OREGON GEOLOGY

Oregon Department of Geology and Mineral Industries
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Retrospective: *The Ore Bin* and *Oregon Geology*, 1939–1999

THROUGH THE EYES OF THE STATE GEOLOGIST

John D. Beaulieu
Oregon State Geologist

Oregon is increasingly challenged with earth-resource and geologic-hazard related decisions. New housing development is often on property with higher risks, or done to increase the density of urban areas. Both these factors are adding to increased losses from natural disasters, a pattern that is evident statewide, nationwide, and even worldwide.

Here in Oregon, local decision-makers are increasingly driven to make decisions without adequate information or training. Some people are calling for state authorities to peer-review geologic reports, believing this alone will solve the problem. But that effort has failed in other states. What is needed is to improve the quality of reports to match the increasing need.

The Department of Geology and Mineral Industries (DOGAMI) is working to improve the information available to Oregon citizens and communities:

1. Our Department conducts research for, compiles, and distributes data the public needs. We have five offices, including a new field office being established in Newport, to better serve the needs of coastal residents. In addition, we have a service center in Portland and a web site to provide information to the public.

2. Better training must be offered to local residents, governments, and communities on the content and the use of technical data. To accomplish this, DOGAMI is targeting public education efforts to audiences who most need the information we have. We are also establishing traveling workshops to bring information to users.

3. Oregon requires geologists and engineers to be registered by the state, requiring certain standards of training and experience.

4. To be effective, the contents of geotechnical reports must meet certain standards. DOGAMI plans to cooperate with the Board of Geologist Examiners to provide better advisory information on the content of properly prepared geologic reports.

5. The quality of information in the reports must also be assured. Some communities are developing mechanisms for peer review within their areas of interest. These success stories must be broadcast by entities like DOGAMI and the Board of Geologist Examiners.

6. For some issues that are of a large scale, or significant in terms of state policy, DOGAMI sometimes does provide review services for local governments. In the past, we have asked that all requests be made through the Governor's Office to help assure proper coordination.

With progress on each of these fronts, we can continue to move toward a culture of high-quality reports and better geologic understanding.

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Cover photo

The magnitude 5.6 "Spring Break Quake" of March 1993 caused several million dollars of damage throughout the mid-Willamette Valley. In this brick building in Newberg, the top story was red-tagged, or declared unsafe to enter, but the street-level floor was not as seriously damaged. *(Photo courtesy of Evelyn Roeloffs, U.S. Geological Survey)*

Through the years of Oregon Geology

Compiled by J.L. Clark and Neva Beck, Oregon Department of Geology and Mineral Industries

For more than 60 years, the Oregon Department of Geology and Mineral Industries has regularly published information about Oregon's geology for technical and nontechnical audiences alike. From 1939 through 1978, the periodical was known as the *Ore Bin,* reflecting the importance of mining to the state and the department's activities (originally, in a somewhat whimsical wordplay, with an additional period and hyphen as *Ore.-Bin*). Since 1979, our magazine has been known as *Oregon Geology,* reflecting a change in the department's contribution to society. Although mining processes and products are still important to Oregon, our growing population has required more information about natural hazards, earthquakes, tsunamis, landslides, floods, and volcanic eruptions.

The following is a compilation of excerpts and articles, mostly without editorial comment, from our magazine with the two names. These articles do not necessarily reflect the typical substance of the periodical. Some articles could have been written only during World War II, and some were written because of the space race in the 1960s. Above all, coverage of new geologic insights or mining practices or other scientific study projects cannot adequately be extracted in a paragraph or two. Instead, the selected articles tend to reflect subjects that can be condensed and made sense of without the context of the times and without technical or scientific expertise.

Please join us on a journey back through time, as seen through the eyes of a magazine devoted to Oregon's natural history, beauty, resources, and—yes—risks.

1939: The beginning

THE ORE.-BIN

This is the first issue of THE ORE.-BIN . . .The State Department of Geology and Mineral Industries will use THE ORE.-BIN to advise the public of the work of the Department, and of new and interesting developments in mining, metallurgy, and geology . . .

Newspapers are encouraged to use any of the material contained in THE ORE.-BIN. It is designed primarily for such use. A credit-line of acknowledgement is requested.

Your comments and criticisms will be appreciated. It is our desire to make THE ORE.-BIN an effective medium for "telling the world" about Oregon, its mineral resources, and possibilities.

January 1939

TOPOGRAPHIC MAPPING IN OREGON

Last year a grant of some $80,000 of PWA funds, the bulk of it ear-marked for topographic work, was allocated to Oregon. Most of this is being used for aerial topographic mapping of the coastal area from about opposite Eugene north to the Columbia River, on account of the need of maps in that area for War Department use in connection with coast defense.

Whether or not more funds will be available this coming year is not known, but since the funds were intended to be used in part in connection with the Federal government's study of strategic minerals, it is hoped that a substantial part of any further funds from this source may be utilized to cover large parts of certain Oregon areas now unmapped, where strategic minerals, particularly chromite and quicksilver, are known to exist.

March 1939

INTRODUCTION TO THE VERY FIRST COLUMN BY A STATE GEOLOGIST

Ever notice that once in a while at any man's mine the lead mule kicks hell out of the trammer boss, or the track tender drops a Jim Crow on his foot, or the timber gang comes to work on the night shift soused to the ears, or the motor-man forgets to duck a chute timber — anyway, once in a while the boss of the outfit (who never does anything but look down the backs of employees' necks) has to don slicker and hard hat and really do a little work?

Earl Nixon, August 1939

1940s: War and peace

2000 WILLOWS DOING FINE, DREDGED LAND

A project aiming at the rehabilitation of land over which gold dredges have passed was begun this year on tailings of the Porter and Company operating near Granite, a report from the Whitman National Forest headquarters indicates.

According to the information on the project, the work is done under an agreement as to dredging federal forest land and involved the planting of 2000 willow trees on the leveled tailings piles. In addition, the dredging company is said to have planted crested wheat grass directly in the rock and that a stand was obtained. The company has done similar planting in Montana, it is said.

The willows, native to the district, were cuttings from 18 to 24 inches in length and were set out during the spring under the supervision of Mel Burke, forest service staff member. Ninety percent of the trees were growing, he indicated Tuesday. Plantings were made along the winding creek channel reconstructed by the company over the ground mined.

August 1941

MINING LABOR

During the past year, the shift of miners to the so-called defense industries because of the high wages paid by "cost-plus" government contracts became so serious that production of metals was adversely effected . . .

Incidentally welders can be trained in two or three weeks; not so with miners. Mining is more than running a machine. After his first year's work underground a miner would have picked up the rudiments of underground mining — if he had had proper instruction, but he would still be a beginner. Real miners, who can recognize and take care of bad ground, who can safely handle explosives, and who can break ground by placing drill holes properly are made only after years of work under a variety of conditions common in underground mines.

September 1942

ALUMINUM DUST TREATMENT FOR SILICOSIS

According to ROCK PRODUCTS, August 1944, interesting results on the use of aluminum dust as an inhalant treatment of silicosis have been published by the Canadian Medical Association.

The treatment used at the McIntyre mine consists of inhalation of aluminum powder. This material is produced by pounding small pieces of thin aluminum sheets into a fine dust, according to a process worked out at the Pittsburgh plant of the Aluminum Company of America. When the aluminum powder is inhaled, the reaction in the lungs coats silica particles with a thin gelatinous film, inhibiting the serious effect of silica on the respiratory organs.

Sept. 1944

WELL, WHAT ARE WE GOING TO DO ABOUT IT?

We're in a war! A real, sea-going, man-sized, knock-hell-out-of-'em-kind of a contest in which men and machines and fuel for the machines and ammunition and BRAINS will win. That's all it takes . . .

All the smelters, all the machine shops, all the factories, all the skilled workmen, and all the money in the land — can't turn out a fighting plane or a battleship unless all of the various essential raw materials are on hand to start with. True, we are taking nitrogen out of the air and making ammunition out of it; we are taking iodine and bromine and even magnesium out of sea water, – but nobody has ever taken quicksilver or chromite or manganese or tungsten or antimony out of air or sea water. They have to be first found and then dug out of the earth. And you can't turn on a flow of chromite, manganese, etc. . . . as you turn on water from a spigot.

Let us all — and the Congress — remember that we can order planes, tanks and boats 'till Hell won't have it, and we can raise taxes to pay for them, but they can't be produced without raw materials. We must supply those raw materials. That's our job — and THAT'S WHAT WE ARE DOING ABOUT IT.

December 1941

CLEAR WRITING IN GEOLOGY

It seems that in our hunt for general principles we feel the need of tagging each observed fact with some word that may connect it with the language in which the great fundamental laws of the universe are proclaimed at the seats of learning. For this reason — I prefer to suggest no other — a Survey author refers to cracks and crevices in rocks as "spaces of discontinuity." . . .

In our writing I believe, however, we are tending to write more plainly — to say "sand" instead of "arenaceous deposit,""clay" instead of "argillaceous stratum," "close folding" instead of "intense plication," "river banks" instead of "riparian borders," "mouth" instead of "debouchure," "shore" instead of "littoral margin," and "the overlying bed is limestone" instead of "the superincumbent material consists of a stratum of calcareous composition."

November 1945

EARTHQUAKE FELT AT KLAMATH FALLS AT NOON DECEMBER 24, 1947

Klamath Falls (central section). (VI) Motion trembling. Felt by several. Rattling of loose objects; buildings creaked. One report of cracked plaster. "Those reporting in rather wide area. Radio Station KFLW reported a momentary distortion at noon." Ground; Rocky.

Klamath Falls. (IV) Motion swaying, rapid onset. Felt by several. Rattling of loose objects and creaking of buildings heard by several. Faint, bumping sounds heard. Pictures on walls and suspended lighting fixtures swayed. Few alarmed.

July 1948

EARTHQUAKES

The recent quake which occurred April 13, 1949, although causing little damage in the Portland area, created considerable interest and concern among individuals, public agencies, engineering firms, power companies, and insurance firms. The State of Washington has inaugurated a special study of the earthquake, the epicenter of which was located by the U.S. Coast and Geodetic Survey between Olympia and Tacoma. Olympia suffered the greatest damage of the cities of the Puget Sound area.

Minor damage to several of its substations in southern Washington was reported by Bonneville Power Administration. The Oregon Section, American Society of Civil Engineers, has undertaken a comprehensive study of earthquake- resistant construction in buildings in Oregon. The study will include both the public safety and economic aspects of the problem.

As would be expected, local insurance firms were besieged by requests for earthquake insurance coverage immediately following the recent disturbance. One large international insurance firm made a study of the earthquake activity in the State, together with the subsurface conditions existing in the areas occupied by the principal cities in the State.

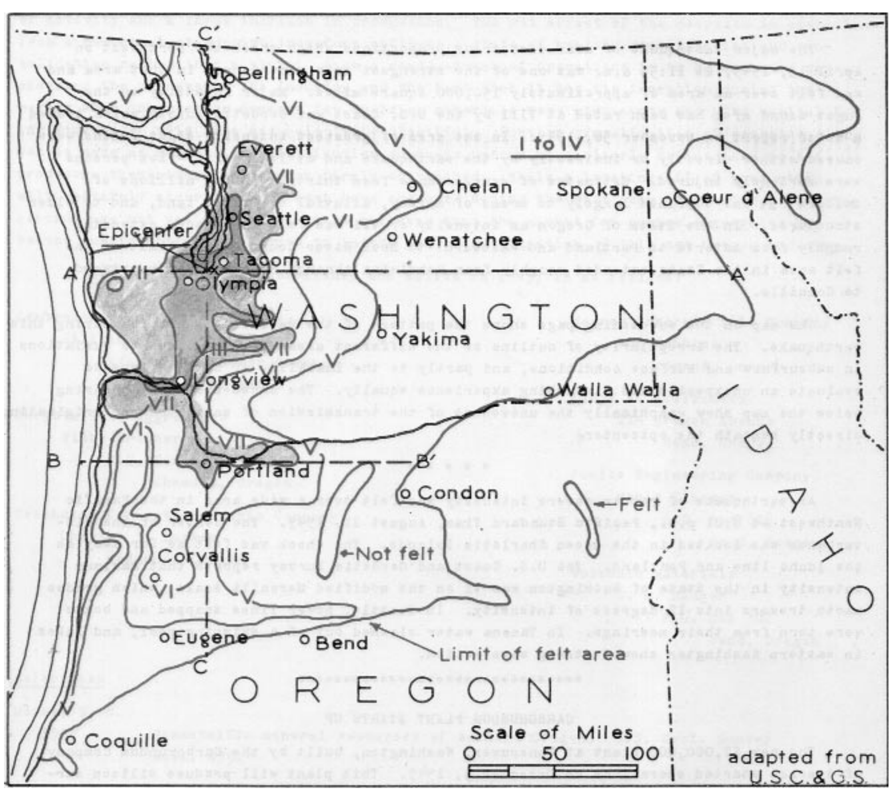
June 1949

MT. HOOD'S VANISHING GLACIERS

Oldtimers who are fond of telling people that "the winters aren't as severe as they used to be . . ." may very well be telling the truth if present glacial activity on Mt. Hood and other continental peaks is taken into consideration . . .

Glacial markings on rocks 500 feet above the present surface of Reid Glacier indicate the amount of shrinkage of one of Mt. Hood's now shrivelled glaciers.

September 1946



Isoseismal map for earthquakes of April 13, 1949, at 11:55:41 PST. Adapted from map prepared by U.S. Coast and Geodetic Survey. December 1949

1950s: The cold war

NEW USE FOR OREGON VOLCANIC GLASS

A new use for Oregon volcanic glass has been developed by the State Department of Geology and Mineral Industries. The volcanic glass when used as a feldspar substitute in a ceramic glaze produces a glaze suitable for stoneware, artware, and terracotta products. Finely ground pumice, volcanic ash, and perlite, forms of volcanic glass found mainly in the central and eastern parts of the State, can be used to replace more costly material shipped into the area from considerable distances. The glaze was perfected after nearly two years of research by Mr. C.W.F. Jacobs, Department Ceramist, who experimented with numerous nonmetallic products found in Oregon.

September 1950

ASTORIA LANDSLIDES

This year, damage from landsliding in Astoria has centered in the western part of town at West Commercial and West First Streets. Twenty-seven houses have been affected, five of which were already abandoned as the result of slippage last winter. The houses in this area will be destroyed unless moved, and the streets, sidewalks, plumbing, landscaping, and other improvements are doomed. In 1950 twenty-three houses in the Coxcomb Hill area were removed or destroyed.

A loss of fifty houses in one city due to geological processes in a matter of a few years is a serious situation, and a brief review of the geology of the area is given so that a better understanding of the underlying cause of the destruction may be had.

January 1954

BLUE CHIP METALS

This atomic age is dependent on metals, and their importance is constantly being brought home to us. This is a development hastened by war and war preparation, but in any case, seemingly, it is an industrial evolution along the course set by the demand for more and improved machines and the inventions of new and more intricate instruments. A greater quantity of the common metals is continually demanded; and "new" metals — new in their practical applications — are becoming increasingly necessary in the ever-expanding industrial field. Cobalt, titanium, columbium, tantalum, germanium, and the so-called rare-earth metals are among those which have become essential to modern industry. Because of price, domestic needs, and metallurgical characteristics, they are the "blue chips" of present-day metallurgy.

February 1952

OREGON NATIVE STONE FOR ROOSEVELT MEMORIAL MUSEUM AT WARM SPRINGS, GEORGIA

As requested by Governor Douglas McKay, DOGAMI has prepared an Oregon stone for presentation to the Franklin D. Roosevelt Memorial Foundation museum at Warm Springs, Georgia. Typical stones from each state in the United States will be placed in the walls of the museum building. The Oregon stone is made out of a rectangular block of gray Ashland granite approximately 18 inches by 13 inches by 4 inches. One polished face, on which OREGON is etched, outlines the boundaries of the state. The stone, which has been on display in the Department's museum in the State Office Building, Portland, will be shipped in a few days to Warm Springs where a simple presentation ceremony has been planned.

March 1952

OIL AND GAS CONSERVATION WEEK PROCLAIMED BY GOVERNOR

The week of November 29 through December 4, 1954, was proclaimed as Oil and Gas Conservation Week by Paul L. Patterson, Governor of the State of Oregon. This State is one of many in which similar proclamations were issued. The need for conservation of natural resources is being recognized by progressive officials and agencies more than ever before. The State of Oregon is cognizant of this need. The 1953 Legislature passed a new oil and gas conservation law, even though the search for oil and gas in the State is in its infancy. In July, Oregon became an associate member of the Interstate Oil Compact Commission, a national organization whose sole purpose is to promote and encourage the conservation of oil and gas and to prevent physical waste.

December 1954

FOSSIL LOCALITIES IN THE COOS BAY AREA, OREGON

Fossil shells are abundant in the sedimentary rocks of the Coos Bay area. Good fossil specimens are most likely to be found where sedimentary rocks are freshly exposed, such as in recent, unweathered road cuts or at the base of cliffs along the coast and the bay where wave action is constantly uncovering new material. Ten easily accessible fossil localities are described in the following text and their location shown on the accompanying map. Localities along the water's edge can generally be reached only at low tide.

June 1955

MAGNETIC DECLINATION IN OREGON

Anyone who uses a compass for surveying or prospecting must take into account the effect of variations in the earth's magnetism on the compass needle. There are only a few places on the earth where the compass points truly north, and even there the direction is not constant for very long. In Oregon the compass points between 18° and 22° east of true north, with local variations of from 5° west to nearly 33° east. This deviation of the compass needle, or angle between magnetic north and true north, is known as magnetic declination.

June 1956

LANDSLIDE DAMAGE

Landslides are far more common than is generally realized. Lack of information about them is probably due to their intermittent occurrence and the relatively small number of people directly affected. The following cost estimates of slide damage in Oregon are given to illustrate their importance and to call attention to the need for further slide study.

The winter of 1955-1956 cost the Multnomah County road department an estimated $125,000 for slide repair, four times the normal yearly cost. Slides in that county, which numbered 109, are exclusive of those on highways and streets maintained by city governments and the State Highway Department. The Portland city water department reported a slide damage this past winter to the main water supply system which will cost an estimated $100,000 to repair. According to the city engineer's office, repairs to Portland city streets and parks necessitated by recent slides will cost about $100,000.

May 1956

1960s: The space race

LAKE COUNTY SPOUTER BECOMES TRUE GEYSER

The hot-water spouter on the Charles Crump ranch in Warner Valley, Lake County, is again making history. It is now a true geyser, erupting at approximately two-minute intervals to a height of 60 feet.

The original spouter, which burst forth from a well on July 1, 1959, sent up a continuous column of steam and hot water more than 150 feet high (see report by Norman Peterson in the September 1959 Ore.-Bin). That action continued for several months, until vandals threw boulders into the 20-inch casing at the top of the well, greatly reducing the volume of flow and height of eruption.

June 1960

GEOMORPHOLOGY OF THE CONTINENTAL TERRACE OFF THE CENTRAL COAST OF OREGON

The major submarine geomorphic features off the Oregon coast are the continental shelf, extending from low water to the first pronounced increase of slope to deeper water, and the continental slope, from the outer edge of the shelf to the decrease of slope at the edge of the abyssal plain. Together, these constitute the continental terrace. The terrace varies in width from more than 70 miles off Astoria to less than 40 miles off Cape Blanco, and extends to the 1,500- to 1,700-fathom depths of the southward-deepening abyssal plain. Off the Columbia River, Astoria Canyon and Astoria Cone alter the shape of the continental terrace.

Astoria Canyon, the only major submarine canyon off the Oregon coast, heads 10 miles west of the mouth of the Columbia at a depth of 70 fathoms, and extends some 60 miles to a depth of 1,000 fathoms, where its identity as a canyon is lost on Astoria Cone. . .

The continental shelf along the Oregon coast differs notably from the average continental shelf. According to Shepard, shelves around the world have an average width of 42 miles, an average slope of 0°07′, and an average depth at the outer edge of 72 fathoms. The shelf along Oregon is 9 to 40 miles wide, slopes 0°08′ to 0°43′, and has a depth at its outer edge of 80 to 100 fathoms. Thus, the Oregon continental shelf is characteristically narrower, steeper, and deeper than the average continental shelf.

May 1962

INDUSTRIAL MINERALS: BUILDING STONE

Interest in Oregon building stone continued at a high level during 1961. Increased use of ornamental stone in commercial buildings and private residences required quantities of local and out-of-state stone. The selection of such stone is based largely on its appearance, and individual tastes with respect to color, texture, and shape vary widely. It is little wonder that shipments come from considerable distances to supply a definite demand and local stones travel far from home for the same reason. Oregon quarries, scattered over the state, produced a variety of colorful stones which spanned the color spectrum from green through yellow and brown to pink. Most were of volcanic origin, with airborne and water-laid tuffs predominating. Some of the state's many lavas were also used, and although they tended to be less colorful they were more interesting texturally. A survey of building stones conducted by the department located a lava outcrop which emits a musical tone when struck. Lavas with warped fossil bubble holes and tuffs which can be carved, glazed, and fired are also available from Oregon quarries.

January 1962

LUNAR LANDSCAPES IN OREGON

As the race to be the first mortals on the moon continues, the questions of how the lunar surface features originated and what rock types they contain are still not answered.

Many of the lunar configurations that are telescopically visible certainly resemble volcanoes and features associated with them. Even if only a part of the moon's surface has been formed by volcanic processes, some of the smaller volcanic forms, such as hummocky lava flow surfaces, spatter cones, and lava tubes could be present. If these features exist, they could provide ready-made shelters to protect men and vehicles from the hostile environment of radiation, high temperatures, and meteorite and dust bombardment.

A reconnaissance of the Bend-Fort Rock area in central Oregon shows that it has a wealth and variety of fresh volcanic landforms that should be of interest to the planners of our lunar programs as well as to the students of volcanology or to those curious about the rocks of Oregon.

March 1963

TSUNAMIS ON THE OREGON COAST

During the early hours of the morning of March 28, 1964 a tsunami struck the Oregon coast. This phenomenon, commonly called a "tidal wave," was generated by the earthquake that had shaken Alaska the evening before. The seismic waves forming the tsunami originated in the vicinity of the earthquake's epicenter and traveled in all directions to ocean shorelines where they were eventually dissipated; in some areas there was substantial loss of life and property.

Residents along the Oregon coast can be thankful that this tsunami caused relatively little loss along our shores. A tsunami of comparable magnitude struck the Hawaiian Islands in 1946, resulting in the loss of 159 lives and a $25 million property damage. Hawaii was 2,300 miles away from the epicenter in the Aleutians of that devastating earthquake, whereas our coast is only about 1,500 miles from Alaska. Oregon was fortunate this time for several reasons: the initial direction of impetus imparted to the seismic waves was away from our coast; the intervening continental shelf topography aided in refracting and dissipating the waves; and, finally, the generally high and rugged coastline of Oregon resulted in ultimate dissipation of the waves on unpopulated shorelines.

. . . Each estuary has its own peculiarities. The location of jetties and sea walls, the existence of tidal flats and sloughs, the shape and length of the channel and the depth and width of the basin enter into the effects abnormal waves can produce. For example, (1) At Coos Bay, the initial wave of about 10 feet above mean high water was dissipated in its travel up the channel by the wide tidal flats and was of negligible height by the time it reached Pony Point about 7 miles up the channel. (2) At Florence, on the Siuslaw River, the initial wave was about 8 feet above mean high water at the Coast Guard Station near the entrance, but due to a fairly narrow channel the wave was apparently only slightly dissipated by the time it reached Florence in the South Slough and surrounding tidal flats. (3) At Reedsport, about 10 miles up the Umpqua River only negligible indications existed of the 14-foot wave that was measured at the entrance. The meandering river with its wide tidal flats quickly dissipated the wave's energy. (4) In Yaquina Bay, four large waves of almost equal height were observed; whereas, in the other estuaries the subsequent waves generally decreased in magnitude following the second wave. This effect at Yaquina Bay could possibly be attributed to a seiche characteristic which is similar to the rocking motion of water from side to side in an open basin.

December 1964

HISTORY OF OREGON EARTHQUAKES

Oregon has experienced many more earthquakes than is generally realized, and a good share of them have occurred in the vicinity of Portland. Since 1841, at least 160 earthquakes have been recorded in Oregon, not including those originating out of the state or at sea but felt here. Prior to 1900, only about 30 quakes had been known. Undoubtedly many more occurred but were not reported because of the scattered population, poor communications, and lack of instrumentation.

Earthquakes having intensities of VIII on the modified Mercalli scale have been reported for Oregon at Port Orford in 1873, at Portland in 1877 and in 1880, and at Milton-Freewater in 1936. Earthquakes with intensities of VII were reported at Umatilla in 1923 and at Portland in 1962; and intensity quakes of VI occurred in Portland in 1953 and at Salem in 1957. Portland alone has been the epicenter for at least 46 earthquakes ranging from II to VII in intensities. Nine of these were V and above.

December 1964

THE TACOMA EARTHQUAKE OF APRIL 29, 1965

About the time Seattle and Tacoma people were going to work on the morning of April 29, 1965, the Pacific Northwest states were shaken by their largest earthquake in decades. The shock was as large, or larger, than the famous Tacoma shock of April 13, 1949. The recent quake was felt over Washington, Oregon, Idaho, and British Columbia, and as far away as Coos Bay, Oregon. Considerable damage occurred in the Tacoma-Seattle area, where at least three persons were killed. The shock was so strong that recordings at most seismograph stations in the Northwest went off scale, and subsequently recorded vibrations were so large that the different waves could not be identified. Consequently, the magnitude of the shock could be determined only at distant stations, where recorded amplitudes were smaller.

The magnitude of the shock was reported to be 6½ (Richter scale) by the Seismological Laboratory in Pasadena, California, and 7 by the Seismographic Stations in Berkeley, California. The maximum intensity was estimated to be VIII (Modified-Mercalli scale) in the Tacoma-Seattle region, decreasing to intensities of VII at Longview, Washington; IV at Corvallis, Oregon; and III at Coos Bay, Oregon. . .

May 1965

INVESTIGATIONS OF THE NOVEMBER 1962 EARTHQUAKE, NORTH OF PORTLAND

The Portland earthquake was the largest shock to occur in Oregon since the recent installations of the several new seismic stations in the Pacific Northwest. Although damage resulting from this shock was minor, as indicated in a preliminary report (Dehlinger and Berg, 1962), the shock is of considerable seismological importance. Because it was large enough to be recorded at the newly installed as well as at many of the older seismic stations, and because its epicentral location was known approximately from the felt area and from on-site recordings of aftershocks, this earthquake has provided the first significant data to be used for constructing travel-time curves for Oregon. The seismograms also provided data for a better understanding of the source mechanism associated with the Portland shock.

. . . Aftershocks nearly always occur subsequent to an earthquake. Numerous aftershocks followed the Portland temblor, about 50 of which were recorded over a period of 18 days by three portable seismic stations in the Portland area.

April 1963

OREGON'S LOST METEORITES

Oregon's Port Orford meteorite has gained worldwide fame as a lost meteorite. Interest in the search for this meteorite has now extended over a period of a hundred years without success. In addition to the Port Orford meteorite, there is evidence that other lost meteorites exist in Oregon . . .

1. One of the largest meteors on record fell on the head of South Slough, Coos County, January 17, 1890, at 11:00 at night, knocking a hole in the hill thirty feet across.

It came from the Northwest and lighted up the heavens in fine style.

A report, as of thunder, awoke people for many miles around. It was plainly heard at Coquille City. Excavations reveal a chunk of lava twenty-two feet across that resembles slag from an iron furnace.

2. Listed as a doubtful fall in the Prior-Hey catalog of meteorites published by the British Museum is a stony meteorite from Mulino, Oregon. A small stony meteorite was sent to the U.S.National Museum in 1927. The meteorite supposedly fell May 4, 1927.

3. In January 1952, an unidentified rancher brought in to J.D. Howard of Klamath Falls a small piece of nickel-iron for analysis. This piece was broken off from a 30-pound mass. Mr. Howard, suspecting the specimen to be meteoritic, forwarded it to Dr. H.H. Nininger at Winslow, Arizona, for verification. Dr. Nininger found it to be a meteorite. He then attempted to learn the location of the main mass, but so far has been unsuccessful. The small piece of the so-called Klamath Falls meteorite is in the Nininger collection at Arizona State University in Tempe. Somewhere in the Klamath Falls area there must be a 30-pound meteorite.

February 1965

WHAT IS A THUNDER EGG?

Thunder eggs are spherical masses of rock that range in size from less than an inch to 4 feet in diameter. Most are about the size of a baseball. They have a knobby rind of drab, siliceous rock and a cavity filled with agate. . .

Thunder eggs are always associated with silicic volcanic rocks such as welded tuffs and rhyolite flows. Millions of years ago, fiery avalanches of this type of molten rock poured out of volcanoes and flowed over the land. In central and south-eastern Oregon there are wide areas in which rocks of this type are well exposed.

October 1965

A IS FOR ALBANY, Z IS FOR ZIRCONIUM

Albany, Oregon, and zirconium are inextricably linked, at least in the thinking of the metallurgists in the Free World who concern themselves with the space-age metals. It was at Albany in 1945 that Dr. W.J. Kroll started work with the United States Bureau of Mines on a research program to develop a process for producing ductile zirconium. . .

Such was the beginning of a development involving many other metals which was to change the economy and character of the city of Albany — and indeed to affect the entire state. The transition from an abandoned small college campus to a nationally recognized center for exotic metals required only 10 years. Starting with an original investment of $140,000 for the old Albany College buildings and ground, the federal government's Albany installation is now valued at $4.5 million.

October 1967

SAMS VALLEY METEORITIC SHOWER

One of Oregon's important meteorites is the 15-pound Sams Valley iron found in 1894 by George P. Lindley of Medford. Recent investigations give evidence to the fact that the Sams Valley meteorite was not an individual fall as was commonly reported, but a shower of which five specimens were found. Three individuals can definitely be accounted for. Other specimens may yet be in the possession of residents of the Sams Valley and Medford areas. It is also quite likely that other meteorites will be found in the Sams Valley area.

August 1967

THE WARNER VALLEY EARTHQUAKE SEQUENCE

A series of earthquakes struck the Warner Valley in southeast Oregon in May and June 1968. The earthquakes caused rockslides and building damage in and near the community of Adel, Oregon, and were of sufficient intensity to rattle dishes in Lakeview, Oregon, 30 miles west of Adel. The largest earthquake with an estimated magnitude of 5.1 on the Richter magnitude scale occurred on May 29, 1968.

. . . The steep cliffs which form the east and west walls of the Warner Valley are upraised blocks or horsts while the valley, containing shallow lakes, is formed by a downdropped crustal block or graben. . . The horst and graben structure of southeast Oregon is characteristic of the physiographic Basin and Range province and extends over Utah, Nevada, Arizona, New Mexico, and parts of Idaho and California.

June 1968

PLEASE SEND US YOUR PHOTOS

Since we have started printing color pictures on the front cover of *Oregon Geology*, we are finding ourselves woefully short of good color photographs showing geologic motifs in Oregon.

We also want to make recommendations for scenery well worth looking at in a new series of black-and-white photos on the back cover of *Oregon Geology*. For that, too, your contributions are invited.

Good glossy prints or transparencies will be the best "hard copy," while digital versions are best in TIFF or EPS format, on the PC or Mac platform.

If you have any photos that you would like to share with other readers of this magazine, please send them to us (you know, "Editor, etc."). If they are used, the printing and credit to you and a one-year free subscription to *Oregon Geology* is all the compensation we can offer. If you wish to have us return your materials, please include a self-addressed envelope.

Information for Contributors

Oregon Geology is designed to reach a wide spectrum of readers interested in the geology and mineral industry of Oregon. Color photos for publication on the front cover are highly welcome, as are letters or notes in response to materials published in the magazine and notices of meetings that may be of interest to our readers.

Two copies of the manuscript should be submitted. If manuscript was prepared on common word-processing equipment, a file copy on diskette should be submitted in place of one paper copy (from Macintosh systems, high-density diskette only). Hard-copy graphics should be camera ready; photographs should be glossies. All illustrations should be clearly marked; captions should be together at the end of the text.

Style is generally that of U.S. Geological Survey publications. (See USGS *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) Bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Include names of reviewers in the acknowledgments.

Conclusions and opinions presented in articles are those of the authors and are not necessarily endorsed by the Oregon Department of Geology and Mineral Industries.

Authors will receive 20 complimentary copies of the issue containing their contribution.

Manuscripts, letters, notices, and photographs should be sent to Klaus Neuendorf, Editor, at the Portland office (address in masthead on first inside page).

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Allow 2 weeks for delivery on all maps plotted on demand.

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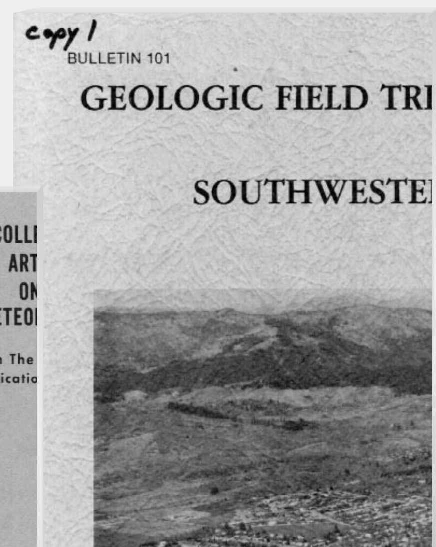
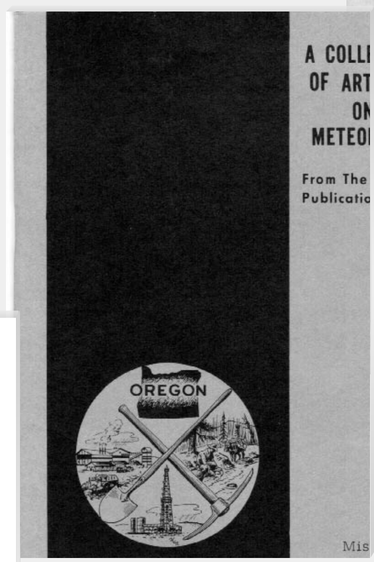
now available from The Nature of the Northwest Information Center

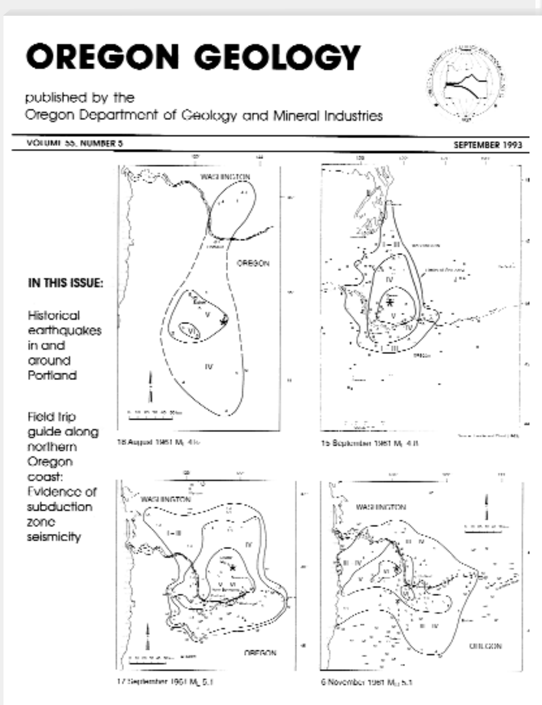
Have any of the excerpts of articles in this issue intrigued you? Do you want to know more? Previous issues of *Oregon Geology* (the *Ore-Bin,* its predecessor) are available, as well as two other publications with compilations of articles. Here are three examples of what is available.



Geologic Field Trips in Western Oregon and Southwestern Washington, Bulletin 101, published 1980, 232 p.

Ten field trips were compiled for the 1980 GSA conference. These detailed trip guides will help you explore and understand the geology of the area. Each has a discussion of the area's geology and a road log to use for finding sites.





A Collection of Articles on Meteorites (From the Ore-Bin), Miscellaneous Paper 11, published 1968, 39 p.

If you are interested in finding out more about the Sams Valley Meteorite mentioned in this issue, the Willamette Meteorite some are trying to get returned to Oregon, or other meteorites that have fallen on Oregon, these seven articles will be of interest.

Previous issues of *Oregon Geology* and the *Ore-Bin*, published since 1939.

If you want information about these topics in this issue, or some other part of Oregon's geology, all previous issues of the *Ore-Bin* and *Oregon Geology* are for sale at $3 each (If the issue is out of print, we will make a photocopy).

1970s: Plate tectonics

VOLCANIC ERUPTIONS: THE PIONEERS' ATTITUDE FROM 1800 TO 1875

. . . Western Oregon and Washington, and much of northern California, are rather effectively walled off from the rest of the nation by the Cascade Range. Any overland routes of approach from the East would bring the traveler into close proximity to these steep and rugged mountains . . . Where and when were volcanic eruptions reported and how many of these reports represent real events?

From the earliest obscure story by the Indian John Hiaton in 1820 to the newspaper comment in the *Washington Standard* of Olympia in 1873 . . . there have been at least 40 reported volcanic events involving seven western mountains:

Reported volcanic eruptions from 1820-1873

Peak	Years
Mt. Baker	1842, 1843, 1846, 1847, 1853, 1854, 1858, 1859, 1860, 1870
Mt. Olympus*	1861
Mt. Rainier	1820, 1841, 1843, 1846, 1854, 1858, 1870, 1873, plus an undetermined date between 1820 and 1854
Mt. St. Helens	1802, 1831, 1832, 1835, 1842 to 1848, 1852 to 1854, 1857
Mt. Hood	1831, 1846, 1854, 1859, 1865
Feather Lake Cinder Cone	circa 1851
Mount Lassen	1857

** Mt. Olympus is not a volcano—ed.*

April 1970

SEISMIC ENERGY RELEASE

Portland area

Of the areas of Oregon, the Portland area has the longest and most complete earthquake history . . . The average seismic energy release rate during the 100-year period from 1870 through 1970 was . . . approximately equivalent to one earthquake of magnitude 4.8 (unified magnitude scale) (intensity MM V) each year. Couch and others (1968) noted that beginning about 1950 the rate of seismic energy release in the Portland area appeared to increase approximately ten times. The higher rate suggests a seismic level equivalent to one magnitude 5.2 earthquake (MM V-VI) approximately each decade. Historical records span too short a time period to indicate whether the change is a singular event or a cyclic change.

Coast Range

The average seismic energy release in the Coast Range for the 100 year period (1870 through 1970) is . . . approximately equivalent to one magnitude 5.0 earthquake (intensity V) each decade.

Willamette Valley

The earthquake activity in the Willamette Valley is distributed over the area with concentrations of epicenters occurring west of Salem and in the vicinity of the middle Santiam River . . . The average seismic energy release for the 100 year period from 1870 through 1970 is . . . approximately equivalent to one magnitude 5.3 (intensity VI) quake each 30 years.

Klamath Mountains

The average energy release rate for the 100 year period from 1870 through 1970 was 2.8 x 1018 ergs per year . . . the total energy released during the 100 year period is clearly dependent on the intensity VIII earthquake which reportedly occurred near Port Orford in 1873. The intensity and location of this earthquake are questionable; consequently, the computed energy release rate may be much too high.

Cascade Range

. . . The average seismic energy release rate during the 100 year period from 1870 through 1970 was 2.7 x 1018 ergs per year. The computed energy release rate is largely dependent on the occurrence of an intensity VIII earthquake near Cascade Locks in 1877. The intensity and location of this earthquake are questionable; consequently, the computed energy release rate may be much too high.

April 1971

OREGON HIGHWAY DEPARTMENT MARKERS

1. On Oregon Highway 18 . . . is a geological marker defining the term "glacial erratic" and pointing to one of the largest of such rocks . . .

2. Beacon Rock, a giant stone pillar of volcanic origin that rises out of the Columbia River on the Washington side, is noted by a historical marker on Interstate 80–N.

3. Also along Interstate 80–N . . . is a marker dedicated to Celilo Falls, ancient fishing grounds of various Indian tribes.

4. In the far northeast corner of Oregon . . . is a geological marker describing the formation of Wallowa Lake . . .

5. Looking out across the John Day River to Sheep Rock on Oregon Highway 19 . . . is a geology marker describing the John Day Fossil Beds.

6. On . . . U.S. 26, about 4 miles west of Millican is a marker that describes a prehistoric river which flowed across the central

Wallowa Lake was formed by glacial moraines. (Photo courtesy of Oregon Department of Transportation)

Oregon desert at this point.

7. On U.S. Highway 20 . . . is a marker that shows the northern limit of the great inland basin, which had no drainage to the sea.

8. A historical marker for Klamath Lake is located on U.S. Highway 97 about nine miles north of Klamath Falls.

9. . . . Fort Rock is noted by a historical marker on Oregon Highway 31 . . .

10. Abert Rim . . . is described by geological markers in two locations, one on Oregon Highway 31 . . . and the other on U.S. Highway 395 . . .

11. A bronze marker describes the origin of a well-preserved lava tube situated on U.S. Highway 97 . . .

October 1971

Multnomah Falls, one of the highest in the US, is one of 11 waterfalls within an 11-mile stretch of the Columbia Gorge. (Photo courtesy Oregon Department of Transportation) February 1979

THE METOLIUS RIVER

The Metolius Springs rise from two groups of orifices about 200 yards apart at the northern base of Black Butte. The water bubbles out of bouldery valley fill at a chilly temperature of 48°F, and the two flows join within a short distance to make up the headwaters of the Metolius River. Total flow from the springs consistently measures from 45,000 to 50,000 gallons per minute the year around. In its 35-mile course northward and eastward to the Deschutes River, the Metolius gains an additional 600,000 gallons of water per minute from springs and tributary streams that drain the east flank of the Cascades.

March 1972

PORTLAND AREA FAULTS

It is concluded that the Portland Hills-Clackamas River alignment is part of a major structural fault system which extends across the state of Oregon to the southeast as far as Steens Mountain. A series of regionally co-aligned morphologic and structural features striking N. 40–50° W. are aligned with the Portland Hills-Clackamas River alignment. Surface and subsurface geology and gravity and magnetic data in the Portland region all support this interpretation.

June 1972

PLATE TECTONICS

The plate tectonic history of Oregon is but one piece of a worldwide jigsaw puzzle encompassing much of geologic time. With the splitting of Pangaea in Mesozoic times, Oregon has occupied the leading edge of the North American Plate as it has impinged upon the ancestral oceanic East Pacific Plate. In the process Oregon has undergone profound subduction type tectonism. In addition, it may have acquired much lithospheric material from other plates, possibly some of the Paleozoic rocks of the Klamaths from Asia, ultramafic rocks and volcanic rocks from the Triassic oceanic crust, and the Siletz River Volcanics from the Eocene deep-sea floor.

In middle Tertiary times, Oregon, along with the rest of western North America, actually caught up with the East Pacific Rise, an event which profoundly altered the pattern of tectonic behavior within the state. Flood basalts and block faulting replaced andesitic volcanism and thrust faulting as the dominant mode of tectonism. The pattern of deformation in late Tertiary times is extremely complex and a plate tectonic model consistent with all the data has yet to be formulated.

August 1972

DEFINITION OF SUNSTONE

"Sunstone" [the Oregon state gemstone] is the name given to a certain variety of feldspar that exhibits a brilliant pink to reddish metallic glitter or shimmer. The metallic glitter results from the reflection of light from myriads of minute flat scales of hematite or other mineral impurities . . .

December 1972

AN ACRE IS MORE THAN JUST 43,560 SQUARE FEET

Geologists take a different view of "land" . . . What lies immediately below the surface is much like the mythical Pandora's Box, which loosed many ills and blessings when opened. Lurking beneath an innocent looking land surface may be a plague of geologic hazards or a wealth of mineral resources which may be set free if the surface land cover is removed and the "box" opened . . . Landslides, subsidence, changes in water table, contamination of potable water, and destruction of natural springs are some of the geologic hazards which may become all too apparent when the land is disturbed.

Mineral resources that may be underlying the land surface include such things as sand and gravel, crushable rock, dimension stone, jetty rock, fill material ground water, oil and gas, coal, metallic ores, and industrial minerals.

January 1973

BEACH EROSION ON SILETZ SPIT

In the winter of 1972–73 severe erosion occurred on Siletz Spit on the central Oregon Coast. One partially constructed house was lost, and others were saved only by the immediate placement of riprap, large rocks installed at the base of the property to prevent wave erosion. This episode of erosion received widespread news coverage. For a time it was feared that the spit might breach, much as Bayocean Spit, on the northern Oregon Coast, had in 1952.

August 1976

AN EXTINCT EVODIA *WOOD FROM OREGON*

During the early Eocene in Oregon, approximately 35 million years ago, a relatively level lowland reached from the base of the Blue Mountains in northeastern Oregon to the Pacific Ocean, which at that time extended into western Oregon. Since the Coast and Cascade Ranges had yet to develop, the entire area was influenced by ocean currents and had a subtropical climate largely free from frost.

. . . The genus *Evodia* can be included among trees which were native to Oregon during Eocene times but which are extinct in the western hemisphere.

September 1976

THE DESCHUTES VALLEY EARTHQUAKE OF APRIL 12, 1976

. . . Reports obtained by personal interviews with the inhabitants of north-central Oregon on April 14, 15, and 16 indicated houses shook, swayed, rattled, creaked, and rocked in the Deschutes Valley during the earthquake. Associated sounds were reported as rumblings like distant thunder, booms similar to sonic booms, and a roaring noise like a strong wind or blasting. At locations more distant from the epicenter, people reported rocking or rolling motions and feelings of queasiness or nausea.

October 1976

THE AGE OF LAVA BUTTE

Lava Butte and its jagged black fields of lava, located 10 mi (16 km) south of Bend along U.S. Highway 97, have been major scenic and geologic attractions since at least 1900.

. . . The radiocarbon age of the carbonized wood, and thus Lava Butte and its associated lava fields and plume deposit, is 6,160±65 years B.P. . .

October 1977

LATE PLEISTOCENE SEDIMENTS AND FLOODS IN THE WILLAMETTE VALLEY

The Spokane Flood produced many effects in the Willamette Valley. The erosional channels near Rocky Butte are especially noteworthy . . .

The Spokane Flood surged westward through the Tualatin River and Lake Oswego channels and, upon reaching the wide-open portion of the Tualatin Valley, deposited loose, poorly sorted, rubbly and bouldery gravel and sand . . .

The flood level in the Tualatin Valley rose high enough to spill with great force across the divide separating the Tualatin and Willamette drainage basins . . . The divide, of unknown preflood elevation, was lowered locally to a little less than 150 ft above sea level . . .

A large flow of Spokane Flood water poured southward through the Oregon City water gap; at the north edge of the Mollala River trench near Canby . . .

The inflow of flood water from the Columbia River temporarily raised the water level in the Willamette Valley to an elevation of 400 ft, forming a body of water named Lake Allison. This 400-ft water level contrasts with the 1,100-ft level of the Spokane Flood east of the Columbia River Gorge, which cuts through the Cascades.

December 1978

(The Spokane Flood is now generally known as Missoula Floods—*ed.*)

STAY OUT OF OLD MINES! (AND OPERATING ONES, TOO)

The recent near-tragedy involving two youngsters at an operating mine in central Oregon prompts the Department to once again issue a warning about the hazards involved with poking around in mines. Mines, particularly old mines, can be most dangerous to life and limb at any time. Rotting timbers, foul air, and weathered rock about to collapse are only a few of the deadly hazards that are encountered by those who decide to explore.

Active mines, even during periods when operations are shut down temporarily, can trap the unwary.

December 1978

Musick mine and Bohemia City, with restored stage house and post office. In foreground is covered portal and mine track. June 1978

1980s: Mt. St. Helens erupts

MOUNT ST. HELENS—AN AERIAL VIEW

. . . the Oregon Army National Guard initiated aerial surveillance activity over Mount St. Helens volcano, Washington, as it began erupting during the afternoon of March 27, 1980.

The first activity sighted was the formation of an explosion crater, flanked by numerous impact craters and accompanied by ash trailing off to the southeast.

By March 30, continued phreatic discharges (ground water explosively flashed into steam) had significantly enlarged the original crater and given birth to a new, smaller crater 100 m (300 ft) to the east. Significant ash fall littered the areas east of the activity, and continuing seismic activity along with thermal melting triggered a series of debris avalanches on the southeast flank of the volcano.

May 1980

REMOTE SENSING OF THE MOUNT ST. HELENS ERUPTION, MAY 18, 1980

. . . a sharp increase in the thermal activity in the crater area of Mount St. Helens was observed at 5:30 a.m. on Sunday, May 18. An increased number of hot spots were noted on the "Boot" and in the bulge area, which had been swelling at a rate of about 5 ft per day since mid-April. However, just as the thermograph recording film was being developed, information was received that a passing aircraft had witnessed an explosive eruption at 8:30 a.m.

The first of four day-time photo missions was launched from Salem. Initial reports indicated that the top of the mountain had been lowered from the old elevation of 9,677 ft to about the 8,300-ft level. A dense, mushroom-shaped plume of ash rose ominously into the stratosphere, obscuring everything to the north and east of the mountain. Large debris flows were moving down the North and South Forks of the Toutle River, destroying roads and bridges and carrying off log decks in the flooding caused by the rapid melting of the mountain's glaciers.

Hot ash flows have continued down the north flank of Mount St. Helens into the former valley of the North Fork of the Toutle River, producing explosions described as "phreatic" upon contact with water in the valley. An infrared thermograph, flown before dawn on Tuesday, May 20, shows a hot ash flow at the base of the north flank and numerous pits caused by phreatic explosions in the North Fork of the Toutle Valley.

June 1980

PLUVIAL LAKE MODOC, KLAMATH COUNTY, OREGON, AND MODOC AND SISKIYOU COUNTIES, CALIFORNIA

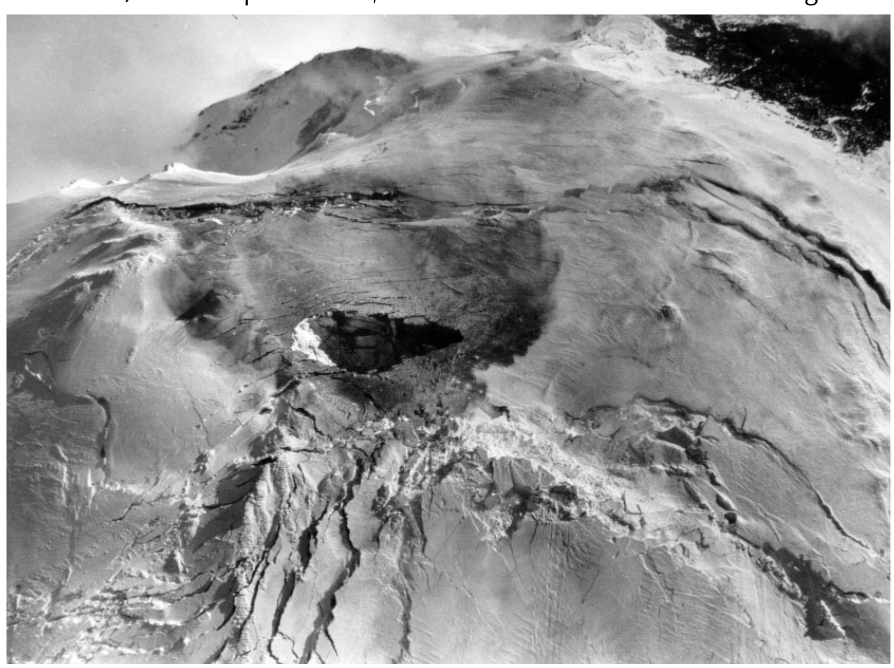
The Klamath Lakes, Upper and Lower, together with Tule Lake are the shrunken remnants of pluvial Lake Modoc (named in this article by the author). The old pluvial lake, which existed in Pleistocene time, consisted of several connected arms with an overall length of nearly 75 mi (120 km). The southern end was in California, south of Tule Lake; the northern end was near Fort Klamath in west-central Klamath County. At maximum extent, the 400 mi (663 km) of shoreline was at the nearly uniform elevation of 4,240 ft (1,292 m) above sea level.

November 1980

OMSI SOUND PROJECT: THE ACOUSTIC EFFECTS OF THE MOUNT ST. HELENS ERUPTION ON MAY 18, 1980

In Hamilton, Montana, about 400 mi due east of Mount St. Helens, the sound of the volcano's eruption on May 18 was described as heavy artillery fire very close by. In the San Juan Islands, people wondered if the Canadian Navy was having gunnery practice. Residents along the central Oregon coast thought they were hearing sonic booms, thunder, and dynamiting all rolled into one 15-minute barrage.

Yet, some who were within 10 mi of the mountain heard nothing.



The beginning of the eruptive phase of Mount St. Helens: The first explosive eruptions on March 27, 1980, at 12:36 p.m. PST, sent an ash column about 6,000 ft above the volcano and opened this 250-ft-wide crater. Photo was taken at about 2 p.m. on that day by Michael Lloyd of *The Oregonian*. May 1980

Since the author was able to hear this house-shaking, window-rattling noise near Netarts on the Oregon coast, 116 mi distant from Mount St. Helens, she was surprised to learn that her daughter in Portland, only 45 mi distant, had heard nothing at all.

December 1980

SURFACE MINED LAND RECLAMATION IN OREGON, 1981

The Mined Land Reclamation (MLR) Program completed a busy and successful year that saw a 17-percent increase in the total acreage bonded; a 34-percent increase in the number of field inspections; major changes in the law, including much stricter requirements for coal and metal mines; and the initiation of an awards program to recognize outstanding reclamation.

March 1982

AN ESTIMATE OF THE GEOTHERMAL POTENTIAL OF NEWBERRY VOLCANO, OREGON

Newberry Volcano is a large Quaternary volcano located in central Oregon about 32 km (20 mi) southeast of Bend (Figure 1). It covers an area of nearly 1,300 km (500 mi) . . . More than 400 cinder cones dot the flanks of the volcano. The most recent activity occurred approximately 1,400 years ago in the summit caldera and resulted in the formation of the Big Obsidian Flow. The volcano is considered dormant but capable of future eruptions (MacLeod and others, 1981).

. . . Fluids at a temperature of 265°C (509°F) were encountered in permeable rocks in the bottom 1.8 m (6 ft) of the hole (Sammel, 1981).

April 1982

THE SALEM METEORITE

The fifth meteorite to be found in Oregon fell on a house in Salem on May 13, 1981. . . The meteorite struck the house of Marion County Deputy Sheriff James P. Price, who was sitting on the curb in front of his home talking to Deputy Sheriff Vincent Wan, who was in his patrol car. Both officers heard a peculiar fast “fluttering” noise, an impact of something hitting the house, and then the sound of small rocks failing near them. Price examined the area by flashlight and within ten minutes found the first and largest piece of the meteorite in front of his driveway. This specimen, which was warm to the touch, had landed within 10 ft of the officers. Because of his training as a physics major at Linfield College, Price recognized the broken specimen as a meteorite.

June 1983

One of North Santiam Sand and Gravel Company’s three trout-rearing ponds situated in mined-out sand and gravel pits near Stayton, Oregon. This company was one of the two runners-up for this year’s award for the Outstanding Mined Land Reclamation Project. December 1982

STABILIZATION OF THE I–84 SAND DUNE

Wind-blown sand originating from a 50-acre sand dune is encroaching upon the travel lanes of Interstate 84 east of The Dalles, Oregon. This sand has been creating a safety hazard to vehicles on I–84 and trains on the adjacent Union Pacific tracks. Annual costs to both agencies have increased significantly in recent years and will continue to increase as the dune moves at a rate of about 250 ft every 10 years . . . At its current rate, and on level ground, this dune could move across the highway in about 130 years.

December 1983

GEOLOGY OF THE PORTLAND WELL FIELD

The Portland Well Field is one of the nation’s largest groundwater development programs. It is designed to provide emergency water in case something happens to the Bull Run watershed, the current major source of water, and to meet peak demand for water during periods of heavy usage. Water-right applications have been filed for over forty production wells with a combined yield of over 150 million gallons per day. Twenty production wells have been constructed with capacities ranging from 1,000 to 10,000 gpm (gallons per minute), producing from fluvial-lacustrine aquifers 100 to 600 ft below ground level.

June 1984

THE 1984 LANDSLIDE AND EARTHQUAKE ACTIVITY ON THE BAKER-HOMESTEAD HIGHWAY NEAR HALFWAY, OREGON

The recent landslide on the north side of the Powder River between the Hole-in-the-Wall and Maiden Gulches closed Oregon Highway 86 at a point 31 mi east of Baker, Oregon . . . What caused the landslide? . . . Could it have been prevented, or, failing this, foreseen earlier so that preparations for more adequate detours could have been undertaken ahead of time? Two moderate earthquakes occurred in the general area at about the time the slide began to move. Were the earthquakes the cause of the Hole-in-the-Wall landslide, or was there another cause? . . . To answer these questions, we undertook an investigation to determine the likely causes of this landslide. Our preliminary determinations indicate that three factors were

An older home succumbs to wave erosion along the Waldport Bayfront. The event occurred during a moederate high tide, but without strong wave activity. May 1987

primarily responsible: Incompetent geological formations, the low angle of stability of these formations, and increased groundwater flow due to recent heavy rains.

May 1985

SCIENTISTS REPORT ON FIVE YEARS OF MOUNT ST. HELENS STUDIES

Eruption predictions: Since May 1980, the USGS has predicted most significant episodes of volcanic activity at Mount St. Helens several hours to three weeks in advance, using a variety of seismic, ground-deformation, and geochemical techniques. These episodes have consisted chiefly of domebuilding extrusions of viscous lava but also included moderate explosive eruptions in 1980. Of the 17 eruptive episodes since May 1980, two occurred with only slight precursory activity and because of that were not predicted . . .

Other Cascade studies: Other volcanoes in the Pacific Northwest's Cascade Range are being studied by scientists in the USGS Volcano Hazards Program. They are monitoring Mount Baker and Mount Rainier in Washington, Mount Hood and Crater Lake in Oregon, and Mount Shasta and Lassen Peak in California to detect any renewal of volcanic activity. USGS geologists also are studying the eruptive histories and potential hazards from future eruptive activity at these volcanoes as well as at Mount Adams and Glacier Peak in Washington and Mount Jefferson, the Three Sisters, and Newberry volcano in Oregon.

September 1985

WALLS WORTH WALKING BY: A TOUR OF THE SOUTH PARK BLOCKS AREA OF DOWNTOWN PORTLAND

Immediately south of the downtown business district of Portland is a group of buildings that demonstrate the use of various industrial minerals and rocks to form exterior facings. Several of the structures are included in the National Register of Historic Places, but others range in age and importance from fairly new and uninteresting to somewhat older and more interesting . . . It is hoped that the present article will enable others to enjoy this hour-and-a-half-long stroll at their own pace and at a time best suited to them. The tour described here starts at Ira's Fountain and works its way west up Market Street to the South Park Blocks, thence back and forth a bit, emerging at last on Fifth Avenue at the County Courthouse and heading southward with a few digressions to the [former] State Office Building.

November 1985

Eagle-Picher Minerals diatomite mine near Juntura [Malheur County]. Diatomite ore is trucked to the mill near Vale and processed into filter-aid products. This was a field trip stop during the 25th Forum on the Geology of Industrial Minerals held in Portland in May 1989. November 1989

EAGLE-PICHER DIATOMITE MINE AND PROCESSING PLANT, EASTERN OREGON

Eagle-Picher Industries, Inc., has commenced production of diatomaceous-earth filter aids at a processing plant located 7 mi west of Vale, Oregon. Crude ore is hauled to the plant from mine sites located northwest of Juntura in Harney and Malheur Counties.

The capital investment for the project was $13.5 million, with the major part of financing provided by Industrial Development Revenue Bonds.

September 1986

OREGON BOASTS FIRST GAS STORAGE SITE AT MIST FIELD

Energy demands on Northwest Natural Gas Company next winter will be met, at least in part, with natural gas from the company's new Columbia County storage field at Mist, the first gas storage site in Oregon.

When it is filled, the storage field will hold 7.5 Bcf of gas, sufficient peaking supplies for "the coldest 60-100 days of winter."

. . . a crew of experienced archeologists "walked every mile" of the route finally used, before trenching of the line was even begun.

This careful attention was rewarded when in the path of the pipeline were found 20 prehistoric Indian sites and seven historic sites, where discoveries have included small Stone Age tools such as mortars, pestles, chopping implements, and small flakes. Such finds indicate, according to the experts, that these sites had been used periodically over the last 6,000–8,000 years.

September 1989

1990s: Understanding geologic hazards

PRELIMINARY ASSESSMENT OF POTENTIAL STRONG EARTHQUAKE GROUND SHAKING IN THE PORTLAND, OREGON, METROPOLITAN AREA

. . . Thus given the extensive unconsolidated sediments in the Willamette Valley and the possible future occurrence of earthquakes of M 6 and larger, strong earthquake ground shaking would appear to pose a potential serious threat to many existing buildings and possibly even to newly constructed buildings in the Portland metropolitan area.

November 1990

MAGNITUDE AND FREQUENCY OF SUBDUCTION-ZONE EARTHQUAKES ALONG THE NORTHERN OREGON COAST IN THE PAST 3,000 YEARS

. . . From these findings of synchroneity, we estimated the length of rupture for the late Holocene earthquakes. The corresponding magnitudes are at least 8.0, based on a rupture length of 175 km, a rupture width of at least 60 km, an average recurrence interval of 400 years, [and] an average convergence rate of 4 cm/yr . . . Using a range of convergence rates (3.5–4.5 cm/yr) and average recurrence intervals (300–500 years), rupture lengths (105–175 km), and rupture widths (60–90 km), calculated magnitudes for five of the last six earthquakes are greater than 8.0 for the central 175 km of the Cascadia subduction zone.

Average recurrence intervals between earthquakes for the estuaries on the northern Oregon coast range between 200 and 600 years . . .

January 1995

CRESCENT CITY'S DESTRUCTIVE HORROR OF 1964

The view of the tidal wave from the lighthouse as described by Peggy Coons, curator of Battery Point Lighthouse in 1964.

Good Friday, March 27th, 1964, the morning was mild. The trade winds that prevail along the Pacific Coast had subsided. Little did I realize, as my husband Roxey and I went about our chores at the lighthouse, that before the next day had dawned high on Battery Island, we would watch four waves play havoc with the town and its people, smashing the city's business center along with some of the beach front homes in Crescent City, CA, and we would have a spectacular view of the whole performance. And as curators here at the lighthouse we would be called on by friends and tourists alike to relive this one night of horror almost every day since.

Perhaps I should stop to explain that Battery Island, three hundred yards from the mainland, is solid rock at the base and about three quarters of an acre, fifty-eight feet at the highest point near the flagpole. The lighthouse, completed in 1856, is 74 feet above mean sea level. The only access to this Historical Monument is walking across the ocean floor at low tide.

. . . We might have slept through the whole thing if I hadn't gotten up to go to the bathroom a little before midnight. I stood at the window, a full moon shining on the water below me. Somehow the first moment I saw the ocean I sensed something was wrong, for all the rocks around the island had disappeared. They were covered with water. I realized it was almost time for high tide, but the rocks are always visible even in the severest of storms. Suddenly I became alarmed and called Roxey. We quickly slipped on some clothes, rushed down the stairs, and grabbed our jackets as we ran outside.

