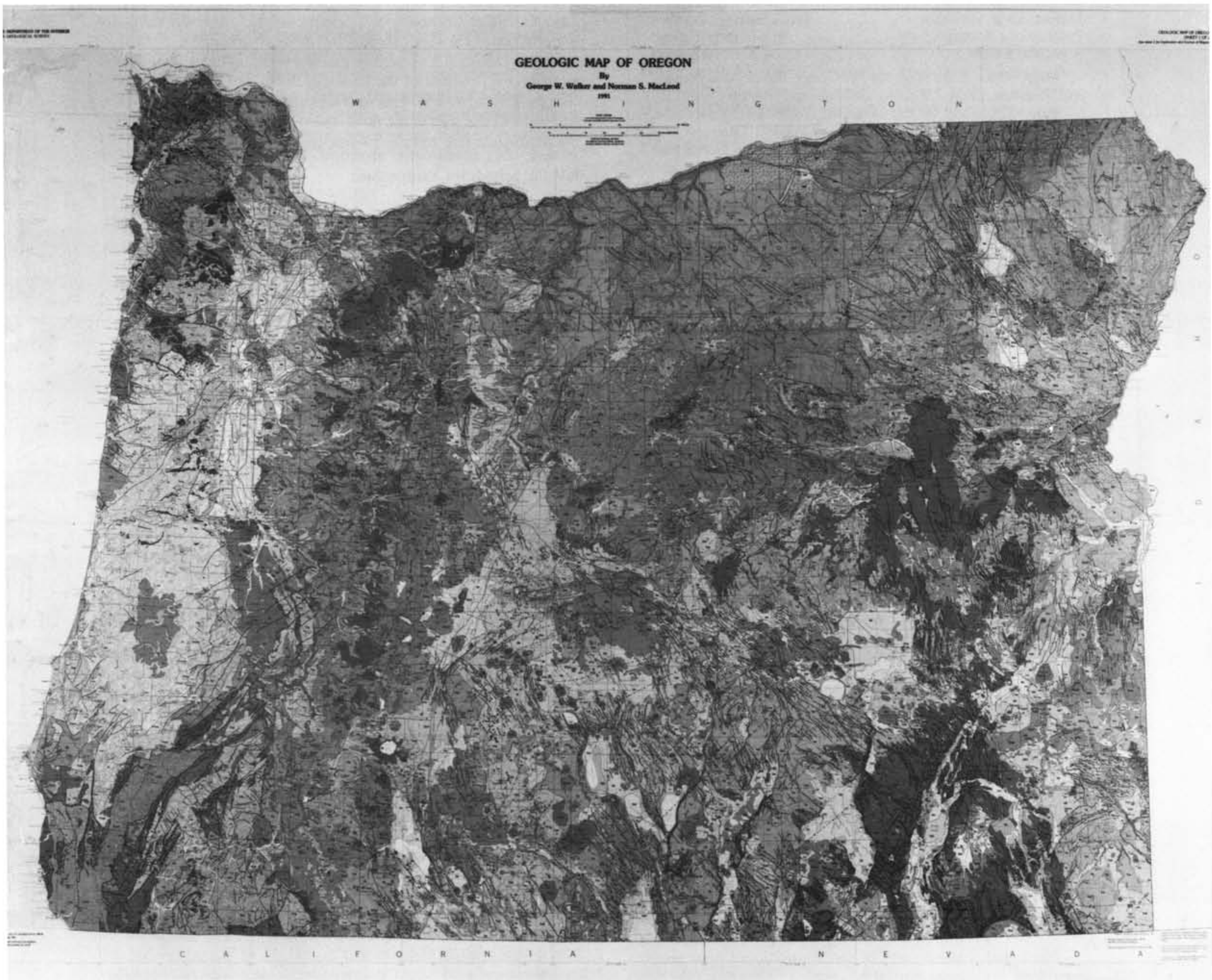
OREGON GEOLOGY

published by the
Oregon Department of Geology and Mineral Industries

VOLUME 54, NUMBER 5 SEPTEMBER 1992



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The Mount Angel Fault: Seismic-Reflection Data and the August 1990 Earthquakes
and
Geothermal Exploration in Oregon, 1991

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(ISSN 0164-3304)

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Published bimonthly in January, March, May, July, September, and November by the Oregon Department of Geology and Mineral Industries. (Volumes 1 through 40 were entitled *The Ore Bin*.)

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Information for contributors

Oregon Geology is designed to reach a wide spectrum of readers interested in the geology and mineral industry of Oregon. Manuscript contributions are invited on both technical and general-interest subjects relating to Oregon geology. Two copies of the manuscript should be submitted, typed double-spaced throughout (including references) and on one side of the paper only. If manuscript was prepared on common word-processing equipment, an ASCII file copy on 5-in. diskette may be submitted in addition to the paper copies. Graphic illustrations should be camera-ready; photographs should be black-and-white glossies. All figures should be clearly marked, and all figure captions should be typed together on a separate sheet of paper.

The style to be followed is generally that of U.S. Geological Survey publications. (See the USGS manual *Suggestions to Authors*, 7th ed., 1991 or recent issues of *Oregon Geology*.) The bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Names of reviewers should be included in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, news, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office of the Oregon Department of Geology and Mineral Industries.

Cover photo

Black-and white-reprint of the multicolored new geologic map of Oregon. A brief description of the new map is elsewhere on this page. The article beginning on page 105, on the history of geology in Oregon, includes a reproduction of the earliest geologic map of the entire state. See page 111 for an interesting illustration of the development of geologic knowledge about Oregon.

OIL AND GAS NEWS

Mist Gas Field activity

During May, June, and July, Nahama and Weagant Energy Company of Bakersfield, California, drilled three wells at the Mist Gas Field, Columbia County. Columbia County 23-31-65 is located in SW¼ sec. 31, T. 6 N., R. 5 W., and reached a total depth of 2,272 ft; Columbia County 32-33-75 is located in SE¼ sec. 33, T. 7 N., R. 5 W., and reached a total depth of 2,548 ft; Adams 31-34-75 is located in NE¼ sec. 34, T. 7 N., R. 5 W., and reached a total depth of 3,413 ft. All three wells are currently suspended. Taylor Drilling Company of Chehalis, Washington, was the drilling contractor for these wells.

During July and August, Nahama and Weagant Energy conducted an extended flow test of the CER 14-26-64 well, located in SW¼ sec. 26, T. 6 N., R. 4 W. This well was drilled during 1991 and is the easternmost gas well in the field. The flow test is used to determine the production rate and gas volume for the well.

NWPA schedules symposium

The Northwest Petroleum Association (NWPA) has scheduled the 1992 annual field symposium for October 11-13 in Lincoln City, Oregon. The theme for the symposium is "New Exploration Concepts and Opportunities for the Pacific Northwest." The symposium chairman is Bob Deacon, consulting geologist. Information can be obtained from NWPA, P.O. Box 6679, Portland, OR 97228-6679. □

New state geologic map available

The Oregon Department of Geology and Mineral Industries (DOGAMI), in cooperation with the U.S. Geological Survey (USGS), announces the release of the complete state geologic map for Oregon. This map is at a scale of approximately ⅛ inch to the mile (1:500,000) and is the product of 15 years of cooperative reconnaissance and compilation geologic mapping by DOGAMI, the USGS, and the Oregon Department of Higher Education.

The new multi-color map presents the entire state on a single map sheet approximately 42 by 54 inches in size. It supersedes and updates two earlier, now out-of-print USGS/DOGAMI reconnaissance geologic maps of the east and west halves of the state. A separate sheet contains explanations of rock units and bibliographic information.

Because of its scale and size, the map is necessarily general in its depiction of the state's geology. Therefore, it is primarily useful as a basis for more meaningful geologic mapping at larger scales and for planning priorities of more detailed geologic map projects by DOGAMI. Current efforts in the state are aiming at geologic mapping at the scale of 2½ inches to the mile (1:24,000). This scale allows a degree of detail that lends itself most readily to practical problem solving in such applications as environmental protection, public safety, economic development, and resource management.

The new map is now available at the Nature of Oregon Information Center, Suite 177, State Office Building, 800 NE Oregon Street # 5, Portland, OR 97232, phone (503) 731-4444. The price is $11.50 (rolled map only); if it is to be mailed, add $3.00 for the mailing tube. Orders may be charged to credit cards by mail, FAX, or phone. FAX number is (503) 731-4066. Orders under $50 require prepayment except for credit-card orders. Purchase by mail and over the counter is also possible at the DOGAMI field offices: 1831 First Street, Baker City, OR 97814, phone (503) 523-3133; and 5375 Monument Drive, Grants Pass, OR 97526, phone (503) 476-2496. □

Geothermal exploration in Oregon, 1991

by George R. Priest, Oregon Department of Geology and Mineral Industries

INTRODUCTION

Geothermal exploration activity decreased in 1991 relative to 1990. No holes were drilled, and the amount of leased federal land continued to decline. The total amount of federal land leased for geothermal resources has declined steadily since the peak in 1983.

DRILLING ACTIVITY AND RESULTS

Figure 1 shows the number of geothermal wells drilled and geothermal drilling permits issued from 1970 to 1991. Figure 2 shows the same information for geothermal prospect wells (depths <610 m). Table 1 lists the Oregon Department of Geology and Mineral Industries (DOGAMI) permits and the geothermal drilling activity for 1991. Two new permits were issued, both for geothermal wells proposed by Anadarko Petroleum in the Borax Lake area of the Alvord Desert.

LEASING

The amount of leased federal land, while still decreasing, stopped the steep slide that occurred in previous years, changing by only a few percent from 1990 to 1991 (Table 2; Figure 3). Leasing revenue rose by about 35 percent, primarily as a result of a sale of competitive (KGRA) leases (Figure 4).

KNOWN GEOTHERMAL RESOURCE AREA (KGRA) SALES

Of the KGRA lands at Newberry that remained available after creation of the Newberry National Volcanic Monument, 6,822.19 acres were offered for lease on June 20, 1991. Bids totaling $71,940 were received for 3,513.21 acres of this land. Eagle Exploration and CE Exploration obtained lease positions.

REGULATORY ACTIONS

Drilling in the Alvord Desert by Anadarko Petroleum Corporation is still stalled pending review of appeals filed by various environmental organizations concerned about potential threats to the Borax Lake chub. No further exploration will occur until the Interior Board of Land Appeals makes a decision.

DIRECT-USE PROJECTS

The direct use of relatively low-temperature geothermal fluids continued in 1991 at about the same level as over the last several years. Most of the activity is centered in Klamath Falls and Vale, including the district heating system in Klamath Falls and the Oregon Trail Mushroom Company, the grain-drying facility of Ag-Dryers, and other direct users in Vale. Other users continue to operate in Ashland, La Grande, and Paisley. In La Grande, a geothermally heated industrial park will be developed on county land east of the Hot Lake resort. Planning and coordination of this park are being handled through Union County Economic Development.

USGS ACTIVITIES

U.S. Geological Survey (USGS) work related to geothermal-energy research in Oregon during 1991 was concentrated mainly at Newberry caldera, Mount Hood, and Crater Lake volcano, and in the Bend area. In addition, hydrothermal fluid flow has been analyzed on a regional scale in the central Oregon Cascade Range.

Dave Morgan and Marshall Gannett designed and initiated a monitoring program for the collecting baseline hydrologic data at Newberry caldera. These data, which are necessary prior to any future permitting of geothermal development adjacent to the newly formed Newberry National Volcanic Monument, will include water

Table 1. *Geothermal permits and drilling activity in Oregon, 1991*

Permit no.	Operator, well, API number	Location	Status, proposed total depth (m)
116	Calif. Energy Co. MZI-11A (deepening) 36-035-90014-80	SW¼ sec. 10 T. 31 S., R. 7½ E. Klamath County	Abandoned; confidential.
117	Calif. Energy Co. MZII-1 (deepening) 36-035-90015-80	SE¼ sec. 13 T. 32 S., R. 6 E. Klamath County	Abandoned; confidential.
118	GEO-Newberry N-1 36-017-90013	SW¼ sec. 25 T. 22 S., R. 12 E. Deschutes County	Unlawfully abandoned; 1,387.
125	GEO-Newberry N-2 36-017-90018	SW¼ sec. 29 T. 21 S., R. 12 E. Deschutes County	Unlawfully abandoned; 1,337.
126	GEO-Newberry N-3 36-017-90019	NE¼ sec. 24 T. 20 S., R. 12 E. Deschutes County	Unlawfully abandoned; 1,220.
131	GEO-Newberry N-4 36-017-90023	NE¼ sec. 35 T. 21 S., R. 13 E. Deschutes County	Unlawfully abandoned; 703.
132	GEO-Newberry N-5 36-017-90024	NE¼ sec. 8 T. 22 S., R. 12 E. Deschutes County	Unlawfully abandoned; 988.
139	Oxbow Power Corp. 77-24 36-031-90001	SE¼ sec. 24 T. 13 S., R. 7½ E. Jefferson County	Suspended; 928.
144	Anadarko Petroleum 52-22A 36-025-90004	NE¼ sec.22 T. 37 S., R. 33 E. Harney County	Canceled.
145	Anadarko Petroleum 66-22A 36-025-90005	SE¼ sec. 22 T. 37 S., R. 33 E. Harney County	Canceled.
146	Calif. Energy Co. MZI-1 36-035-90020	NW¼ sec. 3 T. 30 S., R. 6 E. Klamath County	Canceled.
147	Calif. Energy Co. CE-BH-7 36-017-90032	NW¼ sec. 20 T. 17 S., R. 10 E. Deschutes County	Suspended; confidential.
148	Anadarko Petroleum 25-22A 36-025-90006	SW¼ sec. 22 T. 37 S., R. 33 E. Harney County	Canceled.
149	Calif. Energy Co. CE-BH-5 36-017-90033	NW¼ sec. 25 T. 16 S., R. 9 E. Deschutes County	Canceled.
150	Anadarko Petroleum 55-22A 36-025-90007	NW¼ sec. 22 T. 37 S., R. 33 E. Harney County	Permitted; 762.
151	Anadarko Petroleum 66-22A 36-025-90008	SE¼ sec. 22 T. 37 S., R. 33 E. Harney County	Permitted; 762.

analyses from the caldera lakes, Paulina Creek, wells in the caldera, and hot springs. Additional future monitoring may include more precisely measured evaporation and recharge rates, air-borne infrared surveys to monitor heat flux at thermal features, heat-flow measurements from the floors of East and Paulina Lakes by probes dropped into muddy bottom sediments, systematic sampling of Paulina Creek to determine extracaldera solute flux, and monitoring of outlying wells on the volcano's west side.

John R. Evans (USGS) and Jay J. Zucca (Lawrence-Livermore Laboratory) wrote a chapter, including results of active source high resolution seismic tomography from Newberry volcano, for a book on seismic tomography (Evans and Zucca, 1992). The authors infer that the young silicic magma chamber has largely solidified. They directly image a probable, large, two-phase geothermal reservoir (boiling water) beneath the southern and western ring fracture, and extending west of the caldera.

Craig Weaver and Dan Dzurisin are seeking to establish more complete seismic coverage and leveling data, both of which might be critical for recognizing pumpage-induced seismicity or ground subsidence.

Terry Keith and Keith Bargar completed two reports for U.S. Geological Survey Bulletins on (1) hydrothermal alteration of geothermal drill holes from the flanks of Newberry volcano and within the caldera, and (2) hydrothermal alteration of geothermal drill holes and rock outcrops near Mount Hood.

Bargar also examined hydrothermal alteration in selected samples from the SUNEDCO 58-28 drill hole near Breitenbush Hot Springs. Fluid-inclusion analyses from calcite and anhydrite cleavage chips at several depths within this drill hole allowed the determination of minimum homogenization temperatures. For nine samples from below 800-m depth, temperatures plotted fairly close to the temperature-depth curve reported by Blackwell and others (1986). Maximum homogenization temperatures for most samples are less than 150°C.

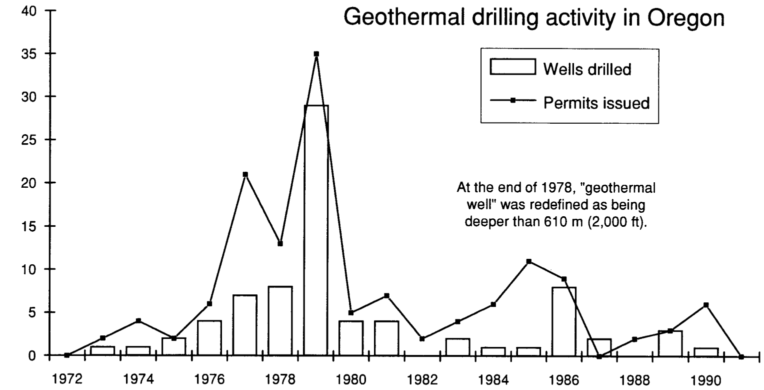

Figure 1. Geothermal well drilling activity in Oregon since 1972.

