Blue Mountains

Landscape of the Blue Mountains

The Blue Mountains physiographic province lies almost entirely in Oregon with only small portions projecting into southeast Washington and west-central Idaho. Covering an area of 55,000 square miles, the triangular-shaped region is defined on the east by the Snake River Canyon, on the south by the Owyhee Uplands and High Lava Plains, and to the west and north by the Deschutes-Umatilla plateau.

Geographically, the province is a cluster of ranges of various orientations and relief. Situated in the northeast corner, the Wallowa and Seven Devils mountains are separated from the centrally located Elkhorn, Greenhorn, Strawberry, and Aldrich ranges by the wide flat Baker and Grande Ronde basins. To the west, the Blue Mountains chain divides this province from the Umatilla basin, and the Ochocos lie along the border with the Deschutes River valley.

From the Ochoco Mountains at 6,000 feet in elevation, the landscape rises eastward to glaciated summits of the Wallowa Mountains. An immense oval-shaped range, the Wallowas include a striking array of canyons carved out by ice and water, nine peaks that reach over 9,000 feet, and seven more in excess of 8,000 feet.

The area possesses several extensive watersheds including the 175-mile-long Grande Ronde River, the 144-mile-long Powder River, and the shorter Imnaha, 75 miles in length. Covering a distance of 284 miles from its point of origin in the Blue Mountains, the John Day is Oregon's longest. The northerly-flowing Snake River cuts a deep gash that divides the Wallowa Mountains of Oregon from the Seven Devils peaks in Idaho. A chief tributary of the Columbia River, the Snake is 1,000 miles in length and drains 110,000 square miles in western Wyoming, northwest Utah, northeast Nevada, and southeast Washington.

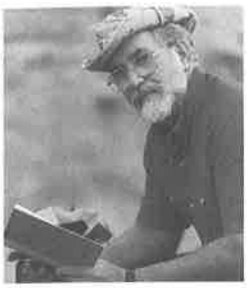
Past and Present

Early geologic work in the Blue Mountains is tied into the region's mineral wealth and production. Waldemar Lindgren's notable *The Gold Belt of the Blue Mountains* in 1901 was followed by James Gilluly's 1930s reports on gold, copper, and lesser minerals, in which he included a summary of the geology. Clyde Ross's 1938 work on the Wallowa Mountains, conducted under the auspices of the Oregon Bureau of Mines and Geology, treats the geology but excludes the ore deposits. A decade later, Warren D. Smith and John Allen published on the Wallowa Mountains. Smith's University of Oregon students attended the annual field camp there, while Allen was charged with compiling a regional handbook of mining prospects for the Oregon Department of Geology and Mineral Industries (DOGAMI).

William Dickinson and Laurence Vigrass's 1965 DOGAMI bulletin on the Suplee and Izee region remains one of the most definitive to date. Their maps, structure, and stratigraphy for some 35,000 feet of Paleozoic, Mesozoic, and Cenozoic strata outline the geology of 250 square miles in Crook, Grant, and Harney counties. Dickinson taught at Stanford University prior to going to the University of Arizona where he directed a new generation of sedimentologists. Since retirement, he continues to work on plate tectonics and is an authority on the western United States. An emeritus professor from the University of Regina, Vigrass works today with the Saskatchewan Department of Mineral Resources. (Photo courtesy W. Dickinson)

As far back as the 1970s, Tracy Vallier and Howard Brooks began to unravel the evolution of the Blue Mountains in accord with plate tectonics. Their publications during the late 1960s treat the geology of the Snake River, and their U.S.G.S. Professional Papers, edited between 1986 to 1995, summarize current thinking on Paleozoic and Mesozoic island arc accretion, batholith intrusions, and mineral resources.

Howard Brooks' ancestors followed the Oregon Trail to Linn County before they settled in Hazelton, Idaho, near the Snake River canyon, where he grew up. A graduate of the Mackay School of Mines, Brooks began with DOGAMI in 1956, working for 35 years in the Baker City office. Since retirement, he has written a new book on the history of gold mining in the Blue Mountains and volunteers at the National Historic Oregon Trail Interpretive Center in Baker City. (Photo courtesy H. Brooks)



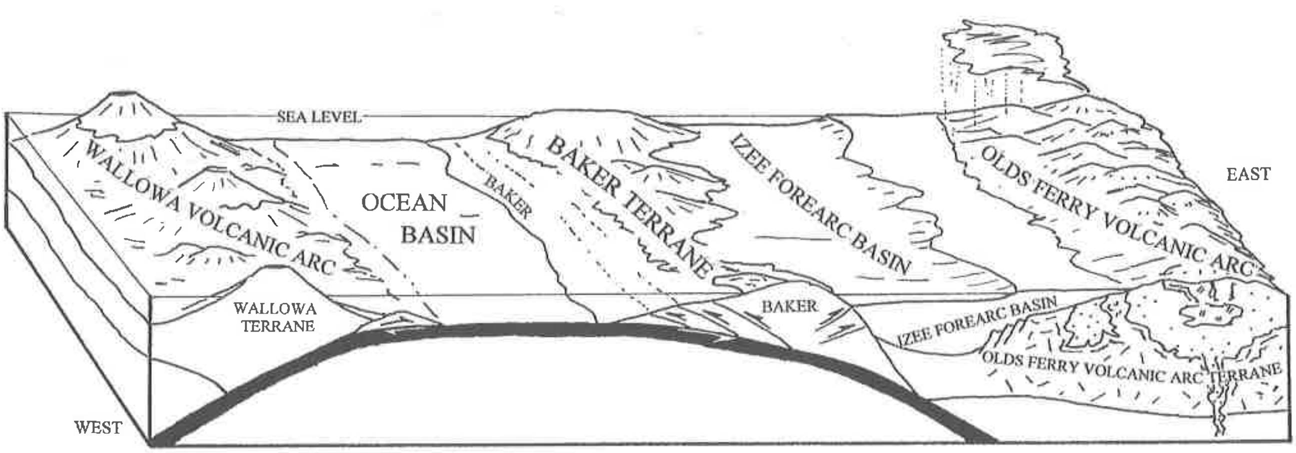
Completing his degree from Oregon State University on the Snake River Canyon in 1967, Tracy Vallier joined the Deep Sea Drilling Project at Scripps Institution of Oceanography before he was assigned to the marine branch of the U.S.G.S. He retired in the late 1990s and currently lectures at several universities. Vallier's life-long interest in Hells Canyon on the Snake River has led to several books that explore the history and geology in combination with his personal experiences there. (Photo courtesy T. Vallier)

George Walker grew up in Palo Alto, California, and graduated from Stanford University in 1948. His involvement in Oregon began as a student when he worked with Aaron Waters on quicksilver deposits in the Horse Heaven Mine. During his career with the U.S.G.S., Walker's projects took him to the most remote areas of eastern Oregon. With his method of what has been called mile-a-minute mapping, he was able to complete 15 minute quadrangles in a week and an entire one-degree by two-degree quadrangle in a field season, much of which was accomplished by driving over unpaved dusty roads. His work culminated in the *Cenozoic Geology of the Blue Mountains*, which he edited in 1990, and his *Geologic Map of Oregon* published with Norm McCloud in 1991. (Photo courtesy C. Walker)

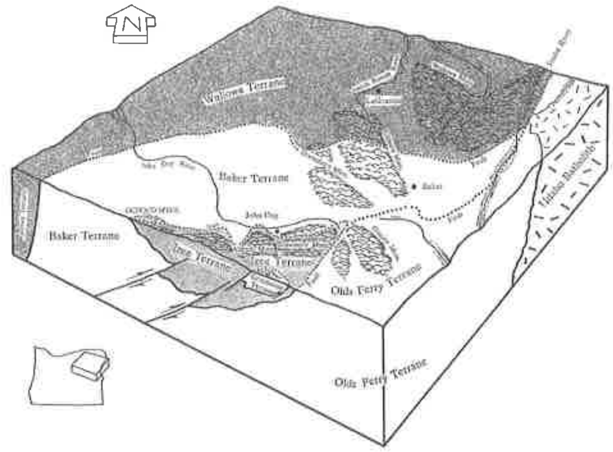
Overview

The geologically unique Blue Mountains are a patchwork of separate blocks (terranes) originating as volcanic island archipelagos and ocean crust in tropical settings well south of their present latitude. Transported during the late Paleozoic and Mesozoic eras, the fragments collided with and were annealed to North America. forming the structural grain of the Blue Mountains.

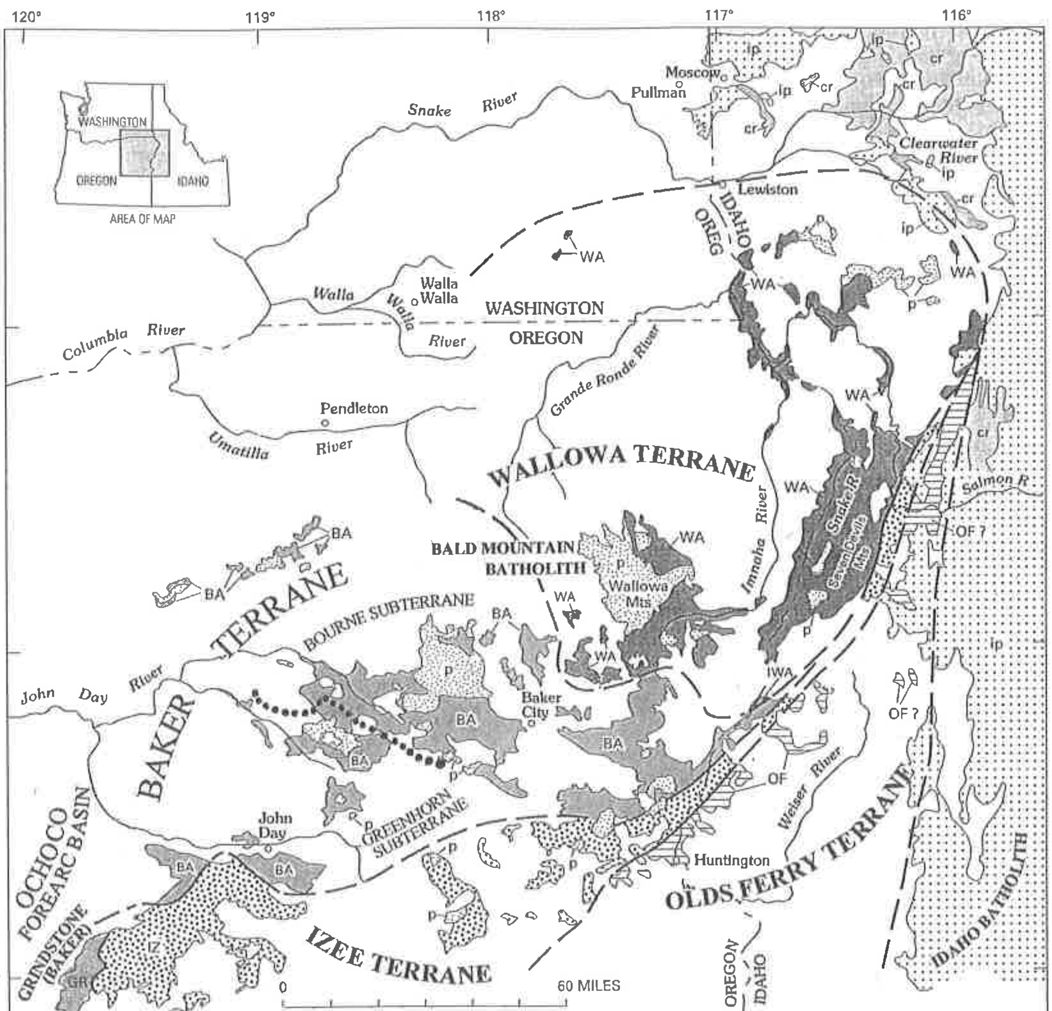
The Baker, Wallowa, Olds Ferry, and Izee terranes, which became the foundation of the Blue Mountains, include distinctive fossils, sediments, and volcanic rocks that provide an opportunity to study the earliest beginnings of the state. Only in the past 30 years have geologists shed light on the details of major events of the past by mapping, describing, and age-dating components of the terranes.



Each of the major Blue Mountains terranes, the Baker, the Wallowa, the Izee, and the Olds Ferry, represents a separate marine setting featuring back-to-back volcanic arcs. (After Brooks, 1979; Brooks and Vallier, 1978; Dickinson, 1995; Dickinson and Thayer, 1978; Dorsey and LaMaskin, 2007; Schwartz, et al., 2010)



Accreted terranes form the foundation of both the Blue Mountains and the Klamath Mountains. In the Blue Mountains, the rocks span the time interval from the Devonian, 400 million years ago, to the early Cretaceous, 140 million years in the past. Arranged in linear belts that extend southwest to northeast, five suites of rocks identified historically were the Grindstone, the Baker, the Wallowa, the Olds Ferry, and the Izee. (After Ave Lallemant, 1995; Brooks, 1979; Dickinson, 1979, 1995; Dickinson and Thayer, 1978; Follo, 1992; Silberling, et al., 1984; Vallier and Brooks, eds., 1995)



TERRANES OF THE BLUE MOUNTAINS REGION

- IZ — Izee terrane
- OF — Olds Ferry terrane
- WA — Wallowa terrane
- BA — Baker terrane
- GR — Grindstone
- Boundary between terranes

ROCKS NOT ASSOCIATED WITH TERRANES

- Cenozoic volcanic and sedimentary rocks
- ip — Late Cretaceous Idaho batholith and related plutonic rocks
- p — Cretaceous to Jurassic plutonic rocks of the Blue Mountains region
- cr — Paleozoic and Precambrian North American cratonal rocks

Late in the Mesozoic Era, a vast shallow seaway covered up to three-fourths of Oregon, depositing thousands of feet of mud, silt, and sand. In this environment, marine reptiles and mollusks of every description populated shallow embayments, while a variety of primitive ferns and horsetails grew along the shore.

During the Cenozoic Era the seaway retreated westward following uplift and folding when phases of volcanism alternated with sedimentation. Lakes, streams, and floodplains provided habitats for mammals and plants and fostered conditions that preserved their remains after lavas periodically engulfed the landscape. A temperate Oligocene environment, around 35 million years ago, was followed in the Miocene by eruptions of the Columbia River lavas that built a thick plateau of basalt unmatched in North America.

As the climate grew colder 2 million years ago, widespread glaciation gave the region its final topographic complexion. Glaciers capped mountain tops and descended into stream valleys. At the height of the Ice Ages, nine major glaciers spread throughout, only to melt and retreat with warmer temperatures.

Geology

Paleozoic-Mesozoic

The Blue Mountains province is a collage of displaced Paleozoic and Mesozoic terranes, some from remote oceans, that were covered by Tertiary lavas and sediments. The word terrane applies to suites of similar rocks, separated by faults, and transported from their place of origin. First named and delineated by Howard Brooks, William Dickinson, Tom Thayer, and Tracy Vallier, the individual terranes of the Blue Mountains were steadily modified with increased knowledge of tectonic processes. In 1984, Norm Silberling of the U.S.G.S. revised and refined the boundaries, while the most recent work raises doubts as to whether the Grindstone and Izee are separate terranes.