The air was still, the sky had an unusual brightness about it. It was light as day. The water shimmering in the moonlight was high over the outer breakwater. We headed for the highest point overlooking the town. The first wave was just reaching the town. Giant logs, trees and other debris were pitching and churning high on the crest of the water as it raced into the city. "My God, no!" I cried, "It will flood the town."

As the impact began, the loud blast of breaking glass and splintering wood reached us, buildings crumpled, cars overturned, some smashed through plate glass windows, while the water plowed down the streets. Within minutes the water came back just as fast as it had gone

Bretz Pond Turtles in the Columbia River Gorge differ visually from Western Pond Turtles in color and construction of their shells. As the importance of wetlands is better understood, geologists can play an important role in understanding wetland processes important to save endangered species. January 1994

in, bringing all manner of things with it. It drained away with terrific speed. The whole beach front was strewn with logs, cars, buildings, trash of every description. Some of the fishing boats were tossed high on the land, others drifted to sea. A few cars and two small buildings that were swept off Citizen's Dock floated away with the water. The water was gone. We could see it piling up a half mile or more beyond the end of the outer breakwater, higher and higher as the minutes passed.

We stood there stunned with fright for we knew there was no way out of here if the water came this high. The lighthouse, serene in the moonlight, had been battered with severe storms for over a century: could it protect us now? We have lived on the island since 1962 and watched the storms come and go, but this was unlike anything we had ever experienced. The light flashed in the tower. We knew we would have to notify the Coast Guard if there was any failure or discrepancy in it. I don't know how long we stood there for we were just too frightened to move, when the second wave churned swiftly by us, gobbling everything in its wake. It picked up all the ruins along the beach front and shoved them right back into town. It didn't seem as large as the first one to us, but it caused considerable damage. Some of the lights faded out along Front Street. As the backflow began we raced frantically around the place, watching the water drain from the bay. We glanced at the tower: the light was still flashing.

We watched the Coast Guard cutter, a big lumber tug, and some of the fishing boats that had received warning and left the harbor riding the tides a good three miles or more off shore. We were getting more frightened now, for the water had receded farther out than before. We knew it had to come back, but when? We screamed at one another in our fright, wondering if it would ever stop, for there was an ominous stillness about it, warning us of more to come.

. . . The water withdrew suddenly, as though someone had pulled the plug out of the basin. The water was here, then gone. We ran around the lighthouse again wondering if we were safe. We kept anticipating something more violent would happen, for the water had receded far out, three fourths of a mile or more beyond the end of the outer breakwater. We were looking down as though from a high mountain into a black abyss of rock, reefs, and shoals, never exposed even at the lowest of tides. A vast labyrinth of caves, basins and pits undreamed of in the wildest of fantasy.

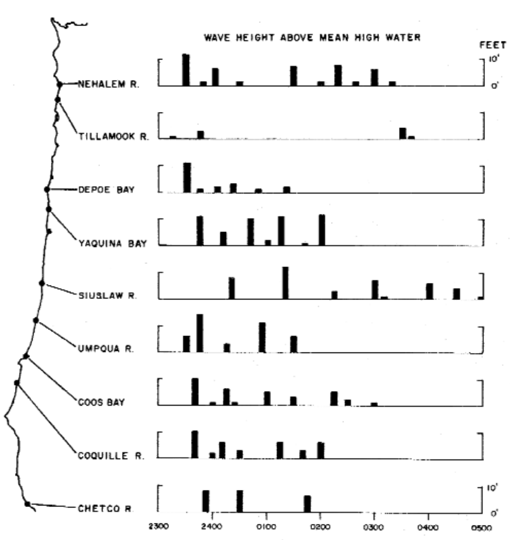
In the distance a dark wall of water was building up rapidly, so the Coast Guard cutter, the lumber tug, and small craft appeared to be riding high above it, with a constant flashing of white at the edge, as the water kept boiling and seething, caught in the rays of the moonlight. The basin was dry. At Citizen's Dock the large lumber barge, loaded with millions of board feet of lumber, was sucked down in the bay. The fishing boats still in the small craft harbor, were pulled down on the floor of the ocean. We clung to one another, asking God to have mercy on us. We prayed for the town and its people. We realized the water would return with more destruction to follow. We kept straining ourselves trying to visualize what would happen next, while the water piled higher and higher in the distance.

Suddenly there it was, a mammoth wall of water barreling in toward us, a terrifying mass of destruction, stretching from the floor of the ocean upwards: it looked much higher than the island, black in the moonlight.

. . . When the tsunami assaulted the town it was like a violent explosion, a thunderous roar mingled with all the confusion. Everywhere we looked, buildings, boats, lumber, everything was shifting around like crazy. The whole front of town moved, changing before our eyes. By this time the fire had raced across the water to the ruptured Texaco Bulk tanks: they started exploding one after the other. The whole sky lit up. It was fantastic.

As the tide turned it was sucking everything back with it: cars, buildings were moving seawards. The old covered bridge, from Sause Fish Dock, that had floated high on the land, came back to drop almost in place. Furniture, beds, mattresses, TVs, radios, clothing, bedding, and other objects were moving by us so fast we could barely discern what some of it was. A siren was blowing. There were lights now in the front of town or along Highway 101. The light in the tower continued to burn. The block on this end of town near the Seaside Peninsula was unharmed.

Across the bay the fire was still raging higher and higher as each tank exploded. Time passed quickly, for everywhere we looked was a



The above chart shows wave heights of 1964 tsunami at various Oregon sites. Four people died at Beverly Beach in the tsunami, and waves damaged property in several locations along the coast. December 1964

Two people died in the 1993 earthquakes in Klamath Falls. This bridge on Hwy 140 shows left lateral displacement across joints in the bridge deck, probably as a result of slumping and settling that caused the bridge deck to rotate.

November 1993

shambles: houses, buildings, lumber, boats, all smashed or moved blocks from where they had been by the onrush of water.

The fifth wave rushed swiftly by us back into town. It just pushed things around. We could observe no noticeable damage this time, but off and on the rest of the night the water kept surging in and out and slopping around in the harbor. At daybreak we made coffee and fixed our breakfast, but we kept checking each change of the tide. We had never seen so many in our knowledge of the sea. The boats continued to ride the surf offshore, waiting for another big one . . .

November 1995

EVALUATING THE EFFECTIVENESS OF DOGAMI'S MINED LAND RECLAMATION PROGRAM

Since 1972, the Mined Land Reclamation (MLR) Program of the Oregon Department of Geology and Mineral Industries (DOGAMI) has been responsible for directing reclamation at mine sites across Oregon. In that time, over 3,000 acres have been reclaimed under DOGAMI's MLR program. What happens to former mine sites after they have met reclamation requirements and have been released from the program? Has reclamation had long-term impact on the overall condition of the sites? What second uses are being supported by these lands? To begin addressing these questions, the MLR Program conducted a field study in 1995 to determine the condition of former mine sites. Field data were collected at 47 former mine sites across Oregon. The landform, vegetation, land use, and other primary site characteristics indicate that the reclamation process has had lasting, beneficial effects on site conditions. This strongly suggests that the MLR program has been effective over an extended period.

January 1996

SAND AND GRAVEL MINE OPERATORS DONATED SAND, EQUIPMENT, AND TIME TO FIGHT FEBRUARY FLOODS

Many Oregonians may not have thought about it at the time, but when they fought the February floods with sandbags, they were using a lot of donated sand. The Oregon Department of Geology and Mineral Industries (DOGAMI) has compiled a list of aggregate operators who provided voluntary assistance during the floods. Thousands of cubic yards of sand were provided at no cost to communities, organizations, and those individuals in need of sandbags. Heavy equipment and operators were donated to deliver materials, construct emergency berms, and in at least one instance rescue a stranded motorist. During the height of the flood, many operators staffed their plants and sales offices around the clock to coordinate delivery of materials. **July 1996**

The floods and landslides of 1996-97 caused several deaths and millions of dollars worth of damage across western and northeastern Oregon. Although flooding was more visible in the news media, more dollar losses were attributable to landslides. **December, 1999**

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Places to see—Recommended by the Oregon Department of Geology and Mineral Industries:

Lake Owyhee, Malheur County (photo courtesy Oregon Department of Transportation)

Lake Owyhee, created by a dam on the Owyhee River, offers boaters an extraordinary view of Miocene volcanism (about 15 million years ago). Ash from that time preserved plant and animal fossils that show a much wetter climate. Rhinoceroses lived next to ancestral horses, deer and antelope. The off-white ash layers, pinkish-gray rhyolite, and dark colored basalt create a colorful palette. The Owyhee Uplands have been uplifted to more than 4,000 feet above sea level, and the resulting stream erosion has produced the deep, narrow, winding canyons seen in the area today. The Owyhee volcanic field includes several calderas, such as at Grassy Mountain and Mahogany Mountain, that are large collapse features better recognized by the distribution of specific types of volcanic rocks rather than by present day topography. These same volcanic processes have been responsible for numerous gold occurrences which have been prospecting targets over the last few years. Typically, the gold occurs as microscopic particles that have been deposited by hot-spring systems. Portland State University graduate students often learn geologic mapping in this area (several theses have been written and abstracts published in *Oregon Geology*).

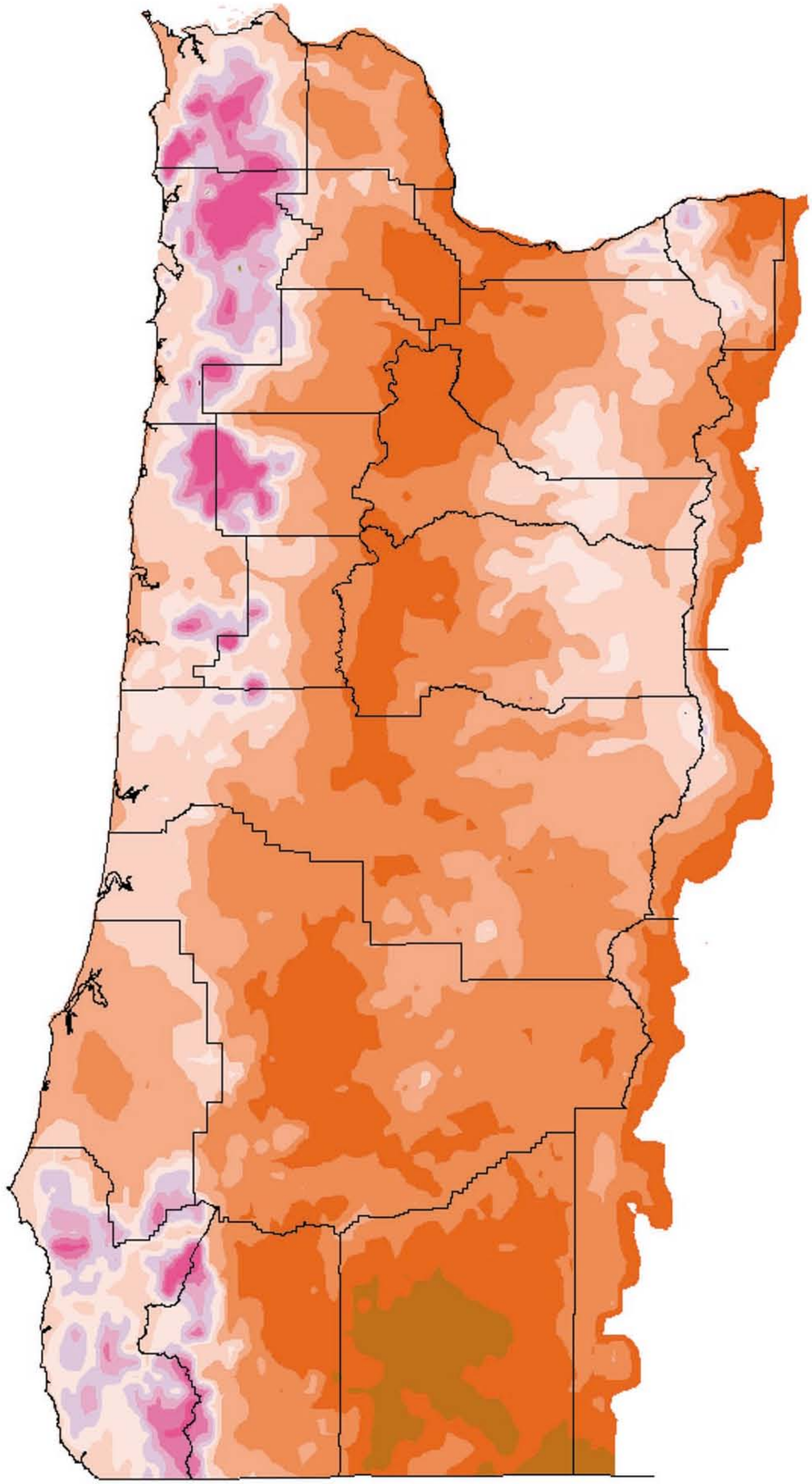
Access: From Interstate I–84 at Ontario south on State Highway 201 toward Adrian. Several roads branch off toward the west to Lake Owyhee State Park, which offers camping sites. Boat rentals are available in the area.

OREGON GEOLOGY

Oregon Department of Geology and Mineral Industries

Volume 62, Number 2, March/April 2000

IN THIS ISSUE:
Relationship between rainfall and debris flows in western Oregon



Contour map: 24-hour rainfall intensity that is likely to initiate fast-moving landslides

THROUGH THE EYES OF THE STATE GEOLOGIST

John D. Beaulieu
Oregon State Geologist

The Oregon Department of Geology and Mineral Industries has been releasing valuable geologic information to the public through a periodical since November 1939. First titled *The Ore.-Bin,* the publication was first produced by hand, using "state-of-the-art" mimeograph equipment in the historic Woodlark Building. This building still stands on SW Oak Street in historic downtown Portland.

Over the years, the manners of production have changed; the format has changed; and the title has changed; (to *Oregon Geology*, beginning in 1979). Through all of this, the purpose remained the same: timely release of interesting information on the geology of Oregon.

Concurrently, this agency has seen the expansion and deepening of the needs for geologic information in a broadening array of problems in the state of Oregon. Included are watersheds, public safety, and environmental protection. To meet this new array of concerns among growing audiences and to begin to address their needs we must enhance that part of our public education efforts that until now has been served under the historic *Ore.-Bin/Oregon Geology* strategy.

Confronted with the choice of maintaining our current periodical with its focus on timely release of topical geologic data or of expanding our communications in a more general way to meet emerging additional audiences we have fashioned a creative solution: — We will do both.

Oregon Geology will become a scientific journal, dedicated to topics of interest about Oregon that are important enough to be part of the researchable literature but perhaps too focused to be published in a magazine with a wider scope. This is an important part of our mission as a science agency, and we are hoping to build a strong forum that scientists and engineers will want to use to convey information about their latest findings and hypotheses. It will become a quarterly publication, and we are expecting the next issue to be published in July.

But there is also a need to present good science to nonscientists, in a way that is accessible, understandable, and usable. This will be the purpose of *Cascadia*. Topics being discussed for future issues include how to deal with a variety of hazards (earthquakes, landslides, volcanoes, etc.) and the geologic history of different areas of the state (how that relates to available resources and land use today). It will also be a quarterly publication, and we are planning an August debut for the magazine.

As a current subscriber you will receive both publications for the duration of your subscription.

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Cover illustration

This contour map shows the levels of rainfall intensities beyond which landslides and debris flows are likely to be triggered in western Oregon. It is the result of a newly refined method of determining such threshold values, which is proposed in the article beginning on the next page.

Relationship between rainfall and debris flows in western Oregon

by Thomas J. Wiley, Oregon Department of Geology and Mineral Industries, Grants Pass field office

ABSTRACT

Records from four storms that hit western Oregon during 1996 and 1997 confirm that the occurrence of many landslides and debris flows can be related to rainfall intensity and duration. Three roughly equivalent methods of measuring rainfall intensity are discussed, including rainfall as a percentage of mean December rainfall, rainfall as a percentage of mean annual precipitation, and rainfall as a multiple of rainy-day normal. Comparisons of landslide locations and rainfall records suggest that absolute thresholds vary widely from place to place but that there is a linear relationship between typical rainfall intensity and rainfall of sufficient intensity to cause sliding. For western Oregon, preliminary threshold values of rainfall intensity/duration combinations that will trigger debris flows are (1) 24-hour rainfall equal to 40 percent of mean December rainfall (alternatively 6.67 percent of mean annual precipitation or 14 rainy-day normals); (2) 12-hour rainfall equal to 25 percent of mean December rainfall (alternatively 4 percent of mean annual precipitation or 8.75 rainy-day normals); or 36-hour rainfall equal to 15 percent of mean December rainfall (alternatively 2.5 percent of mean annual precipitation or 5.25 rainy-day normals).

Rainfall exceeding the listed intensities is likely to trigger landslides and debris flows. Threshold values of rainfall intensity for 24-hour periods are listed for weather stations located west of the crest of the Cascade Range. A map of threshold rainfall rates for 24 hours has been derived from weather records and the State Climatologist's *Map of Mean December Precipitation for Oregon*. Listed thresholds are significant only after approximately 8 in. of autumn rainfall has been recorded. The relationships described here could be used to refine the debris-flow warning system used in western Oregon.

INTRODUCTION

Following is a look at rainfall amounts recorded during four recent western Oregon storms. The data reveal several relationships between rainfall intensity, storm duration, and the occurrence of rapidly moving landslides. The events examined include (1) the February 6–8, 1996, storm that affected northwestern Oregon; (2) the November 18–19, 1996, storm that caused damage in Coos, Douglas, and Lane Counties; (3) the December 8, 1996, storm that hit Josephine and Douglas Counties; and (4) the New Year's Day, 1997, storm that affected Jackson and Josephine Counties. Events (1), (2), and (4) were each accompanied by significant landslide activity and flooding, resulting in disaster declarations by the Governor and responses by the Federal Emergency Management Agency (FEMA). Event (3) was not reported widely, did not trigger a disaster declaration or FEMA involvement, and was not originally included in this study. It was added because rainfall records indicated that debris-flow thresholds had been exceeded. Rainfall records used for this study are from stations reported by the National Weather Service (Figure 1) on the National Climatic Data Center home page and from two monthly publications of the National Oceanic and Atmospheric Administration (NOAA): "Climatological Data, Oregon" and "Hourly Precipitation Data, Oregon." The types of landslides herein termed "debris flows" are not limited to true debris flows but rather comprise all types of fast-moving landslides that occurred during these events. This work is an attempt to refine U.S. Geological Survey work on landslide threshold estimates for selected sites in Oregon (Wilson, 1997) and extend it to cover the state west of the crest of the Cascade Range.

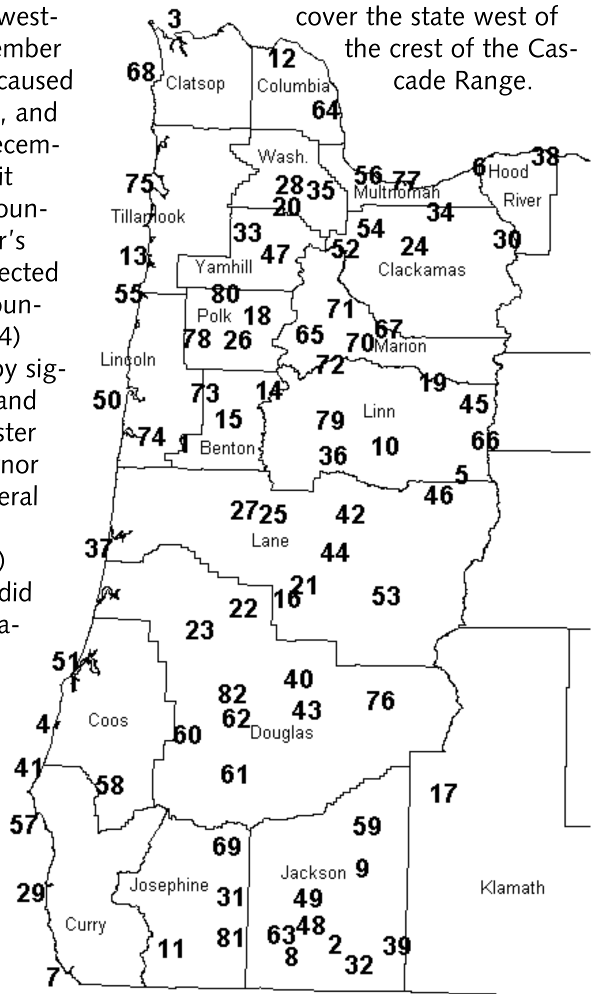

Figure 1. Location of current and historic National Weather Service stations. Stations are identified by numbers and listed in Table 1.

QUANTIFYING TYPICAL RAINFALL

Other factors being equal, slopes are more likely to fail when rainfall occurs in abnormal combinations of intensity and duration. To calculate the boundary between "normal" and "abnormal," an appropriate means of measuring typical rainfall needs to be determined. Three commonly used rainfall measures use mean December rainfall, mean annual precipitation, and rainy-day normal.

The first measure is based on **mean December rainfall.** Throughout western Oregon, December is the rainiest month of the year.[1] Typical December rainfall rates represent annual flow maxima during which almost all slopes are stable. Mean December rainfall has been calculated for most gauges with December data. In addition, the State Climatologist has prepared a map of mean December rainfall that shows values interpolated between gauges (Oregon Climate Service Website, 1999).

A second measure of typical rainfall intensity is based on **mean annual precipitation** (MAP). Representing the average amount of rain that a site receives in a year, MAP is roughly proportional to both the other measures and is available for virtually every station where records have been kept. A MAP map is available from the State Climatologist (Oregon Climate Service Website, 1999).

The third measure is based on **rainy-day normal**. Described most simply, one rainy-day normal equals the amount of rain a site receives in a year, divided by the number of days on which measurable rainfall occurs (Wilson, 1997). So, rainy-day normal gives a measure of the water falling on slopes on a typical rainy day. (Note that the National Weather Service defines the term "rainy-day normal" differently.)

For a given latitude in western Oregon, the mathematical relationship between mean December rainfall and rainy-day normal is more or less linear, with mean December rainfall equal to about 31 times rainy-day normal. (For rain gauges along the coast, the ratio varies from 25 at Brookings to 36 at Astoria.) This proportionality allows for rough conversion between rainy-day normal and mean December rainfall at most sites. Gauges that experience disproportionate amounts of measurable fog, drizzle, or showers during the other eleven months of the year will have somewhat larger ratios. Because rainy-day normal emphasizes low-precipitation events to a greater degree than mean December rainfall, it seems reasonable to expect a better mathematical fit between mean December rainfall and debris-flow thresholds. In contrast to MAP and mean December rainfall, a measure based on rainy-day normal reflects latitudinal variations in storm frequency. Using mean December rainfall is generally more convenient than using rainy-day normal, because the former is available for more sites, published for more sites, or has been recorded for longer periods than have data suitable for calculating the latter.

Throughout western Oregon, mean December rainfall is typically 15–17 percent of mean annual precipitation. The percentage varies systematically, decreasing eastward across the state. Mean annual precipitation, like rainy-day normal, is affected by tendencies to fog, drizzle, and showers in months other than December. In western Oregon, the errors associated with assuming a constant ratio between mean December rainfall and mean annual precipitation average 2.75 percent and range up to 20 percent. The errors associated with assuming a constant ratio change dramatically east of the Cascade Range, where mean December rainfall may be less than 10 percent of mean annual precipitation. December rainfall is not representative of peak rainfall across much of eastern Oregon, and additional investigations should be undertaken before assigning debris-flow thresholds to areas east of the Cascades.

The considerations described above suggest that, for western Oregon, mean December rainfall may currently be the best standard for measuring debris-flow initiation thresholds. Mean December rainfall is calibrated to generally high rainfall rates for which virtually all slopes remain stable, yet is roughly proportional to rainy-day normal and mean annual precipitation. It is not influenced by local tendencies to low-precipitation events such as fog, drizzle, summer rains, and thunderstorms that occur during the other eleven months of the year.

FOUR WESTERN OREGON STORMS

Following are brief histories of the four storms from which data were compiled. These vignettes outline the unique aspects of each. For example, during one storm the combination of melting snow and ice with rising temperatures and rainfall of long duration was critical. Two of the autumn storms seem to have occurred before soils were saturated. None of the storms simply brings rain with constant intensity for 6, 12, or 24 hours and then stops. With this variability in mind, the usefulness of a set of debris-flow thresholds can be increased, if it is calculated in a way that anticipates variability over broad areas and compensates for regional trends. Factors

[1] Only two of the western Oregon stations reporting normal December rainfall in Climatological Data, Oregon (NOAA, 1996a) receive more rain in a normal November or January than they do in a normal December (NOAA, 1997a, b, 1996c). Lookout Point Dam receives an average of 6.93 in. in November and 6.70 in. in December. Idleyld Park NE receives an average of 10.78 in. in November and 10.47 in. in December. In contrast, the National Climatic Data Center Web Site (2000) reports 22 stations (out of 132) that receive more rainfall during a normal November or January than December. At three of those stations the difference exceeded 6 percent (Parkdale II NE, 24 percent; Canary, 10 percent; and Gardiner, 10 percent). The remaining 19 varied by an average of 2.6 percent.

such as storm path, internal variations in intensity, and geologic complexity cannot presently be determined accurately enough to achieve great precision. However, it is possible to define a general statement of conditions that will regularly trigger some sliding within broad areas where thresholds have been exceeded. Such thresholds can be designed and refined by correlating regional historic rainfall duration and intensity to reported damage from fast-moving landslides.

Storm of February 6, 7, and 8, 1996, affecting northwestern Oregon (Figure 2)

Prior to February 6, 1996, northwestern Oregon experienced normal winter weather, including rainfall that was more than adequate to compensate for summer drying. During the week immediately prior to the storm, low temperatures allowed snow and freezing rain to accumulate locally throughout the Portland area and eastward along the Columbia River. Daytime high temperatures rose above freezing on February 5. Even so, the soil remained frozen in many places, causing a light to moderate rainfall to freeze when it hit the ground. Temperatures rose dramatically as overnight lows went from the teens to the forties (degrees Fahrenheit) on February 6. The increase in temperature was accompanied by an increase in rainfall intensity (NOAA, 1996f,g). Maximum daily rainfall amounts reported in the data set used for this study ranged from 2.16 in. in Portland to 7.05 in. at Laurel Mountain. The greatest amount of rain fell in the Coast Range between Clatskanie and Laurel Mountain; amounts decreased southward to Eugene. Near Portland and eastward along the Columbia River Gorge, the combination of heavy rainfall with melting snow and ice triggered numerous landslides and debris flows. "Avalanches" of accumulated frozen rain pellets accompanied landslides in the Gorge area. The long duration of this storm and the relatively spotty distribution of areas that exceeded 24-hour rainfall thresholds suggest that, in calculating rainfall intensity, thresholds for 48- or 72-hour periods may be useful. These data also suggest that rainfall thresholds need to be modified to account for melting snow and ice. The affects of frozen ground on soil drainage and saturation, which in turn influence the potential for sliding, should also be investigated.

Storm of November 18 and 19, 1996, centered on Coos, Douglas, and Lane Counties (Figure 3)

One of the biggest single-day storms in the last 100 years slammed into the south coast on November 18, 1996, and over the next 24 hours worked its way north and east. Several fatalities resulted directly or indirectly from debris flows during this period. Even though the storm occurred early in the season, significant antecedent rainfall had al-

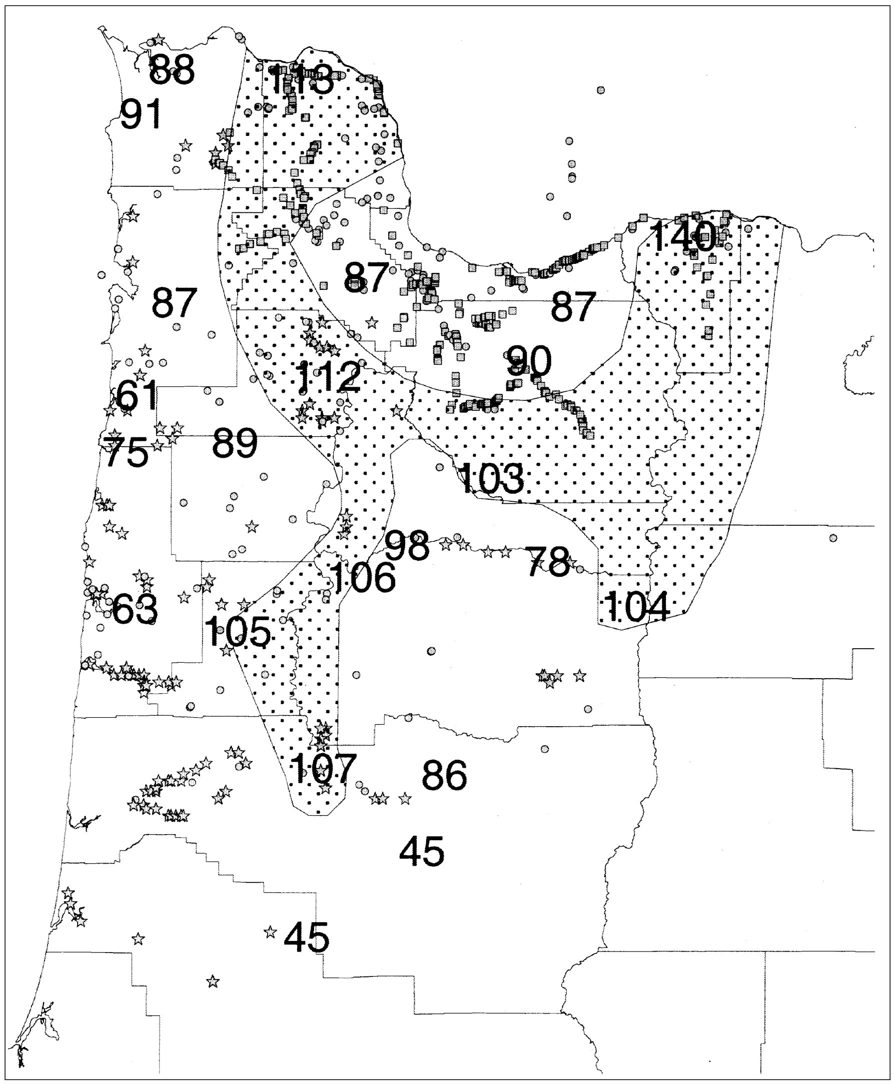

Figure 2. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the February 6–8, 1996, storm in northwest Oregon. Patterned area indicates the approximate zone in which the 24-hour threshold was exceeded. The occurrence of many landslides outside this patterned area probably reflects a de facto increase in intensity caused by melting snow and ice as well as the storm's long duration at somewhat lower intensity. Stars= landslide sites investigated by FEMA, squares = landslides reported by ODOT, Circles = additional slides reported along highways.

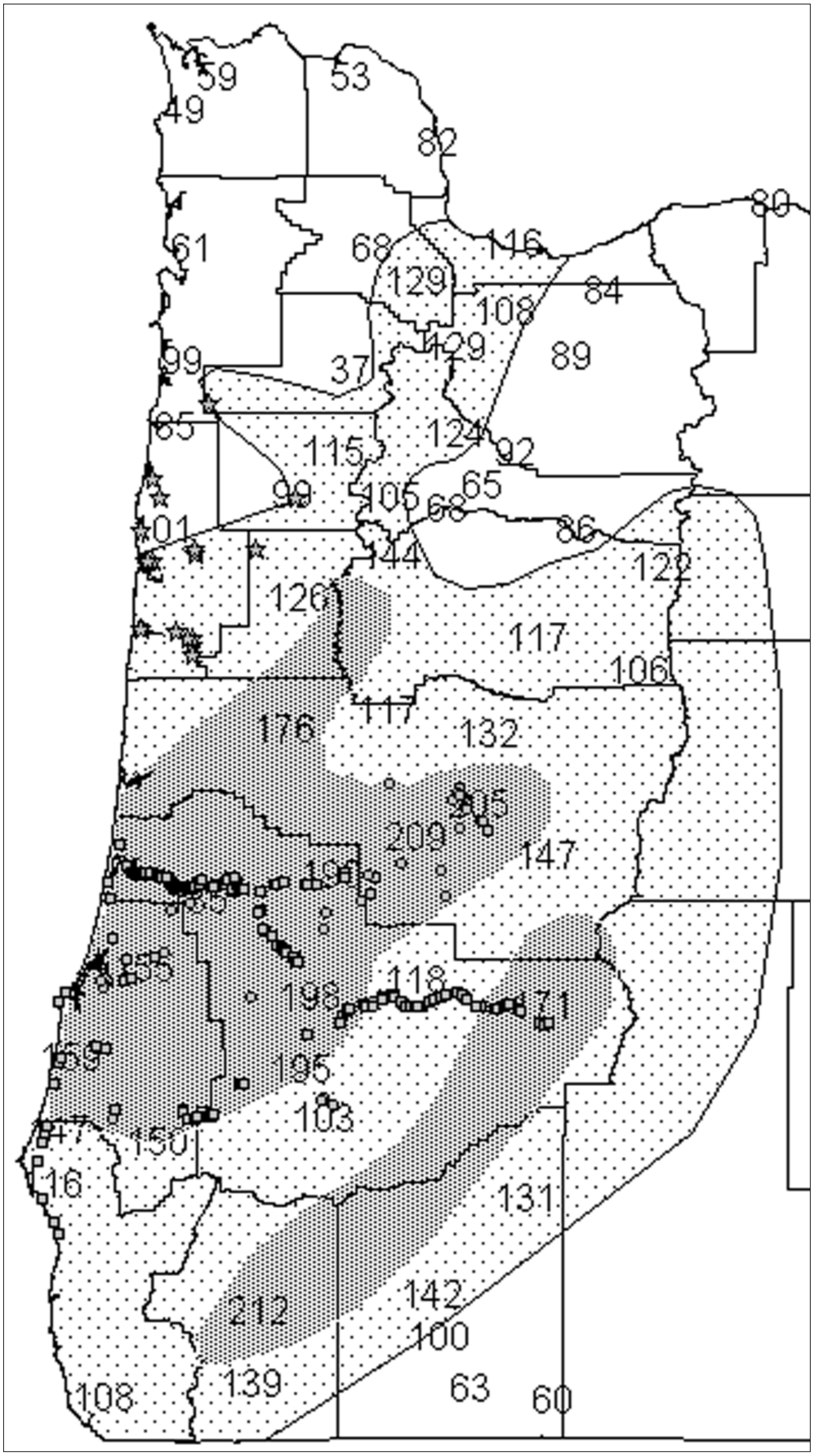

Figure 3. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the November 18–19, 1996, storm centered on the Coos-Douglas-Lane County area. Patterned areas indicate the approximate zones in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Note that 24-hour rainfall at many Portland area stations exceeded that reported during the February storm (Figure 2). Landslide symbols as in Figure 2.

ready accumulated in many areas. In what had been relatively dry areas north of Roseburg, soil moisture probably reached typical winter levels during the storm. Antecedent rainfall records for October and early November ranged from just 2.3 in. at Silver Creek Falls to 17.5 in. at Leaburg in the Western Cascades. The brunt of the storm was felt in Coos, Lane, and Douglas Counties; however, significant 24-hour rainfall occurred from Troutdale (3.28 in.), east of Portland, to Brookings (5.15 in.), at the California border (NOAA, 1996c,d). Many Portland area stations recorded higher 24-hour rainfall totals during this storm than they did during the February event described above. Maximum reported rainfall of 7.33 in. occurred in Langlois, along the coast near the Coos-Curry County line; larger amounts were reported from gauges not used in this study. Landslides and debris flows occurred in areas where more than 8 in. of rain had fallen since October 1 and where rainfall intensity exceeded normal rainfall intensity by large amounts, mainly between Bandon and Cottage Grove. Normal rainfall intensity was exceeded by the greatest margin at Grants Pass, which received 85 percent of its typical December rainfall total in just 24 hours—more than twice the debris-flow threshold proposed in this study. However, the lack of antecedent rainfall in areas north of Salem and southeast of Roseburg, including Grants Pass, corresponds directly to the lack of reported landslide activity in those areas.

Storm of December 8, 1996, in Josephine and Douglas Counties (Figure 4)

On December 8, 1996, heavy rainfall occurred between Brookings (5.56 in.) and Roseburg: (3.53 in.) (NOAA, 1996a,b). Grants Pass and Cave Junction both received more than 4 in. of rain. Significant autumn rainfall, including the November storm described above, had occurred throughout the area prior to December 8. Rainfall was particularly intense in an area underlain by decomposed granitic soils associated with the Grants Pass Pluton. These thick, porous soils seem to require large amounts of antecedent rainfall to reverse the effects of summer drying. The storm had not been widely publicized and did not lead to a disaster declaration; it was "discovered" during a search for rainfall records with intensities exceeding preliminary estimates of debris-flow thresholds. A subsequent search of newspapers covering the affected areas revealed reports of damaging landslides in the Myrtle Creek-Riddle area of Douglas County and in California just south of Josephine County along U.S. Highway 199.

Storm of January 1, 1997, affecting Jackson and Josephine Counties (Figure 5)

On New Year's Eve, 1996, the northern edge of a strong storm moved into the Rogue Valley. By this time, earlier storms had produced enough rain to raise soil moisture to winter levels throughout southwestern Oregon. Reservoirs were typically filled up to or above mandated flood control levels, due to the November and December storms. Intense rainfall occurred from Cave Junction northeast to Prospect and south well into California. Ashland, normally one of the driest spots in western Oregon, received 2.86 in. of rain in 24 hours (NOAA, 1996a,b; 1997a,b).

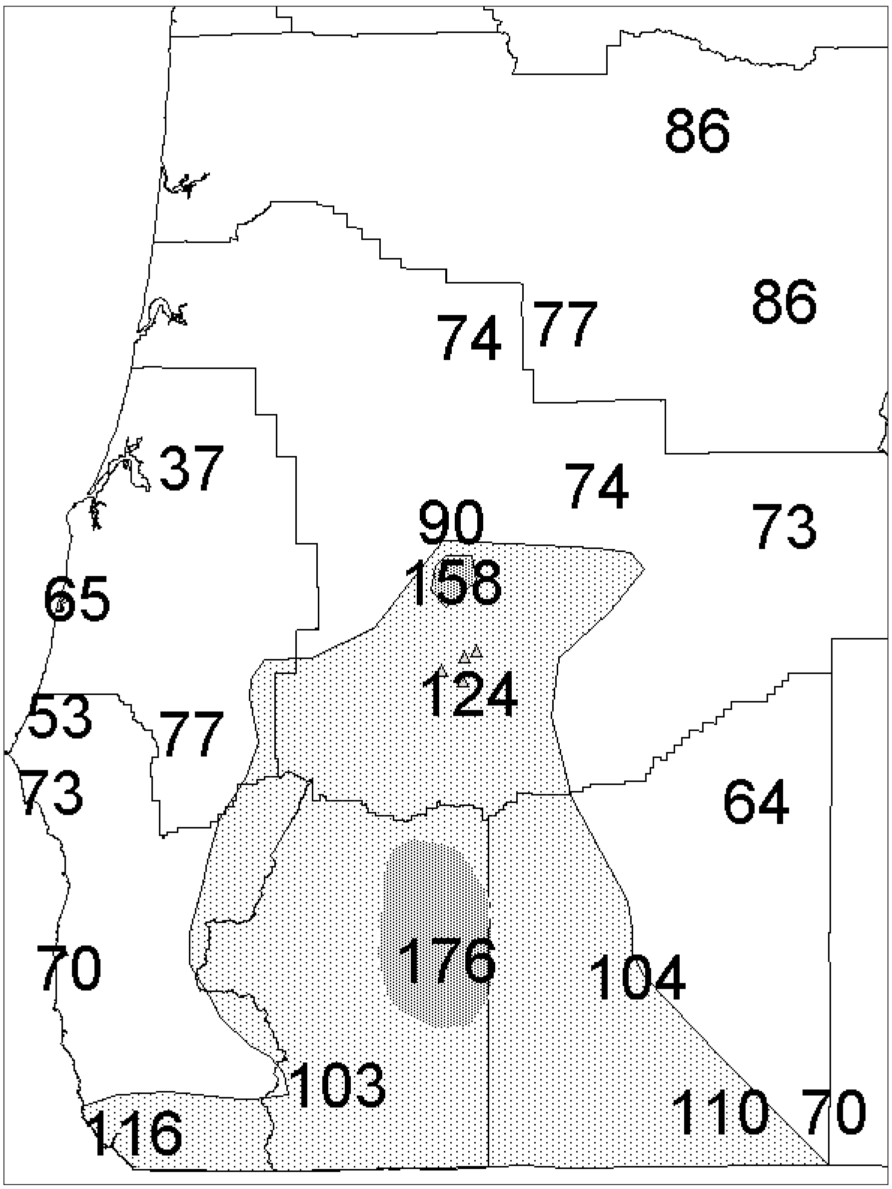

Figure 4. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the December 8, 1996, storm centered on the Josephine-Douglas County area. Patterned areas indicate the approximate zones in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Triangles show locations of slides reported in area newspapers.

CORRELATING THRESHOLD RAINFALL TO THE DISTRIBUTION OF DAMAGING DEBRIS FLOWS

Wilson (1997) examined rainfall records associated with several debris flows in Pacific Coast states. His findings indicate that debris flows may occur when antecedent rainfall requirements have been met and 24-hour rainfall exceeds 14 times the rainy-day normal. This equates to about 40–45 percent of mean December rainfall or about 6.67 percent of mean annual precipitation for sites in western Oregon. The distribution of debris flows and other landslide types during the four western Oregon storms described above confirms that those regions where 24-hour rainfall exceeded 40 percent of mean December rainfall were far more likely to experience damaging slides. A rigorous mathematical best-fit analysis was not undertaken; the 40-percent figure resulted from comparing the locations of landslides mentioned in early media reports to the locations of gauges that exceeded 30, 35, 37.5, 40, 42.5, 45, and 50 percent of mean December rainfall. Accordingly, 40 percent of mean December rainfall was selected as the 24-hour rainfall threshold for gauges in western Oregon. Using this threshold we can expect that at least some gauges in an affected area will indicate that hazardous conditions exist before sliding begins.

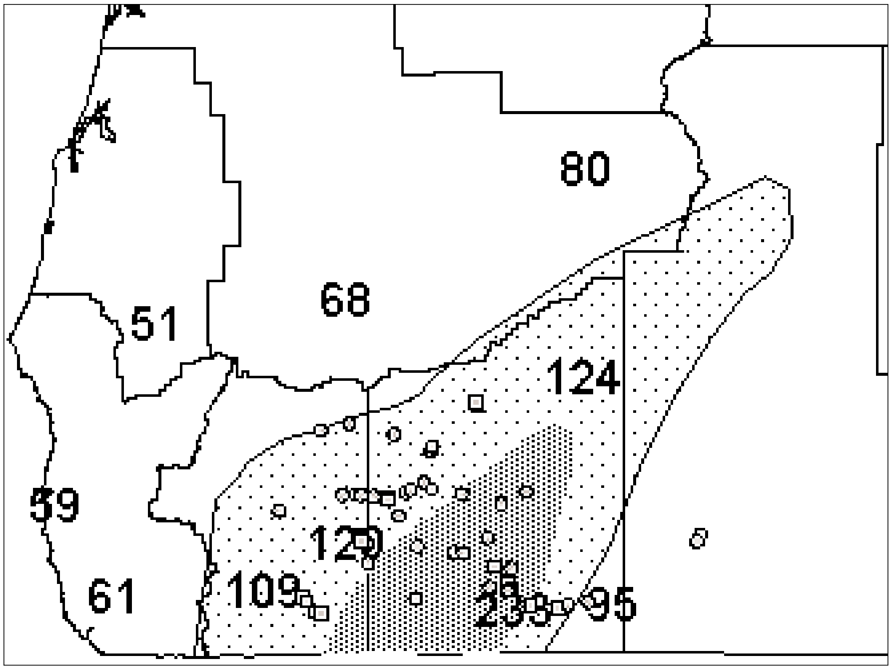

Figure 5. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the January 1, 1997, storm centered on the Jackson-Josephine County area. Patterned areas indicate the approximate zone in which the 24-hour threshold was exceeded, in the darker areas by more than 50 percent. Landslide symbols as in Figure 2.

The percentage may be somewhat low for any specific gauge (where 45 percent may be more accurate). However, the focus is on larger areas—in which one, two, or three gauges probably will not capture rainfall maxima. By the same token, the internal variability of storms insures that if some gauges exceed the 40-percent threshold, then there will be ungauged areas where rainfall is still more intense.

Figures 2–5 show percentages by which some areas met or exceeded their threshold rainfall amounts during each of the four storm events examined here (combined in a patterned area), as well as percentages from selected stations that did not. The areas in which the threshold was exceeded are compared with landslide locations reported by FEMA and ODOT for the February (Figure 2), November (Figure 3), and January (Figure 5) events and with landslide locations reported by local newspapers for the December event (Figure 4). The January storm shows particularly good agreement between areas where 40 percent of mean December rainfall was exceeded and areas where slides occurred.

Because relatively small amounts of data were examined in this study, the thresholds described should be considered preliminary estimates. This is particularly true for drier regions of the state (those with less than 25 in. of annual precipitation), where a relatively large percentage of total rainfall can come from a small number of storms. In those areas, hillsides are probably in equilibrium with greater rainfall intensity than is suggested by the thresholds reported here. Increased thresholds may also be appropriate for these areas, if soils experience any drying between storms. Some important factors have not been considered, e.g., the propensity of high-elevation sites to receive some precipitation as snow rather than rain. Local variations in soil, climate (e.g., north-facing slopes vs. south-facing slopes), and bedrock geology also affect calculation of threshold values but are beyond the scope of this study.

OREGON DEBRIS-FLOW WARNING SYSTEM

Since the four storms occurred, several state agencies have worked together to develop a debris-flow warning system for the northern and central parts of the Coast Range. As originally envisioned, advisories and warnings would be issued whenever any area experiences or is expected to experience any of the following three conditions: 2 in. of rain in 6 hours, 3 in. of rain in 12 hours, or 5 in. of rain in 24 hours.

During the winter of 1998–1999, the system was modified to use those thresholds for coastal gauges at Coos Bay, Reedsport, and Tillamook to issue warnings for Coast Range areas lying downwind along expected storm tracks. For the winter of 1999–2000, the system was again modified to use those thresholds for coastal gauges from Bandon to Seaside and a threshold of 2.5 in. in 24 hours at Ashland. Gauges at Roseburg and Cascade Locks can also be used. However, the system is not designed to issue warnings for most areas east of the Coast Range.

Data from the four storms described above can be used to help evaluate the debris-flow warning system. A closer look at Figures 2–5 reveals several trends:

1. Rainfall at inland stations may exceed thresholds for debris flows before coastal gauges exceed the threshold, or coastal gauges may not exceed the threshold at all. This occurred during the February storm when the Tillamook, Newport, North Bend, Seaside, and Bandon gauges all failed to record 5 in. of rain in any 24-hour period. No warning would have been issued.

2. Storms may miss the gauges. This occurred during the December storm in southern Oregon (Figure 4) when gauges at Bandon, Roseburg, and Ashland reported less than threshold rainfall. No warning would have been issued. Many of the wettest storms approach Oregon

from the southwest (the so-called "pineapple express"), therefore southern Oregon is unevenly served by the current warning system. Storms may also approach the Portland area from Washington along a track between stations at Seaside and Cascade Locks.

3. Melting ice and snow add to rainfall totals. This was significant during the February storm when debris flows occurred at many snowy or icy localities before the thresholds were exceeded (Figure 2). Anticipated snowmelt could be subtracted from debris flow thresholds and the resulting modified thresholds compared to forecast or measured rainfall.

4. The distribution of damaging debris flows reported from these four storms confirms that different stations have different debris-flow thresholds.

5. Comparing the distribution of damaging debris flows to the areas where thresholds were exceeded during the November storm (Figure 3) suggests the need for a significant antecedent-rainfall component in addition to the rainfall thresholds.

The current warning-system thresholds are generally adequate for the central Oregon Coast and the nearby west-central part of the Coast Range. By utilizing data from additional stations and modifying the thresholds to consider the trends described above, the system could serve all of western Oregon.

To supplement the warning system, state agencies have distributed a self-help brochure, entitled *Landslides in Oregon*[2]. Unfortunately, the brochure is somewhat vague when it addresses the question what people should do during dangerous weather, vaccillating between advice to be watchful and instructions for evacuation. The following is an excerpt from that particular section of the brochure:

> *During intense, prolonged rainfall, listen for advisories and warnings over local radio or TV . . .*
>
> *Be aware that you may not be able to receive local broadcasts in canyons and that isolated, very intense rain may occur outside warning areas. You may want to invest in your own rain gauge. "Intense" rainfall is considered over two inches of rain in any four-hour period. Debris flows may occur if this rainfall rate continues for the next few hours . . .*
>
> *Don't assume highways are safe . . .*
>
> *Watch carefully for collapsed pavement, mud, fallen rock, and other debris . . .*
>
> *Plan your evacuation prior to a big storm. If you have several hours advance notice, drive to a location well away from steep slopes and narrow canyons.*
>
> *Once storm intensity has increased, . . . you may need to evacuate by foot.*
>
> *Listen for unusual sounds. If you think there is danger of a landslide, evacuate immediately—don't wait for an official warning.*
>
> *Get away from your home. Be careful but move quickly . . .*

Among other things, this advice implies, somewhat ambiguously, that residents should abandon their homes when "intense" rainfall (2 in. in 4 hours) continues for a few hours after an initial 4 hours. This rainfall intensity suggested as a trigger for evacuation is exceedingly high for any area that is generally drier than the central Coast Range, yet the brochure is distributed statewide. During the four storms studied here, most residents who would have waited to evacuate their homes until, say, 4 in. of rain had fallen in an eight-hour period would have already been involved in slides or would have found themselves trapped on highways blocked by debris flows. In fact, during these four storm events, only gauges at Illahe, Bandon, and Allegany (on November 18) exceeded 4 in. of rain in eight hours, while landslides actually occurred in numerous places well away from these gauges.

ANTECEDENT RAINFALL

Debris flows typically do not occur until soils are thoroughly rewetted following the dry season. The amount of rainfall needed to rewet a soil is termed "antecedent rainfall." Rain that falls early in the season combines with other effects such as shorter days and lower temperatures to increase soil moisture. Once slopes become sufficiently wet, additional intense rainfall may fill soil voids faster than they drain. This produces an increase in hydrostatic pressure that eventually reduces mechanical strength along the base of a slide. It also increases slide mass (as water replaces air in the soil) and the downslope component of gravitational forces acting on the slide.

Antecedent rainfall is considered to be the amount of rainfall needed to moisten the soil to the point that additional water is subject to gravitational drainage. This amount generally reflects five parameters: soil thickness, moisture incorporated in swelling clays, moisture to wet the surfaces of mineral grains, moisture to fill small pore spaces, and soil drainage. Calculating antecedent rainfall requirements is very complex, depending not only on seasonal variations in temperature, humidity, vegetation, and rainfall, but also on the soil thickness, mineralogy, granularity, porosity, and permeability. In laboratory and field experiments antecedent rainfall is often determined by measuring soil moisture or hydrostatic pressure directly.

Antecedent rainfall requirements vary with soil type and climate. For the San Francisco Bay area, Keefer and others (1987) report that antecedent rainfall requirements range from 250 to 400 mm (10–16 in.). That area experiences much longer, drier summers than western Oregon, and antecedent rainfall requirements are expected to be lower here. Wilson and Wieczorek (1995) report that antecedent rainfall requirements approximate the "field capacity" of a soil. Soil surveys by the USDA Natural Resource Conservation Service

[2] Produced jointly by the Oregon Departments of Geology and Mineral Industries, Forestry, and Consumer and Business Services and by Oregon Emergency Management; available from DOGAMI through the Nature of the Northwest Information Center, 800 NE Oregon St., Suite 177, Portland, OR 97232, phone 503-872-2750, web site http://www.naturenw.org.

(NRCS) report "available water capacity," which is a somewhat smaller number than field capacity and would therefore be an even more conservative estimate of antecedent rainfall requirements. Available water capacity in most western Oregon soils ranges from 0.03 to 0.50 in. (1 to 12 mm) of water per inch of soil, with typical 60-in.-thick soil profiles having capacities between 4 and 11 in. (100–280 mm) of water.

In examining the four flood events, significant antecedent rainfall had occurred before the February, December, and January events. During the February storm, most areas in the northwestern part of the state already had significant surface water stored as ice on the ground and in the soil. It seems likely that this ice might have locally reduced near-surface permeability with the affect of decreasing soil drainage rates and increasing the likelihood of developing levels of hydrostatic pressure sufficient to cause instability.

During the November event, however, antecedent thresholds had not been reached in all areas prior to (or even during) the storm. If they had, sliding would presumably have been much worse and far more widespread. A review of antecedent rainfall and debris-flow distribution during the November storm suggests that no less than 8 in. (200 mm) of rain fell in October and November (NOAA, 1996d,e) before debris flows occurred. Figure 6 shows areas where 24-hour rainfall exceeded 40 percent of mean December rainfall **and** 8 in. of antecedent rainfall had occurred. A comparison of Figures 3 and 6 indicates that the lack of antecedent rainfall dramatically reduced the area that experienced slides as a result of that storm. The footprint of areas that exceeded the thresholds of **both** rainfall and antecedent rainfall matches the distribution of slide activity much more closely. In fact, at many Portland area gauges, 24-hour rainfall from the November event (Figure 3) exceeded that of the February storm (Figure 2). Data from the November storm confirm the notion that a single storm of sufficient intensity can exceed the antecedent rainfall requirements, at the same time as rainfall exceeds threshold intensities required to trigger debris flows. This effect underscores the importance of incorporating an antecedent rainfall requirement into warning thresholds.

Water tables may fluctuate on some slopes to the point that saturation or reduced gravitational drainage can accompany an autumn rise in groundwater levels. This effect is heralded by renewed flow in seasonal streams and springs on dry days. It may explain why the Grants Pass-Cave Junction area experienced relatively few landslides during the December 8 event as compared to the January 1 event, even though antecedent rainfall, as defined above, had been exceeded prior to December 8. This area is geologically atypical in that development has occurred largely on thick, coarse-grained allu-

(Continued on page 39)

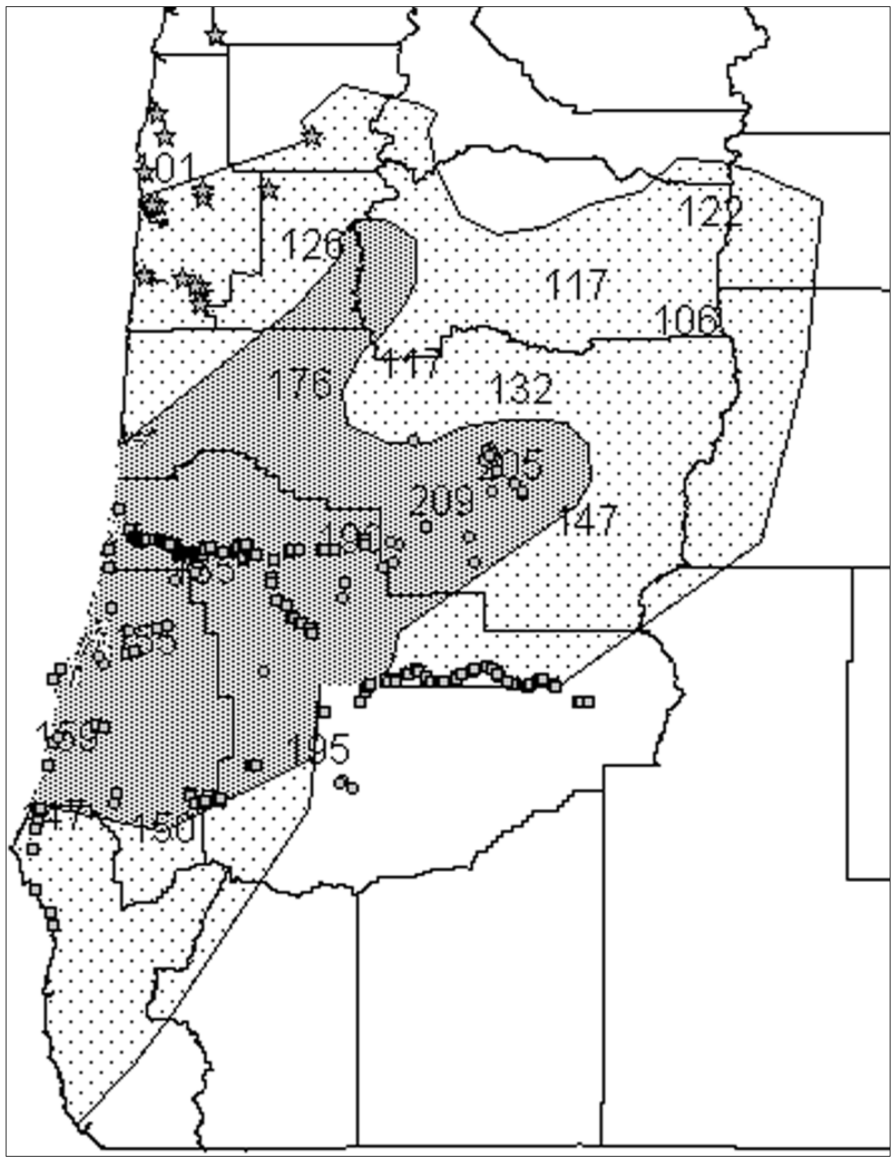

Figure 6. Percentage of preliminary 24-hour threshold rainfall recorded at selected stations during the November 18–19, 1996, storm centered on the Coos-Douglas-Lane County area.—The same as in Figure 3, but the patterned areas are restricted to stations that exceeded the threshold and also received 8 in. or more of antecedent rainfall. Landslide symbols as in Figure 2.

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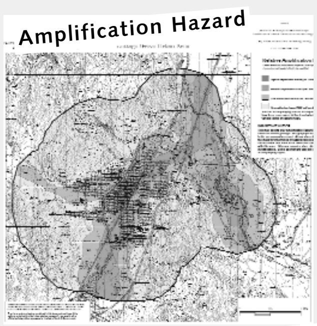

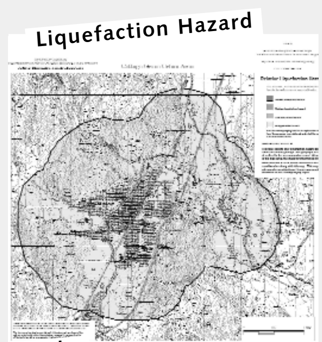

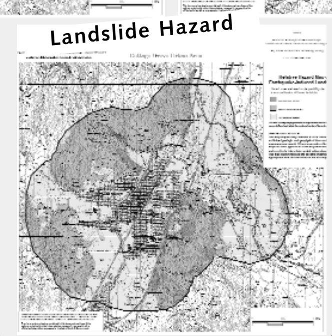

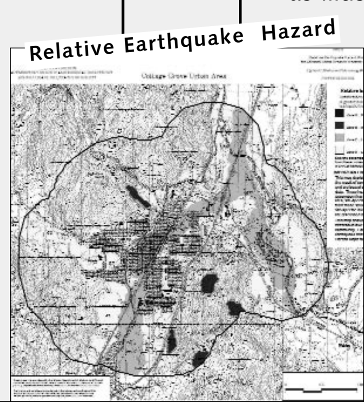

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These four sets of (colored) maps cover urban areas in western Oregon that were not included in similar but more exhaustive studies for major metropolitan regions like Portland, Salem, and Eugene (most recent DOGAMI publications for these: GMS–105, IMS–14, IMS–15, IMS–16). The maps and the data provided on paper and in digital form serve emergency response and hazard mitigation planning as well as land use planning, considerations for seismic retrofitting, and other measures to strengthen homes, buildings, and lifelines.

Each printed report includes paper-copy relative earthquake hazard maps overlaid on U.S. Geological Survey topographic base maps. Available only in digital form are the maps for individual hazards such as ground shaking amplification, liquefaction, and earthquake-induced landsliding, which form the basis for the comprehensive relative earthquake hazard maps, as illustrated on the left.

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IMS–10: Astoria-Warrenton, Brookings, Coquille, Florence-Dunes City, Newport, Reedsport-Winchester Bay, Seaside-Gearhart-Cannon Beach, Tillamook.

(Continued from page 34)

vial and granitic soils that require large amounts of rainfall to raise water tables and achieve saturation.

Until better numbers can be developed, a conservative threshold of 8.00 in. (203 mm) of antecedent rainfall should be used in conjunction with thresholds for rainfall intensity and duration.

It is important to note that antecedent rainfall thresholds can be exceeded **during** a storm as well as before it. Intensity-duration thresholds are not simply added to the antecedent requirement. Both thresholds can be exceeded during the same storm, at the same time, and should be tracked separately. For example, suppose a station with an intensity-duration threshold of 3.5 in. in 24 hours has received 5 in. of rain since the end of September. If the next storm drops 4 in. of rain in 24 hours it will have exceeded both the intensity duration threshold (4>3.5) and the 8-in. antecedent threshold (5+4=9, 9>8). This occurred at many stations during the November storm.

THRESHOLD VALUES FOR WESTERN OREGON

Recognizing that hillsides are in equilibrium with typical rainfall rates and that they generally fail catastrophically during atypical events, we can prepare a set of daily and hourly thresholds for western Oregon. The 24-hour thresholds are based on the slide history reported here. The 6- and 12-hour thresholds are derived from the 24-hour threshold.[3] The thresholds include the following percentages of mean December rainfall in the indicated times: 40 percent in 24 hours, 25 percent in 12 hours, and 15 percent in 6 hours. This equates with mean annual precipitation percentages of 6.67 percent in 24 hours, 4 percent in 12 hours, and 2.5 percent in 6 hours. Rainy-day normal multiples of 14 in 24 hours, 8.75 in 12 hours, and 5.25 in 6 hours give similar thresholds. In addition, a threshold requirement of 8.00 in. (203 mm) of October-November antecedent rainfall is recommended to avoid false alarms early in the wet season.

Table 1 lists 24-hour rainfall intensity thresholds for most western Oregon stations reported by the National Weather Service. These thresholds are combined with a derivative of the map of mean December precipitation (Oregon Climate Service website; Daly and others, 1994, 1997) to produce a map of debris-flow thresholds for western Oregon (Figure 7). This map can provide citizens in high-risk areas with reasonable estimates of rainfall rates that could trigger debris flows. Such thresholds, as well as the preliminary 8-in. antecedent rainfall requirement, should eventually be refined to reflect local geologic conditions, microclimate, soil character, and latitudinal variation in storm frequency.

Existing thresholds for the debris-flow warning system use one set of values for every station but Ashland. Changing to thresholds stated in terms of either mean December rainfall, rainy-day normal, or mean annual precipitation would have the advantage of an inherent compensation for "rain shadows" and other orographic (mountain-related) effects in the areas surrounding the location of the measuring station. For example, if a mountainside near the measuring station typically receives twice as much rain as the station itself, the numbers for both sites will still be the same when stated as multiples of rainy-day normal, December rainfall, or annual precipitation. Warnings issued for the station will, therefore, be appropriate for the surrounding area. This contrasts to trying to use one set of numbers statewide, so that mountainside warnings are not issued until some multiple of the threshold rainfall has fallen (when the statewide threshold is exceeded at the adjacent lowland station).

