Scarberry, 2007; Scarberry, Meigs, and Grunder, 2011; Wells and Heller, 1988)



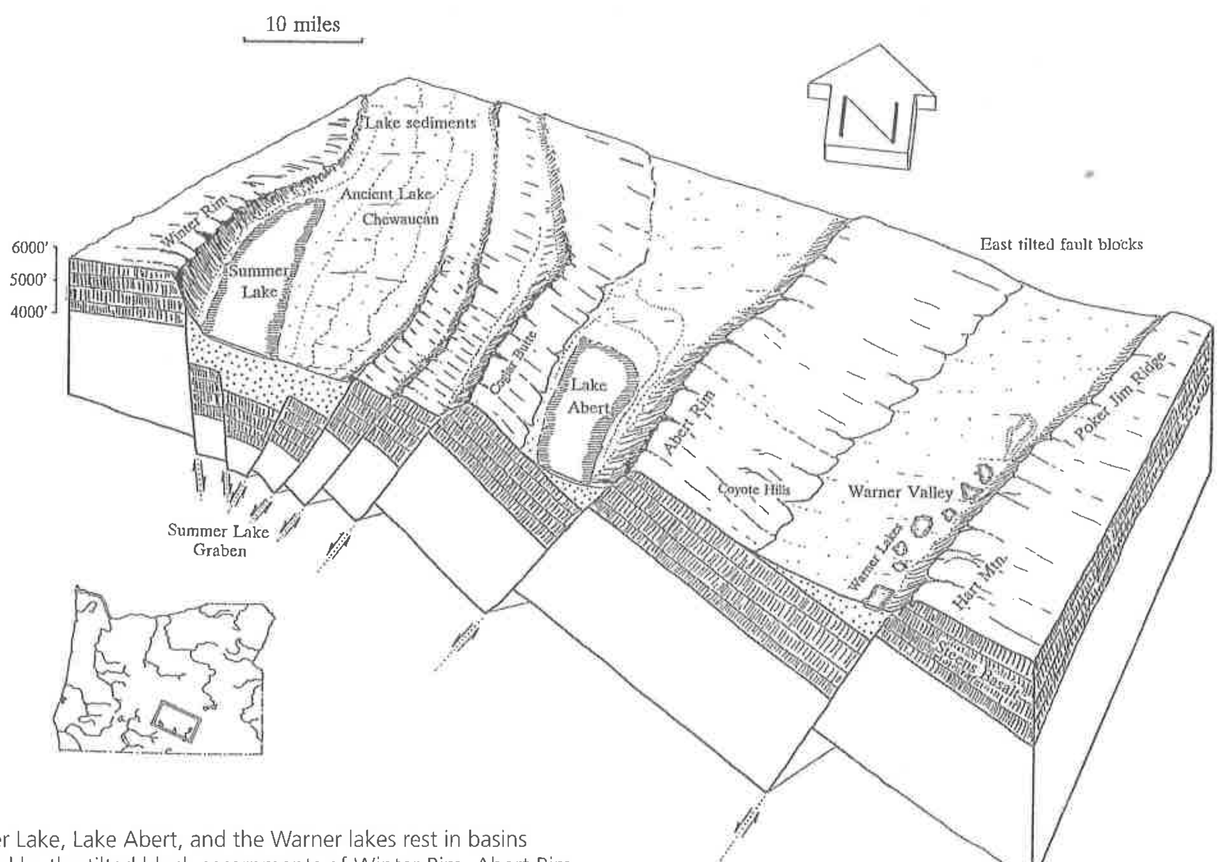
McLoughlin and Eugene-Denio belts post-date and offset the axis of High Cascade volcanoes. The Brothers fault zone, defining the northern boundary of the Basin and Range, has slowed to the point of deactivation since the Miocene in response to the north-northeast faults, which terminate against it.

North-northeast block-faults, dated at 6 million years ago, cut the older northwest fault belts. The younger faults, which define the major topographic character of the province, are several miles apart and show displacements of thousands of feet. Lying at right angles to the stretching direction, most are normal faults, where one side has uplifted to tilt the mountain block adjacent to a deeper valley. The ranges are elongate, and the result is that the basins tend to be open at the north end.

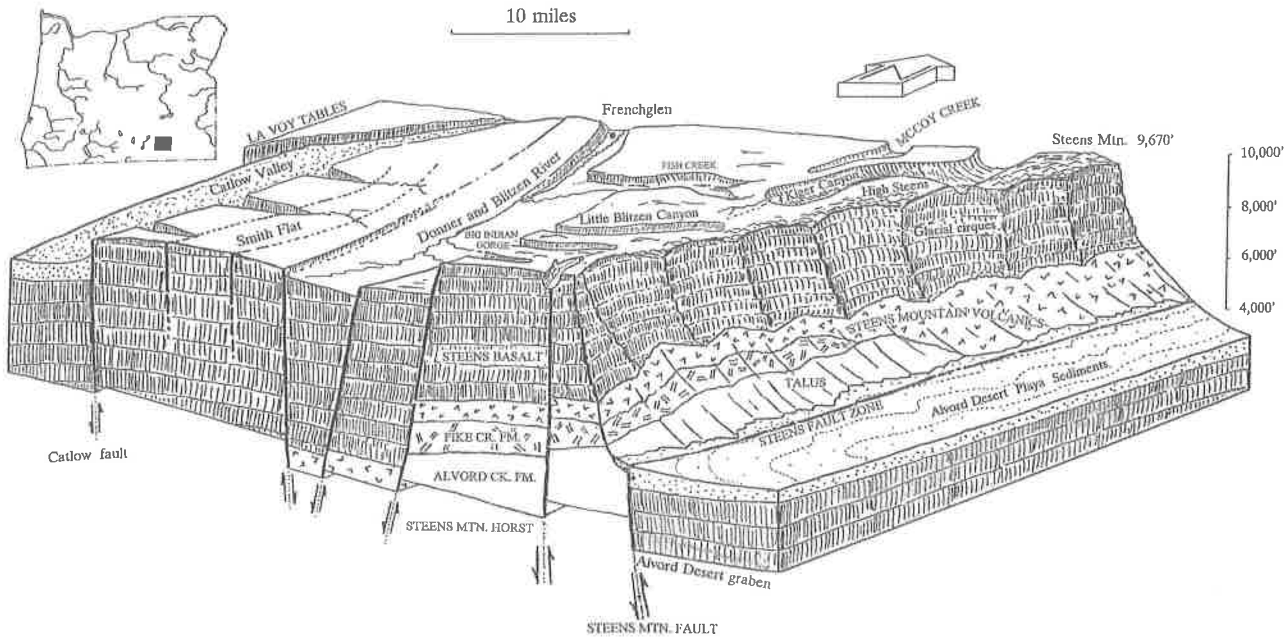
A study by Scarberry and coauthors showed that extensional faulting migrated in a wave from central Nevada toward the Nevada-California border and into southcentral Oregon. Summarizing the timing and progression of faulting, they proposed that the locus shifted westward from the Steens Mountain fault around 10 million years ago, to the Abert Rim fault at 8.7 million years ago, and to the present-day Cascade arc around 5 million years ago.