During the early Paleozoic Era, over 500 million years ago, North America was still part of the emerging super continent Pangaea, which began to break into separate fragments in Triassic time. As the oceanic plates diverged, chains of volcanic islands formed in a tropical (Tethyan) ocean. Carried conveyor-like atop tectonic plates, the island arcs collided with and were affixed or accreted to the West Coast of North America during the late Paleozoic and into the Mesozoic. At that time a vast ocean covered the region that was to become Oregon, and, as each terrane block arrived, it was swept up and attached to the older continental landmass. At the boundary between the plates, layers of sediments, scraped off the lower slab, accumulated as an accretionary wedge.

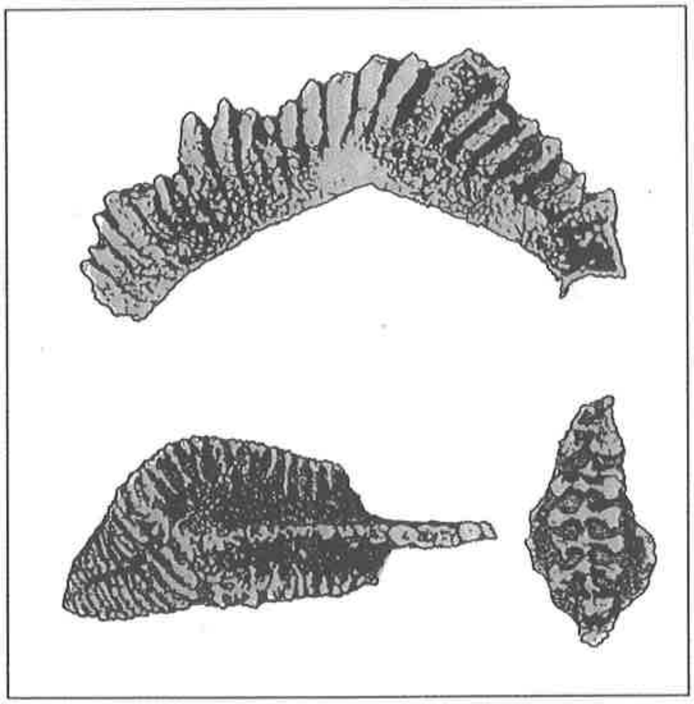
By the 1970s geologists recognized that the individual terranes making up the Blue Mountains had merged (amalgamated) even before accretion, sharing a history of volcanism, sedimentation, and metamorphism. While details of the interactions among the various terranes are still being hammered out, the consensus is that by the middle to late Triassic Period two large volcanic chains, the Wallowa and the Olds Ferry, were adjacent to the margin of North America. The Baker terrane, separating the two, was an ocean-trench-subduction complex with an accretionary wedge, while voluminous sediments of the Izee terrane were deposited in the seaway between the Baker and Olds Ferry island arcs. In the late Triassic, the Wallowa merged with the Olds Ferry, and the amalgam of all terranes was intruded by granitic plutons and annexed to the continent.

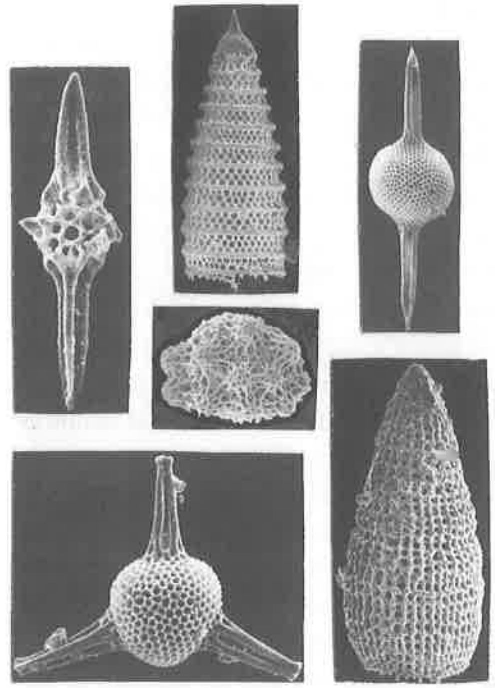
Individual Terranes

Grindstone Terrane

As the oldest and smallest of Oregon's northeastern terranes, the Grindstone is limited to scattered outcrops in Crook, Harney, and Grant counties. Today many geologists no longer regard the tiny Grindstone as an independent terrane but consider it to be part of the much larger Baker assemblage.

The Grindstone suite is composed of early Paleozoic limestone slabs or olistoliths, which became detached from shallow oceanic shelves or volcanic knolls, to slide downslope and mix with late Permian to Triassic rocks in the Izee basin. The Grindstone includes an unnamed 400-million-year-old Devonian sequence overlain by the Mississippian Coffee Creek, the Pennsylvanian Spotted Ridge, and the Permian Coyote Butte formations. During the 1940s, Charles Merriam and Sheridan Berthiaume from Cornell University worked out and named many of the formations, while more





The oldest microfossils known from Oregon are conodonts, the teeth of a primitive Devonian fish found in limestones of the Grindstone terrane (above left). They are less than 1/32nd inch in length. From the Baker terrane, the intricate glassy skeletons of Mesozoic radiolarian microfossils (right) are just 1/64th inch long. (Photos courtesy of N.M. Savage; E. Pessagno)

recently Charles Blome and Bruce Wardlaw of the U.S.G.S. and Merlynd Nestell at the University of Texas refined the stratigraphy and age-dated the rocks using microfossils.

Close to the border between Crook and Harney counties, a 100-foot-thickness of Devonian limestone yields brachiopods, corals and microfossil conodonts. Nearby, over 1,000 feet of limestones, mudstones, sandstones, and cherts of the Coffee Creek Formation includes shallow-water tropical corals and brachiopods, whereas the overlying nonmarine sandstones of the Spotted Ridge Formation record a coastal plain inhabited by ferns and scale trees similar to those in the late Pennsylvanian coal layers of the central and eastern United States. One thousand feet of limestones, cherts, and sandstones of the Coyote Butte make up the uppermost stratum of the Grindstone. This fossiliferous formation yields shallow-water Permian fusulinids, corals, and radiolaria.

Baker Terrane

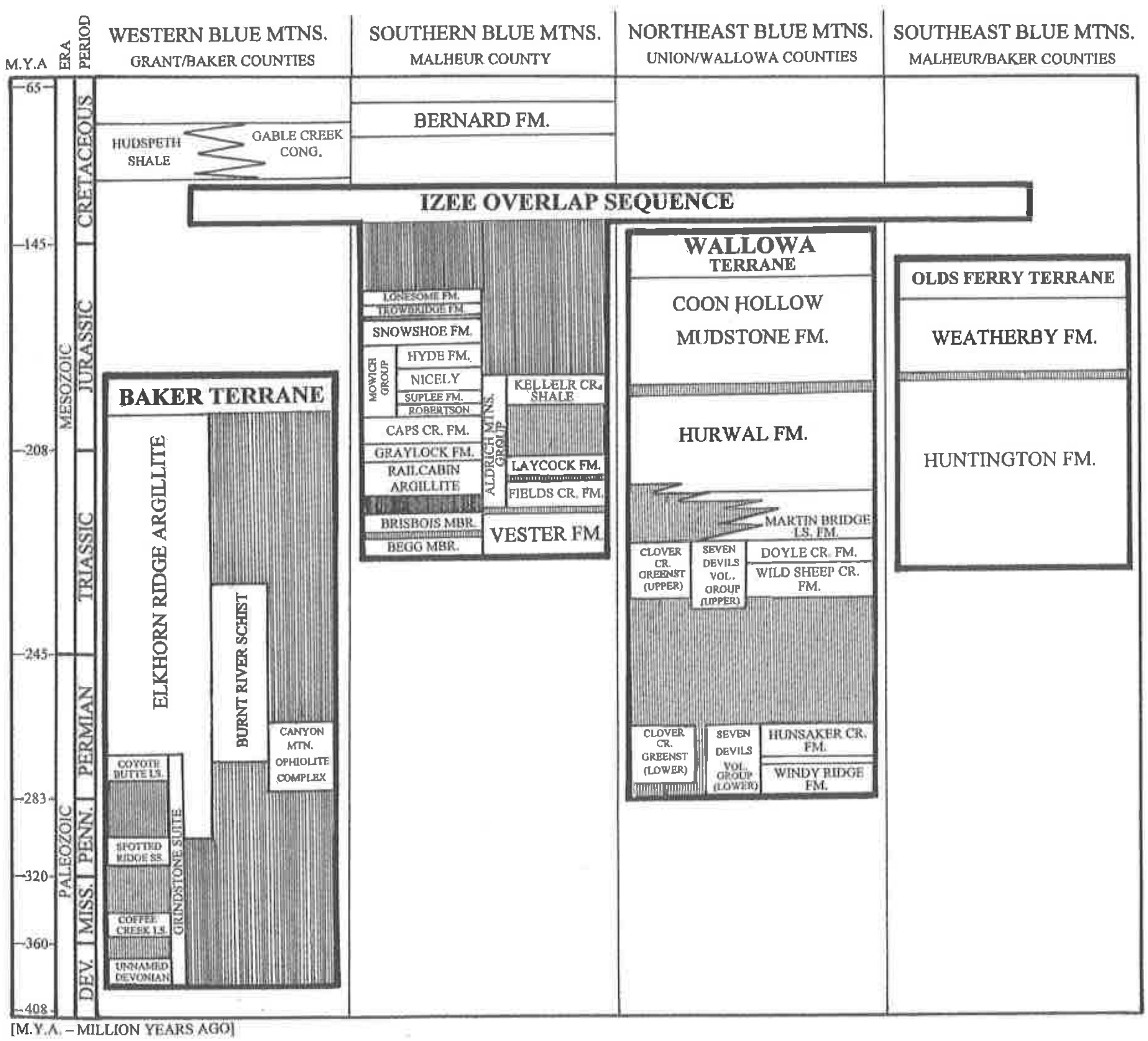
The Baker terrane curves across Grant, Baker, and Wallowa counties in Oregon to Cuddy Mountain in Idaho. This chaotic mixture of deep ocean sediments and volcanic rocks has been metamorphosed, folded, and intruded by plutons. Separating the Olds Ferry to the southeast from the Wallowa terrane on the north, the Baker incorporates fragments of both and represents a subduction zone and mid-ocean basin. As rocks of the Baker terrane were overridden by the oncoming Olds Ferry, they were tightly compressed into an accretionary wedge. Around the margins of the present-day Pacific Ocean, similar prisms of sediments can be found in severely folded and sheared rocks trapped between colliding plates. Deep sea cherts are especially abundant, and ophiolitic fragments are scattered throughout.

Late Paleozoic and Mesozoic exposures of the Baker contain broken mixed blocks of the Permian Canyon Mountain complex, the Permian to Triassic Burnt River Schist, and the Pennsylvanian through Jurassic Elkhorn Ridge Argillite. The Canyon Mountain complex, which covers an area of about six square miles southeast of John Day, is rich in serpentine and is regarded as a nearly complete ophiolite. An ophiolite suite is a predictable succession of ocean crust with mantle peridotites at the base, followed upward by gabbro, basalt dikes, pillow lavas, and capped by deep sea muds and cherts. Because the rock serpentinite, meaning serpent-like, is easily sheared by faulting, it derives its name from the broken polished surfaces that resemble the texture of snakeskin.

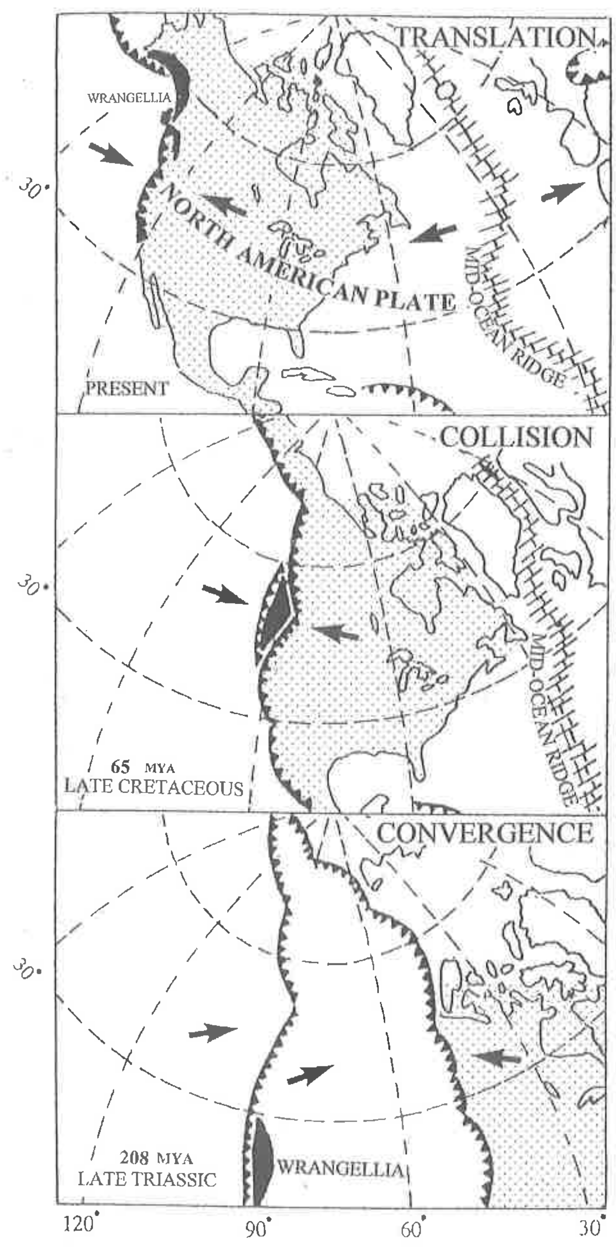
Near Durkee and exposed in the Burnt River Canyon in Baker County, the Burnt River Schist is a 20,000-foot-thick sequence of greenstones, schists, limestones, quartzites, and quartz-rich shales. Limestone and shale pods in the Burnt River Schist yield Triassic microfossils. Where they have undergone the intense effects of heat and pressure, the limestones have recrystallized to marble.

In the vicinity of Baker City and Sumpter, the Elkhorn Ridge Argillite is represented by thick layers of altered mudstones with thinner layers of volcanic ash, chert, and limestones. Fusulinids and corals from the cherts have been dated as Pennsylvanian through late Triassic, but Charles Blome has reported early Jurassic radiolarian faunas in the units near John Day and east of Baker City.