CONCLUSIONS

After autumn rains compensate for summer drying, landslides and debris flows will occur if rainfall intensity and duration exceed certain thresholds. Although rainfall thresholds are influenced by local geology and soil development, over large areas they are generally proportional to typical local rainfall fluxes. Data from four recent storms suggest that slides will occur in western Oregon where 8 in. of rain has fallen since the end of September and 24-hour rainfall exceeds 40 percent of mean December rainfall.

The Oregon debris-flow warning system could be modified to incorporate these findings. Debris-flow advisories would be issued once forecasts indicate that the annual 8 in. antecedent rainfall requirement will be exceeded **and** an amount equal to 40 percent of mean December rainfall is expected during a 24-hour period. Debris-flow warnings would be issued once 8 in. of antecedent rain has fallen and 40 percent of mean December rainfall has been measured in 24 hours. Residents and businesses can estimate local thresholds by finding their location on Figure 7 or by calculating 40 percent of mean December rainfall wherever a gauge has been active for some time.

SUGGESTIONS FOR FUTURE WORK

The thresholds described here are preliminary. They are based on a combination of simple mathematical models and comparisons of historic debris-flow occurrences with associated rainfall. Eventually, more accu-

(Continued on page 42)

[3] This is done using an approximate fit to a curve that parallels the mean of three empirical intensity-duration curves cited in Keefer and others (1987, p. 923). Using even multiples of 5 percent, 0.33 percent, or 0.5 percent for mean December and MAP thresholds, or 0.25 for rainy-day normal thresholds, as is done here, results in 12-hour values that are 5–10 percent higher than a true fit to the mean.

Table 1. 24-hour rainfall thresholds for selected active and historic weather stations in western Oregon as reported by the National Weather Service (NWS) and the National Climatic Data Center (NCDC) calculated three ways: 40 percent of mean December rainfall calculated from (a) stated monthly average in Climatological Data, Oregon, December 1996 (NOAA, 1996a) and (b) mean of December data reported on the NCDC website. In the final column, an alternative 24-hour threshold based on 0.067 times mean annual precipitation (MAP) is shown for comparison. n.d. = not determined

Number	Station	Latitude	Longitude	40 percent Dec (a)	40 percent Dec (b)	0.067 X MAP
1	ALSEA FISH HATCHERY	44.40	-123.75	n.d.	6.54	6.04
2	ASHLAND	42.22	-122.72	1.22	1.22	1.32
3	ASTORIA WSO AP	46.15	-123.88	4.22	4.29	4.43
4	BANDON 2 NNE	43.15	-124.40	3.93	3.66	3.67
5	BELKNAP SPRINGS 8 N	44.30	-122.03	5.11	5.11	4.85
6	BONNEVILLE DAM	45.63	-121.95	n.d.	4.93	4.89
7	BROOKINGS	42.05	-124.28	4.78	5.19	5.18
8	BUNCOM 1 NNE	42.18	-122.98	n.d.	1.67	1.55
9	BUTTE FALLS 1 SE	42.53	-122.55	n.d.	2.27	2.31
10	CASCADIA	44.40	-122.48	3.70	3.76	4.14
11	CAVE JUNCTION 1 WNW	42.17	-123.67	4.43	4.85	3.98
12	CLATSKANIE	46.10	-123.20	3.71	3.85	3.78
13	CLOVERDALE	45.20	-123.90	5.24	5.28	5.72
14	CORVALLIS STATE UNIV	44.63	-123.20	3.09	2.85	2.67
15	CORVALLIS WATER BUREAU	44.52	-123.45	4.98	4.92	4.45
16	COTTAGE GROVE DAM	43.72	-123.05	3.00	n.d.	n.d.
17	CRATER LAKE NPS HDQTRS	42.90	-122.13	n.d.	4.45	4.51
18	DALLAS 2 NE	44.95	-123.28	3.64	3.55	3.26
19	DETROIT DAM	44.72	-122.25	5.59	5.60	5.73
20	DILLEY 1 S	45.48	-123.12	n.d.	3.23	2.94
21	DORENA DAM	43.78	-122.97	2.78	2.87	3.15
22	DRAIN	43.67	-123.32	3.11	3.17	3.06
23	ELKTON 3 SW	43.60	-123.58	3.89	3.87	3.42
24	ESTACADA 2 SE	45.27	-122.32	3.56	3.42	3.81
25	EUGENE WSO AP	44.12	-123.22	3.44	3.33	3.11
26	FALLS CITY 2	44.85	-123.43	5.30	5.14	4.66
27	FERN RIDGE DAM	44.12	-123.30	3.23	2.92	2.66
28	FOREST GROVE	45.53	-123.10	3.06	3.31	2.89
29	GOLD BEACH RANGER STN	42.40	-124.42	5.38	5.40	5.25
30	GOVERNMENT CAMP	45.30	-121.75	n.d.	5.30	5.72
31	GRANTS PASS	42.42	-123.33	2.28	2.20	2.03
32	GREEN SPRINGS POWER PLANT	42.12	-122.57	n.d.	1.60	1.47
33	HASKINS DAM	45.32	-123.35	n.d.	5.67	4.96
34	HEADWORKS PTLD WATER BUR	45.45	-122.15	4.62	4.69	5.36
35	HILLSBORO	45.52	-122.98	2.64	2.74	2.51
36	HOLLEY	44.35	-122.78	n.d.	3.38	3.49
37	HONEYMAN STATE PARK	43.93	-124.10	4.96	4.87	4.52
38	HOOD RIVER EXP STATION	45.68	-121.52	2.40	2.25	1.99
39	HOWARD PRAIRIE DAM	42.22	-122.37	2.33	2.46	2.08
40	IDLEYLD PARK 4 NE	43.37	-122.97	4.19	7.97	5.17

Table 1 (continued)

Number	Station	Latitude	Longitude	40 percent Dec (a)	40 percent Dec (b)	0.067 X MAP
41	LANGLOIS 2	42.92	-124.45	4.96	4.87	4.91
42	LEABURG 1 SW	44.10	-122.68	3.87	3.97	4.23
43	LITTLE RIVER	43.25	-122.92	n.d.	3.39	3.27
44	LOOKOUT POINT DAM	43.92	-122.77	2.68	2.73	2.96
45	MARION FORKS FISH HATCHERY	44.60	-121.95	4.56	4.65	4.45
46	MC KENZIE BRIDGE R S	44.18	-122.12	4.26	4.55	4.65
47	MC MINNVILLE	45.23	-123.18	3.11	2.94	2.71
48	MEDFORD EXPERIMENT STN	42.30	-122.87	1.46	1.47	1.36
49	MEDFORD WSO AP	42.38	-122.88	1.33	1.28	1.21
50	NEWPORT	44.58	-124.05	4.90	4.47	4.49
51	NORTH BEND FAA AP	43.42	-124.25	4.31	4.24	4.14
52	N WILLAMETTE EXP STN	45.28	-122.75	2.78	2.78	2.66
53	OAKRIDGE FISH HATCHERY	43.75	-122.45	2.88	2.67	2.96
54	OREGON CITY	45.35	-122.60	3.06	3.06	3.01
55	OTIS 2 NE	45.03	-123.93	6.22	6.33	6.37
56	PORTLAND WSFO AP	45.60	-122.60	2.45	2.42	2.45
57	PORT ORFORD 2	42.75	-124.50	4.85	4.49	4.58
58	POWERS	42.88	-124.07	4.17	4.32	3.98
59	PROSPECT 2 SW	42.73	-122.52	2.73	2.66	2.68
60	RESTON	43.13	-123.62	n.d.	3.77	3.14
61	RIDDLE	42.95	-123.35	2.22	2.28	2.01
62	ROSEBURG KQEN	43.20	-123.35	2.23	2.40	2.14
63	RUCH	42.23	-123.03	n.d.	1.92	1.72
64	ST HELENS R F D	45.87	-122.82	2.93	2.76	2.73
65	SALEM WSO AP	44.92	-123.02	2.72	2.78	2.63
66	SANTIAM PASS	44.42	-121.87	n.d.	6.02	5.53
67	SCOTTS MILLS 9 SE	44.95	-122.53	5.18	5.06	5.28
68	SEASIDE	45.98	-123.92	4.61	4.74	4.98
69	SEXTON SUMMIT WSMO	42.62	-123.37	n.d.	2.30	2.36
70	SILVER CREEK FALLS	44.87	-122.65	4.84	4.52	5.11
71	SILVERTON	45.00	-122.77	3.00	3.18	3.02
72	STAYTON	44.78	-122.82	3.29	3.33	3.53
73	SUMMIT	44.63	-123.58	n.d.	4.53	4.32
74	TIDEWATER	44.42	-123.90	n.d.	6.08	5.91
75	TILLAMOOK 1 W	45.45	-123.87	5.57	5.81	5.96
76	TOKETEE FALLS	43.28	-122.45	2.99	3.15	3.18
77	TROUTDALE SUBSTATION	45.57	-122.40	2.83	2.68	2.96
78	VALSETZ	44.83	-123.67	n.d.	8.89	8.28
79	WATERLOO	44.50	-122.82	n.d.	2.83	2.97
80	WILLAMINA 2 S	45.05	-123.50	n.d.	3.81	3.44
81	WILLIAMS 1 NW	42.23	-123.28	n.d.	2.70	2.19
82	WINCHESTER	43.28	-123.37	2.38	2.57	2.32

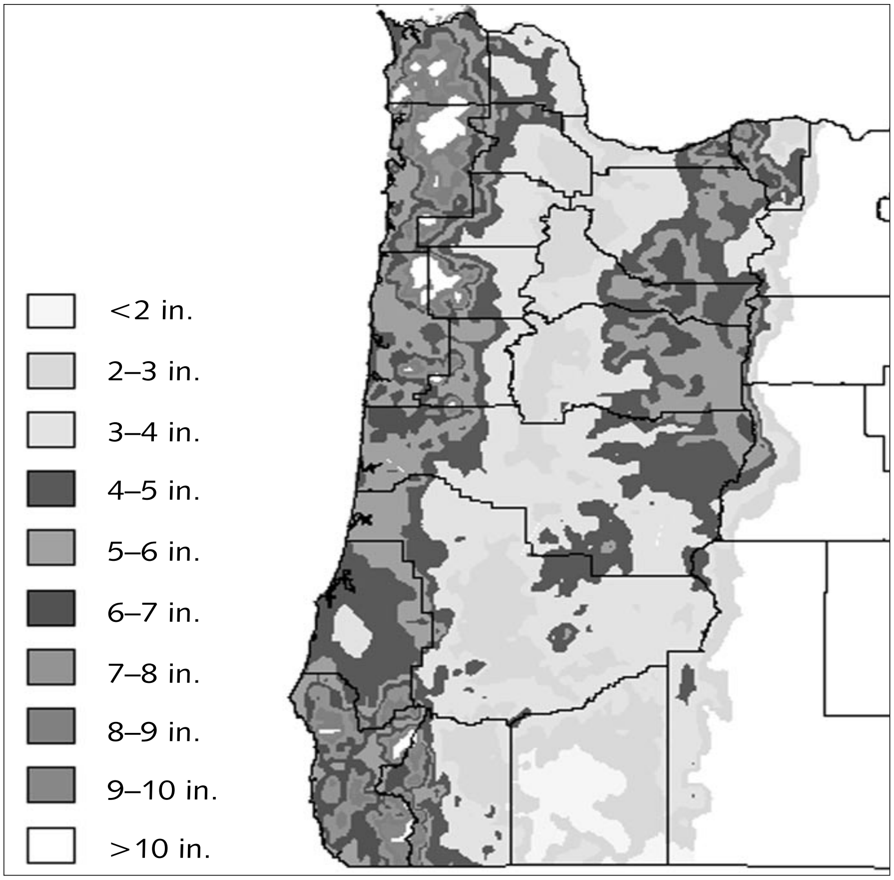

Figure 7. (Colored version on front cover page) Map of proposed 24-hour rainfall intensity-duration thresholds for Oregon. Contours are derived from the State Climatologist's map (Oregon Climate Service website) of mean December precipitation. The contour interval is in inches for the 24-hour threshold. These values can be multiplied by 0.6 for a 12-hour threshold or by 0.375 for a 6-hour threshold. For example, the areas within the <2-in. contour in the Rogue Valley region have 24-hour thresholds ranging from 1 to 2 in., 12-hour thresholds ranging from 0.6 to 1.2 in., and 6-hour thresholds ranging from 0.375 to 0.75 in. Threshold values for locations within the individual areas (see also Table 1) vary according to distance from adjacent contour lines.

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rate models should be produced that consider several additional variables. (1) Chief among these is storm frequency, which results in the north-south divergence between thresholds based on rainy-day normal and mean December rainfall. More accurate intensity-duration thresholds, perhaps incorporating December rainy-day normal or a percentage of the 100-year storm, could probably be calculated to improve the numbers for western Oregon and extend coverage to eastern Oregon. (2) The 8-in. antecedent rainfall threshold reported here is preliminary. Soil maps produced by the Natural Resource Conservation Service (NRCS) should be digitally recast, using reported values for available water capacity and soil thickness to give better local estimates for antecedent rainfall thresholds. (3) The extent to which land has been developed influences the thresholds due to oversteepened slopes, placement of artificial fill, concentration of drainage, and increased flashiness of storm-water drainage. Maps of slides occurring in developed areas should be compared with triggering rainfall to develop local intensity-duration thresholds. (4) Finally, intensity thresholds for rainfall of longer duration should be calculated to provide a more accurate representation of the hazard that accompanies multi-day storms like the February 1996 event.

ACKNOWLEDGMENTS

Shortly after the New Year's Day storm of 1997, John Cassad, a meteorologist in the Medford office of the National Weather Service, contacted the Department of Geology and Mineral Industries to inquire about the possibility of relating rainfall to landslides. Work on this report started a few days later. Raymond Wilson and David Keefer of the U.S. Geological Survey provided a review of the state of practice and critical direction in this investigation. Jon Hofmeister of Dames & Moore [now with the Oregon Department of Geology and Mineral Industries, *ed.*] compiled landslide location data used to check the "ground truth" of the listed thresholds. Critical reviews were provided by John Cassad, Jon Hofmeister, Keith Mills (Oregon Department of Forestry), Dennis Olmstead (Oregon Department of Geology and Mineral Industries), George Taylor (Oregon State Climatologist), and Raymond Wilson.

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———1996d, Hourly precipitation data, Oregon, November 1996: U.S. Department of Commerce, v. 46, no. 11, p. 30–33.

———1996e, Climatological data, Oregon, October 1996: U.S. Department of Commerce, v. 102, no. 10, p. 3–7.

———1996f, Climatological data, Oregon, February 1996: U.S. Department of Commerce, v. 102, no. 2, p. 2–7.

———1996g, Hourly precipitation data, Oregon, February 1996: U.S. Department of Commerce, v. 46, no. 2, p. 28–31.

———1997a, Climatological data, Oregon, January 1997: U. S. Department of Commerce, v. 103, no. 1, p. 2–7.

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DOGAMI PUBLICATIONS

Released January 20, 2000:

Earthquake Scenario and Probabilistic Ground Shaking Maps for the Portland, Oregon, Metropolitan Area, by I. Wong, W. Silva, J. Bott, D. Wright, P. Thomas, N. Gregor, S. Li, M. Mabey, A. Sojourner, and Y. Wang. Interpretive Map Series IMS–15 (one map, $10) and IMS–16 (11 maps, 1 CD, $80).

This set of 12 new maps looks at a number of different possible earthquake scenarios for the Portland metropolitan area, mapping the degree of shaking at the ground surface. These maps differ from earlier earthquake hazard maps for the Portland metropolitan area in that they combine a number of effects and conditions, including bedrock shaking, soil response, and proximity to faults. They also are the first maps to show all known faults in this area, the Portland Hills, East Bank, Oatfield, and Molalla-Canby faults.

Map IMS–15 contains the scenario most significant for possible earthquake damage and most informative for the general user. The remaining set of 11 maps (IMS–16) completes a comprehensive look at the effects of various conditions that might arise from a magnitude 6.8 quake on the Portland Hills fault, or a magnitude 9.0 quake on the Cascadia fault, or other earthquakes of varying probability and strength. IMS–16 also comes with a CD containing GIS layers for all maps and is most useful for engineers, emergency planners, and other technical users.

Released January 26, 2000:

Relative Earthquake Hazard Maps for Selected Urban Areas in Western Oregon, by I.P. Madin and Z. Wang. Interpretive Map Series IMS–7, IMS–8, and IMS–9, scale 1:24,000, 21–24 p. text, 1 compact disk, $20 each set.

Together, the three sets cover 48 inland communities, from Columbia City to Ashland (the set for 9 coastal communities, IMS–10, was released in October 1999), on 28 maps that combine the effects of ground shaking amplification, liquefaction, and earthquake-induced landsliding to show the earthquake hazards relative to the local geologic conditions. The following urban areas are included:

IMS–7: St. Helens-Columbia City-Scappoose, Sandy, Hood River, McMinnville-Dayton-Lafayette, Newberg-Dundee, Sheridan-Willamina, Dallas, Monmouth-Independence.

IMS–8: Canby-Barlow-Aurora, Woodburn-Hubbard, Silverton-Mount Angel, Stayton-Sublimity-Aumsville, Lebanon, Sweet Home.

IMS–9: Cottage Grove, Sutherlin-Oakland, Roseburg, Grants Pass, Ashland.

The compact disk that is part of each map set contains both the printed combined-hazard map and the individual-hazard maps.

The study was conducted by the DOGAMI authors over a period of two-and-a-half years and was funded by the State of Oregon and the U.S. Geological Survey.

Released February 14, 2000:

Water-Induced Landslide Hazards, Eastern Portion of the Eola Hills, Polk County, Oregon, by A.F. Harvey and G.L. Peterson. Interpretive Map Series IMS–5, 1:24,000, $10.

This is the second publication in a two-part pilot project that was supported by federal, state, and local governments. The Eola Hills are a landslide-prone area with intensive development in the western part of Salem—similar to the Salem Hills in the south of Salem that were the subject of the earlier map publication

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Site-specific seismic reports in DOGAMI library nearing 200

Part 3—Oregon counties that are part of the Portland metropolitan area

On May 1, 1994, the Oregon Structural Specialty Code, a part of the Oregon Administrative Rules, was changed to order that a copy of each legally required "seismic site hazard report" should be deposited with the DOGAMI library and accessible to the public for inspection. This growing collection now holds nearly 200 reports. The following list is derived from the records in the library's bibliographic database. It is organized by county and USGS 7½-minute topographic quadrangle.

This list covers the quadrangles that are, completely or partially, part of the Portland metropolitan area. The preceding two parts, counties outside the Portland metropolitan area, were published in the July/August and September/October 1999 issues of *Oregon Geology*. A few reports are associated with more than one quadrangle.

PORTLAND METRO AREA QUADRANGLES

Beaverton

15592. Braun Intertec Corporation (1996): Site-specific seismic evaluation for the proposed Jesuit High School addition, SW Beaverton-Hillsdale Hwy. and SW Apple Way, Portland, Oregon. (Report for Jesuit High School, Project no. EAAX-96-0564, Report no. 09-106-2392; submitted by Soderstrom Architects, P.C., Portland), 12 pages, 2 figs., 33 p. app.

15885. Braun Intertec Corporation (1997): Site-specific seismic evaluation, proposed 74-unit motel, Pacific Hwy. 99W and Durham Road, King City, Oregon. (Report for Super One, Inc., Beaverton, Oregon, Project No. EAAX-96-415A, Report No. 09-117-3446), 13 pages, 3 figs., 20 p. app.

15692. Braun Intertec Corporation (1997b): Site-specific seismic evaluation, proposed Covenant Church, SW Pacific Hwy and SW Naeve Road, Tigard, Oregon. (Report for IMF Development, Project No. EAAX-97-0187), 13 pages, 3 figs., 5 tables, 25 p. app.

15552. Carlson Testing,Tigard (1996): Seismic hazards report, Tigard United Methodist Church, 9845 SW Walnut Place, Tigard, Oregon 97223. (Report prepared for Architect*LA, 805 SE Sherman Street, Portland, Oregon 97214, CTI Job No. 96-4363), 9 pages, 5 figs., 36 p. app.

14883. David J. Newton Associates (1996): Geotechnical investigation and seismic hazard evaluation, proposed recreation/aquatic center, Southwest 125th Avenue at Southwest Conestoga Road, Beaverton, Oregon. (Report for Tualatin Hills Parks and Recreation District, Project No. 568 112. Also submitted by BOORA Architects, Inc., Portland, under project no. 94058.01), 19 pages, 3 figs., 19 p. app.

15883. H.G. Schlicker & Associates (1997): Seismic site hazard investigation, proposed Erickson Place project, 5670 SW Erickson, Beaverton, Oregon. (Report for Dave Amato Associates, P.O. Box 19576, Portland, Oregon 97219, Project No. 971539), 14 pages, 7 figs., 25 p. app.

15926. Squier Associates, Inc. (1998): Site-specific seismic hazards evaluation, JAE East Building addition, Tualatin, Oregon. (Report for Shimizu America Corporation, Tigard, Oreg., Project No. 98328), 6 p.

Camas

15590. Dames & Moore (1996): Groundwater pump station/interstate facility seismic vulnerability study, Portland, Oregon. Final report. (Report prepared for Portland Water Bureau, Job no. 02110-088-004), var. pages, 3 vols., app. 16076. Fujitani Hilts and Associates, Inc. (1999): Seismic site hazard investigation, Fairview City Hall, Fairview, Oregon. (Report prepared for Heery International, Inc., Portland, Oreg., submitted to library by Group Mackenzie, Inc., Portland, Oreg., Fujitani Project no. F-2995.03, Mackenzie Project no. 298314), 10 pages, 1 fig.

12595. Geotechnical Resources, Inc. (1995): Foundation investigation, Fujitsu facility additions, Gresham, Oregon. (Report for Technology Design & Construction Co., Project No. 1.887, deposited by TDC as Project No. 3225), 14 pages, 6 figs., 37 p. app.

15605. Geotechnical Resources, Inc. (1996): Foundation investigation and site-specific seismic hazard study, Act III theaters, Division Street Cinema, Portland, Oregon. (Report for Soderstrom Architects, P.C., submitted by Doug Walton Architect, P.C., Portland, Job No. 2-309), 10 pages, 4 figs., 28 p. app.

15776. Geotechnical Resources, Inc. (1997): Site-specific seismic hazard study, proposed IBEW facility, NE 158th Avenue at Airport Way, Portland, Oregon. (Report for Specht Properties, Inc., Beaverton, Oreg., Job No. 2331), 11 pages, 7 figs.

Canby

14851. Geotechnical Resources, Inc. (1994): Geotechnical investigation, Horton Reservoir No. 2, S Day Road, West Linn, Oregon. (Report for Murray, Smith, and Associates, Consulting Engineers, Portland, Oreg., Job No. 1.585), 7 pages, 2 tables, 4 figs.

Damascus

15887. Braun Intertec Corporation (1997): Site-specific seismic evaluation, Mountain View Golf Course clubhouse, 27195 SE Kelso Road, Boring, Oregon. (Report for Mountain View Golf Club, Boring, Oregon, Project No. EAAX-97-0635, Report No. 09-117-3432), 12 pages, 3 figs., 27 p. app.

Forest Grove

12580. Dames & Moore (1995): Seismic hazard investigation, new police and fire station, Cornelius, Oregon. (Report for City of Cornelius, Job No. 30452-001-016), 8 pages, 2 figs.

15804. GeoEngineers, Inc. (1997): Revised report of geotechnical engineering services, seismic hazard study (incl. response to seismic peer review), Matsushita Electronic Materials, Inc., chemical storage building, Forest Grove, Oregon. (Report prepared for and deposited by Silicon Forest Industries, Inc., Wilsonville, Oregon, Job No. 5797-001-43), 5 pages, 2 p. Response to peer review.

Gladstone

12596. AGI Technologies (1994): Geotechnical investigation/seismic hazard evaluation, proposed new fire station, 6600 SE Lake Road, Milwaukie, Oregon. (Report prepared for Clackamas County Fire District #1. AGI Project No. 30,109.013), 12 pages, 10 figs.

15892. AGRA Earth & Environmental (1998): Seismic hazard study, Eastport Plaza Mall Cinema, Portland, Oregon. (Report prepared for MMI Realty Services, 1901 Avenue of the Stars, Suite 820, Los Angeles, Calif. 90067, Job No. 6-61M-08643-1), 9 pages, 2 figs.

16074. Braun Intertec Corporation (1999): Site-specific seismic evaluation, proposed high school, SE 122d Avenue and SE 132d Avenue, Clackamas County, Oregon. (Report for North Clackamas School District No. 12, Project No. EAAX-96-0405, Report No. 09-076-2177. Revised March 16, 1999.), 13 pages, 3 figs., 24 p. app.

14898. David J. Newton Associates (1996): Geotechnical investigation and seismic hazards evaluation, for the new elementary school, SE 129th Avenue and Masa Lane, Clackamas County, Oregon. (Report for Architects Barrentine Bates Lee AIA, Lake Oswego, Project No. 689 101), 19 pages, 4 figs., 17 p. app.

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15921. PBS Environmental (1998): Seismic hazards report, proposed church, parish hall, and assisted living facilities, St. Anthony Village, Portland, Oregon. (Report for St. Anthony Village Enterprise, Project No. 12691), 6 pages, 1 fig.

Hillsboro

13382. David J. Newton Associates (1995): Geotechnical investigation and seismic hazards report, proposed Hillsboro Union High School, SW Johnson Street and SW 234th Avenue, Hillsboro, Oregon. (Report for Mitchell Nelson Welborn Reiman Partnership, Portland, Oregon, Project No. 372 131), 22 pages, 3 figs., 1 table, 25 p. app.

14888. GeoEngineers, Inc. (1996): Report of geotechnical and seismic services, proposed Asahi [Glass] and Tokai [Carbon] developments, Hillsboro, Oregon. (Report prepared for Graham & James LLP/Riddell Williams P.S., Seattle, Wash., File No. 5069-001-36, deposited by Mackenzie/Saito & Associates, Portland, Project No. 295561. Second copy received 6-12-96 from GeoEngineers.), 10 pages, 3 figs., 17 p. attachments.

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13386. Geotechnical Resources, Inc. (1994): Foundation investigation, Intel D1B-Site X, Hillsboro, Oregon. (Report for Technology Design & Construction Co., Portland, Oreg., Job No. 1.656, deposited by TDC as Project No. 2995), 15 pages, 6 figs., 127 p. app.

12578. Geotechnical Resources, Inc. (1994): Geotechnical investigation, proposed Dawson Creek Development electronics manufacturing facility, Hillsboro, Oregon. (Report for Van Domelen/Looijenga/McGarrigle/Knauf, Consulting Engineers, Portland, Oreg., Job No. 1.644), 8 pages, 3 figs.; App. 3 p., 2 tables, 18 figs.

12594. Geotechnical Resources, Inc. (1995): Site-specific seismic hazard study, IDT facility, Hillsboro, Oregon. (Report for Integrated Device Technology, Hillsboro, Oreg., Job No. 1.908, deposited by Van Domelen/Looijenga/McGarrigle/Knauf, Portland, as copy of report to City of Hillsboro), 10 pages, 9 figs.

15556. Geotechnical Resources, Inc. (1996): Geotechnical investigation and site-specific seismic hazard study, proposed DYNIC USA Corporation facility, Hillsboro, Oregon. (Report for Van Domelen/Loijenga/McGarrigle/Knauf, Portland, Job No. 1913), 9 pages, 2 figs., 30 p. app.

15566. Geotechnical Resources, Inc. (1996): Site-specific seismic hazard study, proposed BOC industrial gas facility, Hillsboro, Oregon. (Report for BOC Process Plants, Murray Hill, NJ/City of Hillsboro, Job No. 1.897, deposited by Fujitani Hilts & Associates, Portland (reviewer), as copy of report to City of Hillsboro), 10 pages, 7 figs.

15629. Kleinfelder, Inc. (1997): Seaport site #WA-METRO-9, Washington County, Hillsboro. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-24), var. pages.

15567. PacRim Geotechnical, Inc. (1996): Report of seismic hazards evaluation, proposed Ronler Acres fire station, 229th Street and Evergreen Road, Hillsboro, Oregon. (Report for City of Hillsboro, PGI Job No. 008-003-02, deposited by Fujitani Hilts & Associates, Portland (reviewer), 7 p., 3 figs., 7 p. app.

Lake Oswego

15802. Braun Intertec Corporation (1997): Site-specific seismic evaluation, proposed new gymnasium, Riverdale School, 11733 SW Breyman Road, Portland, Oregon. (Report for Riverdale School District, Project No. EAAX-97-0465), 16 pages, 3 figs., 26 p. app. + 20 p. geotechnical evaluation.

12584. Dames & Moore (1995): Seismic hazard investigation, planned centers for the humanities and visual arts, Lewis and Clark College, Portland, Oregon. (Report for Lewis and Clark College, Job No. 00288-021-016), 10 pages, 2 figs., 3 tables.

14895. Dames & Moore (1996): Seismic hazard investigation, hospital addition, Providence Milwaukie Hospital, Milwaukie, Oregon. (Report prepared for Andersen Construction Company, Portland, job no. 04156-035-016), 8 pages, 2 figs.

12598. GeoEngineers, Inc. (1995): Report of geotechnical engineering services, proposed John's Landing office building, Portland, Oregon. (Report prepared for Gerding Investment Company, File No. 4190-001-P36, deposited by Mackenzie/Saito & Associates, Portland, Project No. 294416), 18 pages, 4 figs., App. 47 p.

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15956. West Coast Geotech, Inc. (1998): Seismic hazard report, Day Road Middle School site, Clackamas County, Oregon. (Report prepared for West Linn/Wilsonville School District, Project No. W-1238 (update of report of March 28, 1996)), 6 pages, 3 figs., 21 p. app.

Linnton

16052. Braun Intertec Corporation (1998): Site-specific seismic evaluation, proposed St. Pius X parish hall, 1280 NW Saltzman Road, Portland, Oregon. (Report for St. Pius X Catholic Church, Portland, OR, 97229, Project No. EAAX-98-0402), 13 pages, 3 figs., 29 p. app.

12600. David J. Newton Associates (1995): Geotechnical investigation and seismic hazard report for the proposed expansion, Terpenning Recreation Center, NW 158th Ave. and SW Walker Road, Beaverton, Oregon. (Report for Tualatin Hills Parks and Recreation District, Project No. 568 103), 21 pages, 5 figs., App. 18 p.

15806. Geotechnical Resources, Inc. (1997): Site-specific seismic hazard study for the expansion of the Kanto Corporation facility, Rivergate Industrial District, Portland, Oregon. (Report for Industrial Design Corporation, Portland, Oreg., Job No. J/Seismc-2-422), 11 pages, 7 figs.

15817. Wright/Deacon & Associates (1997): Site-Specific Seismic Studies, French-American International School, Portland, Oregon. (Report for Laurence Ferar and Associates, Architects, Portland, Project No. J96-521), 8 pages, 8 figs.

Mount Tabor

16047. Braun Intertec Corporation (1998): Site-specific seismic evaluation, Cherrywood Village Adult Community, SE Cherry Blossom Drive and SE 106th Avenue, Portland, Oregon. (Report for Terrace Construction Company, LLC, Portland, Oregon, Project No. EAAX-98-0205), 14 pages, 3 figs., 36 p. app.

13381. Dames & Moore (1995): Dynamic site response analysis, seismic hazard investigation, central utilities plant expansion, Portland International Airport. (Report for Port of Portland, Job No. 00283-149-016), 9 pages, 4 figs.

14881. Dames & Moore (1996): Seismic site hazard investigation, proposed parking structure and helipad, Providence Portland Medical Center, Portland, Oregon. (Report for Jon R. Jurgens and Associates, Architects, Beaverton, JRJ&A Project No. 95129, D&M Job No. 04156-033-016), 10 pages, 2 figs.

12587. Dames & Moore; Fujitani Hilts & Associates (1995): Seismic hazard investigation, new fueling facilities, Portland International Airport. (Report prepared for Portland Fueling Facilities Corporation. Compiled by Bovay Northwest, Inc., Job No. 1893-010; 3 parts: Seismic hazard investigation [D&M, 1995], Surcharge monitoring, etc. [FH, 1993], Preliminary foundation investigation [D&M, 1970]), var. pages.

12602. Fujitani Hilts and Associates, Inc. (1995): Geotechnical investigation and site-specific hazards study, new East Precinct, Portland, Oregon. (Report prepared for City of Portland, Bureau of General Services, Project No. F-2732-01; second copy received from Mackenzie/Saito & Associates, Portland, under Project No. 295065), 17 pages, 13 figs.

15559. Fujitani Hilts and Associates, Inc. (1996): Site-specific hazards study and geotechnical investigation, proposed Inverness Jail expansion, Portland, Oregon. (Report prepared for KMD Architects and Planners, Portland, Oregon, Project No. F-2830-01), 18 pages, 12 figs., 1 table, 24 p. app.

15922. Fujitani Hilts and Associates, Inc. (1997): Seismic site hazard investigation and geotechnical investigation, proposed new church and parish center, SE Asian Vicariate, Portland, Oregon. (Report prepared for SE Asian Vicariate, Portland, Oregon, Project No. F-2943.01), 15 pages, 6 figs., 6 p. app.

16043. PBS Environmental (1998): Seismic hazards report, proposed day care facility, Portland, Oregon. (Report for Lennar Affordable Housing, Portland, OR, Project No. 12491.06), 6 pages, 7 figs.

13388. Squier Associates (1995): Geotechnical investigation, Airport Embassy Suites Hotel, Portland, Oregon. (Report for Howard Needles Tammen & Bergendoff Co., Kansas City, Mo., Project No. 95987, deposited by Jim Griffith & Associates, Inc., Portland, File No. 473.000), 24 pages, 5 figs., App. 37 p.

12599. West Coast Geotech, Inc. (1995): Seismic hazard report, new Parkrose community center/high school, Portland, Oregon. (Report prepared for Parkrose School District, Project No. W-1190), 5 pages, 2 figs.

Oregon City

16062. Braun Intertec Corporation (1999): Site-specific seismic evaluation, proposed Willamette Falls Hospital addition, 1500 Division Street, Oregon City, Oregon. (Report for Willamette Falls Hospital, Project No. EAAX-99-0132), 14 pages, 3 figs., 22 p. app.

15612. David J. Newton Associates (1997): Geotechnical investigation and seismic hazard evaluation for the Oregon City United Methodist Church, 18955 South End Road, Oregon City, Oregon. (Report for Oregon City United Methodist Church, c/o Architect [Matthew Mattsson, Architect LA, PC, Portland, Oregon], Project No. 724-101), 20 pages, 4 figs., 12 p. app.

Portland

15928. AGI Technologies (1997): Geotechnical engineering study, West Coast [Paramount] Hotel facility, Portland, Oregon. (Report for Kurt R. Jensen & Associates Architects, Seattle, Wash., Project No. 30,562.001), 25 pages, 15 figs., 16 p. app.

14889. AGRA Earth & Environmental (1995): Geotechnical investigation, Liberty Northwest Insurance Building, Portland, Oregon. (Report prepared for The Ashforth Company, Stamford, Conn., Job No. 21-08432-00, submitted by Hoffman Construction Company, Portland, Oreg.), 14 pages, 5 figs., 14 p. app.

14896. AGRA Earth & Environmental (1996): Geotechnical investigation, Metropolitan Exposition Center expansion, Portland, Oregon. (Report prepared for Yost Grube Hall, Portland, Job No. 21-08598-00, submitted by Yost Grube Hall), 15 pages, 3 tables, 6 figs., 17 p. app.

15935. AGRA Earth & Environmental (1998): Site-specific seismic evaluation, Hamilton II replacement housing (site two), SW 12th Avenue and SW Clay Street, Portland, Oregon. (Report prepared for Housing Authority of Portland, Job No. 8-61M-9684-4), 10 pages, 3 figs.

12567. Braun Intertec Corporation (1994): Site-specific seismic evaluation, proposed new fire station, Tomahawk Island Drive, Hayden Island, Portland, Oregon. (Report for Portland Fire Bureau, Project EAAX-94-0383, No. 09-124-4508), 44 pages; attached letter by Braun Intertec, dated Jan 6, 1995, in response to meeting with City officials on report on Jan. 3, 1995, 3 p.)

15592. Braun Intertec Corporation (1996): Site-specific seismic evaluation for the proposed Jesuit High School addition, SW Beaverton-Hillsdale Hwy. and SW Apple Way, Portland, Oregon. (Report for Jesuit High School, Project no. EAAX-96-0564, Report no. 09-106-2392; submitted by Soderstrom Architects, P.C., Portland), 12 pages, 2 figs., 33 p. app.

15884. Braun Intertec Corporation (1997): Site-specific seismic evaluation, proposed 74-unit motel, N. Hayden Island Drive, Portland, Oregon. (Report for Super One, Inc., Beaverton, Oregon, Project No. EAAX-97-0630, Report No. 09-117-3454), 14 pages, 3 figs., 32 p. app.

15590. Dames & Moore (1996): Groundwater pump station/interstate facility seismic vulnerability study, Portland, Oregon. Final report. (Report prepared for Portland Water Bureau, Job no. 02110-088-004), var. pages, 3 vols., app.

13383. David J. Newton Associates (1995): Geotechnical investigation and seismic hazard report for student services building, Portland Community College, Cascade Campus, Portland, Oregon. (Report for Portland Community College, Plant Services Office, Project No. 478 113, revision of Oct. 5, 1994, report), 19 pages, 3 figs., 1 table, 11 p. app.

15551. David J. Newton Associates (1996): Geotechnical investigation and seismic hazard evaluation for the proposed Emmanuel Temple Church, North Missouri Avenue at North Sumner Street, Portland, Oregon. (Report for Emmanuel Temple Church, 1032 North Sumner Street, Portland, Oregon 97217-2500, Project No. 717-101), 19 pages, 4 figs., 17 p. app.

15803. David J. Newton Associates (1997): Geotechnical investigation, proposed PSU student housing and elementary school, PSU project no. 781302, Portland, Oregon. (Report for Portland State University, Facilities Department, Project No. 674 102), 21 pages, 4 figs., 34 p. app.

15615. Fujitani Hilts and Associates, Inc. (1997): Geotechnical and seismic hazard study, College of Urban and Public Affairs, Portland State University. (Report prepared for Portland State University, Director of Facilities, Project No. 2875-01), 18 pages, 13 figs., 3 p. app.

16006. Fujitani Hilts and Associates, Inc. (1998): Seismic site hazard investigation and geotechnical investigation, proposed new parking structure, Portland, Oregon. (Report prepared for Wilshire Financial Services Group, Portland, Oregon, Job No. F-2996.01), 18 pages, 13 figs.

16027. Fujitani Hilts and Associates, Inc. (1998): Seismic site hazard investigation and geotechnical investigation, proposed Park Avenue Lofts, Portland, Oregon. (Report prepared for Enterprise Development, Portland, Oregon, Job No. F-2951.01), 13 pages, 1 table, Figures 1-4, 6 (Fig. 5 missing).

14863. Geotechnical Resources, Inc. (1995): Revised report for site-specific seismic response study, Broadway and Washington parking structure and hotel, Portland, Oregon. (Report for Ralph M. Schlesinger Co., Portland, Job No. 1.678), 11 pages, 1 table, 9 figs.

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16045. Kelly,Patrick B. (1998): Final report on geotechnical investigation and seismic hazards study, proposed new foundation for four reactors, existing building at 3625 N. Suttle Road, Portland, Oregon. (Report for Lacamas Laboratories, Project No. K322.01), 10 p., 5 figs., 11 p. app.

13349. Redmond & Associates (1995): Seismic site characterization and hazard evaluation, proposed North Harbor site, NE Marine Drive, Portland (Multnomah County), Oregon. (Report for Prima Donna Development Corp., Project No. 103.005.G), 6 pages.

15917. Rondema, Don, GeoDesign (1998): Seismic hazard study, proposed Mount St. Joseph assisted-living facility. (Report for KPFF Consulting Engineers, Portland, Oreg., submitted to Sellen Construction, Seattle, Wash., GDI Project Sellen-2), 2 pages.

13387. Wright/Deacon & Associates (1995): Seismic review, The Blazers Boys and Girls Club, NE MLK Blvd. and Roselawn St., Portland, Oregon. (Report for Boys and Girls Clubs of Portland, Project No. J95-353; deposited by JKS Architects, Portland), 7 pages, 3 figs.

Sandy

16075. Braun Intertec Corporation (1999): Site-specific seismic evaluation, proposed Boring fire station addition, 28655 SE Highway 212, Boring, Oregon. (Report for Boring Fire District No. 59, Project No. EAAX-99-0150, Report no. 09-039-3097), 14 pages, 3 figs., 22 p. app.

12581. Dames & Moore (1995): Seismic site hazard investigation, proposed Firwood Road fire station, Permit No. B0154395, Sandy, Oregon. (Report prepared for Sandy Fire District 72, Job number 30453-001-016), 5 pages, 1 fig.

Sauvie Island

15924. John McDonald Engineering (1996): Seismic study for Sauvie Island fire station. (Report for John R. Low Consulting Engineers, Portland, no Job No.), 3 pages.

15925. John McDonald Engineering (1998): Seismic hazards report, permit no. BLD98-01867 Sauvie Island fire station. (Report for City of Portland, no Job No.), 4 pages, 4 p. app.

15632. Kleinfelder, Inc. (1997): Sauvie Island site #MT-SI-1, Multnomah County, Sauvie Island. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC), var. pages.

Scholls

15633. Kleinfelder, Inc. (1997): Butternut Orchard site #WA-SAFETY-222, Washington County, Hillsboro/Aloha. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC), var. pages.

15631. Kleinfelder, Inc. (1997): Rood Bridge Rd. site #WA-HS-1, Washington County, Hillsboro. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC), var. pages.

Sherwood

15291. Kleinfelder, Inc. (1996): Phase I geotechnical study, Oregon Department of Corrections, Dammasch site, Wilsonville, Oregon, ODC #CK-WS-1. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-23), 3 tables (text missing?).

15301. Kleinfelder, Inc. (1996): Phase I geotechnical study, Oregon Department of Corrections, Dammasch Hospital site, Wilsonville, Oregon, ODC #CK-WS-2. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-23), 5 pages, 1 fig., 3 tables.

15300. Kleinfelder, Inc. (1996): Phase I geotechnical study, Oregon Department of Corrections, Wilsonville Tract site, Wilsonville, Oregon, ODC #CK-WS-1. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-23), 5 pages, 1 fig., 3 tables.

15635. Kleinfelder, Inc. (1997): Dammasch site #CK-WS-2, Clackamas County, Wilsonville. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC), var. pages.

15832. Kleinfelder, Inc. (1997): Geotechnical exploration report, medium-security prison and intake facility, Oregon Department of Corrections, Dammasch site, Wilsonville, Oregon, ODC #JF-MA-6. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-23/D01), 17 pages, 4 figs., 57 p. app.

15636. Kleinfelder, Inc. (1997): Tippet Orchard site #CK-WS-3, Clackamas County, Wilsonville. Final report, prison site location analysis, State of Oregon, Department of Corrections. (Report for KPFF Consulting Engineers/ODC, Project No. 60-8080-42/AO1), var. pages.

15918. Kleinfelder, Inc. (1998): Geotechnical exploration report, DOC women's prison and intake center, alternate Wilsonville site, SW Clay Rd., SW Grahams Ferry Rd., and SW Cahalin Rd., Washington County, Oregon. (Report for Oregon Department of Corrections, project number 60-8229-01/A01), 27 pages, 2 figs., 66 p. app. ☐

DOGAMI PUBLICATIONS

(Continued from page 43)

(IMS–6, released in 1999). The areas are important because the sliding is regional and cannot be easily studied or controlled in tax-lot-sized parcels.

The map outlines six levels of risk. The city of Salem and Marion County are in the process of developing hillside ordinances for the study areas, and the overall project is being considered as a model that other communities with similar problems can follow. This is being done with public involvement at each level and technical assistance from DOGAMI.

Released March 6, 2000:

Mist Gas Field Map, 2000 edition. Open-File Report O-00-01, map scale 1:24,000; includes production statistics for 1993–1999. Paper, $8; map on digital disk $25.

The map shows the field divided into quarter sections. It displays location, status, and depth of all existing wells

The production summary includes well names, revenue generated, pressures, production, and other data.

A cumulative report of past production at the Mist Gas Field between 1979 and 1992 is available in a separate release under the title Mist Gas Field Production Figures as DOGAMI Open-File Report O-94-6 (price $5).

Released March 13, 2000:

Mitigating Geologic Hazards in Oregon: A Technical Reference Manual, by John D. Beaulieu and Dennis L. Olmstead, Special Paper 31, 60 p., $20.

Geologic Hazards: Reducing Oregon's Losses, by John D. Beaulieu and Dennis L. Olmstead, Special Paper 32, 27 p., $10.

The two new publications are designed to give policy makers and the general public better tools to reduce the toll of geologic processes on people and property.

Special Paper 31 includes information on Oregon's past disasters, potential for future problems, issues to address when more than one hazard is present (for example, flooding and landslides), and a wide variety of strategies to mitigate hazards. It is primarily designed for planners, emergency managers, and policy makers.

Special Paper 32 is an illustrated summary of this technical manual and is designed for nontechnical users. ☐

Letter to the editor

[Regarding the cover photo of the September/October 1999 issue (*Oregon Geology*, v. 61, no. 5), showing an outcrop of the Eagle Creek Formation near the Columbia River Gorge]

It might be of interest to you that the foreground vegetation shown in the cover photo of Metasequoia Creek fossil tree remains is Japanese Knotweed (*Polygonum cuspidatum*), a Class B noxious weed in Oregon, which is invading many of our open riparian areas. Would be nice if someone could go in and give it a shot of Rodeo (glyphosate) about the time it begins to bloom this year.

Craig Markham
ODOT Wetlands Biologist
1158 Chemeketa St, NE
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(503) 986-3524 (fax)

Correction

The cover photo in our November/December 1999 issue (*Oregon Geology*, v. 61, no 6) was supplied to the Orrs, authors of the main article, by Landslide Technology, Portland. We regret the omission of this credit. *ed.*

OREGON GEOLOGY
Suite 965, 800 NE Oregon Street # 28,
Portland, OR 97232-2162

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Places to see—Recommended by the Oregon Department of Geology and Mineral Industries:

Sand dunes at Honeyman State Park in the Oregon Dunes National Recreation Area (photo courtesy of Oregon Department of Transportation)

Sand dunes that have formed since the end of the Ice Age occupy approximately 140 of Oregon's 310 miles of coast—more than in Washington or California. The oldest dunes are not easily visible any more; they are perched on marine terraces or eroded or covered with vegetation. The post-Ice-Age dunes in the coast segment between Coos Bay and Sea Lion Point (just north of Florence) are the most spectacular parts of the National Recreation Area. This is the longest strip of dunes along the Oregon coast, extending for about 55 mi and mostly about 2 mi but in places up to 3 mi wide. The dunes can be as much as a mile long and nearly 500 ft high. The slipface, the steeper, leeward side of the pictured dune, shows marks of sand streams where the dune corrects its oversteepening slopes.

Access: From Honeyman State Park on U.S. Highway 101 (coastal highway), 3 mi south of Florence. Most dunes are between the park and the ocean. Or look for South Jetty Road (Sand Dunes Drive) closer to Florence.

OREGON GEOLOGY

Oregon Department of Geology and Mineral Industries

Volume 62, Number 3, July 2000

IN THIS ISSUE:

Late Eocene fossil plants of the John Day Formation

and

Geology and Mineralization of the Blue River mining district

DOGAMI PUBLICATIONS

Publications are available from: Nature of the Northwest, 800 NE Oregon St. #5, Portland, OR 97232, info@naturenw.org or www.naturenw.org, (503) 872-2750; or from the DOGAMI field offices in Baker City, 1831 First Street, (541) 523-3133, and Grants Pass, 5375 Monument Drive, (541) 476-2496. See also the gray pages at the center of this issue.

Released April 19, 2000:

Relative Earthquake Hazard Map of the Eugene-Springfield Metropolitan Area, by G.L. Black, Z. Wang, T.J. Wiley, Y. Wang, and D.K. Kiefer. Interpretive Map Series IMS–14, 1 map, scale 1:48,000, 16 p. text, $12.

This map incorporates the latest scientific information showing the risk that residents in the area face from earthquakes. It combines the effects of ground shaking amplification and earthquake-induced landsliding (the third common effect, liquefaction, was found to present no risk) to show the earthquake hazard relative to the local geologic conditions.

THROUGH THE EYES OF THE STATE GEOLOGIST

This column will be continued in our parallel publication, the magazine *Cascadia*. —*ed*

Pilot Project: Eugene-Springfield Earthquake Damage and Loss Estimate. Final Report, January 1999, by B. Vinson and T.H. Miller. Open-File Report O-00-02, 43 p., $10.00.

The preliminary damage and loss estimate for 200 selected buildings in the Eugene-Springfield area was prepared by members of the Department of Civil, Construction, and Environmental Engineering at Oregon State University. The project scope involves the estimation of the immediate facility damage and occupant casualties for 100 buildings in Eugene and 100 buildings in Springfield for an earthquake producing an effective peak ground acceleration of 0.3 *g*, and occurring either at 2 a.m. or at 2 p.m.

Released May 18, 2000:

Memorandum: Cape Cove Landslide, Findings from Field Visit, February 10 and March 10, 2000, by G.R. Priest. Open-File Report O–00–03, 14 p., $6.

The Cape Cove landslide occurred last winter about 13 mi south of Yachats. The 14-page report was produced by DOGAMI geologist George R. Priest for the Oregon Department of Transportation. The Cape Cove landslide affected the coastal Highway 101, when the slope above the highway failed repeatedly from December 1999 through February 2000.

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Cover photo

This splendid view of Broken Top, companion to the Three Sisters in the central Cascade Range, shows the east cirque which contains a small lake impounded by a moraine. Notches in the moraine are reminders of the sometimes overlooked flood hazard such moraine lakes can present. The same year this photo was taken, 1987, saw the publication of a report by the U.S. Geologic Survey describing such volcanic hazards especially in the Three Sisters region (USGS Open-File Report 87–41. See also *Ore Bin*, v.29 [1966], no. 10, p. 182–188). Photo by contributor John H. Whitmer of Issaquah, Wash.

Late Eocene fossil plants of the John Day Formation, Wheeler County, Oregon

by Steven R. Manchester, Florida Museum of Natural History, PO 117800, University of Florida, Gainesville, FL 32611-7800

ABSTRACT

Fossil leaves, fruits, and seeds are described from a late Eocene lacustrine deposit in the lower part of the John Day Formation on the southern slope of Iron Mountain east of Clarno, Wheeler County, Oregon. The Whitecap Knoll locality is closely bracketed with radiometric dates and hence provides a new datum for the evaluation of floristic and climatic change in the late Eocene. The fossil-bearing shale is above the member A ignimbrite, dated 39.17 ± 0.15 Ma, and below a tuff dated 38.4 ± 0.7 Ma and is considered to be about 38.8 Ma. The plant assemblage includes an aquatic component (*Nelumbo*, *Ceratophyllum*), and a woodland component with broad-leaved deciduous plants (Platanaceae, Fagaceae, Juglandaceae, Ulmaceae, Aceraceae), a few broad-leaved evergreen plants (*Mahonia*, *Cinnamomophyllum*), and a few unidentified ferns but apparently no conifers. The flora lacks the diversity of broad-leaved evergreen taxa present in the middle Eocene floras of the underlying Clarno Formation, but retains a few "Clarno taxa" not known in the overlying Bridge Creek flora (*Ailanthus* and *Eucommia*). The intermediate character of this flora in comparison with middle Eocene lacustrine floras of the Clarno Formation and lower Oligocene floras of the Bridge Creek flora provides some evidence for a gradational transition from the Eocene subtropical vegetation to the Oligocene temperate forests in this region.

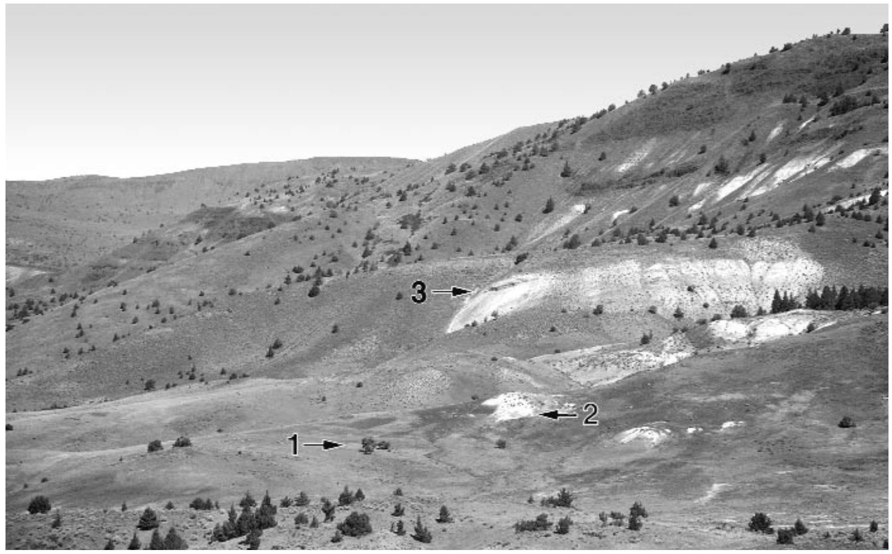

Figure 1. Oblique northwesterly aerial view of the south slope of Iron Mountain, showing (1) position of the lacustrine shale from which the Whitecap Knoll flora has been obtained, (2) the Whitecap Knoll locality from which the Ar/Ar date was obtained, and (3) the lacustrine shales of the Slanting Leaf Beds (Iron Mountain assemblage) of the Bridge Creek flora of the John Day Formation.

Figure 2. Students working at the Whitecap Knoll shale locality, with Whitecap Knoll in central part of the image and Slanting Leaf Beds to the far left.

INTRODUCTION

Paleontologically, the John Day Formation of Oregon is probably best known for its spectacular mammalian fossils of early Miocene age (e.g., Cope, 1880, 1886; Thorpe 1925; Merriam, 1930; Rensberger, 1973) and the still older plant fossil assemblages of the lower Oligocene Bridge Creek flora (Chaney, 1927; Meyer and Manchester, 1997). However, fossils from the lowermost part of the formation, which includes late Eocene strata, have received relatively little attention. Floras of late Eocene age are known from the John Day Formation in the Gray Butte area of Jefferson County, but the precise ages are difficult to determine because the associated volcanic rocks there are highly altered (Smith and others, 1998).

The Whitecap Knoll flora (Figures 1, 2; Bestland and Retallack, 1994) near the northern boundary of the Clarno Unit of John Day Fossil Beds National Monument in Wheeler County, Oregon, provides a rare opportunity to examine a late Eocene plant community that is well bracketed with radiometric dates. These dates indicate that the deposit and the species contained within it are approximately 38.8 million years old. This flora thus provides an important datum for purposes of correlation with less securely dated fossil localities in western North America. The Whitecap Knoll locality is situated near several other paleobotanically important sites (Figure 3), including sites of the underlying Clarno Formation, e.g., the Nut Beds (Manchester, 1981, 1994), the Hancock Canyon wood and leaf localities (Manchester, 1986), and Hancock Quarry (McKee, 1970; Manchester, 1994, p. 13); and of the overlying John Day Formation, such as the Slanting Leaf Beds[1] locality (Figure 1). The geology of this area has been reviewed by Bestland and others (1999) and Retallack and others (2000).

The climatic shift near the end of the Eocene from warm, equable conditions to cooler, more seasonal conditions has received much attention (e.g., Chaney, 1948; Retallack, 1992; Wolfe, 1992; Smith and others, 1998). The middle Eocene Clarno Nut Beds flora (about 44 million years old) has many tropical elements such as cycads, palms, and bananas (Manchester, 1994), indicating frost-free conditions; but the early Oligocene Slanting Leaf Beds (33.6 ± 0.19 Ma; Swisher in Bestland and Retallack, 1994, p. 137) has mostly temperate deciduous species (Meyer and Manchester, 1997). The Eocene-Oligocene boundary is currently placed at about 34 m.y. (Prothero, 1995); thus the Slanting Leaf Beds assemblage provides a glimpse of the vegetation that became established within about half a million years after the boundary. Was the climatic and floristic change abrupt, occurring over a brief interval of less than one million years, or was it rather gradual?

Detailed investigations of paleosol and alluvial sequences of the Clarno and John Day Formations in Wheeler and Grant Counties, Oregon, with ages approximated on the basis of inferred rates of sedimentation and stratigraphic position in relation to several radiometrically dated horizons, led Bestland and others (1997) to infer stepwise climatic changes across the Eocene-Oligocene transition. They recognized three major paleoclimatic shifts: from tropical to subtropical conditions at 42–43 Ma, subtropical to humid temperate conditions near the end of the Eocene at 34 Ma, and from humid temperate to subhumid temperate conditions at 30 Ma. Bestland and others (1997) note that these shifts seem to be in accord with climatic changes inferred from marine deposits and from paleobotanical studies in the Pacific Northwest. However, our understanding of vegetational and floristic change through the late Eocene remains sketchy and in danger of overgeneralization.

Wolfe (1992, p. 428) called attention to physiognomic differences between vegetation of the John Day Gulch flora of the Clarno Formation (assumed to be about 40 m.y. old but not radiometrically dated) and the Bridge Creek flora of the John Day Formation (radiometrically dated at 33.6–32.6 Ma; McIntosh and others, 1997). Whereas the former fossil assemblage is interpreted as Microphyllous Broad-Leaved Evergreen forest and contains thermophilic plants such as cycads and bananas (genus *Ensete*), the latter represents broad-leaved deciduous forest. The diverse leaf and fruit flora of John Day Gulch has not yet been described, and its age remains speculative. However, if the age estimate of the John Day Gulch assemblage is correct, there remains a gap of about seven million years between these floras; and, as Wolfe acknowledged, it is not certain whether this vegetational change, and the inferred climatic change, occurred gradually over the interval or more abruptly. Nevertheless, Wolfe concluded that there was indeed an abrupt increase of mean annual range of temperature near 33 Ma, based in part on comparison with floras in southwestern Montana. A succession of five floras through 900 m of section of the John Day Formation near Gray Butte, Jefferson County, indicates that the principal interval of climatic cooling may have been ca. 38–39 m.y. earlier, but precise radiometric control is lacking (Smith and others, 1998).

Epoch	Horizon	Unit	Radiometric age
Oligocene	John Day Formation	Slanting Leaf Beds	33.6±0.19 Ma
Eocene	John Day Formation	Whitecap Knoll tuff	38.4±0.7 Ma
Eocene	John Day Formation	Whitecap Knoll shale	
Eocene	John Day Formation	John Day member A ignimbrite	39.17±0.15 Ma
Eocene	Clarno Formation	Hancock Quarry	
Eocene	Clarno Formation	Nut Beds	43.76±0.29 Ma

Figure 3. Chart showing the relative stratigraphic positions and radiometric ages of floras and lithologic units in the vicinity of the Clarno Unit, John Day Fossil Beds National Monument.

[1] This informal name, also used by Bestland and others (1999), applies to the locality formerly referred to as Dugout Gulch by Chaney (1927) and as Iron Mountain assemblage by Meyer and Manchester (1997).

The Whitecap Knoll flora, bracketed by radiometric dates indicating an age of about 38.8 ± 0.7 million years, provides a new datum that helps to assess the transition between warm-climate vegetation of the Clarno Formation, and cooler vegetation of the overlying Bridge Creek flora. The purpose of this investigation is to evaluate the diversity, taxonomic affinities, and climatic implications of the Whitecap Knoll flora in comparison with middle Eocene and early Oligocene assemblages of the same region.

GEOLOGIC SETTING

The Whitecap Knoll assemblage takes its name from a white-topped bluff that is somewhat more resistant to erosion than surrounding strata due to an indurated white tuff (Figures 1, 2). The tuff itself has been dated at 38.4 ± 0.7 Ma based on $^{40}Ar/^{39}Ar$ analyses by C.C. Swisher III (Bestland and Retallack, 1994), providing a minimum age for the underlying fossil assemblage. The fissile, tan, lacustrine shales occur about 4 m below the white tuff, being separated by brownish to tan paleosols (referred to as an Alfisol-like paleosol; Getahun and Retallack, 1991). The shales are among sediments overlying a prominent basaltic andesite, locally mapped as member B, and are situated about 100 m above the basal ignimbrite of the John Day Formation, dated at 39.22 ± 0.03 Ma (Bestland and Retallack, 1994).

The dated white tuff of Whitecap Knoll can be traced at least 3 km east of the knoll along the southern slope of Iron Mountain. Bestland and Retallack (1994) and Bestland and others (1999) referred to this as member F tuff, because it correlates with a white tuff exposed in a cut of Highway 218 about 5 mi to the west-southwest; Robinson and Brem (1981) believed this white tuff to correspond with the member F tuff in its type area to the west near Ashwood. However, the age of the Whitecap Knoll tuff (38.4 ± 0.7 Ma), is significantly older than member F tuff in its type area (32.3 ± 0.12; Smith and others, 1998). The proper correlation of this tuff with respect to the members designated in the Ashwood area remains speculative, although it is certainly well below the distinctive member G tuff, which lies stratigraphically above the Slanting Leaf Beds (Bestland and Retallack, 1994).

METHODOLOGY

The fossil-bearing lacustrine shale of Whitecap Knoll ranges from 1 to 3 m in thickness, and is intermittently exposed over a distance of about 3 km. This treatment is based on specimens excavated from the westernmost exposure of the shale, immediately below Whitecap Knoll. It is located at 44°56.2'N., 120°25.07'W., about 3 km north-northeast of Hancock Field Station on private land adjoining the Clarno Unit of John Day Fossil Beds National Monument. The site is reached in about 30 minutes by a foot path from the field station. Scattered leaf, fruit, and seed remains and occasional fish scales were recovered by splitting the shale with hammers and chisels. We were disappointed to find that freshly removed damp shale quickly disintegrated into small fragments upon exposure as it began to dry, at the same time destroying the fossils. However, this problem was alleviated by wrapping the freshly removed fossil specimens immediately in several layers of toilet tissue, which slowed the drying process sufficiently to prevent cracking. Although the fossils are extremely rare, continued excavation over a few weeks time resulted in a collection sufficient to allow this preliminary evaluation of the flora. Fractured specimens were reassembled with Elmer's glue.

A few specimens from this locality were viewed in the collection of the John Day Fossil Beds National Monument (those cited by Bestland and Retallack, 1994). Additional samples were collected during the summers of 1995–1997 and have been deposited in the Paleobotanical Collection of the Florida Museum of Natural History. All specimens cited in the present paper that have catalog numbers prefixed by UF are housed at the Paleobotanical Collection of the Florida Museum of Natural History, University of Florida, Gainesville, Florida. Samples of the shale were also processed for palynology, but no pollen was found to be preserved.