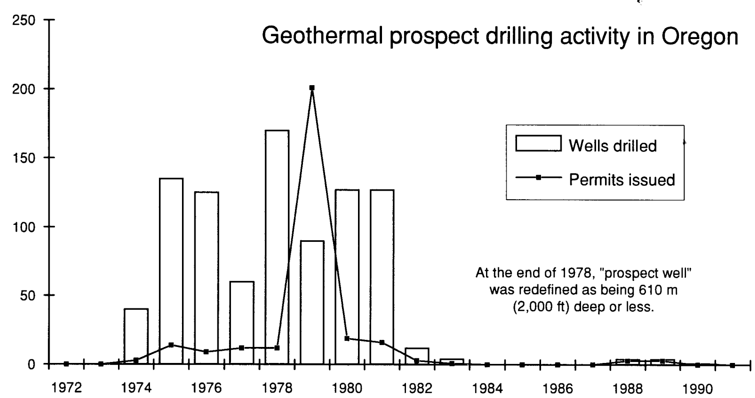

Figure 2. Geothermal prospect well drilling activity in Oregon since 1972.

Crater Lake studies by Charlie Bacon resulted in the completion of several manuscripts now being published in scientific journals: (1) partially melted granodiorite blocks ejected in the caldera-forming eruptions; (2) pre-eruptive volatile contents of Holocene silicic magmas; (3) petrology of pre-Mazama rhyodacite lavas; and (4) distribution of lithic clast types in deposits of the climactic eruption. A short field season was devoted to completing sampling of the southern caldera walls in order to finalize geologic panoramas.

A diverse study of Mount Hood and surrounding area continues, with emphasis mainly on hydrology and volcanic hazards. Willie Scott, Jim Vallance, and Tom Pierson concentrated on stratigraphic studies and mapping of late Pleistocene and Holocene pyroclastic-flow and debris-flow deposits on the south and west flanks of Mount Hood and in the Sandy River drainage. Cynthia Gardner began a paleomagnetic study of the three most recent eruptive periods. Bob Tilling and Joe Arth obtained strontium and neodymium isotope analyses from several samples—main-stage lavas as well as post-glacial eruptive products—previously analyzed for major and trace elements by Craig White (Boise State University). These reconnaissance data demonstrate a remarkable uniformity in isotopic composition, which needs to be confirmed by a broader sampling of the volcano's output through time and from rocks on all flanks. Dave Sherrod mapped pre-Mount Hood strata north of the volcano, where three previously unrecognized faults cut Pleistocene andesite and basalt on Blue Ridge. The faults strike north to north-northwest and have displacements of less than 60 m, but they probably have been inactive in Holocene time.

Sherrod's previous mapping of a part of the Cascade Range from south of the Three Sisters to Crater Lake was published as a full-color map (Sherrod, 1991). Potassium-argon ages obtained for this publication indicate that the age of Mount Thielsen is about 0.3 Ma. In view of the amount of erosion at Thielsen, it seems likely that Diamond Peak and Mount Bailey are younger than about 0.1 Ma.

Middle Pleistocene pyroclastic deposits in the Bend area received attention, because their relatively youthful age and silicic composition indicate magma-related geothermal systems that might still retain heat. A newly published map shows the distribution of part of these deposits (Mimura, 1992). Additional work to better secure the age of the Bend deposits was conducted by Cynthia Gardner and Andrei Sarna-Wojcicki, who, in conjunction with Brittain Hill (Oregon State University) and Rob Negrini (California State University, Bakersfield), determined the paleomagnetic signatures of the Bend deposits and presumably correlative distal ash beds. The paleomagnetic study (Gardner and others, 1992) supports earlier geochemical evidence correlating the Shevlin Park and Desert Spring Tuffs near Bend with Summer Lake (JJ) and Rye Patch Dam ash beds, respectively. Although the Shevlin Park Tuff and the Summer Lake ash bed have virtually identical paleomagnetic directions, which is strong evidence for their deposition during the same eruptive episode, present age interpretations differ by 200,000 years.

In an effort to better understand circulation of hydrothermal waters in the Cascade Range, Bob Mariner, Bill Evans, and Steve Ingebritsen have begun examining iodine-129 concentrations in some of the hot-spring waters. An Eocene age for the iodine is indicated by a sample collected from John Bigelow's thermal well at Belknap Hot Springs. When considered with the anomalously high N_2/Ar ratio of the dissolved gases and the ^{15}N-enriched nature of the gases, these data may indicate the presence of Eocene marine

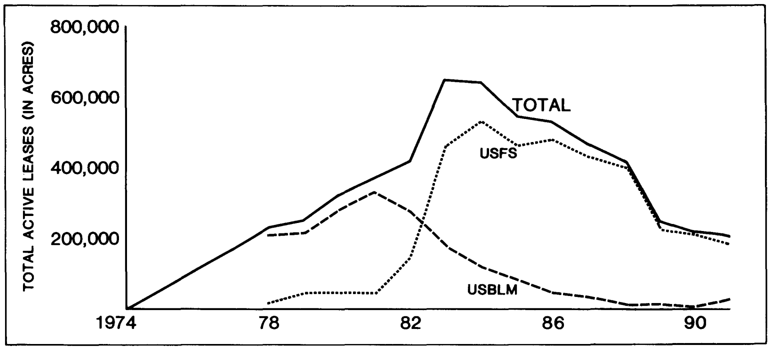

Figure 3. Active geothermal leases on federal lands in Oregon from the inception of leasing in 1974 through December 1991.

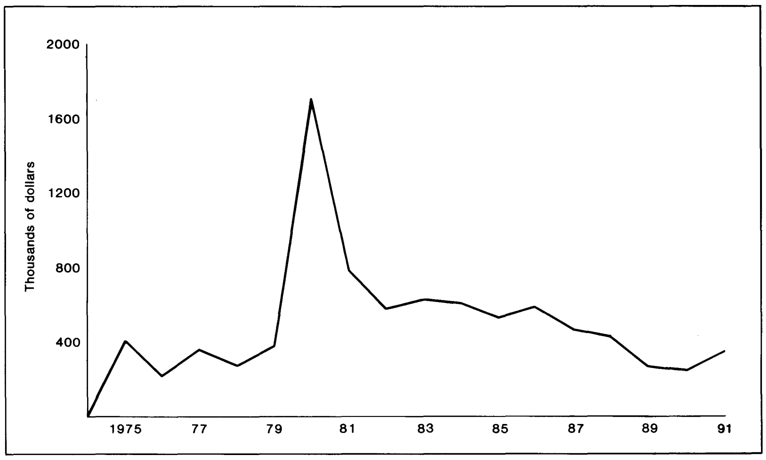

Figure 4. Federal income from geothermal leases in Oregon from the inception of leasing in 1974 through December 1991.

rocks beneath the High Cascades. The preliminary nature of these findings is stressed, however; another sample is being analyzed, and several more sites may need sampling before the age interpretation can withstand scrutiny.

Results of Ingebritsen's modeling of fluid flow from the High Cascades westward into the Western Cascades have been summarized (Ingebritsen and others, 1992), and a fuller data set and description of the hydrologic and geologic setting are available to support these interpretations (Ingebritsen and others, 1991). Four drill holes were completed in 1991 to test geothermal gradients. They range in depth from 90 to 150 m and were sited near the boundary between the Western Cascade and High Cascade physiographic subprovinces to better constrain the heat-flow map and perhaps resolve some of the controversy regarding location of heat sources. Publication of the heat-flow values is awaiting thermal conductivity measurements.

Table 2. *Geothermal leases in Oregon in 1991*

Types of leases	Numbers	Acres
Federal leases in effect:		
Noncompetitive, USFS	126	181,074.65
Noncompetitive, USBLM	2	942.79
KGRA, USFS	10	5,533.19
KGRA, USBLM	7	16,465.12
Total leases issued (since 1974):		
Noncompetitive, USFS	369	693,839.97
Noncompetitive, USBLM	266	406,157.79
KGRA, USFS	17	17,357.80
KGRA, USBLM	62	118,307.85
Total leases relinquished (since 1974):		
Noncompetitive, USFS	243	512,765.32
Noncompetitive, USBLM	264	405,215.00
KGRA, USFS	7	11,824.61
KGR, USBLM	55	101,842.73
Lease applications pending	97	—

DOGAMI APPLIED RESEARCH

Analysis of geophysical and geologic data from the Santiam Pass 77-24 drill hole, drilled for a scientific drilling program administered by DOGAMI and completed in 1990, was aimed at a better understanding of the geologic history and regional heat flow near the axis of active volcanism in the Cascades. A final temperature log in 1991, about one year after drilling, showed continued cooling of the hole by cold water entering at a depth of 150 m (Figure 7). Whereas large-volume, rapid flow of cold ground water occurs above 180 m, rock alteration greatly curtails this flow at greater depths (Hill and others, 1991). The low temperatures in the continuous temperature-depth curves from 180 m to 900 m are caused by flow of the cold shallow water that descends down the open borehole and exits at about 900 m (Hill and others, 1991). This effect is apparent when the bottom-hole temperatures taken during drilling are compared with the cooler temperatures measured after drilling (Figure 7). Heat flow measured below 718 m is 86-204 mW/m^2, bracketing the average of 105 mW/m^2 for the High Cascade Range (Hill and others, 1991). Heat flow and gradients inferred from the bottom-hole temperatures taken during drilling in the upper part of the hole are generally below average for the High Cascade Range.

This hole and nearby temperature gradient holes are not deep enough to determine with certainty the regional thermal structure or fluid flow conditions. However, it is clear that the anomalously low gradients in the upper part of the Santiam Pass hole are the result of infiltration of cold meteoric water. This masking effect of cold ground water at shallow depths in young volcanic terrains is well known and apparently extends to great depths at the crest of the High Cascades in central Oregon.

Those interested in conducting scientific studies of the drill hole or samples are encouraged to contact this author for further information. Plugging of the hole has been delayed by a year so that the hole will be accessible for experiments in the early summer of 1992, but it will be plugged and abandoned thereafter. Drill core and cuttings from the hole are stored at Oregon State University (OSU) in Corvallis. Contact Brittain E. Hill, Department of Geosciences, Oregon State University, Corvallis, OR 97331-5506 (phone 503-737-1201) for access to cores and cuttings.

Core from four temperature-gradient holes was donated to DOGAMI by UNOCAL in 1988 and is currently available for use in research projects. The UNOCAL holes, drilled in the central High Cascades (see Figure 5), reached depths ranging from 250 to 610 m. No temperature data are publicly available from the holes, but detailed lithologic logs of the diamond cores have been produced as part of DOGAMI's scientific drilling program. The core is stored at Oregon State University, and representative samples are available for inspection at DOGAMI.

In late 1991, DOGAMI began working collaboratively with the Bonneville Power Administration (BPA) on a project aimed at reducing exploration costs in young volcanic terrain and updating geothermal resource estimates in the Oregon Cascades. DOGAMI will study existing temperature-depth and geophysical

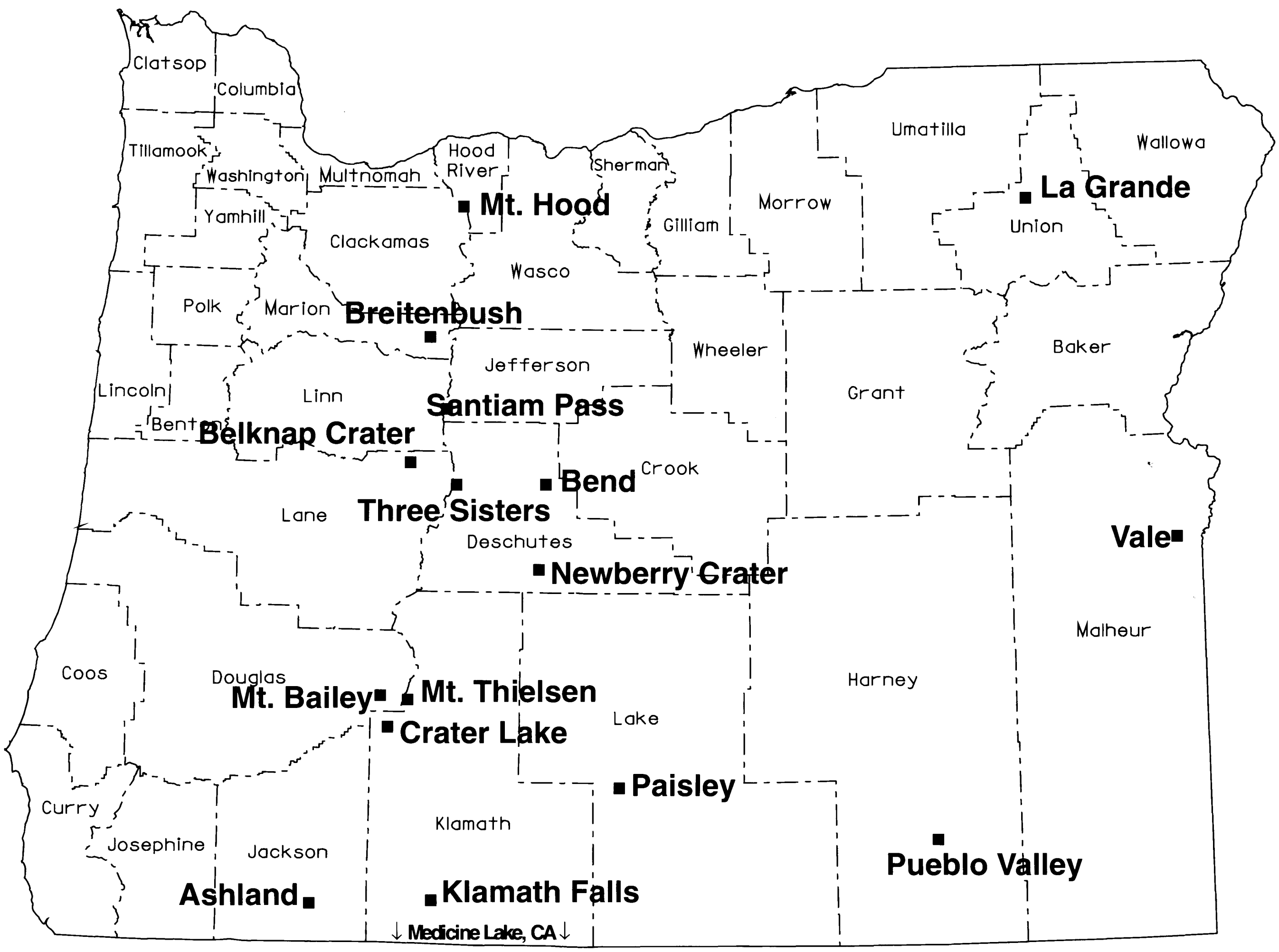

Figure 5. Major areas of geothermal activity in Oregon during 1991 that are discussed in the text.

data from young volcanic areas of Oregon to determine whether a means can be developed to predict the thickness of the cold, isothermal part of the volcanic pile known as the "rain curtain" or "cold water blanket." Exploration costs could be cut significantly if it were known in advance how deep to drill to penetrate depths below this zone. At present, most companies simply drill to depths of 1.2 km to obtain reliable temperature gradients in this terrain, whereas in many cases shallower holes could be drilled for the same information.

The DOGAMI-BPA project will also update estimates of the geothermal power potential of the Oregon Cascades and Newberry volcano. Results of the study will be available in 1993.

GEO-HEAT CENTER, OIT

The Geo-Heat Center, Oregon Institute of Technology (OIT), Klamath Falls, provides geothermal developers with (1) preliminary engineering, technical and development assistance; (2) research to aid in resource and technical development problems; and (3) information and educational materials to stimulate development. This program is supported by the Geothermal Division of the U.S. Department of Energy.

During 1991, technical assistance was provided to 309 developers throughout the U.S., including 77 in Oregon. Typical users of the program were individuals, businesses, public institutions, and municipal governments. They received assistance in the forms of information and data on geothermal resource sites, preliminary engineering, review of consultant designs, equipment selection, and troubleshooting of problems after projects were completed.

In Oregon, the most significant development has been the drilling of 12 geothermal injection wells in the Klamath Falls area, many of which received technical assistance.

Geothermal direct-use research was applied in three areas to assist users with reducing costs of developing, designing and operating low-temperature projects. In 1991, these included corrosion evaluation of brazed plate heat exchangers, environmental impact of using vertical pump turbine oil, injection well design, and data acquisition techniques for well testing and long-term monitoring.

The technology transfer program is designed to provide the general public, potential users, consulting engineers and government agencies with information on geothermal resources and their uses, including geothermal heat pumps. Technical information on project designs, technology advances, new products and material selections were provided to potential users and designers of geothermal systems. This effort included publication of the *Geothermal Direct Use Engineering and Design Guidebook*, 2nd edition, and of the quarterly *Bulletin* and topical papers; arrangement of presentations and tours of geothermal facilities; and maintaining a geothermal library. For publication listings and information on the technical assistance program, contact the Geo-Heat Center, Oregon Institute of Technology, 3201 Campus Drive, Klamath Falls, OR 97601, phone (503) 885-1750.