In Nevada, the initial block-faulting stage was succeeded by listric or detachment faulting. In this case, normal faults curve at depth to a shallow angle or even horizontally as the crust is extended. Listric faulting typically yields a topographic pattern where the tops of the fault-block surfaces slope away from a central axis, in contrast to randomly tilted blocks.

To determine ages and movement along the north-northeast faults in central Oregon, Silvio Pezzopane and Ray Weldon at the University of Oregon looked at the offset of late Quaternary deposits. Fresh fault scarps and vertical displacement of Pleistocene lake sediments were recorded at Goose Lake, Warner Valley, Abert Rim, Slide Mountain-Winter Ridge (Ana River), and Steens Mountain. With the exception of the 1968 Adel earthquake, which was generated by motion along the Warner Valley fault, activity at these localities dates back around 2,000 years.



Summer Lake, Lake Abert, and the Warner lakes rest in basins enclosed by the tilted block escarpments of Winter Rim, Abert Rim, Warner Rim, Catlow Rim, and Hart Mountain. (After Baldwin, 1976)



The long-lived Steens Mountain fault has been active over the past 10 million years. Severely carved by Pleistocene ice masses, the up-thrown block of the Steens Mountain escarpment displays the classic features of glacial erosion. (After Baldwin, 1976; Evans and Geisler, 2001)

At the base of Abert Rim, fault scarps displace late Pleistocene and Holocene lake and alluvial deposits. In this view toward the north, the faulted blocks of Abert Rim are clearly delineated. (Photo courtesy E. Baldwin)

Flood Basalts and Age Progression

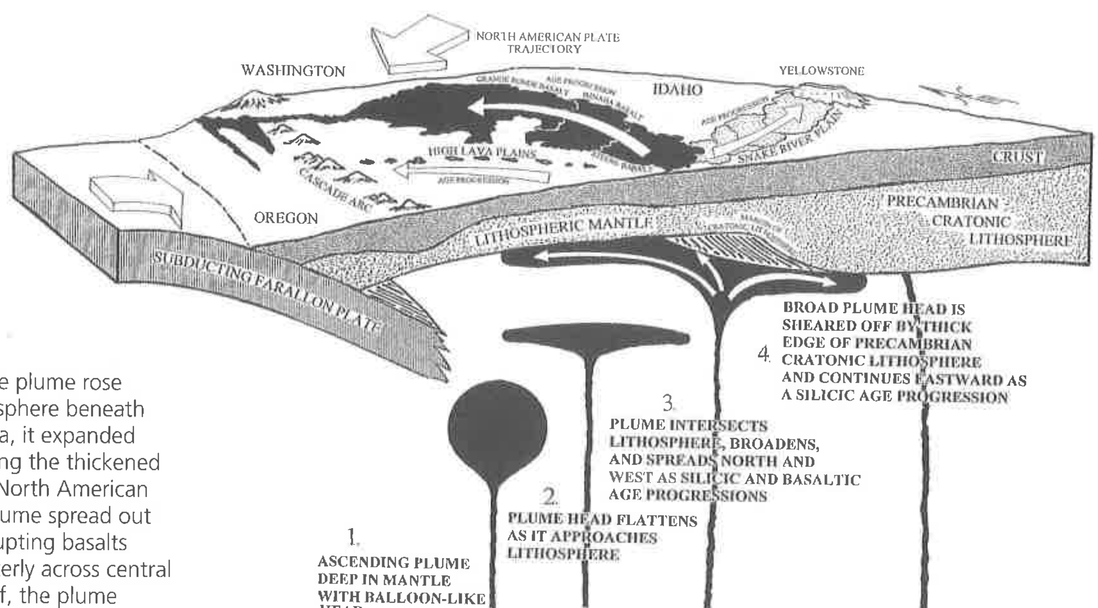
Extension and faulting, that traversed the province, were accompanied by surges of volcanic activity. Late Tertiary lavas, which covered large regions in eastern Oregon, have been attributed to a mantle plume, while Quaternary volcanism has been associated with both crustal extension and a residual hot spot. The oldest eruptions from the Coleman Hills and Rabbit Hills volcanic complex along Abert Rim were dated at 29.3 to 21.7 million years ago. These bimodal rhyolitic and basaltic lavas formed much of the early Miocene landscape well before the extrusion of Steens flows 17 million years ago.

Volcanism on the eastern margin of the Oregon Basin and Range began in the middle Miocene with flood basalts from source vents near Steens Mountain. Originating from what is interpreted to be a huge shield volcano, the voluminous flows form a subprovince of the Columbia plateau. While subduction may have played a role in Steens volcanism, evidence is lacking for the older idea of back-arc spreading. Current thinking instead emphasizes the importance of a mantle plume.