FOSSIL PLANTS

The Whitecap Knoll flora includes three kinds of ferns, three kinds of monocots, and at least 16 species of dicots, including both extinct and extant genera. Among the genera still living today, some are still native in western North America (*Alnus*, *Quercus*, *Mahonia*, *Acer*), while others are native today in eastern North America (*Decodon*), eastern Asia (*Dipteronia*, *Craigia*, *Eucommia*), or both (*Hydrangea*, *Nelumbo*).

The three kinds of ferns (Figure 4A–C) are known only from fragments of the foliage, without fertile parts, and are thus difficult to identify relative to modern fern genera. One of the ferns, with featherlike venation (Figure 4B), appears to match a species present in the White Cliffs locality of the Clarno Formation.

Conifers are notable by their absence in this flora. Pine occurs stratigraphically below, in the Clarno Formation, and above in the Bridge Creek flora, but the distinctive needles and winged seeds are, so far, lacking from the Whitecap Knoll assemblage. The lack of *Sequoia* (common in lacustrine shales of the Clarno Formation) and the absence of *Metasequoia*, which is so common in the overlying Slanting Leaf Beds (and all other Bridge Creek flora localities), is particularly noteworthy. Getahun and Retallack (1991) and Bestland and Retallack (1994) reported *Metasequoia* from Whitecap Knoll, but I reexamined the cited specimen (JODA 3857) and could not agree with the previous identification. The specimen was

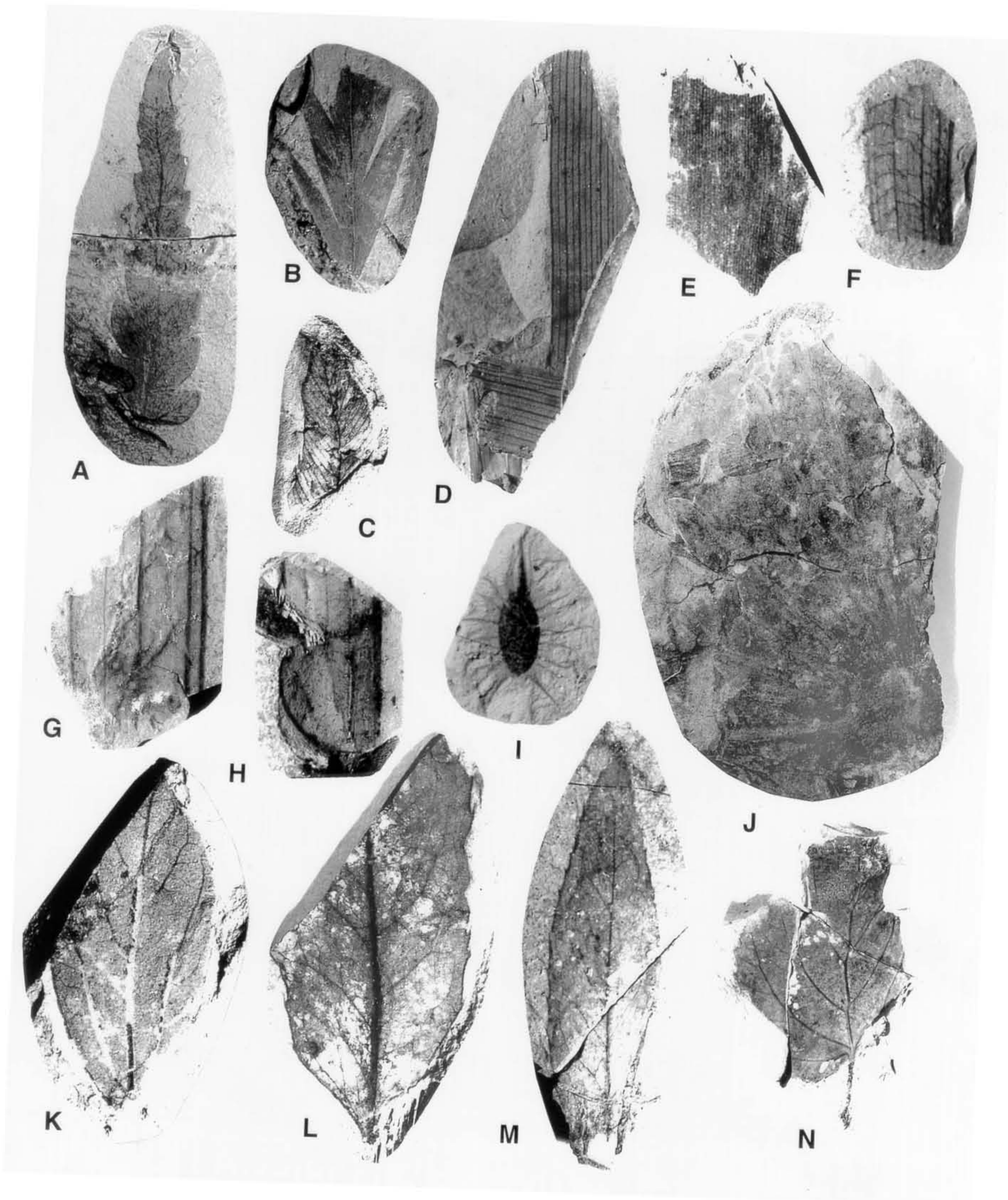

Figure 4. A. Fern 1, UF26285, x1.5. B. Fern 2, UF26289, x1.5. C. Fern 3, UF26287, x2. D. Monocot 1, UF26293, x2.5. E. Monocot 2, UF26294, x2.5. F. Monocot 3, UF26298, x2.5. G. Monocot 3, UF26304, x1.5. H. Monocot 3, UF26303, x1.5. I. Pondweed, *Ceratophyllum*, spiny fruit, UF26262, x2.5. J. Lotus leaf, *Nelumbo*, UF26344., x1. K. Lauraceae: *Cinnamomophyllum*, UF26281, x2.5. L. *Mahonia*, UF26307, x2. M. *Mahonia*, UF26310, x1.5. N. Sycamore, *Platanus*, UF26331, x1.

presumed to be a seed cone but does not show any cone scales. In our excavations, we looked especially for conifer foliage but did not observe even a single needle that could represent *Metasequoia*. *Metasequoia* was present already in the middle Eocene of Washington and British Columbia (Basinger, 1981; Wehr and Schorn, 1992). Its arrival in central Oregon evidently was sometime after 38 Ma but prior to 33 Ma.

Monocots are locally common in the assemblage, represented mostly by fragmentary remains. There are three kinds, distinguishable by their venation patterns. The first (Figure 4D) has three main orders of parallel veins organized in such a way that veins of intermediate thickness alternate with the thickest veins, with much finer parallel veins lying between them. Short, thin, wavy cross veins connect between the thickest veins and the adjacent medium-thick veins. The second kind (Figure 4E) has parallel veins that are all about equal in strength and closely spaced cross veins. The third kind (Figure 4F–H) has widely spaced thick veins interspersed with one to three veins of intermediate thickness, and with five to ten very fine veins occurring between the adjacent thick and medium-thick veins. In this species, the cross veins are more widely spaced than in the second kind. They are wavy and traverse between adjacent medium or thick veins, uninterrupted by the finer veins. Although the precise affinities of these plants are uncertain, their venation does not correspond to *Sabalites*, the palm leaves found in older floras of the region (Hancock Canyon and Nut Beds).

Ceratophyllaceae. The pondweed, *Ceratophyllum*, a rootless plant that grows submerged below the water surface, is represented in the fossil flora by its distinctive elliptical spiny fruit (Figure 4I). Although not previously known from the Tertiary of Oregon, the fruits of this genus are recorded from the middle Eocene of Washington (Wehr, 1995) as well as the Paleocene of Montana, Eocene of Wyoming, and Miocene of Nevada (Herendeen and others, 1990).

Nelumbonaceae. *Nelumbo*, the lotus, is confirmed by fragments of the large peltate floating leaves, with primary veins radiating in all directions from the center of the lamina (Figure 4J). A fine honeycomb pattern of thin veins visible under the dissecting microscope verifies that this is *Nelumbo* rather than one of the other genera of waterlilies. This represents the first report of lotus fossils from Oregon. Although widespread in the fossil record (e.g., Hickey, 1977), *Nelumbo* is more restricted in its modern distribution, with one species in eastern North America, extending south to Colombia, and a second species extending from warm parts of Asia to Australia.

Lauraceae. The Avocado family is represented by some entire-margined leaves corresponding to *Cinnamomophyllum* (a fossil genus for leaves similar to those of Cinnamon) in having a strong pair of basal secondary veins that depart from the midvein well above the base of the lamina and ascend more than $^2/_3$ the length of the lamina before looping at the margin (Figure 4K). There is also a vein that runs directly along the margin. Such leaves occur in more than one living genus of the Lauraceae, so the precise identity with modern genera remains uncertain. Another leaf that might represent the Lauraceae is slender, with entire margins and more standard pinnate secondary venation (Figure 7A) and is provisionally placed in *Litseaphyllum*.

Berberidaceae (*Mahonia*). The Oregon grape genus is represented by a few leaflets in the assemblage (Figures 4L,M). Each leaflet has a serrate margin with a thick marginal vein and spiny teeth. The secondary veins are pinnate and camptodromous, giving rise near the margin to tertiary veins that either loop or enter the teeth. The same genus is present in the Slanting Leaf Beds and other assemblages of the Bridge Creek flora, but that species, *M. simplex*, is distinguished by fewer secondary veins and fewer but more prominent teeth.

Platanaceae. The sycamore family is represented by many fragmentary leaf specimens with regularly spaced blunt teeth (e.g., Figures 4N, 5E,H,I) and by a few isolated fruitlets (Figure 5C). As is the case with most extant species of *Platanus*, the base of the petiole is much enlarged (Figure 5D). There is no trace of *Macginitiea*, the common extinct sycamore (plane tree) of the Clarno Formation (also known from the Sumner Spring flora of the John Day Formation near Gray Butte; Manchester, 1986; McFadden, 1986).

Ulmaceae. Elm was also a component of the flora, as indicated by a few fragmentary specimens of *Ulmus* leaves (e.g., Figure 6F) showing the characteristic thick petiole, basally asymmetrical lamina, and serrate margin. In addition, two of the distinctive winged fruits have been recovered (e.g., Figure 6K). *Ulmus* is present both in the Clarno and Bridge Creek floras, but is more diverse in the later.

Fagaceae (*Quercus*, 2 species). The oaks are represented by two kinds of leaves in the assemblage. Both have narrow elliptical laminae with many (15–20) pairs of secondary veins. One kind (Figure 5A) has mostly entire-margined leaves but with a few inconspicuous teeth where secondary veins enter the margin, particularly in the upper half of the leaf. The other type (Figures 5B,G) has regularly spaced prominent, often spiny teeth corresponding to each of the secondary veins. This second kind is similar in general form to *Castanea* as well as *Quercus*, but the former is ruled out by the presence of a marginal vein in the fossil laminae—a feature of oaks but not chestnuts.

Betulaceae. The genus *Alnus* (alder) is represented by a few fragmentary leaves (Figures 5F, 6A). They are similar in form and venation to *Alnus heterodonta* of the Bridge Creek and West Branch Creek floras but tend to have more subtle teeth. As yet, the distinctive fruits and fruiting cones have not been recovered, although they are common in the Clarno and Bridge Creek floras.

Juglandaceae. The walnut family is represented by at least one kind of leaflet (Figures 6B,C) and two genera of wind-dispersed winged nuts in the Whitecap Knoll assemblage. *Palaeocarya* is the name given to fossil winged nuts that resemble the fruits of two modern genera in the Juglandaceae: *Engelhardia* (of modern Asian distribution), and *Oreomunnea* (of modern tropical American distribution). The fruits of *Palaeocarya* from Whitecap Knoll (Figures 6L,M) are similar—in form

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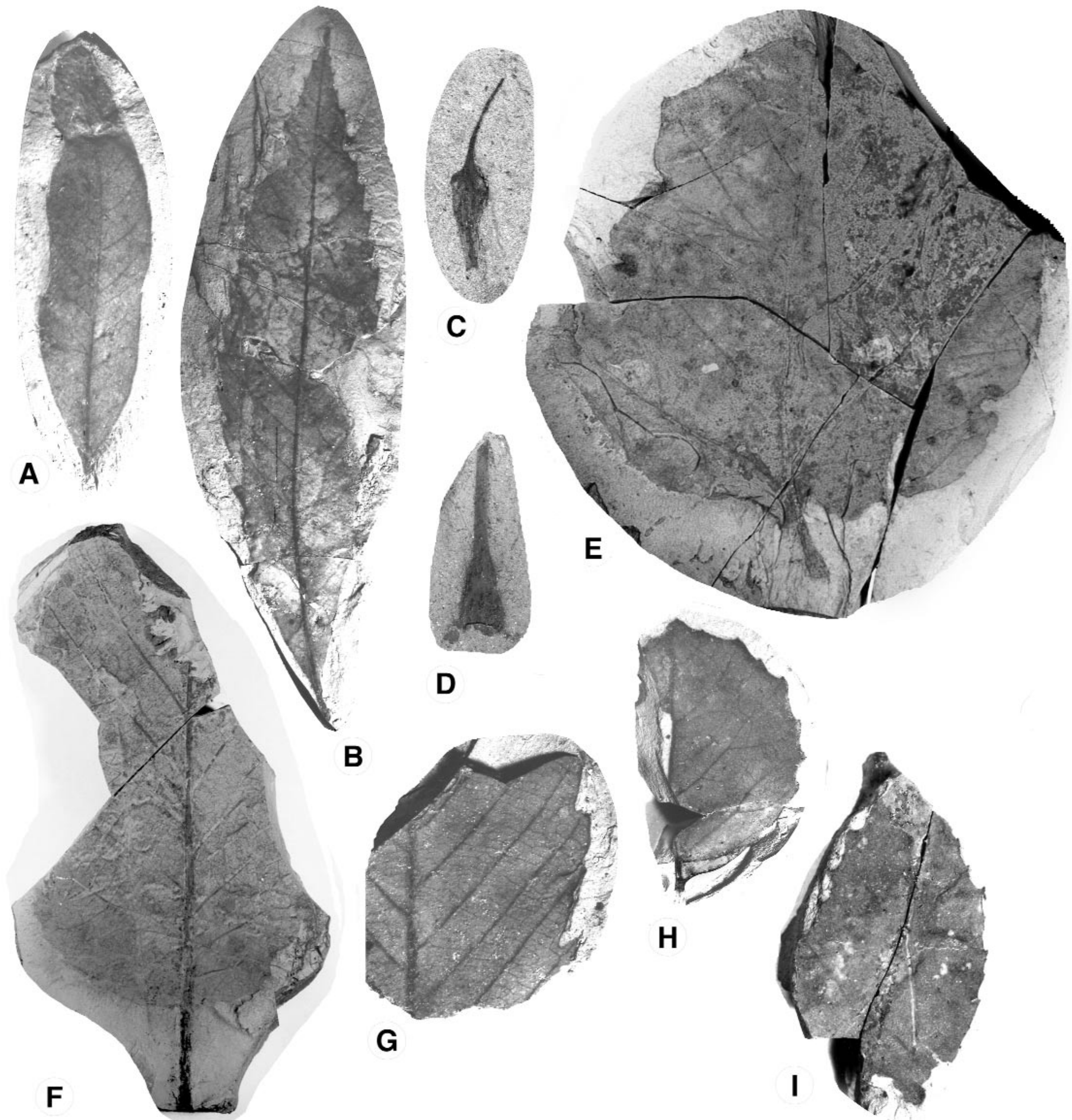

Figure 5. A. Oak leaf, *Quercus*, with a few small teeth on the margin, UF26354, x1.5. B. *Quercus* with more prominent teeth, UF26072, x1. C. Sycamore fruitlet, *Platanus*, UF26386, x3. D. Characteristic expanded petiole base of *Platanus*, UF30544 x1. E. *Platanus* leaf, UF30896, x1. F. Alder, *Alnus*, UF26339, X1. G. *Quercus* with detail of venation, UF26371, x2. H. *Platanus*, UF26077, x1. I. *Platanus*, UF26329, x1.5.

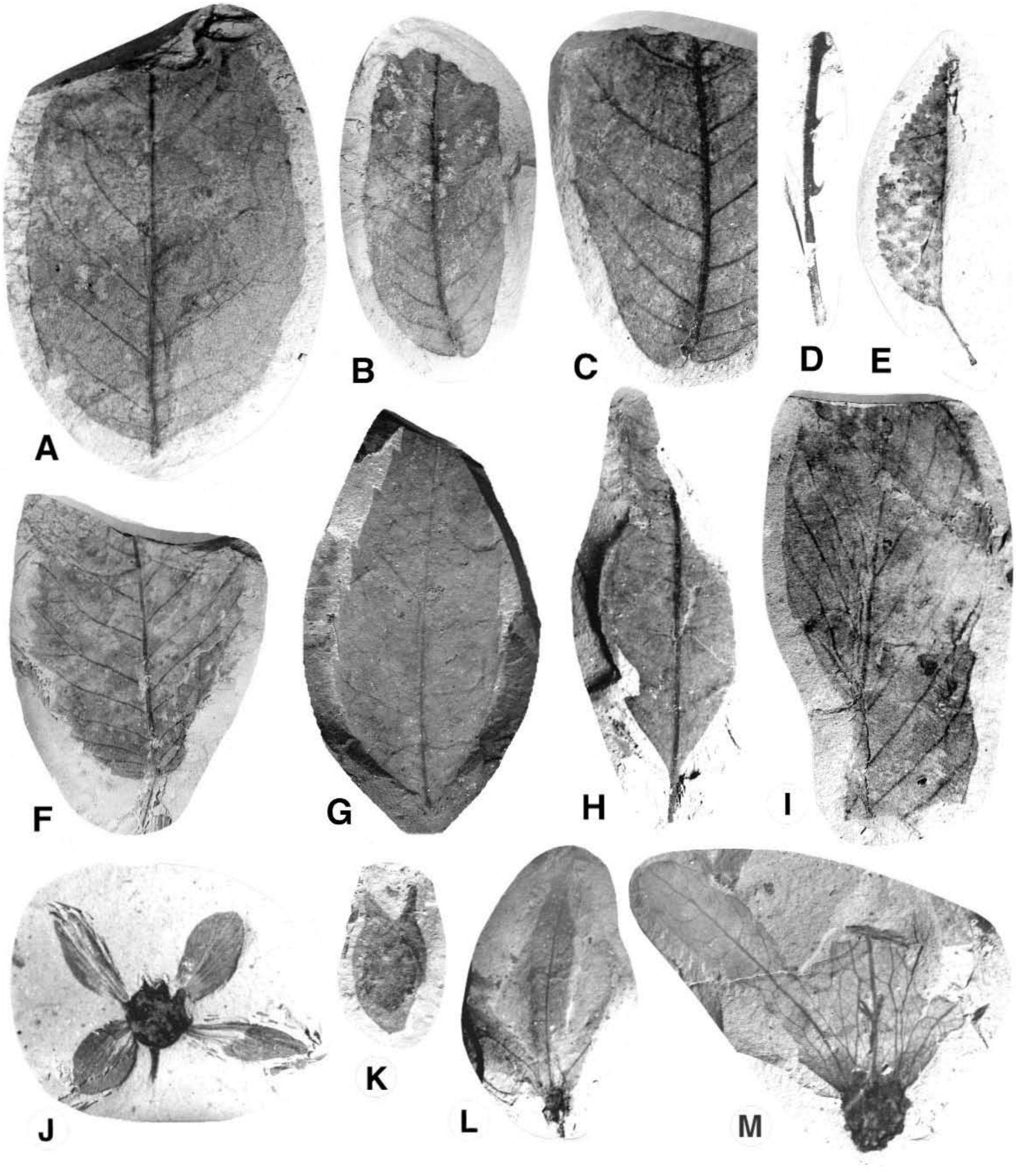

Figure 6. A. *Alnus*, UF26347, x2. B. Juglandaceae, UF26073, x1 C. Counterpart of the leaflet in B, UF26073′, x2. D. Rose family prickly twig, UF26277, x1. E. Rose leaflet, *Rosa* sp., UF26273, x2. F. Elm leaf, *Ulmus* sp., UF26264., x1. G. Unidentified leaflet, UF30895, x1.25. H. *Decodon*, UF26284, x2. I. Rhamnaceae, showing very closely spaced tertiary veins, UF26369, x3. J. 4-winged fruit of *Cruciptera*, UF26231, x2.5. K. Winged fruit of Elm, *Ulmus*, UF 26313, x4. L. *Palaeocarya*, UF26074, x1.1. M. *Palaeocarya*, UF26248, x2.

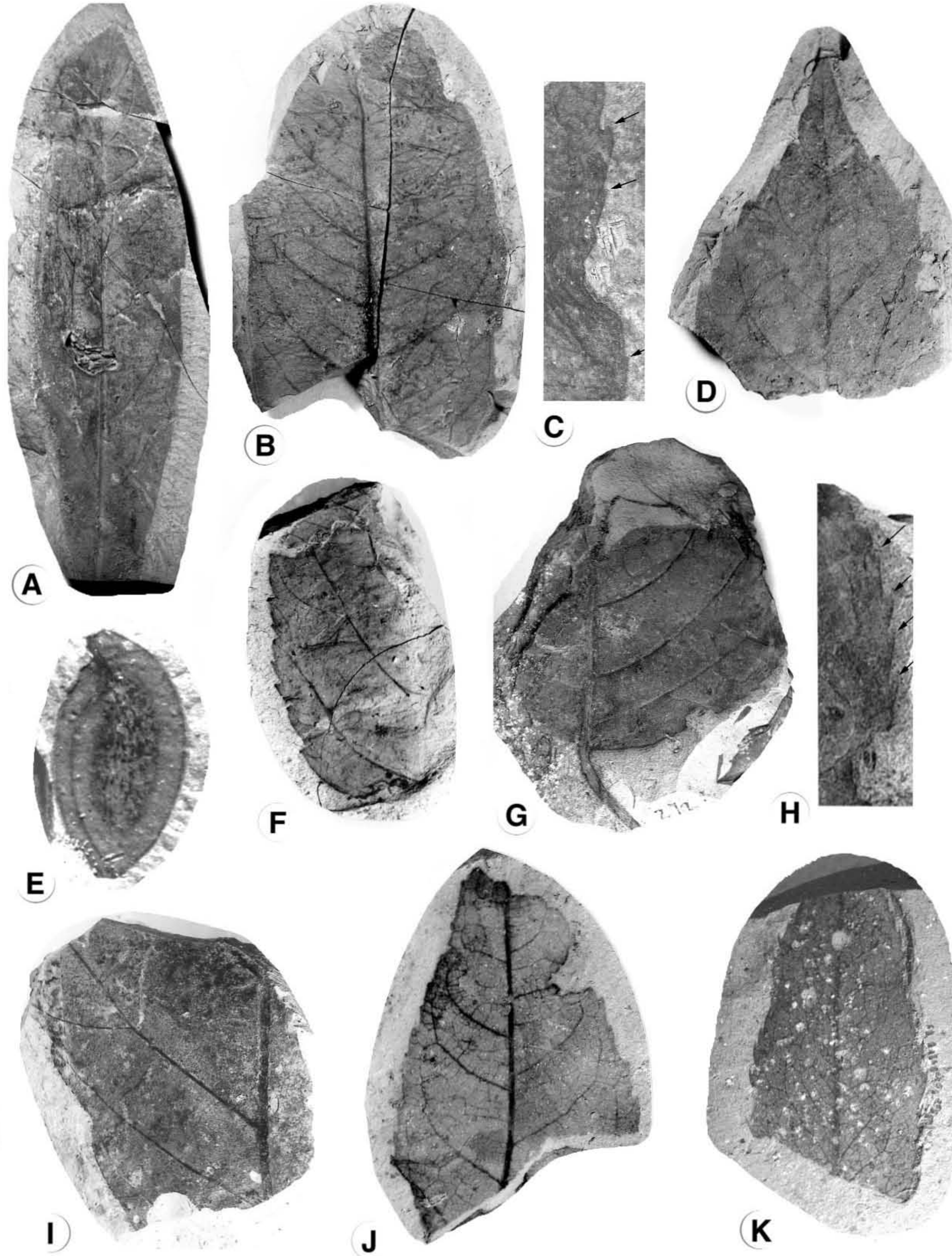

Figure 7. A. *Litseaphyllum*, UF 30540, x1. B. Unidentified leaf with prominent intersecondary veins and fine marginal serration, UF26346, x1. C. Detail of margin from B, showing teeth (arrows), x3. D. Apical portion of an unidentified serrate leaf, possibly *Acer*, UF 26352, x1.5. E. Elliptical winged fruit of *Eucommia montana*, UF , UF26321 x4. F. Unidentified serrate leaf, UF26345, x2. G. Basal portion of a leaf with prominent petiole, UF 26327, x1. H. Detail of margin from G, showing teeth (arrows), x. 2.5. I. Unidentified leaf with crenulate margin, UF26340, x1.25. J. Unidentified serrate leaves, UF26342, x 2.5. K. Small serrate leaf, UF26306, x 3.

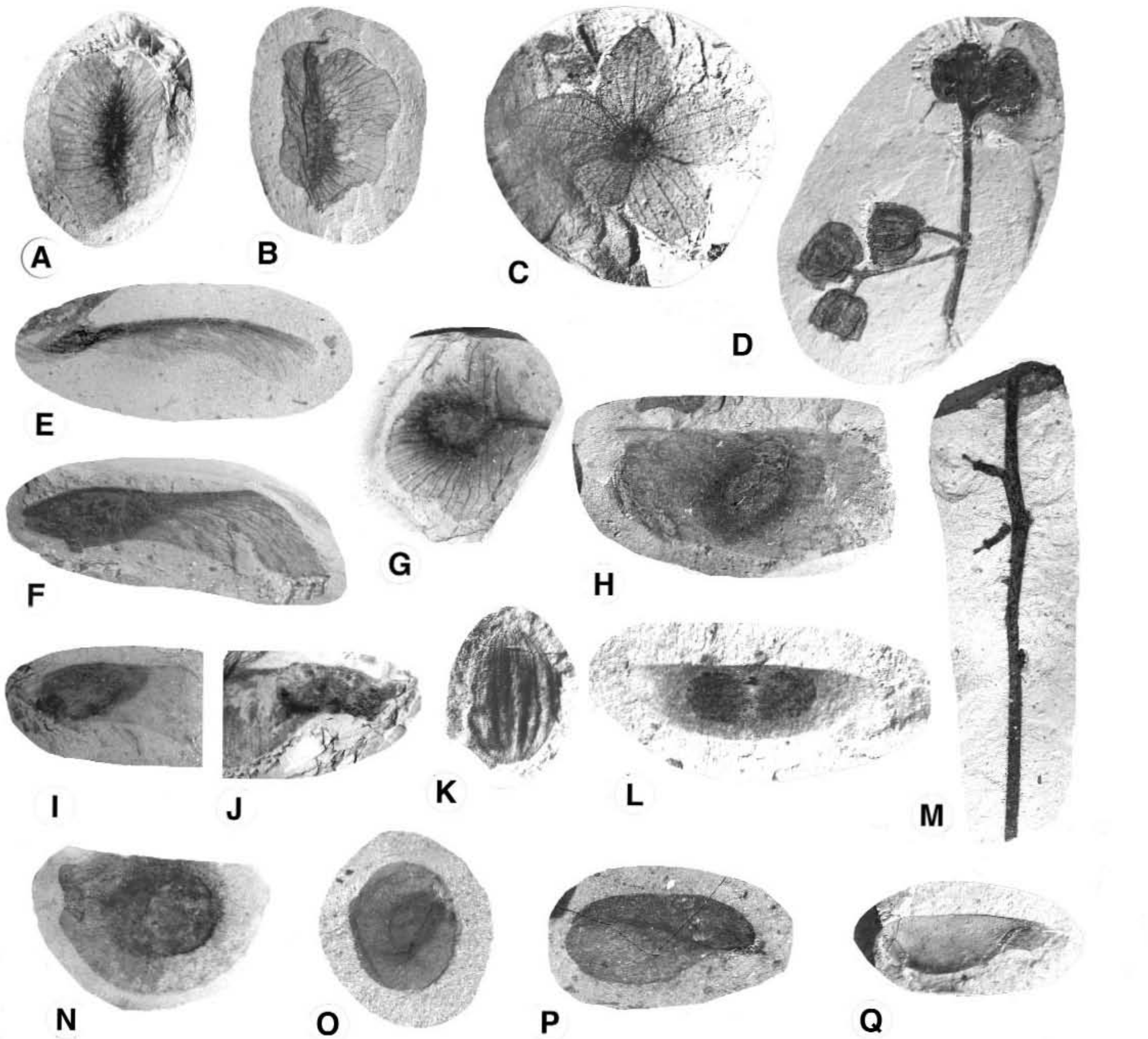

Figure 8. A. Winged fruit valve of *Craigia*, UF26261, x2. B. *Craigia*, UF26259, x2. C. *Florissantia ashwilli*, UF26271, x1.5. D. *Hydrangea infructescence*, UF26376, x2.5. E. *Acer* 1, UF26242, x2.5. F. *Acer* 2, 30533, X2.5. G. *Dipteronia* winged fruit, UF26428, x2. H. *Ailanthus*, UF26255, x2. I. *Acer*, UF26241, x2. J. *Acer*, UF26240, x2. K. *Nyssa*, UF26383, x1.5. L. *Catalpa*, UF26394, x6. M. Unidentified fruiting axis with fruits previously shed, 26392, x 1.5. N. Unidentified winged seed with prominent attachment scar, UF26244, x2. O. *Beckerospermum ovalicarpa* seed, UF26391, x3.5. P. Unidenfied winged seed, UF30546, x4. Q. Unidentified winged seed, UF26377, x2.

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and venation of the trilobed wing and in presence of a long style—to those known from the West Branch Creek and Cherry Creek lacustrine shale localities of the Clarno Formation.

Cruciptera is an extinct genus of the walnut family with a nut surrounded by four orthogonally arranged, straplike wings (Figure 6J). Getahun and Retallack (1991) referred to these winged fruits as *Tetrapteris*, a modern genus of the Malphigiaceae, but subsequent study showed that they belong to the fossil genus *Cruciptera* of the Juglandaceae. *Cruciptera simsonii* is a characteristic species of the Clarno Formation, occurring at the Nut Beds and in lacustrine deposits of West Branch Creek and Cherry Creek (Manchester, 1991). Whereas the *C. simsonii* specimens have a wing span of 21–41.5 mm, the *Cruciptera* fruits at Whitecap Knoll range only from 12 to17 mm, placing it in the size range of *Cruciptera schaarschmidtii*, a species first described from the middle Eocene of Germany (Manchester and others, 1994). Similarly small fruits with wingspans of 12–19.5 mm (n=16) also occur in the Sumner Spring assemblage.

Eucommiaceae. Distinctive elliptical winged fruits of *Eucommia*, a genus native only to China today, are especially abundant in the deposit (Figure 7E). In their review of the North American fossil record of this genus, Call and Dilcher (1997, Figures 29,30) illustrated two Whitecap Knoll specimens which they assigned to the *Eucommia montana*—a species known also from lacustrine shales of the Clarno Formation and from localities in Montana, Utah, and Colorado. Although present in the middle Eocene shales of the Clarno Formation, this genus has never been observed in the Bridge Creek flora.

Malvaceae. *Craigia* is a genus of the Malvaceae (as broadly circumscribed including Tiliaceae) that grows today in southern China and Vietnam. The genus has an excellent fossil record, based on its distinctive winged fruit valves (Figures 8A,B), from the Tertiary of Europe and Asia as well as western North America. In North America, *Craigia* is common in the Bridge Creek flora (Meyer and Manchester, 1997; called *Pteleaecarpum* by Manchester and Meyer, 1987). The genus is not known from middle Eocene deposits of the Clarno Formation, (not found in the Nut Beds, West Branch Creek, or Cherry Creek) but does occur in the presumed late Eocene John Day Gulch flora.

Flowers of the extinct genus ***Florissantia*** are known from Eocene and Oligocene localities in western North America (Manchester, 1992) and the Miocene of Sikhote Alin (Manchester, 1999). The small size of the Whitecap Knoll calyces and prominence of sepal lobes (Figure 8C) identifies the species as *Florissantia ashwilli*, which also occurs in the Sumner Spring flora at Gray Butte. Although formerly placed in the Sterculiaceae, that family has recently been merged with Tiliaceae and Bombacaceae in the more broadly circumscribed Malvaceae.

Hydrangeaceae. *Hydrangea* is represented by a single fruiting branch (Figure 8D). The woody fruit capsules show a flat apical disk and remnants of at least two styles and have prominent longitudinal ribs, conforming to the fruits of other modern and fossil species. The attractive four-parted calyces, known both in the Clarno Formation (Manchester, 1994, pl. 58, fig. 6) and in the Bridge Creek flora (Meyer and Manchester, 1997, pl. 45, figs. 7,8), have not yet been recovered from the Whitecap Knoll assemblage.

Rosaceae. The rose genus, *Rosa*, can be recognized on the basis of its small leaflets with closely spaced, rounded teeth (Figure 6E). Stems with rosaceous prickles have also been recovered (Figure 6D). *Rosa* is not known from the Clarno Formation but occurs in the Slanting Leaf Beds and other localities of the Bridge Creek flora (Meyer and Manchester, 1997).

Nyssaceae. The impression of an ellipsoidal woody fruit with longitudinal ribs (Figure 8K) is similar to that which might be made by the stone of *Nyssa*, the tupelo tree. However, this identification remains uncertain because the impression of germination valves could not be seen. *Nyssa* is represented in the Nut Beds flora of the Clarno Formation but has not been confirmed in the Bridge Creek flora. Some of the modern species grow along lakes and streams and in swampy areas.

Sapindaceae. The maple family, traditionally called the Aceraceae but now merged with the Sapindaceae (Judd and others, 1999), is represented in the Whitecap Knoll flora by two extant genera: *Acer* and *Dipteronia*. Four fragmentary *Acer* fruits have been recovered from the Whitecap Knoll assemblage (Figures 8E,F,I,J). No complete leaves have been recovered, but one fragmentary specimen (Figure 7D) appears to represent one of the lobes of a maple leaf. *Acer* is not found in the middle Eocene lacustrine assemblages of the Clarno Formation but occurs in the late Eocene John Day Gulch and at the Sumner Spring assemblages.

Native to China today, *Dipteronia* has distinctive fruits that are readily recognized as fossils (Figure 8G; Manchester, 1999). The fruits are also known as rare components of Clarno lacustrine localities. A single specimen has been identified in the Bridge Creek flora (Meyer and Manchester, 1997, pl. 60, fig. 18). They are sometimes encountered in the Sumner Spring flora near Gray Butte (McFadden, 1986).

Rhamnaceae. A small leaf with entire to slightly undulating margins, pinnate secondary veins, and thin, very closely spaced, parallel tertiary veins (Figure 6I) compares favorably with leaves of extant *Berchemia* and *Rhamnidium* of the Rhamnaceae.

Simaroubaceae. The Chinese tree of heaven, *Ailanthus*, is known from a single specimen of its characteristic biwinged fruit (Figure 8H). *Ailanthus* occurs in lacustrine floras of the Clarno Formation and in the Sumner Spring flora at Gray Butte but has never been observed in the Bridge Creek flora.

Lythraceae. A small slender leaf with an intramarginal vein and irregular tertiary venation (Figure 6H) corresponds to those identified as *Decodon* from the the Bridge Creek flora (Meyer and Manchester, 1997). The leaves correspond in venation to the single living species, *D. verticillata* of eastern North America, but the lamina is relatively small, as are those from the Sumner Spring and Bridge Creek floras. The genus is known from silicified fruits in the Clarno Nut Beds flora (Manchester, 1994).

Bignoniaceae. *Catalpa* is recognized by a single seed (Figure 8L), which is bilaterally symmetrical with a straight, straplike wing on either side of the central body and with a tuft of hairs at the distal margin of each wing. *Catalpa* seeds are also present at two assemblages of the Bridge Creek flora (Meyer and Manchester, 1997).

Beckerospermum. This is a winged seed of uncertain affinity (Figure 8O) that is relatively common at the Slanting Leaf Beds and most other localities of the Bridge Creek flora (Meyer and Manchester, 1997) and is also known from the Mormon Creek flora of Montana (Becker, 1960, pl. 30, figs. 16-20) and Haynes Creek flora of Idaho (Axelrod, 1998, pl. 9, fig. 6).

Unidentified reproductive structures. A few of the fruits and seeds from Whitecap Knoll remain mysterious. Included are a fruiting axis from which the fruits had shed prior to fossilization (Figure 8M), an oval winged seed (Figure 8N), and some laterally winged seeds (Figures 8P,Q). Although superficially similar to seeds of *Cedrela* and pinaceous conifers, the cellular patterns of the wings do not correspond (Howard Schorn, written communication, March 2000).

Unidentified leaves. Current collections include several leaf types whose identity remains uncertain. I illustrated them here in the hope that future work will be able to link them to fossils from other sites and/or to extant genera. They include a serrate leaflet with the secondary veins terminating in prominent acute teeth (Figure 6G), a leaf with common intersecondary veins and very finely serrate margin (Figures 7B,C), one with a crenulate margin (Figure 7I), and three additional serrate leaf types (Figures 7F,J,K).

VEGETATION TYPE

The Whitecap Knoll plant assemblage includes elements representing both the aquatic plant community of the lake and the surrounding forest community. The aquatic indicators are *Ceratophyllum*, which grows suspended in the water without roots, and *Nelumbo*, which has floating leaves with long petioles that attach a rhizome located at the bottom of the pond or lake. Together, these plants indicate quiet water conditions and relatively shallow water depth. *Decodon* is also at home in shallow water areas. It is likely that some of the unidentified monocot foliage represents marshy plants like *Typha* (cattail).

Aside from the aquatic plants and the three kinds of ferns, the remaining plants represent woody trees and shrubs. Some were broad-leaved evergreens, including Oregon grape (*Mahonia*) and perhaps *Cinnamomophyllum*, but most appear to have been deciduous (e.g., *Platanus*, *Quercus*, *Ulmus*, *Acer*, *Dipteronia*, *Rosa*, *Catalpa*). These plants are typical of temperate forest today.

COMPARISON WITH OLDER AND YOUNGER FLORAS IN THE REGION

The Whitecap Knoll flora has a moderate diversity of about 35 species, but this is lower than the Nut Beds (173 species), West Branch Creek (55 species), and the Slanting Leaf Beds (44 species). It lacks remains of palms, cycads, bananas, Menispermaceae and other thermophilic indicators common in the Clarno Formation Nut Beds, West Branch Creek, Gosner Road, and John Day Gulch localities. Table 1 compares the taxonomic composition of the Whitecap Knoll flora with specified Clarno and John Day Formation floras. Elements shared with the Clarno flora but not known from the Bridge Creek flora include *Ailanthus*, and *Eucommia*. Two genera are shared with the Bridge Creek flora that are not known from the Clarno: *Rosa* and *Catalpa*.

At the species level, the Whitecap Knoll flora shows greater similarity to the Sumner Spring flora near Gray Butte than to the Clarno or Bridge Creek floras. In the cases of *Florissantia*, and *Cruciptera*, the Whitecap Knoll species is distinct both from those in the middle Eocene localities of the Clarno Formation (West Branch Creek, White Cliffs, Gosner Road), and from those in the Oligocene Bridge Creek flora but corresponds to those known from the late Eocene Sumner Spring flora. The Sumner Spring flora is situated stratigraphically below John Day Formation member B basalts, in lacustrine sediments interpreted to represent John Day member A (Smith and others, 1998). In contrast, the Whitecap Knoll flora occurs above basalts that were mapped as member B (Bestland and others, 1999). Whether the member B basalts are actually coeval in these different areas, is uncertain. Whole-rock radiometric dates of this basalt show a lack of precision due to alteration (Smith and others, 1998). If the B basalts are assumed to be coeval, then the Sumner Spring flora predates the Whitecap Knoll flora. However, the maximum age of the Sumner Spring flora is constrained by the radiometric dates of 39.22 ± 0.03 Ma on the basal ignimbrite of the Formation. If the Whitecap Knoll flora is correctly placed at about 38.8 Ma, then the Sumner Spring flora would be less than a million years older.

The Whitecap Knoll flora is about five million years older than the overlying Slanting Leaf Beds assemblage and differs in various respects, due to the disappearance of some taxa and the appearance of new ones, perhaps partially in response to changing climate. The apparent absence of conifers is striking, compared to the Clarno localities which have *Pinus*, *Sequoia*, and Taxaceae. *Metasequoia*, which was to become a dominant in the Slanting Leaf Beds and other assemblages of the Bridge Creek flora, is not seen in the Whitecap Knoll flora, although it was already present in the middle Eocene of Washington. Its arrival in the John Day basin evidently occurred sometime between 38 and 33.8 Ma.

CLIMATE

The floristic composition suggests temperate climate. Exclusively tropical to subtropical plants such as cycads, palms, bananas, and various families of lianas, seem to be absent, suggesting winters with frost. With the exception of Oregon grape, which is known to tolerate freezing temperatures, broad-leaved ever-

Table 1. List of the plant genera in the Whitecap Knoll assemblage, showing shared (×) occurrences in other selected Eocene and Oligocene assemblages of north-central Oregon: NB = Nut Beds, WBC= West Branch Creek, JDG = John Day Gulch, WCK = Whitecap Knoll, SS= Sumner Spring, SLB= Slanting Leaf Beds, FO = Fossil-Wheeler High School

	Clarno Formation			John Day Formation			
Taxa	**NB**	**WBC**	**JDG**	**WCK**	**SS**	**SLB**	**FO**
Fern 1 (Figure 4A)				×			
Fern 2 (Figure 4B)		×		×			
Fern 3 (Figure 4C)				×			
Monocot 1 (Figure 4D)				×			
Monocot 2 (Figure 4E)				×			
Monocot 3 (Figure 4F-H)				×			
Ceratophyllum (Figure 4I)				×			
Nelumbo (Figure 4J)				×			
Cinnamomophyllum (Figure 4K)	×	×	×	×	×	×	
Mahonia (Figure 4L,M)		×	×	×	×	×	×
Platanus (Figure 4N, 5E,H,I)	×	×	×	×	×	×	×
Quercus sp. 1 (Figure 5A)				×	×		
Quercus sp. 2 (Figure 5B,G)				×		×	×
Alnus (Figure 5F, 6A)		×	×	×	×	×	×
Palaeocarya (Figure 6L,M)	×	×	×	×	×	×	×
Cruciptera (Figure 6J)	×	×	×	×	×	×	×
Eucommia (Figure 7E)		×	×	×	×		
Ulmus (Figure 6F,K)		×	×	×	×	×	×
Hydrangea (Figure 8D)	×	×		×		×	×
Rosa (Figure 6D,E)				×	×	×	×
Rhamnaceae (Figure 6I)	×	×	×	×			
Acer (Figure 8E,F,I,J)			×	×	×	×	×
Dipteronia (Figure 8G)		×		×	×		
Ailanthus (Figure 8H)		×	×	×	×		
Florissantia (Figure 8C)		×	×	×	×	×	×
Craigia (Figure 8A,B)			×	×		×	×
Decodon (Figure 6H)	×	×	×	×	×	×	×
Beckerospermum (Figure 8O)				×	×	×	×
Catalpa (Figure 8L)				×			×

green plants are also rare: the flora is dominated by deciduous elements. The absence of large-leaved broad-leaved evergreens is another indication that the climate was not as warm as during deposition of the Clarno Formation. This suggests that the transition to temperate climate had already occurred by about 38.8 Ma.

Using the simple linear correlation reported by Wolfe (1979; also Wing and Greenwood, 1993) between the percentage of dicotyledonous species with entire-margined (not serrated or lobed) leaves and mean annual temperature derived from modern vegetation, it is possible to infer the approximate mean annual temperature (MAT) of fossil leaf assemblages. For this exercise, I used the equation derived from Wolfe's work on modern vegetation of China (Wolfe, 1979): MAT (°C) = $1.14 + 0.306 \times E$, where E is the percentage of entire-margined leaves. The dicotyledonous leaves from Whitecap Knoll include five species that are entire margined and 14 that are not (toothed or spiny along the margin). Hence, about 26 percent are entire margined, in comparison with 23 percent in Iron Mountain (Slanting Leaf Beds). Table 2 compares the results of this univariate evaluation of MAT for selected floras of the Clarno and John Day Formations.

The Whitecap Knoll flora indicates a MAT only about 1° higher than that of the Slanting Leaf Beds (considering the margin for error, they can be considered as overlapping) but perhaps 8° lower than that of the Nut Beds, and 5° lower than White Cliffs. The Oligocene assemblage of Fossil, Oregon (ca. 32.6 Ma, McIntosh and others, 1997; Meyer and Manchester, 1997), actually appears a few degrees warmer than the Whitecap Knoll flora (Table 2). Based on the relatively low values of MAT computed for both the Sumner Spring and the Whitecap Knoll flora, we may infer that the regional cooling had already occurred or was in progress by 38.8 Ma, well before the Eocene-Oligocene boundary (34 m.y.).

Our current understanding of the Whitecap Knoll flora remains limited by the relatively small number of samples, filling only three drawers in our museum cabinets (vs. 30 drawers from West Branch Creek, 25 from the Iron Mountain assemblage). It may be that continued collecting will bring forth significant additional taxa helpful to a more reliable reconstruction of the flora and climate.

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Table 2. Comparison of conifer abundance, diversity of dicotyledons, proportion of entire-margined leaves and inferred Mean Annual Temperature (MAT) for selected floras of the Clarno and John Day Formations, north-central Oregon

	Clarno Formation				John Day Formation			
	West Branch Creek	Nut Beds	White Cliffs	John Day Gulch	Sumner Spring	Whitecap Knoll	Slanting Leaf Beds	Fossil
Age (to nearest 0.5 Ma)	45	44	44.5	40	38	39	33	32.5
No. conifers	3	3	3	5	1	0	2	2
No. dicot species	41	69	61	40	19	19	31	53
No. entire margined	17	33	26	12	4	5	7	19
Percent entire margined	42	52	43	30	21	26	23	35
Inferred MAT (°C)	14	17	14	10.3	7.6	9	8–9	11–12

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Letter to the authors

of "The other face of Oregon: Geologic processes that shape our state," in the November/December 1999 issue of *Oregon Geology* (v. 61, no. 6, p. 131–150), Reprinted here in part, with permission.

I'd like to commend you on tackling a summary article on this important theme. I have studied hazardous geologic processes for nearly 20 years and have been involved in extensive outreach and educational efforts about those same hazards; so I realize how important this topic is—I sincerely hope my comments will be helpful in future revisions of this article—which I hope to see.

Re. lateral blasts:

On p. 131 you note (and I agree) that the "media will often pump up any event to catastrophic levels" The closeup focus of some media coverage (often with minimal background information) pumps events up simply by virtue of its lack of context.

I think one way to encourage a better resolution or visualization of the hazards by the media is to repeatedly emphasize to them that natural events such as lahars, pyroclastic flows, etc., follow natural laws and tend to behave, within certain ranges of probability anyway, in reasonably expectable ways. For example, lahars have a certain physical scale and range of behaviors (flow depth, runout distance, velocity, etc.) when flowing along a valley bottom. To this end, I strongly believe that we earth scientists should very carefully consider what we say and how we say it when explaining these processes. One of the reasons for my concern about this is my experience that the general public does not adequately understand the nature and scale of many hazardous natural processes. On one recent TLC "documentary" about Mount Rainier hazards, for example, a geologist made the claim that lahars from Mount Rainier would inundate Seattle—not one effort was made to discuss the flow limitations of lahars and how they might be topographically channeled! The result of such statements could more properly be called "tabloid journalism" than documentary journalism.

I think that your statement that "lateral blasts are not uncommon in Cascade volcanoes" exaggerates the hazard of this kind of eruption and is one example of where discussion of natural processes should have included better definition of the nature, scale, and frequency of the hazardous process. The public visualizes "lateral blast" as having the same scale and power as the 1980 event. In truth, most of the recognized Holocene sedimentologic evidence for lateral explosions in the Cascades is that of events that probably were considerably less energetic and less extensive than the Mount St. Helens blast. Examples are found at Mount Rainier (F and S tephra layers) and the Sugar Bowl and March 1982, February 1983, and May 1984 small explosive events at Mount St. Helens). I certainly agree that a Mount St. Helens 1980-scale event is possible; we have analogs at Bezymianny, Kamtchatka, and probably elsewhere. But I don't think there is any evidence that would justify us to say it's "not uncommon".

Were the truly catastrophic events humongous?—heck yes, but we need to show that lesser events (though potentially very serious and relatively huge in their own right) are much more common, that those processes obey the laws of physics, and that they commonly have a scale and flow behavior that constrains their extent topographically. Encouraging this realistic understanding reduces the sensationalism and allows interpretation of hazard maps as positive information for planning and preparedness options, not as frightening scenarios of "doom and gloom."

Re. increased volcanism:

[Article, p. 146: ". . . and there is speculation that the Northwest may be entering another period of volcanic activity."—*ed.*]

While W.E. Scott (1980; Geoscience Canada, v. 17, no. 3) notes a statistical clustering of eruptive activity that seems to show a period of increased volcanism over the past 4,000 years, I don't know of any evidence to suggest that we are now "entering another period of volcanic activity."

Re. the Bonneville landslide:

[Article, p. 135: ". . . massive slides that took place around 300 years ago—the same time as the last great subduction earthquake."—*ed.*]

New radiocarbon ages on the Bonneville landslide have created a fair amount of interest; however, there is no compelling evidence so far to say it occurred "at the same time as the last great subduction zone earthquake." In fact, [a new study] shows that the rockslide-debris avalanche (not "earth flow") is most likely to have occurred in the century and a half before A.D. 1700, with the highest probability roughly between about 1550 and 1670 (estimating). In fact, although there are no high-quality master chronologies of tree ring data for the area near the Bonneville slide, I did measure the ring width and latewood width of the sample we dated and have attempted to cross-date these series with those of old-growth trees near Carson and west of Mount Hood. So far, a matrix of best possible matches does not include A.D. 1699 as the date of the last ring—what it would be if the Bonneville landslide were triggered by the great Cascadia earthquake of 1/26/1700. While our data still permit the slide to be generated by the great Cascadia quake, we should include other hypotheses on its cause until we get better resolution of the age—and because of the nature of the slide, those hypotheses could certainly include triggering by a regional shallow-crustal fault or even a slab earthquake.

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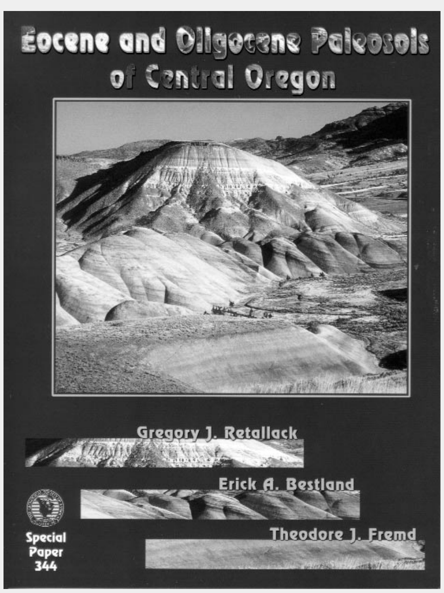

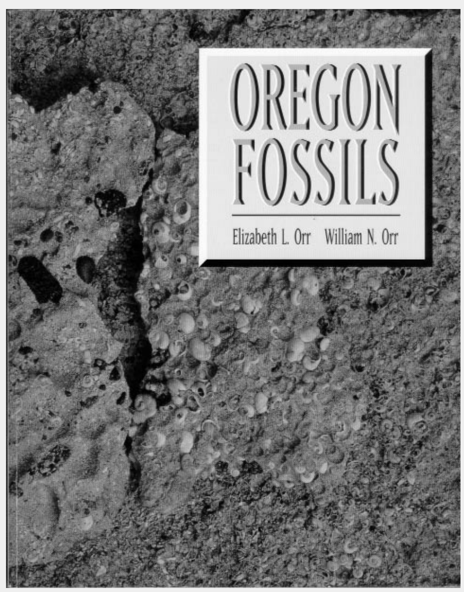

Oregon Fossils, by Elizabeth L. and William N. Orr, published 1999 by Kendall/Hunt; 381 pages, $40.95.

This book grew out of the Orrs' 1981 *Handbook of Oregon Plant and Animal Fossils* and their 1984 *Bibliography of Oregon Paleontology*. While this book is not meant to include every fossil found in Oregon, it is a richly illustrated, comprehensive overview, which also tells of the major events and people involved.

Fossil Shells from Western Oregon, by Ellen J. Moore (formerly of the U.S. Geological Survey), published 2000 by Chintimini Press, Corvallis, Oregon; 131 pages, $12.

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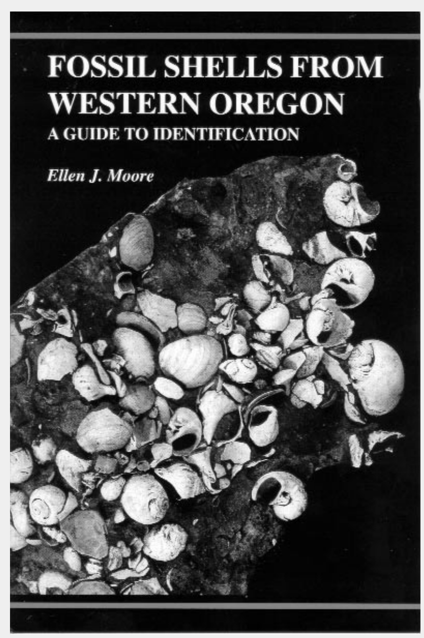

The geology and mineralization of the northern portion of the Blue River mining district, Lane and Linn Counties, Oregon

by Robert E. Streiff, Geologist, Newmont Mining Corporation, P.O. Box 669, Carlin, Nevada 89822-0669

ABSTRACT

The geology and mineralization of the Blue River mining district of Oregon has not been described in any detail, nor is it well understood. Base metal sulfides are noticeably lacking in the district compared to some of the other Oregon Cascade districts. The morphology of the veins is generally more complex, with stockworks and sheeted vein sets common, compared to other Cascade districts such as Bohemia and North Santiam. Mineralization at Blue River consists mainly of quartz-adularia-pyrite veins with significant base metals reported at depth in only two veins: the Lucky Boy and Rowena (Callaghan and Buddington, 1938). The northern arc of mineralization is characterized by a general lack of base metal sulfides and an increase in carbonates compared to the central part of the district. Gold values are associated with pyrite in quartz-adularia veins and are erratic but locally high grade. All of these characteristics suggest that the Blue River district represents a higher level volcanogenic epithermal system than other Cascade districts such as Bohemia or North Santiam. The increase in base metal sulfides toward the Nimrod stock and the increase in carbonates away from the stock indicate a crude zoning which suggests that the Nimrod stock may be related to the mineralization. Only the northern portion of the district has been studied in any great detail and is described in this paper.

Two major phases of faulting, three stages of mineralization and three vein-types have been identified in the northern portion of the Blue River district. Early stages of mineralization, which occupy small fault sets, contain quartz with pyrite plus traces of galena and sphalerite. They do not contain significant gold mineralization in the northern part of the district. Geochemical evidence in addition to crosscutting relationships strongly suggest that economic gold mineralization is intimately associated with pyrite in a later episodic quartz-adularia-pyrite event. These quartz-adularia-pyrite veins contain very erratic bonanza-type gold mineralization. This gold mineralization tends to be controlled by either proximity to northwest vein intersections or to dioritic dikes. Vein sediments are also associated with the later quartz-adularia mineralization, suggesting boiling as a depositional mechanism. Vuggy quartz-pyrite without adularia marks the end of this phase. Carbonate minerals, consisting mainly of calcite but also including some dolomite and ankerite, are found as a late-stage mineralization event that may or may not contain significant precious metals. Gold in the carbonate portions of the veins may be associated with a late-stage quartz-pyrite event which occurs as colloform bands within the carbonates, similar to the President Mine in the Bohemia mining district (Streiff, 1994). These carbonate minerals comprise the bulk of the gangue minerals in a few of the veins, such as the Great Northern and Higgins. Carbonate mineralization cuts earlier quartz-adularia and quartz-pyrite veining in some deposits, such as the Poorman. Post-mineralization right-lateral faulting cuts all mineralization in many of the veins. Alteration and mineralization indicate that the Blue River veins fit a quartz-adularia epithermal model. The presence of illite and montmorillonite indicate that depositional conditions were relatively basic and low in temperature.

INTRODUCTION

The Blue River mining district is located in the Western Cascade physiographic province of Oregon, on a ridge dividing the Calapooya and McKenzie Rivers approximately 45 mi east of Eugene. The ridge averages 1,372 m (4,500 ft) in altitude and has been heavily glaciated on north-facing slopes. The district has

Table 1. Summary of Cascade mining district production 1880–1930
(after Callahan and Buddington, 1938, page 24)

District	Production ranking	Gold (ounces)	Silver (dollar value)	Copper (pounds)	Lead (pounds)	Zinc (pounds)	Total dollar value
Salmon Creek	7	48.38	0	0	0	0	$1,000
North Santiam	5	277.63	$1,146	14,206	3,336	12,528	$10,544
Quartzville	2	8,402.29	$2,894	0	0	0	$176,585
Blue River	3	7,727.89	$8,601	257	0	0	$168,300
Bohemia	1	28,285.55	$6,473	14,831	120,816	0	$599,442
Buzzard	4	1,080.51	0	0	0	0	$24,000
Barron	6	63.79	0	0	0	0	$1,500

had a very modest gold production (7,727 oz) and consequently has not been thoroughly examined, especially in comparison with some of the other Cascade mining districts such as Bohemia or Quartzville. The lack of interest in the Blue River district is unwarranted, since a comparison of the recorded productions of the various districts shows that Blue River has produced almost the same amount of gold as Quartzville, the second largest producer in the Oregon Cascades (Table 1). Blue River gold production might even exceed

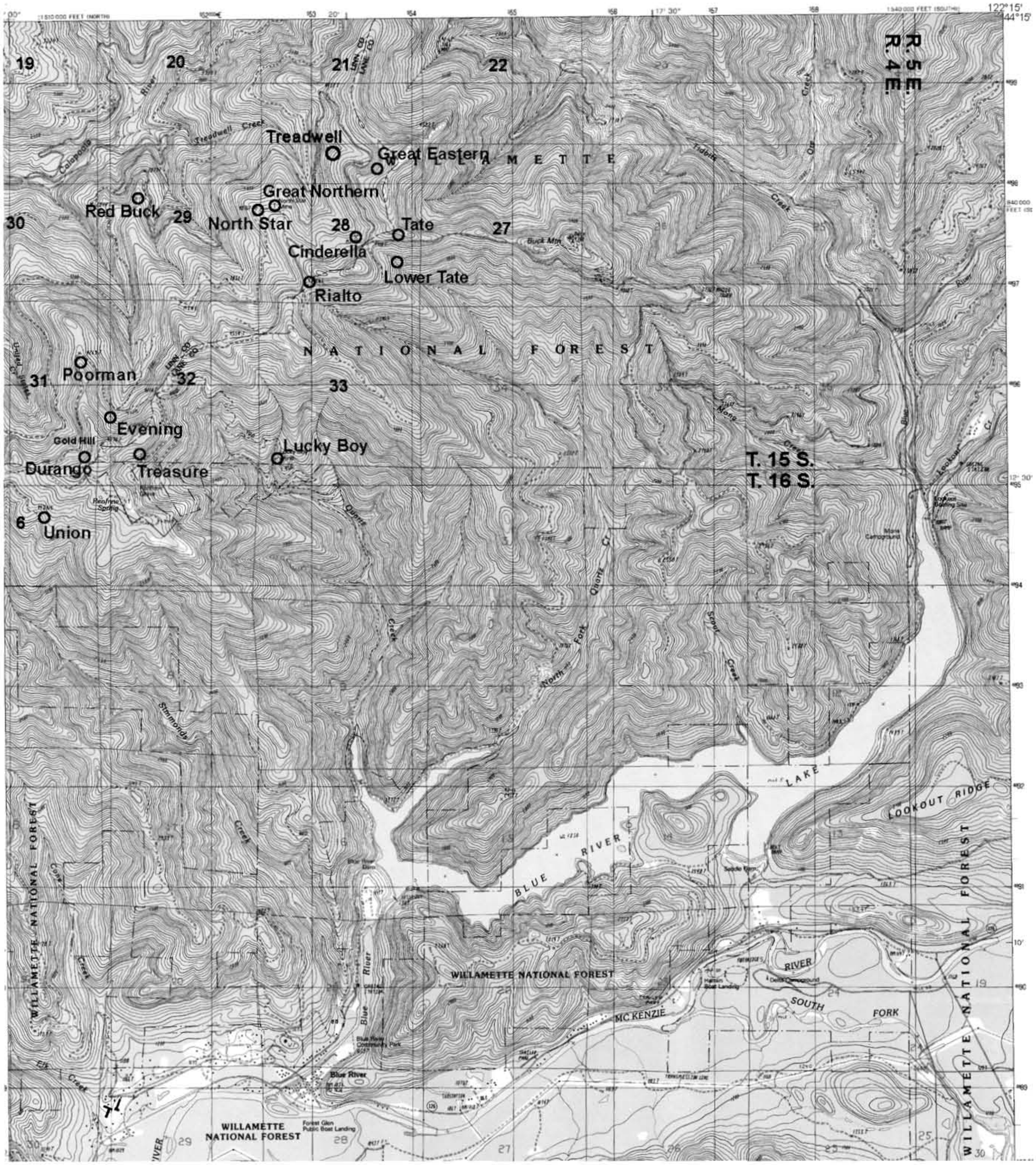

Figure 1. Map of most (north 5/6) of Blue River 7½-minute quadrangle, showing approximate locations (circles with names) of mines and prospects mentioned in this paper. Digital Raster Graphic (DRG) 044122b3.

Quartzville if additional unreported production were included. The literature on the district is confined mainly to Tuck (1927) and Callaghan and Buddington (1938). Some additional information can be found in Diller (1900), Stafford (1904), and Parks and Swartley (1918). Later publications, including Oregon Department of Geology and Mineral Industries Bulletins 14-D (DOGAMI, 1951) and 61 (DOGAMI, 1968) put the Blue River district in context with the Cascade stratigraphy but tend to restate earlier reports on the individual prospects.

The northern portion of the district which is described in this paper consists mainly of secs. 21, 27, 28, 29, 30 and 31, T. 15 S., R. 4 E., (Figure 1). This area includes the following mines or prospects: Cinderella, Evening, Great Eastern, Great Northern, Higgins, North Star, Nimrod, Poorman, Red Buck, Sochwich, Tate, and Treadwell. Also included in this discussion are the Union and Uncle Sam prospects in sec. 6, T. 16 S., R. 4 E. A mineralized belt appears to arc westward from the Tate Mine (sec. 28) to the Red Buck (sec. 29). A second, similar belt extends southwest from the Poorman (sec. 31) through the Durango to the Uncle Sam and Union (sec. 2). Exposures of the veins are generally poor and consist mainly of surface trenches and outcrops with limited underground access.