ACTIVITIES OF OREGON DEPARTMENT OF ENERGY

In 1991, the Oregon Department of Energy (ODOE) performed geothermal research for outside organizations and provided assistance to the public. Research included work for Bonneville Power Administration (BPA) and joint work with the Washington State Energy Office (WSEO). Technical assistance includes giving talks to the public and professionals, answering siting questions and reviewing tax credit applications.

Geothermal research completed in 1991 for BPA included economic impact studies and creating a power plan database. For the first task, ODOE estimated local economic impacts of a 100-megawatt (MW) geothermal power plant project. These impact estimates were done for hypothetical projects in Deschutes and Harney Counties, Oregon. Further research for BPA includes assembling a database of existing geothermal power plants in the United States. Data on more than 60 plants is collected on a FoxBASE+/Mac™ data base program. This task is nearing completion in early 1992.

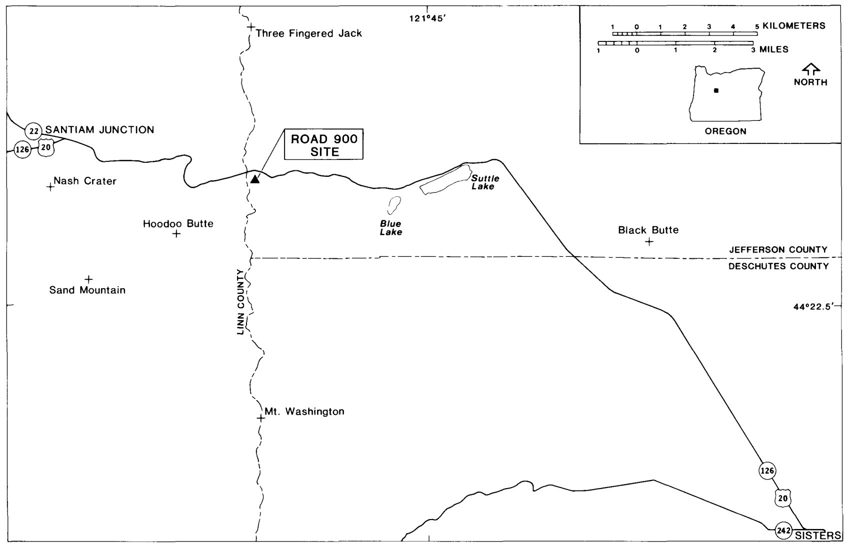

Figure 6. Location of drill site for drill hole 77-24, Santiam Pass scientific drilling project. Hole is located about 100 m south of Highway 22 on Forest Road 900.

Geothermal research in 1991 with WSEO included digital mapping of the Newberry volcano and Pueblo Valley areas, covering several 7½-minute quadrangles and including layers for cultural resources, roads, topography, and well location. This work is part of a regional effort to create renewable energy site maps for the northwestern states. One site was digitized by ODOE in 1991. The Pueblo Valley site will be digitized in 1992. The goal is to include all significant renewable energy sites in all northwestern states.

ODOE's geothermal specialist reported results of the Harney County study and published a paper for the annual Geothermal Resources Council meeting.

ODOE's geothermal specialist met several times in 1991 with state and regional environmental organizations to discuss the acceptability of future power plants. Much progress is being made in explaining alternative power supply impacts to these groups.

ODOE continues to certify geothermal tax credits for both homes and businesses in the state. ODOE's tax credit staff assumed responsibility for geothermal tax credit reviews from the geothermal program manager in 1991. Staff reviewed 130 residential tax credit applications in 1991. In addition, 123 residential systems received final certification, the prerequisite for tax credit applications. The total number of submitted geothermal business energy tax credit applications were reviewed in 1991; all were ground source heat pumps. This brings the total number of geothermal business energy tax credits issued from 1980 through 1991 to 48.

ODOE responds to public inquiries on geothermal energy development. ODOE answered 114 such inquiries in 1991. These inquiries have averaged 127 requests annually since 1984.

BONNEVILLE POWER ADMINISTRATION

The Bonneville Power Administration (BPA) issued a solicitation for three geothermal pilot projects located in the Pacific Northwest. The purpose of the solicitation is to initiate development in three areas with potential for large-scale power production. Ability to solve technical and siting problems will be tested, thus allowing regional utilities to gauge future availability of this resource.

From the seven proposals received, three 30-MW projects were selected in December for further consideration. The proposed projects are located at Newberry volcano and Vale in Oregon and at Glass Mountain (Medicine Lake area) near the Oregon border in northern California. Contract discussions will be held in early 1992. Commercial operation for all three projects is expected in 1995 or 1996.

BPA funded work by the Water Resources Division of the USGS to design a hydrologic monitoring network at Newberry volcano. The purpose of the network is to establish a baseline of predevelopment data which can be used to assess impacts of future geothermal power projects. The USDA Forest Service will cofund implementation of this design in 1992. Baseline monitoring programs will also be designed for air quality and biology in 1992. The USGS also designed a hydrologic monitoring network for the Borax Lake area.

A two-year study by Portland State University to characterize the Alvord Valley geothermal system began in 1991. The study is being done by Anna St. John and Michael Cummings.

As previously mentioned, BPA is also funding DOGAMI to perform a study to better characterize the "cold water blanket" in the

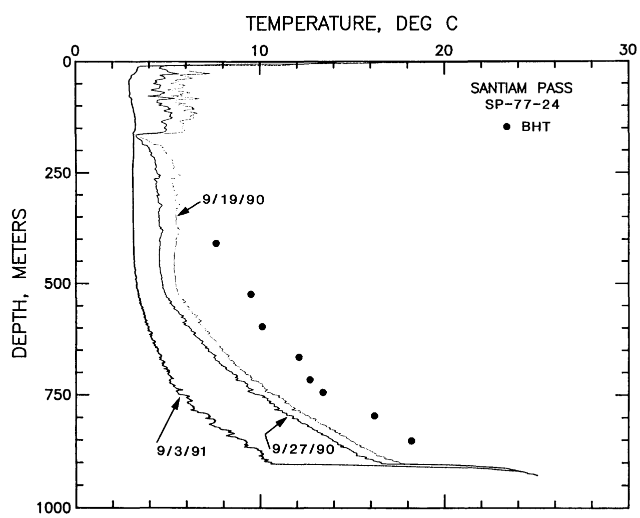

Figure 7. Temperature-depth data from Santiam Pass drill hole 77-24. Note the rapid increase of temperature near the bottom and continued cooling of the lower part of the well by cold ground water entering at about 150 m, flowing down the open hole, and exiting at about 900 m. Gradients estimated from bottom-hole temperatures (BHT) are on the order of 15°C/km between 160 and 750 m, about 50–60°C/km between 750 and 850 m, and about 100-120°C/km at the bottom of the hole (Hill and others, 1991).

Cascades and update the Casacade geothermal resource assessment. Results of these studies are expected in mid-1993.

ODOE completed studies of the economic impacts of a 100-MW geothermal project in two Oregon counties. The two resulting reports, "Economic Impacts of Geothermal Development in Deschutes County, Oregon," and "Economic Impacts of Geothermal Development in Harney County, Oregon," are available from ODOE or BPA.

"Geothermal: A Regulatory Guide to Leasing, Permitting, and Licensing in Idaho, Montana, Oregon, and Washington" was prepared by the Washington State Energy Office, in cooperation with the ODOE and the other state offices. This publication is also available from ODOE and BPA.

ACTIVITIES OF OREGON WATER RESOURCES DEPARTMENT

The low-temperature geothermal resources program of the Oregon Water Resources Department (WRD) has been assigned to Sam Allison. Sam is an Oregon Certified Engineering Geologist and a 20-year employee of WRD.

WRD's Division 230 administrative rules deal with low-temperature geothermal resources. This division contains standards and procedures for low-temperature geothermal production and injection wells and effluent disposal systems. It also contains definitions for "substantial thermal alteration" and "substantial thermal interference."

Users in the Klamath Falls area have not completely switched to injection of spent geothermal effluent. OIT is constructing a second injection well for its system. The Oregon Department of Transportation is reconstructing a geothermal well used for de-icing Esplanade Street. Several smaller users have experienced difficulties in constructing and gaining access to injection wells.

Last summer, the District Utility Services Company tested production and injection wells for a heat pump system at the Inn of the Seventh Mountain near Bend. The company is also in the process of planning a system in the Lloyd Center area of Portland.

RESEARCH BY OREGON STATE UNIVERSITY

Brittain E. Hill has completed his studies at Oregon State University (OSU) with a dissertation on silicic rocks in the Three Sisters/ Broken Top area (Hill, 1991). He works part-time for DOGAMI as the field supervisor for scientific work on the scientific drill hole at Santiam Pass. He plans to summarize the data collected there in a series of publications.

Jack Dymond and Robert Collier of the OSU Oceanography Department finished their investigation at Crater Lake National Park. Their objective was to determine whether or not geothermal inputs exist on the floor of the lake. Data collected in 1989 from a surface ship and submarine were analyzed and summarized in a final report to the National Park Service. Further information is now available from the National Park Service, Pacific Northwest Region, 83 South King Street, Suite 212, Seattle, Washington 98104.

MOUNT MAZAMA AREA (CRATER LAKE AREA)

The reader is referred to Black and Priest (1988) and Priest (1990) for a detailed history of geothermal development issues at Mount Mazama. The California Energy Company leases and the leasing unit on the flanks of Mount Mazama are officially under suspension by BLM, so no new exploration can occur on the leases and no leasing fees are being collected until the suspension is lifted. It seems unlikely that any new exploration activity will occur in the near future.

ACKNOWLEDGMENTS

Numerous individuals in government and industry cooperated in preparing this summary. Jacki Clark of the U.S. Bureau of Land Management provided the federal leasing data. Dan Wermiel of DOGAMI furnished the data on drilling permits. George Darr of BPA, Alex Sifford of ODOE, and Sam Allison of WRD provided information on their agencies' activities for the year. Paul Lienau of OIT provided information on OIT activities and the status of direct-use projects around the state. David Sherrod of the USGS supplied an account of USGS activities in Oregon. Jack Dymond of Oregon State University provided information on his study of Crater Lake.

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AIPG announces annual meeting

The American Institute of Professional Geologists (AIPG) will hold its 1992 Annual Meeting September 27-30 at South Lake Tahoe, Nevada.

Theme of the meeting will be "Geological Reason, a Basis for Decisions Affecting Society." Five technical sessions will each consist of 20-minute presentations by three invited speakers and a panel discussion with written questions from the audience. Poster sessions with both volunteered and invited contributions may follow.

Three field trips before and two after the meeting will fit with the theme (technical) sessions. Workshops are planned but still tentative. Keynote speaker will be T.S. Ary, Director of the U.S. Bureau of Mines.

For information on any matter relating to the meeting, contact Jonathan G. Price, Nevada Bureau of Mines and Geology, Mail Stop 178, University of Nevada, Reno, NV 89557-0088; phone (702) 784-6691, FAX (702) 784-1709. —*AIPG news release*

A history of geologic study in Oregon

by Elizabeth L. Orr, Librarian, and William N. Orr, Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403

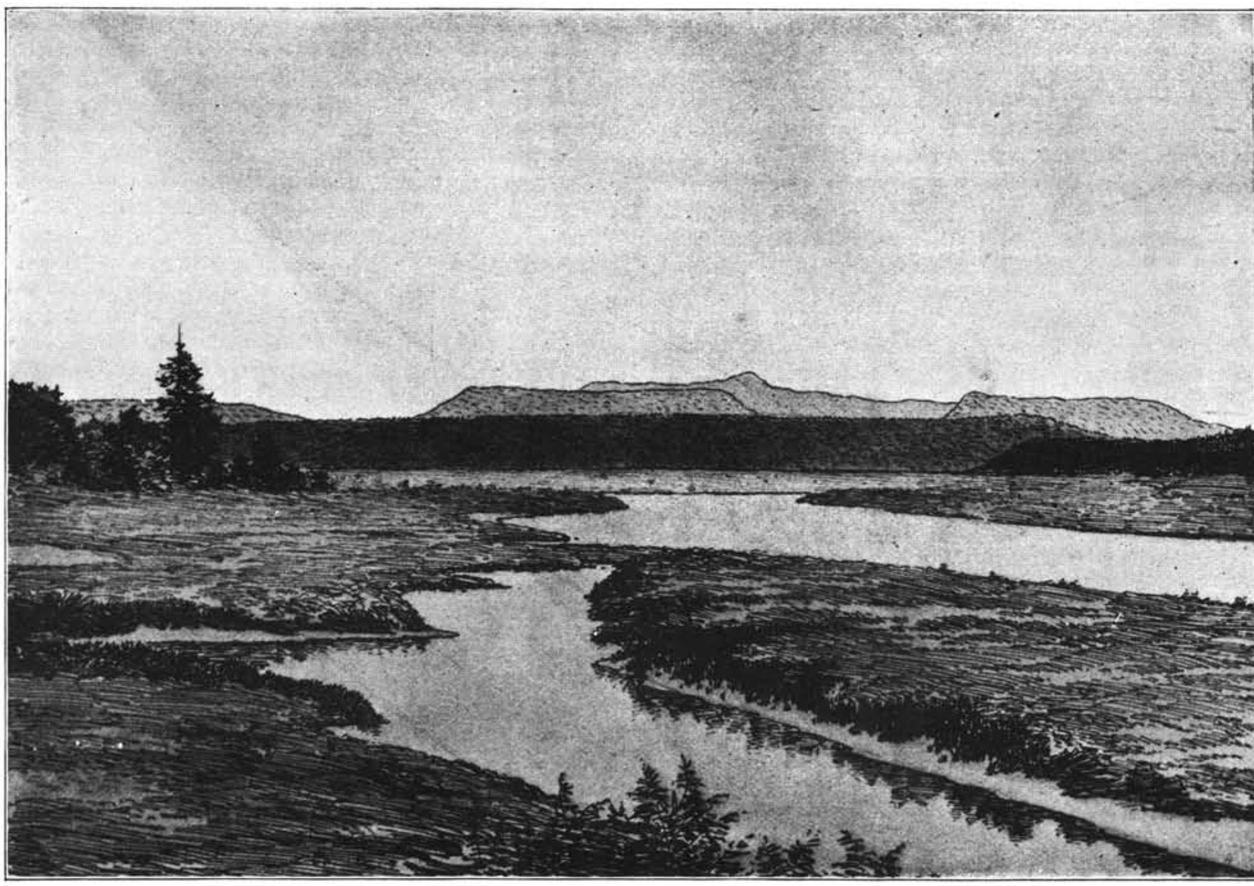
The following article is a somewhat simplified version of a chapter from the new book, Geology of Oregon, *by Elizabeth Orr, William Orr, and E.M. Baldwin, that is scheduled to be published by Kendall-Hunt later this year. —eds.*

The currency of science is the published literature. In this regard, the record of publications reflects the history of the development of geological sciences in Oregon.

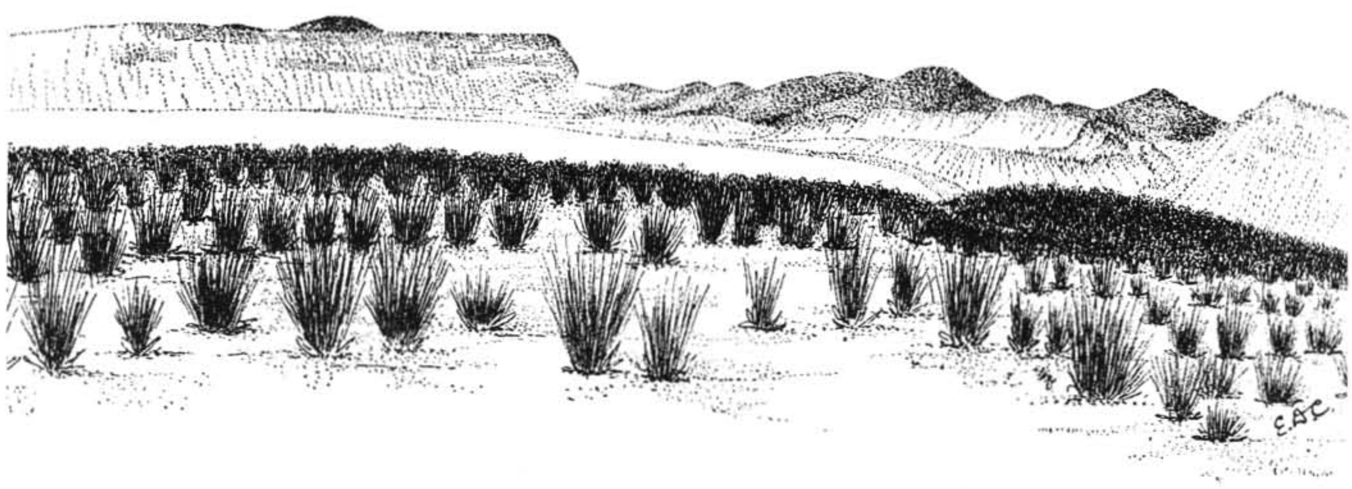
EXPLORING EXPEDITIONS

The study of geology in the Pacific Northwest began obliquely with the Lewis and Clark expedition, commissioned by President Thomas Jefferson in 1803 to explore the West to the Pacific Ocean. President Jefferson, in a lengthy letter of instructions, exhorted the party to look for the "remains and accounts of any [animals] which may be deemed rare or extinct. The mineral productions of every kind . . . [and] volcanic appearances." Jefferson was convinced that animals did not become extinct; and since he had seen bones of the giant sloth, *Megalonyx*, in Virginia, he felt that these huge beasts had migrated westward instead of disappearing from the earth. However, no one with training in geology accompanied the expedition. Thus, the resulting *History of Expedition under the Command of Lewis and Clark to the Sources of the Missouri, Thence Across the Rocky Mountains and Down the Columbia*, published in 1814, is of minimal geologic relevance.