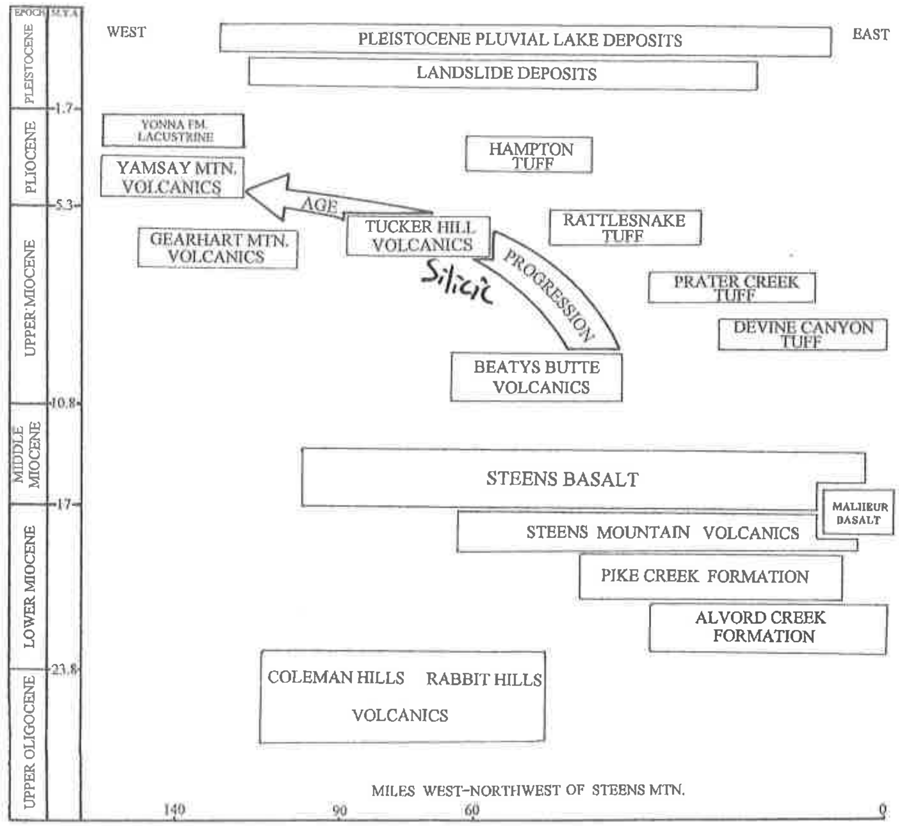
A plume is a section of the mantle where heat becomes concentrated so that it moves upward as a hot spot. When the westward-moving North American crustal plate was passing over a hot spot, the plume rose and spread along the base of the crust to delaminate the overlying layer and emerge as Steens basalts. After being deflected northward to the Columbia plateau, the plume tail erupted across the Snake River Plain of Idaho and into the Yellowstone Plateau in Wyoming, where it is situated today. Currently, the heat source and origin of the Yellowstone hot spot, precisely how it works, its size, and depth are poorly understood. It may be much larger and deeper than previously thought, extending in excess of 500 miles into the mantle.

The concept of hot spots and mantle plumes was first proposed in the 1960s when several volcanic provinces were linked to their presence. Volcanic hot spots are known from dozens of sites around the globe, and recognition of these centers is a matter of tracing a chain of volcanoes back to its source or oldest vent. This is the case with the Hawaiian Islands, where intermittent volcanic activity from a mantle plume has left a string of eruptions.

The 17-million-year-old Steens lavas spread southward to the Pueblo Mountains and west to Abert Rim. The thickness varies widely because of the uneven subsurface enveloped by the basalts. In places it is well over one-half mile deep, covering as much as 20,000 square miles, for a total volume of almost 8,000 cubic miles. In the vicinity of Alvord Creek, the "great flow" of Steens Mountain is over 900 feet and is characterized by individual columns,



As the Yellowstone mantle plume rose and approached the lithosphere beneath the crust of North America, it expanded and flattened. Encountering the thickened edge of the Precambrian North American craton, the head of the plume spread out to penetrate the crust, erupting basalts that prograded northwesterly across central Oregon. After shearing off, the plume continued across Idaho. (After Murphy, et al., 1998; Camp and Hanan, 2008; Jordan, 2009; Pierce and Morgan, 2009)



Tertiary volcanic stratigraphy of the Basin and Range (After Camp, Ross, and Hanson, 2003; Scarberry, Meigs, and Grunder, 2010; Walker, 1979)

Glaciation along the front of Steen Mountain (looking south) is illustrated by the well-developed cirque valleys. (Photo courtesy Oregon State Highway Department) which measure as much as five feet across and rise to 300 feet. Victor Camp estimates that the greatest volume of the Steens erupted in less than 50,000 years, even though sporadic activity might have continued over a 200,000-year-interval.

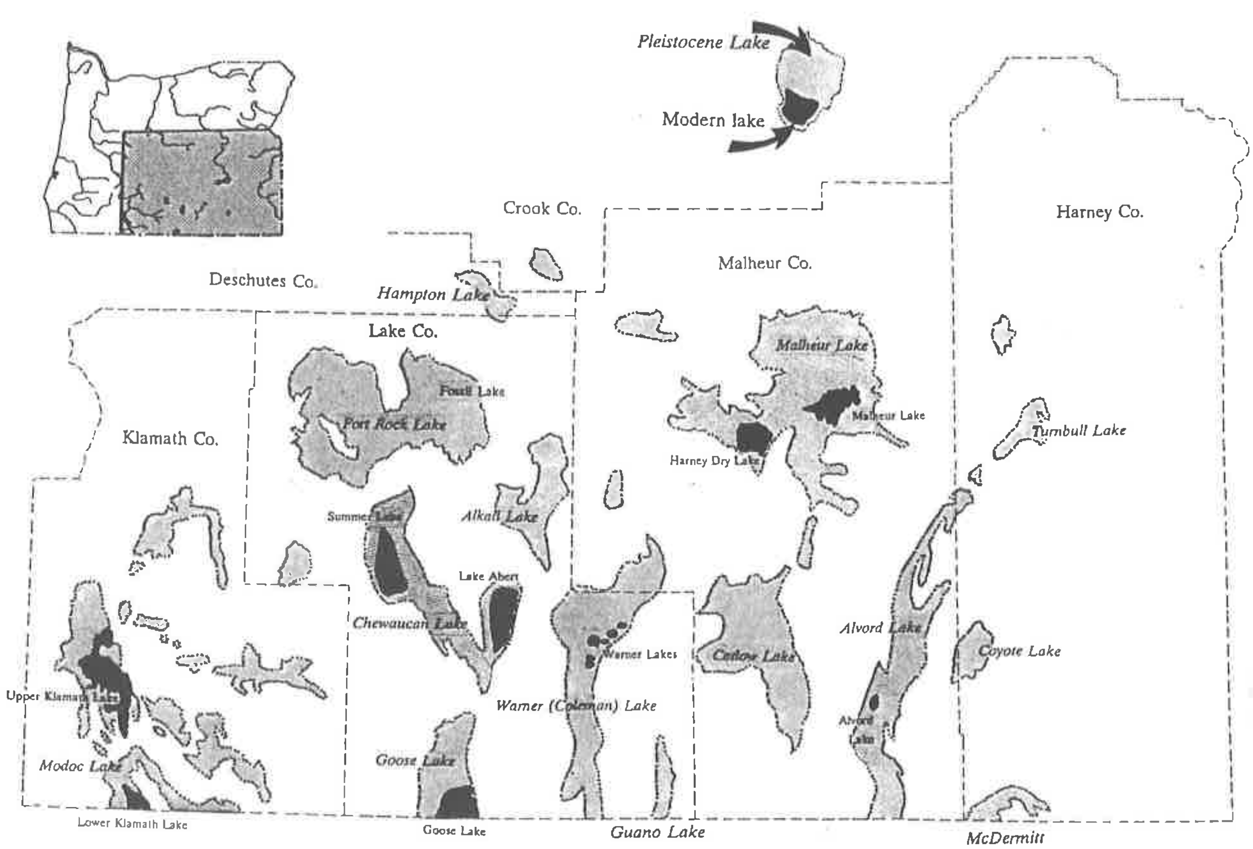
Noting the similarity in age and chemistry between the Steens and the Columbia River basalts, Camp assigned the Steens as the oldest formation within the Columbia River Basalt Group. Moreover, he considers the Malheur Gorge basalt to be a sequence of the lower (oldest) Steens layers. The Malheur Gorge flows, which erupted 16.5 to 15.7 million years ago, correspond to the Imnaha Basalt and the Grande Ronde Basalt and produced around 15 cubic miles of lava from vents along the Middle and South forks of the Malheur River.