HISTORY

The recorded history of the Blue River district is largely that of the Lucky Boy Mine, which was discovered in 1887 and was in production from about 1898 to 1915 (Tuck, 1927). Most of the other mines and prospects were discovered and worked during this period (Tuck, 1927). The Great Northern, the second largest producer (about 1,200 oz) in the district, is located in the northern part of the district. Minor production from this northern area is implied from the Cinderella, Higgins, Poorman, Red Buck, Tate, Uncle Sam and Union (Callaghan and Buddington, 1938).

Kenneth O. Watkins was active in the northern part of the district in the early 1960s. In 1960, Watkins shipped, from a surface trench on the Cinderella Mine, about five tons of ore averaging 63.0 g/ton (1.84 oz/ton) gold and 33.1 g/ton (1.19 oz/ton) silver to the Tacoma, Wash., smelter. The price of gold, however, prevented serious development (H.E.L. Barton, a geologist retained by the claim owner in the 1950s, oral communication, 1977).

Coarse gold was discovered in a surface trench on the Tate ground by the author in 1986. A mapping and sampling program followed that resulted in the discovery of coarse gold in a new vein (the Nimrod) by William Barton in 1992. Mapping and sampling is ongoing at present.

REGIONAL GEOLOGY

The Cascade Range is the product of arc volcanism that has been active since Eocene times (McBirney and others, 1974; Power, 1984). In Oregon, the Cascade Range has been subdivided into two belts of volcanic rocks, the Western Cascades of Eocene to Pliocene age and the High Cascades of Pliocene to recent age (Peck and others, 1964; Priest and Vogt, 1983). The Blue River mining district lies within the Tertiary Western Cascades physiographic province of Oregon.

The Western Cascades consist of flows and pyroclastic and volcaniclastic sediments that were deposited from numerous volcanic centers (Peck and others, 1964). Minor folding of the Western Cascades, along a northeast-trending fold axis, occurred during several periods in the late Eocene and late Miocene (Peck and others, 1964). The High Cascades, consisting mainly of basaltic to andesitic flows and of stratovolcano complexes, fill a north-south-trending graben that developed in older volcanic rocks (Priest and Vogt, 1983).

DISTRICT GEOLOGY

An active volcanic center existed in the Blue River area during the Oligocene to early Miocene (Peck, 1960). Interstratified flows, tuffs, lahars, and volcanic breccias of basaltic to andesitic composition of the Sardine Formation have been mapped and divided into two informal units by Streiff (after Tuck, 1928):

Andesitic and pyroclastic flows that fill erosional paleotopographic features characterize the lower unit (at least 200 m or 650 ft thick). The lower unit is cut by numerous basaltic andesite dikes, which are presumed to be feeders for the upper unit. The upper unit (at least 50 m or 160 ft thick) consists predominantly of basaltic andesite flows. Numerous dioritic dikes crosscut all volcanic units. Crosscutting relationships show that the epithermal veins of the district postdate the various dikes and are therefore younger than the associated volcanic and intrusive rocks. Pervasive propylitic alteration can be found in all volcanic and intrusive rocks in the district.

The district is thought to be related to the Nimrod stock, a large granodiorite stock roughly 4.1 km (2½ mi) long and 2.4 km (1½ mi) wide, which is exposed by the McKenzie River south of the district (Callaghan and Buddington, 1938). Slight zoning of mineralization in the district strongly suggests this relationship. Pyritization and argillic alteration of the Nimrod stock is similar to the outer pyritic halo of many porphyry systems.

LOCAL SURFACE GEOLOGY

Currently ongoing mapping by the author has shown that erosion has removed most of the upper basaltic-andesite unit, so that only isolated outcrops remain on the ridge above about 1,448 m (4,750 ft). This unit consists of numerous massive flows of basaltic andesite. The lower unit consists of a complex sequence of onlapping andesite flows, pyroclastic flows, volcanic breccias composed of andesite fragments in a matrix of tuff, and isolated lacustrine tuffs. Numerous andesitic and basaltic-andesite dikes invade these volcanics. The andesitic dikes are presumed to be the hypabyssal equivalent of the lower unit, while the less altered basaltic-andesite dikes are presumed to be feeders to the upper unit. A large sequence of thin volcanic flow breccias fills a north-south-striking paleovalley in the andesites at the Tate and Great Eastern Mines, forming the ridge between these two deposits. In this paper, this flow breccia is informally referred to as the "Tate breccia sequence." Individual flow thickness in the breccia sequence varies from 0.6 m to more than 6 m (2–20 ft). The volcanic breccias consist of angular andesite boulders, from 10.2 cm to more than 75 cm (4–30 in.) across, suspended in a silty tuff matrix. Propylitic alteration has affected the tuff matrix more than the clasts, giving the flows a distinct color contrast from clasts to matrix. Postdepositional silica has filled voids between clasts in some individual flows. The paleovalley appears to dip to the south. Several small, isolated lacustrine tuffs are intercalated with the breccia sequence on the margins of the paleovalley.

Several previously unmapped dioritic dikes occur in the northern area of the district. One of them, ~100 m (330 ft) east of the Tate vein, strikes about N. 30° E. and dips steeply to the south. It is approximately 46 m (150 ft) wide. Contact metamorphism, consisting of knots and veinlets of chlorite and magnetite, occurs in a halo approximately 30 m (100 ft) around this dike. Two smaller dioritic dikes occur west of the Great Northern Mine. The North Star vein follows a 12.2-m (40-ft)-wide, fresh-looking, fine-grained diorite dike that strikes N. 10° W. and dips steeply to the south. The Nimrod vein follows a 3- to 4.5-m (10- to 15-ft)-wide argillic to sericitically-altered, fine-grained dioritic dike trending N. 40° W. and dipping steeply to the west. All three of these veins contain high-grade gold mineralization, suggesting a relationship to the dioritic dikes. The developed portion of the Poorman vein occupies a fault contact between the small dioritic plug at Gold Hill and Sardine Formation volcanic rocks. The Gold Hill diorite plug appears larger than previously mapped by Callaghan and Buddington (1938). Additional unmapped dikes are thought to exist in the Blue River district.

STRUCTURE

The veins occupy minor faults of unknown total displacement. Two main northwest conjugate fault sets are recognized. One set strikes from N. 40° to N. 60° W. and dips steeply to the southwest. A second set strikes from nearly due north to N. 20° W. and dips steeply to the west. Mineralized zones occupy relatively small strike lengths along much more continuous fault zones. These mineralized areas are often near the intersections of the northwest-striking faults with the more northerly striking faults. Mineralization tends to occur on either fault set approximately 45–150 m (150–500 ft) away from these intersections. A third fault set, striking N. 50°–70° E. and dipping steeply to the southeast, has also been observed. This northeast-striking set is much weaker than the two northwest sets and does not appear to control significant mineralization.

A postmineralization faulting event displaced the quartz and carbonate mineralization in several of the veins, including the Cinderella, Nimrod, and Tate. Moderate brecciation, some gouge formation and heavy postmineralization oxidation characterize this late faulting. Free gold has been found smeared along the slickensides in the Nimrod and Tate veins. Slickensides tend to be oriented nearly horizontal, with kinematic indicators suggesting a possible right-lateral displacement similar to the Bohemia mining district to the south of Blue River (McChesney, 1987; Streiff, 1994). The slickensides tend to have a slight rake (10° or less) toward the south.

Vein morphology tends to be more complex than in other Cascade districts such as Bohemia or North Santiam and consists of either numerous anastomosing branches, such as at the Tate and Nimrod, or as parallel, sheeted veins like the Great Northern, Poorman, Red Buck, and Union. Wallrock lithology tends to determine the vein morphology. Tuffs and volcanic breccia units tend to host anastomosing, bifurcating vein systems, while flow rocks such as andesite tend to host more simple sheeted vein sets. Mineralized zones are shorter in strike length than those in other Cascade districts such as Bohemia. These mineralized zones typically consist of anastomosing quartz-adularia veins from 15 cm to 91 cm (6–36 in.) wide that have a strike length of about 150 m (500 ft). Barren, argillically altered fault zones typically extend several hundred meters beyond the mineralized segments. Small topographic lows or streambeds tend to follow the outcrops of a number of the veins, including the Great Eastern, Nimrod, and Tate.

ALTERATION

Alteration types found in the northern portion of the Blue River mining district include propylitic, argillic, and sericitic alteration plus silicification. Earlier pervasive propylitic alteration is overprinted by later argillic and sericitic alteration or silicification. Alteration in the northern part of the Blue River district tends to be lower in intensity than in the Bohemia district, with propylitic assemblages dominating.

The volcanic rocks show pervasive propylitic alteration throughout the Blue River district. Locally, this alteration consists of chlorite + calcite + magnetite ± epidote. Chlorite is pervasive and is found both replacing mafic minerals and within the groundmass. Epidote appears to be slightly later and is often structurally controlled. Calcite is often found replacing plagioclase and is also in the matrix. Magnetite is a minor, local constituent replacing mafics in the various volcanic rocks. Magnetite and chlorite tend to increase in abundance in the contact-metamorphic aureoles surrounding intrusive dikes. These minerals occur as knots and veinlets adjacent to the Tate dike.

Argillic alteration occurs as an outer alteration envelope around sericitic zones. Argillic alteration consists mainly of illite grading outward to montmorillonite, which replaces both plagioclase and groundmass with <1 percent disseminated pyrite. Groundmass can look slightly bleached in some locations but is sometimes fresh looking in other locations. Argillic alteration is often found in the fault systems where mineralization is not significant, such as at the Treadwell Mine or in extensions of the mineralized faults well outside of the mineralized segments, such as the northern extension of the Great Eastern fault. The footwall diorite at the Poorman adit is argillically altered, with white clay (illite?) replacing plagioclase. Argillic alteration can also occur as broad envelopes surrounding some of the larger sheeted vein systems, such as in the Great Northern, Red Buck, and Union systems.

Sericitic alteration forms 0.3- to 3-m (1- to 10-ft) envelopes in the dioritic dike hosting the Nimrod vein. This alteration consists of sericite or illite, pyrite, and chlorite with local silicification. Sericite replaces both mafics and groundmass. Chlorite replaces mafics and appears to be a retrograde alteration product. Pyrite occurs as 1-mm cubes disseminated in the dike around the vein.

Silicification often occurs as 5- to 20-mm (0.2- to 0.8-in.) envelopes around quartz veining and is most intense within the vein, where it completely replaces breccia clasts and vein sediments locally. Silicification in the Nimrod vein appears to occur both simultaneously with and postdating gold mineralization. Silicified vein sediments suggest a post-boiling remobilization of some of the silica or a very late stage silicification event.

Elsewhere, sericitic alteration forms very restricted alteration envelopes around the quartz veins or occurs as local envelopes within a more pervasive argillic envelope. It is often most recognizable in volcanic clasts within the quartz veins. Sericite is generally found replacing mafics and feldspars. Usually, a noticeable increase in disseminated pyrite accompanies sericitic alteration. Silicification is restricted to volcanic clasts within the quartz veins or as very narrow (<1 m) envelopes in the volcanics at the quartz-vein contacts. No pervasive or extensive silicification has been noted.

VEIN MINERALOGY

At least three stages of mineralization have been identified in the northern Blue River veins. These three stages have been classified based on crosscutting relationships, brecciation, and colloform banding. Oxidation followed these mineralization events. All three stages exhibit crustification, colloform banding, and other features of open-space filling.

Stage 1

Quartz, pyrite, and traces of sphalerite and galena characterize the earliest mineralization in the northern Blue River veins. Base metal sulfides tend to decrease in abundance, as distance from the Nimrod stock increases. The gangue often consists of cherty, light-gray quartz. Silicification is common. Gold values tend to be low, at least in the northern part of the district. Base metal sulfides are generally lacking in the Blue River district compared to other Cascade districts such as Bohemia, Quartzville, and North Santiam. Diller (1900) notes that galena and sphalerite were observed only in the Lucky Boy Mine. The Rowena Mine is the only other mine in the district known to contain significant base metal sulfides. Many of the references to sulfides in the literature probably refer to pyrite. In some prospects such as the Poorman and Union, a milky white bull quartz containing 2–5 percent coarsely crystalline pyrite but no base metal sulfides may represent this early phase of mineralization.

Stage 2

A brecciation event and subsequent mineralization mark the beginning of stage 2 quartz-adularia-pyrite mineralization. The quartz contains various amounts of pyrite (1–5 percent) with only traces of other sulfides present. The quartz and adularia form alternating crustiform bands, with adularia tending to be slightly later than the quartz. Several brecciation events and associated vein sediments followed by renewed quartz-adularia-pyrite mineralization have been seen in the Nimrod vein, with later quartz-adularia-pyrite cementing earlier breccia clasts of quartz-adularia-pyrite. Silicification overprints all phases. Silicified vein sediments and subrounded breccia clasts indicate that boiling probably occurred. Coarse free gold can often be found associated with pyrite in all the quartz-adularia events. The gold can be found just within breccia clasts or just in later interclast fillings associated with pyrite or goethite pseudomorphs after pyrite. A later vuggy quartz and pyrite event has been noted in the Nimrod and Tate veins. Coarse gold has also been found in vugs of this late stage quartz. In general however, gold mineralization is intimately associated with pyrite in this phase. Diller (1900) reported some of the pyrite to be very rich in gold values.

Stage 3

The quartz-adularia-pyrite phase is followed by minor refracturing and stage 3 carbonate mineralization. Manganiferous calcite is the most common carbonate mineral in the veins, with lesser ankerite and probably some dolomite present. The calcite occurs as massive white calcite or as small scalenohedral crystals that line vugs and open fractures within the veins. Locally, the calcite is sometimes brown or black in color. Some ankerite has been found with calcite lining vugs in the adularia. Carbonates appear to be distal to the center of the Blue River district and are not limited to the northern arc of mineralization. Extensive manganese wad, containing trace amounts of gold, has been reported from the Great Western claims south of the main district (W. Barton, oral communication, 1997). Only few exposures of unoxidized carbonates are found in the district. Unoxidized carbonates are locally present on some of the adit dumps. Callaghan and Buddington (1938) report carbonates underground at the Higgins and Great Northern Mines, which are currently inaccessible. Many veins are inferred to carry carbonates due to the presence of significant quantities of manganese-limonite wad. Veins with significant manganese wad include the Cinderella, Great Northern, Higgins, Poorman, and the northeast-striking vein on the lower Tate. At the Poorman, mapping has shown that the manganese wad veining crosscuts earlier quartz-pyrite veining. Vuggy, crystalline quartz fragments are present in the heavy manganese wad portions of the Cinderella, Great Northern, and Poorman veins, suggesting that some quartz was deposited during the time of carbonate mineralization. This quartz mineralization may be responsible for gold values locally found in these veins.

This late carbonate stage contains no sulfides and is thought to be low in gold and silver, although manganese-limonite wad can locally carry appreciable values. The gold values associated with the manganese wad may be due to quartz-pyrite mineralization deposited during the same time period as the carbonates as a result of periodic boiling, similar to the mineralization at the President Mine in the Bohemia mining district (Streiff, 1994). No unoxidized carbonate ore shoots containing significant gold are currently exposed in the district.

Oxidation

Oxidation and weathering occurred following the carbonate stage. The carbonates were particularly susceptible to weathering, and are responsible for much of the residual limonite and manganese minerals. Sulfides were mainly leached away, so that the net result is probably a slight concentration of gold in the oxidized zone and a liberation of fine gold from encapsulation. However, cellular, boxwork quartz common to the oxidized portions of base metal veins such as in the Bohemia district is conspicuously absent in Blue River, which suggests a lack of significant sulfide mineralization.

Fine gold liberated during oxidation may have moved chemically, probably by manganese, to the lower oxidized zone and recrystallized on the surface of goethite pseudomorphs in coarser leaves and wires. The importance of this chemical enrichment in the veins is probably minor.

Erosion has been rapid in the district which has very steep slopes. Therefore, the level of oxidation is relatively shallow (≤ 60 m), since the outcrop is stripped off by erosion shortly after oxidation. The depth of oxidation tends to be deeper on ridge tops than near the bottoms of the stream valleys. Glaciation in the upper north-facing slopes has also rapidly removed the vein material. Shallow topographic depressions or small streambeds mark many of the vein outcrops.

Small amounts of anglesite are not uncommon in the oxidized zone, occurring as small greenish-yellow crystals. Some perfectly translucent, coarsely crystalline quartz is present and has been found lining limonite-stained vugs and boxwork at the Cinderella Mine. This quartz is probably a late supergene remobilization of earlier quartz existing in the vein. In some cases, this quartz can clearly be seen postdating initial oxidation of the host vein rock.

VEIN GEOCHEMISTRY

Geochemical analyses on 40 vein and fault samples indicate elevated levels of antimony, arsenic, copper, lead, mercury, and zinc (Table 2). The three toxic metals, antimony, arsenic, and mercury, tend to correlate well with each other and to a lesser extent with gold (Figures 2 and 3). Arsenic is elevated compared to antimony and mercury. Lead and zinc both are significantly elevated compared to copper. The base metals tend to correlate well with one another (Figure 4) but do not correlate well with the toxic metals such as arsenic (Figure 5) or with gold (Figure 6), which suggests that the gold mineralization is related to the mineralization of the epithermal toxic metals rather than the base metals. However, the limited size of the geochemical database makes definitive interpretations difficult.

INDIVIDUAL PROSPECTS

A detailed description of the characteristics of some of the individual mines and prospects illustrates both the similarities and differences found in the northern part of the Blue River mining district. Only the better studied deposits are described.

Cinderella Mine

The Cinderella Mine is located in a glacial cirque on the north side of the ridge near the center of sec. 28. The main vein extends south from the old workings across Cinderella saddle into the McKenzie River drainage, striking N. 40°–45° W. and dipping steeply to the south. Production has come from two segments of the vein on the north side

(Continued on page 77)

Table 2. Geochemical analyses of samples from the Blue River mining district, Oregon
(n.d. = not determined)

General sample location	AU (oz/ton)	AG (oz/ton)	SB (ppm)	AS (ppm)	HG (ppb)	MO (ppm)	TL (ppm)	CU (ppm)	PB (ppm)	ZN (ppm)
#1515 RDCUT	<0.002	n.d.	<2.0	20.0	<1.0	<1.0	<10.0	58.0	68.0	114.0
#1515 RDCUT	0.036	n.d.	2.0	40.0	<1.0	<1.0	<10.0	166.0	174.0	162.0
#1515 RDCUT	0.096	n.d.	<2.0	68.0	<1.0	4.0	<10.0	541.0	456.0	180.0
#1515 RDCUT	<0.002	n.d.	<2.0	<2.0	<1.0	<1.0	<10.0	20.0	<2.0	70.0
CINDERELLA	0.150	0.20	15.0	60.0	155.0	n.d.	n.d.	171.0	n.d.	n.d.
CINDERELLA	0.012	0.18	32.0	190.0	50.0	n.d.	n.d.	n.d.	n.d.	n.d.
CINDERELLA	0.002	0.04	7.0	12.0	40.0	n.d.	n.d.	n.d.	n.d.	n.d.
CINDERELLA	0.015	0.05	5.0	36.0	40.0	n.d.	n.d.	n.d.	n.d.	n.d.
CINDERELLA	0.180	0.20	9.0	22.0	140.0	n.d.	n.d.	n.d.	n.d.	n.d.
CINDERELLA	0.002	0.04	10.0	20.0	15.0	n.d.	n.d.	n.d.	n.d.	n.d.
CINDERELLA	0.149	0.20	203.0	123.0	398.0	n.d.	n.d.	90.0	121.0	164.0
CINDERELLA	0.062	0.03	2.0	18.0	1.0	1.0	n.d.	88.0	44.0	92.0
GREAT NORTHERN	0.074	0.13	2.0	40.0	1.0	1.0	n.d.	357.0	454.0	668.0
LOWER TATE	0.073	0.05	24.0	33.0	43.0	n.d.	n.d.	51.0	35.0	64.0
LOWER TATE	0.000	0.00	14.0	36.0	50.0	n.d.	n.d.	17.0	12.0	60.0
LOWER TATE	0.054	0.25	6.0	50.0	1.0	9.0	n.d.	1,505.0	5,780.0	2,990.0
LOWER TATE	0.057	0.22	2.0	28.0	1.0	3.0	n.d.	446.0	1,215.0	1,500.0
NIMROD	0.055	0.00	55.0	68.0	77.0	n.d.	n.d.	157.0	289.0	272.0
NIMROD	0.310	0.65	47.0	39.0	97.0	n.d.	n.d.	173.0	324.0	186.0
NIMROD	0.302	0.80	51.0	58.0	18.0	n.d.	n.d.	192.0	339.0	403.0
NIMROD	1.300	2.20	64.0	56.0	10.0	n.d.	n.d.	147.0	147.0	145.0
NIMROD	0.522	0.40	31.0	47.0	61.0	n.d.	n.d.	218.0	189.0	430.0
NIMROD	0.003	0.00	26.0	43.0	61.0	n.d.	n.d.	137.0	138.0	133.0
NIMROD	0.042	n.d.	2.0	50.0	<1.0	<1.0	<10.0	132.0	156.0	326.0
NIMROD	0.010	n.d.	4.0	162.0	<1.0	7.0	<10.0	158.0	678.0	186.0
NIMROD	0.097	0.10	95.0	79.0	82.0	n.d.	n.d.	137.0	114.0	172.0
NORTH STAR	0.241	0.40	15.0	45.0	235.0	n.d.	n.d.	140.0	n.d.	n.d.
NORTH STAR	0.477	0.30	52.0	52.0	20.0	n.d.	n.d.	93.0	312.0	231.0
NORTH STAR	0.344	0.35	56.0	42.0	64.0	n.d.	n.d.	138.0	290.0	254.0
NORTH STAR	0.057	0.00	49.0	37.0	60.0	n.d.	n.d.	49.0	150.0	149.0
NORTH STAR	0.128	0.19	4.0	52.0	1.0	1.0	n.d.	156.0	1240.0	706.0
POORMAN	0.005	1.40	16.0	516.0	1.0	3.0	n.d.	119.0	270.0	226.0
POORMAN	0.063	0.51	4.0	272.0	1.0	1.0	n.d.	43.0	48.0	148.0
RD#2820 ADIT	0.018	n.d.	2.0	74.0	<1.0	2.0	<10.0	49.0	142.0	202.0
RED BUCK	0.011	0.00	39.0	129.0	94.0	n.d.	n.d.	32.0	112.0	86.0
RED BUCK	0.010	0.00	40.0	132.0	201.0	n.d.	n.d.	48.0	98.0	169.0
RED BUCK	0.005	0.00	34.0	122.0	36.0	n.d.	n.d.	32.0	19.0	48.0
RED BUCK	0.002	0.02	2.0	162.0	1.0	1.0	n.d.	7.0	10.0	62.0
TATE	0.001	0.03	13.0	14.0	10.0	n.d.	n.d.	n.d.	n.d.	n.d.
TATE	0.010	0.00	73.0	165.0	173.0	n.d.	n.d.	137.0	129.0	47.0

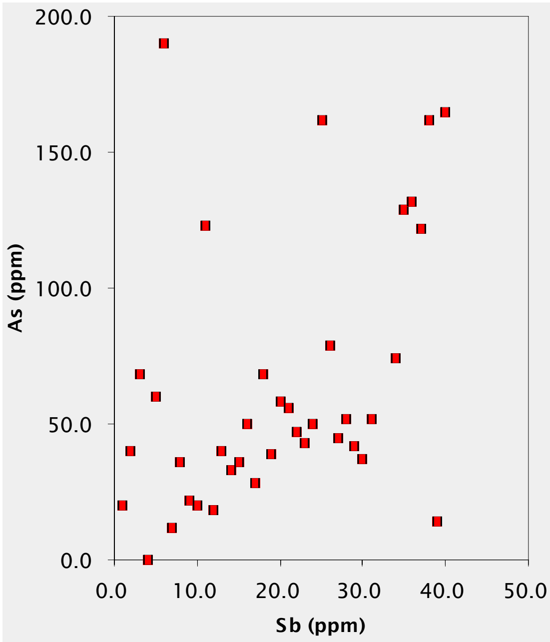

Figure 2. Scattergram of arsenic vs. antimony in the Blue River district. Data from Table 2.

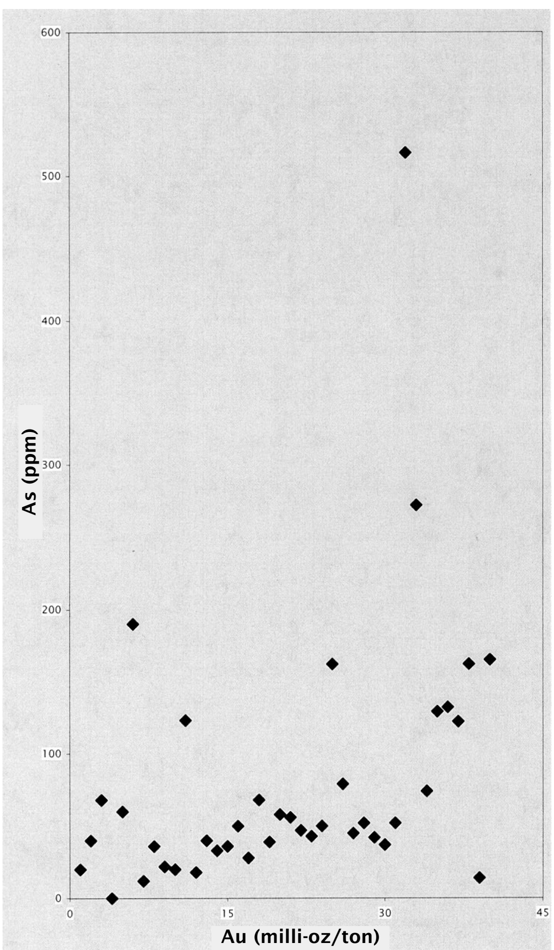

Figure 3. Scattergram of arsenic vs. gold in the Blue River district. Data from Table 2.

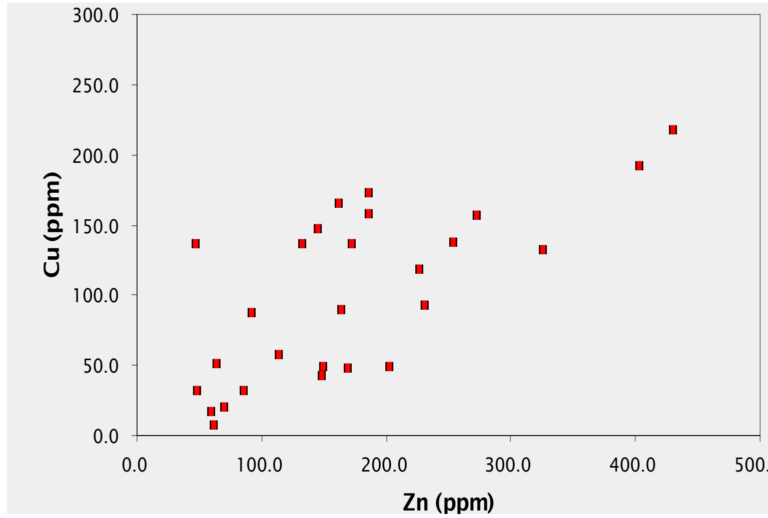

Figure 4. Scattergram of copper vs. zinc in the Blue River district. Data from Table 2.

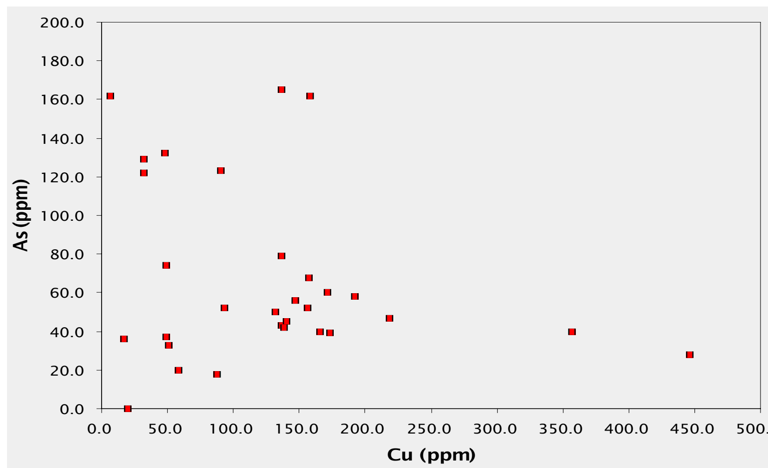

Figure 5. Scattergram of arsenic vs. copper in the Blue River district. Data from Table 2.

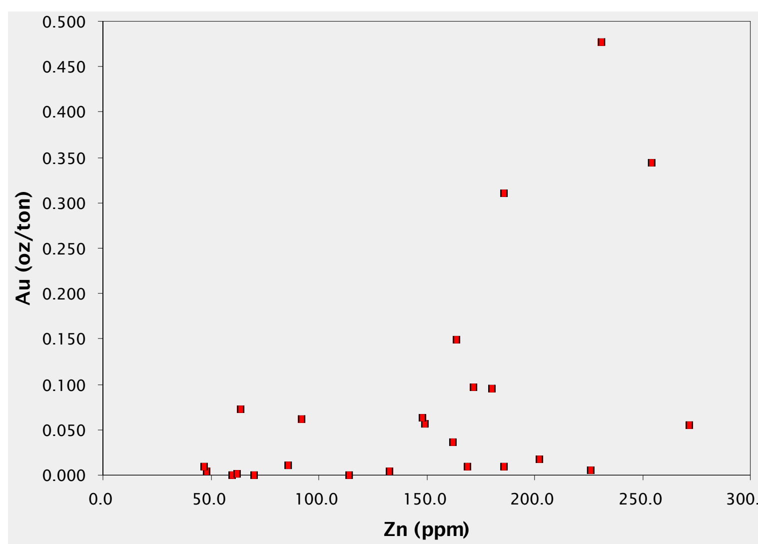

Figure 6. Scattergram of gold vs. zinc in the Blue River district. Data from Table 2.

(Continued from page 74)
of the ridge. Several small stopes were mined in the original workings which are now caved. Five tons averaging 63.0 g/ton gold (1.84 oz/ton) and 33.1 g/ton silver (1.19 oz/ton) were shipped from a surface cut on the Cinderella vein above the main workings (H.E.L. Barton, oral communication, 1977).

The 20- to 61-cm (8- to 24-in.)-wide vein consists of a rubble of wallrock and quartz suspended in a matrix of limonite, manganese wad, and various clays. Argillic alteration occurs in a broad envelope up to 10 m (33 ft) around the vein but may be due to oxidation of a higher grade alteration type. A postmineralization shear follows the hanging wall in the vicinity of the original adits. The vein is completely oxidized. It consists of a single structure at the old workings but splays into three or four anastomosing veins on the ridgetop south of the workings, where it enters the Tate breccia sequence. The south ore zone is located on the main vein near this splay. Gold mineralization occurs both as free gold suspended in the clay-wad matrix and in individual quartz fragments associated with goethite pseudomorphs after pyrite. Carbonates probably made up the bulk of the gangue mineralogy before oxidation. The vein rubble containing abundant manganese and limonite suggests that the carbonate may have originally been ankerite. The outcrop is very similar to the President Mine in the Bohemia mining district, where gold is associated with a quartz phase within a complex dolomite gangue assemblage (Streiff, 1994). Limited geochemistry from the vein indicates that mercury values tend to be higher than normal and arsenic and antimony values higher than the base metals.

Great Eastern

The Great Eastern vein crops out on the north side of the main ridge just below the summit in the northeast quarter of sec. 28. There is no evidence of historical production. The mineralized portion of the vein is hosted by the Tate breccia sequence. The original adit is caved. Several dozer trenches follow the vein south, from the adit to near the top of the ridge. The vein strikes N. 45° W. and dips 70°–85° degrees to the south. The quartz vein averages 0.9 m (36 in.) near the adit, but mineralization pinches out both north and south of the adit. The overall strike length of the quartz-mineralized zone is approximately 122–152 m (400–500 ft). A shear zone extends north and south beyond the mineralized section.

The vein consists of 25–102 cm (10–40 in.) of white quartz containing 1–5 percent very fine grained disseminated pyrite. No adularia or other sulfides have been observed. Oxidation extends only a few meters below the surface. The vein appears to occupy a single fault plane, but exposures are poor. Although some areas of the vein locally assay as high as 10 g/ton (0.34 oz/ton) of gold, no mineable ore shoots have yet been identified. The Great Eastern fault zone can be found in the cutbank of USDA Forest Service (USFS) Road 2820, approximately 152 m (500 ft) northwest of the old adit portal, where the road crosses a small drainage. The 9-m (30-ft)-wide fault zone consists of four to five parallel shears that are 15–102 cm (6–40 in.) wide. Argillic alteration is most intense within the shears and forms a low-grade envelope around the zone. The fault zone is not mineralized at this location. The drainage has formed along the outcrop of the fault zone.

Great Northern

The Great Northern Mine workings are located in NW¼ sec. 28. A USFS road passes between the upper and lower adits. Both adits are completely caved. However, the first 46 m (150 ft) of the lower adit was open for mapping in 1986, including a 12-m (40-ft) crosscut that exposed the western vein. Most of the production, estimated to be approximately 1,200 oz of gold, has been from the western vein (H.E.L. Barton, oral communication, 1977). Various trenches expose the vein south of the main adits.

The Great Northern consists of two parallel veins approximately 30 ft apart striking N. 25° W. and dipping 70°–85° to the east. The vein system is hosted mainly by andesite. The eastern vein is poorly exposed.

The western vein has been heavily stoped underground. It ranges from 30 to 122 cm (12–48 in.) in width and consists of a rubble of andesite wallrock fragments and quartz supported by a limonite-manganese wad clay gouge, similar to the Cinderella vein. A postmineralization shear is located on the hanging wall of the vein in the lower adit. The accessible portions of the veins are completely oxidized. Gold is found within the limonite-manganese wad gouge and as small flakes associated with goethite pseudomorphs after pyrite in the quartz fragments. The gold is probably related to the quartz phase of mineralization. Callaghan and Buddington (1938) report lenses of white calcite without pyrite and minor associated quartz up to 3 m (10 ft) long and 0.31 m (1 ft) wide within a 1-m (3.05-ft) sheared zone in the currently inaccessible lower drift. Abundant calcite and quartz cementing an angular andesite breccia can be found on the lower adit dump. Calcite was also reported in the Cummins adit northwest of the main workings. The calcite is probably the source of the manganese wad in oxidized sections of the veins as suggested by Callaghan and Buddington (1938). Carbonates such as ankerite may also be present.

Nimrod Vein

The Nimrod vein, discovered in 1992 by William Barton during a mapping and sampling program, is located west of the Great Northern. No old workings are present on the Nimrod vein. The Nimrod affords the opportunity to examine an undisturbed, high-grade gold occurrence.

The Nimrod vein strikes N. 42° W. and dips 70°–80° south. In the discovery cut, the vein is hosted by a 9.1-m (30-ft)-wide, fine-grained, porphyritic, sericitically altered dioritic dike. This dike is much more highly altered than the dike hosting the North Star No. 5 vein. The Nimrod vein averages 30.5 cm (12 in.) in width, is completely oxidized at the outcrop, and contains appreciable but erratically distributed free gold. A stockwork of 2.5- to 10.2-cm (1- to 4-in.) veins occur up to 7.6 m (25 ft) into the hanging wall of the main vein. These stockwork veins also strike about N. 40° W. but dip more steeply south, so that they appear to intersect the main Nimrod vein below the outcrop. These small stockwork veins also contain appreciable free gold, including one vuggy quartz vein that produces near-perfect gold octahedra up to 2 mm across. Local pockets or enrichments of gold can be found where several of these small stockwork veins intersect. Post-mineralization faulting has occurred along the Nimrod vein itself. The fault plane locally cuts quartz mineralization and exhibits near-horizontal slickensides.

The main Nimrod vein consists of multiple quartz and quartz-adularia phases containing 1–5 percent goethite pseudomorphs after pyrite. Traces of sulfides have been found, consisting mainly of pyrite, with minor galena and sphalerite in early breccia fragments cemented by later quartz-adularia. Locally, associated anglesite may indicate galena in the unoxidized portion of the vein. However, no cellular boxwork quartz has been found. Early quartz-adularia mineralization cements silicified, sulfide-bearing breccia and hosts free gold associated with goethite pseudomorphs after pyrite. At least two of such quartz-adularia events can be seen . Some silicified vein sediments can be found filling voids in the early phases. A later vuggy quartz event cuts earlier quartz-adularia phases and silicified breccia clasts. Free gold is also present in this vuggy quartz and can be found either in vugs with white clay (kaolin or illite?) or associated with goethite pseudomorphs after pyrite. This gold mineralization can assay as high as 336 g/ton (9.80 oz/ton) of gold and averages about 51 g/ton (1.50 oz/ton) gold. Geochemistry from a limited number of mineralized vein samples indicates that base metal sulfides are roughly twice as abundant as the toxic metals.

The exposure of the Nimrod vein in a lower cut shows a weaker vein with less alteration and more carbonate in the vein. Float between the two main cuts shows some free gold from additional, currently unexposed ore shoots. The quartz-mineralized portion of the Nimrod vein is currently known to be at least 152 m (500 ft). The full lateral extent of the mineralized zone has not yet been determined.

A vein thought to be the Pooler (Parks and Swartley, 1916) is just south of the Nimrod and is probably intersected by the Nimrod under a dump from an old adit. This vein strikes N. 20° W. and dips steeply south. The partly caved adit follows a strong argillically altered shear zone up to 1.5 m (5 ft) wide, hosting narrow, anastomosing quartz veining. Trenches above the adit indicate that the veining widens from 0.3 to 0.6 m (1–2 ft) and consists of vuggy, coarsely crystalline quartz cementing angular tuff breccia fragments. Some goethite pseudomorphs after pyrite are present which locally host free gold. The Nimrod vein either merges with or is offset by this shear zone. The northern extension of this Pooler vein consists of two argillically altered 0.6-m (2-ft) shear zones without quartz mineralization that are exposed in a cut about 180 m (300 ft) north of the partly caved adit.

North Star

The North Star vein crops out approximately 152 m (500 ft) west of the main Great Northern adits, close to the west sideline of sec. 28, near the crest of a small ridge. The vein is exposed in the cutbank of the same USFS road that cuts the Great Northern vein. It has been prospected by several trenches and two short adits which are now caved. The vein assays 8.6 g/ton (0.25 oz/ton) gold across 102 cm (40 in.) in the road cut. Assay values in the mineralized portion of the vein are as high as 25.7 g/ton (0.75 oz/ton) gold. The North Star vein strikes about N. 20° W. and dips steeply southwest. The vein follows a 15.2-m (50-ft)-wide, fine-grained, porphyritic diorite dike which is sericitically altered along the vein margins but otherwise appears fresh. Fine-grained intrusive rock crops out west of the vein in the road cut also. The vein consists of quartz-adularia containing pyrite which cements an angular andesite or diorite breccia fragments plus quartz clasts containing some minor sphalerite. Oxidation is relatively shallow, and sulfides can be found within a few feet of the surface. The mineralized section is approximately 122 m (400 ft) along the strike of a small fault that extends northwest and southeast of the quartz-adularia mineralization. Limited geochemistry from mineralized vein samples indicates that the base metals are twice as abundant as the toxic metals, similar to the Nimrod vein.

Poorman

The Poorman group of patented claims occupies a ridge mainly in the eastern half of sec. 31. The Poorman is included in this discussion of the northern arc of mineralization at Blue River because of the similarity of the mineralization, especially later carbonate mineralization. The main adit is on the east side of the ridge near the boundary between secs. 31 and 32. The first 300 ft of the adit are partly accessible (Figure 7). Numerous outcrops and subcrops of a coarse-grained dioritic plug are present on the southern portion of the

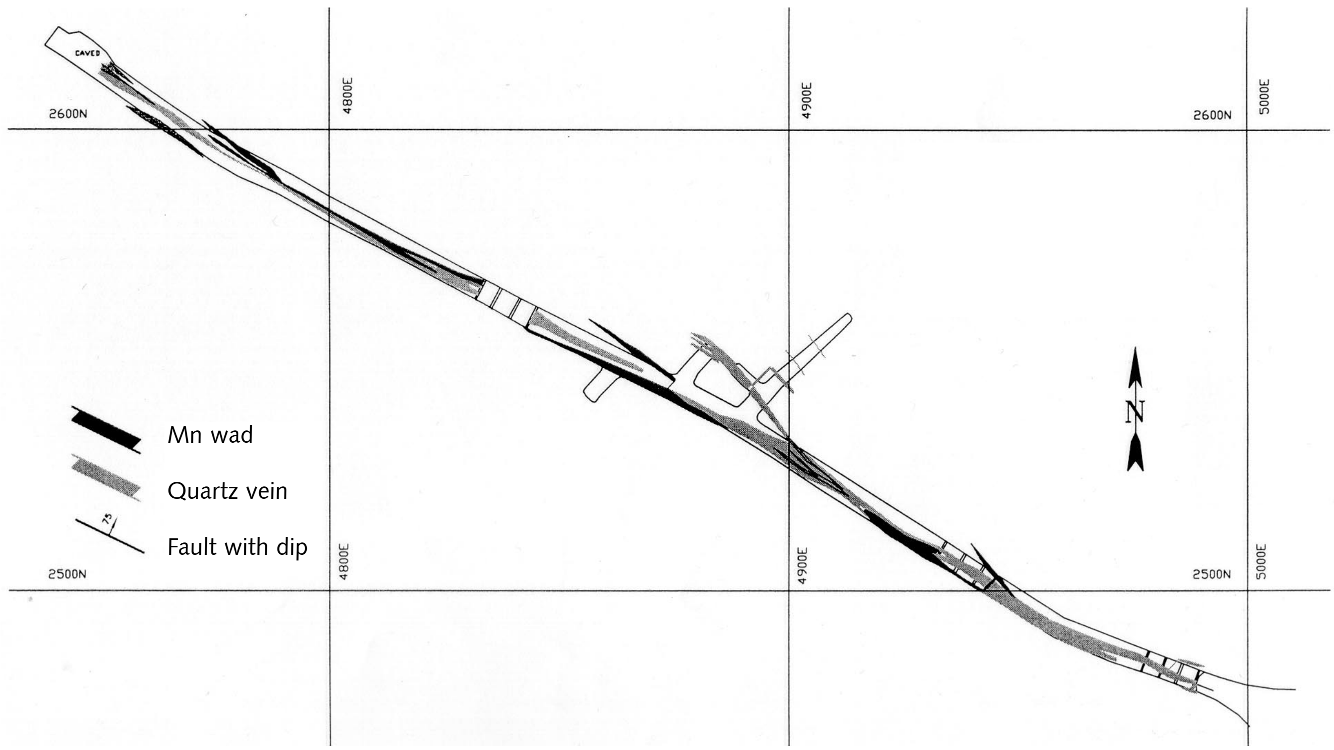

Figure 7. Poorman adit, Blue River mining district, interpretive geology.

claims, while typical andesitic flows and pyroclastics occur on the northern half of the claims.

The main adit drifts on a vein striking about N. 50° W. and dipping steeply south. Several crosscuts in the drift show that the vein occurs on a fault contact between the hanging wall of diorite and a footwall of andesites intercalated with some tuff. The vein consists of an early stage of massive, vuggy quartz containing a few percent of oxidized to partly oxidized fine-grained goethite pseudomorphs after pyrite, cut and offset by a later oxidized carbonate mineralization. Both types of mineralization pinch and swell from <10 cm up to 1.5 m (4–60 in.) wide. The later carbonate mineralization consists of the typical manganese-limonite wad and clay-supported rubble of volcanic rock and earlier quartz. Only a trace of original calcite remains in the vein locally. The carbonate nature of this later mineralization is inferred from the abundance of manganese wad. Grab and channel samples of the earlier vuggy quartz and pyrite mineralization indicate low gold grades, up to 1.7 g/ton (0.050 oz/ton). Channel samples of the later carbonate mineralization indicate gold grades as high as 51 g/ton (1.50 oz/ton). Although Parks and Swartley (1916) report sulfides, the only sulfide found at the Poorman is pyrite. Base metal sulfides have not been seen, nor is much boxwork quartz present in the oxidized portions of the vein. Geochemical analyses of two samples show relatively low base metals.

Red Buck

The Red Buck workings are near the center of the eastern half of sec. 29. The caved adit is just above the USFS Road 2820. Several caved trenches and shallow shafts are on the hillside above the adit to the top of the small ridge, where some old dozer trenches cut the zone. The best exposure of the Red Buck vein system is found in the road cut of two USFS spur roads. One road is on the west side of the ridge near the summit. The second road (682) is west of the first in a draw. A broad zone of alteration hosted by lapilli tuff is exposed and contains two main quartz veins and numerous small quartz stringers. This zone is at least 30.5 m (100 ft) wide.

Most of the old workings are centered on the more northern of the two quartz veins. This vein strikes about N. 60° W. and dips steeply northeast in the road cut. However, this may be a local roll in the vein. The quartz vein is from 0.3 to 1.0 m wide (1–3 ft) and consists of quartz cementing angular breccia clasts of lapilli tuff. The quartz is vuggy and shows some colloform banding. The vein is completely oxidized with moderate limonite stain and traces of goethite locally. Numerous quartz stringers 0.5–1.5 cm (0.2–0.6 in.) across are present in the hanging wall of the vein. The southern vein is parallel to the main vein and about 22 m (75 ft) south. This southern vein is similar in composition to the main vein but is narrower (0.2–0.5 m or 10–18 in. wide) and dips steeply to the south. The lapilli tuff wallrock hosting both veins is bleached, argillically altered and limonite-stained for up to 15 m (50 ft) around the veins. This broad zone of alteration does not host significant gold mineralization. Geochemically, values of base metals are significantly lower at the Red Buck than in most other veins in the northern arc of mineralization. It is unclear why such a broad zone of alteration should contain such insignificant geochemical values.

Tate Mine

The main Tate workings are almost in the center of E½ sec. 28, near the top of the ridge. USFS Road 1510 cuts the Tate vein system just below the main adits and offers good exposures of both the Tate veins and the volcanic breccia host rock. The adits are all caved. Old workings, in elevation approximately 91 m (300 ft) below the main workings, explore a complex system of intersecting northwest and northeast veins, which appear unrelated to the main Tate vein system. One adit in this lower group of workings is still accessible (Figure 8). Stafford (1904) listed this property as the Noonday.

The main Tate workings explore an anastomosing vein system striking due north and dipping nearly vertical. Several parallel to subparallel veins, 30.5–122 cm (12–48 in.) wide and consisting of quartz-adularia with minor pyrite, are exposed by trenching. These veins are hosted by the Tate breccia sequence. The host rock has probably influenced the anastomosing form of the Tate vein. The breccias are argillically altered near the veins and contain a pyritization halo up to 6.1 m (20 ft). Sericitic alteration, if present, has been masked by weathering. Several of the individual volcanic breccia units are mineralized with chalcedonic quartz, pyrite, and some hematite. This mineralization is probably deuteric in nature. These mineralized flows do not contain significant gold values.

The central Tate vein consists of colloform quartz and quartz-adularia with 1–10 percent goethite pseudomorphs after pyrite that cements angular breccia clasts of tuff or andesite from the breccia unit. Some weathered sphalerite was noted by Callaghan and Buddington (1938). The colloform banding consists of outer paired sequences of quartz-adularia and an inner late-stage vuggy quartz that tends to wrap around individual breccia clasts. Postmineralization faulting has left near-horizontal slickensides on the hanging wall contact of this vein. The movement appears to be right-lateral. Free gold has been found either associated with goethite pseudomorphs after pyrite in the quartz-adularia or as vug fillings in the late quartz event. One sample was found with free gold attached to goethite pseudomorphs along a wallrock contact. A sample across the vein assayed 15.4 g/ton (0.45 oz/ton) of gold.

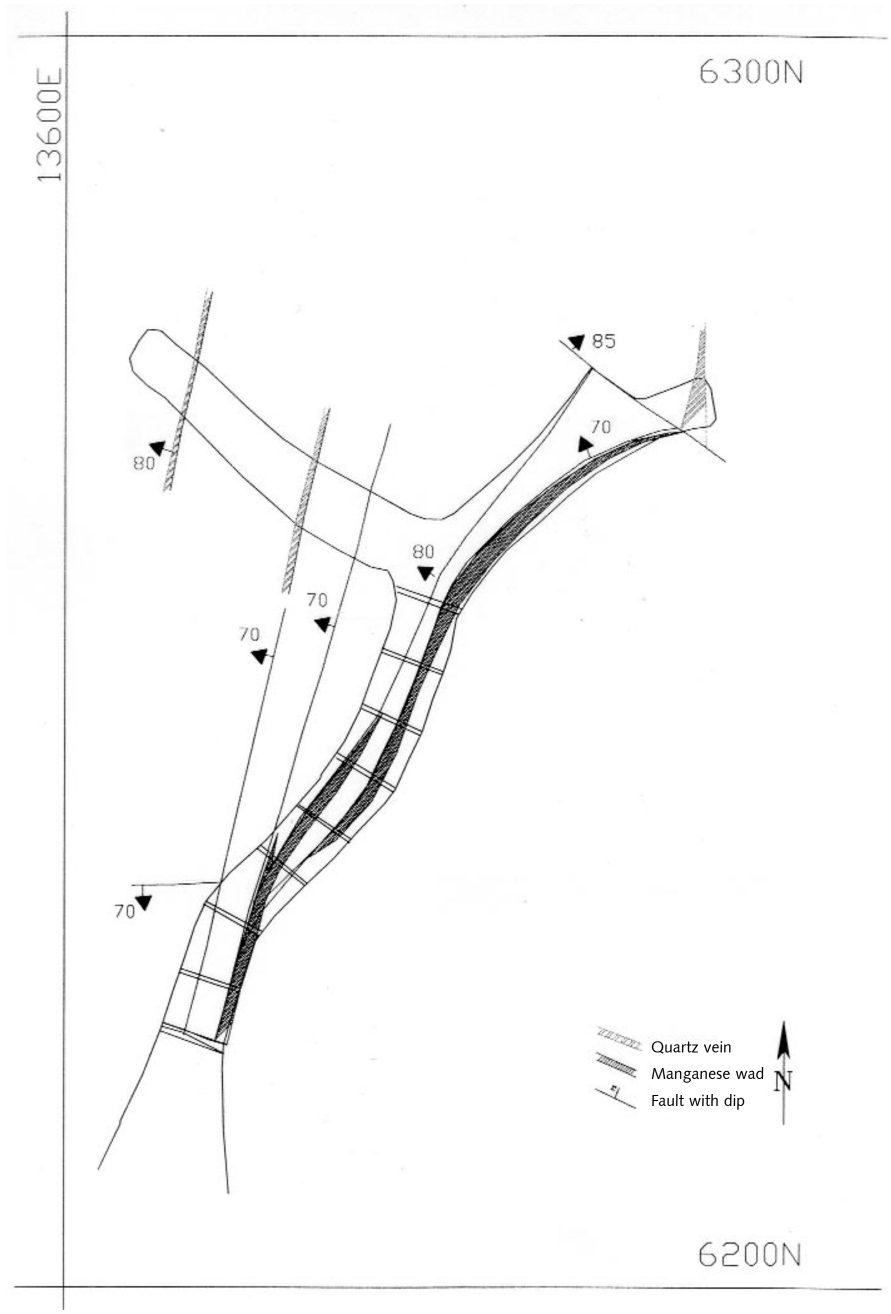

Figure 8. Lower Tate adit, Blue River mining district, interpretive geology.

The quartz-adularia mineralization in the main Tate fault system has a strike length of at least 122 m (400 ft). The mineralization pinches out to the south. The extent of the mineralization to the north is unknown. A similar-looking quartz-adularia vein with angular breccia clasts crops out on the ridgetop about 100 m (300 ft) east of the Tate workings, where a coarse-grained dioritic dike, striking about N. 20° E., crosses the ridge and is cut by the vein. This vein strikes roughly N. 30°–40° W., parallel to the Cinderella vein. A wide zone of alteration in the road cut of USFS Road 1510, hosted by a coarse-grained diorite, contains little or no quartz. The lower workings, which are about 91 m (300 ft) in elevation below and to the south of the main Tate adits, explore a complex area of narrow, intersecting northwest and northeast veins. The upper adit, as described in Callaghan and Buddington (1938), is still accessible (Figure 8). It drifts approximately 24 m (80 ft) on a N. 40° E. shear zone that consists of brecciated andesite with abundant gouge and manganese wad containing some quartz fragments. Several parallel quartz veins averaging 10.2 cm (4 in.) in width are exposed by a north-trending crosscut. The first 9.1 m (30 ft) of the drift has caved and has been retimbered. A sample at the portal assayed 5.1 g/ton (0.15 oz/ton) of gold. The bulk of the adit, which was sampled on 5-ft centers, shows very low gold values, however. The northeast shear is cut off at the face of the drift by a 10.2-cm (4-in.) quartz vein trending N. 7° E. and dipping nearly vertically. Drag folding of the shear indicates a near-horizontal right-lateral movement of the north-trending quartz vein.

Treadwell Mine

The Treadwell Mine is located in the lower part of sec. 21, near the sec. 28 line. The old adit is caved and is located about 15 m (50 ft) above USFS Road 2820. This road cuts the Treadwell vein and exposes it in the road cut.

The Treadwell consists of a 1.8- to 3.1-m (6- to 10-ft)-wide shear zone trending N. 40° W. and dipping 75°–80° southwest. The shear contains heavy gouge and consists of argillically altered volcanic rocks with moderate (3–5 percent) pyrite. No other sulfides are present. Oxidation is shallow, with sulfides exposed in the road cut along with minor quartz stringers. Some calcite and very minor quartz can be found on the dump of the adit. No significant gold values were found. It is possible that the Treadwell shear may be the same fault that hosts the Cinderella mineralization to the southeast.

Union Mine

The Union Mine is located in sec. 2, T. 16 S., R. 4 W., in the headwaters of Simmonds Creek on the extreme western side of the district. The vein system is prospected by two main levels and numerous short adits and prospect pits. The upper adit, approximately 100 ft above the lower or crosscut adit, drifts along the main Union vein for about 400 ft. Several crosscuts expose parallel veins. The lower crosscut adit is sketched and described in Callaghan and Buddington (1938). The 1,200 ft of development reported by Callaghan and Buddington (1938) is on two levels, not one. The lower level map in their report scales out to be only approximately 800 ft on that level. Both adits are open but in poor condition. The Republican Mine reported by Diller (1900) is the same as the main workings on the Union claims. The Happy Jack property described by Stafford (1904) is now part of the Union group of claims.

The Union vein system consists of a broad zone of alteration hosting a set of subparallel sheeted quartz veins ranging from a few millimeters up to ~1 m across. The Union zone is similar to the Red Buck zone, except the host rock at the Union is a fine-grained andesite instead of a lapilli tuff. Argillic alteration is more restricted at the Union and forms overlapping halos around the principal veins and fault zones.

The main Union vein strikes N. 40°–45° W. and dips 70°–80° to the south. A postmineralization fault zone, consisting of about 6–12 in. of clay and granular andesite fragments plus some quartz clasts, forms the footwall of the quartz vein. The fault has formed very distinct slickenside walls on each side of the gouge. The quartz vein consists of quartz (and some adularia?) containing 1–2 percent pyrite which has oxidized to goethite pseudomorphs in many areas. The vein consists of a single quartz vein that locally breaks into anastomosing sets of stringers that join back into a single vein. Angular, equant andesite breccia clasts are commonly hosted within the vein. Crustification and vuggy, coarsely crystalline quartz around breccia clasts is common. Gold values appear erratically associated with the pyrite. The sulfides reported by Callaghan and Buddington (1938) must refer to pyrite, the only sulfide found at the Union Mine.

A subparallel vein, narrower than the main vein, is exposed for several hundred feet in the upper adit. This vein is located ~30–40 ft in the hanging wall of the main vein and is similar to the main vein. It also has associated postmineralization faulting along the footwall. The lower adit map from Callaghan and Buddington (1938) indicates several subparallel veins in both the hanging wall and the footwall of the main structure. Although mapping is mostly incomplete, there is a suggestion that the smaller veins located in the hanging wall and footwall may not be parallel but instead cross each other at low angles (<15°). There is also some evidence that suggests that the Union may consist of an en-echelon set of quartz veins.

DISCUSSION

Crustification, colloform banding, anomalous antimony, arsenic and mercury geochemistry, silicification, vein sediments, and complex anastomosing vein morphology in the northern part of the district are characteristic of epithermal deposits. Epithermal characteristics in other Cascade districts, particularly the Bohemia district, have been previously reported (Lutton, 1962; McChesney, 1987; Katsura, 1988; Streiff, 1994). The complex vein morphologies, more extensive silicification, carbonates, general lack of significant base metals, and auriferous pyrite suggest that the northern Blue River veins are an upper level epithermal system, higher in relative elevation than the Bohemia or North Santiam epithermal systems. The relatively short strike lengths of the mineralization indicate a smaller system than in some of the other Cascade districts such as Bohemia. The Cascade district most similar to the northern Blue River district is the Quartzville district, which also contains fewer base metal sulfides and relatively coarse, pocket-type gold.

Zoning appears to be an important ore-controlling feature in the Blue River district. A central copper-rich base metal zone, represented by the Rowena Mine, is surrounded to the west by an arc of zinc-lead-copper base metal veins. Base metal sulfides decrease in abundance toward the north, while occurrences of auriferous pyrite in quartz and pockets of coarse gold increase. A northern, outer carbonate zone interfingers with an auriferous pyrite-quartz zone. This carbonate mineralization often appears to cut earlier quartz-adularia veining. Gold mineralization appears to be most significant in the outer base metal sulfide and auriferous pyrite zones. This may be due in part to an arc of later quartz-adularia-pyrite mineralization that overlaps and overprints earlier mineralization. The Blue River veins tend to dip south toward the Nimrod stock, and zoning appears to arc northward away from the stock, strongly implying that the Nimrod stock does control mineralization in the district. Zoning of the Blue River district plus extensive pyritization and argillic alteration of the stock itself suggests that the Blue River area may host a porphyry copper system at depth (Power and others, 1981; Power, 1984). Mineral zonation probably consisted of "shells" or "domes" over the Nimrod stock prior to erosion of the volcanic pile.

Electrum-bearing pyrite is the major gold occurrence in the northern part of the Blue River district and is contained within stage 2 veining only. This suggests that perhaps stage 2 is an upper level quartz-pyrite epithermal event, while stage 1 represents deeper base metal epithermal mineralization below the elevation of precious metals mineralization. Deeper stage 1 mineralization being overprinted by shallower stage 2 mineralization is suggestive of an evolving hydrothermal system that collapsed in upon itself over time as the heat source for hydrothermal activity cooled. This is similar to the Bohemia mining district, where vein paragenesis, mineral associations, and geochemistry all imply a collapsing system over time.

The quartz-adularia veins of the Blue River district fit into a quartz-adularia epithermal model. Argillic alteration consists of illite grading outward into montmorillonite clays. Thermodynamics of these clay minerals suggest that the Blue River veins were deposited by relatively low temperature (<250°C) and moderate ph solutions (4–6). Episodic boiling suggests shallow depths.

The gold mineralization tends to be "pockety" or very erratic and occurs in very small ore shoots with limited strike length. Most of the significant gold mineralization is found near the center of zones of relatively short strike-length (<152 m or 500 ft) containing quartz-pyrite mineralization which occupies small right-lateral faults with strike lengths up to several hundred meters. Callaghan and Buddington (1938) describe the vein in the lower drift of the Evening Mine (p. 118) as pinching out or narrowing toward the face of the drift into a shear zone of altered rock without quartz mineralization. This is typical of the lenticular nature of the quartz mineralization over several hundred meters in the Blue River fault systems. These zones of quartz mineralization are often near fault intersections, especially between north- and northwest-striking faults as in the Lucky Boy Mine. The mineralization tends to be on a limb of one of the faults, often 100 m or so from the actual fault intersection. This "diamond pattern" of conjugate vein systems is very noticeable in the Cinderella-Tate and Great Northern areas. Another favorable location for gold mineralization is proximal to dioritic dikes, such as at the North Star, Nimrod, and Tate Mines. Some veins follow and are hosted by dikes, such as the North Star No.5 and Nimrod veins. Careful geologic mapping will probably reveal additional gold mineralization.

ACKNOWLEDGMENTS

The manuscript was reviewed by Helen Robinson. I wish to thank my colleague Bill Barton for his companionship on long treks through the district; thoughtful geologic observations and discussions, and his hospitality during my visits to the Blue River district. Many thanks also to his wife Barbara, who put up with both of us.

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BOOK REVIEW

Fossil Shells from Western Oregon. A Guide to Identification, by Ellen J. Moore, published 2000 by Chintimini Press, Corvallis, Oregon; 131 pages, $12. [See also page 68.]

Ellen Moore has done an outstanding job on her new book, *Fossil Shells from Western Oregon*. It is a book necessary for anyone who beachcombs or has any curiosity about shells.

A nice, easy-to-understand style, along with lucid descriptions, make Moore's book especially good for nonprofessional paleontologists.

The book is roughly divided into four parts. Introductory chapters on geologic time, fossils, geologic processes, and history conclude with glances at fossils occurring elsewhere in Oregon, those older than Tertiary in the western part of the state, and fossils other than shells from western Oregon. The second portion of the book has sections arranged by location, northwest, west-central, and southwest. These areas are in turn subdivided by geologic formations arranged from oldest to youngest. The third portion of the book is organized by age, beginning with Eocene and ending with Pleistocene, while the final part is "Geologic Excursions" (field trips) to specific regions of the coast such as Cape Kiwanda or Depoe Bay.

At the core of this book are excellent descriptions and illustrations of diagnostic as well as common invertebrate marine species from the Coast Range and Willamette Valley. For this, the author draws on her own considerable knowledge, having authored many of the significant publications on Oregon Tertiary invertebrates. Abundant photographs and diagrams throughout contribute to the ease of understanding.

Expanded from her earlier work, *Fossil Mollusks of Coastal Oregon*, the glove-compartment-size book is an indispensable tool for professional and nonprofessional paleontologists in Oregon. At the price, it is a definite bargain. Fossil Shells from Western Oregon can be ordered from Moore at Chintimini Press, 3324 SW Chintimini Avenue, Corvallis, Oregon, 97333, for $12, which includes postage.

—Elizabeth L. and William N. Orr
University of Oregon

[Editor's note: Copies available from the Nature of the Northwest Information Center in Portland—see page 65— or any DOGAMI field office—see page 50—are signed by the author.]

(Continued from page 50)

Released July 14, 2000:

Geologic Map of the Summerville Quadrangle, Union County, Oregon, by M.L. Ferns and I.P. Madin, 1999. Geological Map Series GMS-111, map scale 1:24,000, 23 p. text, $10.

The new geologic map encompasses one of the most spectacular and youthful rangefront fault systems in northeastern Oregon and the dramatic escarpment that culminates in Mount Emily with its commanding view of the valley. The fault zone may have been active in the past 10,000 years and may be capable of producing earthquakes up to magnitude 7.

Mapped landslide deposits around the flanks of Mount Emily point toward another geologic hazard in the quadrangle. The map also includes information from water wells to help identify the important groundwater resources in the area.