On the basis of its distinctive metamorphic and deformation history, the central part of the Baker terrane was split into two belts in 1995, which were informally named the Bourne and Greenhorn subterranes by Mark Ferns and Howard Brooks. Assemblages of the Elkhorn Ridge Argillite, consistent with the make-up of an accretionary wedge, are



Stratigraphy of the Blue Mountains terranes. (After Armentrout, Cole, and TerBest, 1979; Dickinson and Vigrass, 1965; Dorsey and LaMaskin, 2007; Follo, 1994; Imlay, 1980, 1986; LaMaskin, Dorsey, and Vervoort, 2008; LaMaskin, et al., 2009; Silberling, et al., 1987; Vallier and Brooks, eds., 1986, 1994, 1995; Walker, ed., 1990; White, et al., 1992)



One model for the convergence, collision, and translation of Wrangellia shows that the North American plate, moving in a northwesterly direction, captured and swept up the Wrangellia superterrane before shifting the individual slices along faults toward Alaska. (After Brooks, 1979; Jones, Silberling, and Hillhouse; 1977; Kays, Stimac, and Goebel, 2006; Moore, 1991; Stanley, 1987)

included in the northern Bourne subterrane. The southern Greenhorn is a mélange of serpentine and volcanic sediments. Separated by the east-west Cave Creek fault near Burnt River Canyon, the belts have undergone varying degrees of metamorphism in which the Bourne was buried deep in the collision zone, whereas the position of the Greenhorn was somewhat shallower.

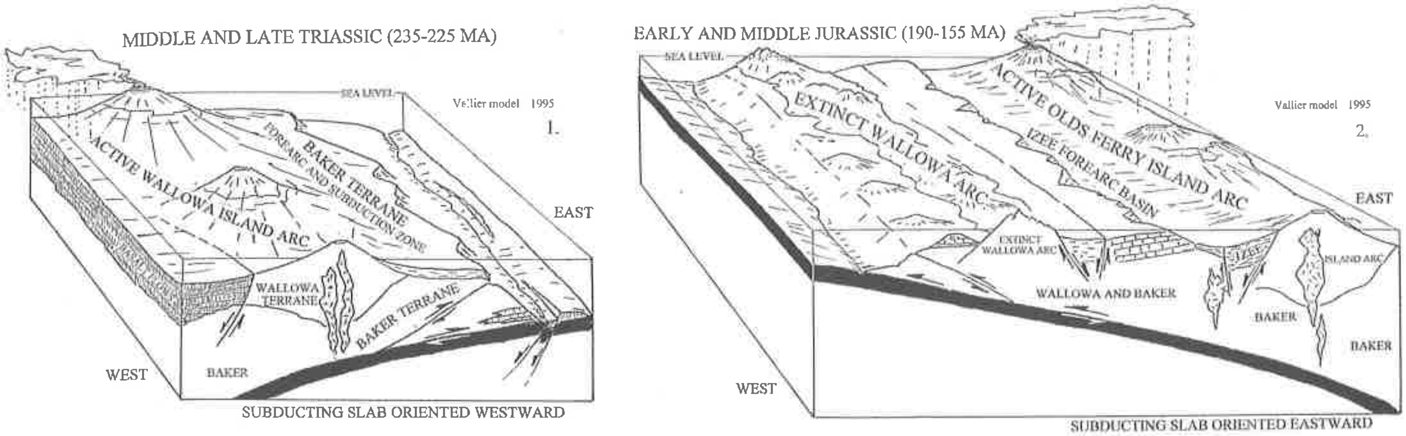
Wallowa Terrane

The Wallowa is the northern-most terrane of the Blue Mountains province, underlying the Wallowa Mountains in Oregon and the Seven Devils range in Idaho. Isolated exposures appear north of Walla Walla, Washington, and south of Lewiston, Idaho, while continuous sections can be traced for over a hundred miles in the Snake River Canyon.

The puzzle of the Wallowa volcanic island arc has undergone modifications, and several models have been presented to explain its complexities. David Jones of the U.S.G.S. found striking similarities between Mesozoic rocks and fossils in scattered slivers from the Blue Mountains in Oregon and those of the Wrangell Mountains in Alaska, leading him to propose the concept of a superterrane Wrangellia. During the Triassic Period, Wrangellia was a single crustal block or a large igneous province situated in the tropical western Pacific. Transported eastward atop a tectonic plate, it collided with and was accreted to North America. After attachment, Wrangellia was sheared up by large-scale faults that translated or conveyed the individual pieces northward to Canada and Alaska, a distance of 1,500 miles.

George Stanley at the University of Montana believes the Wallowa terrane originated as an island archipelago within a larger volcanic center but not as part of a superterrane. By mid-Jurassic time, the edifice was close to North America and associated with other Blue Mountains terranes. Stanley's studies of Triassic fossils in the Wallowa package suggest that it may have an endemic linkage with the Alaskan Wrangellia but that it shows little affinity with other North American fragments.

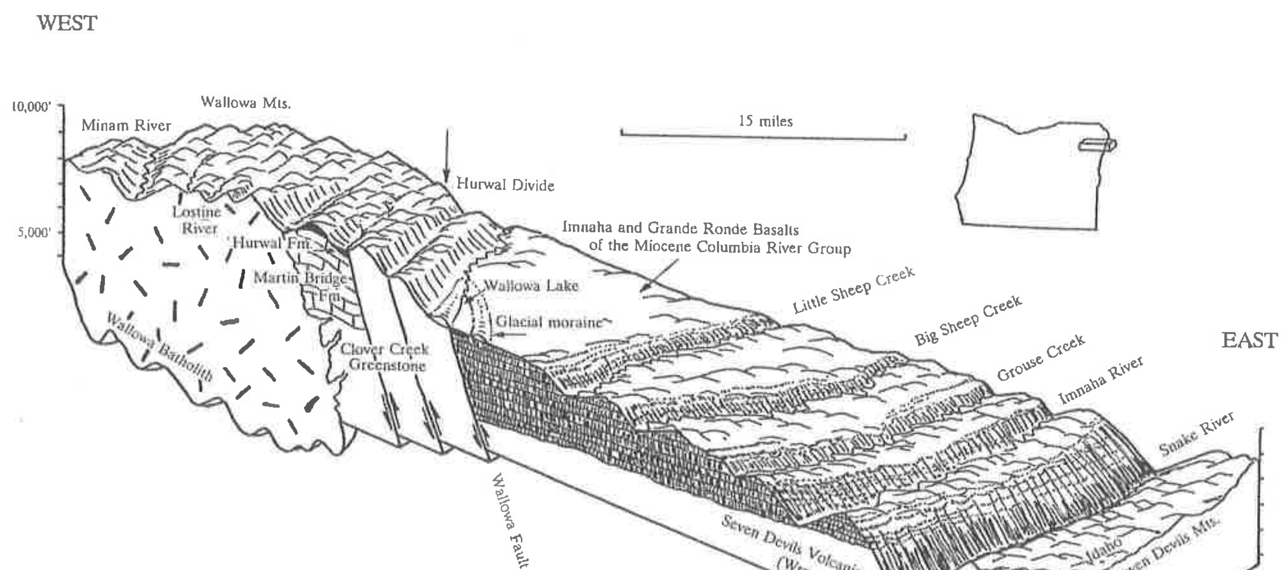
The Wallowa terrane is composed of a diversity of Permian to Jurassic volcanic and sedimentary rocks of the Seven Devils Volcanic Group, the Clover Creek Greenstone, the Martin Bridge, and the Hurwal formations. Named by Tracy Vallier in 1977,



One scenario illustrating the evolution of the Blue Mountains features a major reorientation of the subduction slab, which shifted from west-dipping during the Triassic to east-dipping in the Jurassic. (After Vallier, 1995)

the oldest Seven Devils Group was divided into the Windy Ridge, the Hunsaker Creek, the Wild Sheep Creek, and the Doyle Creek formations. These rocks partially correlate with the Clover Creek Greenstone, a 4,000-foot-thick sequence in northern Baker County that contains cool-water boreal Permian brachiopods in its lower intervals but only scarce Triassic fossils in the upper portion. Volcanic flows of the Windy Ridge Formation, erupted in a submarine environment, are limited to exposures along the Snake River at the Oxbow, whereas the shallow-water Hunsaker Creek Formation was deposited in a basin adjacent to a volcanically active but eroding island arc. Exposed along the Snake and Salmon river canyons as well as in the Seven Devils and Wallowa mountains, the Hunsaker Creek has well-preserved crinoids, Permian bryozoa, and mollusks in limestone lenses. Volcanic rocks of the Wild Sheep Creek and volcaniclastics of the Doyle Creek accumulated in a forearc or interarc basin. Limestones between lava flows contain the Triassic deep-water flat clam *Daonella*.

During the late Triassic to early Jurassic, the Martin Bridge and Hurwal episodes record a variety of



Structures along the eastern flank of the Wallowa Mountains from the Minam to the Snake River. (After Follo, 1994; Smith and Allen, 1941; Vallier, 1977, 1995; Walker, ed., 1990; White, 1994) marine environments. Following a lull in volcanic activity, Martin Bridge limestones accumulated atop a shallow shelf dotted with reefs. An abrupt change to a deeper oceanic slope and basin is recorded by coarse-grained breccias and conglomerates present in the strata.

Renewed volcanism and submergence of the Martin Bridge carbonate platform coincided with a shift to deep-water turbidites of the Hurwal Formation. Erosional channels cut into Hurwal mudstones filled with conglomerates and breccias, some of which may have been derived from the Baker terrane. Fossil mollusks, corals, and marine reptiles within the Martin Bridge and Hurwal are remarkably similar to faunas of the western Pacific, central Europe, and the Himalayan Mountains, reflecting the exotic nature of the displaced Wallowa terrane.

Exposed along the Snake River, Jurassic Coon Hollow mudstones, sandstones, and conglomerates, deposited atop the uneven eroded surfaces of the Wild Sheep Creek and Doyle Creek formations, are the uppermost layers of the Wallowa terrane. Fragmentary plants and occasional invertebrates, carried by streams onto deltas and floodplains, record nonmarine and nearshore conditions and a temperate rainy climate.

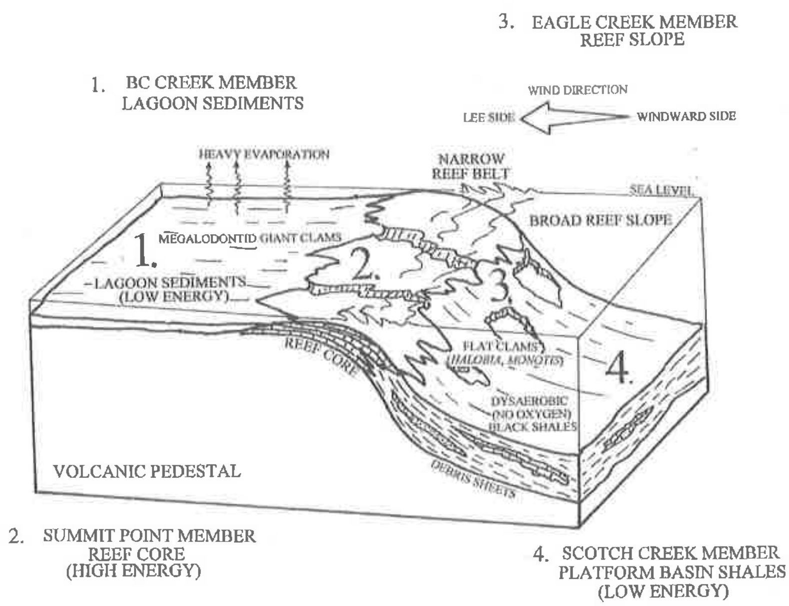
Compressional forces that accompanied the accretion process in late Mesozoic time intensely deformed the Wallowa terrane, locally overturning entire folds.

Izee Terrane

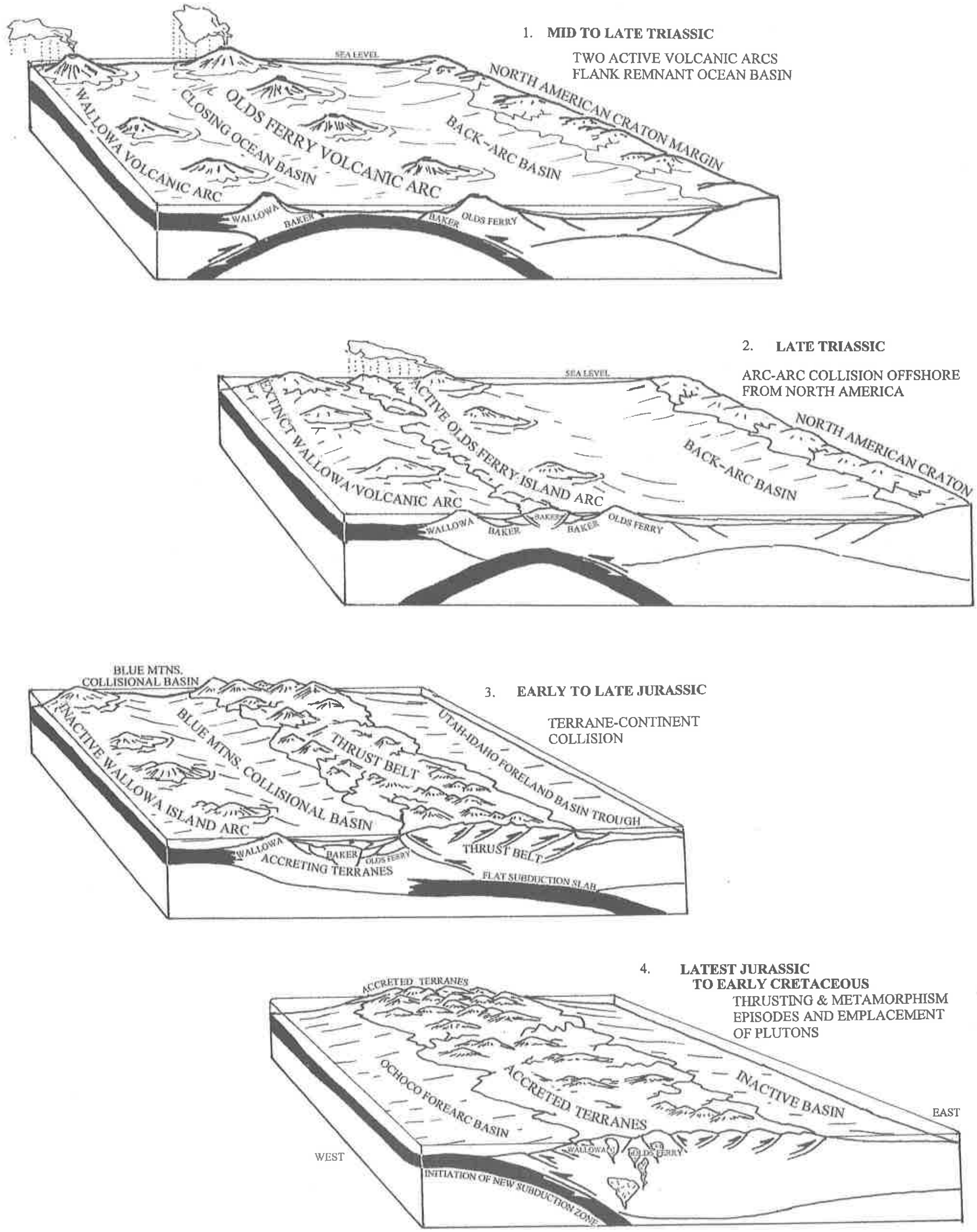
Originally designated as a separate terrane, Izee sediments have been recently interpreted as deposits in a forearc basin between the Wallowa and Olds Ferry volcanic arcs. The assemblage is regarded as an overlap sequence, covering the older rocks of the Wallowa, Baker, and Olds Ferry terranes. This suggests that at least part of Izee sedimentation took place after amalgamation of the older crustal fragments, which leaves its status as a fault-bounded terrane in doubt.