Thirty years went by, including nearly ten years of debate in Congress, before a bill was passed on May 14, 1836, to outfit an exploring expedition to the southern polar regions as well as along the Pacific islands and the northwest coast of this continent. One purpose of this exploring expedition was to test the theory presented in Paris in 1721 and debated in America years later that holes in the polar regions led to the hollow interior of the earth. Theories such as this, combined with the desire for political and military expansion, economic gain, and scientific curiosity about western North America, led Congress to allocate funds for an expedition of six ships commanded by Charles Wilkes. The *Vincennes*, *Peacock*, *Relief*, *Porpoise*, *Sea Gull*, and *Flying Fish*



View looking toward Saddle Mountain from Youngs River below Olney, Clatsop County. Illustration from "A geological reconnaissance in northwestern Oregon," by J.S. Diller, U.S. Geological Survey 17th Annual Report, 1896.



Silver Lake, Lake County, looking southeast. Illustration from E.D. Cope, "The Silver Lake of Oregon and its region," American Naturalist, *v. 23, 1889.*

left Norfolk, Virginia, on August 17, 1838, with a team of scientists that included geologist James Dwight Dana. Dana, then 25 years of age, had taught at Yale University.

Rounding Cape Horn, the ships criss-crossed the Pacific, landing near Puget Sound on May 2, 1841. Arriving later than the others, the *Peacock*, with Dana aboard, was destroyed on a bar at the entrance to the Columbia River, but everyone survived the mishap. The Wilkes party explored between Puget Sound and Fort Vancouver before crossing the Washington Cascades and conducting surveys of the Columbia River Gorge. In August 1841, Commander Wilkes directed a party of men led by Lieutenant George Emmons to journey overland across the Klamaths to San Francisco, where they would meet with the *Vincennes* on September 30. The entire expedition returned to New York in June 1842.

Dana accompanied the San Francisco group, and his report provided a concise, geologic account of the region through which he traveled. Leaving the "Willammet" district, the party traversed the Umpqua Valley and climbed what Dana called the "Umpqua Mountains" and "a most disorderly collection of high, precipitous ridges and deep secluded valleys enveloped in forests." He was obviously referring to the Klamaths and Siskiyous in the area where the group was soon to encounter the Shasta River.

The magnificent volume 10 of the *United States Exploring Expedition during the Years 1838, 1839, 1840, 1841, 1842, under the Command of Charles Wilkes* contains Dana's "Geological Observations on Oregon and Northern California." The 145 pages contain the first formal geologic observations in this area. Unfortunately, Congress was in a parsimonious mood when it came to funding publication of the 18 volumes and 11 atlases of the expedition's final report, which took 30 years to complete, and allowed only 100 copies to be printed. For each state of the nation there was to be one copy, and the remaining copies were to go to foreign governments. Three private copies were given out, one of them to Dana, who also received $16,000 in pay for writing volumes 7, 10, 13, and 14. At the outset, 30 copies of volume 10 were destroyed by fire and never replaced. An angry Dana had 100 copies printed with his own funds and distributed them to private libraries. One of these "unofficial" copies exists in Oregon, at the University of Oregon Library in Eugene, although the accompanying atlas of illustrations is missing.

Dana observed and wrote extensively on the geologic features of Oregon, commenting on the mountain ranges bordering the oceans and the evidence of volcanic activity and describing the "abundance of basaltic rocks over its [Oregon's] surface," the granites of the Klamath area, and other rocks. The coastal rock units he listed were assigned to the Tertiary; the molluscs he collected from the Astoria Formation were subsequently identified by Timothy Conrad, renowned invertebrate paleontologist with the Philadelphia Academy of Sciences. Descriptions of fossil cetacean bones, fish, crustaceans, foraminifers, echinoids, and plants were incorporated in the report.

With his concluding remarks, Dana assessed Oregon's potential as a goal for settlers: "Although Oregon may rank as the best portion of western America, still it appears that the land available for the support of man is small . . . only the coast section within one hundred miles of the sea . . . is [at] all fitted for agriculture. And in this coast section there is a large part which is mountainous or buried beneath heavy forests. The forests may be felled more easily than the mountains, and notwithstanding their size, they will not long bid defiance to the hardy axeman of America. The middle section is in some parts a good grazing tract; the interior is good for little or nothing."

WESTERN JOURNEYS

Charles Fremont, although not a trained geologist, cannot be ignored in the history of the early geologic examination of the West. Certainly a person of curious and quixotic nature, Fremont could be called a "scientific explorer." He married Jessie Benton, daughter of the influential Senator Thomas Hart Benton from Missouri. After that, Fremont had no difficulty obtaining appointments and funding from Congress for his trips across the continent, including one in 1843 to survey the Oregon Territory. The purpose of this, his second of three western journeys, was political as well as scientific. The expedition was charged with reporting on the topography and collecting geologic and botanical specimens in order to gain any knowledge of the interior that might prove useful in substantiating the claim of the United States Government to the "valley of the Columbia."

The Fremont party of 39 men, which included the German map maker Charles Preuss, departed in the spring of 1843. Once the group had crossed the Rockies, it journeyed down the south bank of the Columbia to The Dalles. After a brief side trip to Fort Vancouver for supplies, the party explored the region east of the Cascades to Klamath Lake and south into California. Fremont's journal contains some notes of geologic interest; his main contribution, however, was a collection of some fossil plant specimens from the Cascades. These he sent to James Hall, New York State paleontologist, along with a map of Oregon and California.

The same year in which Congress restricted Dana's volume 10 to 100 copies, 1848, it generously funded the publication of 20,000 copies of Fremont's "Geographical Memoir upon Upper California" and Preuss' "Map of Oregon and Upper California." Most of the map was, in actuality, a synthesis of data on Oregon and California from previous trips and other sources. An earlier "Map of the Exploring Expedition to the Rocky Mountains in the Year 1842 and to Oregon and California in the Years 1843-4," published by Preuss in 1845, was well drawn and accurate, but the Willamette Valley and the Coast Range were left blank. These maps, as well as others of this period, were topographic only and lacked geology.

PACIFIC RAILROAD SURVEYS, 1853-1855

In 1853, an act of Congress was once again instrumental in furthering geologic knowledge of the Pacific Northwest. The act was designated to employ "such portion of the Corps of Topographical Engineers . . . to make such explorations and surveys . . . to ascertain the most practical and economical route for a railroad from the Mississippi River to the Pacific Ocean." Congress budgeted the sum of $150,000 for this project and sent out "a mineralogist and geologist, physician, [and] naturalist" under the leadership of the Army Corps of Topographical Engineers. These explorations, known as the Pacific Railroad Surveys, were conducted from 1853 to 1855, and the geologists employed to survey Oregon and northern California were John Evans and John S. Newberry.

The first Pacific Railroad Survey funded by the U.S. Government set out from St. Paul in 1853. John Evans was hired as the geologist of the expedition that was overseen by Isaac Ingalls Stevens, newly appointed Governor of the Washington Territory. Evans, whose training was in medicine, was charged with the geological reconnaissance of Oregon. Once in Oregon Territory, Evans began his work on the Columbia River, exploring much of Washington but eventually finding himself 150 miles south, on the Umpqua River. He then traversed to Empire, near Coos Bay, before returning north by way of the Willamette Valley and Vancouver. Unfortunately, the "Geological Survey of Oregon and Washington Territories" by Evans was never received by Stevens and was thought to have been lost. A partial log of Evans' trip was found 50 years later and deposited at the Smithsonian. The log was never officially published, although typewritten copies entitled "Route from Fort Vancouver, 1854-56" are available. With many gaps, however, and with references in the notes only to the lithology, the report is of limited geologic value.

Newberry, a professor of geology and chemistry of the School of Mines at Columbia College, New York, was titled the geologist and botanist of the survey that left San Francisco in 1855. This party was under the leadership of Lieutenant R.S. Williamson and Lieutenant Henry L. Abbot of the Topographical Engineers.

Once over the Sierra and the Klamath Mountains, the men spent a month crossing and recrossing the Cascades near the Three Sisters. Newberry was able to study the geology of the Cascade and John Day regions in great detail. The variety and color of the John Day beds impressed Newberry: "Some are pure white, others pink, orange, blue, brown, or green. The sections made by their exposure have a picturesque and peculiar appearance." Following the "Mpto-ly-as" (Metolius) and Deschutes Rivers, Newberry reported on the stratigraphy and structure of the canyons. The warm springs of the Deschutes were examined and analyzed separately by E.N. Horsford, who accompanied the party.

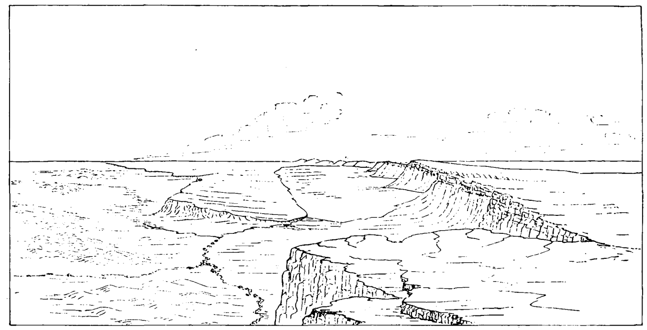
Newberry was the first to differentiate between the coastal chain in California and the Oregon Cascades. He correctly identified glacial features in the Cascades and erosional evidence in the Columbia River canyon. His most significant economic contribution was an account of the coal mining possibilities of "Coose Bay," Vancouver Island, and Cape Flattery.

Volume 6 of the Pacific Railroad Survey report was submitted to the War Department in 1855 and included the "Reports on the Geology, Botany, and Zoology of Northern California and Oregon," in which John Newberry's "Geological Report on Routes in California and Oregon" with its beautifully tinted plates appeared.

U.S. GEOLOGICAL SURVEY

With the end of the Civil War in 1865, the Government began funding excursions to the West in order to carry out observations in the natural sciences. Many publications resulted from four great western surveys conducted between 1867 and 1879 under Clarence King, Ferdinand V. Hayden, John Wesley Powell, and George M. Wheeler. Subsequently, the tasks and many of the scientific workers of those surveys were incorporated in the newly created U.S. Geological Survey (USGS) within the Department of the Interior.

Representative of the earliest published studies dealing with Oregon are Leo Lesquereux' "Description of Miocene Species of California and Oregon" in an 1883 monograph from the Hayden survey; Israel C. Russell's "A Geological Reconnaissance in Southern Oregon" of 1884, from the Wheeler survey; and the 1899 report on "The Coos Bay Coal Field, Oregon" by J.S. Diller, who between 1898 and 1903 also produced the first three Oregon folios for the USGS *Geologic Atlas of the United States*.



Sketch of Lake Abert, Lake County. Illustration from "A Geological Reconnaissance in Southern Oregon," by I.C. Russell, published in U.S. Geological Survey Fourth Annual Report, *1884.*

TURN OF THE CENTURY

About 1865, Thomas Condon had begun an informal study of Oregon geology and paleontology while he was stationed as a missionary at The Dalles. Condon made frequent trips to the John Day fossil beds, collecting mammal bones and leaves. His interest in geologic studies eventually forced him to choose between the ministry and a career in geology, a decision that came when he accepted an academic appointment at Forest Grove College in 1873.

The increasing attention given to Oregon geology precipitated the creation of the office of State Geologist in the fall of 1872. The appointment fell to Thomas Condon, and it was his duty "to make geological examination of different parts of the State from time to time," a job that was to pay $1,000 in gold annually. Several years after his appointment, the University of Oregon opened at Eugene, and Condon accepted a position there as a professor of geology in 1876.

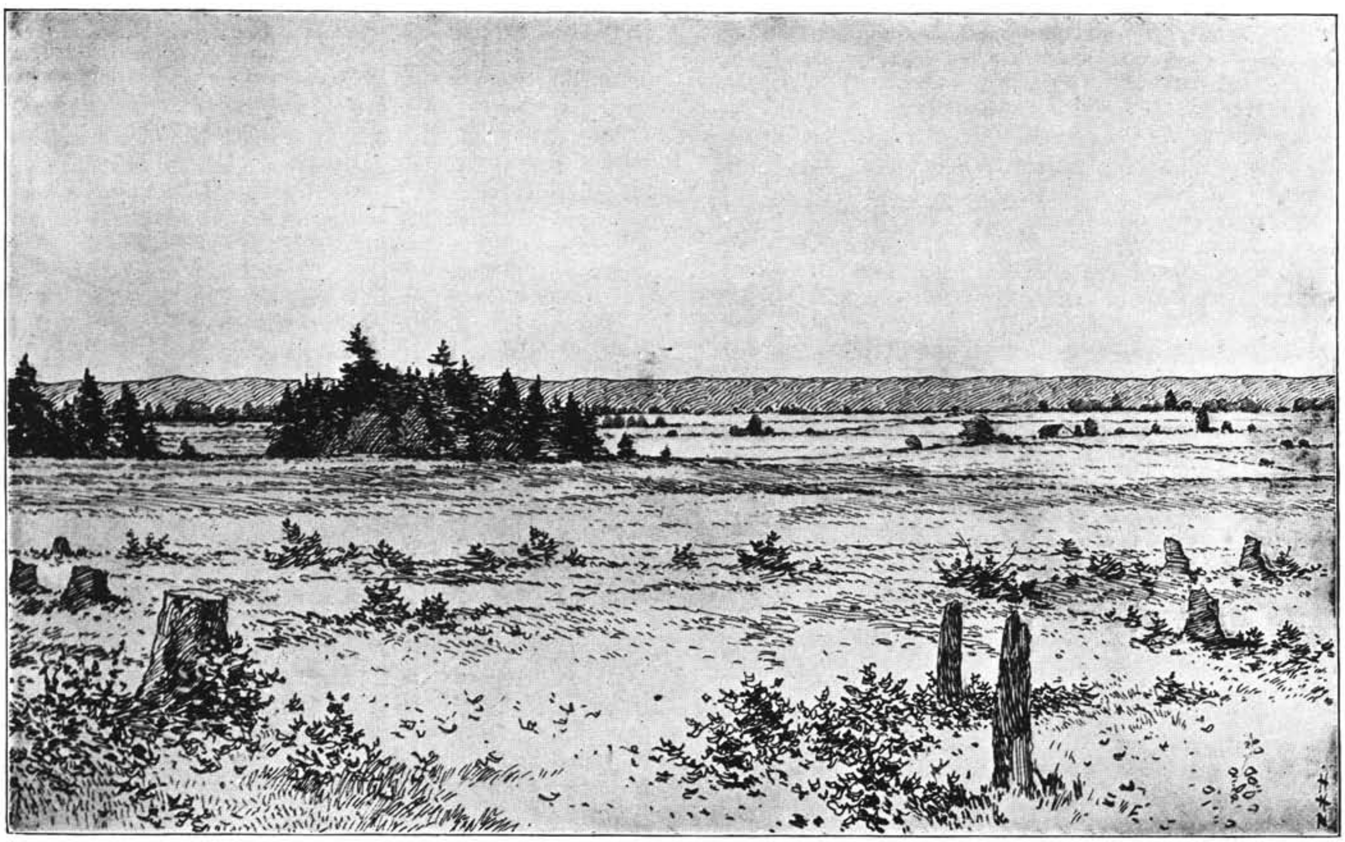
Condon, in his capacity as geology professor and State Geologist, living and working for years in Oregon, was in the position to develop a comprehensive theory on the geologic origin of the state. Condon's ideas were published in 1902 as *The Two Islands and What Came of Them*. This book appeared about 100 years after Lewis and Clark had reached the Northwest and 53 years after Dana's "Geological Observations." The significance of the book is that it attempts to summarize knowledge and scientific expertise on Oregon geology in order to draw conclusions about Oregon's geologic past, a task much more difficult than Dana's because of the increased information available around the turn of the century. In his introduction, Condon states, "But this large body of information is so scattered that few have the time to collect enough of it to form a continuous unity of its history." One of Condon's greatest contributions to expanding the knowledge of Oregon's geology was an outgrowth of his own intense interest in science. Condon carried on a voluminous correspondence with several prominent eastern scientists such as John Newberry, who had seen Condon's Miocene fossil leaves and requested more material. Condon had sent specimens to, and corresponded with, Spencer Baird of the Smithsonian Institution, Edward Cope of the Academy of Natural Sciences, Joseph Leidy of Philadelphia, O.C. Marsh of Yale University, and John C. Merriam of the University of California. Thus, the scientific community was not only aware of Oregon's geologic resources, but many took the time to come to Oregon to see the geology firsthand. Articles on Oregon paleontology and geology proliferated around the turn of the century as a consequence of these activities.