Crushed rock is the only mineral resource mined from the Summerville quadrangle, but the new map shows that sand and gravel resources exist as well as low-temperature geothermal resources.

Two adjoining maps were completed and published earlier: of the Tucker Flat quadrangle (GMS–110, 1997) and the Fly Valley quadrangle (GMS–113, 1998). □

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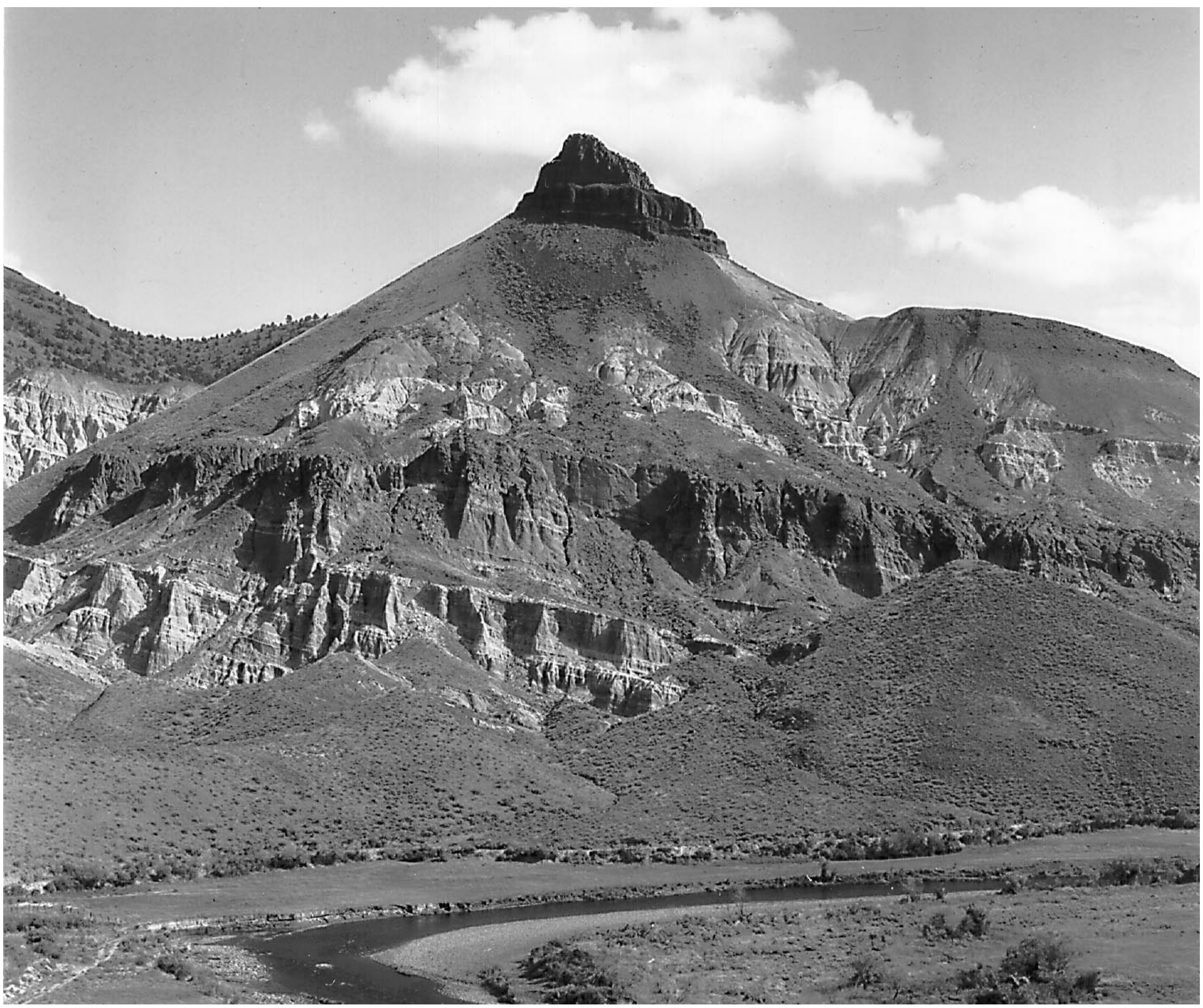
Places to see—Recommended by the Oregon Department of Geology and Mineral Industries:

Sheep Rock, one of the landmarks in the John Day Fossil Beds National Monument, Grant County (National Park Service photo, negative no. 370).

Below a cap of erosion-resistant basalt, eroded channels lead down throught 1,000 ft of ancient volcanic ash to the John Day River. This ash, now turned to claystone, contains the fossils of plants and animals from 25 million years ago. Sheep Rock is located 2 mi north of the junction of U.S. Highway 26 and Oregon Highway 19, west of Dayville, close to the John Day Fossil Beds National Monument headquarters at the Cant Ranch on Highway 19.



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Seymour appointed to DOGAMI Governing Board

Barbara Ann Proebstel Seymour of Salem was appointed by Governor John Kitzhaber and confirmed by the Oregon Senate at the end of June to serve as Governing Board member of the Oregon Department of Geology and Mineral Industries (DOGAMI). She succeeds Arleen N. Barnett of Portland. In addition to Seymour, the three-member Board includes Donald W. Christensen of Depoe Bay, the current chair, and Vera E. Simonton of Pendleton.

Seymour was born in Baker City, Oregon. Her father, Robert I. Proebstel, was general manager of the general store in Cornucopia at the time of her birth. The region experienced much gold mining activity at that time, so she calls herself "a gold mining child."

She grew up mostly on the family's ranch in Haines in northwest Baker County, went to school in Haines,

Barbara Ann Proebstel Seymour

Baker City, and Pendleton, and received degrees in law from the University of Oregon. After she and her husband had practiced law together in Florence, Oregon, the family moved to Salem in 1964. Here, Barbara Seymour worked in the Office of the Legislative Counsel until her retirement in 1997. The Seymours' three children all live in Oregon and have given them eight grandchildren.

Seymour has a story to tell about the beginning of her contact with DOGAMI. We'll give you her own words: "I was interested in mining as my grandfather was in mining camps as a hardware man and my grandmother taught school in mining camps. Although they were deceased before I was born, I inherited an interest in mining and mining history from my Dad. When my daughter's mother-in-law, Marian Mack, wanted to look into the Sampson Mine at Sumpter because her grandfather was a blacksmith for the Sampson Mining Company, I went in [to the DOGAMI Baker City field office —ed] to locate the mine. There I met a very knowledgeable lady, Jan Durflinger, who helped me locate the mine, one of

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Cover photo

Metolius River, originating between Three Fingered Jack and Santiam Pass on the eastern slope of the central Oregon High Cascades, is the best known example of the large-volume discharges of groundwater found in the region. The head of the Metolius emerges from the ground as a full-size river. The article beginning on the next page discusses age and provenance of some of the waters that are supplied by the Cascade Range mountains. Photo no. A-823 by Oregon Department of Transportation.

Springs in the Oregon Cascades: Where does the water come from? And how old is it?

by Elizabeth R. James and Michael Manga, Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, and Timothy P. Rose, Analytical and Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550

ABSTRACT

Isotopic and temperature measurements from large, cold springs in the central Oregon Cascades are used to understand where this groundwater comes from and how old it is. In particular, we employ the isotopes of helium, carbon, oxygen, and hydrogen to address these issues and to understand some aspects of the subsurface geology in this region. We find that large, cold springs in the central Oregon Cascades are recharged near the Cascades crest up to 50 km from the springs. We also find that the large springs in the study area discharge water that is a few years old. Finally, we show that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles to several of the springs such as the Metolius River and Lower Opal Springs.

INTRODUCTION

Surface water is a valuable resource to the east of the High Cascades. Rapid population growth in Deschutes County over the last 25 years has placed heavy demands on available surface water resources in the region (Caldwell, 1998). From Mount Jefferson in Oregon south to Lassen Peak in California, cold springs discharge groundwater in high volume, providing much of the base flow to regional rivers. Some of these springs are so large that they emerge from the ground as mature rivers, and as such, they are arguably among the most scenic spots in the region (Figure 1). Aside from their aesthetic value, however, the springs also provide a unique way of learning about regional hydrogeology. The goal of this paper is to show how natural isotopic tracer measurements and temperature measurements of spring water can be used to study both the hydrology of the area (Figure 2) and some aspects of the subsurface geology.

Where did the water come from? How old is the water? These are two of the most commonly asked questions about the hydrogeology of

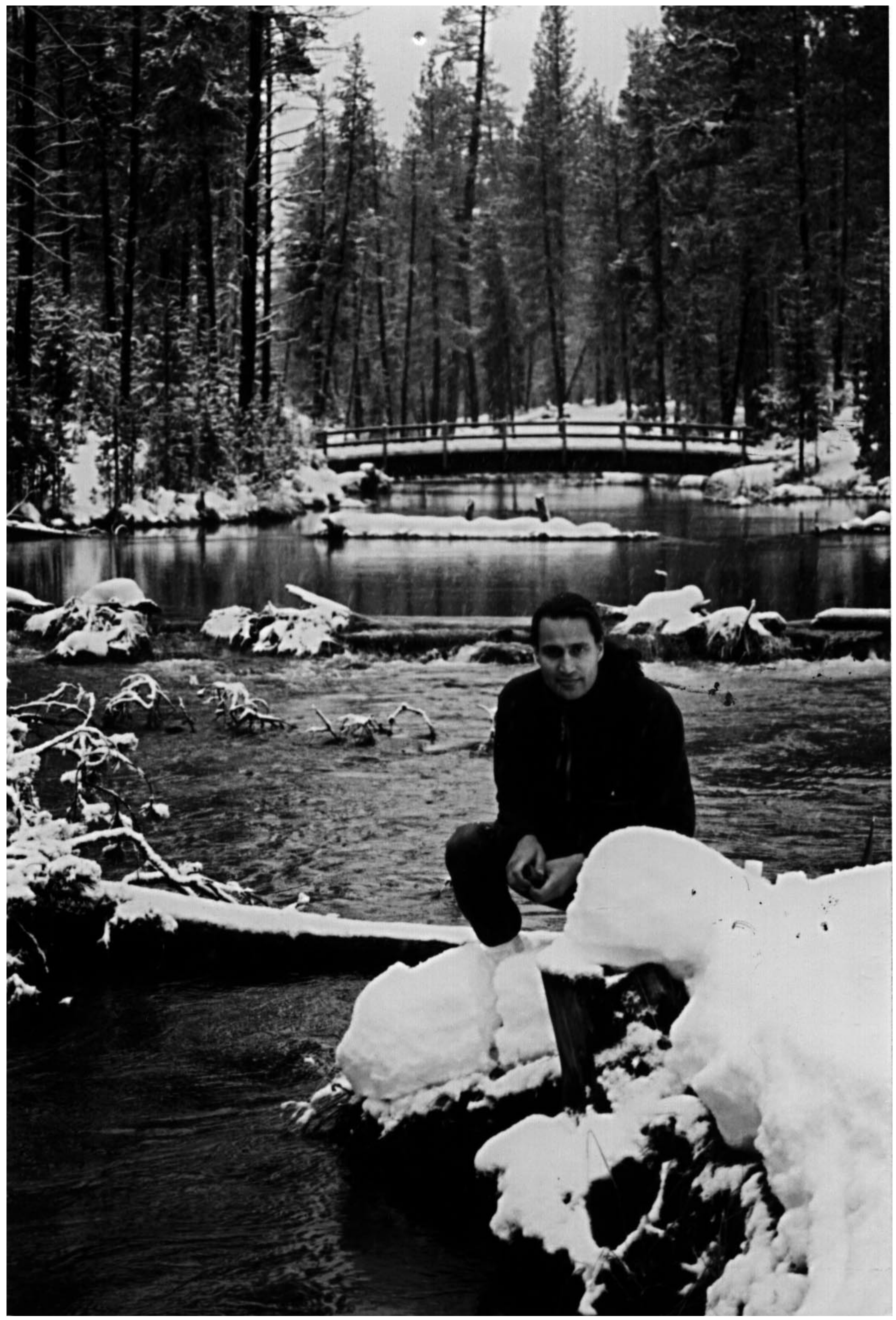

Figure 1. Fall River, central Oregon.

springs. Isotopic tracers present in the water can be used to elucidate both of these questions. After discussing some background information, we describe how tracers and temperature measurements can be used to address the two questions posed above, as well as provide a unique way of studying the subsurface geology.

GEOLOGIC AND HYDROLOGIC SETTING

Local hydrology is determined in large part by local geology. In central Oregon, the local geology is dominated by the Cascade arc, which began to form 40 million years ago as the Farralon Plate subducted beneath the North American plate (Orr and Orr, 1996). Starting around 7.5 million years ago, the line of eruptive centers shifted eastward and the belt of active volcan-

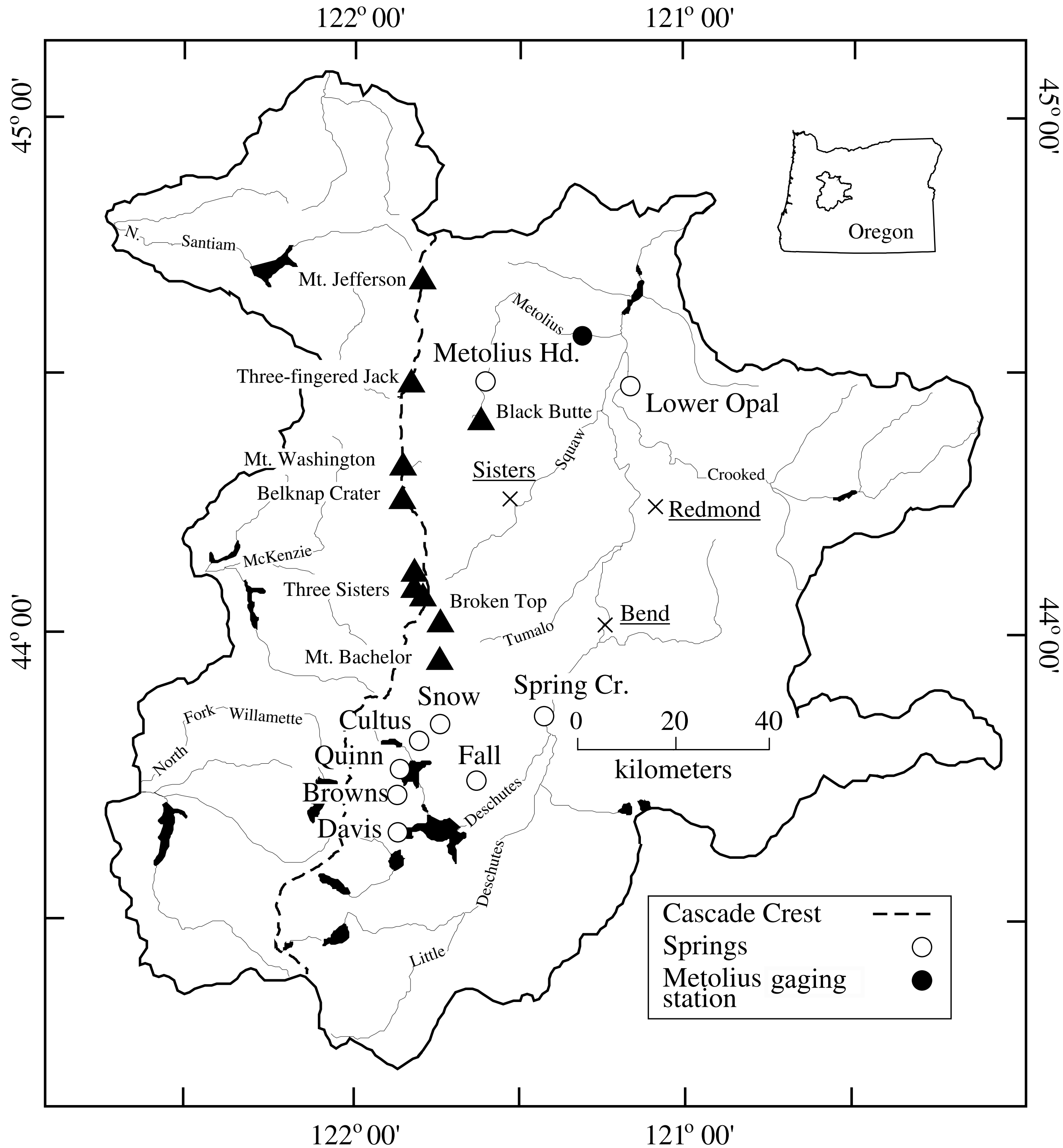

Figure 2. Map of the study region, showing locations of springs discussed in this paper.

ism narrowed to the location of the modern High Cascades. From 7.5 to 5 million years ago, the Cascades volcanoes extruded large volumes of basalt and basaltic andesite lava. The Deschutes Formation to the east of the modern crest of the High Cascades is a remnant of this volcanic episode. During this period, the tectonic regime changed from a compressional to an extensional one, and the early High Cascades subsided (Smith, 1991). This change in tectonic regime may be responsible for some of the unique geologic features of the central Oregon Cascades.

From north of Mount Jefferson to the south of Crater Lake, the crest of the High Cascades is a broad, nearly continuous ridge of overlapping basalt and basaltic andesite lava flows erupted from shield volcanoes (Ingebritsen and others 1994). To the north and south of this region, volcanism occurred primarily at isolated stratovolcanoes (Sherrod and Smith, 1990). The volume of erupted material and regional heat flow are estimated to be higher in central Oregon than in the regions to the north and south (Priest, 1990; Sherrod and Smith, 1990). The most recent volcanic activity in central Oregon occurred at Belknap Crater 1,500 years ago and at South Sister 1,900 years ago (Wood and Kienle, 1990).

The High Cascades produce a dramatic rain-shadow effect to the east of the range. Precipitation in the High Cascades of Oregon is as high as 3 m rainfall equivalent per year, but in the Bend area to the east, precipitation is as low as 0.25 m per year. Along the Cascade crest, the combination of heavy precipitation and permeable volcanic rocks serves to make this the primary recharge area for springs (Ingebritsen and others, 1989; Manga, 1997). Snowmelt is the primary source of groundwater recharge.

East of the crest, where aquifers are typically composed of permeable Quaternary volcanic rocks, most rivers and streams are fed by large-volume springs that discharge cold water, while thermal springs are relatively scarce (Meinzer, 1927). These spring-fed streams are characterized by relatively constant discharge throughout the year, with peak flows only several times larger than base-flow (Whiting and Stamm, 1995). The large cold springs often emerge at the surface contacts between permeable volcanic units and less permeable sediments (Manga, 1998). Cold springs are typically mixed cation bicarbonate waters, with concentrations of total dissolved solids typically ranging from 30 mg/L to 300 mg/L (Caldwell, 1998).

WHERE DOES THE WATER COME FROM?

This question can be addressed by analyzing the oxygen and hydrogen isotope content of the spring water. There are three naturally occurring stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) and two stable isotopes of hydrogen (^{1}H and ^{2}H). The utility of these isotopes in hydrologic investigations stems from the fact that they "fractionate" in a predictable manner (Clark and Fritz, 1997). As water moves through the hydrologic cycle, the relative abundance of the heavy vs. the light isotopes will change depending on the physical processes that are in operation.

In Oregon, air masses predominantly move eastward over the Cascade Range, where adiabatic cooling causes the water vapor to condense and form precipitation. During condensation, the heavy isotopes are preferentially enriched in the condensed phase (rain or snow). The degree of isotope fractionation is highly dependent on temperature and the degree of prior rainout, and, as a result, the degree of fractionation will also change with altitude (Dansgaard, 1964).

In the High Cascades, most precipitation occurs as snow. Local changes in the isotopic composition of a snow pack may occur through cycles of freezing and thawing, but for this analysis we assume that the isotopic composition of the snowmelt is approximately the same when it infiltrates the ground. If we know the relationship between elevation and isotopic composition of precipitation, we can estimate the mean recharge elevation of a spring from its isotopic composition. This is possible because the isotopic composition of groundwater does not change substantially between the recharge area and the spring (except due to mixing processes).

In order to determine recharge areas for the large cold springs in central Oregon, we collected 76 snow samples and 56 spring samples from the region shown in Figure 2. The data and experimental methods are reported in James (1999); selected data are reported in Table 1. All results are reported in the conventional δ-notation as per mil (parts per thousand or ‰) deviations from Standard Mean Ocean Water (SMOW).

Analysis of the snow core data reveals that the $\delta^{18}O$ values systematically decrease by 0.18‰ for every 100-m rise in elevation for the central Oregon Cascades (James, 1999). This is similar to relationships found elsewhere in the Northwest (Clarke and others, 1982; Rose and others, 1996). We assume that the groundwater is young enough to be directly comparable to modern precipitation. As we will show later, this assumption is reasonable. Figure 3 shows graphically how recharge elevations are determined.

In general, the $\delta^{18}O$ values of the springs indicate a significant component of recharge from high elevation areas in the Cascade Range. However, the distance between the recharge area and the discharge point can vary considerably. For example, Quinn River, Cultus River, and Browns Creek are all recharged near the crest of the Cascades, approximately 10 km west of the spring discharge area (Figure 2). Two other springs, the Metolius and Lower Opal, appear to have recharge areas located much farther from the springs. The Metolius River, which is located at an elevation of 920 m, is recharged at a mean elevation of 2,200 m. The $\delta^{18}O$ value of this spring suggests it is derived from recharge areas near the crest of the High Cascades, over 30 km from the spring. Lower Opal spring, which emerges at 520 m, also appears to have a component of recharge derived from the High Cascades (elevation approximately 2,500 m), which is over 50 km from the spring. For the latter two examples, the large elevation difference between the recharge area and the discharge point (Figure 3) implies a deeper, more regional groundwater flow path.

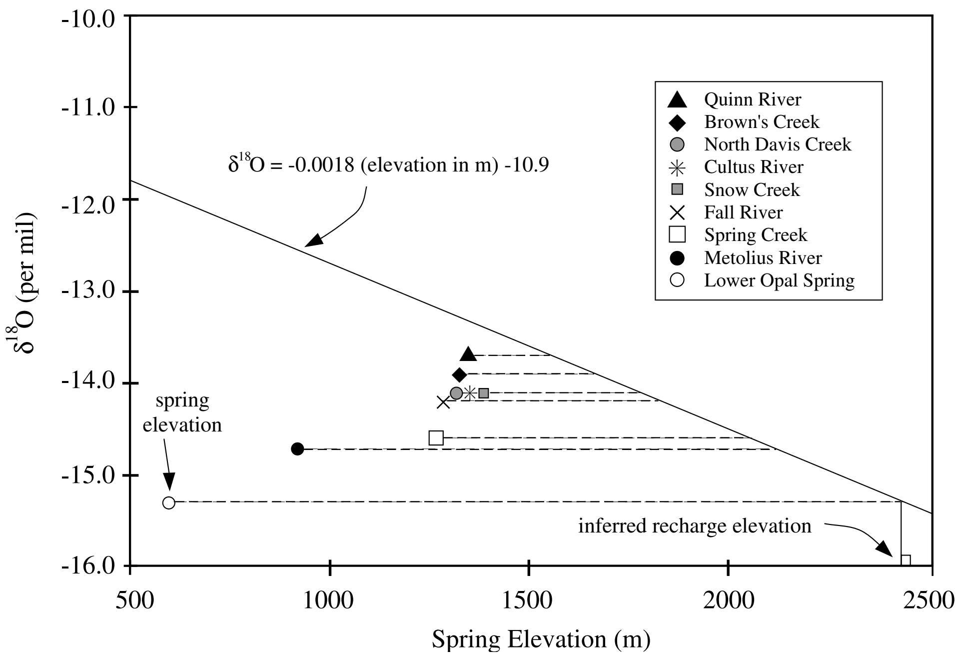

Figure 3. Plot of sample (spring) elevation vs. $\delta^{18}O$ values. The mean recharge elevation for springs can be determined by tracing the horizontal lines from the points representing the springs to the least-squares best-fit line of snow-core data from James and others (2000) for the relationship between snowpack $\delta^{18}O$ values and altitude.

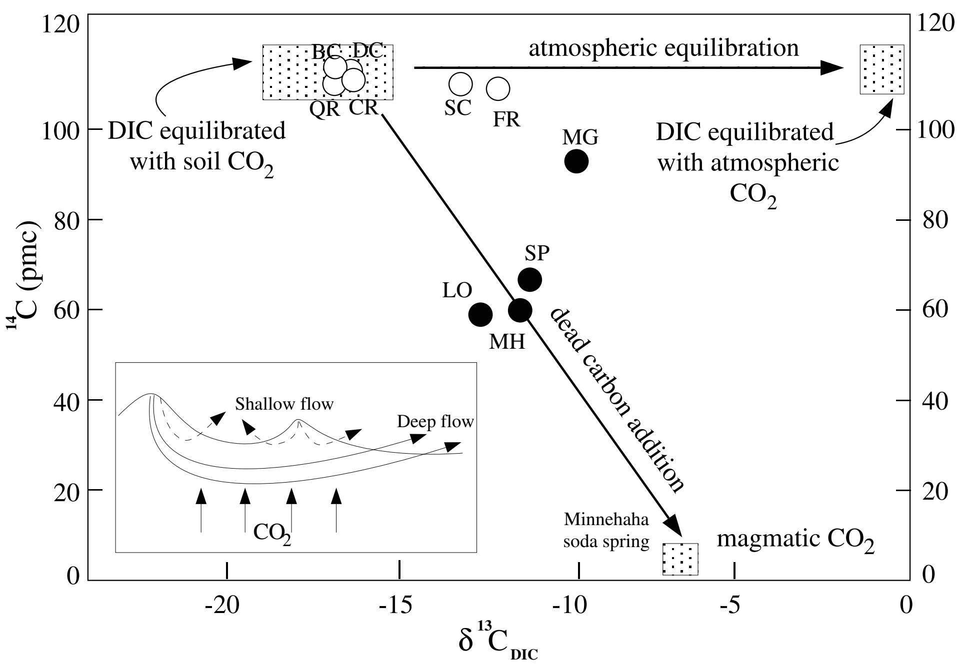

Figure 4. Plot of ^{14}C (in percent of modern carbon–pmc) vs. $\delta^{13}C$ values for groundwater samples. The stippled boxes represent the three endmember carbon isotope compositions: Dissolved inorganic carbon (DIC) equilibrated with soil CO_2, atmosphere CO_2, and "dead" CO_2 gas of magmatic origin. The latter endmember composition is represented by Minnehaha soda spring that is located in southern Oregon and has a ^{14}C content near zero. All spring samples have a pH between 7.0 and 8.5. The inset is a schematic illustration of the addition of magmatic CO_2 to deeply circulating groundwater. Solid circles represent deep flow and open cirlces represent shallow flow. Spring abbreviations are described in Table 1.

HOW OLD IS THE WATER?

Measuring natural isotopic tracers is one of the most straightforward ways of determining the "age" of the water. An analysis of tracer data, however, is often complicated by the fact that recharge usually occurs not at one particular location but instead along the entire length of an aquifer. Any given water sample is therefore likely to be a mixture of water of different ages. An "apparent age," however, can be determined from an analysis of helium and tritium isotopes (Jenkins and Clarke, 1976).

Three reservoirs may contribute helium to groundwater—the atmosphere, the mantle, and the crust. The $^3He/^4He$ ratio in the atmosphere is 1.386×10^{-6} (Marty and Le Cloarec, 1992). ^3He is also produced in the atmosphere by the decay of tritium (^3H), the radioactive isotope of hydrogen.

Although ^3H is produced naturally in the upper atmosphere, concentrations increased dramatically as a result of thermonuclear weapons testing during the 1950s and 1960s. Tritium undergoes beta-decay to ^3He with a half-life of 12.3 years. Thus, water with a component of groundwater recharged during the era of atmospheric weapons testing may contain a substantial amount of tritogenic helium. The mantle has a $^3He/^4He$ ratio on the order of 10^{-5} (Craig and Lupton, 1981) and is therefore enriched in ^3He relative to the atmosphere. ^4He is produced in the crust from U/Th decay.

Samples were collected from four springs for helium isotope analysis. Analytical procedures are described in James (1999). An apparent age of groundwater (i.e., the age the groundwater would be, assuming no mixing of groundwater of different ages) is obtained from the amount of tritogenic helium, $^3He_{trit}$, and ^3H in the sample (e.g., Poreda and others, 1988), using the formula:

$$\text{apparent age (yrs)} = \frac{12.43}{\ln 2} \times \ln\left[1 + \left(\frac{^3He_{trit}}{^3H}\right)\right].$$

For this method to work, we must subtract the contributions of ^3He from other sources. We assume equilibration with atmospheric helium during recharge. The sample values were corrected for excess air, i.e., air derived from the dissolution of small air bubbles caused by fluctuations in the water table (Heaton and Vogel, 1981), by measuring the concentration of Ar, which is derived solely from the atmosphere. Following this correction, the only two possible sources of excess ^3He in the groundwater are a mantle source or tritium decay. If we assume that there is no mantle contribution to these springs, then the apparent ages of Browns Creek, Quinn River, Cultus River, and Metolius River are 0.7, 2.1, 2.5, and 47.4 years, respectively (James and others, 2000). Our previous assumption that spring water is young enough to be comparable to modern precipitation is reasonable in light of the young ages of three of these springs. As we will show in the next section, the older "age" of the Metolius may be a result of the dissolution of magmatic gases in the groundwater. Indeed, this spring contains both excess ^4He and ^3He, which is indicative of a mantle or possibly a crustal source of Helium.

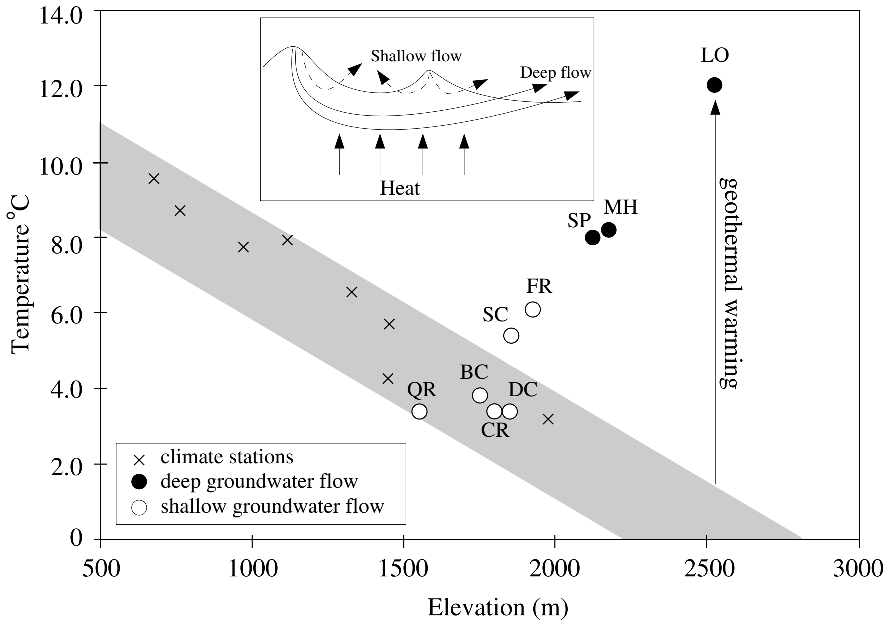

Figure 5. Relationship between elevation and temperature for Oregon climate stations and for springs discussed in this analysis. The climate stations are plotted at their actual elevations and the springs are plotted at their inferred mean recharge elevations as determined from oxygen isotope analyses of the water. The springs that lie significantly outside of the gray band have been warmed substantially from their presumed recharge temperature, represented by the average surface temperature of the recharge area. These springs (solid circles) are likely to discharge deeply circulating groundwater, whereas the spring waters that have lower temperatures (open circles) discharge shallow-circulating groundwater.

WHAT CAN WE LEARN ABOUT SUBSURFACE GEOLOGY FROM TRACER ANALYSES?

As groundwater flows through an aquifer, its solute chemistry may change due to water-rock interaction or dissolution of a volatile phase. Because the central Oregon Cascades are dominated by Quaternary volcanism, dissolved magmatic gases or fluids may be present in the groundwater. Thus, by analyzing the chemistry of the groundwater, we may be able to learn something about the subsurface geology of the region and the nature of the flow path (e.g., depth of the flow path).

A sensitive means of testing this hypothesis is to measure the carbon isotope content of the spring water. The dissolved inorganic carbon in most groundwater is derived from two main reservoirs—the soil CO_2 gas and carbonate minerals. The general lack of carbonate minerals in shallow volcanic aquifers of this region suggests that calcite dissolution has little influence on the dissolved carbon isotopic composition or concentration. Moreover, the amount of calcite that might be present should be negligible in comparison to the volume of water moving through the aquifer system. The volcanic arc, however, may be an additional source of magmatic CO_2.

Three isotopes of carbon are in the terrestrial environment. Of these isotopes, ^{12}C and ^{13}C are stable, and

Table 1. Flow, isotope, and temperature data for springs discussed in this analysis (pmc = percent of modern carbon; TU = tritium units [1 TU = 1 tritium atom per 10^{18} hydrogen atoms]; E = ×10; n.d. = not determined)

Spring	Elevation (m)	Recharge elev. (m)	Temperature (°C)	Discharge[a] (m^3/s)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	^{14}C (pmc)	^{4}He (atoms/g)	^{3}He (atoms/g)	Ar (atoms/g)	^{3}H (TU)	$^{3}He/^{3}H$ age (yrs)
Browns (BC)	1,332	1,750	3.8	1.1	-13.9	-16.4	115.3	1.18E^{12}	1.63E^{6}	1.13E^{16}	6.9	0.7
Cultus (CR)	1,356	1,800	3.4	1.8	-14.1	-15.8	113.9	1.15E^{12}	1.65E^{6}	1.04E^{16}	9.0	2.5
Fall (FR)	1,286	1,900	6.1	4.2	-14.2	-11.8	110.9	n.d.	n.d.	n.d.	n.d.	n.d.
Lower Opal (LO)[b]	597	2,525	12	6.8	-15.3	-12.7	60.0	n.d.	n.d.	n.d.	0.8	n.d.
Metolius (MH)	920	2,175	8.2	3.1	-14.7	-11.5	61.3	1.71E^{12}	4.89E^{6}	9.56E^{15}	4.0	47.7
Metolius gag.(MG)	602	n.d.	8.4	49.0	-13.5	-9.7	93.7	n.d.	n.d.	n.d.	n.d.	n.d.
N. Davis (DC)	1,323	1,850	3.4	n.d.	-14.1	-15.8	114.0	n.d.	n.d.	n.d.	n.d.	n.d.
Quinn (QR)	1,354	1,550	3.4	0.7	-13.7	-16.5	112.3	1.16E^{12}	1.66E^{6}	1.05E^{16}	8.1[c]	2.1
Snow (SC)	1,378	1,850	5.5	0.8	-14.1	-12.9	111.1	n.d.	n.d.	n.d.	n.d.	n.d.
Spring (SP)	1,268	2,125	8.0	3.5	-14.6	-11.5	67.5	n.d.	n.d.	n.d.	n.d.	n.d.

[a] USGS gaging station measurements, except Metolius: from Meinzer (1927)

[b] Data from Caldwell (1998)

[c] Data from Manga (1997)

^{14}C is radioactive with a half-life of 5,730 years. Because magmatic CO_2 is very old, it does not contain ^{14}C. Given the young ^{3}He-^{3}H ages of these waters, it is logical to assume that if the groundwater has a low amount of ^{14}C, then it may contain dissolved magmatic CO_2 (Allard and others, 1991; Rose and Davisson, 1996; Rose and others, 1996; Sorey and others, 1998).

Water was collected from nine cold springs for carbon isotope analysis. Analytical procedures are described in James and others (1999). ^{14}C results are reported as a percent of modern carbon (pmc) relative to 0.95 times the specific activity of the NIST oxalic acid standard reference material. $\delta^{13}C$ content is reported as the conventional per mil deviation from the Pee Dee belemnite (PDB) standard.

Of the large cold springs in central Oregon, the Metolius, Spring Creek, and Lower Opal, are found to have a low ^{14}C content, which we interpret to indicate the presence of dissolved magmatic CO_2 (Figure 4). Recall that the Metolius River also contains a large amount of excess dissolved ^{3}He. The dissolved magmatic carbon present in this spring is consistent with a magmatic origin for some of the ^{3}He. In this case the "age" of the groundwater may therefore be substantially younger than the 47 years calculated from the tritium and helium analysis.

We can calculate the flux of magmatic CO_2 dissolved in these three springs, given their discharge rates and the magmatic carbon concentrations. For the Metolius River, Spring Creek, and Lower Opal Springs, the annual fluxes of dissolved magmatic CO_2 are 2.4, 1.8, and 4.4×10^6 kg, respectively (James and others, 1999). We also collected a water sample from near the Metolius gaging station. We calculate the flux of magmatic CO_2 at the gaging station to be 8.0×10^6 kg/yr. The Metolius and Lower Opal drainages encompass approximately 75 km of the volcanic arc. This implies that the average dissolved magmatic CO_2 flux for this region is approximately 3.4×10^5 kg/yr per kilometer of arc (see James and others, 1999, for details of this calculation).

Though this flux is small compared to the flux of CO_2 from the craters of active volcanoes (Brantley and Koepenick, 1995), it is consistent with what we would expect on the basis of heat flow data collected in this area. The mean magmatic intrusion rate for this region is estimated to be between 9 and 50 km^3/m.y. per km of arc, based on heat flow measurements (Ingebritsen and others, 1989; Blackwell and others, 1990). For this estimated magmatic intrusion rate, we can calculate the flux of magmatic CO_2 that we would expect to be released from the solidification of a magma with a density of 3.0 g/cm^3. We assume complete degassing of a magma with a CO_2 content between 0.075 and 0.65 weight percent (Garcia and others, 1979; Gerlach and Graeber, 1985; Roggensack and others, 1997; Sisson and Bronto, 1998). With these assumptions, we would predict a flux of magmatic CO_2 between 2.0×10^4 and 9.8×10^5 kg/yr per kilometer of arc. Our estimated flux falls within this range, which is consistent with the fact that the heat and CO_2 fluxes are both produced by the cooling and solidification of magma at depth.

That only three of the large springs contain dissolved magmatic gas suggests that either the diffuse flux of magmatic gas is unevenly distributed or that groundwater circulation dissolves magmatic volatiles only along deep flow paths. Temperature measurements made at the springs indicate that the latter case is more likely. Based on regional estimates of heat flow, it is possible to calculate the expected amount of geothermal warming of groundwater by using simple mass and energy balance arguments (Brott and others, 1981; Manga, 1998). For this analysis, we assume that groundwater circulation occurs at a sufficient rate that all geothermal heat is discharged at the spring and that there is no surface conductive heat flow (Ingebritsen and others, 1989). Background geothermal heat flow measurements in the region are estimated to range between 110 and 130 mW/m^2 (Blackwell and others, 1982; Ingebritsen and others, 1992).

From the oxygen and hydrogen isotope analysis we found that the recharge area of the Metolius was along the Cascade crest. From this result, we estimate the drainage area to be approximately 400 km^2. The expected change in temperature of the Metolius groundwater can be calculated from the equation

$$\Delta T = \frac{Q}{\rho C} \times \frac{\text{drainage area}}{\text{spring discharge}}$$

where ΔT is the expected geothermal warming, Q is the background heat flow, ρ is the density of water, and C is the heat capacity of water (Manga, 1998). Based on borehole temperature measurements taken near the Cascade crest, near-surface groundwater is about 3°C (Ingebritsen and others, 1994). The Metolius temperature is 8.2°C. From the above equation, we obtain a Q of approximately 160 mW/m^2. This value is higher than the heat flow of 110 to 130 mW/m^2 found by Blackwell and others (1982) and Ingebritsen and others (1992). Our higher value may indicate that the Metolius drains a larger region than previously assumed, or that the mean discharge is lower than assumed.

Relatively high temperature measurements indicate that the Metolius, Lower Opal, and Spring Creek all discharge deeply circulating groundwater. Because these three springs also show a component of dissolved magmatic CO_2, we can conclude that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles, whereas the shallow groundwater does not.

Other springs in this region do not appear to have warmed substantially beyond the near-surface temperatures of the recharge area (Figure 5). From this observation we can conclude that Quinn River, Cultus River, Browns Creek, and Davis Creek discharge groundwater from shallow circulation.

CONCLUDING REMARKS

By integrating a suite of tracer measurements with temperature measurements, we have answered the two questions posed at the beginning of this paper. First, we have identified mean groundwater recharge elevations for large, cold springs in the central Oregon Cascades. Three of these springs have average recharge areas that are located farther from the spring than might be assumed by topographic considerations alone. We have also determined that the apparent groundwater ages for large, cold springs in this region are on the order of several years. Thus, in this region of the Cascades, groundwater residence times are short, groundwater flow rates are rapid, and aquifer permeabilities are high. We have also learned about the interaction between geologic and hydrologic processes from these measurements, in particular that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles to the springs. These findings, which address the pattern of groundwater flow in one small region of central Oregon can help with studies on a larger scale, such as that undertaken by the U.S. Geological Survey (e.g., Caldwell, 1998).

The signs marking the headwaters of two of the large cold springs in central Oregon summarize some of these issues. At the headwaters of the Quinn River, a sign states:

> The crystal-clear water from this spring may have fallen several years ago as snow in the High Cascades. Each year, as the snow melts, most of the water seeps into cracks of this "geologically young" country and travels through underground channels.

Answering the first question posed above involves a determination of the recharge area. As this sign states, the recharge area for the Quinn River is in the Cascades. A more precise recharge elevation can be determined by analyzing the oxygen and hydrogen isotope composition of the water. The "age" of the water can also be determined with isotopic tracers. The sign states that water is several years old. By measuring the concentration of the radioactive isotope of hydrogen (tritium) and its decay product (helium-3) in the spring water, it is possible to determine the mean age of water. The sign also addresses the fact that the water flows through geologically young terrain. As the water flows through the young, volcanic rocks, it may dissolve magmatic gases released at depth by the solidification of intruded magma. Carbon isotopes and helium isotopes, in addition to temperature measurements, can be used to understand these geologic processes.

The Metolius headwaters are marked by a sign stating the following:

> Down this path a full-sized river, the Metolius, flows ice cold from huge springs. The springs appear to originate from beneath Black Butte. However, geologists say this is misleading and believe the springs have their origin in the Cascade Range to the west.

Based on topographic considerations alone, the Metolius River appears to discharge water derived from Black Butte. But a tracer analysis of the water indicates that the spring actually discharges water derived from much farther to the west, in the high-elevation Cascade Range. This sign also emphasizes the cold temperature of the spring water. While these springs are in fact quite cold (about 8°C), they do carry a significant amount of heat derived from geothermal sources at depth. Temperature measurements taken at the springs can be used to estimate the amount of heat acquired as the groundwater flows through the subsurface.

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Oil and gas exploration and development in Oregon, 1999

by Dan E. Wermiel, Geologist, Oregon Department of Geology and Mineral Industries

ABSTRACT

There was an increase in oil and gas leasing activity during 1999, compared to 1998. The increase was in part due to an oil and gas lease sale held by Columbia County where 5,087 acres were acquired by three companies. The acreage leased was located within or in proximity to the Mist Gas Field. Four U.S. Bureau of Land Management (BLM) lease sales were held during the year, and no offers were received. During the year, the BLM sold three over-the-counter noncompetitive leases consisting of 13,885 acres located in Jefferson and Wheeler Counties in eastern Oregon. A total of 56,126 federal acres were under lease at year's end. The State of Oregon conducted no lease sales during the year. Eight State of Oregon tracts were under lease at year's end, comprising 3,741 acres, the same as 1998.

Seven exploratory wells and one redrill were drilled in Oregon by Enerfin Resources during 1999. All were drilled at the Mist Gas Field. Of these, five exploratory wells were successful natural gas wells. The other two exploratory wells and the redrill were plugged and abandoned.

At the Mist Gas Field, 21 wells were productive during 1999. A total of 1.6 billion cubic feet (Bcf) of natural gas was produced during the year with a total value of $3.3 million.

The Oregon Department of Geology and Mineral Industries (DOGAMI) has an oil and gas internet webpage that contains production and other data, drilling application forms, statutes and rules, and other information including links to other webpages. The address is http://sarvis.dogami.state.or.us/oil/homepage.htm.

DOGAMI conducted a triennial review of administrative rules related to oil and gas during the year, and several minor changes were made.

LEASING ACTIVITY

Leasing activity in Oregon increased during 1999, compared to 1998. This was in part due to an oil and gas lease sale held by Columbia County, where 5,087 acres were acquired. The leases were offered through an oral auction bidding system. Enerfin Resources, Houston, Texas acquired the majority of the acreage consisting of 2,931 acres, while, while Anders Elgerd, Lakewood, Colorado, acquired by 1,277 acres for Gold Coast Resources and 879 acres for Oregon Petroleum. The leases were all located within or in proximity to the Mist Gas Field, Columbia County, Oregon. The majority of the acreage was acquired for a minimum bid of $1.00 per acre, and the highest bid of $10.00 per acre was received for a 120-acre parcel located in sec. 29, T. 4 N., R. 4 W., south of Mist Gas Field. Columbia County acquired total receipts of $19,739 for bids and first-year rental of $2.50 per acre at the lease sale.

The total federal acres under lease in Oregon increased during 1999. The U.S. Bureau of Land Management (BLM) held four lease sales during 1999, at which no bids were received. However, the BLM sold three over-the-counter noncompetitive leases consisting of 13,885 acres during the year. These leases are located in Jefferson and Wheeler Counties in eastern Oregon. A total of 56,127 federal acres was under lease at year's end in Oregon, an increase from the 31,374 federal acres under lease at the end of 1998. Total leasing income to the BLM was $62,490 during 1999.

The State of Oregon held no lease sales during 1999, and no new leases were issued. At year's end, eight State of Oregon tracts were under lease, comprising 3,741 acres, which is the same as at the end of 1998. Total rental income to the State of Oregon was $3,741 during 1999.

DRILLING AND EXPLORATION ACTIVITY

Seven exploratory wells and one redrill were drilled by Enerfin Resources in Oregon during 1999. This is about the same drilling level as the six exploratory wells and two redrills drilled during 1998.

All the wells drilled in Oregon during 1999 were located at the Mist Gas Field, Columbia County, where most of the state's oil and gas drilling activity has occurred since the field was discovered in 1979.

Of the wells drilled during 1999, five exploratory wells were successful natural gas wells, while two exploratory wells and the redrill were plugged and abandoned. The successful natural gas wells are the CC 11–34–75, located in NW ¼ sec. 34, T. 7 N., R. 5 W., drilled to a total depth of 3,106 ft; CC 14–22–75, located in SW ¼ sec. 22, T. 7 N., R. 5 W., drilled to a total depth of 2,976 ft.; CC 14–32–75, located in SW ¼ sec. 32, T. 7 N., R. 5 W., drilled to a total depth of 3,229 ft.; CC 32–28–75, located in NE ¼ sec. 28, T. 7 N., R. 5 W., drilled to a total depth of 2,863 ft; and LF 33–22–75, located in SE ¼ sec. 22, T. 7 N., R. 5 W., drilled to a total depth of 3,011 ft. These wells are all located in the northern part of the Mist Gas Field. At year's end, two of the wells were hooked to pipeline and on production, and three were suspended awaiting pipeline connection.

The wells and redrill that were plugged and abandoned during 1999 are the JH 43–26–64, located in SE ¼ sec. 26, T. 6 N., R. 4 W , drilled to a total depth of 4,610 ft. This is the easternmost well drilled to date at Mist Gas Field. The CC 12–2–65, located in NW ¼ sec. 2, T. 6 N., R. 5 W., was drilled to a depth of 2,731 ft. and then redrilled to a depth of 2,863 ft., before it was plugged and abandoned.

In addition to drilling exploratory wells at Mist Gas Field, Enerfin Resources plugged and abandoned four suspended natural gas wells that had depleted reservoirs and were determined to have no future beneficial use for underground natural gas storage or any other purpose. These wells are the CC 34–31–65 RD, located in SE ¼ sec. 31, T. 6 N., R. 5 W.; CC 44–8–64, located in SE ¼ sec. 8, T. 6 N., R. 4 W.; LF 31–36–65, located in NE ¼ sec. 31, T. 6 N., R. 5 W.; and the LF 43–32–65, located in SE ¼ sec. 32, T. 6 N., R. 5 W.

During 1999, DOGAMI issued five permits to drill. Permit activity is listed in Table 1.

PRODUCTION

The Mist Gas Field was operated by Enerfin Resources and Northwest Natural during 1999. During the year, 21 natural gas wells were productive at the Mist Gas Field, 17 operated by Enerfin Resources and four operated by Northwest Natural. This is slightly higher than the 19 wells productive at the Mist Gas Field during 1998. Natural gas production for the year totaled 1.6 billion cubic feet (Bcf) of natural gas, a higher volume than the 1.3 Bcf of natural gas produced during 1998. The increase in natural gas production at the Mist Gas Field during 1999 can be attributed to the addition of new exploratory wells being completed by Enerfin Resources and connected to pipeline.

The natural gas price remained constant all year at 24 cents per them, which is slightly higher than the 23 cents per them during 1998. The total value of natural gas produced at Mist Gas Field during 1999 was about $3.3 million, which is greater than the $2.6 million during 1998. This increase is a result of the greater amount of natural gas produced and the higher natural gas price during 1999. Cumulatively, the Mist Gas Field has produced about 65 Bcf of natural gas with a total value of $125 million since it was discovered in 1979.

GAS STORAGE

The Mist and the Calvin Creek Underground Natural Gas Storage Projects are operated by Northwest Natural and were both operational during 1999. The Mist Gas Storage Project has nine injection-withdrawal service wells and 13 monitoring service wells. The Calvin Creek Gas Storage Project currently has 3 injection-withdrawal service wells and four monitoring service wells. Further development to increase storage capacity is expected to occur next year. The two gas storage projects have a total storage capacity of about 15 Bcf of natural gas in the reservoirs at pressures between approximately 400 and 1,000 psi and will provide maximum daily peak capability of approximately 145 million cubic feet (MMcf) of natural gas per day.

A total of 7.6 Bcf of natural gas was injected into, and 7.2 Bcf of natural gas was withdrawn from, the natural gas storage projects during 1999.

During 1999, Northwest Natural began construction of an additional South Mist Feeder natural gas pipeline from Mist Gas Field to the west side of the Portland, Oregon, metropolitan area. This 24-in. pipeline generally follows the route of the existing 16-in. pipeline and will significantly increase the capacity of natural gas that Northwest Natural can deliver from the Mist Gas Field and the Mist and Calvin Creek Underground Natural Gas Storage Projects to the Portland area. Additional pipeline construction is proposed by Northwest Natural to extend the 24-in. South Mist Feeder pipeline to Clackamas County , Oregon.

Northwest Natural continued testing the depleted Busch Pool, located in SW ¼ sec. 15, T. 6 N., R. 5 W., during 1999 to determine if it has any possible future use for underground natural gas storage. Previous natural gas injection testing of this pool was unsuccessful because of water invasion into the reservoir. Northwest Natural began an evaluation during 1998 and continued during 1999 with its attempt to clear the reservoir of water and return it to usefulness for natural gas storage. In this process, natural gas is injected into the reservoir at a pressure slightly greater than initial reservoir pressure, The evaluation was ongoing at year's end.

OTHER ACTIVITIES

DOGAMI has constructed an oil and gas internet homepage. The webpage address is http://sarvis.dogami.state.or.us/oil/homepage.htm.

Included on this homepage are Mist Gas Field production figures and data, oil and gas statutes and administrative rules, permit application forms and other forms, publication list, and other information related to oil and gas exploration and production information as well as other agency activities. A historical database that shows wells drilled in Oregon, locations, dates, total depth, available well logs and samples, references and other data has been completed and will be added to the homepage.

The Northwest Energy Association (NWEA) was active during the year with over 100 members. At its regular monthly meetings, speakers give talks on subjects related to energy matters in the Pacific Northwest. A webpage is being developed which intends to provide information on the NWEA schedule of activities, including the plans for the 2000 fall symposium. For more information, contact the NWEA, P.O. Box 6679, Portland, OR 97228.

Triennial revisions to Oregon Ad-

(Continued on page 98)

Figure 1. During 1999, Enerfin Resources drilled and successfully completed the Columbia County 14–22–75 natural gas well at the Mist Gas Field. The top picture shows the location before drill site construction was begun. The bottom picture shows the same view of the drill site following drilling and completion of the natural gas well, including the wellhead production equipment. The Department's geologic and engineering expertise is applied in the location and design of well drilling, the conduct of development operations, the production of resources, and the final plugging of wells and cleanup and reclamation of drill sites.

Table 1. Oil and gas permit activity in Oregon, 1999

Permit number	Operator, well, API number	Location	Status, depth(ft) TD=total depth PTD=proposed TD
458	Enerfin Resources CC 34-31-65 RD 36-009-00284-01	SE ¼ sec. 31 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 1,902 ft.
459	Enerfin Resources CC 44-8-64 36-009-00285	SE ¼ sec. 8 T. 6 N., R. 4 W. Columbia County	Abandoned; TD 1,810 ft.
477	Enerfin Resources LF 43-32-65 36-009-00302	SE ¼ sec. 32 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 1,909 ft.
478	Enerfin Resources LF 31-36-65 36-009-00303	NE ¼ sec. 36 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 3,987 ft.
511	Enerfin Resources Larkin 43-32-65 36-009-00331	SE ¼ sec. 23 T. 6 N., R. 5 W. Columbia County	Permit extended.
513	Enerfin Resources JH 14-23-64 36-009-00332	SW ¼ sec. 23 T. 6 N., R. 4 W. Columbia County	Permit withdrawn.
516	Enerfin Resources JH 43-22-64 36-009-00335	SE ¼ sec. 22 T. 6 N., R. 4 W. Columbia County	Permit withdrawn.
517	Enerfin Resources CC 14-22-75 36-009-00336	SW ¼ sec. 22 T. 7 N.. R. 5 W. Columbia County	Suspended, gas; TD 2,976 ft.
518	Enerfin Resources CC 32-28-75 36-009-00337	NE ¼ sec. 28 T. 7 N., R. 5 W. Columbia County	Suspended, gas; TD 2,863 ft.
519	Enerfin Resources LF 33-22-75 36-009-00338	NW ¼ sec. 22 T. 7 N., R. 5 W. Columbia County	Suspended, gas; TD 3,011 ft.
520	Enerfin Resources Adams 44-28-75 36-009-00339	SE ¼ sec. 28 T. 7 N. R. 5 W. Columbia County	Permit withdrawn.
522	Enerfin Resources CC 14-32-75 36-009-00341	SW ¼ sec. 32 T. 6 N., R. 5 W. Columbia County	Completed, gas; TD 3,229 ft.
523	Enerfin Resources JH 43-26-64 36-009-00342	SE ¼ sec. 26 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 4,610 ft.
524	Enerfin Resources CC 11-34-75 36-009-00343	NW ¼ sec. 34 T. 7 N., R. 5 W. Columbia County	Completed, gas; TD 3,230 ft.
525	Enerfin Resources JH 11-26-64 36-009-00344	NW ¼ sec. 26 T. 6 N., R. 4 W. Columbia County	Permit canceled.
526	Enerfin Resources JH 32-26-64 36-009-00345	NE ¼ sec. 26 T. 6 N., R. 5 W. Columbia County	Application, PTD 4,520 ft.
527	Enerfin Resources CC 12-2-65 36-009-00346	NW ¼ sec. 2 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 2,731 ft.
527RD	Enerfin Resources CC 12-2-65 RD 36-009-00346-01	NW ¼ sec. 2 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 2,863 ft.
528	Enerfin Resources CC 23-28-75 36-009-00347	SW ¼ sec. 28 T. 7 N., R. 5 W. Columbia County	Application, PTD 2,825 ft.

(Continued from page 96)
ministrative Rules Chapter 632 Division 10 (oil and gas), Division 15 (information and seismic test holes) and Division 20 (geothermal) were completed during the year. Input was solicited from the industry and interested parties for revisions to the regulations. Several minor adjustments were made to the rules but no significant changes. The boundary of the Mist Gas Field was adjusted to the north to include the area of recently completed natural gas wells. The rules are available on the DOGAMI webpage; other information can be obtained by contacting DOGAMI.

The annually updated Mist Gas Field Map, DOGAMI Open-File Report O–00–01, shows the Mist Gas Field divided into quarter sections. It displays location, status, and depth of all wells drilled to date at the field and serves as a basis for locating new ones. It also shows the area and wells that are used for storage of natural gas. The attached production summary for 1993–1999 includes well names, pressures, and production data. Production data are also available on the DOGAMI web page. The map and accompanying production data are useful tools for administrators and planners as well as explorers and producers of natural gas.

A cumulative report of past production at Mist Gas Field between 1979 and 1992 is available in a separate release under the title *Mist Gas Field Production Figures* as DOGAMI Open-File Report O–94–6. Contact the Nature of the Northwest Information Center (503-872-2750) for a complete publication list. □

DOGAMI honored twice

The Oregon Department of Geology and Mineral Industries received two of the five 1999 Awards in Excellence given by the Western States Seismic Policy Council (WSSPC). These awards recognize achievement in different areas of earthquake mitigation, preparedness, and response. The DOGAMI awards were in the category "Educational Outreach Programs," one to schools and the other to business and government.

The school program focused especially on an instructional curriculum for tsunami education, educational exhibits on frequently visited beaches, and information pieces and take-away educational items for visitors to coastal hotels and motels.

The program award for "outreach to business/government" went to the DOGAMI-administered Day Care and Head Start Retrofit program. SAFECO Insurance Company, Fred Meyer, Peake Sun Systems, and CAT-Head Start worked together with DOGAMI.

At DOGAMI, most of the work on these programs was directed and carried out by former State Geologist Donald A. Hull and former administrative assistant Angie Karel. □

K-Ar results from the southern Oregon-northern California Cascade Range

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ABSTRACT

Nearly 180 new whole-rock potassium-argon age dates from the southern Oregon Cascade volcanic province are reported, each with a corresponding major- and trace-element geochemical analysis. K-Ar results from the Klamath River canyon region astride the California-Oregon border delineate no obvious temporal break in volcanic activity. However, 25 mi farther to the north in the Mount McLoughlin-Brown Mountain-Little Butte Creek region, a time gap in volcanic activity has been documented to exist between 17 and 7 Ma. Mafic volcanic activity, which marks the inception of renewed volcanism between 6 and 7 Ma ago, is compositionally quite diverse, ranging from olivine trachybasalt to low-potassium high-alumina olivine tholeiite basalt.

INTRODUCTION

The purpose of this article is to summarize a ten-year accumulation of potassium-argon (K-Ar) whole-rock age determinations that were gathered in support of numerous student mapping projects across the High Cascades of southernmost Oregon and northernmost California (Figure 1). These student mapping projects were part of my long-range goal to map the geology of the region between Mount Shasta and Crater Lake National Park. Naturally, understanding the field relationships is a necessary prerequisite to understanding the geologic history and volcanic petrology of this large area. In large part, the funding to accomplish the field work came from Franklin & Marshall College and the Keck Geology Consortium. The latter organization is an alliance of twelve small liberal arts colleges whose geology departments produce a disproportionate number of graduates who eventually go on and earn Ph.D. degrees. This group of institutions was originally chosen and funded by the William M. Keck Foundation of Los Angeles.

METHODOLOGY

Argon isotopic analysis was performed at Case Western Reserve University in Cleveland, Ohio. K_2O values were determined in duplicate through an XRF (X-ray fluorescence) flux-fusion technique utilized at Franklin & Marshall College to accomplish whole-rock major-element geochemical analysis.

K-Ar age determinations

Over the years, nearly 180 samples have been analyzed for whole-rock K-Ar ages. Preparation of the samples proceeded in the following manner: Samples from which all outward signs of weathering had been removed were crushed. An aliquot of the resulting coarse rock fragments was split from the bulk sample with a stainless-steel geochemical sample splitter and crushed with an alumina-plate-equipped mullite grinder. The output was sieved in order to collect the rock particles within the size fraction of 18–35 mesh. The stainless steel sieves used were reserved for K-Ar work only. Sample powders were washed repeatedly with deionized water and methanol and dried thoroughly to insure powder-free samples.

Between 3 and 8 grams of rock from the 18- to 35-mesh fraction was weighed out to the nearest 0.00001 grams and transferred into a 99.999-percent molybdenum crucible. Six samples at a time were hung in individual quartz bell jars and baked out for at least six hours at 360°F. First, a measured aliquot of ^{38}Ar tracer was extracted under vacuum and frozen onto clean activated charcoal immediately prior to beginning the sample fusion process. With a step-wise heating procedure, the sample was completely fused in an RF induction furnace by holding it at 1,600°C for twelve minutes, during which time the tracer is released to mix thoroughly with the gases from the melted sample. Hot Ti "getters" were employed to remove reactive gases liberated with the inert gases during the fusion process. The gas sample was cooled, frozen onto a second aliquot of clean activated charcoal, thawed and released back to a vapor state, and cleaned again by exposure to a hot SAES Ti "getter." Once cooled, the gas sample was introduced into a MS–10 mass spectrometer interfaced with an IBM personal computer. Peak intensities resulting from ^{40}Ar, ^{38}Ar, and ^{36}Ar in the gas sample were measured with a Carey 401 vibrating reed electrometer; in addition, background counts were measured on both sides of each peak. A data set consisted of measuring ^{40}Ar peak + two background positions down through ^{36}Ar peak + two background positions; and then reversing the process, measuring ^{36}Ar, etc., returning to ^{40}Ar and its background positions. Six to eight data sets were collected per sample measurement. The $^{40}Ar/^{36}Ar$ ratios determined for these data sets (two per set) were used to calculate the age of the sample. Aliquots of an atmospheric Ar sample were measured two to three times during a batch of six samples by measuring five to seven sets of data and calculating the mean of these 10 to 14 $^{40}Ar/^{36}Ar$

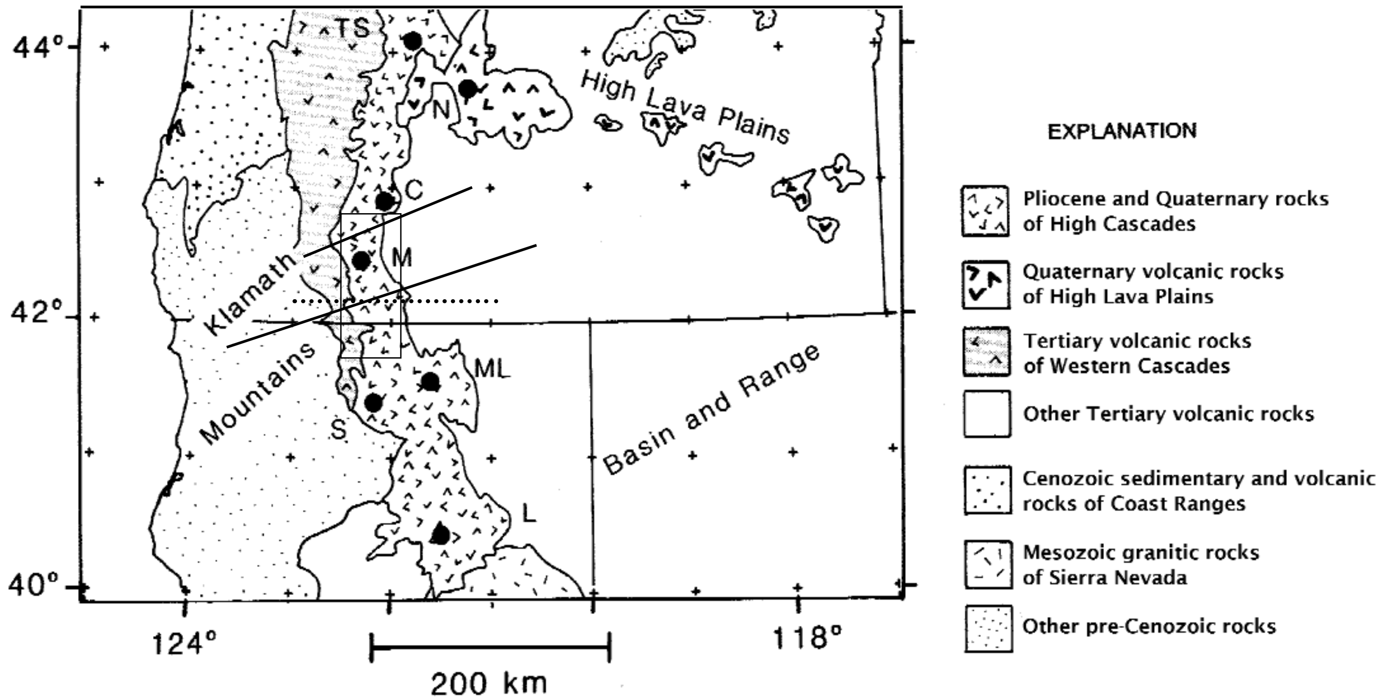

Figure 1. Generalized geologic map showing major Cascade volcanoes (filled circles), the region under discussion in this paper (rectangular outline), the approximate border between the northern and southern segments of the study area (dotted line), and two structural boundary lines discussed in the section "K-Ar results." Letters refer to volcanoes: TS = Three Sisters, N = Newberry Crater, C = Crater Lake, M = Mount McLoughlin, ML = Medicine Lake, S = Mount Shasta, and L = Lassen Peak. Modified from Blakely and Jachens (1990).

ratios, thus providing a correction for the diffusion of atmospheric Ar into the vacuum system.