Two roughly parallel volcanic series, one in the Oregon Great Basin and the other in the High Lava Plains, erupted from southeast to northwest. Between 10.5 to 5 million years ago, the volcanic wave propagated at the rate of 20 miles every million years, slowing to 9 to 18 miles every million years after that. The northern belt in the High Lava Plains has twice the number of vents as in the southern area. Bimodal volcanism, which accompanied the progression, was characterized by a change in the composition of the lavas from rhyolitic to basaltic.

In the late Miocene, eruptions at Beatys Butte in the Basin and Range were the most easterly and oldest at 10.4 years ago. Those at Tucker Hill occurred at 7.4 million years ago, and the westerly Pliocene Yamsay Mountain eruptions were 4.7 years in the past. The eruptions from the Pliocene Yamsay shield cone were also bimodal, beginning with basaltic then rhyolitic lava. But near the end of its cycle, small amounts of basalt again were extruded from its flanks. At Gearhart Mountain, basalts are overlain by a veneer of andesitic lavas.

Pleistocene Glaciers, Lakes, and Precipitation

The Pleistocene Epoch opened almost 2 million years ago with increased precipitation and low temperatures, alpine glaciers, and pluvial lakes. This environment provided a rich habitat for hoofed



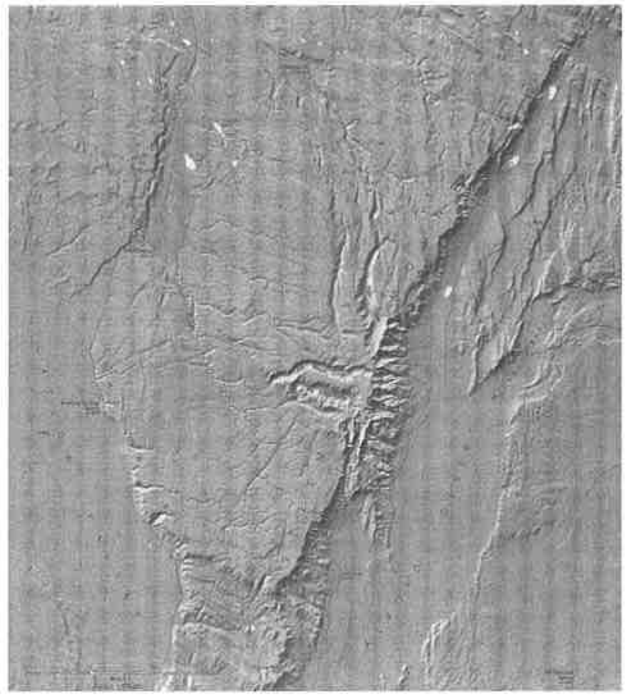
The small playas and pluvial lakes that dot the Great Basin today are mere remnants of much larger bodies of water that diminished rapidly at the end of the Ice Ages. (After Allison, 1982; Dicken and Dicken, 1985; Dugas, 1998; Negrini, 2002) mammals, giant sloths, predators, fish, and birds, whose skeletal remains are exposed in the old lakebeds.

Dependent on precipitation, ephemeral lakes change dramatically with variations in climate, and today during an interglacial warm phase, the water bodies are shrinking. In the Ice Ages, nine pluvial lakes occupied central Oregon. The largest of these was Lake Modoc covering over 1,000 square miles. Smaller in size, Lake Chewaucan, Lake Coleman, now Warner Lakes, and Alvord Lake each spread over 500 square miles.

Pleistocene lakes, some of which were long-lived and extensive, persisted over considerable areas of the Great Basin. Old terraces and wave-cut benches clearly mark former water levels and shorelines of the lakes, but exploration with boreholes or ground penetrating radar yields an even clearer picture of beaches, deltas, spits, channels, and other geomorphic features. The identification and mapping of paleo-shorelines at Summer Lake, Lake Chewaucan, and Lake Alvord confirmed the stages of fluctuating water levels and climates.

In 2000, boreholes drilled into the Summer Lake basin revealed environmental changes throughout the past 250,000 years. Andrew Cohen at the University of Arizona analyzed the ostracods (flea-sized aquatic arthropods), pollen, water chemistry, and lake sediments to demonstrate that alterations in salinity, inflow, and biologic productivity correlate with global cooling and the waning and waxing of the North American continental ice sheet. Temperatures dropped substantially between 250,000 and 165,000 years ago, then briefly warmed from 100,000 to 89,000, followed by a cooling trend from that time onward. At California State University, Robert Negrini's research on paleo-climate data from Quaternary sediments in lakes Modoc and Chewaucan in Oregon and Lake Lahontan in Nevada showed similar results.

As recently as 7,700 years in the past, Summer Lake and the Chewaucan Marshes were impacted by the catastrophic explosion of Mount Mazama (Crater Lake). Even though 60 miles from the volcanic source, the basin was covered with tremendous volumes of pumice and ash, which created a dune field in the northeast corner of Summer Lake and along lower Chewaucan Marsh.



The dramatic glaciated face of Steens Mountain stretches northward along the margin of the province. Cooling during the Pleistocene fostered the onset of extensive ice masses on the Steens, the only range in the Oregon Great Basin that saw glaciation. Because of the steep gradients and greater precipitation at higher altitudes, the ridgeline has been thoroughly dissected by erosion. In cases where glaciers cut into the east rim of the mountain, the crest migrated westward. Working on both sides of a rock face, ice left only thin-walled canyons, but, when moving slowly through a basin, it carved symmetrical U-shaped valleys. (Courtesy University of Oregon)

By mapping pluvial Lake Alvord in 2007, David Wilkins and William Clement from Boise State University concluded that the ongoing ebb and flow of waters eastward through Big Sand Gap into Lake Coyote probably maintained Lake Alvord at a fairly constant level. Deron Carter at Central Washington University further suggested that large floods from Lake Alvord, some 13,000 years ago, burst into Coyote basin and from there through the Crooked Creek and Owyhee River drainages to the Snake River.