Condon was not alone in pushing forward the boundaries of geologic knowledge in Oregon. Among those who worked in the northwest, mineralogist and stratigrapher Joseph S. Diller stands out as having contributed significantly to the geologic record. Diller produced 56 papers and maps on Oregon while employed by the U.S. Geological Survey. Among his important early works are "The Bohemia Mining Region of Western Oregon" (1900), the first extensive study of the newly created Crater Lake National Park (1902), and a number of outstanding geologic quadrangle maps of southwestern Oregon for the *Geologic Atlas of the United States*. The "Port Orford Folio" was issued in 1903 and the "Riddle Folio" in 1924.

Diller's efforts produced the first detailed geologic maps of portions of Oregon. Up to this point, a number of maps on the geology of the United States had been composed, such as William Maclure's work, *A Map of the United States, Colored Geologically* (1809), but in spite of the title these maps covered only the eastern part of the country. *Gray's Geological Map of the United States*, by Charles H. Hitchcock, professor of geology at Dartmouth, was issued in 1876 and is typical of the maps of the time, depicting the geology of the country in broad strokes. The hand-colored Hitchcock map shows the Cascades as volcanic, the Willamette Valley and the coastline as Tertiary, some Cretaceous rocks in the Klamaths and southeastern Oregon, and the remainder of Oregon (Coast Range, eastern Oregon, Klamaths) as "Eozoic," that is, pre-Silurian. From the 1850s to after 1870, the first regional geologic maps of the Pacific states included only areas of California and a number of profiles of Vancouver Island.

Most of the early maps, if they showed Oregon at all, were concerned with the Coast Range only. Then, in 1906, Ellen Condon McCornack contributed *A Student's Geological Map of Oregon, With Notes*, the first complete geologic map on which Oregon is not part of a larger geographic unit. The 25 pages of text provide a summary of Oregon's geologic history. On the map, the geology, from pre-Cretaceous through Pleistocene, is not colored but depicted by patterns. In drawing up the map, McCornack was able to rely on publications by Condon, Diller, and Russell, and on the work of another USGS geologist, W. Lindgren, who contributed the report, "The Gold Belt of the Blue Mountains of Oregon," to the USGS Annual Report of 1901.

Diller's publishing record was nearly matched by that of Edward Drinker Cope, vertebrate paleontologist, whose work focused on the John Day and Great Basin regions. His 1,000-page *Vertebrata of the Tertiary Formations of the West* appeared as an 1883 monograph from the Hayden survey, and "The Silver Lake of Oregon" (1889) described Oregon fossils in the *American Naturalist*, where his first discussion of John Day fossils was published in 1873. Cope often collected fossils under difficult conditions. At one point Cope was conducting his field work with a team of four mules and a wagon and was reduced to eating bacon, stewed tomatoes, and crumbled biscuits, even feasting on cold canned tomatoes for breakfast.



View looking north from Forest Grove, Washington County. Illustration from "A Geological Reconnaissance in Northwestern Oregon," by J.S. Diller, published in U.S. Geological Survey 17th Annual Report, *1896.*

Eventually, another overview of Oregon geology was synthesized, this time by two geologists of the University of Oregon, Warren DuPré Smith, a field geologist, and Earl L. Packard, a paleontologist. "Salient Features of the Geology of Oregon" was issued in 1919 as an article in the *Journal of Geology* and as a University of Oregon *Bulletin*. This short account of 42 pages takes "an inventory of our knowledge" of Oregon geology, presenting it in a fairly technical manner. Most of the text deals with stratigraphy, although there is a short section on the geologic history and economics of the state. Smith, serving as chairman of the Geology Department some time after Thomas Condon, received numerous requests for copies of the publication, which was not distributed commercially but which he sent out without charge.

Classic papers on Oregon's geology concluded this early period: Ira A. Williams' *The Columbia River Gorge: Its Geologic History*, with outstanding photographs, appeared in 1916. It was soon followed by J. Harlen Bretz' controversial papers, "The Channeled Scablands of the Columbia Plateau" (1923) and "The Spokane Flood Beyond the Channeled Scablands" (1925). Geologists dismissed Bretz' ideas and were slow to accept the notion of large-scale floods.

FOLLOWING DECADES

Geological sciences in the state took several steps forward in the 1930s. The first of these occurred with the beginning of the school year in 1932, when a new department of science at the State College in Corvallis began to train students in geology. A shy, well-known paleontologist, Earl L. Packard, was the reluctant dean of the new science school. Prior to this time, geology classes had been taught at Corvallis by the School of Mines. In 1932, the School of Geology, along with other science departments, was transferred from the University of Oregon at Eugene to Corvallis, where all science programs were combined. The purpose of the reorganization was to reduce duplication in class offerings during times of financial stress. The decision was based on recommendations made after a survey of Oregon higher education had been conducted. In the sciences, the major argument soon emerged over the issue of which school should offer "pure" science as opposed to "applied" science.

As a result of this arrangement, 86 sets of science journals were moved from the University of Oregon to the library at Corvallis. These books were never fully processed at the State College, and the transfer of books ceased in 1933, when O.F. Stafford, University of Oregon librarian and Dean Packard's official representative at the University of Oregon, refused to allow Beilstein's *Handbook of Organic Chemistry* to be moved from the Eugene campus. After a decade of unhappiness, protest, and conflict, the State Board of Higher Education restored the natural sciences to Eugene in 1942.

Yet another milestone was reached in 1937 with the initiation of a State geology department. Some years earlier, in 1911, the State Legislature had created a State department of geology, nearly 40 years after Thomas Condon's appointment as the first State Geologist. This "Oregon Bureau of Mines and Geology" was first incorporated into the Oregon Agricultural College at Corvallis; beset with financial and administrative problems, however, the Bureau disbanded in 1923. In spite of these troubles, the Bureau had contributed significantly to the geologic literature by issuing bulletins, short papers, maps, and miscellaneous publications.

In an attempt to rectify the situation, the Legislature created the present Department of Geology and Mineral Industries (DOGAMI) in 1937 with a biennial operating budget of $60,000. The new department was also to administer the distribution of an additional $40,000 to encourage placer mining through grubstake loans of $50 a year to any prospector who applied and met the requirements. The Department's first Bulletin in 1937 contained the legislation that established the department and controlled the mining activity in the state. The following year, 1938, ten Bulletins were released. Clyde P. Ross' *The Geology of Part of the Wallowa Mountains* (Bulletin 3) sold for $.50; and Henry C. Dake's *The Gem Minerals of Oregon* (Bulletin 7) for $.10. During 1938, the Department also issued the monthly *Press Bulletin*, which was replaced a year later by the *ORE.-BIN* (spelled thus, until both spelling and format were changed in 1962) and was sent free to libraries, universities, colleges, and legislators. Earl K. Nixon, first Director of the department, stated that the purpose of the publication was "to advise the public of the work of the Department and of new and interesting developments in mining, metallurgy, and geology." In 1979, the *Ore Bin* became *Oregon Geology*, the title reflecting a change in emphasis in the geology of the state in more recent years.

Milestones of geologic exploration from this time were Howel Williams' *The Ancient Volcanoes of Oregon* and Ralph W. Chaney's *The Ancient Forests of Oregon* (both 1948). They represented the culmination of many years of work in Oregon. Chaney, a significant force in Oregon paleobotany for decades, wrote and published extensively in the state until his death in 1971 at the age of 81 years.

Ewart M. Baldwin, a professor of geology at the University of Oregon, was another geologist who worked and published extensively in the state. The first edition of his *Geology of Oregon* appeared in 1959, just 57 years after Condon's synthesis of Oregon geology. As it had been with Condon, Baldwin had lived in Oregon for a number of years and was faced with the task of gathering and compiling information from an overwhelming number of sources. His first edition, written in a nontechnical manner, was "concerned mainly with the historical geology of Oregon." The initial edition of Baldwin's book was issued and distributed by the University of Oregon bookstore and sold for about $2.

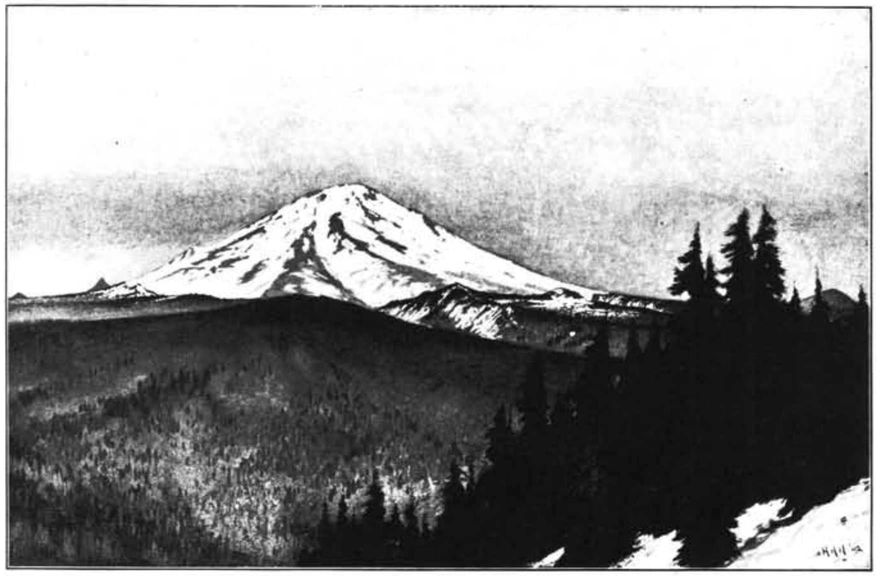
Since the late 1960s and continuing to the present, the theories of continental drift and plate tectonics have had great impact on geologic research and literature in Oregon. Gaining acceptance only after years of controversy, continental drift theory was synthesized in 1960 by Harry Hess of Princeton University, who compiled facts about the creation and movement of the sea floor in a hypothesis that he called "geopoetry."

From that point forward, the concept of plate tectonics took almost 10 years to cross the continent to the West Coast, where it was ushered in with Robert Dott's "Circum-Pacific Late Cenozoic Structural Rejuvenation—Implications for Sea Floor Spreading" of 1969. Dott briefly reported on the "widely acclaimed hypothesis of sea floor spreading, and especially its latest refinement, the lithosphere plate hypothesis," touching briefly on its impact in Oregon. He felt, rightly enough, that these "rare simplifying generalizations of knowledge [will] provide powerful new bases for formulating and rapidly testing questions about the earth." In 1970, Tanya Atwater published her extensive study "Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of Western North America." As knowledge of tectonics expanded, the theory that much of the western margin of North America was made up of accreted terranes was supported by D.L. Jones, N.J. Silberling, and J. Hillhouse in "Wrangellia—a Displaced Terrane in Northwestern North America" (1977) and W.P. Irwin's "Ophiolitic Terranes of California, Oregon, and Nevada" (1978).

As early as 1965, before plate tectonics or accretion theories had been fully accepted, W.R. Dickinson and L.W. Vigrass, in their *Geology of the Suplee-Izee Area, Crook, Grant, and Harney Counties, Oregon*, puzzled over the geology of central Oregon. These problems were readily explained in the 1978 paper, "Paleogeographic and Paleotectonic Implications of Mesozoic Stratigraphy and Structure in the John Day Inlier of Central Oregon," by W.R. Dickinson and T.P. Thayer. The 1978 paper by H.C. Brooks and T.L. Vallier, "Mesozoic Rocks and Tectonic Evolution of Eastern Oregon and Western Idaho," summarized the tectonic knowledge of the Blue Mountains at this point.

Cascadia, the Geologic Evolution of the Pacific Northwest, appeared in 1972. The author, versatile E. Bates McKee, pilot, hockey player, and yachtsman as well as geologist, began teaching at the University of Washington in 1958. Energetic and enthusiastic, McKee gathered together the material for his book, taking sabbatical leave from 1970 to 1971 in order to complete the manuscript. McKee died in 1982 in a plane crash while doing field work in the Cascades. *Cascadia* was written for the layman, student, and geologist to provide "an introduction to the evolution of the Northwest landscape." The geology of Oregon is included along with that of Washington, British Columbia, and parts of Idaho; consequently, some of the geologic details are cursory because such a wide region is covered.

Notable regional compilations in these decades focused on the Cascades and western Oregon. The classic paper by Dallas L. Peck and others, *Geology of the Central and Northern Parts of the Western Cascade Range in Oregon* (1964) was supplemented by *Geology and Geothermal Resources of the Central Oregon Cascade Range* of 1983, edited by G.R. Priest and B.F. Vogt. Geologists P.D. Snavely, Jr., and H.C. Wagner summarized the *Tertiary Geologic History of Western Oregon and Washington* in 1963. John E. Allen's book, *The Magnificent Gateway*, a geologic guide to the Columbia River, was issued in 1979.



"Mount Mazama restored," as J.S. Diller presumed it would have looked in his time, had it not erupted. Illustration from Diller's 1902 study of Crater Lake National Park, U.S. Geological Survey Professional Paper 3.

Other significant contributions to the expanding knowledge of Oregon's geology were the book *Mineral and Water Resources of Oregon* of 1969, prepared by the U.S. Geological Survey in cooperation with DOGAMI; and the *Handbook of Oregon Plant and Animal Fossils* (1981) by William N. and Elizabeth L. Orr, which collected all of the paleontological material for the state under one title. Two further additions were the state geologic map and the chart produced in the nationwide COSUNA project: *Geologic Map of Oregon West of the 121st Meridian* (1961), by Francis G. Wells and Dallas L. Peck; its companion piece, *Geologic Map of Oregon East of the 121st Meridian* (1977), by George W. Walker; and the *Correlation of Stratigraphic Units of North America, Northwest Region* (1988), a compilation of regional stratigraphy. [The two halves of the state geologic map have now been replaced by a one-piece, complete *Geologic Map of Oregon* (1991). See announcement elsewhere in this issue. —ed.]

GEOLOGIC LITERATURE ON OREGON

The first bibliography of Oregon geology was the *Bibliography of the Geology, Paleontology, Mineralogy, Petrology, and Mineral Resources of Oregon*, compiled by C. Henderson and J. Winstanley and published in 1912. The number of articles listed in this bibliography reflects the interest generated by the early explorations that had opened Oregon to a multitude of geologic workers. A review of the citations in the bibliography shows clearly that the early publications gave sweeping overviews of the region, whereas the studies after the 1870s narrowed their subject matter to more localized topics. The majority of publications during this period focused on paleontology, followed by those on physiographic features.