Uncertainty in the K-Ar ages was determined by assuming a 0.3-percent uncertainty in the measured isotopic compositions of the sample and the ^{38}Ar tracer, a 1.0-percent uncertainty in the volume of the tracer, a 2.0-perent uncertainty in the sample homogeneity, and an uncertainty of 0.8 percent in the measurement of the K_2O content. Naturally, as the age of the sample gets younger and/or the K_2O content gets lower, the age uncertainty will be larger. A thorough petrographic inspection of a potential sample's thin section was conducted to insure an absolute minimum of samples whose age uncertainty was a high percentage of the actual radiometric age. Two considerations have proved successful to the author: (1) Make sure that none of the ferromagnesian minerals show alteration to serpentine (iddingsite seems to make relatively little difference) and that there is very little to no devitrified glass product in the groundmass of a sample; and (2) be aware that for the most part, the ages reported herein represent the actual time at which the sample's temperature passed through its closure temperature for argon retention, approximately 150°–200°C. For many samples this issue presents no problems. However, for some of the older pre-late Miocene samples and those from locations near vent structures, the ages reported could be minimum ages due to the diffusion of ^{40}Ar out of the system. ^{40}Ar/^{39}Ar dating is required to determine crystallization ages for those samples with more complex geologic histories.

XRF METHODOLOGY

The coarse rock fragments not used for K-Ar analyses were crushed in an alumina-plate-equipped mullite grinder manufactured by the Bico Corporation and in a Spex shatter box equipped with a ceramic grinding vessel. All rock powder was ground to <80 mesh in particle size. 3.6000 (±0.0002) grams of lithium tetraborate ($Li_2B_4O_7$) was weighed out into a clean glass bottle, followed by 0.4000 (±0.0001) grams of the rock powder, and mixed for 10 minutes in a Spex mixer mill. The homogeneous powder was transferred into a 25-cc., 95-percent Pt/5-percent Au crucible, and 3 drops of a 2-percent solution of lithium iodide (LiI) was added to the powder to reduce the viscosity of the mixture, which was then mounted on a standard ring stand and heated over a Meeker burner. During the heating, the crucible was covered with a 95-percent Pt/5-percent Au lid which also acted as the mold into which the molten sample was poured and cast into a 29-mm-diameter disk. The bottom of the Pt lid is flat and highly polished, thus the side of the disk in contact with the Pt lid is the one that will eventually be exposed to the primary X-ray beam during the actual XRF analytical determination of chemical composition.

The heating period was normally 10 minutes, with the crucible being held with a pair of Pt-tipped tongs and the sample being vigorously stirred at the three-, six-, and nine-minute marks. After three vigorous stirrings of the molten sample to insure its homogeneity, the Pt lid was removed from the crucible with tongs and held over a second Meeker burner to maintain its high temperature. Simultaneously, the crucible was removed quickly from suspension on the ring stand over the first burner, and its contents were poured into the hot Pt lid in order to cast a glass disk. With some practice, virtually all of the crucible's content was transferred to the lid. Immediately upon completing the pouring event, the still-hot crucible was dropped into a warm beaker containing sufficient 4N HCl to cover the crucible.The lid, which had been held quite level, was now carefully placed onto a flat surface (in our lab, this is a flat polished piece of granite). The sample cooled in 3 to 5 minutes, so that the glass disk could be labeled with a magic marker on the side of the disk exposed to the air. The disk can be stored indefinitely in a desiccator. The major elements are then determined together with Sr, Zr, Cr and V.

Trace element analysis was accomplished by weighing out 7.0000 (±0.0001) grams of whole-rock powder, adding 1.4000 (±0.0002) grams of high-purity microcrystalline cellulose, mixing for 10 minutes, and pressing the sample into a briquette. Copolywax powder was substituted for cellulose when the whole-rock SiO_2 content was >55 weight percent. Data were reported as parts per million (ppm). The elements measured this way included Rb, Sr, Y, Zr, Nb, Ni, Ga, Cu, Zn, U, Th, Co, Pb, Sc, Cr, and V. Elements La, Ce, and Ba were calibrated by means of an L X-ray line and inclusion of a mass absorption correction.

Working curves for each element of interest were determined by analyzing 55 geochemical rock standards. Accepted chemical data for each of these rock standards have been synthesized by Abbey (1983) and Govindaraju (1994). Between 30 and 55 data points were gathered for each working curve; various elemental interferences were also taken into account, e.g., SrK_β on Zr, RbK_β on Y, etc. The Rh Compton peak was utilized for a mass absorption correction. Slope and intercept values, together with correction factors for the various wavelength interferences, were calculated and then stored on a computer. A Philips 2404 X-ray fluorescence vacuum spectrometer equipped with a 102-position sample changer and a 4-Kw Rh X-ray tube was used for automated data acquisition and reduction.

The amount of ferrous iron was titrated using a modified Reichen and Fahey (1962) method, and loss on ignition was determined by heating an exact aliquot of the sample at 950°C for one hour. The X-ray procedure determined total Fe content as Fe_2O_3T.

K-AR RESULTS

Table 1 contains the K-Ar results for nearly 180 samples organized by the 1:24,000 quadrangle from which the sample was collected, the quadrangles listed in alphabetic order and with exact UTM coordinates. Those samples from the State of Oregon come first in Table 1, followed by those from California. Also, sufficient analytical data are given for each sample to satisfy those readers who are geochronologists. Several samples were analyzed in duplicate, several years apart, to provide insight into the analytical precision of the methodology.

Table 2 contains a major- and trace-element whole-rock chemical analysis for each of the samples listed in Table 1. These data, too, are organized by state and quadrangle.

The data set is divided into two latitudinal groups, a northern contingent containing the samples from the southern boundary of Crater Lake National Park to Oregon Route 66, which connects Klamath Falls to Keno and Ashland, and a southern contingent of samples from south of this line to the headwaters of the Little Shasta River west of Macdoel, Calif. (see dotted line in Figure 1). On the basis of the geologic time boundaries of Stanley (1999), all the samples reported in this study are Neogene in age, that is, <24.0 million years old. The absolute time boundaries between the early, middle, and late Miocene, the Pliocene, and the Pleistocene epochs are 16, 11, 5.3, and 1.8 million years (Ma), respectively. Following Priest (1990) for correlation of volcanic episodes and absolute geologic time, I use the following differentiation: 35–17 Ma, early Western Cascade volcanism; 16.9–7.5 Ma, late Western Cascade volcanism; 7.4–4.0 Ma, early High Cascade volcanism; and 3.9–0 Ma, late High Cascade volcanism.

Figure 2a shows plots of silica versus age, with data from the northern portion of the study area depicted in the left diagram and data from the southern portion in the right. The northern (left-hand) plot shows an age gap of approximately 10 million years in the rock record to the north (17 to 7 Ma), whereas no such gap is apparent in the southern dataset. Noticeable is also the paucity of samples more silica-rich than andesite: Two dacitic samples appear in the northern segment of the dataset and a few more dacite to rhyolite samples farther south, but, on the whole, the data set is overwhelmingly dominated by basalts and andesites. Also evident in Figure 2a for the southern data segment is a more pronounced relationship between declining silica content and lower radiometric age. For ages older than 10 Ma, the extruded igneous rocks range from basalt through rhyolite, but for volcanic rocks <10 Ma the compositional range is much narrower, only basalt through andesite. It is also noteworthy that basalts and andesites were extruded in both regions over the entire period of time from the early Miocene through the late Pleistocene; only the more siliceous compositions dwindle in relative importance with decreasing age and only in the southern study area. Lastly, it is worth noting that most of the pyroclastic units mapped are from the southern region and are >17 Ma in age.

Figure 2b plots K_2O versus age. (Potassium can serve as an indicator for other large ionic lithophile [LIL] elements, too.) Notable results of the plot are that (1) the K_2O content of the samples older than 7.4 Ma decreases, both north and south, with decreasing age and (2) all southern samples with K_2O > 2 per cent are mid-Miocene in age or older.

In Figure 2c, which depicts the K_2O-SiO_2 relationship of the samples, there are two idiosyncratic groupings in the northern area: the high-K_2O/low-silica samples that are LIL-enriched mafic basalts marking the renewal of volcanism between 7 and 6 million years ago, and a large group of samples that originate from one small area south of Lake of the Woods in Oregon. The data points from the southern region are much more contiguous except at the high-silica end, where they are more scattered. Cursory examination of the two diagrams in Figure 2c in the silica range of 50–60 per cent provides two insights: First, the data points can be thought of as constituting two parallel lines each, offset from one another with some scatter and with K_2O increasing as SiO_2 increases. One interpretation of the lines showing higher K_2O content is that they represent batches of magma that had greater crustal residence times and therefore more time for assimilation to occur, before they were extruded onto the Earth's surface. Second, the slopes of the trends depicted are different for the two regions, indicating that the K_2O values at 55 per cent SiO_2 may reflect significantly thicker or less dense continental crust and/or a more steeply inclined subduction zone in the southern region—which perhaps implies the existence of a major tear fault in the subducted plate in the vicinity of the arbitrarily selected boundary between the two regions described in this study.

Nearly a decade ago, Guffanti and Weaver (1988) proposed a division of the Cascade volcanic arc into five segments defined on the basis

(Continued on page 107)

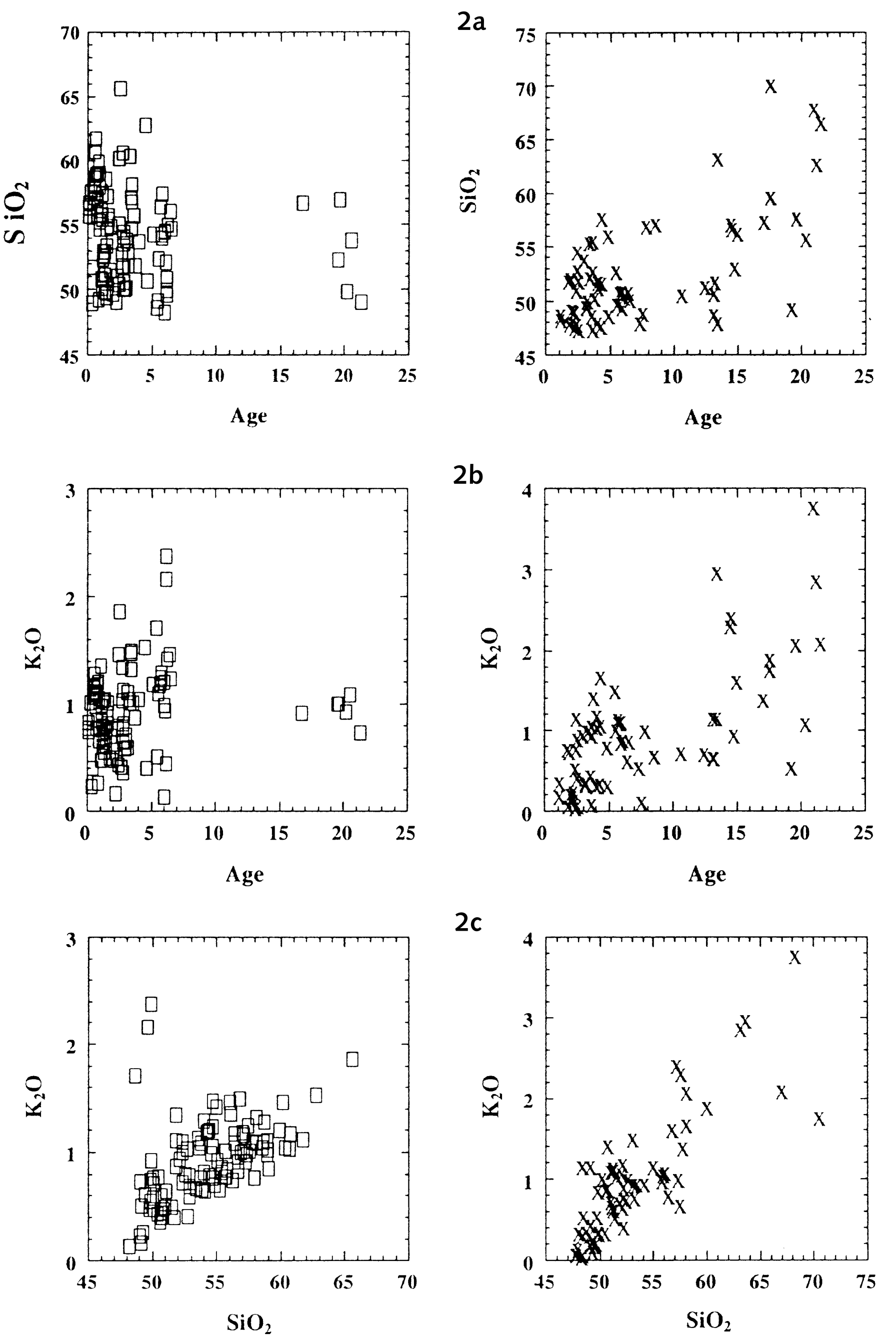

Figure 2. Plots of silica (SiO_2) and potash (K_2O) versus age and each other, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. Values are weight percent for chemical content and million years for age.

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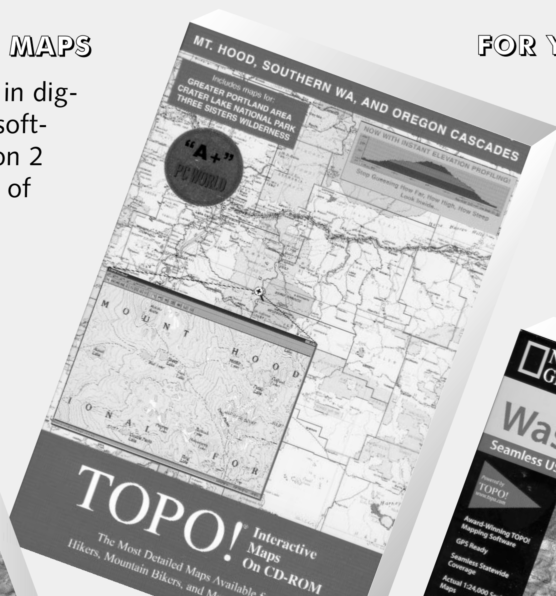

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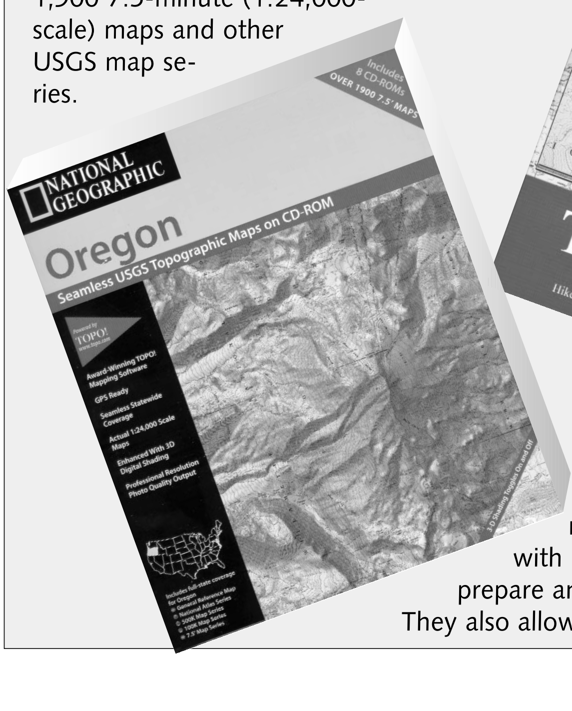

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(Continued from page 102)

of spatial, temporal, and compositional distribution of the constituent volcanoes. The boundary between their segments three and four was essentially the state boundary between Oregon and California. In a later gravity study, Blakely and Jachens (1990) found their gravity data consistent with much of the interpretation by Guffanti and Weaver (1988). However, they located the structural boundary equivalent to the boundary between segments three and four of Guffanti and Weaver (1988) farther north by approximately 30 km. That location is nearly coincident with the regional boundary employed in this study.

Blakely and Jachens pointed out that the Guffanti-Weaver segment boundary in question was, according to Guffanti's own judgment, the least constrained of all their boundaries; it was based on a change in the ratio between andesitic and basaltic vents but not on published chemical analyses, which appeared in 1989 (Blakely and Jachens, 1990, p. 19,447 to -48). The detailed and plentiful geochemistry presented in the present paper supports the structural boundary suggested by the isostatic residual gravity data of Blakely and Jachens (1990). In further discussions by Blakely and others (1997), the authors go on to effectively argue from a geophysical perspective that the northeast-trending gravity anomalies are most likely caused by upper crustal structures that predate the early Miocene through Pleistocene volcanism discussed in this paper. These crustal structures reflected in the gravity data control to some degree the locations of Cascade volcanism. Thus, Cascade segmentation may be influenced by similar effects.

During the earliest phase of renewed volcanism in the northern segment between 7 and 6 million years ago, many varieties of volcanic rocks were extruded, particularly basalts. They are best exposed in the vicinity of Robinson Butte, particularly in the small canyons cut by both the North and South Fork Little Butte Creeks. Initial igneous activity after a 10-million year hiatus runs the gamut from nepheline-normative trachybasalt (Figure 3), which contains >1 weight percent P_2O_5 and 2,000 ppm Sr, to low-K_2O, high-alumina olivine tholeiite basalts, to several basalts that are quartz normative. In addition, a thick andesite lava flow that contains, in textural equilibrium, a phenocryst mineral assemblage of

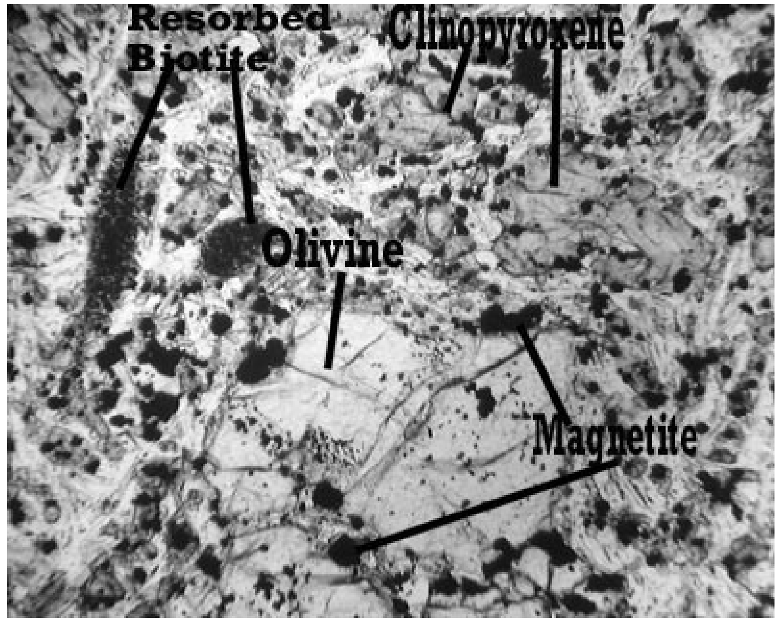

Figure 3. Thin section photomicrograph of a 6-m.y.-old trachybasalt. Image is 3mm × 2mm.

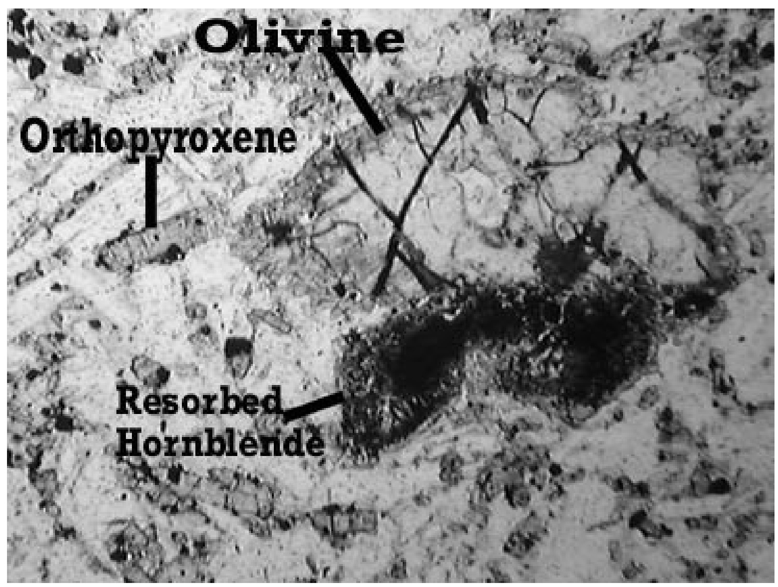

Figure 4. Thin section photomicrograph of hornblende-olivine textural relationship in a 5.6-m.y.-old andesite flow. Image is 3mm × 2mm.

hornblende and olivine is presently exposed in an abandoned trap-rock quarry 3.3 mi southwest of Mount McLoughlin. This unusual mineral assemblage is depicted in Figure 4 and suggests a crystallization depth of 30–40 km for the olivine and the co-precipitating hornblende at elevated P_{H_2O}. Why such a wide variety of extrusive igneous rocks, especially the LIL-enriched basalts, in this relatively small area in southern Oregon at this period of geologic time? I fully realize that "correlation is not causality," but one has to wonder about the coincidence of this unusually diverse occurrence of volcanic rocks and the segmentation boundary proposed by Blakely and Jachens (1990). Perhaps these contact zones

(Continued on page 120)

Table 1. K-Ar analytical results from volcanic rocks of the southern Oregon and northern California Cascades. Samples are listed by their quadrangle location, with quadrangles in alphabetic order and divided into Oregon and California quadrangles. Ar* = radiogenic Ar. E = ×10.

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Oregon									
Aspen Lake									
92-81	37	6	10	573890E4690150N	2 pyr. And.	1.17	9.539E-13	17.07	0.57 ± 0.10
92-82	37	6	10	574430E4690890N	2 pyr., ol. B.A.	0.98	1.60E-12	16.22	1.13 ± 0.02
92-83	37	6	10	574770E4691390N	2 pyr. And.	1.04	2.029E-12	35.92	1.36 ± 0.04
92-27	37	6	26	575290E4685000N	ol., 2 pyr. B.A.	1.16	7.773E-13	6.72	0.47 ± 0.04
92-47	37	6	21	573320E4687210N	2 pyr. And.	0.85	9.449E-13	14.85	0.77 ± 0.04
92-48	37	6	22	574130E4687980N	ol. B.A.	1.06	1.305E-12	9.95	0.86 ± 0.02
Brown Mtn.									
91-69	37	4	16	553580E4689280N	ol., cpx B.A.	1.49	7.34E-12	61.21	3.42 ± 0.06
91-68	37	4	24	558540E4687570N	ol., 2 pyr. B.A.	1.32	6.43E-12	48.74	3.38 ± 0.06
91-76	37	5	30	560480E4685340N	ol-phyric B.	0.77	3.06E-12	35.28	2.77 ± 0.05
91-39	38	5	6	560440E4683270N	ol-phyric B.	0.58	2.44E-12	39.53	2.92 ± 0.07
91-63	37	4	26	555750E4685200N	ol, cpx B.	0.66	2.81E-12	35.65	2.96 ± 0.06
91-43	38	4	4	552830E4682560N	cpx, ol B.A.	1.29	1.08E-11	54.37	5.82 ± 0.17
91-44	38	4	4	552800E4682690N	cpx, ol B.	0.4	2.65E-12	22.3	4.60 ± 0.34
91-46	37	4	32	552140E4684400N	ol, cpx B.A.	1.18	8.64E-12	66.33	5.08 ± 0.13
91-84	38	5	19	560630E4677920N	hbl, 2 pyr. And.	1.25	1.04E-11	72.40	5.77 ± 0.09
91-85	38	5	19	559340E4677760N	2 pyr, ol B.	0.65	2.61E-12	45.11	2.78 ± 0.10
94-16	38	4	23	556180E4677690N	ol,cpx B.	0.47	1.34E-12	5.52	1.97 ± 0.08
94-20	38	4	11	555670E4680720N	ol, cpx-phyric B.A.	1.11	5.06E-12	41.82	3.16 ± 0.12
94-21A	38	4	10	554850E4681630N	ol, cpx B.	0.71	3.03E-12	43.17	2.96 ± 0.11
AL94-51	38	4	12	557520E4681380N	ol B.	0.41	1.55E-12	14.29	2.63 ± 0.32
RSP-131	37	4	20	551600E4686870N	ol, cpx B.	2.39	2.12E-11	80.02	6.14 ± 0.15
84-16	37	4	8	552220E4689980N	ol, cpx B.	0.4	2.12E-13	1.07	0.40 ± 0.30
Chicken Hills									
95-16	40	6	35	576170E4654930N	ol., cpx B.	0.42	6.867E-13	10.67	1.14 ± 0.19
95-20	41	6	10	575010E4652620N	ol B.	0.93	8.853E-12	56.68	6.6 ± 0.19
95-21	40	6	12	577580E4662100N	ol., cpx B.	1.25	NA	47.20	4.10 ± 0.1
95-22	40	6	12	577380E4661950N	ol B.	0.37	2.655E-12	42.44	4.98 ± 0.18
95-25	40	6	23	576370E4659010N	2 pyr., ol. B.A.	1.74	1.10E-11	28.58	4.39 ± 0.24
95-28	40	6	10	574020E4661780N	ol. B.	1.01	5.37E-12	50.11	3.69 ± 0.11
95-48	40	7	6	578540E4663180N	ol. B.	0.81	2.232E-13	10.11	1.91 ± 0.34
95-50	40	6	12	578050E4662260N	ol., cpx B.	0.59	NA	27.90	2.4 ± 0.1
95-59	40	6	14	576760E4660040N	ol. B.	0.37	2.171E-12	29.19	4.07 ± 0.22
95-61	40	6	1	578590E4663130N	ol. B.	0.96	3.507E-12	36.61	2.54 ± 0.11
95-70	40	7	32	580260E4655690N	ol. B.	0.17	1.871E-12	2.27	7.6 ± 6.6
95-71	40	6	23	575620E4659070N	ol. B.A.	1.06	5.845E-12	20.26	3.83 ± 0.32
95-74	41	7	4	582180E4653380N	ol. B.	0.95	8.429E-12	60.49	6.15 ± 0.17
96-10	41	6	4	573380E4653900N	ol., cpx B.	1.16	9.85E-12	43.19	5.9 ± 0.2
AG95-87	40	6	13	576960E4659740N	ol. B.	1.12	7.05E-12	19.01	4.37 ± 0.39
SR-64	40	6	26	576310E4657150N	ol. B.	0.11	NA	8.90	2.4 ± 0.5
SR-106	40	6	28	572760E4656510N	ol. B.	0.92	7.90E-12	60.27	5.95 ± 0.16
97-51	40	6	16	573130E4659960N	ol. B.A.	1	5.30E-12	49.29	3.7 ± 0.1
MH95-33	40	7	31	579780E4655720N	ol. B.	0.25	4.106E-13	4.73	1.14 ± 0.30
Devils Peak									
96-20	34	6	6	568960E4722780N	2 pyr., ol. And.	1.28	1.047E-12	18.78	0.57 ± 0.05
96-22	34	6	6	568520E4722540N	2 pyr., hbl And.	1.12	9.688E-13	19.98	0.60 ± 0.05

[1] All sample locations in California differ in Township and Range notation from those in Oregon and, therefore, are marked accordingly.
[2] B. = Basalt; TrB. = Trachybasalt; B.A. = Basaltic Andesite; And. = Andesite; D. = Dacite; T. = Tuff; ol = olivine; pyr = pyroxene; hbl = hornblende; cpx = clinopyroxene

Table 1. (Continued)

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Hamaker Mtn.									
95-3	40	7	22	584770E4658360N	2 pyr., ol. B.A.	1.01	4.314E^{-12}	20.62	2.96 ± 0.24
95-4	40	7	16	583260E4660560N	2 pyr., B.A.	1.22	4.408E^{-12}	53.28	2.51 ± 0.07
MH95-39	40	7	33	583260E4655080N	2 pyr., ol. B.A.	1.74	7.227E^{-12}	27.33	2.88 ± 0.17
Lake of the Woods North									
BS92-77	36	5	4	563120E4702350N	ol. B.	0.48	7.74E^{-13}	15.61	1.12 ± 0.05
CG-100	35	5	35	565480E4703360N	ol. B.	0.55	1.05E^{-12}	26.67	1.32 ± 0.06
92-75	35	5	34	564830E4702680N	2 pyr., ol. B.A.	1.36	2.00E^{-12}	4.74	1.02 ± 0.09
86-62	36	5	1	568050E4701820N	opx, ol. And.	1.01	3.1E^{-13}	0.48	0.21 ± 0.18
92-73	36	5	24	567880E4697710N	ol. B.	0.47	7.82E^{-13}	7.25	1.16 ± 0.05
92-77	36	5	14	566320E4697920N	ol. B.	1.03	1.81E^{-12}	29.30	1.22 ± 0.04
MG91-63	36	5	15	564430E4698840N	ol. B.	0.36	1.44E^{-12}	18.84	2.78 ± 0.09
MG91-22	36	5	16	563040E4699310N	ol. B.	0.16	5.03E^{-13}	13.59	2.19 ± 0.14
MG91-56	36	5	16	562800E4698160N	ol., cpx B.A.	1.01	2.29E^{-12}	28.07	1.58 ± 0.03
92-86	36	5	34	565180E4693850N	ol., cpx B.	0.74	1.52E^{-12}	14.77	1.42 ± 0.05
84-52	37	5	4	563070E4692550N	ol. B.	0.61	1.30E^{-12}	11.05	1.48 ± 0.04
92-85	36	6	30	569820E4694820N	ol. B.	0.72	1.18E^{-12}	10.91	1.14 ± 0.10
Lake of the Woods South									
91-3	38	5	3	565210E4681780N	ol. B.	0.26	3.07E^{-13}	3.78	0.82 ± 0.08
91-79	37	5	28	563170E4686240N	2 pyr. And.	1.04	4.87E^{-12}	47.69	3.25 ± 0.05
92-53	37	5	33	562150E4683500N	2 pyr., ol. B.A.	0.7	1.807E^{-12}	38.19	1.79 ± 0.04
RB92-21	37	5	34	564480E4684490N	2 pyr. D.	1.86	6.625E^{-12}	48.73	2.47 ± 0.04
92-43	37	6	29	570310E4686410N	2 pyr., hbl And.	0.98	8.90E^{-13}	8.29	0.63 ± 0.05
92-44	37	6	17	570790E4689480N	2 pyr. And.	1.02	1.355E^{-12}	19.77	0.92 ± 0.02
92-62	37	6	4	570860E4690060N	2 pyr. And.	1.21	1.40E^{-12}	17.87	0.80 ± 0.03
92-63	37	6	8	571750E4691170N	2 pyr. And.	1.11	1.135E^{-12}	12.75	0.71 ± 0.06
92-84	37	6	31	569150E4684120N	2 pyr., ol. B.A.	0.66	8.591E^{-13}	9.68	0.90 ± 0.05
94-5	38	5	2	565520E4682080N	2 pyr. And.	1.46	5.153E^{-12}	50.98	2.45 ± 0.08
92-87	37	5	11	565700E4689880N	ol., 2 pyr. B.A.	1.09	1.059E^{-12}	12.24	0.68 ± 0.09
DH94-50	38	5	12	567080E4681540N	2 pyr., ol. B.A.	0.86	1.333E^{-12}	30.85	1.08 ± 0.05
DH94-106	38	5	2	566970E4682040N	2 pyr. And.	1.03	3.978E^{-12}	36.14	2.68 ± 0.11
JP92-2	37	5	14	566040E4688820N	2 pyr. And.	0.92	2.058E^{-12}	43.81	1.55 ± 0.04
94AH-96	37	5	21	563170E4687310N	2 pyr. And.	1.01	4.83E^{-12}	20.59	3.32 ± 0.27
Little Chinquapin Mtn.									
BS94-53	38	5	30	559590E4675860N	2 pyr., ol. B.	0.78	2.68E^{-12}	13.66	2.39 ± 0.31
94-14	38	4	26	556500E4676720N	ol. B.	0.65	2.081E^{-11}	30.29	2.22 ± 0.12
Mares Egg Spring									
96-28	33	6	28	57194E472649N	2 pyr., ol. And.	0.77	9.841E^{-13}	21.80	0.89 ± 0.07
Mount McLoughlin									
84-62	36	5	32	561680E4693150N	cpx, ol. B.	0.59	2.66E^{-12}	22.52	3.14 ± 0.07
84-50	36	5	17	560790E5697980N	cpx, ol. B.A.	0.93	3.24E^{-12}	23.27	2.42 ± 0.15
84-48	36	4	13	558480E4698420N	cpx, ol. B.A.	0.78	1.03E^{-14}	2.31	0.08 ± 0.03
84-21	36	4	27	554880E4694980N	2 pyr., ol. B.A.	1.21	1.04E^{-11}	39.02	5.97 ± 0.36
84-38	36	4	14	556350E4699160N	2 pyr., ol. B.A.	0.78	6.27E^{-14}	~0.0	<0.15
91-89	36	4	20	551420E4697090N	hbl, ol., 2 pyr. And.	1.16	9.39E^{-12}	63.2	5.62 ± 0.09
M91-85	36	4	16	552530E4698290N	2 pyr., ol. And.	1.46	1.35E^{-11}	65.97	6.43 ± 0.10
HC-44	37	4	4	553930E4692520N	cpx, ol B.A.	1.04	5.94E^{-12}	23.5	3.97 ± 0.08
HC-49	37	4	2	556480E4692740N	2 pyr., ol. And.	0.91	2.18E^{-12}	24.75	1.67 ± 0.03
HC-67	37	4	2	556420E4692120N	2 pyr., ol. B.A.	1.01	5.18E^{-12}	50.95	3.56 ± 0.06
91-49	36	4	15	555350E4698770N	2 pyr., ol. B.A.	0.83	6.37E^{-14}	0.73	0.05 ± 0.03
91-52	36	4	10	554860E4699940N	2 pyr., ol. B.A.	0.74	8.93E^{-14}	2.27	0.08 ± 0.03
14-K-1	36	4	35	555810E4694330N	ol., cpx B.A.	1.47	7.26E^{-12}	65.37	3.43 ± 0.06
92-66	35	5	31	559230E4703520N	ol. B.	0.5	1.26E^{-12}	7.43	1.76 ± 0.08

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*/gm$	Percent $^{40}Ar^*$	Age (Ma)
Mule Hill									
95-29	40	6	8	570930E4661380N	ol., 2 pyr. B.A.	1.42	1.277E-11	61.08	6.24 ± 0.17
95-30	40	5	23	565660E4658700N	ol. B.	0.47	1.742E-12	18.56	2.57 ± 0.24
95-33	40	5	24	567930E4658280N	ol., cpx B.	0.21	6.839E-13	15.34	2.26 ± 0.26
95-75	40	6	30	569830E4657290N	ol., cpx B.	0.31	1.013E-12	16.56	2.27 ± 0.24
95-77	40	5	2	565610E4662470N	2 pyr., ol. B.A.	1.05	5.20E-12	43.81	3.44 ± 0.12
95-26	41	6	9	572380E4652500N	ol. B.	0.61	6.523E-12	64.80	7.41 ± 0.19
96-1	41	6	8	571560E4652560N	cpx, ol. B.	1.18	1.016E-11	40.02	5.97 ± 0.23
96-2	41	6	8	571180E4652610N	ol., cpx B.	0.42	1.956E-12	21.15	3.23 ± 0.25
96-3	41	6	5	570980E4652750N	ol. B.	1.07	8.559E-12	47.27	5.55 ± 0.18
96-5	41	6	6	569800E4653890N	ol. B.	1.2	1.00E-11	41.58	5.80 ± 0.2
96-6	40	5	36	568380E4655340N	ol. B.	1.22	2.375E-11	53.53	13.5 ± 0.4
96-7	40	5	36	568380E4655340N	cpx And.	2.36	4.936E-11	47.50	14.5 ± 0.5
96-8	40	6	31	569060E4655170N	ol. B.	1.22	2.33E-11	77.86	13.2 ± 0.3
96-9	41	6	5	570980E4653080N	cpx, ol. B.	0.13	4.86E-13	11.29	2.6 ± 0.4
97-22	40	5	3	565230E4663570N	ol. B.	0.43	1.51E-12	20.17	2.4 ± 0.2
97-35	41	6	5	570560E4652730N	ol., cpx B.	0.41	1.40E-11	32.71	3.26 ± 0.16
97-37	41	6	7	570340E4652200N	D.	2.15	6.71E-11	71.42	21.6 ± 0.5
97-46	41	5	1	567880E4652630N	ol., cpx B.	0.39	1.78E-12	26.75	3.2 ± 0.2
97-47	41	5	1	567850E4652800N	cpx, ol. B	0.13	3.62E-12	6.44	1.9 ± 0.3
97-54	41	6	9	572380E4652500N	hbl-bearing D.	2.46	4.78E-11	42.89	13.5 ± 0.5
97-55	41	6	7	570340E4652200N	Rhyolite	1.82	4.644E-11	26.67	17.6 ± 0.7
CW6-5	40	5	35	565540E4654340N	ol., cpx B.	0.28	8.38E-13	6.49	2.1 ± 0.3
CW6-9	40	5	36	566950E4654320N	cpx And.	1.68	3.64E-11	82.88	15.0 ± 0.4
CW9-13B	40	5	11	566160E4661520N	ol., cpx B.	0.14	7.373E-13	25.03	3.66 ± 0.24
S97-21	40	6	31	568800E4654930N	ol., cpx And.	2.47	5.192E-11	24.95	14.6 ± 0.9
S97-62	40	5	13	568410E4660800N	cpx, ol. B.A.	1.57	1.24E-11	39.07	5.5 ± 0.2
S97-87	40	5	1	567350E4663000N	ol., 2 pyr B.	1.48	8.091E-12	66.02	3.79 ± 0.10
97-54Z	41	6	9	572380E4652500N	And. T.	1.45	3.592E-11	33.89	17.1 ± 0.8
JM97-27D	48	3	14	567960E4650440N	ol. B.	1.16	9.75E-12	63.07	5.83 ± 0.15
Parker Mtn.									
95-34	40	5	7	559730E4661480N	ol. B.A.	0.83	2.968E-12	5.39	2.48 ± 0.50
97-2	41	5	5	561420E4654000N	cpx, ol. B.	0.25	8.03E-13	8.16	2.2 ± 0.3
97-16	40	4	36	558690E4654810N	ol., cpx B.	0.69	6.49E-12	42.74	6.5 ± 0.2
97-41	40	5	8	560470E4660720N	ol. B.	0.84	2.22E-12	9.69	1.8 ± 0.2
86-85	48N	4W	19	554350E4650280N	ol., cpx B.	0.51	2.672E-12	16.64	3.64 ± 0.38
Pelican Bay									
92-74	36	6	34	574070E4694640N	ol. B.A.	0.84	1.363E-12	10.09	1.13 ± 0.09
92-89	36	6	10	573240E4699800N	ol. B.	0.6	1.034E-12	11.24	1.20 ± 0.04
92-80	36	6	3	573430E4702260N	2 pyr., ol. And.	1.09	7.086E-13	10.94	0.45 ± 0.04
AG92-75	36	6	27	573970E4695170N	2 pyr. B.A.	0.76	1.608E-12	16.85	1.47 ± 0.04
Pelican Butte									
86-59	35	6	20	570270E4706940N	ol, 2 pyr And.	1.1	8.48E-13	4.26	0.54 ± 0.05
92-91	35	6	20	571500E4705900N	2 pyr And.	1.1	8.62E-13	13.60	0.54 ± 0.05
96-11	35	5	2	565610E4711220N	ol B.	0.69	1.225E-12	25.04	1.23 ± 0.08
96-13	34	6	30	569830E4714120N	ol B.	0.79	1.506E-12	25.91	1.32 ± 0.08
96-17	34	6	18	568960E4717660N	ol B. A.	0.82	1.94E-12	3.01	1.64 ± 0.40

Table 1. (Continued)

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^{*}/gm$	Percent $^{40}Ar^{*}$	Age (Ma)
Robinson Butte									
91-61	37	4	7	549310E4690380N	2 pyr. And.	1	$2.84E^{-11}$	87.29	19.6 ± 0.3
92-21	37	4	19	549130E4687930N	ol., cpx TrB.	2.16	$1.907E^{-11}$	66.11	6.13 ± 0.10
92-24	37	3	13	549060E4688670N	ol., 2 pyr. B.A.	1.09	$3.234E^{-11}$	88.48	20.5 ± 0.3
JB91-56	37	4	18	550220E4688230N	ol., cpx TrB.	1.71	$1.318E^{-11}$	75.03	5.35 ± 0.09
92-26	37	3	14	546460E4688530N	ol., B.	0.93	$2.725E^{-11}$	74.76	20.2 ± 0.3
92-41	37	3	23	546830E4688050N	ol., 2 pyr. B.A.	1	$2.826E^{-11}$	53.15	19.5 ± 0.3
94-40	37	3	35	546830E4684510N	ol. B.	0.51	$3.99E^{-12}$	46.08	5.43 ± 0.18
RSP-94	37	4	20	551370E4686920N	ol., 2 pyr. B.A.	1.19	$9.835E^{-12}$	67.42	5.73 ± 0.15
94-42	37	4	31	549980E4683960N	ol., 2 pyr. B.A.	1.1	$8.777E^{-12}$	63.64	5.54 ± 0.15
Rustler Peak									
86-47	35	4	14	556560E4707940N	ol. B.A.	0.67	$1.365E^{-12}$	25.46	1.42 ± 0.09
86-48	34	4	16	553570E4718550N	hbl. And.	1.53	$9.767E^{-12}$	45.37	4.43 ± 0.15
Spencer Creek									
95-68	39	7	20	580350E4667530N	ol. B.	0.8	$1.375E^{-12}$	17.72	1.19 ± 0.11
95-69	39	7	29	581460E4666740N	ol. B.	0.13	$3.703E^{-13}$	6.00	2.0 ± 0.3
Surveyor Mountain									
95-46	39	6	19	570060E4668640N	ol., 2 pyr. B.A.	0.82	$3.25E^{-12}$	27.26	2.76 ± 0.16
91-21	38	5	35	567030E4674140N	ol. B.	0.76	$2.06E^{-12}$	14.82	1.88 ± 0.22
94-36	38	5	28	562740E4676280N	cpx, ol. B.A.	1.13	$4.52E^{-12}$	41.82	2.78 ± 0.10
91-15	38	5	21	562460E4676880N	ol. B.	0.5	$1.67E^{-12}$	34.00	2.32 ± 0.11
97-28	39	5	35	565680E4664840N	cpx, ol. B.	0.87	$4.60E^{-12}$	10.51	3.7 ± 0.3
94-4	38	5	34	565150E4674700N	ol., 2 pyr. B.A.	0.79	$3.20E^{-12}$	30.62	2.81 ± 0.14
Willow Lake									
84-26	36	4	18	549660E4699130N	ol. B.A.	0.99	$8.57E^{-11}$	48.32	6.01 ± 0.30
91-60	37	4	6	550340E4692860N	ol. B.	0.94	$8.21E^{-11}$	67.63	6.06 ± 0.10
JB91-41	37	4	6	549550E4692920N	ol. B.	0.44	$3.875E^{-12}$	42.50	6.11 ± 0.21
91-89	36	4	20	551420E4697090N	hbl., ol., 2 pyr. B.A.	1.16	$9.39E^{-12}$	63.20	5.62 ± 0.09
KWW33-91	36	4	18	549760E4698310N	ol., 2 pyr. B.A.	1.24	$1.16E^{-11}$	62.19	6.48 ± 0.10
KWW25-91	36	4	8	551140E4699920N	ol., 2 pyr. B.A.	0.78	$7.39E^{-13}$	13.08	0.66 ± 0.02
California									
Copco									
86-88	48N	4W	29	554910E4648520N	ol. B.	1.1	$6.508E^{-12}$	15.86	4.11 ± 0.45
86-92	48N	4W	30	553530E4648620N	hbl. And.	0.75	$9.289E^{-12}$	14.87	8.59 ± 0.59
Panther Rock									
97-66	46N	3W	14	568690E4630910N	hbl. And.	1.15	$3.40E^{-11}$	65.56	20.4 ± 0.5
Secret Spring									
B'3	48N	2W	30	571540E4647080N	2 pyr., ol. B.A.	1.01	$2.18E^{-11}$	54.46	15.0 ± 0.4
B'317	48N	2W	30	571540E4647080N	2 pyr., ol. B.A.	0.32	$2.00E^{-12}$	19.00	4.35 ± 0.39
B'3	48N	2W	30	569910E4649580N	ol. B.	1.01	$2.12E^{-11}$	61.54	14.5 ± 0.4
Anders-1	48N	3W	22	567100E4647890N	Dacite T.	3.85	$1.17E^{-10}$	74.99	21.0 ± 0.5
K97-78	48N	2W	20	572320E4648530N	cpx, ol. B.	0.78	$1.41E^{-11}$	27.39	12.5 ± 0.5
97-68	48N	3W	32	563520E4636540N	ol. B.A.	1.12	$5.99E^{-12}$	62.52	3.7 ± 0.1
A24	48N	3W	25	569070E4647020N	ol. B.	0.61	$1.70E^{-11}$	63.29	19.25 ± 0.51
A73	48N	3W	23	567600E4648290N	pyr. D.	2.92	$8.95E^{-11}$	66.65	21.17 ± 0.54
K97-43	48N	2W	30	570610E4647510N	ol. B.	0.73	$1.39E^{-11}$	24.37	13.19 ± 0.80
L-24	47N	3W	1	569540E4644070N	ol., 2 pyr. B.A.	0.86	$6.12E^{-12}$	39.30	4.94 ± 0.19
97-53	48N	3W	26	567890E4646770N	2 pyr. And.	2.14	$6.06E^{-11}$	47.29	19.6 ± 0.6
L-42	48N	3W	27	566610E4646570N	2 pyr. And.	1.06	$1.21E^{-11}$	32.64	7.9 ± 0.4
K97-24	48N	2W	30	571850E4647060N	cpx, ol. B.	0.72	$1.38E^{-11}$	62.70	13.3 ± 0.4
JM97-16	48N	3W	24	570170E4649320N	pyr., And. T.	1.95	$4.96E^{-11}$	45.69	17.6 ± 0.6
K97-23[3]	48N	2W	30	571710E4647080N	cpx, ol. B.	0.79	$1.22E^{-11}$	53.93	10.7 ± 0.3

[3] Sample from neck of Secret Spring volcano exposed by a large landslide. Age listed is a minimum age.

Table 2. Major- and trace-element whole-rock chemical analyses for each of the samples for which a K-Ar age . . . ⇨

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Oregon																			
Aspen Lake																			
92-81	60.70	0.67	17.81	2.98	2.49	0.09	3.09	6.31	3.78	1.17	0.15	0.55	99.79	5.75	16.7	982	15	63	125
92-82	57.34	0.60	19.10	1.87	3.89	0.09	3.90	7.55	3.60	0.98	0.10	1.04	100.06	6.19	14.4	800	13.2	44	136
92-83	58.54	0.65	18.84	2.89	2.75	0.08	3.05	7.11	3.86	1.04	0.12	0.80	99.73	5.95	18.3	788	15.1	55	134
92-27	57.10	0.87	17.55	1.88	5.04	0.12	4.22	7.36	3.45	1.16	0.27	1.05	100.07	7.48	19.5	614	21.5	113	154
92-47	59.02	0.68	18.48	2.47	3.38	0.10	3.69	7.17	3.88	0.85	0.13	0.29	100.14	6.23	13	1,215	14.2	50	131
92-48	54.69	1.01	17.44	3.25	4.54	0.14	4.60	7.30	3.86	1.05	0.39	0.92	99.19	8.30	17.1	606	26.8	140	167
Brown Mtn.																			
91-69	56.77	1.01	17.15	3.30	4.10	0.12	4.02	6.96	4.01	1.49	0.26	0.58	99.77	7.86	24.8	599	34	132	181
91-68	58.07	0.84	17.54	3.02	3.82	0.12	3.40	6.56	4.67	1.32	0.18	0.86	100.40	7.27	23.6	640	26.6	98	158
91-76	50.04	0.95	14.97	3.63	5.01	0.15	10.63	9.82	2.67	0.77	0.33	0.72	99.69	9.20	8.3	981	21.1	74	201
91-39	50.01	0.99	16.07	2.64	6.07	0.15	9.38	9.88	2.95	0.58	0.31	0.39	99.42	9.39	5.1	737	23.8	80	198
91-63	53.83	0.73	17.36	3.10	4.22	0.12	6.41	9.41	3.38	0.66	0.16	0.55	99.93	7.79	7.4	905	14.6	35	210
91-43	54.01	1.14	17.10	5.60	3.68	0.12	3.50	7.26	3.85	1.29	0.50	1.57	99.62	9.69	12.1	811	37.4	130	192
91-44	50.70	0.68	16.10	2.40	5.90	0.15	9.11	10.68	2.49	0.40	0.15	0.91	99.67	8.96	5.3	566	16.3	32	247
91-46	54.20	1.15	17.75	3.52	4.50	0.14	4.38	7.87	4.10	1.18	0.50	0.76	100.05	8.52	11.1	920	33.5	118	194
91-84	57.41	0.78	17.50	4.27	2.49	0.08	3.08	6.46	4.13	1.25	0.25	1.82	99.52	7.04	9.7	1,014	23.3	72	144
91-85	54.08	0.91	17.16	3.06	5.09	0.14	6.28	8.41	3.39	0.65	0.21	0.41	99.79	8.72	11.4	557	21.4	67	194
94-16	49.71	1.20	18.09	1.39	7.79	0.16	6.74	10.25	3.20	0.47	0.20	1.26	100.46	10.05	6.8	469	30	68	229
94-20	51.86	1.04	16.76	5.30	3.08	0.13	6.85	9.16	3.92	1.11	0.44	0.49	100.14	8.72	11.9	1,283	17	104	225
94-21A	50.09	0.88	16.70	4.08	4.97	0.15	8.21	10.02	3.23	0.71	0.33	1.18	100.55	9.60	8.5	875	18.3	64	233
AL94-51	52.75	0.93	18.08	2.30	5.81	0.14	5.37	8.13	3.68	0.41	0.25	1.60	99.45	8.76	3.8	683	19.2	78	175
RSP94-131	49.77	1.07	15.56	5.41	3.10	0.14	7.49	9.70	3.35	2.39	0.64	0.74	99.36	8.86	22.4	2,246	19.2	140	210
84-16	51.70	0.95	18.05	2.33	5.88	0.14	6.84	9.98	3.19	0.40	0.13	0.88	100.47	8.86	4.9	811	21.1	53	210
Chicken Hills																			
95-16	48.77	1.46	16.91	2.54	7.75	0.17	8.19	9.68	2.97	0.42	0.27	0.97	100.10	11.15	4.8	444	26.6	112	247
95-20	50.63	1.46	17.97	5.65	4.84	0.16	5.16	7.96	4.02	0.93	0.51	0.95	100.24	11.03	7.8	747	25.4	112	195
95-21	52.17	1.19	17.11	4.66	3.99	0.14	5.61	8.73	3.72	1.25	0.39	1.02	99.98	9.09	12.9	1,052	19.7	117	205
95-22	49.06	1.04	18.35	4.45	4.59	0.15	6.63	9.69	3.40	0.37	0.28	1.59	99.60	9.55	2	793	17.1	55	249
95-25	58.15	1.13	17.12	3.06	4.06	0.11	2.60	6.28	4.34	1.74	0.31	0.95	99.85	7.57	28.9	677	20	147	210
95-28	53.23	1.27	17.25	2.47	6.24	0.15	5.53	8.46	3.62	1.01	0.39	0.85	100.47	9.40	13.8	663	26	125	225
95-48	52.50	1.04	17.94	2.24	6.34	0.14	6.35	8.36	3.41	0.81	0.30	0.79	100.22	9.29	9.6	663	20	114	185
95-50	51.46	1.23	17.39	3.05	6.63	0.16	6.59	8.63	3.53	0.59	0.28	0.66	100.20	10.42	7.2	551	21.1	91	191
95-59	48.45	1.31	17.28	4.01	6.58	0.17	7.53	10.40	2.91	0.37	0.21	0.94	100.16	11.32	5	465	22.4	71	245
95-61	52.32	1.17	18.25	3.52	4.86	0.16	5.00	8.37	3.73	0.96	0.38	1.51	100.23	8.92	6.1	854	21.4	145	192
95-70	49.34	1.23	17.16	2.98	6.44	0.16	7.70	11.15	2.93	0.17	0.23	0.67	100.16	10.14	2.4	730	18.8	67	270
95-71	52.68	1.32	17.34	2.70	6.28	0.15	5.34	8.38	3.60	1.06	0.40	1.00	100.25	9.68	13.7	724	20.9	130	199
95-74	50.77	1.33	17.19	4.82	5.31	0.17	6.32	8.36	3.67	0.95	0.52	1.01	100.42	10.72	9.7	650	27.5	120	218
96-10	51.11	1.30	17.62	3.25	6.42	0.17	5.24	8.21	3.76	1.16	0.57	0.62	99.43	10.38	9.7	768	29	139	208
AG95-87	52.12	1.17	16.93	1.08	7.19	0.14	6.46	8.88	3.45	1.13	0.40	1.30	100.25	9.07	10.5	1,062	19	116	200
SR-64	48.34	0.96	17.37	1.55	7.84	0.16	9.11	11.48	2.53	0.11	0.06	0.92	100.43	10.26	2.1	261	22.6	47	226
SR-106	49.85	1.28	17.28	4.94	5.46	0.17	6.46	8.85	3.47	0.92	0.46	0.72	99.86	11.01	10.1	749	29.9	108	182
97-51	53.21	1.25	17.41	2.79	5.92	0.15	5.30	8.25	3.82	1.00	0.40	0.86	100.36	9.37	10.8	692	27	127	220
MH95-33	49.20	1.34	17.10	3.06	6.73	0.16	7.51	10.89	2.92	0.25	0.22	0.43	99.81	10.54	2.8	676	21.4	83	220
Devils Peak																			
96-20	58.66	0.74	17.63	1.95	4.18	0.14	3.88	6.57	3.94	1.28	0.23	0.52	99.72	6.60	18.7	720	19	157	128
96-22	61.66	0.54	18.11	2.35	2.60	0.09	2.68	5.78	4.27	1.12	0.12	0.56	99.88	5.24	15	830	12	80	103
Hamaker Mtn.																			
95-3	54.21	0.96	18.65	2.61	5.21	0.14	4.46	8.02	3.72	1.01	0.33	1.15	100.47	8.40	10.7	776	21.5	148	172
95-4	55.01	1.12	18.09	2.23	5.62	0.14	3.90	7.87	3.92	1.22	0.31	0.97	100.40	8.48	18.6	742	22.1	144	188
MH95-39	53.07	1.13	18.06	4.31	3.94	0.14	4.50	7.91	3.69	1.74	0.51	0.61	99.61	8.69	16.7	1,284	22.8	180	198

. . . is reported. Major-element data are in weight percent; trace-element data are in parts per million (ppm).