Lake Modoc in the Klamath basin expanded and contracted periodically during the Pliocene and Pleistocene, and at one time the water may have discharged into the Klamath River and from there emptied into the Pacific Ocean. Layers of volcanic ash and debris record some of Oregon's only Pliocene sediments, easily recognized in road cuts by the even laminations of the Yonna Formation.

Although scarce, a variety of fossils are present in the strata.

Geologic Hazards

A considerable expenditure of research, time, and money is currently underway on geologic hazards throughout the Pacific Northwest. In central Oregon, however, earthquakes and landslides are infrequent, and available recorded data are often lacking, thus directing the focus toward the western portion of the state.

Earthquakes

Holocene earthquakes in this province tend to be moderate in magnitude and average once every ten years. Seismic activity is associated with a clusters of young north-northeast trending faults projecting from the eastern California shear zone.

There have been few studies on Quaternary faulting and related earthquakes here. In 1993, Silvio Pezzopane, then at the University of Oregon, used aerial photographs, field mapping, and published studies to locate and identify active faults. By characterizing potential quake sizes and frequencies of recurrence, Pezzopane calculated a 10 percent chance of a seismic event of magnitude 7.0 taking place in central Oregon every 1,000 years.

In the early 1900s, Paisley in Lake County experienced several small shocks, but in 1923 and 1925 strong quakes at Lakeview along the Abert Rim fault registered a 6.0 intensity. A 1968 earthquake swarm near Adel, related to the Warner Valley fault, measured 5.1 on the Richter scale. Over a ten-day period, the shaking damaged chimneys, produced cracks in the ground, and increased flows at hot springs. Within the Chewaucan basin a total of 12 earthquakes have been recorded historically. The largest in 1999 had a 4.3 magnitude.

Earthquakes near Klamath Falls originate from faults along the Klamath graben. Mapped in 2008 by George Priest, the east and west faults, which delineate the graben, extend almost to Crater Lake and are part of a regional network responsible for at least 12 significant events over the past 50 years. There were moderate quakes near Klamath Falls in 1947 and again in 1949, but one on September 20, 1993, with a magnitude of 3.9, was followed by a second shaking measuring 5.9 on the Richter scale.

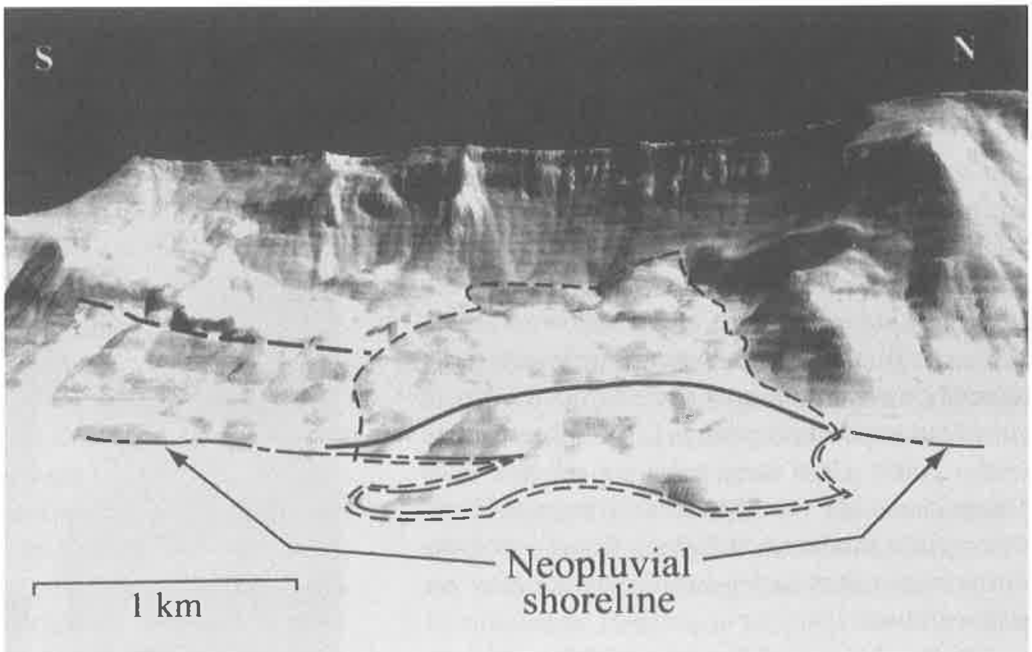
Landslides and slumping generated by the 1993 Klamath Falls earthquakes were visible over an area of 150 square miles surrounding the epicenter. Boulders such as this one, which fell on Highway 190 at Upper Klamath Lake, rolled downslope from steep cliff faces. One fatality resulted when falling rocks struck a car on Highway 97 near Modoc Point. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Diminishing aftershocks lasting several months were centered in the Mountain Lakes Wilderness on the west side of the graben. Felt as far away as Coos Bay, Eugene, and Chico, California, the quakes resulted in two deaths and extensive structural damage.

In connection with the quakes, flows from springs increased by 20 percent, and well levels rose about six to seven feet. Water in some private wells became grayish and smelled of rotten eggs, but geothermal water temperatures were unchanged.

Landslides

Holocene slides are not common in this province, and most are debris flows caused by summer downpours. However, there is evidence of gigantic landslides in thick volcanic and tuffaceous sedimentary rocks along the Winter Ridge-Slide Mountain escarpment bordering the Summer Lake basin. By characterizing the deposits, Thomas Badger, Washington State Department of Transportation, and Robert Watters at the University of Nevada concluded that the slides took place during the late Pleistocene and that the large volumes of debris, the sudden nature of the activity, and the lengthy time frame of occurrences indicated a strong shaking.



Along the west side of Summer Lake, the Bennett Flat and the Foster Creek landslides occurred from 900,000 to 17,000 years ago. These were single events, while the Punchbowl slide (in the photo) occurred in multiple episodes, most recently 10,000 years ago. (Oblique view from U.S.G.S. digital elevation model; Courtesy T. Badger)

Natural Resources

Uranium and Mercury

Although a score of metallic ores have been known for years in the Oregon Basin and Range, only uranium and mercury have been mined. About 200 tons of uranium ore were extracted from volcanic rocks at sites northwest of Lakeview. Shipments in 1955 were the first uranium ores marketed in the state, but the processing mill closed ten years later. Located in the Fremont National Forest and overseen by the U.S. Department of Agriculture, the abandoned mines are subject to clean-up under federal and state regulations. Contaminated ponds and radioactive stockpiles pose hazards to residents, recreational users, wildlife, and to surface streams and groundwater. In 2005 the U.S. Environmental Protection Agency began a remedial action program, capping the most polluted soils, neutralizing the acidity of the ponds, and recontouring. However, a clean-up plan for the plume of contaminated groundwater, which is spreading through a shallow regional aquifer, remains to be implemented.