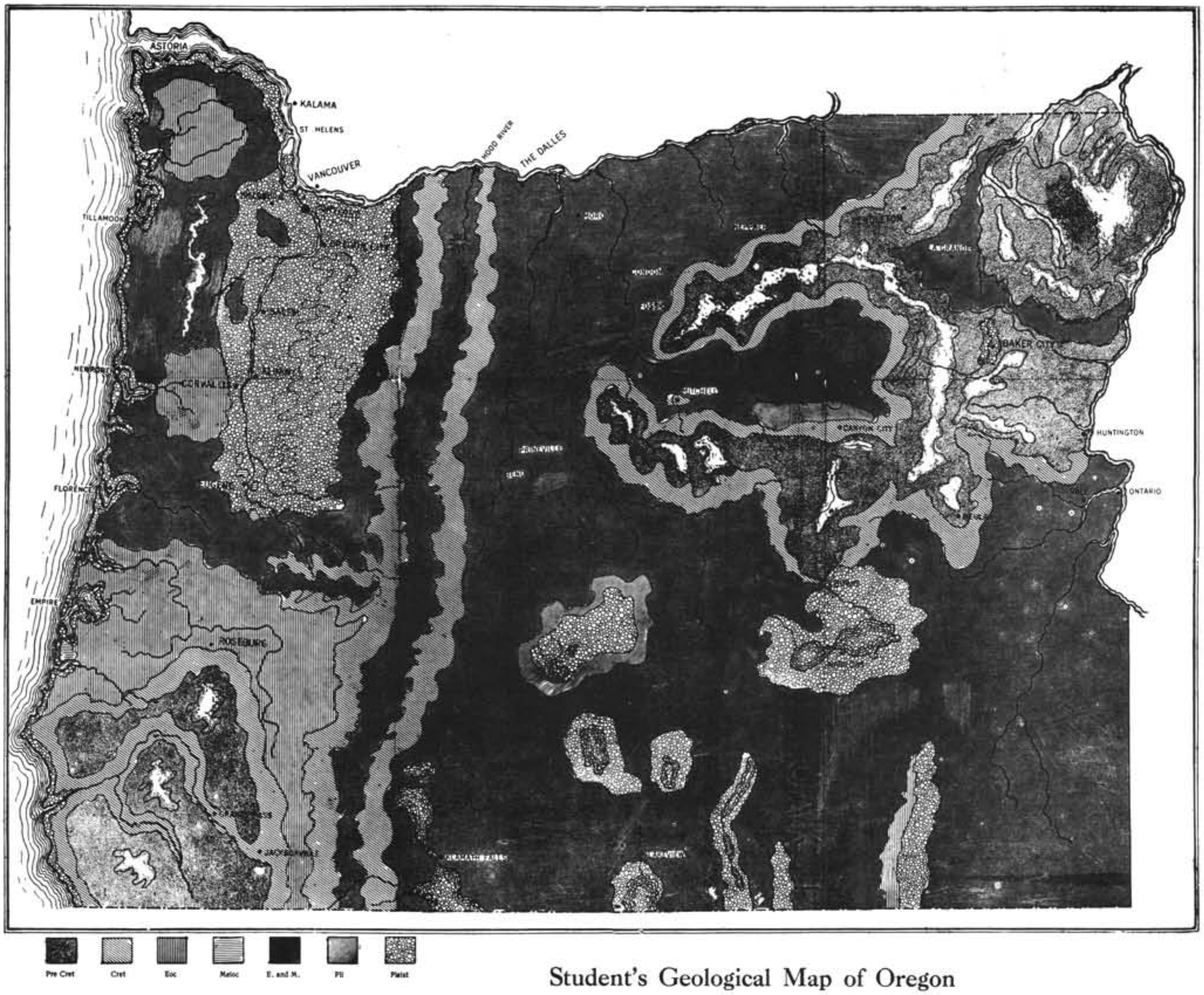
In 1936, R.C. Treasher and E.T. Hodge produced the *Bibliography of the Geology and Mineral Resources of Oregon*, which appeared just a decade after D.E. Dixon's 1926 *Bibliography of the Geology of Oregon*. Examination of all three bibliographies shows a striking increase in the number of articles on Oregon geology: Treasher and Hodge list 2,155 publications, as compared to Dixon's 1,065 and Henderson and Winstanley's 493 items.

In the bibliographies of 1926 and 1936, publications on mines and minerals, followed by those on paleontology and regional topics, constituted the bulk of geologic literature. During these decades the emphasis was definitely on economic geology. Gold was treated in 302 articles, coal in 110, copper in 98, and iron in 91. This interest is also reflected in the number of publications dealing with counties that have a high amount of mining activity, such as Baker County (118), Klamath County (92), Josephine County (81), and Jackson County (79), whereas Lane County appeared in only 17 publications and Multnomah County in 9. Individual paleontologists were the most prolific researchers, led by John C. Merriam, who produced 44 papers on vertebrate paleontology, and Ralph W. Chaney, who published 28 studies on paleobotany.

From 1940 to 1960, the subject matter of geologic literature again showed gradually changing trends. The preponderance, as shown in the literature, was on minerals, secondly on rock formations and regional areas, while the number of papers on paleontology declined. A total of 2,069 papers was listed in the several supplements to the 1936 bibliography that were published by DOGAMI. The emphasis was still on the mining industry in both geologic literature and research, with 77 articles on gold, 78 on chromite, and a surge of papers on oil and gas (113), most of them produced by DOGAMI. The counties most often cited in the literature were Clackamas, Lake, Lane, Lincoln, Douglas, Baker, and Grant—areas that were being closely examined for their economic resource potential as well as surveyed for regional geologic data. Thus, for example, Lincoln County was reviewed for fossil localities, landslide hazards, coastal geology, agates, and a variety of minor subjects. By the end of the 1950s, research in fields of Oregon geology was becoming more diversified. Ground water, volcanology, structural geology, and petrology were expanding fields of study.

Topics in geologic literature were spread fairly evenly over broad areas from the 1960s to the 1980s. Approximately 975 citations were on geologic formations, 850 on areas of regional interest, 735 on minerals, 563 on paleontology, 334 on ground water, 286 on geomorphology, 260 on structure, 250 on volcanology, 235 on tectonics, and 199 on petrology. The total number of papers on geology of Oregon listed in the *Bibliography of the Geology and Mineral Resources of Oregon* supplements was 4,549 for the 20-year period.

Areas generating the most interest were in eastern and southern Oregon: Malheur (160), Grant (117), and Harney (121) Counties in the east and southeast; Klamath (118) and Lake (146) Counties in the south; and Coos (111) and Curry (130) Counties on the coast. Much of the activity was in regional mapping and in studies of the structure, stratigraphy, mineral resources, and paleontology. Volcan-



First geologic map exclusively of Oregon: A Student's Geological Map of Oregon, with Notes, *by Ellen Condon McCornack, 1906.*

ism ranked high as a field of study during the period. In evidence of this interest, 227 citations were devoted to the Columbia River basalts, followed by 101 on the John Day Formation, and 78 on the Clarno Formation. Coastal regions were examined for mineral resources, coastal processes, paleontology, and stratigraphy.

After 1980, research was further refined into narrow categories such as tectonophysics, strontium isotopes, clay mineralogy, diagenesis, and organic materials. However, the lines between the individual fields became blurred with the development of interdisciplinary fields of research. Delineation of formations (1,145) led in citations in the literature, followed by economic geology (994), regional topics (779), volcanology (622), paleontology (540), and ground water (471). The number of papers on aspects of tectonics doubled after 1980. The total number of publications for the period from 1980 to 1990 was 2,244.

It is interesting to note that research focused on the same counties as earlier (1960-1980), with the exception of Deschutes County, where intensive explorations at Newberry Crater contributed significant data. Malheur County studies showed a preponderance of articles on the McDermitt caldera; in Klamath County, hydrogeothermal exploration and study of Crater Lake dominated; whereas in Lake County, volcanism, mineral resources, and some geothermal research accounted for the emphasis. Several geologic maps as well as maps of mineral resources were produced on Curry County.

Finding solutions to the geologic problems faced today is really no more difficult than in the past. In recent years, the focus has been on seismicity and earthquake hazards, geothermal research, economic resources, and environmental concerns. The geologic literature will reflect these trends as they continue to mature.

ACKNOWLEDGMENTS

The authors would like to thank Ewart Baldwin, Richard Heinzkill, Carol McKillip, and Lloyd Staples of the University of Oregon for reading the manuscript and giving suggestions.

SUGGESTED FURTHER READING

An extensive bibliography will be included in the upcoming book mentioned at the beginning of this article.

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The Mount Angel fault: Implications of seismic-reflection data and the Woodburn, Oregon, earthquake sequence of August 1990

by K. Werner[1], J. Nábelek[2], R. Yeats[1], and S. Malone[3]

INTRODUCTION

The Mount Angel fault is part of the northwest-trending Gales Creek-Mount Angel structural zone (Beeson and others, 1985) that extends across much of northwestern Oregon (Figure 1). On the basis of water-well data and outcropping Columbia River basalt (Figure 2), Hampton (1972) originally mapped the Mount Angel fault in the northern Willamette Valley from the edge of the Waldo Hills to just northwest of the city of Mount Angel. By incorporating commercial seismic-reflection data, we can now extend the fault northwestward to Woodburn. The southeastern extent of the fault is poorly constrained due to poor exposure in the Waldo Hills. However, the fault may continue into the Western Cascades, where it appears to have formed a barrier to three of four Silver Falls flows of the Miocene Columbia River basalt (Beeson and others, 1989). In addition, a Ginkgo intracanyon flow of the Columbia River basalt is dextrally offset approximately 1 km across the fault due to faulting or a sharp jog in the canyon (M. Beeson, personal communication, 1989).

The following discussion of the geologic structure of the Mount Angel fault is largely based on the interpretation of seismic-reflection data in the northern Willamette Valley. The seismic-reflection data are tied to a synthetic seismogram of the DeShazer 13-22 petroleum exploratory well (Werner, 1991). Recent seismicity near Woodburn was probably related to the Mount Angel fault and suggests that the fault is active.

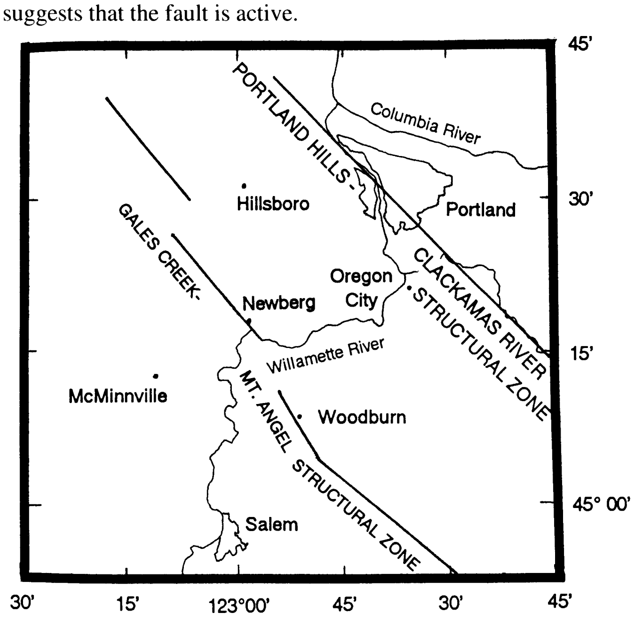

Figure 1. Map showing the Gales Creek-Mount Angel structural zone and Portland Hills-Clackamas River structural zone.

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Table 1. *Woodburn seismicity*

Earthquake	Latitude	Longitude	Date	Magnitude
1	45.133	-122.886	7/3/80	1.7
2	45.142	-122.874	8/20/83	1.2
3	45.165	-122.871	9/9/83	1.6
4	45.153	-122.847	8/14/90	2.0
5	45.113	-122.877	8/14/90	2.5
6	45.118	-122.860	8/22/90	2.4
7	45.132	-122.867	8/22/90	2.2
8	45.120	-122.871	8/23/90	2.4
9	45.107	-122.866	8/23/90	1.4

GEOLOGIC EVIDENCE FOR THE MOUNT ANGEL FAULT

The Mount Angel fault vertically offsets Columbia River basalt and younger sedimentary strata down to the southwest as shown on two seismic-reflection lines and one water-well cross section located in the southeastern portion of the northern Willamette Valley (Figure 3). No vertical offset is evident on the east-west seismic-reflection line that goes through Hubbard (Figure 2). The amount of vertical offset of the top of Columbia River basalt increases to the southeast of Woodburn. The vertical offset is approximately 100 m on seismic section A-A′ (Figure 4), 200 m on seismic section B-B′ (Figure 5), and 250+ m on cross section C-C′ (Figure 6). The amount of offset calculated for cross sections A-A′ and B-B′ is based on average velocities (determined from depths in wells and the corresponding two-way travel time on seismic-reflection lines [Werner, 1991]) and stacking velocities, both of which are in general agreement.

The 250+ m of separation on cross section C-C′ is based on the difference in altitude between the top of Columbia River basalt in a water well and the altitude of Mount Angel (Figure 6). Mount Angel has an elevation of 85 m above the valley floor and is composed of both Grande Ronde Basalt and the younger Frenchman Springs Member of the Columbia River Basalt Group (M. Beeson, personal communication, 1990). The presence of the Frenchman Springs Member at the top of Mount Angel indicates that little of the Columbia River basalt section has been eroded, so the displacement is probably not much more than 250 m. The 250+ m offset determined at Mount Angel may not represent the vertical slip across the entire Mount Angel fault zone. Because of the steep northeast side of Mount Angel, the topographic high of Mount Angel (and the adjacent Columbia River basalt exposure to the northwest) may be caused by a positive flower or pop-up structure as shown in Figure 7.

The dip of the Mount Angel fault is poorly constrained; furthermore, the fault probably consists of several splays with different dips. Due to the poor constraint on dip, seismic reflectors could have a reverse or normal sense of offset. The best constraints

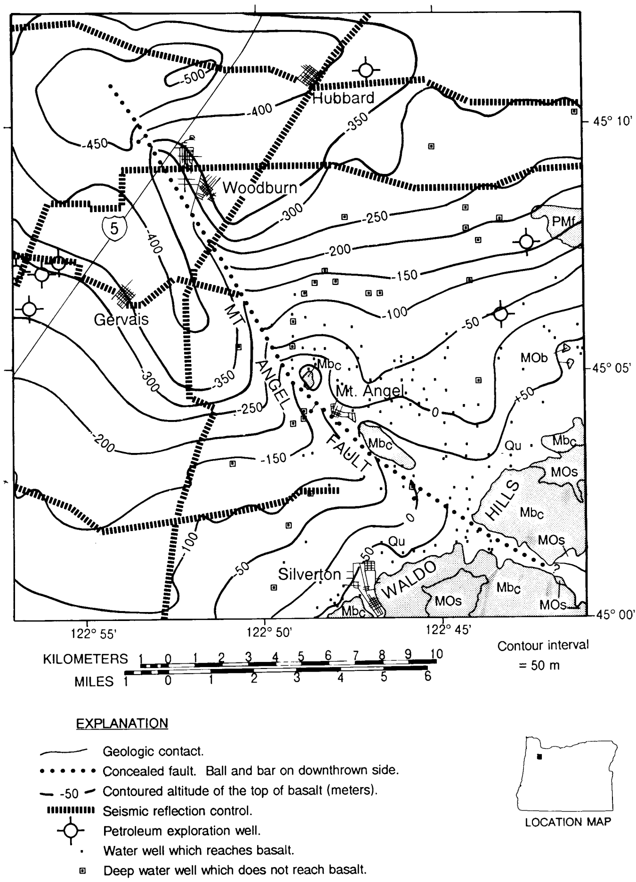

Figure 2. Contour map on the top of basalt, which is primarily Columbia River basalt except near outcropping MOb. Geologic units are labeled as follows: Qu = Quaternary undifferentiated sediment; PMf = Pliocene and Miocene fluvial and lacustrine sediments; Mb_c = Miocene Columbia River basalt; MOs = Miocene and Oligocene sedimentary rock; MOb = Miocene and Oligocene basalt.

on the sense of offset and near-surface dip of the fault are offset reflectors present on seismic line B-B′ (Figure 5). On the basis of the offset reflectors, the near-surface portion of the Mount Angel fault (or this splay of the fault) appears to have an apparent reverse offset and dips approximately 65° to the northeast.

Progressive displacement occurred on the Mount Angel fault as shown by differentially offset reflectors. The top of Columbia River basalt is offset 200 m along seismic section B-B′, while an overlying reflector in Pliocene and Miocene fluvial and lacustrine sediments appears to be vertically separated 41 to 96 m (depending on which reflectors are matched across the fault). We prefer the reflector offset shown in Figure 5, an offset of 96 m. Seismic line resolution is inadequate to determine if the fault deforms younger sediments.

Deformation associated with the Mount Angel fault appears to have occurred both before and during (or after) deposition of Pliocene to Miocene sediments. An angular unconformity at the base of Pliocene and Miocene sediments indicates pre-sediment deformation. Onlapping Pliocene and Miocene sediment reflectors are themselves warped into a syncline (structural relief on one reflector in Pliocene and Miocene sediments is approximately 45 m) due to continued deformation during or after their deposition (Figures 4 and 5).

RELATIVE MOTION ALONG THE MOUNT ANGEL AND GALES CREEK FAULTS

The Gales Creek and Mount Angel faults comprise a major northwest-trending linear structural zone more than 150 km long (Figure 1) (Beeson and others, 1985, 1989). The structural zone appears to consist of en echelon faults rather than one continuous fault. Both vertical and horizontal separations are evident along the Gales Creek and Mount Angel faults. Mumford (1988) noted approximately 200 m of vertical separation along the Gales Creek fault in southeast Clatsop County. Similarly, seismic lines as well as the topographic high of Mount Angel indicate 100 to more than 250 m of vertical separation (northeast side up) along the Mount Angel fault in the Mount Angel area.

The vertical separation across the Mount Angel fault is probably a result of local compression (extension is possible but less likely) across the fault zone. It does not appear to be related to strike-slip motion. The vertical separation is not due to dextral strike-slip motion, because the Columbia River basalt is generally dipping northeastward in the Mount Angel area (Figure 2), and dextral strike-slip motion would serve to counteract uplift on the northeast side of the fault. Sinistral strike-slip motion would be consistent with the differential vertical offset observed; however, it would be inconsistent with relative motion along similarly oriented faults and inconsistent with the current north-south direction of horizontal maximum compression determined from borehole breakouts and seismicity in western Oregon (Werner and others, 1991).