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
77	31	3.9	21.1	45	49	19	439	13	27	1.5	5	6.3	1.3	14	1.3	0.57±0.10	–	–	–	–	–	–	–
36	43	2.9	20.8	62	57	21	303	9	16	0.7	3.4	5	1	17	0.8	1.13±0.02	–	–	–	–	–	–	–
24	16	2	19.1	65	44	20	376	9	20	1.4	4.1	5.9	1.3	17	1.3	1.36±0.04	–	–	–	–	–	–	–
39	49	7.2	21.1	58	72	24	528	17	36	1.7	4.2	8.2	1.6	19	1.9	0.47±0.04	–	–	–	–	–	–	–
21	37	3.2	22.3	24	57	20	316	13	27	1.2	3	4	1	15	0.9	0.77±0.04	–	–	–	–	–	–	–
69	102	8.2	20.7	67	84	28	494	23	43	0.6	3.5	7.1	1.3	21	2.1	0.86±0.02	–	–	–	–	–	–	–
38	91	5.3	21.2	90	73	22	478	15	33	1.7	4.8	6.1	1.5	23	1.8	3.42±0.06	–	–	–	–	–	–	–
17	48	4.2	21.6	57	69	23	455	16	31	2.4	3.4	7.2	1.7	17	1.9	3.38±0.06	–	–	–	–	–	–	–
184	529	4.4	18.2	59	70	42	369	16	34	0.8	3.5	5.4	1.3	29	1.7	2.77±0.05	2.4	0.3	18	3.6	1.15	0.5	0.26
151	356	3.4	18.5	48	69	42	277	15	33	1.8	2.1	3.8	1.4	30	1.9	2.92±0.07	–	–	–	–	–	–	–
28	216	3	20.9	91	65	30	224	9	21	0.7	3.7	4.3	1.3	23	1	2.96±0.06	–	–	–	–	–	–	–
25	63	7.7	21.8	34	79	26	513	23	49	1.6	3.2	5.7	1.7	19	2.3	5.82±0.17	–	–	–	–	–	–	–
127	482	2.6	18.2	70	64	39	181	6	13	1.5	4	3.6	1.3	32	1.2	4.6±0.34	–	–	–	–	–	–	–
27	64	8	22.7	36	71	21	497	22	49	1.7	4.1	4.9	1.8	21	2.9	5.08±0.13	–	–	–	–	–	–	–
25	30	3.7	22.9	87	53	22	404	14	28	0.3	4.1	4.6	1.6	15	1.6	5.77±0.09	–	–	–	–	–	–	–
82	178	4.1	20.8	75	69	32	316	10	24	0.8	4.5	4.6	1.4	23	1.7	2.78±0.10	–	–	–	–	–	–	–
57	166	3.1	20.4	66	69	31	246	12	27	2.5	3.8	3.8	1.2	32	2.7	1.97±0.08	–	–	–	–	–	–	–
54	192	8.3	23.6	80	94	23	476	25.6	50.3	1.8	6.5	4.1	1.7	19	1.7	3.16±0.12	–	–	–	–	–	–	–
76	341	6.9	21.4	78	80	27	305	17	40	1.7	6	3.5	1.4	28	2	2.96±0.11	–	–	–	–	–	–	–
73	153	5.5	20.5	69	73	25	401	13.7	31.9	0.9	2.1	8.9	1	23	1.8	2.63±0.32	–	–	–	–	–	–	–
115	231	2.8	18.4	101	78	33	1925	41.3	103.7	4.5	8.2	7.4	1.5	36	1.8	6.14±0.15	–	–	–	–	–	–	–
48	146	2.6	20.4	67	58	33	167	12	23	0.5	3	3.2	1	26	1.7	0.40±0.30	–	–	–	–	–	–	–
140	284	8.2	19	72	79	39	258	12	29.4	0.8	1.2	6	–	31	2.61	1.14±0.19	2.4	<0.3	15	3.75	1.34	0.8	0.4
63	70	7.4	20.2	56	86	30	531	17	32.3	0.7	0.8	6.6	–	23	2.21	6.6±0.19	2.5	<0.3	20	4.68	1.53	0.7	0.35
69	104	6.6	20.6	73	80	28	592	19.2	47.2	0.8	2.7	6.2	2.7	23	1.72	4.1±0.1	0.6	23	4.74	1.47	0.6	0.27	–
107	128	4.4	19.7	79	81	31	353	8.8	30.6	0.2	0.9	5.4	–	28	–	4.98±0.18	–	–	–	–	–	–	–
11	24	6.9	20.8	43	72	17	581	15.9	41.2	1.8	4.1	10.3	–	20	–	4.39±0.24	–	–	–	–	–	–	–
56	100	9.1	20.6	78	83	26	449	16	43.7	1.1	1.6	8.3	–	25	–	3.69±0.11	–	–	–	–	–	–	–
123	181	6.8	19.9	66	79	28	382	15.7	38.7	0.6	1.3	7.9	<.3	24	2.01	1.91±0.34	2.4	19	3.78	1.32	0.6	0.27	–
98	170	5.2	19.3	72	76	30	286	9.7	30.1	0.4	0.8	7.7	2.2	24	2.15	2.4±0.1	<.3	13	3.43	1.14	0.6	0.32	–
117	181	5.1	18.9	88	76	41	245	10.1	19.1	0.3	0.7	6.5	–	30	–	4.07±0.22	–	–	–	–	–	–	–
52	87	7.7	21.8	73	84	23	668	24.9	54.8	0.3	3.2	8.2	–	23	–	2.54±0.11	–	–	–	–	–	–	–
79	207	5.3	19	65	66	30	177	9.5	30.4	0.2	1.8	6.1	–	32	–	7.6±6.6	–	–	–	–	–	–	–
53	94	8.7	21.5	50	81	26	471	15.7	48.9	0.3	2	8.8	3	23	2.15	3.83±0.32	<.3	21	4.61	1.41	0.6	0.33	–
84	202	8.2	18.1	42	99	33	502	16.8	39.2	1.2	0.6	4.9	2.7	25	2.49	6.15±0.17	<.3	23	4.88	1.54	0.7	0.37	–
68	106	9	22.2	77	83	34	561	24	50	1.8	3.3	5.8	–	24	–	5.9±0.2	–	–	–	–	–	–	–
126	180	6.5	20.4	83	86	32	519	16.9	49.3	1.6	2.6	6	2.8	23	1.95	4.37±0.39	0.3	24	4.55	1.51	0.6	0.25	–
156	228	3.6	16.3	75	62	39	68	3.5	8	0.2	1	5.3	1.2	33	2.32	2.4±0.5	<.3	7	2.1	0.87	0.6	0.32	–
99	173	7.3	19.8	292	82	32	459	18.1	35.5	0.9	0.9	4.8	–	25	–	5.95±0.16	–	–	–	–	–	–	–
51	98	7.3	22.5	84	75	28	560	25	49	1.5	4.3	3.3	–	27	–	3.7±0.1	–	–	–	–	–	–	–
80	199	5.4	18.3	60	70	32	140	10	30.8	0.8	1.1	6	2	32	2.35	1.14±0.30	0.5	14	3.24	1.2	0.7	0.34	–
51	93	6.5	21.3	51	70	19	610	20	46	1.7	4.5	6.5	–	17	–	0.57±0.05	–	–	–	–	–	–	–
21	24	3	21.5	37	50	14	432	15	36	1.7	5.3	6.3	–	10	–	0.60±0.05	–	–	–	–	–	–	–
34	37	7.7	21.3	76	79	21.5	628	20.3	50.1	1.4	2.8	9.5	–	21	–	2.96±0.24	–	–	–	–	–	–	–
18	40	7.3	21.7	91	75	18.2	576	18.8	37.3	1.3	1.9	9.8	3.1	23	2.06	2.51±0.07	<.3	19	4.23	1.34	0.7	0.29	
66	59	6.4	20.5	79	86	23	1013	25	63.6	2.1	3	9.8	–	22	–	2.88±0.17	–	–	–	–	–	–	–

(Continued on next page

Table 2. *(Continued)*

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Lake of the Woods North																			
BS92-77	50.08	0.96	17.21	2.18	6.46	0.14	9.34	8.53	3.29	0.48	0.19	0.32	99.18	9.36	2.8	636	16.5	67	199
CG91-100	49.83	1.19	17.13	2.69	7.60	0.15	7.23	9.06	3.34	0.55	0.29	0.60	99.66	11.14	7.7	509	26.2	101	206
92-75	56.11	1.01	17.15	2.37	5.29	0.13	4.36	7.65	3.36	1.36	0.39	0.95	100.13	8.25	19.4	612	24.8	155	172
86-62	57.58	0.84	17.67	2.35	4.09	0.11	4.08	7.25	3.44	1.01	0.20	1.35	99.97	6.90	13.8	701	22.2	108	156
92-73	50.83	1.11	18.67	2.08	6.53	0.15	6.37	8.77	3.71	0.47	0.20	0.50	99.39	9.34	3.9	608	17.1	76	176
92-77	52.66	1.03	16.61	3.36	4.78	0.13	7.24	8.92	3.23	1.03	0.34	0.61	99.94	8.67	11.4	968	20.3	93	207
MG-91-63	50.60	0.73	15.37	2.43	6.35	0.15	10.60	9.57	2.73	0.36	0.11	0.58	99.58	9.49	5.8	469	13.5	49	188
MG-91-22	49.08	0.89	17.07	1.29	7.20	0.15	9.62	11.15	2.31	0.16	0.10	0.87	99.89	9.29	3.2	426	24.7	35	222
MG-91-56	55.65	0.93	18.39	1.47	5.53	0.12	4.62	8.12	3.61	1.01	0.23	0.73	100.41	7.62	16	669	21.8	105	183
92-86	49.80	1.22	16.92	3.41	5.90	0.15	7.25	9.75	3.11	0.74	0.34	0.87	99.46	9.97	12.5	669	25.2	106	249
84-52	49.38	1.17	16.57	5.25	4.22	0.15	7.95	9.31	3.22	0.61	0.34	1.09	99.26	9.94	10	623	20.2	96	193
92-85	52.34	1.10	17.48	3.84	4.83	0.14	6.08	8.40	3.66	0.72	0.24	0.53	99.36	9.21	10.7	613	22.8	78	204
Lake of the Woods South																			
91-3	49.24	1.05	17.46	3.14	5.89	0.15	7.58	10.59	2.86	0.26	0.10	1.25	99.57	9.69	3.2	492	27.1	55	214
91-79	60.28	0.59	18.38	2.68	2.82	0.09	2.91	6.22	3.98	1.04	0.13	0.82	99.94	5.81	11.9	780	13.2	68	106
92-53	54.86	0.77	17.94	2.57	4.52	0.12	5.76	7.27	3.44	0.70	0.14	1.53	99.62	7.59	6.1	805	20.9	60	159
RB92-21	65.61	0.86	16.01	2.88	2.19	0.08	0.91	3.24	5.12	1.86	0.22	1.19	100.17	5.31	26	446	25	156	67
92-43	58.88	0.71	17.86	2.57	3.28	0.10	3.62	6.91	3.57	0.98	0.20	0.66	99.34	6.22	15.8	1,161	13.7	71	140
92-44	58.96	0.69	17.72	3.00	2.74	0.09	3.83	6.66	3.89	1.02	0.15	0.43	99.18	6.05	13.1	1,038	14	66	134
92-62	59.89	0.66	18.17	3.07	2.70	0.09	3.19	6.37	4.27	1.21	0.16	0.62	100.40	6.07	16.7	980	14.8	65	125
92-63	58.91	0.67	17.34	1.64	3.77	0.09	3.90	6.69	4.10	1.11	0.14	1.36	99.72	5.83	14.1	1,031	13.7	62	130
92-84	55.26	0.87	18.75	4.17	2.77	0.11	4.31	8.32	3.93	0.66	0.20	0.59	99.94	7.25	6.6	1,199	16.2	47	180
94-5	60.18	0.64	17.72	3.18	2.41	0.09	2.74	5.71	4.29	1.46	0.16	1.08	99.66	5.86	23.2	598	16.4	109	119
92-87	56.41	0.89	17.34	2.92	4.30	0.11	4.81	6.31	3.33	1.09	0.27	2.35	100.13	7.70	17	748	20.1	105	157
DH94-50	55.39	0.86	17.48	2.47	4.25	0.11	5.87	8.00	3.87	0.86	0.21	0.70	100.07	7.19	10.2	1,098	12	88	147
DH94-106	60.61	0.60	18.47	3.28	2.00	0.08	2.73	6.02	4.29	1.03	0.14	1.40	100.65	5.50	9.7	885	8.6	73	108
JP92-2	57.23	0.78	18.59	2.25	4.19	0.10	4.18	7.58	3.87	0.92	0.26	0.24	100.19	6.91	12.3	1,292	18.4	93	126
AH94-96	57.10	0.87	18.47	2.86	3.88	0.10	4.19	7.08	3.87	1.01	0.22	0.96	100.61	7.17	11.3	1,182	20	69	167
Little Chinquapin Mtn.																			
BS94-53	50.41	1.43	17.43	3.38	7.43	0.18	5.15	9.83	2.76	0.78	0.29	1.31	100.38	11.64	7	616	24	86	190
94-14	51.06	1.03	17.56	4.70	4.52	0.15	6.82	9.55	3.41	0.65	0.24	0.76	100.45	9.72	8.6	686	23	76	212
Mares Egg Spring																			
96-28	57.91	0.78	18.54	2.13	3.84	0.10	3.79	7.21	4.01	0.77	0.16	0.57	99.81	6.40	8.9	990	12	70	144
Mount McLoughlin																			
84-62	52.87	0.91	18.09	4.27	3.83	0.13	5.26	8.80	3.45	0.59	0.18	1.04	99.42	8.53	5.8	723	26.7	57	209
84-50	55.06	0.86	18.56	1.87	5.22	0.11	4.65	7.57	4.27	0.93	0.24	0.55	99.89	7.67	12.4	792	17.6	81	178
84-48	55.65	0.78	19.21	2.30	4.50	0.10	4.08	8.00	4.11	0.78	0.13	0.45	100.09	7.30	7.8	852	15.5	50	179
91-89	56.41	0.80	18.11	2.95	3.87	0.11	4.02	6.99	4.05	1.17	0.26	1.27	100.01	7.25	9.7	861	16.1	74	163
M91-85A	56.00	1.02	17.92	3.30	4.50	0.12	3.68	7.01	3.97	1.46	0.51	0.88	100.37	8.30	13.2	937	23.1	123	158
84-21	54.45	1.06	18.31	2.91	5.21	0.14	3.81	7.69	4.24	1.21	0.51	0.63	100.17	8.70	11.7	840	24.4	114	196
HC-91-44	53.67	1.09	18.15	2.78	5.86	0.14	5.14	7.85	3.89	1.04	0.25	0.83	100.69	9.29	13.8	858	36.2	65	214
HC-91-49A	56.66	0.79	18.33	2.68	3.49	0.10	4.19	7.52	3.54	0.91	0.24	0.91	99.36	6.56	11.7	1,276	16.6	82	151
HC-91-67	55.67	0.75	18.10	2.80	4.06	0.11	4.04	7.00	3.95	1.01	0.16	1.62	99.27	7.31	12.3	768	23.1	66	144
91-49	56.65	0.78	18.88	2.01	4.48	0.11	3.55	7.80	3.73	0.83	0.13	0.80	99.75	6.99	8.5	870	15.5	51	172
91-52	56.27	0.78	18.66	2.51	4.06	0.10	4.02	8.12	3.76	0.74	0.13	0.37	99.52	7.02	7	865	14.4	45	182
14K-91	54.68	1.01	16.10	3.61	3.71	0.13	5.35	8.69	3.96	1.47	0.48	0.38	99.57	7.73	18.9	1,137	227	139	202
84-38	55.69	0.76	18.85	3.04	3.83	0.10	4.55	7.78	4.13	0.78	0.12	0.34	99.97	7.30	7.7	877	7.3	48	164
92-66	51.48	0.99	17.05	3.78	4.90	0.14	7.05	9.34	3.19	0.50	0.18	0.78	99.38	9.23	4.8	690	21.8	77	228

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
251	241	4.4	20	90	75	44	181	4.1	16.5	0.8	3	3.7	–	27	–	1.12±0.05	–	–	–	–	–	–	–
107	160	4.4	18.3	49	77	39	290	17	32	1.4	1.6	–	1.6	29	2.4	1.32±0.06	–	–	–	–	–	–	–
34	49	8.6	21.3	68	75	26	541	21	45	1.3	4	8.5	1.7	22	2	1.02±0.09	–	–	–	–	–	–	–
32	43	5.7	21.6	51	72	22	470	16	32	1.5	0.4	7.4	1.5	19	1.8	0.21±0.18	–	–	–	–	–	–	–
92	133	3.1	21.7	61	69	29	283	7.4	24.6	0.4	1.7	4.5	1.4	25	1.8	1.16±0.05	–	–	–	–	–	–	–
80	203	6	21.7	71	77	35	414	19	37	1.3	5	6	1.6	23	1.6	1.22±0.04	–	–	–	–	–	–	–
175	605	3.3	13.6	59	65	38	150	4.2	10.8	0	0	4.9	1.2	28	1.1	2.78±0.09	–	–	–	–	–	–	–
128	311	1.7	17.3	87	61	42	72	3.4	8.2	1.2	3.4	2.1	2.2	37	2.1	2.19±0.14	1.4	0.3	7	2.1	0.83	0.5	0.38
21	93	5	21.4	48	68	22	386	12	24	1.4	3.3	9.6	1.3	23	1.3	1.58±0.03	2.3	0.3	12	3	1.04	0.6	
55	194	6.5	21.4	59	83	37	341	21	44	1.6	3.2	3.9	1.5	29	1.7	1.42±0.05	–	–	–	–	–	–	–
126	363	6.8	20.4	64	81	31	299	18.6	45	1.5	3.9	4.4	1.5	26	1.8	1.48±0.04	–	–	–	–	–	–	–
76	95	4.4	21.1	110	79	34	326	11	26	1.2	4	5.4	1.3	24	1.5	1.14±0.10	–	–	–	–	–	–	–
91	239	1.1	17.6	83	62	41	113	4.3	13	1.3	3.7	5.1	1.1	34	2.31	0.82±0.08	1.5	<.3	9	2.45	0.98	0.6	0.32
6	15	3.2	22.3	65	54	18	308	8	16	1.4	3.2	4.7	1.1	12	0.9	3.25±0.05	–	–	–	–	–	–	–
70	165	2.4	21.2	27	61	32	209	12	20	1.7	3.1	3.5	0.9	19	1.5	1.79±0.04	–	–	–	–	–	–	–
3	4	6.2	19.2	20	74	7.1	590	16	36	2.3	4.9	9	1.7	13	2.82	2.47±0.04	3.9	<.3	25	4.85	1.45	0.9	0.42
18	31	3.7	22.9	28	59	21	376	15	34	1.6	1.5	6.9	1.4	12	1.2	0.63±0.05	–	–	–	–	–	–	–
41	54	4	22	50	58	22	377	14	25	2.6	5.3	8.2	1.2	14	1	0.92±0.02	–	–	–	–	–	–	–
17	35	3.8	21.1	47	52	18	439	13	27	1.5	5.3	6.5	1.1	13	0.9	0.80±0.03	–	–	–	–	–	–	–
37	44	3.5	20.9	56	61	20	379	13	26	2.3	2.8	6.3	1.2	15	0.9	0.71±0.06	–	–	–	–	–	–	–
14	25	3.3	23.2	42	58	25	213	12	29	0.5	4.1	3.2	1.2	18	0.9	0.90±0.05	–	–	–	–	–	–	–
24	51	4.6	21	36	53	12	553	15	31	2.1	5.7	6.6	1.4	14	2	2.45±0.08	–	–	–	–	–	–	–
65	106	2.9	21.6	83	66	26	508	16	34	2	3.8	5.4	1.5	15	1.4	0.68±0.09	–	–	–	–	–	–	–
79	163	3.9	17.8	43	58	20	331	12.3	2.4	1	1.2	4	1	17	1.2	1.08±0.05	–	–	–	–	–	–	–
25	46	2.9	18.9	29	56	14	272	13	30.1	0.5	1.5	9.5	0.9	13	1.2	2.68±0.11	–	–	–	–	–	–	–
29	21	1.5	21.4	28	59	–	390	20	40	1.6	5.3	–	–	–	–	1.55±0.04	–	–	–	–	–	–	–
51	87	2.3	19.8	75	68	–	–	–	–	0.9	1	–	–	–	–	3.32±0.27	–	–	–	–	–	–	–
91	74	4	19	68	73	34	420	12	24	1	1	–	1	24	2.2	2.39±0.31	–	–	–	–	–	–	–
89	295	4.4	20.2	57	72	33	302	12.8	36	1.3	5.1	4	1.3	26	2.6	2.22±0.12	–	–	–	–	–	–	–
34	32	2.7	22	31	53	20	304	14	34	0.8	4.7	2.4	–	17	–	0.89±0.07	–	–	–	–	–	–	–
51	124	3.3	20.9	60	69	32	284	15	28	1.6	3.5	4.4	1.3	24	1.7	3.14±0.07	–	–	–	–	–	–	–
42	77	4.7	23	63	65	24	328	13.2	28.1	1	4.4	4.8	1.4	19	1.48	2.42±0.15	2.49	0.24	15.18	3.23	1.19	0.62	0.2
17.6	26	2.4	22.5	99	59	22	224	7	14	1.4	3.5	4.7	1.1	20	0.8	0.08±0.03	1.82	0.36	11.42	2.25	0.83	0.55	0.16
27	89	4.1	22.9	148	63	22	344	10	23	1.3	4.6	5.1	1.4	17	0.9	5.62±0.09	–	–	–	–	–	–	–
16.4	50	8.2	23.2	44	73	23	638	22	46	1	3.6	5.2	1.7	18	1.7	6.43±0.10	–	–	–	–	–	–	–
10	32	7.4	23.3	60	65	24	528	20	42	0.7	3.8	6	1.7	17	1.7	5.97±0.36	–	–	–	–	–	–	–
49	58	3.8	22.2	105	78	33	399	14	26	1.3	4.1	5.3	1.7	23	2.2	3.97±0.08	2.1	0.5	16	4	1.35	0.7	0.37
25	60	3.4	23.3	57	65	25	432	21	46	2.2	3.5	4.4	1.3	17	1	1.67±0.03	–	–	–	–	–	–	–
32	78	3.7	21.3	39	56	23	424	15	24	1.6	4.6	7.2	1.4	18	1.4	3.56±0.06	2.3	0.3	16	3.6	1.19	0.6	0.25
21	24	3	22.3	52	62	21	237	9	19	1.1	4.5	3.7	1.5	18	1.2	0.05±0.03	–	–	–	–	–	–	–
26	45	2.5	22.3	19	56	22	234	8	19	1.3	3.3	2.4	1.6	20	1.1	0.08±0.03	–	–	–	–	–	–	–
34	100	9.7	23.7	36	76	27	581	34	59	1.9	8.8	5.5	1.7	20	1.25	3.43±0.06	3.8	0.6	25	5	1.4	0.6	0.2
40	28	2.4	22.6	50	57	23	224	7	14	1.3	4.4	3.9	1	17	1	<0.15	1.79	0.14	13.45	2.63	1.01	0.57	0.19
68	156	4.1	21	77	68	36	269	12	25	1.9	3.7	5.1	1.3	26	1.4	1.76±0.08	–	–	–	–	–	–	–

(Continued on next page

Table 2. *(Continued)*

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Mule Hill																			
95-29	54.96	1.12	17.86	4.16	4.14	0.14	3.45	7.29	4.10	1.42	0.61	0.58	99.83	8.76	14.3	649	30.5	180	189
95-30	52.32	0.79	17.59	2.73	5.17	0.14	6.61	10.63	3.10	0.47	0.14	0.64	100.33	8.48	6.8	678	14.1	47	224
95-33	48.00	1.11	17.66	4.25	5.95	0.17	7.87	11.10	3.03	0.21	0.18	0.96	100.49	10.86	2.7	377	23.8	67	222
95-75	49.38	1.07	18.53	5.55	4.23	0.16	6.38	10.04	3.11	0.31	0.16	1.06	99.98	10.25	2.7	510	25.6	64	205
95-77	55.90	1.05	17.70	3.55	4.12	0.13	3.80	7.66	4.09	1.05	0.29	0.83	100.17	8.13	13.7	770	28.3	106	177
95-26	48.47	1.32	17.00	2.54	8.00	0.17	7.46	9.97	2.87	0.61	0.35	1.06	99.82	11.43	7.1	439	24.3	83	263
96-1	51.39	1.32	17.34	3.12	6.66	0.17	5.55	7.99	3.81	1.18	0.59	0.86	99.98	10.52	12.3	752	27	141	205
96-2	49.90	1.02	18.16	2.28	6.92	0.15	7.17	9.77	3.32	0.42	0.15	0.56	99.82	9.97	4.9	548	20	63	227
96-3	50.23	1.24	17.30	5.54	4.53	0.16	5.79	8.56	3.75	1.07	0.46	0.95	99.58	10.57	9.8	924	25	102	226
96-5	51.29	1.33	18.20	7.47	2.94	0.17	3.65	7.72	4.04	1.20	0.75	1.08	99.84	10.74	5.9	818	30	163	196
96-6	48.45	1.79	15.45	4.88	6.29	0.16	7.80	8.27	3.25	1.22	0.59	1.50	99.65	11.87	17.8	637	42	148	242
96-7	57.61	1.33	16.86	5.94	2.22	0.13	2.17	5.31	3.93	2.36	0.45	1.85	100.16	8.41	40	500	44	266	176
96-8	49.16	1.82	16.14	4.61	6.41	0.16	6.49	8.54	3.40	1.22	0.57	0.74	99.26	11.73	16.8	667	29	149	251
96-9	47.85	0.90	17.74	2.47	6.63	0.16	9.24	11.22	2.57	0.13	0.07	1.03	100.01	9.84	1.4	271	23	47	203
97-22	50.40	1.11	17.80	3.33	6.11	0.17	7.45	9.35	3.51	0.43	0.25	0.53	100.44	10.12	0.9	517	23	82	210
97-35	50.55	0.99	18.38	3.35	5.77	0.15	6.69	9.83	3.43	0.41	0.15	0.81	100.51	9.76	2.7	581	18	58	214
97-37	67.08	0.81	15.82	2.30	1.04	0.06	0.56	2.48	5.70	2.15	0.20	2.08	100.28	3.46	29.5	353	39	263	49
97-46	49.94	1.08	18.02	2.96	6.66	0.16	7.22	9.97	3.36	0.39	0.15	0.53	100.44	10.36	2.3	566	20	58	242
97-47	48.38	0.74	17.53	3.20	5.78	0.16	9.44	11.08	2.33	0.13	0.11	1.49	100.37	9.62	0.9	386	19	47	215
97-54	63.72	0.69	14.86	3.41	1.36	0.12	1.14	2.64	2.91	3.02	0.19	6.46	100.52	4.92	43.9	266	33	262	63
97-55	70.54	0.70	13.00	3.69	0.21	0.06	0.50	2.30	4.26	1.82	0.22	2.99	100.29	3.92	24.2	297	28.4	208	45
CW9-13B	47.85	1.08	17.21	1.94	8.06	0.17	9.16	11.33	2.60	0.14	0.12	0.87	100.53	10.90	0	327	22	59	262
CW6-5	49.99	0.74	18.16	3.52	5.15	0.16	7.36	11.69	2.70	0.28	0.11	0.80	100.66	9.24	1	437	18	49	240
CW6-9	56.37	1.73	15.97	4.95	4.57	0.16	2.36	5.55	4.77	1.67	0.78	1.40	100.28	10.03	23.4	526	146	157	212
S97-21	57.20	1.29	16.37	4.72	3.00	0.12	2.49	5.51	3.66	2.47	0.46	2.33	99.62	8.05	42.9	519	40	273	172
S97-62	53.16	1.13	17.56	3.80	4.99	0.16	4.52	7.53	3.59	1.57	0.69	0.80	99.50	9.35	13.8	652	33.3	179	171
S97-87	50.74	1.11	16.46	2.05	6.15	0.14	6.77	9.94	3.12	1.48	0.53	0.83	99.32	8.88	22.4	1,325	23.3	153	224
97-54Z	57.82	1.09	15.64	4.41	2.04	0.14	2.56	5.08	2.84	1.45	0.48	7.10	100.65	6.68	23.3	462	27.7	162	108
JM97-27D	50.98	1.26	17.35	2.74	6.73	0.17	5.23	8.30	3.61	1.16	0.62	1.01	99.16	10.22	10.3	747	23.1	131	201
Parker Mtn.																			
95-34	53.28	1.10	18.34	4.31	4.46	0.14	4.86	8.00	3.96	0.83	0.34	0.65	100.27	9.27	11.2	700	17.8	90	188
97-2	49.51	0.74	18.03	2.88	5.68	0.16	8.09	11.51	2.53	0.25	0.11	1.01	100.50	9.19	1	416	19	51	224
97-16	51.24	0.93	17.94	4.32	4.29	0.15	6.16	10.35	3.24	0.69	0.39	0.72	100.42	9.19	3.5	736	19	72	245
97-41	52.29	1.12	18.50	1.99	6.55	0.15	5.37	8.69	3.83	0.84	0.32	0.67	100.32	9.27	8.8	665	21	92	204
86-85	49.14	1.62	16.58	2.60	8.37	0.18	7.12	9.38	3.16	0.51	0.34	0.72	99.72	11.90	7.5	404	30	114	257
Pelican Bay																			
92-74	55.80	1.12	17.07	3.69	5.08	0.14	3.98	7.66	3.92	0.84	0.18	0.49	99.97	9.34	10.4	700	20.8	59	263
92-89	50.74	0.88	17.18	3.07	5.73	0.14	8.92	8.56	2.82	0.60	0.18	0.70	99.52	9.44	8.6	614	17.7	60	175
92-80	58.04	0.81	17.13	2.81	3.92	0.11	4.47	7.16	3.64	1.09	0.21	0.75	100.14	7.17	15	727	20.4	108	148
AG92-75	54.72	0.90	18.55	3.49	4.32	0.12	4.84	8.05	3.56	0.76	0.15	0.61	100.07	8.29	8.2	772	12.5	57	186
Pelican Butte																			
86-59	58.61	0.79	17.47	1.81	4.25	0.10	3.75	6.94	3.90	1.10	0.17	1.07	99.96	6.53	17.4	681	18	106	153
92-91	57.75	0.78	18.00	2.19	3.99	0.10	3.76	7.07	3.98	1.10	0.17	0.55	99.44	6.62	16.6	844	17.5	94	159
96-11	52.90	0.95	18.81	3.31	5.25	0.14	5.12	8.00	3.62	0.69	0.22	0.87	99.88	9.14	7.7	609	19	78	181
96-13	52.86	0.96	18.04	4.94	3.22	0.13	5.87	8.68	3.53	0.79	0.21	0.43	99.66	8.52	11.8	691	20	98	197
96-17	55.42	0.76	18.44	2.22	4.66	0.12	5.00	8.04	3.52	0.82	0.16	0.64	99.80	7.40	14.3	615	16	88	165

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
23	41	12.1	20.6	70	93	19	583	28.7	60.8	0.2	1.1	11.2	–	22	–	6.24±0.17	–	–	–	–	–	–	–
48	155	4	18.5	35	66	27	195	8.5	25.5	0.9	1.3	5.1	–	29	–	2.57±0.24	–	–	–	–	–	–	–
159	221	4.2	16.7	102	72	41	166	2	7.2	0.9	0.6	5	–	31	–	2.26±0.26	–	–	–	–	–	–	–
133	176	4.7	18.3	73	75	38	312	13.8	25.8	0.5	1.2	5.8	–	29	–	2.27±0.24	–	–	–	–	–	–	–
26	63	7.2	21.9	34	73	17	454	18.2	34.7	1.5	2.3	6.4	–	22	–	3.44±0.12	–	–	–	–	–	–	–
131	247	6.8	18.4	91	88	38	307	11.6	23.3	0.3	0.8	6.5	–	32	–	7.41±0.19	–	–	–	–	–	–	–
64	110	9.3	23.1	94	81	33	582	23	51	1.8	3.7	7.3	–	22	–	5.97±0.23	–	–	–	–	–	–	–
113	133	2.9	21.7	91	66	38	254	9	28	1.3	3.2	2.5	–	24	–	3.23±0.25	–	–	–	–	–	–	–
90	135	6.3	21.9	85	77	29	535	17	44	2.3	6.3	4.7	–	22	–	5.55±0.18	–	–	–	–	–	–	–
55	98	11.2	23.1	45	99	30	763	28	62	1.1	4.5	7.5	–	21	–	5.8±0.2	–	–	–	–	–	–	–
178	370	10.4	22.3	64	106	49	530	24	47	2.3	3.8	5.7	–	25	–	13.5±0.4	–	–	–	–	–	–	–
30	41	10.4	22.3	60	90	18	787	28	57	1.9	7.5	8.4	–	20	–	14.5±0.5	–	–	–	–	–	–	–
115	213	11.6	21.7	59	101	41	556	19	50	1.1	5.6	4.9	–	26	–	13.2±0.3	–	–	–	–	–	–	–
163	224	1.4	17.7	97	58	45	103	4	11	1.6	4	1.8	–	32	–	2.6±0.4	–	–	–	–	–	–	–
109	222	3.9	17.1	75	69	41	264	13	33	0.9	<0.5	–	–	–	–	2.4±0.2	–	–	–	–	–	–	–
115	124	3	21.6	100	67	43	244	7	24	1.5	4.3	3.3	–	27	–	3.26±0.16	–	–	–	–	–	–	–
4	11	11.5	20.5	8	93	4	760	30	59	2.8	7.8	9.9	–	13	–	21.6±0.5	–	–	–	–	–	–	–
102	131	2.7	21.2	115	65	37	248	9	27	1.7	3.5	2.8	–	26	–	3.2±0.2	–	–	–	–	–	–	–
199	413	2.5	17.5	83	59	44	386	10	28	0.9	3.5	2.5	–	33	–	1.9±0.3	–	–	–	–	–	–	–
16	29	10.9	19.4	19	70	12	782	27	55	2.9	8.4	9.9	–	16	–	13.5±0.5	–	–	–	–	–	–	–
4.6	21	10.5	17.9	16.9	72	4.5	633	23.4	49.3	1.6	5.1	11.6	–	13	–	17.6±0.7	–	–	–	–	–	–	–
134	272	1.6	19.6	104	64	43	81	4	19	1.1	3.7	2.1	–	33	–	2.1±0.3	–	–	–	–	–	–	–
80	207	2.4	18.5	82	60	37	196	6	18	0.7	2.7	2.3	–	32	–	15.0±0.4	–	–	–	–	–	–	–
5	15	4.3	23.8	33	93	15	725	56	58	1.2	5.7	8.4	–	26	–	3.66±0.24	–	–	–	–	–	–	–
18.8	36	12.3	20.6	66	93	11.7	769	33.8	57.9	1.3	5.2	13.4	–	20	–	14.6±0.9	–	–	–	–	–	–	–
40.7	64	12.8	20.5	75	88	22.3	590	25.4	65.2	0.5	1.8	9.9	–	19	–	5.5±0.2	–	–	–	–	–	–	–
79.2	166	6.9	20.1	79.4	72.1	28.5	1067	32.3	70.3	1.5	3.2	6.4	–	24	–	3.79±0.10	–	–	–	–	–	–	–
6	26	9.1	19	23.1	88	10.5	704	22.3	50.8	1.1	3.5	9.7	–	20	–	17.1±0.8	–	–	–	–	–	–	–
56	102	9.5	20.6	75	91	28.4	550	19.1	57.5	0.6	2.1	8.8	–	25	–	5.83±0.15	–	–	–	–	–	–	–
48	68	5.7	20.8	58	78	26	400	11.9	28.5	0.6	1	7.5	–	21	–	2.48±0.50	–	–	–	–	–	–	–
111	285	2.7	18.7	69	54	38	148	7	22	0.6	3.7	2.3	–	32	–	2.2±0.3	–	–	–	–	–	–	–
43	145	5.3	19.9	79	68	29	387	18	46	1.1	4.2	4.8	–	28	–	6.5±0.2	–	–	–	–	–	–	–
45	89	5.3	22	78	74	30	460	12	36	1.2	4.5	5.2	–	22	–	1.8±0.2	–	–	–	–	–	–	–
104	208	6.6	21.7	79	80	37	358	10	26	1.1	3.9	3.7	–	25	–	3.64±0.38	–	–	–	–	–	–	–
7	21	3.3	22.9	105	78	27	355	10	22	1.5	4.7	4.9	1.6	26	1.6	1.13±0.09	–	–	–	–	–	–	–
248	309	4	19.8	65	79	46	261	8	21	1.1	4.4	3.8	1.2	23	1.5	1.20±0.04	–	–	–	–	–	–	–
57	101	4.6	18.8	53	68	25	444	16	29	0.8	1.8	8.5	1.4	18	1.8	0.45±0.04	–	–	–	–	–	–	–
39	101	3.4	20.3	43	71	23	286	5.3	24.1	1.5	2.7	5.1	1.4	21	1.4	1.47±0.04	–	–	–	–	–	–	–
31	51	5.4	21.3	49	66	22	401	14	33	2.4	4.8	5.4	1.3	19	–	0.54±0.05	–	–	–	–	–	–	–
25	28	4.8	22.5	62	65	22	393	15	33	2.1	5.4	6.3	1.3	18	1	0.54±0.05	–	–	–	–	–	–	–
60	85	4	21.6	57	75	29	357	13	32	1.1	3.5	5.5	–	23	–	1.23±0.08	–	–	–	–	–	–	–
74	128	4.4	20.7	49	72	33	376	11	34	1.6	4.2	5.4	–	25	–	1.32±0.08	–	–	–	–	–	–	–
80	82	3.8	21.5	53	64	30	375	16	37	1.2	4.5	5.5	–	20	–	1.64±0.40	–	–	–	–	–	–	–

(Continued on next page

Table 2. ***(Continued)***

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Robinson Butte																			
91-61	56.89	0.64	19.11	3.30	3.21	0.10	3.17	7.62	3.57	1.00	0.16	1.68	100.45	6.87	10.6	844	13	59	132
92-21	49.62	1.06	15.41	5.58	3.11	0.13	7.83	9.25	3.33	2.16	0.63	1.56	99.67	9.04	21.3	2,187	22.6	65	183
92-24	53.79	0.89	17.27	3.19	4.93	0.13	5.54	7.97	3.58	1.09	0.30	1.11	99.79	8.67	23.4	643	24.8	120	181
JB91-56	48.60	1.36	14.56	5.19	4.14	0.13	8.37	9.28	3.99	1.71	1.11	1.16	99.60	9.79	15.4	1,718	21.6	105	220
92-26	49.88	1.39	16.64	6.33	3.71	0.14	5.82	9.32	3.37	0.93	0.48	1.38	99.39	10.45	13.8	653	29	122	236
92-41	52.29	0.91	18.11	3.96	4.30	0.13	5.28	8.97	3.12	1.00	0.24	1.21	99.52	8.74	11	859	21.4	73	212
94-40	49.10	0.66	13.45	2.81	6.52	0.14	15.59	8.21	2.28	0.51	0.12	0.83	100.22	10.06	4.8	804	13.7	30	182
RSP94-94	53.71	1.16	17.38	3.23	4.92	0.15	4.83	8.00	3.96	1.19	0.48	0.91	99.92	8.70	10.4	968	24.5	132	170
94-42	51.82	1.05	17.54	6.75	2.28	0.14	5.88	7.98	3.78	1.10	0.35	1.65	100.32	9.28	9	1,392	19	56	158
Rustler Peak																			
86-47	53.37	0.85	18.17	2.54	5.33	0.13	5.77	8.71	3.42	0.67	0.17	1.00	100.13	8.46	8.7	627	27	81	194
86-48	62.76	0.48	18.28	2.28	2.37	0.10	1.56	4.57	4.46	1.53	0.20	0.91	99.50	4.91	15.9	859	10	98	71
Spencer Creek																			
95-68	52.52	0.87	19.35	2.08	5.46	0.12	5.63	8.91	3.39	0.80	0.17	0.87	100.17	8.15	9.1	709	15	70	788
95-69	48.21	0.93	17.45	2.94	6.46	0.17	9.13	11.64	2.50	0.13	0.12	0.77	100.45	10.12	2.4	270	22.8	48	225
Surveyor Mtn.																			
95-46	54.02	1.02	17.95	2.38	5.99	0.14	5.13	8.11	3.72	0.82	0.29	0.55	100.12	9.04	12.1	689	16.7	86	177
91-21	53.71	1.05	17.88	3.27	5.00	0.14	5.24	7.93	3.89	0.76	0.27	0.81	99.95	8.83	10.7	592	24.5	97	171
94-36	53.52	1.05	17.69	2.95	5.07	0.13	5.63	8.04	3.83	1.13	0.36	0.83	100.23	8.58	11.5	1,118	22.7	110	192
91-15	51.01	0.91	17.64	2.31	5.92	0.13	7.70	8.72	3.18	0.50	0.16	1.27	99.45	8.89	3.6	876	15.9	44	221
97-28	51.83	1.00	18.04	2.66	5.69	0.15	6.23	9.59	3.49	0.87	0.36	0.47	100.38	8.98	7.6	738	19	95	214
94-4	54.40	0.83	18.20	2.51	5.15	0.12	5.12	8.47	3.74	0.79	0.15	0.98	100.46	8.23	11.3	723	17.1	58	204
Willow Lake																			
84-26	54.53	0.87	18.55	4.44	3.27	0.12	4.41	7.13	4.50	0.99	0.20	1.02	100.03	8.07	8.4	1,133	14.1	25	168
91-60	52.12	1.20	17.27	3.53	6.05	0.16	5.14	7.75	3.99	0.94	0.51	1.31	99.97	10.25	7.8	817	23.4	66	185
JB91-41	50.80	0.70	16.20	3.42	5.68	0.15	9.01	9.85	2.98	0.44	0.16	0.62	100.01	9.73	4.2	636	14.7	15	193
91-89	56.41	0.80	18.11	2.95	3.87	0.11	4.02	6.99	4.05	1.17	0.26	1.27	100.01	7.25	9.7	861	16.1	74	163
KWW-91-33	54.72	1.09	17.90	3.15	4.77	0.13	4.02	7.24	3.82	1.24	0.47	1.68	100.23	8.45	9.8	877	34.7	105	182
KWW-91-25	55.74	0.78	18.67	2.16	4.47	0.10	4.38	8.18	3.89	0.78	0.13	0.40	99.68	7.13	7.1	851	14.8	55	106
California																			
Copco																			
86-88	51.65	1.04	16.85	4.03	4.10	0.13	6.76	8.95	3.23	1.10	0.36	1.62	99.82	8.59	14.3	879	21	107	204
86-92	57.56	0.65	18.70	3.74	2.47	0.09	3.27	7.44	3.61	0.75	0.17	1.21	99.66	6.49	3.7	1,036	12	50	123
Panther Rock																			
97-66	56.14	0.65	18.17	3.60	3.15	0.10	4.11	7.76	3.34	1.15	0.22	1.50	99.89	7.10	9.6	976	16.4	89	144
Secret Spring																			
B'3	53.55	0.89	17.26	3.59	5.38	0.13	5.49	8.40	3.40	1.01	0.30	0.79	100.19	9.57	9.6	773	16.5	97	182
B'317	48.09	1.31	15.53	4.60	6.30	0.18	9.60	10.64	2.45	0.41	0.25	0.79	100.15	11.60	5.3	459	25.6	86	269
B'3	53.55	0.89	17.26	3.59	5.38	0.13	5.49	8.40	3.40	1.01	0.30	0.79	100.19	9.57	9.6	773	16.5	97	182
Anders-1	68.31	0.71	15.04	3.45	0.48	0.05	0.49	1.89	4.58	3.83	0.15	1.04	100.02	3.98	97	223	31	404	32
K97-78	51.83	0.94	17.35	4.67	3.95	0.13	7.78	8.84	3.04	0.78	0.27	0.86	100.44	9.06	9.3	765	11	69	179
97-68	56.00	1.00	17.46	3.27	4.48	0.13	4.22	7.53	4.01	1.12	0.36	0.58	100.16	8.25	10.1	800	20	142	170
A24	49.77	1.11	15.99	8.33	–	0.15	8.56	8.95	2.85	0.61	0.25	1.88	98.45	8.33	8.9	466	16.4	84	209
A73	63.16	1.23	15.41	6.09	–	0.10	0.58	3.05	4.49	2.92	0.40	2.21	99.64	6.09	74.5	369	41	344	91
K97-43	51.15	0.83	18.53	4.34	3.97	0.12	7.08	9.25	3.09	0.73	0.22	0.54	99.85	8.75	7.9	875	8.2	56	186
L-24	56.26	0.71	17.84	2.62	4.55	0.12	4.25	7.29	3.84	0.85	0.18	1.11	99.62	7.68	10.9	728	9.1	50	132
97-53	58.14	1.13	16.46	1.70	4.68	0.14	3.10	6.47	3.58	2.14	0.36	2.33	100.23	6.90	50.1	551	28.1	232	151
L-42	57.38	0.53	19.40	3.82	1.50	0.06	2.45	7.67	3.83	1.06	0.19	1.79	99.68	5.49	7.8	1,102	4.7	45	65
K97-24	52.22	0.73	17.43	2.72	4.76	0.12	8.06	9.32	3.05	0.72	0.20	0.56	99.89	8.01	9.6	763	8.5	57	170
JM97-16	60.08	0.76	15.72	4.01	0.78	0.12	1.79	3.52	2.63	1.95	0.23	8.94	100.53	4.88	44.5	359	37	220	55
K97-23	51.09	0.52	18.52	4.76	2.50	0.12	7.71	10.24	2.52	0.79	0.17	1.50	100.44	7.54	12.5	890	6	47	147

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
6	25	3.5	23.1	59	51	17	286	8	15	1	4	4.6	1.2	13	0.8	19.6±0.3	2.2	0.4	10	2.2	0.82	0.3	0.16
81	168	5.1	20.7	104	74	34.5	1749	43.8	92	2.4	7.9	9	–	18	1.3	6.13±0.10	2.9	<.3	50	8.87	2.36	0.8	0.2
67	161	4.5	20.6	29	76	20	619	26.7	62.1	2	6	6.3	–	20	–	20.5±0.3	–	–	–	–	–	–	–
97	242	16.7	24.5	86	118	36	905	55.4	93	2.1	8.2	5.4	2.3	21	1.3	5.35±0.09	3.4	0.6	49	6.47	1.93	0.6	0.2
158	287	8	17.9	61	102	35	467	24	42	0.3	3.3	6.3	1.3	28	2.3	20.2±0.3	–	–	–	–	–	–	–
53	133	5	22.2	72	76	33	365	17	26	0.7	3.3	7.7	1.2	23	1.4	19.5±0.3	–	–	–	–	–	–	–
263	879	1.3	15.5	69	71	47	138	9	21	–	–	–	0.8	29	1.7	5.43±0.18	–	–	–	–	–	–	–
34	74	7.8	21.7	37	70	25	523	19	43.9	0.9	1.2	5	1.2	20	2.4	5.73±0.15	–	–	–	–	–	–	–
135	194	4.7	23.2	43	76	18	506	15.2	39.3	1.8	6.5	3.9	1.3	19	2.2	5.54±0.15	–	–	–	–	–	–	–
61	125	4.1	20.5	79	70	32	302	11	33	1.7	4.8	4.5	–	26	–	1.42±0.09	–	–	–	–	–	–	–
5	26	4.4	17.1	22	60	7	494	13	37	1.2	3.3	2.4	–	33	–	4.43±0.15	–	–	–	–	–	–	–
78	84	4.3	19.5	71	73	26	270	8.6	20	0.4	2	4.6	–	24	–	1.19±0.11	–	–	–	–	–	–	–
171	234	3.3	16	91	67	41	60	5.6	7.8	0.5	1	5.5	–	39	–	2.0±0.3	–	–	–	–	–	–	–
53	88	5.5	20.5	40	75	24	408	12.7	31.4	0.6	1.2	8.8	–	24		2.76±0.16	–	–	–	–	–	–	–
61	118	4.3	18.7	70	73	28	368	14	31	1	4.7	5.9	1.5	22	2.4	1.88±0.22	–	–	–	–	–	–	–
76	134	5.5	22.8	90	74	17	527	21.1	45.8	1	3.3	5.8	1.6	24	2.5	2.78±0.10	–	–	–	–	–	–	–
106	306	2.9	20.5	79	69	34	215	9	22	1.1	3.5	3	1.3	25	1.1	2.32±0.11	–	–	–	–	–	–	–
54	118	6.9	19	94	72	29	592	16	43	<0.5	2.7	–	–	–	–	3.7±0.3	–	–	–	–	–	–	–
42	75	3.5	22.6	170	64	24	319	9	19	1.3	4.3	4.3	1.3	22	1.7	2.81±0.14	–	–	–	–	–	–	–
51	108	2.1	20.2	52	69	28	493	11	21	–	0.8	–	1.3	17	0.8	6.01±0.30	–	–	–	–	–	–	–
48	101	5.7	21.7	51	75	33	551	15	31	2.1	3.5	5.1	1.3	22	1.8	6.06±0.10	–	–	–	–	–	–	–
148	656	2.4	18.3	84	70	44	278	4.8	12	1.4	3.2	3.9	1.3	28	1.1	6.11±0.21	0.9	<.3	8	1.97	0.76	0.3	0.16
27	89	4.3	23.2	148	63	22	344	10	23	0.7	4.1	4.4	1.4	17	0.9	5.62±0.09	–	–	–	–	–	–	–
33	71	5	20.4	85	81	27	578	29	52	1.9	1.3	–	1.6	18	2.5	6.48±0.10	–	–	–	–	–	–	–
16	15	1	20.2	39.5	66	18	224	8	16	0.7	3.3	–	1.1	10	0.9	0.66±0.02	–	–	–	–	–	–	–
138	238	6.2	20.5	72	85	32	692	25	59	2.2	5.4	4.8	–	24	–	4.11±0.45	–	–	–	–	–	–	–
25	46	2.5	21.8	51	63	21	213	9	27	2	4.8	2.8	–	17	–	8.59±0.59	–	–	–	–	–	–	–
45	77	3.5	20.4	38.2	65	18.6	238	9.9	30.2	1.1	2.1	3.5	–	17	–	20.4±0.5	–	–	–	–	–	–	–
142	196	5.1	21.1	76	70	26	345	12.7	31.5	2.8	1.1	6.1	–	17	–	15.0±0.4	–	–	–	–	–	–	–
217	298	6.1	17.1	103	92	44	246	10.4	20.5	1.1	2.2	5.8	–	32	–	4.35±0.39	–	–	–	–	–	–	–
142	196	5.1	21.1	76	70	26	345	12.7	31.5	2.8	1.1	6.1	–	17	–	14.5±0.4	–	–	–	–	–	–	–
3.5	12	15.5	19	7	56	6	940	31	52	3.2	11.9	13	–	10	–	21.0±0.5	–	–	–	–	–	–	–
128	299	4.7	17.8	57	70	21	267	12.7	34	0.7	2.5	7.2	–	23	–	12.5±0.5	–	–	–	–	–	–	–
37	62	7.9	21.7	53	79	26	453	20	49	2.1	4.8	2.3	–	20	–	3.7±0.1	–	–	–	–	–	–	–
207	416	6.4	17.7	53	82	34.6	258	8.4	17.7	1	0.7	6.2	–	27	–	19.25±0.51	–	–	–	–	–	–	–
1.3	6.3	14.7	19.9	9.3	88	6.7	857	33.1	65	2.9	7.5	12.9	–	22	–	21.17±0.54	–	–	–	–	–	–	–
115	198	3.6	18.3	122	67.4	30.4	195	7	24.2	0.6	1.6	7.6	1.1	23	1.66	13.19±0.80	0.22	13.4	2.51	0.78	0.34	0.15	–
44	148	3.2	21.1	37	73.7	20.6	393	8.4	26.8	1.2	2.7	13.2	–	19	–	4.94±0.19	–	–	–	–	–	–	–
27.8	49	12.4	19.4	42	85	17.5	577	23.1	56.7	0.9	5.4	10.8	–	21	–	19.6±0.6	–	–	–	–	–	–	–
12.7	58	2	20.4	25.2	60	10.7	366	6.5	35.8	0.6	1.9	17.6	–	14	–	7.9±0.4	–	–	–	–	–	–	–
105	304	3.4	17.5	64	69	34	244	8.7	31.2	0.6	1.5	8.1	–	23	–	13.3±0.4	–	–	–	–	–	–	–
12.8	41	11.2	17.9	22	66	8.5	863	29.9	59.8	1.8	6.2	11.3	–	16	–	17.6±0.6	–	–	–	–	–	–	–
72	230	2.2	17.9	58	60	28	273	9.1	25.7	1.6	2.7	6.6	0.9	23	1.85	10.7±0.3	0.12	12.9	2.57	0.92	0.26	0.16	–

(Continued from page 107)

between crustal blocks of differing densities, as they propose, provide an easier path to the surface for magmas generated at various levels within the lithosphere and upper reaches of the asthenosphere.

GEOCHEMICAL RESULTS

For a broad view of regional petrogenesis, Figure 5 shows three MgO-major element variation diagrams, while Figure 6 shows three MgO-trace element variation diagrams. Both sets of diagrams provide a large-scale context in which to begin a general discussion of the regional petrology and geochemistry. The MgO-SiO_2 relationship, interpreted in light of detailed thin-section petrography, suggests olivine phenocryst fractionation with poikilitically enclosed Cr-spinel grains, which has a significant role to play in mafic mineral evolution. This conclusion is substantiated by the Ni-MgO diagram (Figure 6a) which depicts a rapidly declining whole-rock Ni content as a function of decreasing MgO. Both Cr and Co follow a very similar pattern. The Al_2O_3 trend (Figure 5b) suggests that plagioclase crystal fractionation plays a rather minor role until MgO decreases to values ≤4 weight percent, because the Al_2O_3 concentration increases as a function of decreasing MgO. This conclusion is corroborated by the Sr-MgO diagram (Figure 6b), which depicts an increasing Sr whole-rock content as MgO declines. The Fe_2O_3T trend (Figure 5c) decreases at MgO values ≤5 weight percent, which approximately coincides with the petrographic occurrence of titanomagnetite as a significant microphenocryst to phenocryst phase. Given the density of titanomagnetite compared to the magma that surrounds it, titanomagnetite crystals are likely participants in any gravity-driven magmatic differentiation process. As one might surmise, both V and Ti follow a very similar geochemical pattern. In distinct contrast

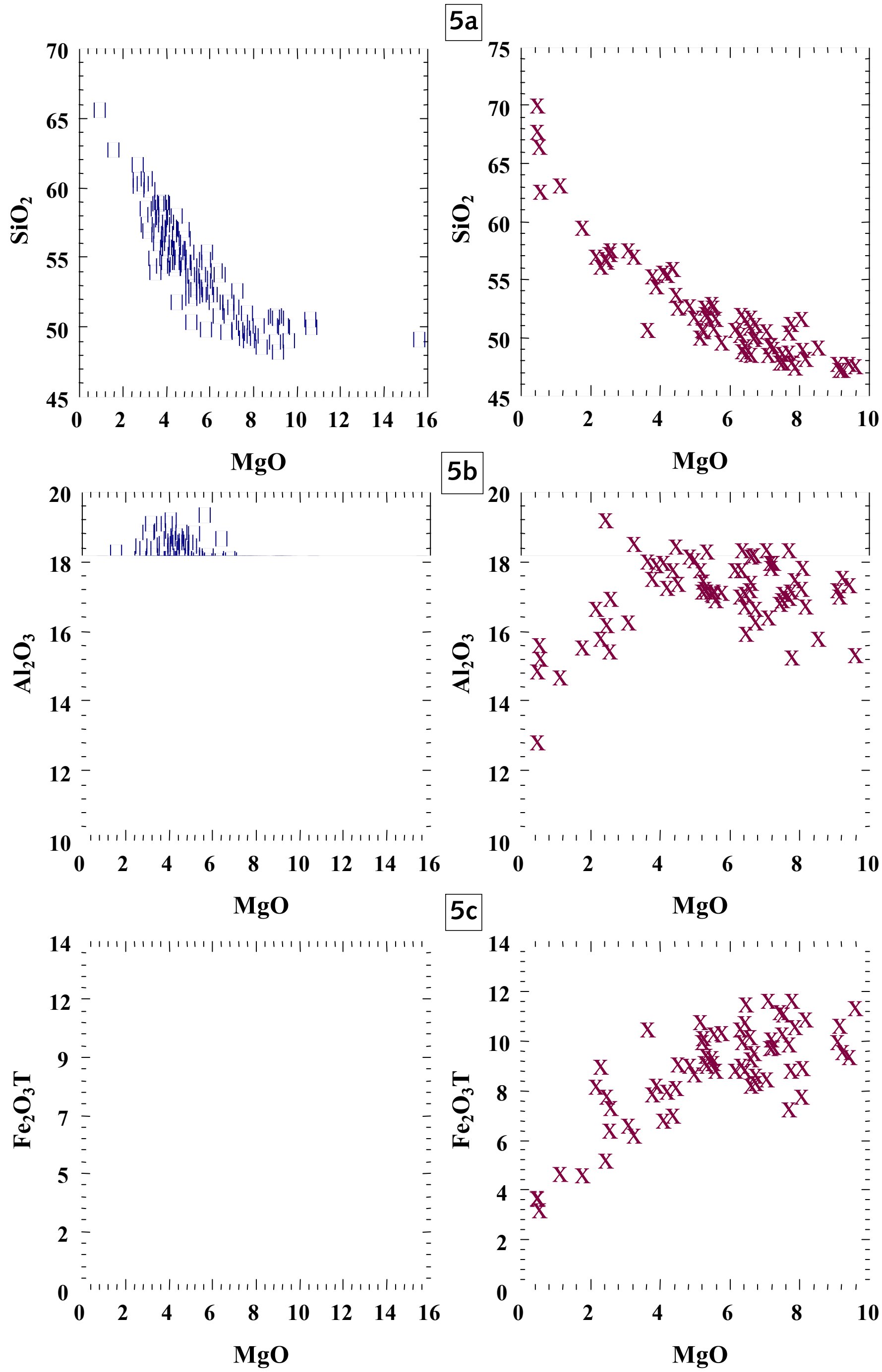

Figure 5. Plots of MgO versus three major elements, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. Values are in weight percent.

to many of these declining elemental patterns as MgO decreases, Ba (Figure 6c) behaves as an incompatible element, depicting a behavior more extreme than that of either Al_2O_3 or Sr. This is to be expected because petrographic data indicate that in no case did the K_2O content of those magmas currently represented as lavas sampled in this study reach a concentration level that would have potassium feldspar, most likely sanidine, crystallize as a liquidus phase. Since Ba^{+2} proxies for K^{+1} in numerous minerals due to ionic size similarities, these two elements tend to behave similarly in terms of geochemistry. Invariably, K_2O appears in

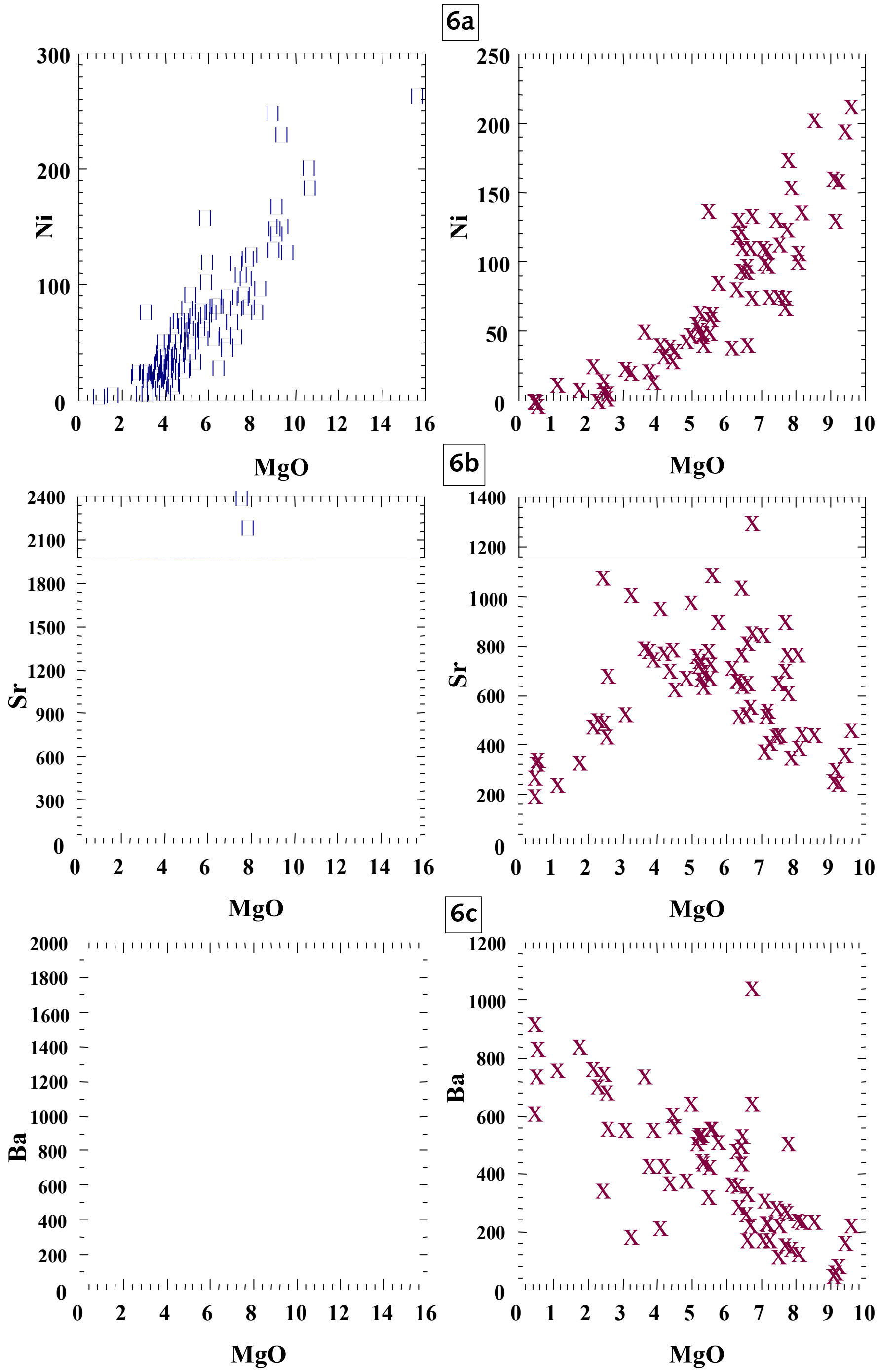

Figure 6. Plots of MgO versus three trace elements, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. MgO values are in weight percent; trace-element values in parts per million (ppm).

the groundmass feldspar phase, confirming potassium feldspar's role as a near-solidus phase. The only exception can be found in some latest Miocene-earliest Pliocene mafic trachybasalt lavas found in the drainage of the South Fork Little Butte Creek in both the Robinson Butte and Brown Mountain quadrangles. In these lavas, small (0.4-1.2 mm) phenocrysts of magnesian biotite, which is also a potassium-rich mineral, occur together with olivine and clinopyroxene. Many biotite crystals show strong evidence of dehydration and oxidation reactions, which most likely occurred during transit to the Earth's surface. Potassium feldspar is still confined to groundmass status in these lavas, too.

CONCLUSION

Detailed K-Ar geochronology is a necessary tool for all field geologists who are attempting to work out the geologic history of specific volcanic regions. Since individual lava flows extruded in volcanic regions where compressive stress is strong tend to be less voluminous than their counterparts extruded in volcanic regions undergoing extension, seldom is an area completely covered by a blanket of lava as in the case of some of the Columbia River basalt flows. Consequently, accurate volcanic stratigraphy is frequently difficult to determine due to the lack of convincing layer-on-layer deposition. Hence the need for a tool determining absolute age such as the K-Ar method, which makes more exact comparisons and a more defined stratigraphic column possible.

What are the large-scale unanswered questions with regard to the regional volcanic geology? Ascertaining whether or not the 10-million-year hiatus in volcanism documented here for the region to the west and southwest of Mount McLoughlin exists over a larger area is a good place to begin. What was the ultimate cause of the cessation of volcanism approximately 17 million years ago and what set it off again six to eight million years ago? What was the nature of the initial volcanic eruptions that put an end to the gap in volcanic activity? Are the initially extruded lavas consistently trace-element-enriched trachybasalts as identified in this study? Why is there a relatively quick changeover to a more typical orogenic suite of volcanic rocks soon after the renewal of volcanism?

From a more petrological point of view: Would studying the strontium, neodymium, and lead radiogenic isotopic systems and the oxygen nonradiogenic system as function of sample age provide valuable insights into the origin of these lavas within the Earth's lower crust and/or upper mantle? For instance, the late Quaternary, very fine grained two-pyroxene andesites extruded from Brown Mountain have an $^{87}Sr/^{86}Sr$ mean ratio of 0.70367 ± 1, while the time-correlative, quite porphyritic two-pyroxene basaltic andesite lavas from Mount McLoughlin have a mean value of 0.70324 ± 1 (Mertzman, unpublished data). These two large volcanic edifices are nearest neighbors in the Cascades of southern Oregon. The data speak to the strontium-isotopic heterogeneity of the crust/mantle region beneath this one small region. What other isotopic variations exist, when the entire spectrum of bulk compositions is examined? Further, do the isotopic signatures for nearly primary, little fractionated basalts vary over time and if so, how? What do such data tell us about regional magma generation?

The data reported in this paper provide a substantial time-stratigraphic framework upon which a number of more detailed studies can be based. Many unanswered questions with regard to the volcanic geology of southern Oregon and northern California remain, a sufficient number to keep interested geologists busy for decades.

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many. We visited, and some time after my inquiries, the Baker Regional Geologist, Mark Ferns, wrote and asked me if I might be interested in applying for membership on the Board."

Seymour's interest in DOGAMI's work has many facets. She says about herself: "In college, I had many friends who were interested in geography and geology and I went on field trips with them. I am interested in landslides from experience along Oceanside coastline; in oil and gas since drafting the oil and gas severance tax bill; in water, underground water channels, and geothermal resources from ranch and legislative experience and drafting legislation; in gravel excavation also from ranch and legislative experience; in gold mining in Baker County; and in geologic mapping for purposes of information needed for environment and energy conservation and to prevent injury and property damage. I am interested in natural resource conservation but believe that economic development can be continued compatibly with some resource development. I am also interested in funding issues related to compatible conservation and development, as well as disaster preparation and prevention issues." ☐

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Klaus K. Neuendorf, Editor

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Released August 3, 2000:

Earthquake-induced slope instability: Relative hazard map, western portion of the Salem Hills, Marion County, Oregon, by R.J. Hofmeister, Y. Wang, and D.K. Keefer. Interpretive Map Series IMS–17, scale 1:24,000, $12.

Earthquake-induced slope instability: Relative hazard map, eastern portion of the Eola Hills, Polk County, Oregon, by R.J. Hofmeister and Y. Wang. Interpretive Map Series IMS–18, scale 1:24,000, $12.

Earthquake-induced slope instability: Methodology of relative hazard mapping, western portion of the Salem Hills, Marion County, Oregon, by R.J. Hofmeister, Y. Wang, and D.K. Keefer. Special Paper 30, 73 p., $15.

Released August 24, 2000:

Tsunami hazard map of the Gold Beach area, Curry County, Oregon, by G.R. Priest, Myers, E., Baptista, A., and Kamphaus, R.A. Interpretive Map Series IMS–13, 3 p. text, map scale 1:12,000.

Released August 24, 2000:

Penrose Conference 2000, Great Cascadia Earthquake Tricentennial. Program summary and abstracts, compiled by J.J. Clague, B.F. Atwater, K. Wang, Y. Wang, and I. Wong. Special Paper 33, 156 p., $15. ☐

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Places to see—Recommended by the Oregon Department of Geology and Mineral Industries:

Moccasin Lake in the Eagle Cap Wilderness of the Wallowa Mountains, with Eagle Cap in the background.

This tarn lake, filling an ice-gouged rock basin, lies in the center of the Wallowas at an elevation of nearly 7,500 ft. It is one of the many marks left from the carving done by Pleistocene ice, which covered a large portion of these "Oregon Alps." Nine large glaciers radiated out from here during the ice age between two million and 10,000 years ago. The rock at the core of the Wallowa Mountains is the Wallowa batholith, granite from a magma upwelling in Late Jurassic and Early Cretaceous time (between 160 million and 120 million years ago) that also cemented together a great diversity of still older, "exotic" terranes—blocks of the Earth's crust that traversed the Pacific Ocean and attached themselves to the (then) edge of the North American continent.

Access: One road leads to within about 7 mi of this area: from State Route 82 south along the Lostine River. Trails converge here from several directions, including a trailhead near the south end of Wallowa Lake. This is not only a wilderness area but the most precious inner core of it, protected by special regulations. Before any visit one should definitely consult with the U.S. Forest Service Visitor Center in Enterprise, (541) 426-4978. A map of the Eagle Cap Wilderness Area is available from DOGAMI's Nature of the Northwest Information Center (see page 103).