Borax

Along the eastern Steens Mountain escarpment, hot springs in the Alvord basin contain sodium bicarbonate and sodium chloride along with concentrations of fluoride, arsenic, and boron compounds. Of these, borax salts were mined from Borax Lake, an 800-foot-wide pool that discharges water at 97° Fahrenheit. Between 1898 and 1907, the 20 Mule Team Borax Company produced 1,700 tons annually.

Removing borax in wagons drawn by teams of mules, the 20 Mule Team Company became the Rose Valley Borax Company after a legal struggle over the name. Borax house, on the shore of the lake, was built with blocks of borax sod. Lake water directly behind the building is fed by hot artesian springs impregnated with the borax salts. Some ruins of the old operation still remain. (Photo courtesy Condon Collection).

Gemstones

The state gem, the heliote or sunstone, is a calcium-rich, clear oligoclase feldspar that varies in color from orange, yellow, or red, to green and blue. The color depends on the amount of hematite in the stone, ranging from a low of 20-parts-per-million for yellow to 200-parts-per-million for red. The most valuable are the deep orange to red sunstones, some of which are priced over $1,000 per carat. Three of Oregon's sunstone localities are privately owned, and only the one on Bureau of Land Management property in Lake County is open to the public. Here these gems are referred to as "Plush diamonds," after the nearby town of Plush. Commercial producers in Harney County send the uncut stones to Asia for faceting before they are sold worldwide.

Precious fire and blue opals are also part of the state's gemstone resources. With mines in Morrow and Lake counties, Oregon ranks as the seventh largest producer in the United States. Opals are a hydrated form of quartz derived primarily from volcanic ash, which crystallizes at low temperatures. The annual income from both opals and sunstones is close to $1.5 million.

The Crump Geyser, which was activated in 1959, began with considerable violence when the subsurface waters were penetrated by a well drilling operation. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Geothermal energy

Because it is a province of high temperature gradients, a thin crust, and numerous faults, the Great Basin is distinguished by its thermal resources. Extension and thinning brings heated rocks into contact with near-surface waters, which emerge as hot springs through faults and fractures. Similarly, hydrothermal fluids may come into contact with magma at depths before the circulating waters reach the surface. Heat flow varies considerably from place to place, but higher temperatures are found in the mountains, whereas lower temperatures characterize the valleys.

In 2007 the Oregon legislature passed a renewable energy bill that identified geothermal resources as marketable. Explorations by the U.S. Department of Energy and DOGAMI are focused on seven sites with high potential. Most are in the Great Basin and Owyhee regions.

In the Alvord basin, thermal waters at Alvord Hot Springs, Mickey Springs, and Borax Lake can be identified by high mounds of precipitated calcium carbonate, built up where they emerge from faults along the base of scarps. With temperatures averaging 160° Fahrenheit, waters at Alvord Springs flow eastward from the Steens Mountain fault into a small bath house, whereas Mickey Springs releases water through vents into pools and a mud pot. Just north of Borax Lake, springs emerge from fractures at 220°, before entering the lake.

Possible geothermal exploration in the Alvord Basin by the Anadarko Petroleum Company led to the purchase of Borax Lake by The Nature Conservancy in 1982 to protect the endangered Borax Lake chub (fish). In 2000 the Bureau of Land Management further restricted geothermal development with the Steens Mountain Cooperative Management and Protection Act.

North of Lakeview and Warner Valley, Crump Geyser and Hunters Hot Springs lie in a 50-foot-wide zone of faults along Warner Rim. Hunters Hot Springs has been drilled and cased. About every 30 seconds, the geyser-like pulsating water spurts 40 or 50 feet in the air, issuing from the ground at 180° Fahrenheit. The waters and surroundings have been commercially developed. Arsenic from the mine tailings near Lakeview have been detected in the spring water.

At Klamath Falls, the Geo-Heat Center at Oregon Institute of Technology utilizes local geothermal resources for practical applications. Initially the Institute harnessed the heat to warm a swimming pool and classrooms, but in 2009 OIT drilled into a fracture zone a mile below ground, tapping into 300° water for powering a plant to heat the entire campus. A recent paper by John Lund and coauthors from the Institute provides an overview of Oregon's geothermal development.