Although dip-slip motion appears to be important locally along the Mount Angel fault, right-lateral motion has probably been more important in forming the Gales Creek-Mount Angel structural zone. Along the Gales Creek fault, Mumford (1988) inferred right-

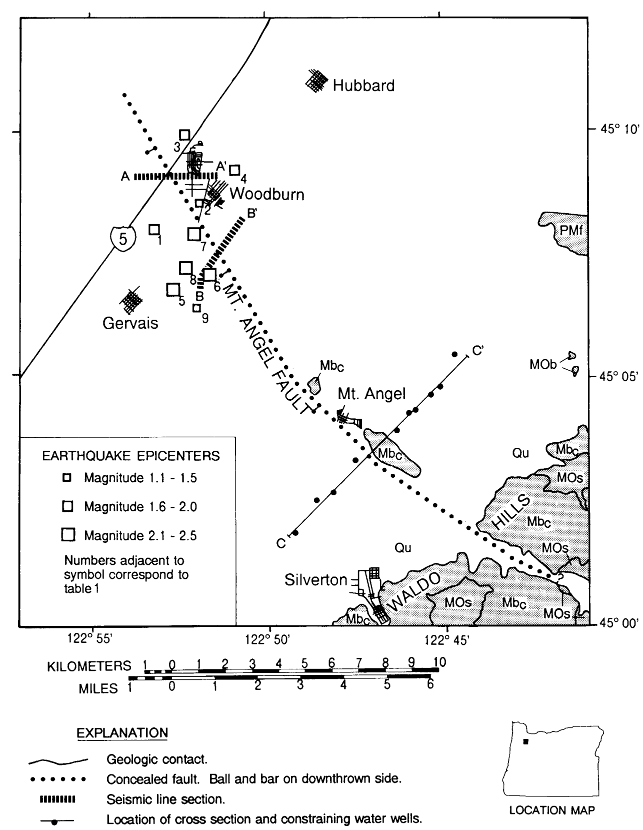

Figure 3. Epicenters of earthquakes near the Mount Angel fault and location of seismic and water-well cross sections. Number corresponding to each earthquake refers to Table 1. Geologic units as in Figure 2.

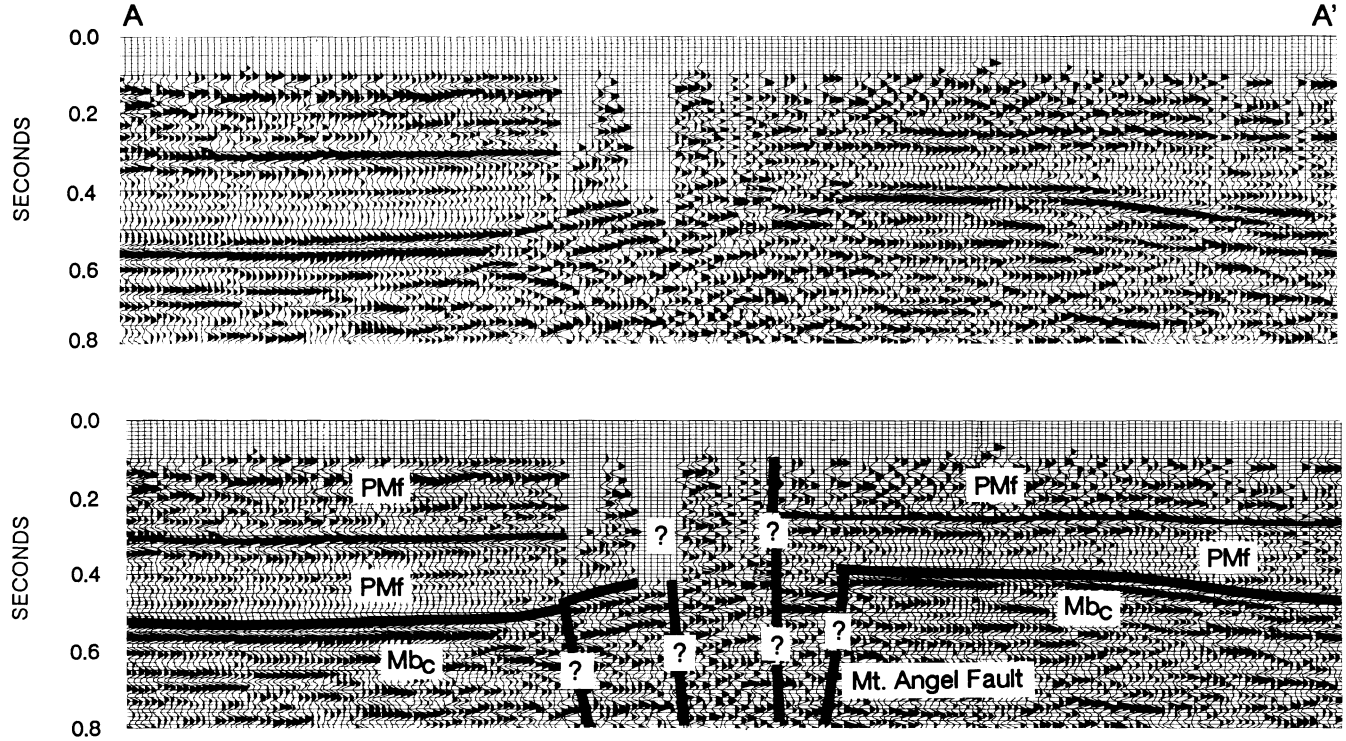

Figure 4. Seismic section A-A′ across Mount Angel fault. Location shown in Figure 3; geologic units as in Figure 2. Because fault is difficult to locate due, in part, to data gaps and may consist of more than one splay, it is shown to be vertical. Note greater vertical separation of top of Mb_c than of reflector within PMf.

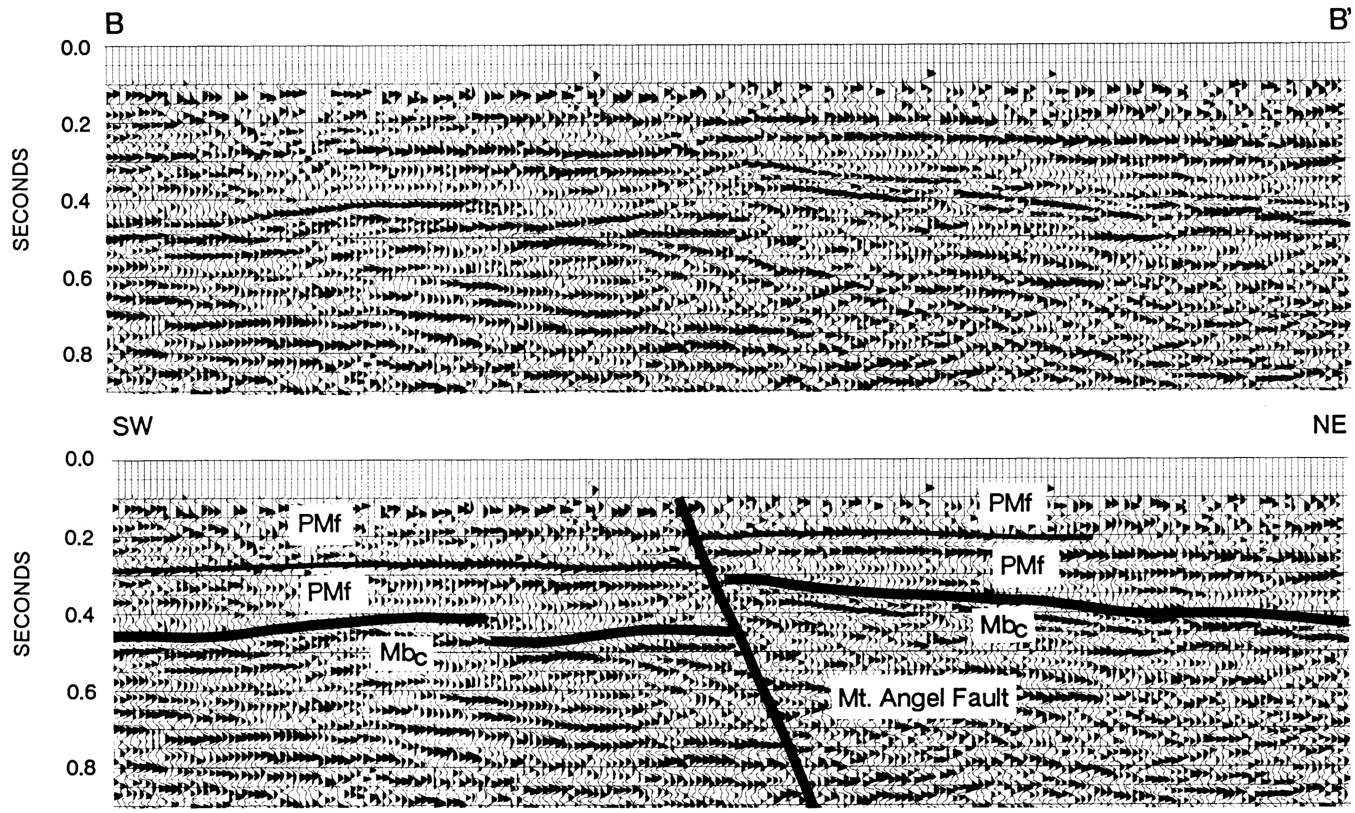

Figure 5. Seismic section B-B′ across Mount Angel fault. Location shown in Figure 3; geologic units as in Figure 2. Fault appears to have reverse separation and to dip northeast. Note greater vertical separation of top of Mb_c than of reflector within PMf.

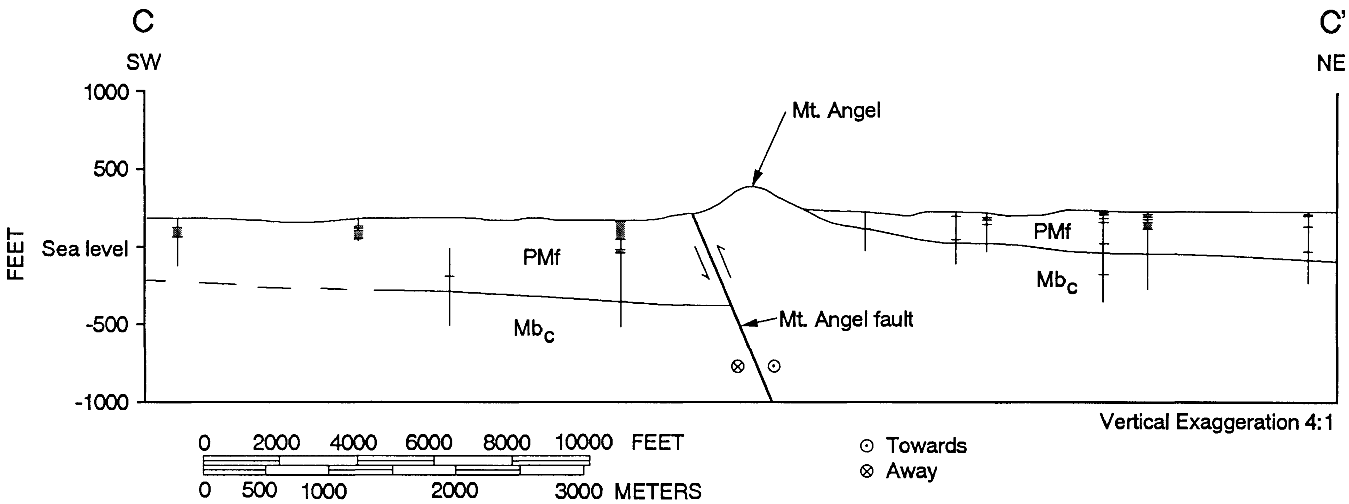

Figure 6. Structural cross section C-C′ of the Mount Angel fault, based on water wells. Location of cross section and constraining water wells shown in Figure 3; geologic units as in Figure 2. A few wells were located on the basis of information from farmers or drillers of Staco Well Services. Only those intervals of wells that were logged are shown. The near-surface dip of the fault is interpretive and based on cross section B-B′. The base of Mb_C is unconstrained. Conglomerate intervals are indicated by two horizontal lines with shading between them. Very thin conglomerate lenses are shown by a horizontal line.

lateral motion from offset northeast-trending faults, and Safley (1989) noted a 2-m-thick gouge zone and slickenside surface. The slickenside surface indicates right-lateral oblique-slip motion; the rake of the slickensides is 25° SE. Similarly, motion along the Mount Angel fault has probably been largely right-lateral, because of its similar orientation to the Gales Creek fault, the linearity of the zone, a possible 1-km dextral offset of the Miocene Ginkgo intracanyon flow, and the current north-south direction of maximum horizontal compression.

SEISMICITY

On August 14, 22, and 23, 1990, a series of six small earthquakes with coda magnitudes (m_c) of 2.0, 2.5, 2.4, 2.2, 2.4, and 1.4 occurred with epicenters near Woodburn (Figure 3, Table 1). The epicenters also correspond to the northwestern end of the Mount Angel fault. Epicentral errors for these events are about ±2 km. In 1980 and 1983, three events with $m_c \leq 1.7$ also occurred in this locality (Figure 3, Table 1).

Initial routine locations by the Washington Regional Seismograph Network (WRSN) for the August 1990 events indicated a hypocenter depth of about 30 km (±5 km). However, wave-form modeling indicates a substantially shallower hypocenter depth of 15-20 km. The routine hypocenter determination made by WRSN might have been biased by an inappropriate structure (for Oregon, WRSN routinely uses a structure based on a refraction line in the Cascade graben) and inadequate station coverage (the nearest station was 60 km from the epicenter). Relocating the earthquake by using a structure for western Washington shifts the hypocenter estimates to 20-25 km, in much better agreement with waveform modeling.

The August 1990 series of events was recorded by the IRIS/OSU broadband seismic station in Corvallis (COR; epicentral distance 68 km) as well as the WRSN. For all events, the wave forms recorded at any given station are remarkably similar (Figure 8), indicating essentially identical locations and mechanisms. Two alternative focal mechanisms, constrained by wave-form modeling of Corvallis station (COR) seismograms and first-motion data, are shown in Figure 9. A range of solutions between the solid and dashed focal mechanisms would satisfy the data. The solutions were determined by means of a coarse grid search, i.e., varying strike from 320° to 360°, dip from 70° to 110°, and rake of the slip angle from 140° to 220°, all by 10° intervals. The preferred focal-plane solution, the one that results in the closest match between the forward-modeled seismogram and the actual seismogram, is shown by the dashed lines. It is a right-lateral strike-slip fault with a small normal component on a plane striking north-south and dipping steeply to the east. The strike indicated by the preferred focal mechanism solution is somewhat more northerly than the surface-fault strike, based on seismic-reflection data, and shows a slight normal component of slip—contrary to seismic reflection data that appear to show that since the Miocene, on average, the motion on the Mount Angel fault has had a thrust component. However, a pure strike-slip mechanism for the earthquakes is acceptable by our data.

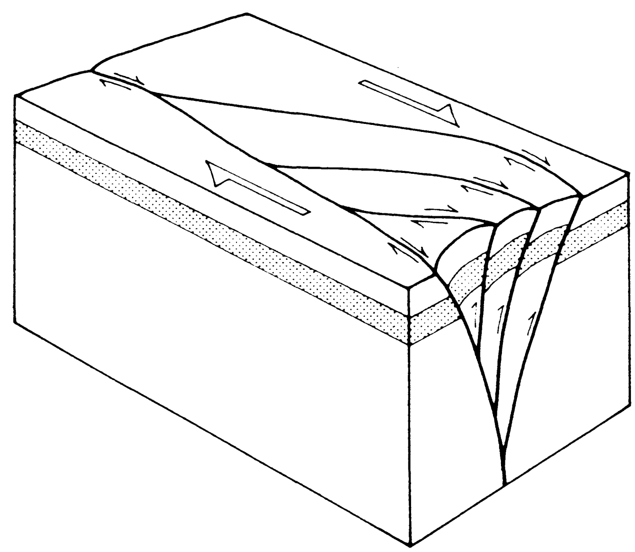

Figure 7. Schematic three-dimensional model of a Mount Angel pop-up structure from Woodcock and Fischer (1986). The number of splays shown does not necessarily correspond to the Mount Angel fault.