A continuous 12-mile-thick succession of Triassic to Jurassic rocks depicts varying depths and distinct environments for the Izee. On the basis of structure, petrology, and fossils, the strata were divided into numerous formations by Dickinson and Vigrass. Ammonites and radiolaria, inhabiting a Tethyan, tropical marine environment during the late Triassic, were supplanted by invertebrates of a boreal nature by the middle Jurassic, evidence that the terrane had moved from warmer to cooler latitudes. Exposures are limited in areal extent from Suplee and Izee in Crook and Grant counties eastward to the John Day inlier in Wheeler County. The older rocks are revealed in the inlier or erosional window cut through a covering of younger rocks.

Within Izee strata, the mid-Triassic Vester Formation is separated from the Triassic to Jurassic Aldrich Group by the northeast-southwest trending Poison Creek Fault. Both have a selection of cephalopods,



Some of the best exposures of early Mesozoic shallow-water limestones in North America are found in the Martin Bridge intervals. The lagoon and reef settings are rich in mollusks, corals, crinoids, and microfossils, whereas the deep-water fauna consists of radiolaria, flat clams, ammonites, and marine reptiles. Utilizing changes in deposition, George Stanley divided the Martin Bridge into four members, the BC Creek, the Summit Point, the Eagle Creek, and the Scotch Creek, representing reef lagoon, reef core, reef slope, and a deep water basin respectively. Gigantic clams (bivalves) in the BC Creek lagoon lived in gregarious colonial assemblages. (After Stanley, McRoberts, and Whalen, 2008)



Sequential models reconstruct intervals of sedimention, volcanism, plate collision, and terrane accretion in the Blue Mountains between the Triassic and Cretaceous. (After Dorsey and LaMaskin, 2007; Lamaskin, et al., 2009) brachiopods, and pelecypods. The presence of thick-shelled oysters in the earliest Begg Formation suggests the shallow waters of a marine shelf and shoreline. The Jurassic Mowich Group, which is less than 500 feet thick in most places, includes the sandy nearshore Suplee Formation and limestone reefs of the Robertson Formation that are largely made up of tightly packed colonies of plicatostylid clams (*Lithiotis*). Comprising the upper layers of the Izee basin, the Snowshoe, Trowbridge, and Lonesome formations reach thicknesses of 4,000 feet. Ammonites are particularly numerous in the Snowshoe, but fossils are scarce in the other two.

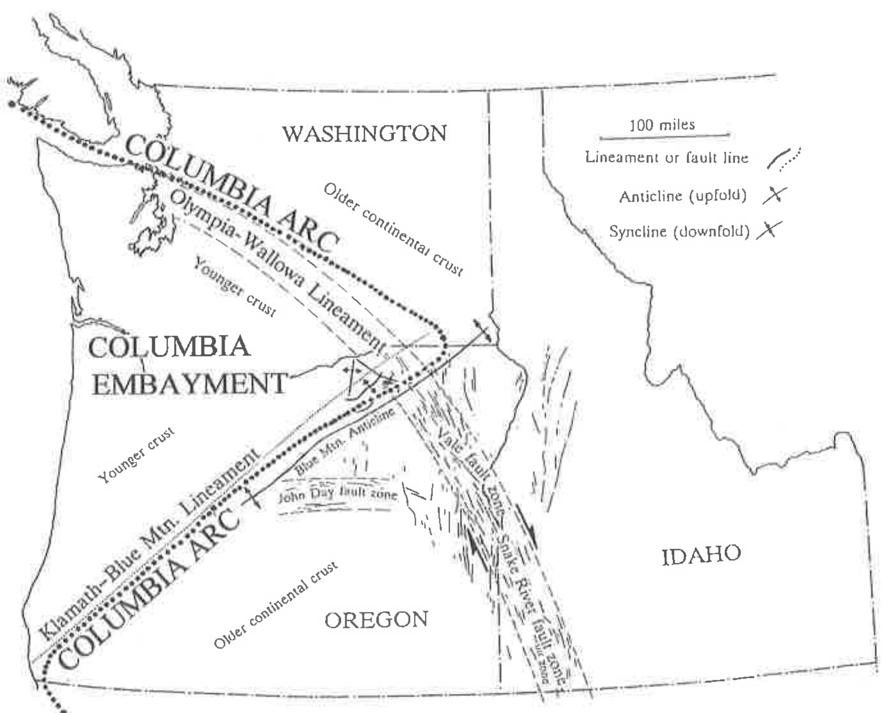
Thrusting of the Izee terrane that began during the late Jurassic gradually intensified into the Cretaceous. The intrusion of granites along with episodes of folding greatly complicates the interpretation of Izee tectonic history.

Olds Ferry Terrane

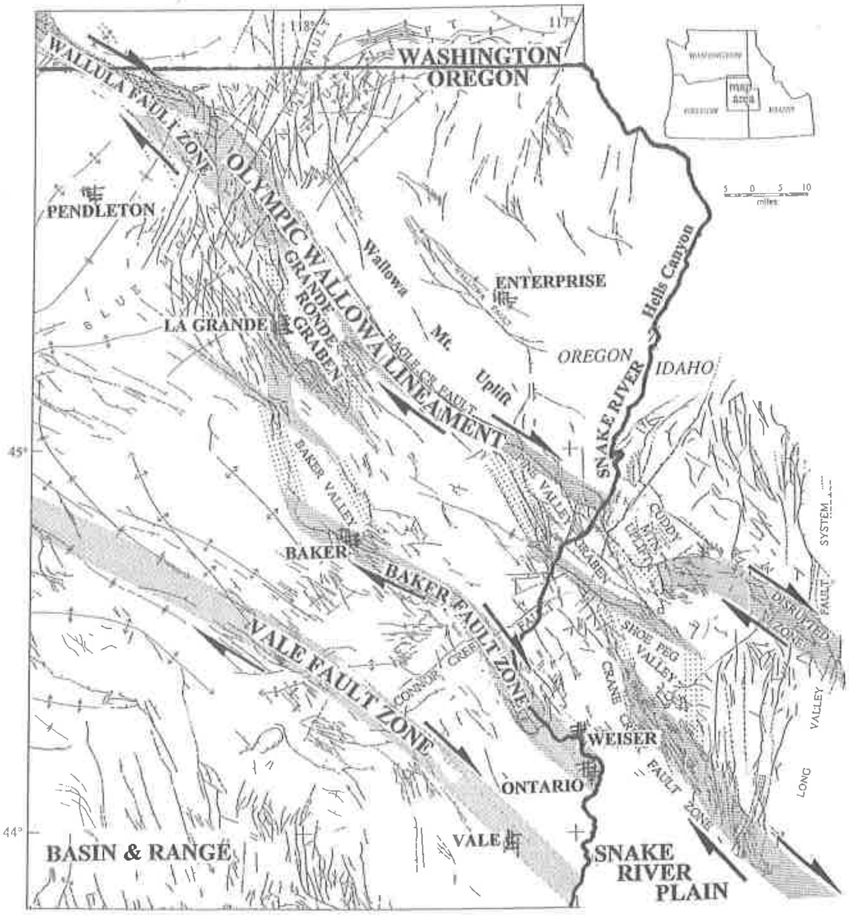
The Olds Ferry terrane extends toward the northeast in a curved alignment of isolated exposures from Huntington in Malheur County to Cuddy Mountain, Idaho. Triassic to lower Jurassic Huntington and the middle Jurassic Weatherby formations of this terrane were described by Howard Brooks and more recently refined by Todd LaMaskin. Along the flanks of the Olds Ferry island arc, volcanic flows, tuff, breccia, and conglomerates of the Huntington Formation interfinger with sandstone and siltstone beds bearing ammonites and clams. A distinctive limestone layer in the lower Huntington reflects a brief quiet period between volcanic eruptions. In contrast to other Blue Mountains terranes, Olds Ferry rocks show only minimal folding toward the end of the Jurassic.

Above the Huntington, the Weatherby Formation is exposed in the Ironside Mountain inlier. The Weatherby consists of volcaniclastic sedimentary rocks, shallow marine limestone pods with ammonites, and nonmarine conglomerates covered by black marine shales and turbidites eroded from the Olds Ferry volcanic arc. The Connor Creek fault, which separates the Weatherby from the Baker terrane, can be traced in a southwesterly direction for almost 30 miles across the Snake River from Idaho.

In their overview, Rebecca Dorsey and Todd LaMaskin divided the volcanics and sediments of the Blue Mountains into two distinct phases or megasequences, thick covering layers that represent separate well-defined lengthy stages during the evolution of the province. The transition between the two megasequences reflects a significant change in the regional tectonic setting from multiple small, arc-related basins to a single large-scale marine trough.



The Olympic-Wallowa and Klamath-Blue Mountains lineaments are enormous features that run for hundreds of miles. The OWL strikes southeast-northwest from Puget Sound to the Snake River and parallels the Wallula and Eagle Creek faults. It crosses the southwest to northeast-trending Blue Mountains anticline, a major Tertiary structure from Powell Buttes in Crook County almost to Lewiston, Idaho. The anticline folded upward in the Oligocene, around 35 million years ago, recording strong northwest-southeast compression. The Klamath-Blue Mountains lineament strikes northeast-southwest for a distance of 400 miles and is slightly north of the Blue Mountains anticline. (After Lawrence, 1976; Mann and Meyer, 1993)



Elongate pull-apart basins or grabens such as the Baker, Grande Ronde, and Pine Creek valleys develop along megashears. They are the product of east-west crustal extension south of the Olympic-Wallowa lineament where thinning (extension) is greatest. (After Hooper and Conrey, 1989; Mann and Meyer, 1993; Riddihough, Finn, and Couch, 1986; Walker and Robinson, 1990)

Batholiths and Granitic Rocks

From the Paleozoic to Mesozoic eras, the Blue Mountains terranes were intruded by batholiths and smaller plutons and altered by heat and pressure. A mass of coarse-grained crystalline rock, batholiths invade the crust and cool slowly. Tracy Vallier divided the bodies by age into the late Paleozoic and Triassic plutons of the Wallowa and Baker terranes, the middle Triassic to early Jurassic of the Olds Ferry, and the later Jurassic to early Cretaceous batholiths, which intruded all of the terranes. In the Elkhorn Mountains, the 144-square-mile Bald Mountain batholith is smaller than the Wallowa batholith at the core of the Wallowa Mountains, which covers 324 square miles and is the largest in Oregon.

Faulting and Structure

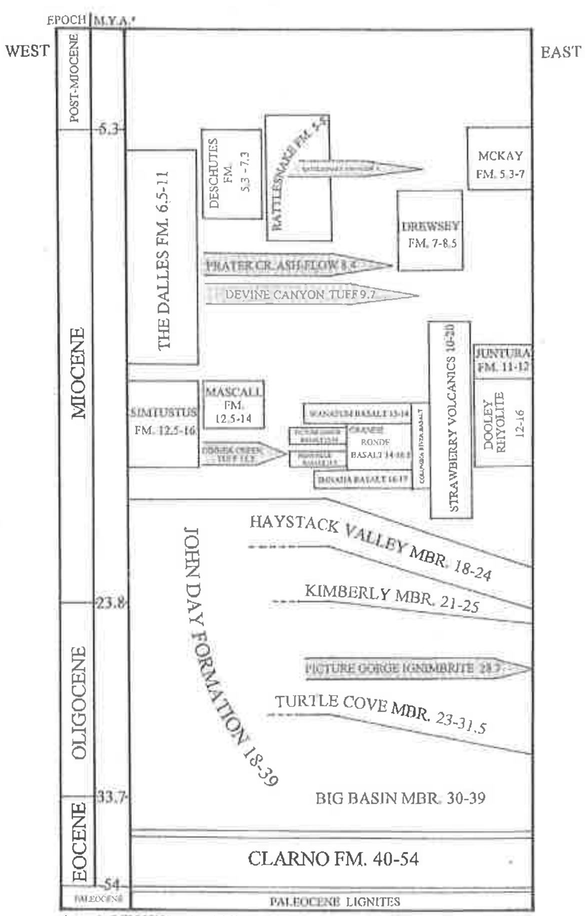
Lineaments are visible on the surface but are of such magnitude that they can be seen best on high-altitude aerial photographs or satellite images. Although poorly understood, they are thought to be megashears, lengthy strike-slip faults above some type of boundary or structure buried deep in the crust. Lineaments are expressed along interconnected faults, folds, and grabens or by more subtle features such as the straight alignment of stream valleys or volcanoes.

Cretaceous—Marine Seaway

With the end of accretion in the early Cretaceous, a shallow seaway spread over wide expanses of the Northwest. The shoreline meandered diagonally from the Klamath Mountains to the Blue Mountains and into Washington and Idaho. Among a diversity of inhabitants in the Oregon ocean, the many species of coiled, shelled cephalopods or ammonites are useful in age-dating the rocks. Reptiles such as *Ichthyosaurs*, *Plesiosaurs*, and primitive crocodiles occupied the marine niche, along with flying *Pterosaurs* that fed on fish.

Late Cretaceous sediments atop the older rocks of the Baker and Izee terranes were deposited in a lengthy forearc trough stretching from the Ochoco Mountains in central Oregon to the Klamath

A lengthy Cretaceous basin stretched from the Ochoco Mountains in central Oregon, to the Klamath Mountains in the southwest, and on to the Great Valley of California. (After Dorsey and Lenegan, 2007; Housen and Dorsey, 2005; Kleinhans, Barcells-Baldwin, and Jones, 1984; Wyld and Wright, 2001)



Tertiary stratigraphy of the Blue Mountains. (After Armentrout, et al., 1988; McClaughry, Gordon, and Ferns, 2009; McClaughry, et al., 2009; Retallack, Bestland, and Fremd, 2000; Walker, ed., 1990)

Mountains and the Great Valley of California. Similarities between the ammonites and clams in the Bernard, Hudspeth, and Gable Creek formations from the eastern part of the state to those of the Hornbrook at Grave Creek in Jackson County support this picture. In Wheeler County, coarse-grained conglomerates, mudstones, and turbidites of the Gable Creek and Hudspeth formations are revealed in the Mitchell inlier, a 70-square-mile window through the younger volcanic covering. These were immense deep-sea fan deposits, whereas fossils in exposures at Bernard Ranch imply shallower water.

Paleomagnetic studies of Cretaceous rocks in the Ochoco basin indicate that they were originally situated at 40° latitude. This, in turn, indicated to Bernie Housen of Western Washington University and Rebecca Dorsey that the basin may have been adjacent to the Sierra Nevada Mountains of California during the Cretaceous and that the Blue Mountains are a link between the Sierras and British Columbia.