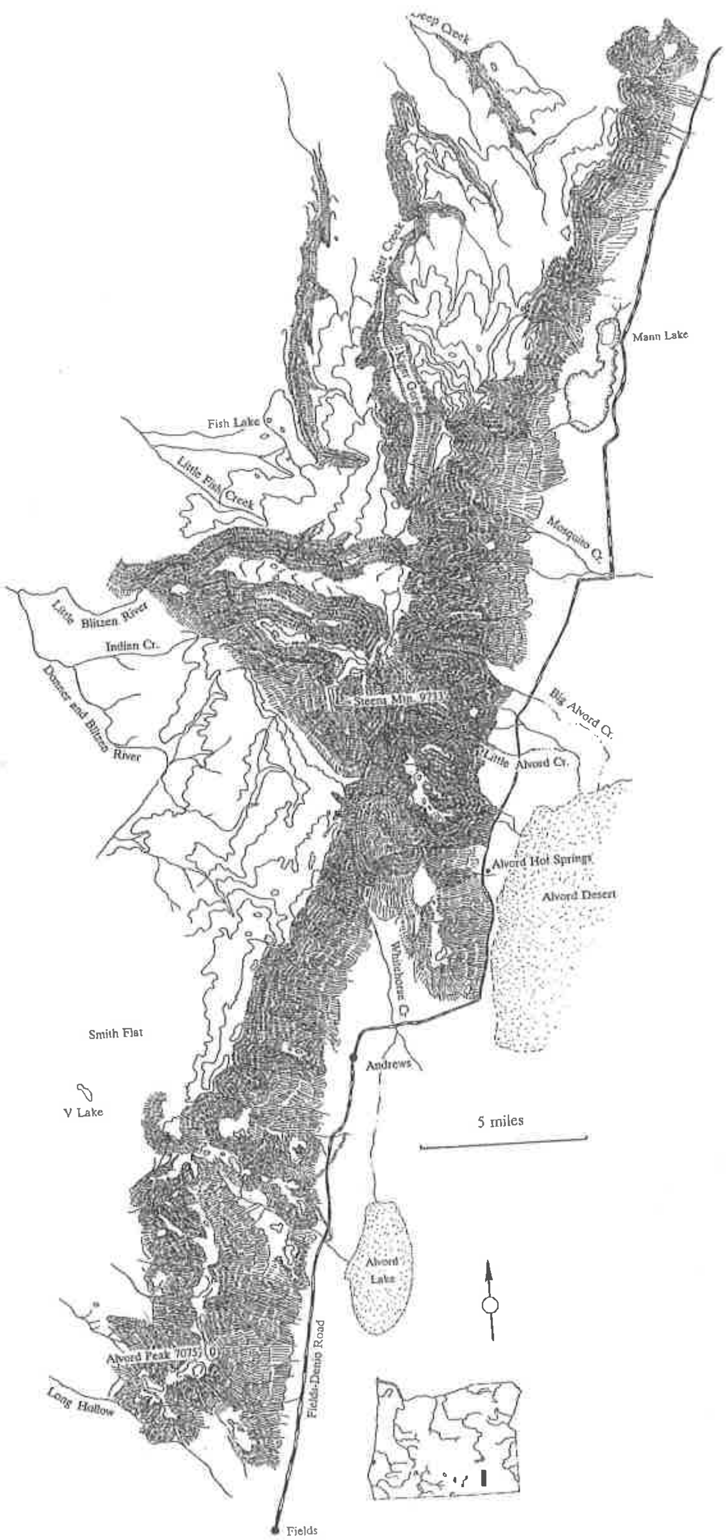
Surface and Groundwater

The Oregon Basin and Range is semiarid with precipitation ranging from less than eight inches annually in the lowlands to 30 inches at the higher reaches. Water is supplied by snowmelt, rainfall, or springs, but much of it either percolates into the shallow playas or is lost to evaporation.

Almost all streams in the province have no outlet to the sea. The exception is the Klamath River that exits to the Pacific Ocean. Many of the smaller creeks, especially those in the dry interior, are intermittent. The larger rivers, with headwaters on the ridge tops, are perennial, and flows are augmented by groundwater stored in porous Tertiary volcanic and sedimentary rocks. Aquifers within interbeds between fractured basalt flows, which are recharged from uplands, are the most reliable. Over the volcanic rubble, thick sedimentary layers of mud, sand, gravel, and diatomite that accumulated in Pleistocene lakebeds are covered by thin alluvial deposits. With low permeability, these sources are marginal, and saline water is often encountered in wells drilled near the playas.

An overview and field guide in 2009 by Michael Cummings from Portland State University examines the impact of the 50-mile-long Steens Mountain scarp on ground and surface water storage, evaporation, and geothermal conditions. The

During infrequent wet years, precipitation ponds in the Alvord basin, which was occupied by a 12-mile-wide and 70-mile-long lake during the Ice Ages. Today a glistening white alkali crust, which rims the water, is residue left after summer evaporation. (The photo is looking east from Steens Mountain across Alvord basin; Courtesy Condon Collection).



A spectacular view of Steens Mountain glacial and fault topography can be seen when driving north along the Fields-Denio Road from Fields near the Oregon border. Pleistocene valley glaciers scalloped the layers into U-shaped canyons and sharp ridges at Kiger Gorge, Little Indian Canyon, and Little Blitzen Canyon. Basins, contoured by glaciation, are occupied by shallow lakes.

numerous snow-fed streams, which emerge from the east and west slopes, supply hot springs and cold artesian wells along with domestic and irrigation demands.

A 2007 study by Marshall Gannett of the U.S.G.S. provides a picture of the groundwater hydrology of the Upper Klamath basin in both Oregon and California. Of the three formerly large water bodies, Upper and Lower Klamath and Tule lakes, only Upper Klamath remains as an important source of surface water for irrigation. The other two have been drained and used for agriculture. Historically, surface water supplied domestic and irrigation needs, but groundwater pumping has increased by 50 percent in the past 10 years, bringing a 15-foot decline in water levels.

Currently experiencing severe deficiencies in both ground and surface water, the Klamath basin lacks an overall hydrogeologic plan by the Oregon Water Resources Department. Farmers, who had welcomed government reclamation projects for irrigation, discovered in the 1990s that they didn't actually own "federal" water. This has led to the present tangle of water rights, political disputes, and additional "solutions." Today, the buying, selling, borrowing, and juggling of water rights from place to place or from person to person are being tried in an effort to apportion the dwindling resource. Gannett surmises that the water table may recover with a reduction in pumping.

Geologic Highlights

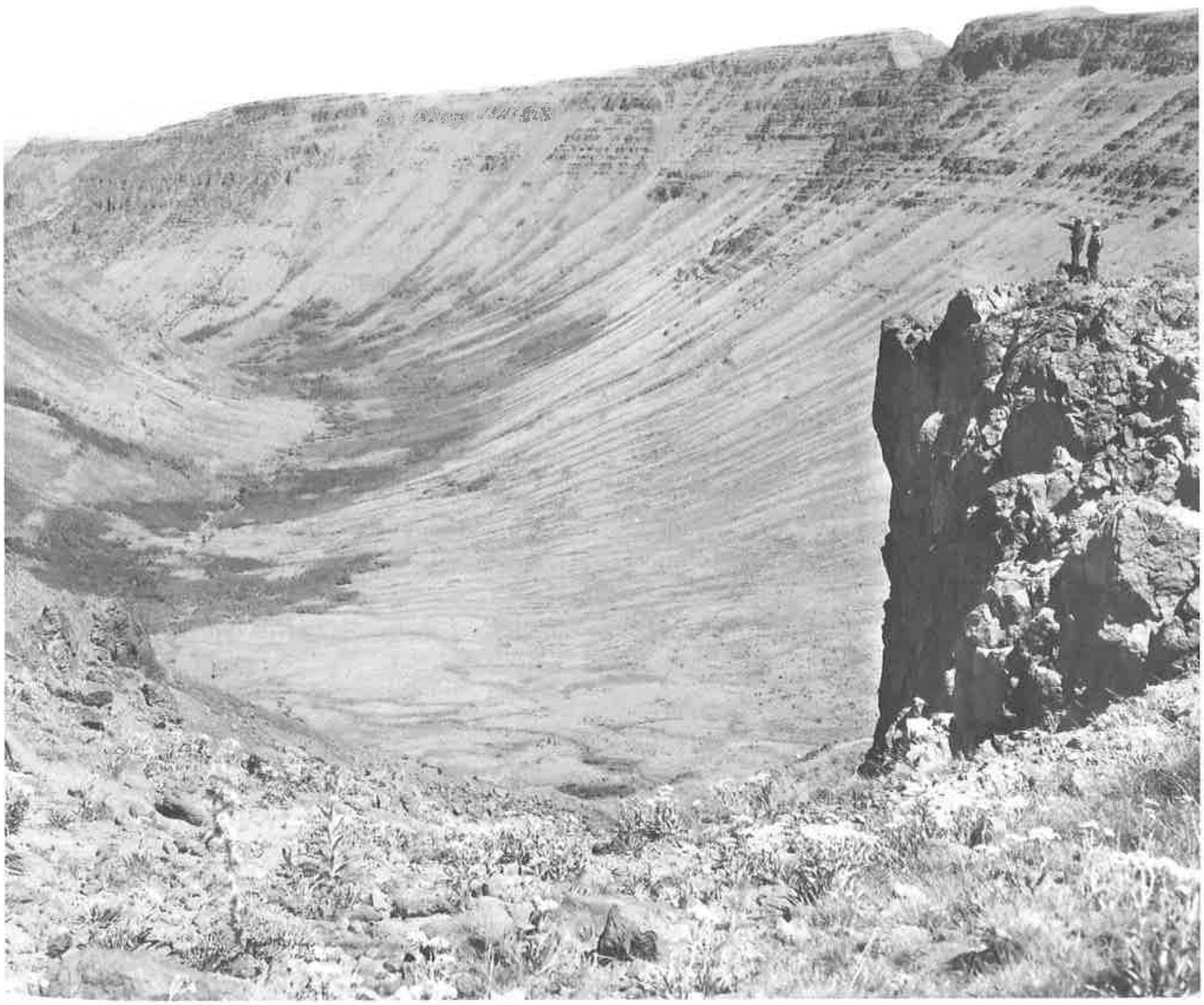
Basin and Range topography is a mixture of precipitous escarpments, gently sloping meadows, and flat lakebeds. Sagebrush, saltbush, and other xeric shrubs of the high desert country contrast with the lush watered grasses growing in the broad depressions, all of which give the landscape an arresting variety.