The location and focal mechanisms of the earthquakes indicate that the quakes are probably occurring on a deep extension of the

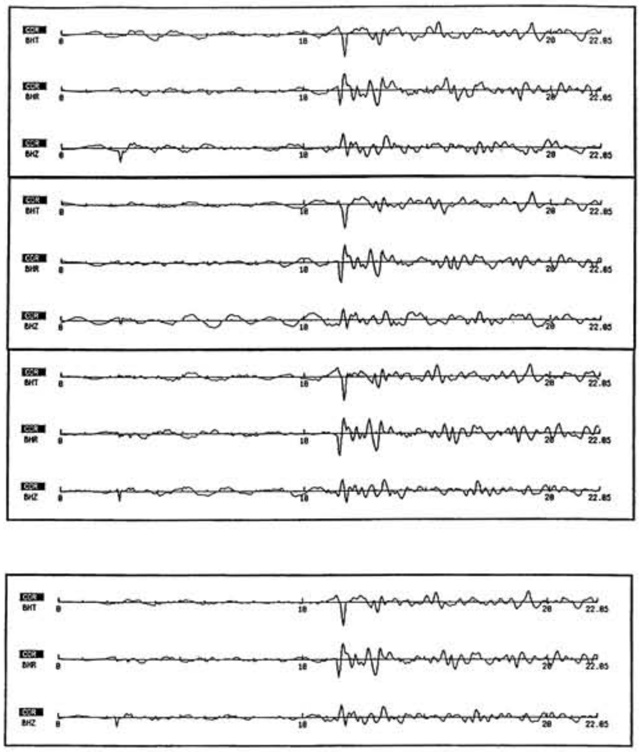

Figure 8. Top three sets of seismograms are displacement records from Corvallis for the largest three events of the Woodburn earthquake sequence. The peaks and troughs of the prominent phases of the three events align to within the digitizing interval (20 samps/s) of the records, which indicates that the events occurred essentially at the same spot. The bottom set of records is the sum of the three individual traces. The signal-to-noise ratio at the longer periods is improved.

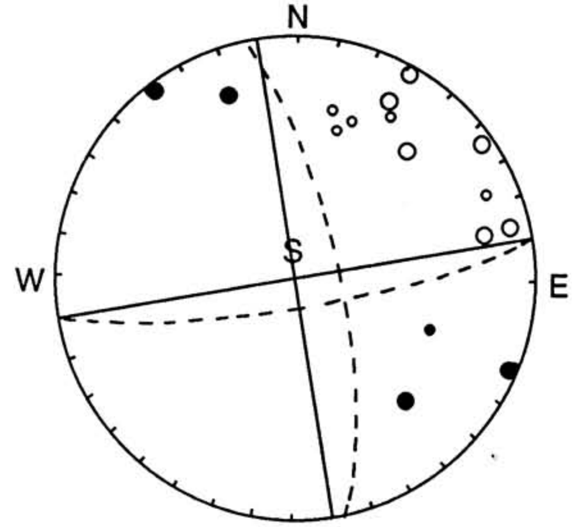

Figure 9. Two possible composite focal mechanisms for the six August 1990 earthquakes near Woodburn. Open circles indicate dilatation at a given station; solid circles indicate compression. Larger circles indicate a stronger first motion.

Mount Angel fault. Although the association between the earthquakes and the surface fault is somewhat tentative due to the depth of the earthquakes, the tectonic stress implied by both is consistent.

TECTONIC IMPLICATIONS

The trend and sense of motion of the Gales Creek-Mount Angel structural zone are similar to those of the Portland Hills-Clackamas River structural zone in the Portland area (Figure 1). The Portland Hills-Clackamas River structural zone is a major structural feature consisting of faults and folds generated in response to dextral movement (Beeson and others, 1989). Recent seismicity, including a M_w=5.1 earthquake on November 6, 1962, with its epicenter in the Portland area and a swarm of small earthquakes in October 1991, appears to be related to motion along the Portland Hills-Clackamas structural zone (Yelin and Patton, 1991). Together, the Gales Creek-Mount Angel and Portland Hills-Clackamas River structural zones may take up dextral shear imposed on the upper plate by oblique subduction of the Juan de Fuca Plate beneath the North American Plate.

Dextral shear has been noted by Wells and Heller (1988) and Wells (1990) as an important mechanism for generating rotation observed in paleomagnetic results. Wells and Heller (1988) conclude that dextral shear is responsible for about 40 percent of post-15-Ma rotation. Coastal sites of 15-Ma flows of Grande Ronde Basalt show an average rotation of 22° clockwise when compared to sites on the Columbia River Plateau; rotation decreases from the coast eastward (Wells and Heller, 1988). Tectonic models explaining the paleomagnetic results have varied from rotation of a single Coast Range block to distributed shear on many smaller

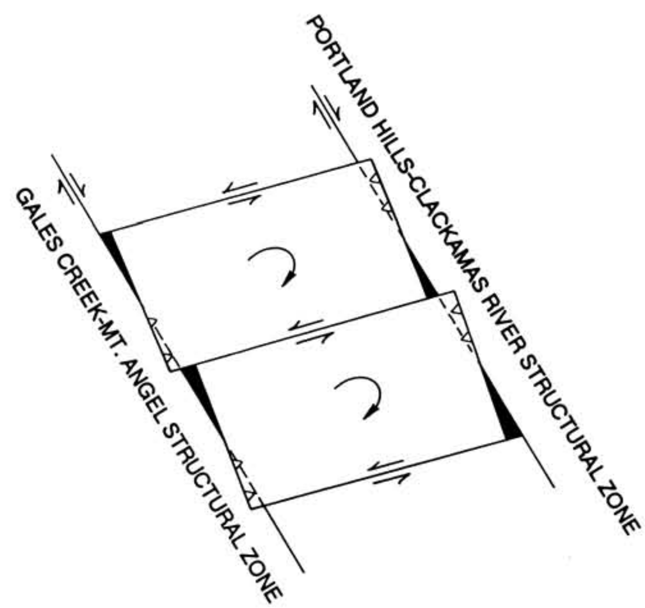

Figure 10. Model for block rotation between the Gales Creek-Mount Angel structural zone and Portland Hills-Clackamas River structural zone. It is based on a model applied to rotation of blocks near the intersection of the San Andreas and San Jacinto faults, California, by Christie-Blick and Biddle (1985).

faults (Sheriff, 1984; Wells and Heller, 1988). Wells and Heller (1988) argue that the tectonic processes responsible for rotation are operating on an intermediate scale (10^2-10^4 m). Such a scale is consistent with the model of rotation shown in Figure 10 (after Christie-Blick and Biddle, 1985) between the Portland Hills-Clackamas River and Gales Creek-Mount Angel structural zones. Wells and Coe (1985) demonstrate rotation in southwestern Washington along similar major dextral north-northwest-trending faults and west-northwest-trending sinistral R′ riedel shears.

Rotation of intermediate-sized blocks leads to space problems and differential local compression and extension along shear zones as shown in Figure 10. The differential compression associated with rotation could in turn explain the different amounts of vertical separation along the Mount Angel fault.

The Gales Creek-Mount Angel structural zone appears to have been active from Columbia River basalt time to possibly the present. Motion on the Mount Angel fault during the middle Miocene resulted in the formation of a barrier by the time the Silver Falls flows were extruded. Warping and offset of Pliocene and Miocene sediments indicate that deformation continued during the Neogene. The Gales Creek-Mount Angel structural zone may presently be active, if the August 1990 seismicity indeed occurred on a deep extension of the Mount Angel fault.

CONCLUSIONS

According to water-well and seismic-reflection data, the Mount Angel fault extends from the town of Mount Angel north-northwestward to Woodburn. Locally, the fault vertically offsets the top of Columbia River basalt up to 250+ m and appears to offset a reflector corresponding to Pliocene and Miocene fluvial and lacustrine sediments by 96 m. Structural relief on the Pliocene and Miocene fluvial and lacustrine sediments, which form a syncline along the south side of the fault, is 45 m.

A series of small earthquakes of m_c=2.0, 2.5, 2.4, 2.2, 2.4, and 1.4 occurred on August 14, 22, and 23, 1990, with epicenters along the northwest end of the Mount Angel fault. Routine locations indicated a depth of about 30 km; however, wave-form modeling indicates a substantially shallower hypocenter depth of 15-20 km. The preferred composite focal mechanism solution is a right-lateral strike-slip fault with a small normal component on a plane striking north and dipping steeply to the west. The locations and focal mechanisms of the earthquakes are consistent with their being on a deep extension of the Mount Angel fault.

The Mount Angel fault is part of the Gales Creek-Mount Angel structural zone, which appears to be taking up dextral shear imposed on the upper plate by subduction of the Juan de Fuca Plate beneath the North American Plate.

ACKNOWLEDGMENTS

Support was provided by U.S. Geological Survey National Earthquake Hazard Reduction Program Grant No. 14-08-0001-G1522 awarded to R.S. Yeats. Additional funding was provided by ARCO Oil and Gas Company, the Peter P. Johnsen Scholarship Committee, and the Oregon Department of Geology and Mineral Industries. We thank the many people and companies who were helpful in supplying data and facilities. Thanks also to Matthew Mabey for reviewing the paper and Camela Carstarphen for drafting many of the figures.

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New southeast Oregon geologic map released

Resources of basalt and sand and gravel were identified as economic mineral commodities in the Jonesboro quadrangle in southeastern Oregon. The Oregon Department of Geology and Mineral Industries (DOGAMI) has released a new geologic map of this Owyhee region quadrangle.

Geology and Mineral Resources Map of the Jonesboro Quadrangle, Malheur County, Oregon, by James G. Evans. DOGAMI Geological Map Series GMS-66, two plates (one two-color geologic map, scale 1:24,000, with explanations and brief discussions; and one sheet containing geologic cross sections and geochemical data tables). Price $6.

The Jonesboro quadrangle (like some geographic features of the area) were named after the Jones Ranch that is located on the Malheur River east of Juntura. The quadrangle straddles the river and includes part of the Sperry Creek Wilderness Study Area. The rocks exposed in the quadrangle are predominantly basalts and reflect a volcanic history that dates back to Miocene time, about 16 million years ago. Over the last approximately five million years, the Miocene rocks were faulted, uplifted, and eroded into a fairly gentle landscape with elevations mostly between 4,000 and 5,000 feet.

Production of the map was funded jointly by DOGAMI, the Oregon State Lottery, and the COGEOMAP Program of the U.S. Geological Survey as part of a cooperative effort to map the west half of the 1° by 2° Boise sheet in eastern Oregon.

The new report, DOGAMI map GMS-66, is now available at the Nature of Oregon Information Center, Suite 177, State Office Building, 800 NE Oregon Street #5, Portland, Oregon 97232-2109, phone (503) 731-4444. Orders may be charged to credit cards by mail, FAX, or phone. FAX number is (503) 731-4066. Orders under $50 require prepayment except for credit-card orders. Purchase by mail and over the counter is also possible at the DOGAMI field offices: 1831 First Street, Baker City, OR 97814, phone (503) 523-3133; and 5375 Monument Drive, Grants Pass, OR 97526, phone (503) 476-2496. □

Note to our readers

The column **MINERAL EXPLORATION ACTIVITY** will return to its accustomed place in the next issue. □

THESIS ABSTRACTS

The Department maintains a collection of theses and dissertations on Oregon geology. From time to time, we print abstracts of new acquisitions that in our opinion are of general interest to our readers.

Physical volcanology of Holocene airfall deposits from Mount Mazama, Crater Lake, Oregon, Simon R. Young, (Ph.D., University of Lancaster, 1990), 307 p.

The 6,845±50 yrs BP caldera-forming eruption of Mount Mazama (Crater Lake, Oregon) was preceded within 200 years by two plinian eruptions producing voluminous airfall deposits followed by lava flows. This study concentrates on these two airfall deposits as well as the complex airfall deposits from the climactic eruption, which are distributed over ~1.7 million km^2 of northwest America.

Tephro-stratigraphic mapping of airfall units throughout south-central Oregon has revealed the presence of five lobes of coarse pumice deposits and two widespread ash units which are important marker horizons. Detailed grainsize data have been generated by sieving and measurement of maximum clast sizes, and these are used to characterize each deposit and as input data for clast dispersal models of plinian airfall eruptions. Geochemical variations between each deposit generally support the models already developed for Mount Mazama, and geochemical techniques have been used to deduce the source of distal "Mazama ash." The role of volatiles in each eruption is reviewed and, along with the rate of vent and conduit erosion, is found to be vital in controlling eruptive evolution.

Deduction of column height and mass eruption rate for various stages during each eruption has been possible through the use of clast dispersal models and, when combined with eruptive velocity and vent and conduit dimensions, has produced a detailed physical model of eruptive development. This has then been linked to field characteristics to provide significant new information about the physical volcanology of plinian airfall eruptions.

Revised volume estimates for the climactic airfall eruption, including distal fine ash, give a volume of ~20 km^3 (dense rock equivalent), with a maximum column height of ~55 km occurring immediately prior to column collapse and ignimbrite generation. This eruption is thus one of the most intense and voluminous ultra-plinian eruptions yet documented.

Island-arc petrogenesis and crustal growth: Examples from Oregon and Alaska, by Lisanne G. Pearcy (Ph.D., Stanford University, 1991), 184 p.

The bulk compositions determined by mass balance of two exposed sections of intraoceanic island-arc crust, the Talkeetna volcanics and Border Ranges ultramafic-mafic complex in southeastern Alaska and the Canyon Mountain Complex in northeastern Oregon, are basalt (MgO = 11 percent) and probably basaltic andesite (MgO = 8 percent), respectively, with unfractionated REE abundances approximately 10 times chondrite. Simple accretion of arcs such as these cannot generate a LREE-enriched, andesitic, post-Archean continental crust; that requires modification of their bulk compositions by a combination of processes, including (a) delamination of basal cumulates to make the crust less mafic, (b) addition of alkalic magmas and accreted rocks to enrich the average crust in LREE and other lithophile elements, and (c) partial melting of the lower crust combined with delamination of the residue to do both of the above.

The 2- to 3-km-thick ultramafic-to-mafic "transition zone" (TZ) in the Early Permian Canyon Mountain Complex represents the products of mantle melts that crystallized in a nascent island-arc setting. This zone consists of complexly interlayered pyroxene-rich cumulate rocks, with igneous textures and mineralogy pointing to formation by in-situ crystallization and fractionation at 5-10.5 kb (15-30 km depth) under water-poor conditions. Major- and trace-element compositions of clinopyroxene and the order and relative proportions of phases crystallized indicate that parental magmas were primitive island-arc tholeiitic basalts with some similarities to boninites. Variations in clinopyroxene chemistry reveal trace-element heterogeneity in the parental melts, which may be due to either variable source compositions or disequilibrium mantle melting. Magmas entered the TZ in at least three batches, forming crude, large-scale, cyclic units in some locations. During slow cooling, the TZ rocks were apparently deformed and uplifted to near-surface levels.

The entire Canyon Mountain Complex most likely represents incipient arc magmatism in the Olds Ferry terrane. The complex was transferred to the dismembered forearc region (i.e., Baker terrane) by tectonic erosion of the leading edge of the arc crust. It was then uplifted and emplaced within serpentinite-matrix melange along faults lubricated by serpentinite diapirs.

Geology and Petrology of the Mount Jefferson area, High Cascade Range, Oregon, by Richard M. Conrey (Ph.D., Washington State University, 1991, 357 p.

An area of approximately 150 km^2 surrounding Mount Jefferson is underlain by a volcanic field of andesite and dacite composition. The area is thus one of the few places in the High Cascades in Oregon, like Mount Hood, South Sister, and Crater Lake, where intermediate and siliceous rocks are abundant. A complex history of activity during the past 0.7 Ma is preserved at Mount Jefferson; 158 units were mapped. There is no evidence of an underlying "mafic platform" of overlapping basaltic andesite shield volcanoes. Due to the onset of extensive glacial erosion about 0.8 Ma, preservation of older rocks is rare. Exposures of 1.0- to 3.5-Ma andesites and dacites at the margins of the area, however, suggest that andesite and dacite-dominated volcanism around Mount Jefferson may be of several million years duration.

$^{87}Sr/^{86}Sr$ isotopic ratios range from 0.77028 to 0.7036 in mafic and intermediate rocks at Mount Jefferson; ratios in dacites and rhyodacites are nearly constant at 0.7033-0.7034. There is also a significant variation of Pb isotope ratios in mafic and intermediate rocks. The isotope data require the participation of three processes in magma genesis: partial melting of typical suboceanic mantle and mafic lower crust, and either crustal assimilation by mafic magmas or subduction of crustal materials and contamination of the underlying mantle.

Abundant trace-element data rule out crystal fractionation as the dominant petrogenetic mechanism: many incompatible trace elements fail to increase with supposed degree of differentiation. Mineraologic evidence from detailed studies of the youngest andesites and dacites requires mixing of mafic and siliceous magmas. Convective mixing of magmas may account for the uniqueness of phenocrysts in dacites and andesites: chaotic turbulent convection would carry each phenocryst along a different pathway.

Profound differences exist in the mineralogy and chemistry of intermediate and siliceous rocks erupted before and after the development of an intra-arc graben 4-5 Ma in the Cascade Range. Pre-graben dacites and thyodacites were buffered between NNO and QFM, amphibole free, and richer in incompatible trace elements; post-graben siliceous magmas were buffered 1-2 log units above NNO, and are invariably amphibole-bearing gneisses in the middle crust, while the latter were formed by partial melting of garnet-bearing amphibolites in the deep crust. Amphibole was not a near-liquidus phase during mixing of pre-graben mafic and siliceous magmas; hence, Fe/Mg ratios and TiO_2 contents were not buffered during mixing-induced fractionation, and the pre-graben series of rocks is tholeiitic. Conversely, amphibole was a near-liquidus phase during post-graben mixing events, and a calc-alkaline series of rocks resulted. □

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