Cenozoic

By the end of the Mesozoic Era and the beginning of the Cenozoic, 66 million years ago, the sea had withdrawn to the west, while the Cascades had yet to develop. During the accretion process, the Blue Mountains had been elevated well above sea level with intensive erosion as well as ongoing, but intermittent, volcanic activity. Paleocene strata are known only at two locations, a flora at Denning Spring in Umatilla County and freshwater diatoms from Imbler in Union County, neither with a formational designation. In contrast, the Eocene through Miocene epochs are characterized by extensive lava, ash, and sediments rich with fossils.

Eocene

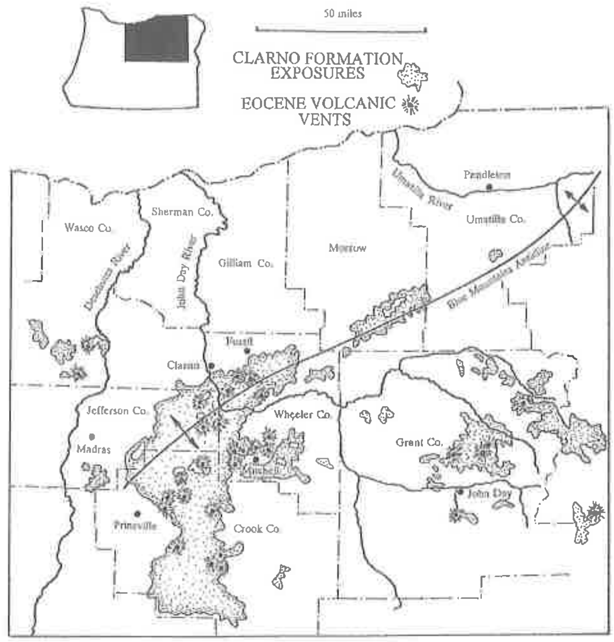
The eastern Oregon climate during the Eocene Clarno interval from 54 to 40 million years ago was sub-tropical to tropical. Andesitic and basaltic lavas from volcanic cones scattered throughout the western Blue Mountains, along with lahars, multicolored soils, and tuffaceous sediments, make up the blend of the Clarno Formation. The tectonic setting of Clarno volcanism is not well understood, but the timing of the eruptions matches that of the Challis activity in Idaho, leading to speculation that the two are related to a magmatic arc extending diagonally northeast by southwest across Oregon, Idaho, and Montana. Peter Hooper's 1995 model for Clarno volcanism appeals to thinning of the crust where extensional processes and regional stretching brought the heated mantle close to the surface.

When volcanic ash mixes with water it forms lahars, which mobilize and flow like syrup on even the slightest slope. Lahars and individual uninterrupted deposits of the Clarno reach thicknesses of 1,000 feet in Wheeler County. A variety of plant and animal remains, entombed in the mudflows, typify ancient stream and lake habitats, where avocado, cinnamon, palm, and even bananas grew in a frost-free climate. A diversity of large land mammals such as rhinoceros and brontothere, along with the sheep-like oreodons, shared the habitat with bear-like predators. A peculiar aquatic rhinoceros, not unlike a modern hippopotamus, wallowed in the shallows, where it was preyed upon by crocodiles. The Clarno is perhaps most famous for its many species of tropical nuts, fruits, and seeds, found in exposures just east of the old townsite of Clarno. Many are so well-preserved that they appear modern.

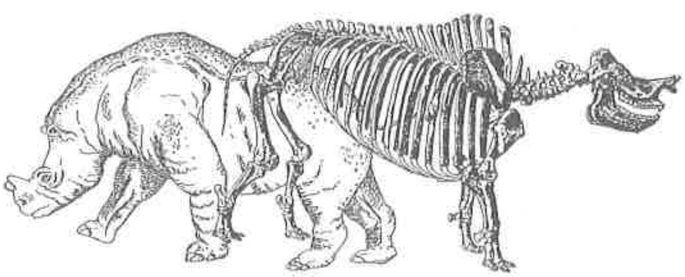
Oligocene-Miocene

Clarno volcanic episodes diminished with the onset of the John Day period, spanning the late Eocene to early Miocene. John Day rhyolitic lavas covered an area of some 35,000 square miles in Jefferson, Crook, Wheeler, and Grant counties with incandescent gas-charged clouds of ash, which cooled as the distinctive ignimbrites.

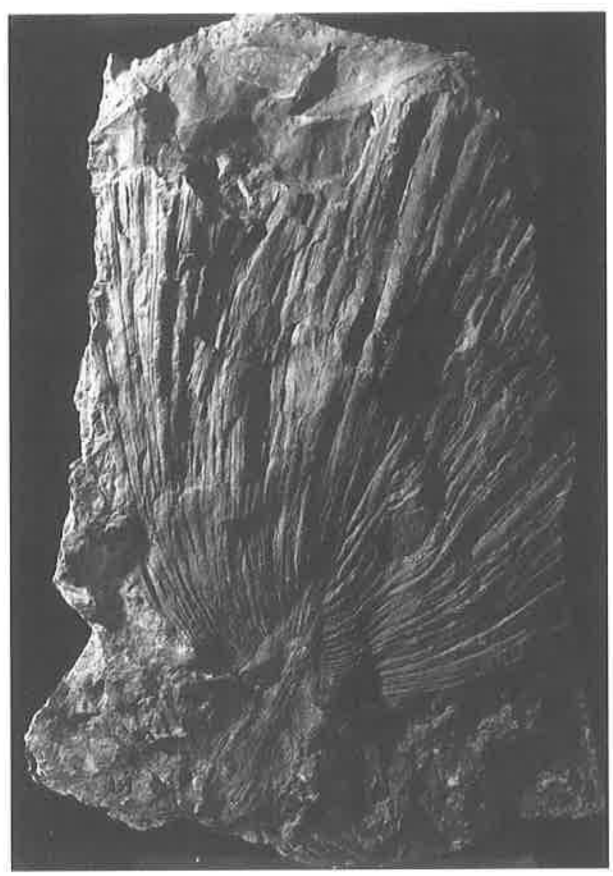
The superb quality and quantity of both plant and animal fossils from the John Day Formation are almost unmatched. Sluggish streams and quiet lakes, which encouraged plant growth and attracted



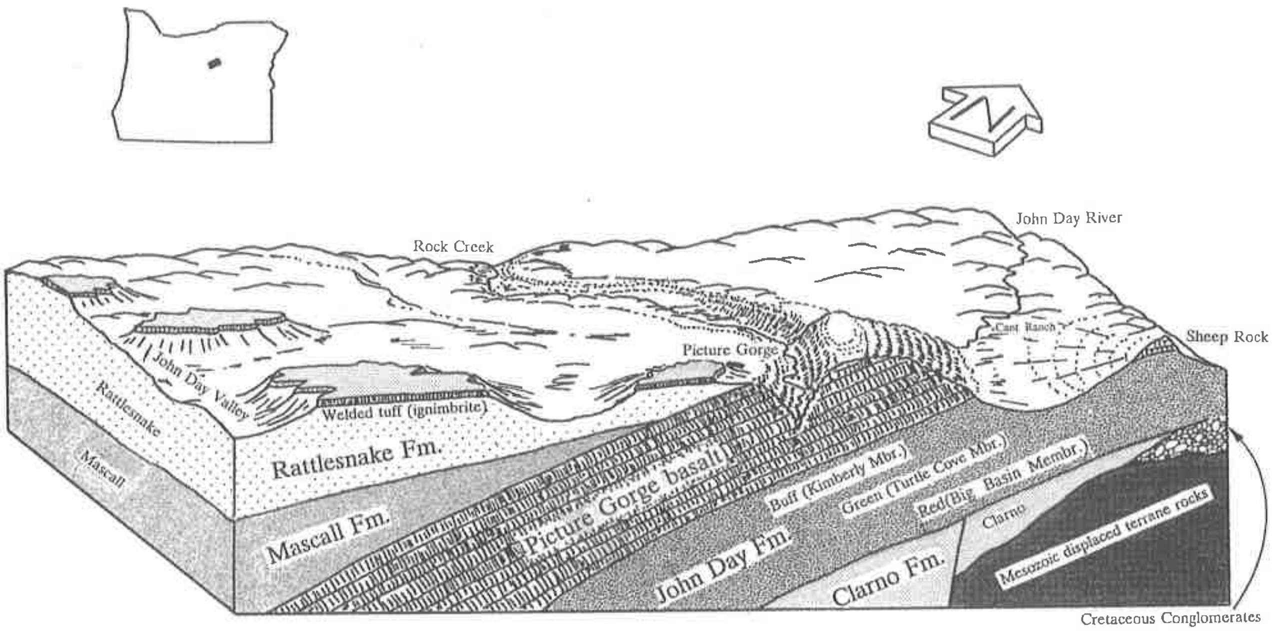
In eastern Oregon, mudflows and volcanics of the Eocene Clarno Formation are distributed across vast areas from Grant to Jefferson and Wasco counties. (After McClaughry, et al., 2009; Robinson, Walker, and McKee, 1990; Smith, et al., 1998; Walker and Robinson, 1990)



Living in eastern Oregon during the Eocene, brontotheres were similar to a rhinoceros in bulk and structure. (After Orr and Orr, 1999)



An Eocene palm leaf *Sabalites* from the Clarno Formation measures over two feet in length. (Photo courtesy Oregon Department of Geology and Mineral Industries)

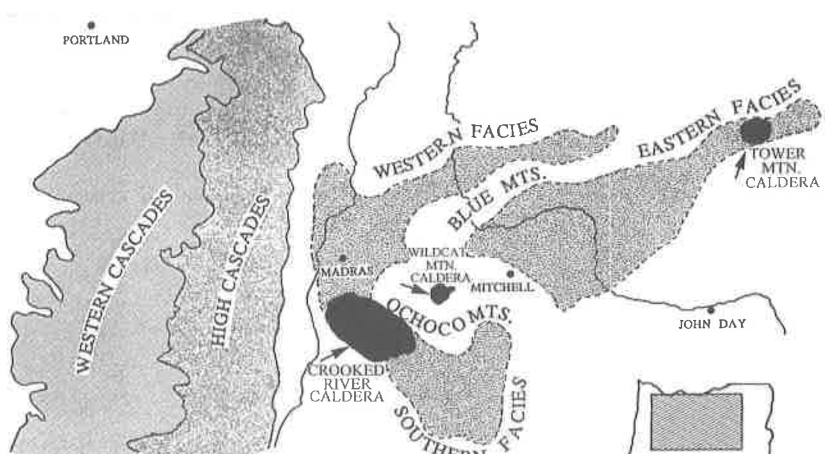


Changes in the John Day climate are reflected by the nature and color of the sediments. In 1901, John Merriam, at the University of California, divided John Day strata into three members based on color. His units were refined in 1972 by Richard Fisher and John Rensberger of the University of Washington into the highly oxidized, deep red claystones of the oldest Big Basin member, the pea green Turtle Cove tuffaceous claystones, and the cream-to-buff-colored tuffs and conglomerates of the youngest Kimberly and Haystack Valley sequence. Fossil plants, animals, and soils chronicle paleo-environmental variations as lakes and rivers gave way to open grasslands. On the basis of fossil soils (paleosols), Greg Retallack of the University of Oregon further separated the Big Basin Member into three units. (After Baldwin, 1976)

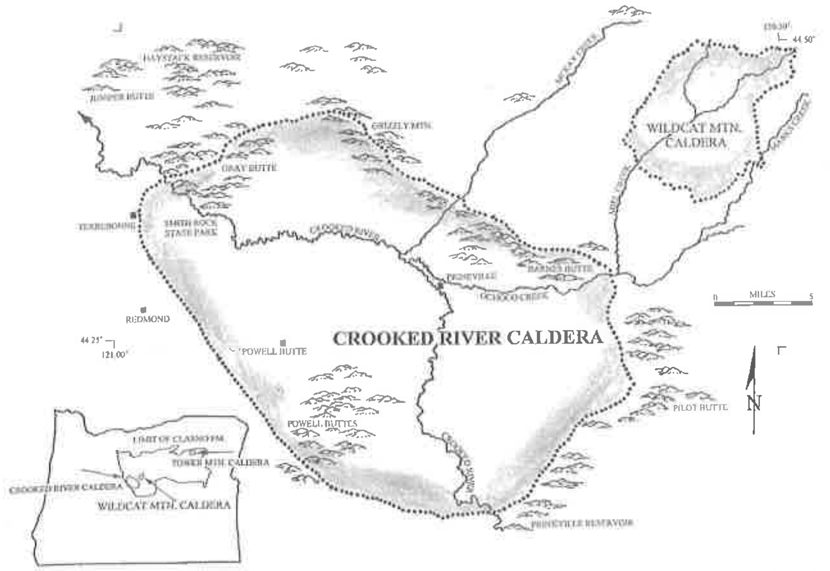
animals, provided optimum conditions for preservation. Because they only date back between 18 to 39 million years, most of the plants and animals look somewhat familiar, although none of the species precisely corresponds to those living today.

Crooked River Caldera

The question of the volcanic sources for the Clarno and John Day formations has long been the topic of speculation and controversy. Cascade vents or smaller buttes toward the west were proposed, while the notion of a single volcano or caldera was discounted. Recent mapping on the extreme western edge of the Blue Mountains by Mark Ferns and Jason McClaughry of DOGAMI led to the discovery of three large-scale caldera complexes. They identified the oldest Wildcat Mountain in Crook County at the crest of the Ochoco Mountains, the Crooked



The John Day Formation has been further divided into three geographic areas: the eastern facies along the John Day River, the southern on the Crooked River, and the western on the Deschutes River. (After Merriam, 1901; Fisher and Rensberger, 1972; Retallack, Bestland, and Fremd, 2000; Woodburne and Robinson, 1977)



Volcanics of the Eocene Clarno and Oligocene John Day formations have been traced to three large calderas in central Oregon, the Wildcat, Tower Mountain, and Crooked River. (After Ferns and McClaughry, 2006; Fisher and Rensberger, 1972; McClaughry, et al., 2009; Walker and Robinson, 1990)

River caldera near Prineville in Jefferson and Crook counties, and the youngest Tower Mountain near Ukiah in Umatilla County.

A thick pile of rhyolitic tuff, the Wildcat Mountain caldera, dated at 43.8 to 36 million years old, is the foremost structure in the Ochoco volcanic field. Formed with the eruption of Steins Pillar Tuff, the deeply eroded caldera lies 12 miles northeast of Prineville. Rocks of the Ochoco field are equivalent to those of the Clarno Formation.

John Day eruptions from numerous vents in the Tower Mountain and Crooked River volcanic complex are dated around 28 to 29 million years ago. Roughly 10 miles wide, the Tower Mountain caldera has a ponded core of tuff and is surrounded by a ring of rhyolite domes. These rocks are equivalent to the eastern facies of the John Day.