Mountain Ranges

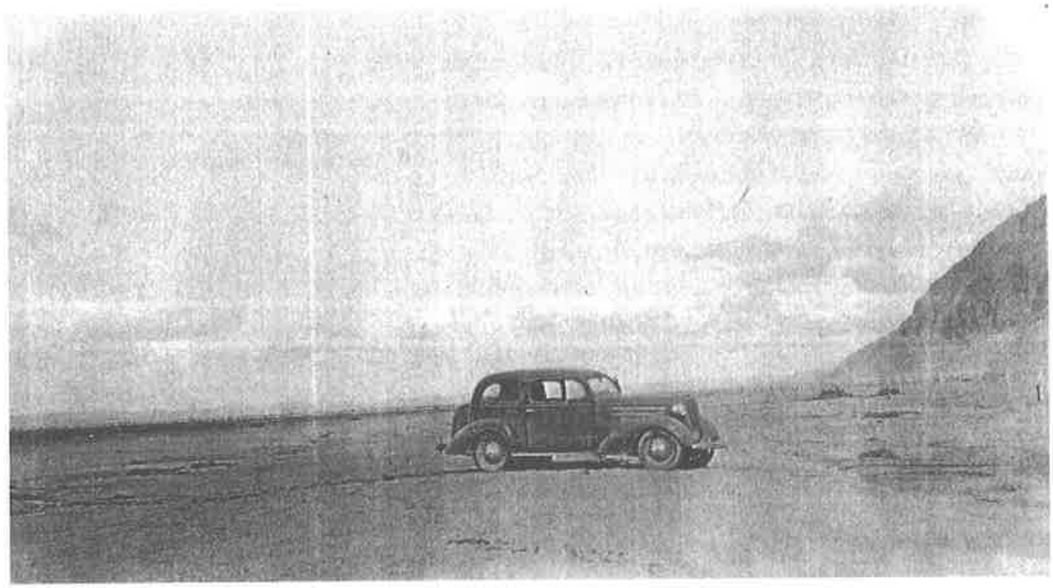
Five north-south-trending ridges, Modoc Rim, Winter Rim, Abert Rim, and Hart and Steens mountains break the province into basins. Of these the Hart and Steens mountains are the most prominent. Rising over a mile above the desert floor, Steens Mountain is a large fault block (horst), where layers of thick flood basalts, sediments, and volcanic ash from eruptions in Harney basin have been fractured into several pieces. The northernmost portion tilted toward the west as the block rose, giving that side a gentle slope into Catlow Valley, whereas the abrupt eastern face drops precipitously into the Alvord desert.

Hart Mountain, which merges northward with Poker Jim Ridge, is part of a fault block complex whose sheer western wall projects more than 3,000 feet above Warner Valley. The Hart Mountain Antelope Refuge, dedicated in 1936, encompasses 215,000 acres and is overseen by the federal government. The refuge is home to pronghorn antelope and mule deer, varieties of birds, rodents, and predators.

On Steens Mountain, erratics were carried by glacial ice from snow-covered heights to be dropped some distance from the original outcrop. Many are large in size, as emphasized by the hat on the rock. (Photo from Evans and Geisler, 2001)



Looking north into Kiger Gorge, the flat-bottom and U-shape of a glaciated valley are unmistakable, as are the distinct flows of Steens Basalt in the walls. Along the rim on the top right, back-to-back glaciers cut through at The Big Nick. (Photo courtesy Oregon State Highway Department)



The Warner Valley is occupied today by Bluejoint, Stone Corral, Campbell, Flagstaff, Hart, and Crump lakes, as well as by other small remnants of what was originally a much a much broader water body. At Bluejoint, runoff from the low hill to the right sends enough water into the playa to grow a sparse stand of bluejoint grass. (Photo taken in 1936; courtesy Oregon State Archives)

Lakes and Valleys

Between the high mountains, lakes of varying sizes occupy the depressions. With no outlets, the lakes are maintained by rainfall and small amounts of water issuing from springs and snow-fed streams. When the water vanishes during periods of low precipitation, the lakes may break into a string of ponds, or the valley may even become a dry meadow. Since the late Pleistocene, water levels have fluctuated considerably.

Ancient Lake Modoc, which once reached nearly 75 miles in length, has receded to the present-day disconnected Upper and Lower Klamath lakes and Tule Lake in California. The broad expanses of Yonna and Langell valleys are dry portions of Lake Modoc.

Pluvial Lake Chewaucan, whose remnants are Summer Lake, Lake Abert, and the Chewaucan Marshes, was originally almost 375 feet deep. The marsh at the north end of Summer Lake is fed by Ana River.

Alvord and Guano lakes

On either side of Steens Mountain, the mud floors of Alvord and Guano basins have been broken into gigantic fissures with polygonal patterns. Ranging in size from 50 to 1,000 feet long and up to 15 feet deep, huge cracks developed in the clay of the dry lakebeds after water levels dropped enough to cause shrinkage and contraction. The fissures form irregular shapes so large that they may not be obvious when standing nearby. The mud polygons on Guano Lake are up to 100 feet across making them the largest structures of this type known in North America.