Lavas from the Crooked River caldera were bimodal, producing both basalts and rhyolites of the John Day Formation. Between the Prineville Reservoir to the southeast, Gray Butte to the northwest, and the Ochoco Mountains to the east, the Crooked River caldera is 25-by-18-miles in diameter and projects into the Deschutes-Umatilla plateau. This

Following the eruption and collapse of the Crooked River caldera, rhyolitic flows, domes, and dikes from the Powell Buttes, Gray Butte, Barnes Butte, and Ochoco Reservoir centers were emplaced along the rim of the structure. (In the photograph looking north-northwest along the Crooked River canyon, Powell Buttes is at the top left; photo courtesy Condon Collection).

enormous structure is bounded by the Klamath-Blue Mountains lineament and is positioned at the junction of the Brothers Fault zone and Sisters fault systems.

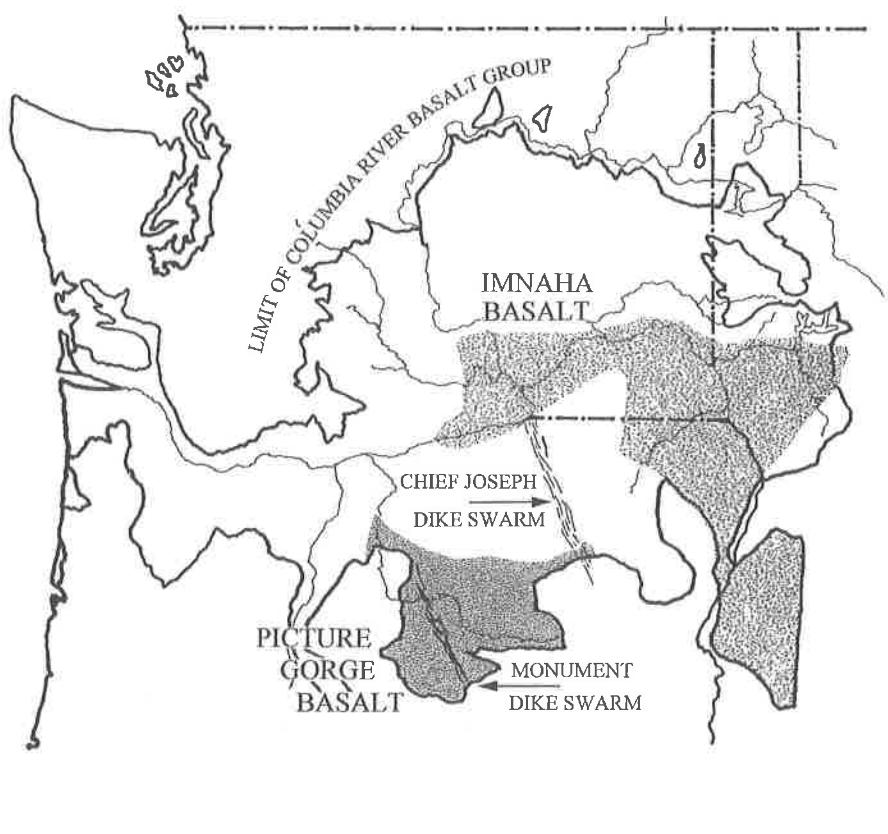
Its construction began 29.5 million years ago with explosive tuff from Smith Rock, an Oligocene facies of the John Day Formation. Collapse of the caldera was followed by rhyolite flows at Ochoco Reservoir and emplacement of Gray Butte, Powell Buttes, Grizzly Mountain, Juniper, and Pilot buttes. Barnes Butte and other domes may be smaller calderas within the larger, older Crooked River center. Debris from the Crooked River eruption and collapse can be traced over 10,000 square miles, primarily to the northeast of the main caldera.

Miocene

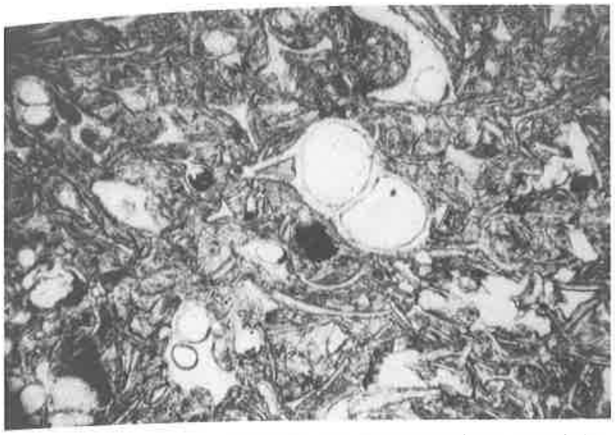
Over a period from 17 to 6 million years ago, multiple flows of Miocene Columbia River basalts poured westward from cracks and fissures in the Blue Mountains and adjacent Washington and Idaho. Obscuring the older formations and creating a broad platform over eastern Washington and northeast Oregon, the lavas overlapped each other until only the highest of the older outcrops projected above the layers.

The individual flows have been identified by their chemical and mineral composition and traced back to the northwest trending Monument and Chief Joseph dike swarms. In the John Day Valley, Monument fissures fed the dark-gray, coarse-grained Picture Gorge basalt, which filled deep canyons and smoothed out the topography. Geologists speculate that the ancestral Blue Mountains uplift confined the spread of Picture Gorge flows to the southern Columbia plateau. An estimated 21,000 dikes from the Chief Joseph field in the Wallowa Mountains erupted the Imnaha basalts, followed by the Grande Ronde and Wanapum.

The sheer breadth and volume of the Columbia River lavas tend to overshadow middle to late Miocene volcanic events elsewhere in the area. The andesitic Sawtooth Crater, Strawberry Mountain, and Dry Mountain volcanoes each evolved as separate edifices, which, in turn, line up with a fourth volcano of the same composition at Gearhart Mountain in the Basin and Range. Along this northeastward-trending zone, the centers are spaced at regular 100-mile intervals, but their distribution is still to be explained. The vents do not seem to be related to subduction, but they may be situated above at a major crustal boundary or



Sources of the Miocene Columbia River basalts in the Blue Mountains have been traced to the Chief Joseph and Monument dikes. (After Anderson, et al., 1987; Hooper, 1997; Tolan, et al., 2009; Walker, ed., 1990)



The thin section of a Rattlesnake ash-flow ignimbrite reveals its composition as a mass of broken glassy shards. (Photo courtesy Oregon Department of Geology and Mineral Industries)

anomaly. The characteristic stiff, slow-flowing andesites, produced at these sites, are of a type that typically accompanies very explosive eruptions.

Middle Miocene lavas at the southern extent of the province originated from a north-south line of dikes and vents beginning at Dooley Mountain and Unity Reservoir and continuing through the Lake Owyhee and McDermitt volcanic fields in the Oregon-Idaho graben.

By middle to late Miocene time, the shoreline of the Pacific Ocean had retreated westward, and the rising Cascade Range brought increasingly drier and temperate climates to eastern Oregon. Volcanism was confined to local eruptions of lava and showers of ash. With headwaters in the Blue Mountains, streams collected and redeposited volcanic debris into isolated depressions atop the Columbia River basalts, providing ideal sites for the burial and preservation of all manner of fossils. The Mascall and Rattlesnake formations in Crook and Grant counties and the Juntura and Drewsey formations in Harney and Malheur counties are known for their vertebrate assemblages.

Hoofed mammals, rodents, and predators of the Mascall Formation, in association with broadleaf plants, suggest an open woodland and savannah. Above the Mascall, sands, gravels, and silts of the 5-to-8-million-year-old Rattlesnake Formation have fewer fossils, but many are quite modern in aspect, although camels, rhinoceros, and mastodon give the formation an exotic complexion.

At the southern edge of the province, abundant middle Miocene vertebrates have been recovered from mudstones, volcanic tuffs, and sandstones of ancient lakes and streams near Juntura. Ephemeral lakes filled and then drained periodically when rivers were dammed by lava and ash. Many of the bones from the Juntura and Drewsey formations are broken and show wear, reflecting postmortem water transport and redeposition.

Pliocene sediments in Oregon are nearly as rare as those of the Paleocene, but Jay Van Tassel from Eastern Oregon State University has located and described a remarkable assemblage of diatoms, fish, invertebrates, and mammals from Baker City which date to that epoch.

Pleistocene—Carving the Mountains

Glaciation impacted eastern Oregon during the Pleistocene or Ice Ages beginning a little less than 2 million years ago and winding down about 11,000 years in the past. This period was marked by cycles of glacial advance and retreat, each episode lasting about 150,000 to 200,000 years, as moving ice straightened and deepened stream valleys. Continental glaciation, where huge ice sheets expanded southward, was more typical of the Great Lakes and upper Mississippi Valley. In western North America, continental ice sheets pushed into Washington, Idaho, and Montana, but in Oregon only ice caps and valley glaciers were present.

With the exception of the Ochoco Mountains, all of the ranges in the Blue Mountains display the unmistakable signs of alpine glacial striations on bedrock, layers of till, moraines, and strings of lakes gouged in valley floors. The higher basins are distinctively U-shaped in cross-section, the result of incision by slow-moving ice. Great symmetrical piles of till or moraines, left by melting glaciers, are easily identified by the poorly sorted mixture of angular pebbles, boulders, and clay. Perhaps the most dramatic are the lateral and end moraines, which dammed Wallowa Lake, now adjacent to the small community of Joseph. Joseph itself is built upon an ancient outwash plain, characterized by irregular hummocky ground that spread out in front of melting ice.

At the height of the Ice Ages, the Wallowa Mountains had nine large glaciers, each more than 10 miles long, which radiated outward from the center. The longest were the Lostine glacier at 22

Serrated ridges (arêtes) and amphitheatre-like cirques of the Wallowa wilderness are signs of glacial topography. (Photo courtesy U.S. Forest Service)

miles, the Minam at 21 miles, and the Imnaha at 20 miles. Averaging 1,000 feet in thickness, these ice masses extended down the valleys but failed to cover the ridges above 8,500 feet, thus a true ice cap did not develop. As late as 1929, the last glacier on the ridge above Glacier Lake in the Eagle Cap Wilderness was 800 feet long, 60 feet wide, and 24 feet thick. Today only small stagnant sheets of ice occupy a few of the high cirque basins.

Geologic Hazards

Earthquakes

The Snake River canyon experiences periodic earthquakes measuring up to 6.0 on the Mercalli intensity scale. A Mercalli estimate is based on eyewitness reports and damage and not on precise seismograph measurements that are recorded on the Richter scale.

Between the Brownlee Dam and Homestead on the Oregon side and Cuddy Mountain in Idaho a wide zone of northwest-striking faults, associated with pull-apart grabens and basins, is one of Oregon's most active seismic regions. The earliest records of quakes here in 1913 and in 1916 caused minimal damage. Geologists have concluded that seismicity along the Snake River is associated with the Olympic-Wallowa lineament, which parallels the Pine Creek Valley and Brownlee faults. Seismologists with the U.S.G.S., Gary Mann and Charles Meyer have reported that a number of moderate-sized earthquakes took place between 1981 and 1984 near Brownlee Dam, at the approximate intersection of the Pine Creek Valley and Cuddy Mountain faults.

Landslides

Landslides are a product of factors that affect the stability of a slope, and in the geologically complicated Blue Mountains differences in rock types, fracturing, long-term undercutting by creeks and rivers, and periodic seismic activity are all part of the equation. Although the moderate rate of precipitation here reduces the incidence of slides, it is not unusual for a combination of conditions to result in rock avalanches.

Along the Snake River and Hells Canyon, Tracy Vallier notes that some of the most spectacular visible features are underlain by earthflows. At Wild Sheep Rapids, Granite Rapids, Johnson Bar, and Big Bar, Pleistocene slide debris surged into the riverbed from steep walls. The Rush Creek landslide north of Hat Point moved 20 million cubic meters of material into Hells Canyon from the Idaho side, building a dam nearly 400 feet high. Even though of uncertain date, rubble from the slide overlies accumulations from the Bonneville flood but is covered by Mt. Mazama ash, placing the date from 15,000 to 7,700 years ago.

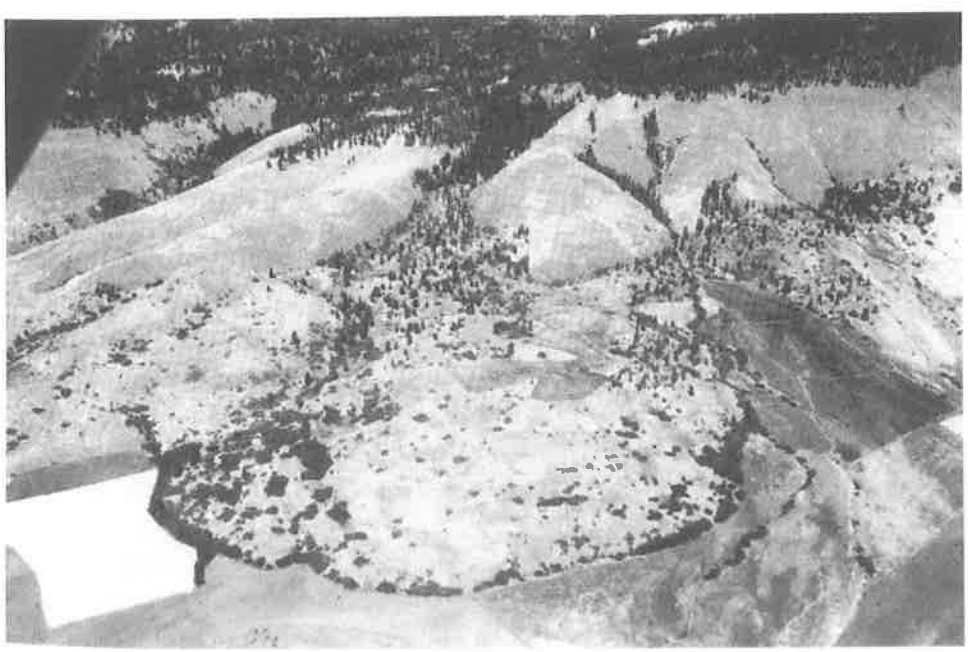
Unusually heavy precipitation in 1984 generated the notorious slide at Hole-in-the-Wall south of Sparta in Baker County. The slow-moving event

Debris from an ancient landslide at Pittsburg Landing on the Snake River was smoothed over and reworked by the subsequent surging waters of the Bonneville flood. (Photo courtesy T. Vallier)

began in August, when large fissures and cracks, opening high on a slope above the Powder River, initiated slumping which continued to accelerate. Highway 86 was completely covered with rocks and debris, even as the slide made its way across the river, where blockage created a 20-foot-deep reservoir.

Decomposing lavas and tuffs of the John Day and Deschutes formations are particularly prone to mass movement along steep canyon walls of the Deschutes and Crooked rivers. The older landslides are obscured by vegetation, whereas the more recent ones are bare of plants and soil cover. Near Prineville, some of the slide-prone areas have been confused with stable lava flows and have become fashionable for the placement of housing.

Since completion by the Bureau of Reclamation in 1920 for irrigation and flood control, the Ochoco Reservoir on the Crooked River has been plagued by leakage and structural problems related to its positioning on landslide deposits. The right abutment is secured in Clarno and John Day rocks, while the left is anchored in younger layers of the Deschutes Formation. Because of continuous seepage related to sinkholes in the slide debris, the dam was emptied in 1993, modified, repaired, then refilled.



A combination of melting snow and heavy rainfall throughout Oregon during February, 1996, caused a landslide near Summerville at the north end of the Grande Ronde Valley. Part of an ancient slide, the debris moved from Pumpkin Ridge eastward toward Highway 82 and the river. (Photo courtesy R. Carson).

Natural Resources

With the exception of the copper in volcanic layers of the Wallowa terrane, economic minerals in the Blue Mountains such as gold, silver, and zinc are primarily associated with veins in rocks of the Baker terrane. Hot fluids, impregnated with metals, were emplaced into fractures during the Mesozoic intrusion of granitic plutons.

Gold

This province has produced about three-fourths of Oregon's gold, most of which occurs in a strip 40 miles wide and 120 miles long from the John Day to the Snake River and into Idaho. As noted by Howard Brooks, there are countless placer workings within this belt and more than 14 lode mines. Lode gold in veins is mined by tunneling along the tabular bodies, whereas placers are worked by sluicing with water and panning in streams. Because gold is seven times heavier than quartz and almost twenty times heavier than water, it settles on the deepest levels of a streambed.

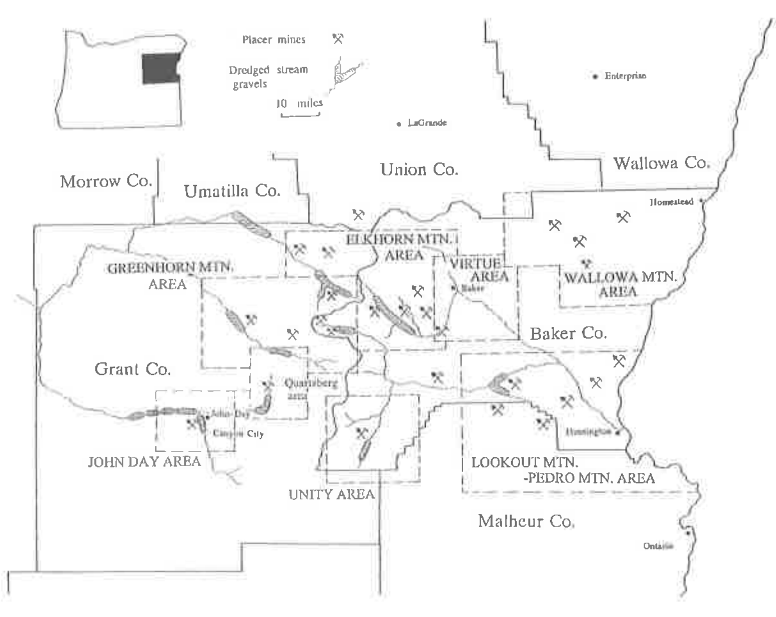
Mining substantially changed the face of eastern Oregon, which had no permanent settlements in the years before Henry Griffin and his party from Portland made the original discovery of placer gold west of Baker City in 1861. Diggings in the Canyon Creek drainage were so rich that within a year a tent city of 1,000 men appeared, and shortly thereafter prospectors were working in most of the gold-bearing areas of the Blue Mountains and Idaho.

Water was needed for flushing out gold, and when that commodity became scarce extensive ditches were dug to bring it to the placers. The Auburn ditch, parts of which are still used by the municipality of Baker City, was completed in 1863. The Rye Valley ditch was finished in 1864, and the 100-mile-long El Dorado in 1873 brought water from the head of Burnt River to the Malheur district.

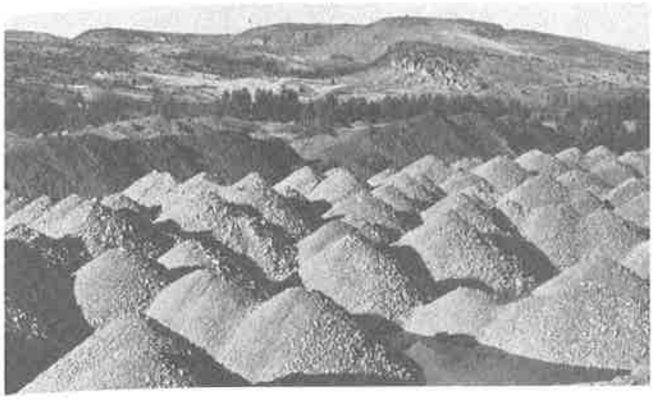
Lode gold was discovered in 1862 at the Virtue mine on the Powder River, where a 10-stamp mill was constructed to process the ore. Stamp mills, employing heavy steel rods, pulverized the rock to extract the gold. The Virtue and Sanger mines in the Wallowa Mountains and the Connor Creek mine near Lookout Mountain dominated lode gold production until the early 1900s when operations at the Cornucopia mines began. Ranking as the top lode producer, the Cornucopia district was most active from the late 1930s to closure in 1941. The values of the gold extracted would be about $350 million at today's prices.

Early gold totals for the Blue Mountains can only be estimated because there are no exact figures, and much of it was sent to the mint at San Francisco where it was credited to California. Placer mines had an approximate yield of 630,500 ounces in comparison to lode operations, which totaled just over 825,300 ounces between 1900 and 1965, after which amounts dropped off dramatically.

Data on private companies is no longer available to the public. Since the 1990s, recreational operators



Major gold mining districts in the Blue Mountains (After Brooks, 2007; Brooks and Ramp, 1968)



By processing the gravels, bucket line dredges such as the one used in Sumpter (above right) in 1913 substantially aided gold production. Almost 100 years later, the still-exposed 2,600 acres of dredge tailings in Sumpter Valley (above left) are slowly being covered by vegetation. (Photos courtesy Oregon Department of Geology and Mineral Industries and Oregon State Highway Department).

using small portable dredges have accounted for most of Oregon's gold recovery.

Silver and Copper

Silver and copper ores are typically removed with gold as part of the extraction process, and in the Blue Mountains silver production peaked between 1900 and 1965, the most lucrative period. Beginning in 1897, copper was mined from the Permian Hunsaker Creek Formation at the Iron Dyke Mine on the Snake River. In the 1930s, output from the Iron Dyke was the highest in the state, after which the mine went through several changes in ownership, reduced production, and then closure. It reopened for a few years in 1979, when 20,000 ounces of gold, 40,000 ounces of silver, and 1,900 tons of copper were extracted.

In June, 1913, one of the state's largest nuggets, weighing 80.4 ounces, was recovered in placer gravels near Susanville in Grant County. Today the five-inch-long specimen, on display at the U.S. Bank of Oregon in Baker City, would be worth almost $160,000. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Mercury

In the Clarno Formation, mercury sulfide or cinnabar is associated with intrusive volcanic plugs and along fault planes. The Horse Heaven district in Jefferson County, responsible for the highest yields in the state, operated between 1934 and 1958, when the reserves were exhausted. Overall, the mine produced 17,214 flasks of quicksilver. Mercury processing has the potential to release high levels of toxic contaminants, and since 2002 state and federal agencies have begun a program to inventory and evaluate historic mine sites.

Thundereggs is a popular name for geodes, agate-filled gas pockets. Thundereggs were designated as the official state rock by the 1965 Oregon legislature. (Photo courtesy Oregon Department of Geology and Mineral Industries)

Thundereggs

The gem-like thunderegg, a spherical nodule or geode, is not a rock but a body of opal, agate, or chalcedony with a knobby drab exterior. Thundereggs form in a variety of ways, but the process typically begins when a hollow cavity, produced by a gas bubble in highly viscous lavas, is lined or filled with crystals. Ranging from less than one inch to over four feet, most geodes average close to a baseball in size. Geodes can be found in many of the volcanic terrains, but they are especially common in rhyolitic lavas of eastern Oregon, where some commercial collecting is permitted.

Industrial rock. Diatomite is mined from the Miocene Juntura and Drewsey formations in Malheur and Harney counties. Diatoms are siliceous single-celled aquatic plants, which accumulated on the floor of ancient freshwater lakes. White to buff in color, diatomite beds vary from a few inches to 20 feet in thickness. First mined in 1917, diatomite is used as an abrasive, as an absorbent, as a filler in paints, for cat litter, and for filtering chemicals, drinking water, and liquid food products. Eagle-Pitcher Minerals, Inc., near Vale, is the major Oregon producer.

Bentonite claystones, along with zeolites, are extracted from open-pits in the Miocene Sucker Creek Formation of Malheur County and from the John Day Formation in Crook County. Derived from decomposed volcanic ash, bentonite is highly expansive when wet. Known commercially as fuller's earth, it is marketed for cat litter, as sealants, and for numerous industrial purposes. Teague Mineral Products, supplier of bentonites, also mines zeolites. Zeolites have a limited market, serving to control odors, to stabilize toxic waste, as an animal food supplement, and for a variety of agricultural applications.

Geothermal Energy

The potential for geothermal energy in the Blue Mountains is only moderate in contrast to that of the High Lava Plains, the Basin and Range, or the Cascades. In the Grande Ronde Valley, commercial spas and public facilities have been opened at thermal springs and wells near Hot Lake, Cove, and Union. Waters at Hot Lake are the warmest at 185° Fahrenheit, while those at the other two resorts average 100° or less.

Thermal waters follow narrow conduits along fault zones to reach the surface. This has the effect of localizing the hot waters so that near Hot Lake, for example, a cold water well is less than 150 feet from the heat source for the spa.

Surface and groundwater

The Blue Mountains is a region of modest ground and surface water with rainfall averaging 25 inches a year. Much of the supply is depleted by consumptive use for irrigation, and occasional summer downpours add little. The groundwater picture is tied into the structure of large sedimentary basins, underlain by Columbia River basalts, and the surrounding high mountains of basalts and granite intrusions. Both the sediments and basalts are the primary aquifers, while the granites characteristically have very low permeability and yield only small quantities of water. Interlayers and faults within the Tertiary lavas may supply a steady flow but can be slow to recharge and are prone to decline regionally. Sedimentary layers in the valleys can supply copious amounts of good quality water.

Beneath the floor of the Grande Ronde and Baker valleys, the Columbia River basalts are widespread and the most heavily developed aquifer. Many of the agricultural wells, which penetrate the basalt, have been deepened repeatedly as the upper layers are depleted. In addition to agriculture, municipal wells for Baker, LaGrande, and Union rely on these units. Sedimentary fans, deposited where the Grande Ronde River, Ladd Creek, Powder River, and other perennial streams enter the flat lowlands, serve as extensive aquifers. Often several hundred feet thick, they can produce as much as 2,500 gallons a minute of good quality water.

Primary aquifers in the John Day basin occur within flows of the Miocene basalts or in Quaternary alluvium along the John Day and tributary stream valleys. Alluvium in the upper reaches of the river provides water for shallow wells.

The availability of surface water in all portions of the province varies. High winter and spring runoff, accompanied by melting snow, is followed by low summer flows and negligible precipitation, when usage is greatest. Small headwater creeks draining the uplands tend to be intermittent, and during late summer they are reduced to isolated pools or dry up entirely. Even the larger Grande Ronde and Powder rivers are greatly diminished. Storage reservoirs help to supply current demands, but they fail to meet all the needs for agriculture, wildlife, and water standards.

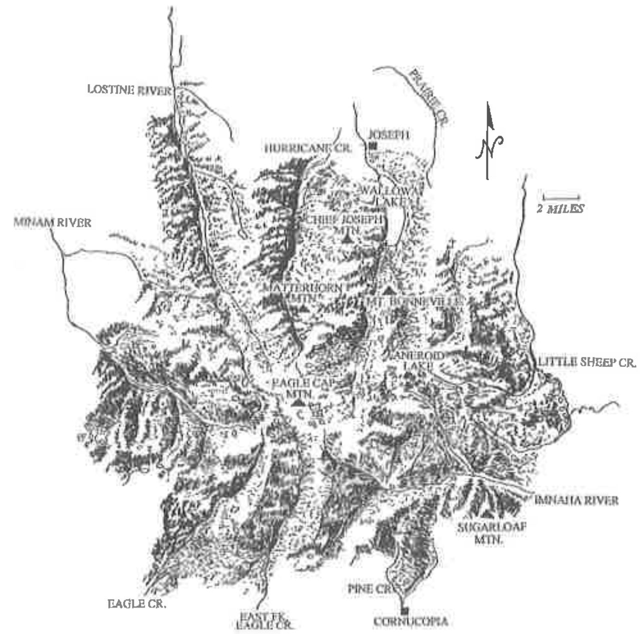
Geologic Highlights

The Wallowa Mountains

Variously called the Granite Mountains, the Powder Mountains, the Eagle Mountains, or the Switzerland of Oregon, the rugged peaks of northeast Oregon were officially designated as the Wallowa Mountains by the U.S. Board of Geographic Names. Wallowa comes from the Nez Perce language and means a series of stakes arranged in a triangular pattern for catching fish, as were used in the Wallowa River. The Wallowas extend into Idaho, where they are known as the Seven Devils Mountains. Between these two ranges, the Snake River has carved the deep Hells Canyon gorge.

Shaped by separate episodes of Ice Age glaciation, a diversity of peaks in the Wallowa Mountains reach heights of nearly two miles above sea level and produce a sharply serrated skyline. Southwest of Wallowa Lake, Matterhorn Mountain, composed of blue-white marble, rises to 10,004 feet opposite Sacajawea Peak at 9,880 feet.

At three and one-half miles long and three-fourths of a mile wide, Wallowa Lake is the largest of the 100 lakes in the Blue Mountains province. Nearly 4,440 feet in elevation, it is hemmed in by lateral moraines of glacial till that date back only a few thousand years.



Heavily scalloped by alpine glaciers, the Wallowa Mountains are among the most rugged in Oregon.

Steins Pillar

About 20 miles east of Prineville in Crook County, Steins Pillar is one of the most imposing of the columns eroded from layers of welded tuff. The original spelling was Steens Pillar, named after Major Enoch Steen of the U.S. Army who explored this region for road development in the 1860s. As often happens with place names, it was misspelled so frequently that the incorrect version became official.

In this southward view, the community of Joseph lies at the bottom right on the irregular glacial outwash plain. Penned in by glacial moraines, Wallowa Lake is in the center, and Mt. Bonneville is toward the back. (Photo by D.A. Rahm; courtesy Condon Collection)

An erosional remnant of volcanic ash-flow tuffs of the Clarno and John Day formations, Steins Pillar stands 350 feet high. Oxidizing iron from the volcanics has stained the surface yellow-brown. (Photo courtesy Oregon State Highway Department)

The construction of Steins Pillar began about 40 million years ago with incandescent ash and pumice of the Clarno Formation. These were, in turn, covered with John Day volcanic and sedimentary debris. Upon cooling, the layers split into long vertical joints, and, over millions of years, erosion enlarged the cracks to isolate the steep columns seen today. The height of each pillar imparts some idea of the incredible volume of ash that has been stripped away.

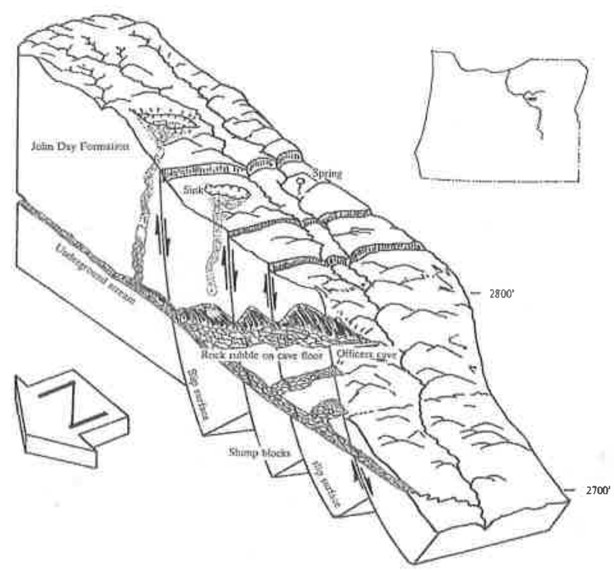
Officer's Cave

Although the Blue Mountains are not known for caves, one of Oregon's most noteworthy geologic features is Officer's Cave south of Kimberly in Grant County. Named after the homesteading Floyd Officer family, it is among the largest developed in non-karst terrain in North America. Unusual processes of erosion and landslides in soft clays and silts carved out the cave during heavy rain storms, when surface and groundwater water scoured steep gullies and removed entire underground sections. Huge broken blocks of the John Day Formation, which have fallen from the roof, lie tipped in all directions.

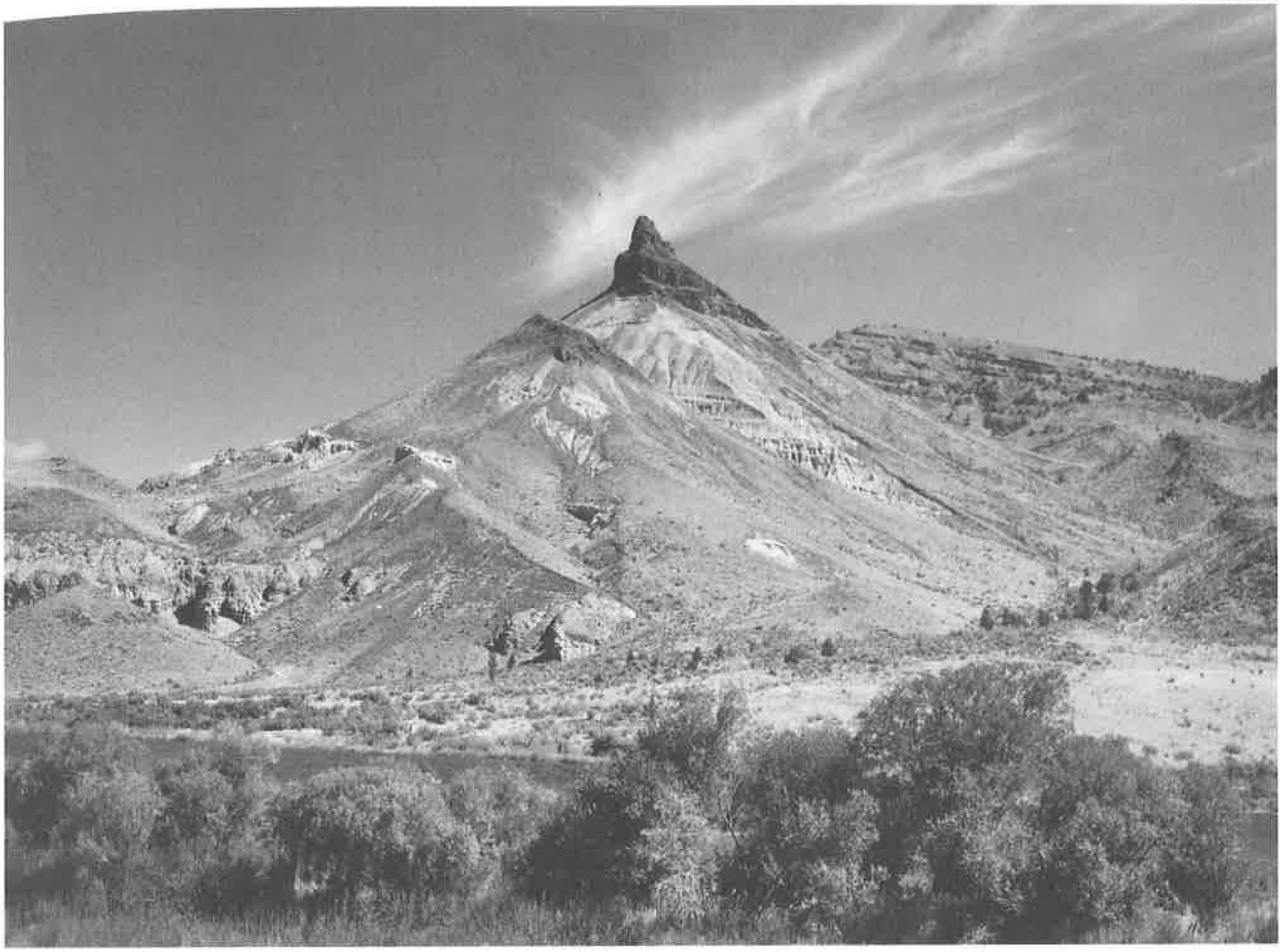
John Day Fossil Beds National Monument

The 14,400 acres of the John Day Fossil Beds National Monument, which reveal the Cenozoic history of the southwestern edge of the Blue Mountains, was set aside as a federal preserve in 1974. A new display center opened at the Sheep Rock station in 2004, providing a concise overview of the regional geology and paleontology.

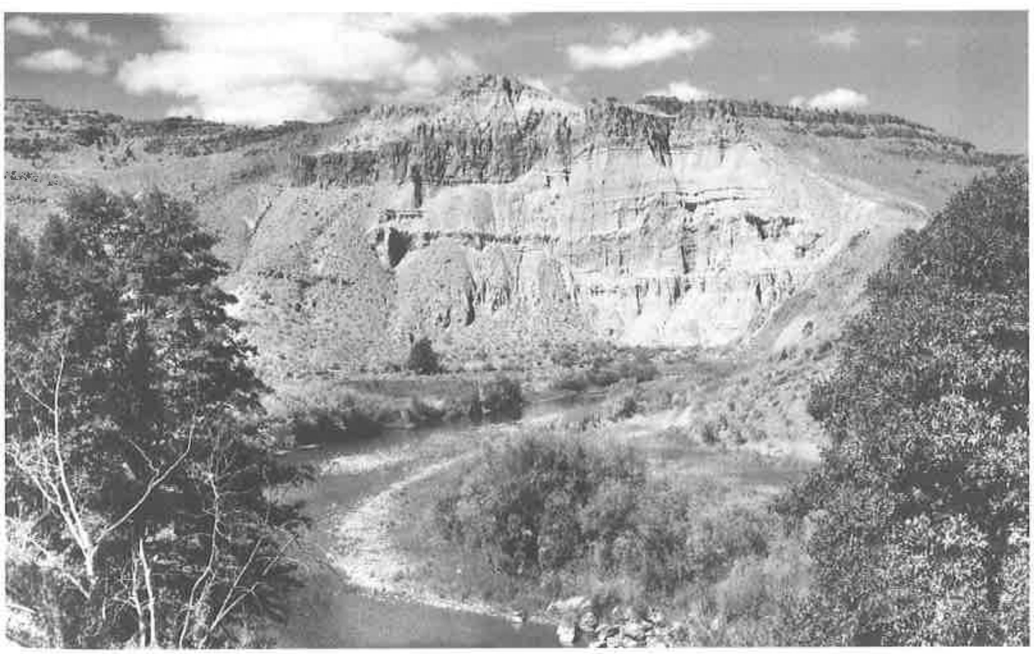
At three different areas in the park—Clarno, the Painted Hills, and Picture Gorge in Grant and Wheeler counties—visitors are treated to a fascinating array of 44-to-6-million-year-old animals and plants, entombed in colorful volcanic and sedimentary layers.



A maze of differing levels, Officer's Cave was over 700 feet long when first explored in 1914, but since then it has increased substantially because the soft John Day Formation is particularly susceptible to erosion. Examined in 1975, it measured over 1,500 feet in length. Underground channels follow the east-west direction of nearby Officer's Cave Ridge. (after Parker, Shown, and Ratzlaff, 1964)



Near Dayville, the headquarters of the park at Picture Gorge and Sheep Rock tells the story of life here 18 to 30 million years ago. Picture Gorge received its name because of ancient Indian pictographs on the canyon walls, while Sheep Rock is so-called because at certain angles the projecting cap of Columbia River Basalt resembles an animal head. The green and buff-colored volcanic tuffs of the middle and upper John Day beds make Sheep Rock one of the most familiar sights in eastern Oregon. (Photo courtesy Oregon State Highway Department)



North of the main park headquarters, Cathedral Rock provides a good look at the middle John Day green Turtle Cove Member. Near the skyline, the 28-million-year-old Picture Gorge ignimbrite appears as a dark layer tens of feet thick. (Photo courtesy Oregon State Highway Department)

Approximately 15 miles southwest of the town of Fossil, the Eocene Clarno unit is well-known for its tropical suite of fruits, nuts, and vertebrate bones, the oldest in the park. The mudflows or lahars are particularly distinctive, eroding into steep cliffs, spires, and columns that follow vertical fracture lines in the softer sediments.

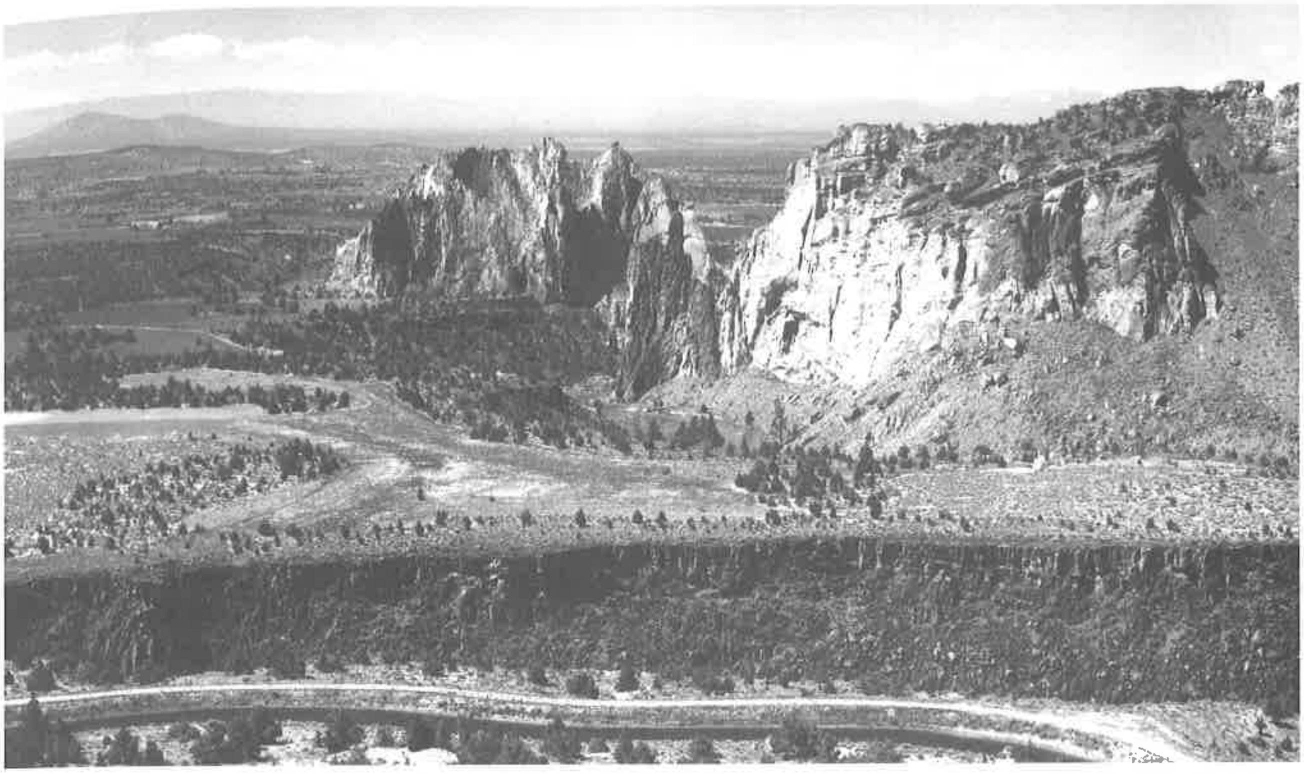
The badlands physiography at the Painted Hills location, six miles northwest of Mitchell, reveals variegated exposures of rust-red soils alternating with yellow and light brown tuffs of the John Day Formation. The John Day is famous for both vertebrate and plant fossils. Among these, remains of the sheep-like *Oreodon*, herds of which inhabited grassy savannas, are commonly encountered, as are leaves of the *Metasequoia*, for which the temperate Bridge Creek flora is famous.

Grand Canyon of the Snake River

Even though the exact geographic length of the Grand Canyon of the Snake River (Hells Canyon) varies, Tracy Vallier's excellent guide to the geology and topography of the area places it as that stretch from the Oxbow to the mouth of the Grande Ronde River. From the summit of He Devil Peak in Idaho, Hells Canyon has an average depth of 8,000 feet, substantially greater than the Grand Canyon of the Colorado. Hat Point, on the Oregon side, offers a panorama of vertical cliffs, a sharply cut chasm, and narrow ledges high above the river.

Dated at 250 million years, the oldest rocks exposed in the canyon walls are Permian, deposited long before the Snake River existed. Broken and shattered by folding, the layers were later buried by Miocene lava flows. Faulting produced the deep

The scenery today in the Snake River canyon resulted from erosion of the successive basalt flows. As the area was slowly elevated, tributary rivers from the mountains incised down through the deposits. For almost two-thirds of its route through the gorge, the river dissects the dark-colored Imnaha basalts, which reach thicknesses of 6,000 feet. (Photo courtesy Oregon State Highway Department)



Carved by the Crooked River into vertical pillars and precipitous cliffs, Smith Rock lies near the western rim of the Crooked River caldera. (Photo courtesy of Oregon State Highway Department)

intermontane basins and raised mountains, which received a final molding by Pleistocene ice and the Bonneville flood some 15,000 years ago.

Smith Rock

The pinnacles, walls, and cliffs at Smith Rock State Park, seven miles northeast of Redmond, are nationally known by climbers, hikers, and geologists. Named for its discoverer John Smith, the sheriff of Linn County in the mid 1880s, the Smith Rock edifice rises over 400 feet above the Deschutes River floor, has an elevation of 3,200 feet, and is visible for miles.

At the junction of three physiographic provinces, Smith Rock displays successive layers of colorful tuffs, eroded into fantastic shapes. The monolith is one of several rhyolitic domes along the northwestern margin of the Crooked River caldera that sent lavas, ash, and mudflows of the John Day across the landscape 30 million years ago. Much later, the ancestral Crooked River cut its channel down through the tan, red, and green John Day strata to shape the vertical walls of Smith Rock.