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IN THIS ISSUE:

Field and Stable Isotope Indicators of Geothermal Resource Potential, Central Lake County.
The Development of the Portland, Oregon, Building Code—50 Years of Evolution, 1945–1995.
Evaluating the Effectiveness of DOGAMI's Mined Land Reclamation Program.

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Cover photo

With this splendid view of the summit of Mount Hood, seen from the 6,600-ft level, just above Timberline Lodge, we are sending you our best wishes for a happy new year and our thanks for your being faithful readers of and contributors to *Oregon Geology*. We hope to continue our work with your attention and support. (Photo courtesy Oregon Department of Transportation)

The publishers and editors

What's your earthquake IQ?

Scientists frequently warn Oregonians about seismic hazards and increasing seismic safety standards; however, the current level of awareness and preparedness does not ensure protection of lives and property from even moderate earthquake shaking. To support earthquake awareness, this quiz was modified from a quiz developed by staff member Mei Mei Wang for the November 1995 Fall Institute of the Oregon Building Officials Association.

1. What is generally considered to be a "major" earthquake?
   a. Magnitude 6.
   b. Magnitude 7.
   c. Magnitude 8.
   d. Intensity VII.
2. When will the next big earthquake be?
   a. More likely during the next full moon.
   b. No one knows. No one can reliably predict "when, where, and how big" the next earthquake will be.
   c. Sometime soon in the morning, since earthquakes generally occur in the morning.
   d. Never. Earthquakes don't occur in Oregon.
3. What should you do during an earthquake?
   a. Get frantic and scream.
   b. Duck, cover and hold on.
   c. Remain quiet and pass out.
   d. It really depends on where you are.
4. What should you do immediately after an earthquake?
   a. Go about your business and pretend it never happened.
   b. Call your family and friends and tie up the phone lines.
   c. Check for injuries, hazards (fire, gas leaks, spills, etc.), clean up, expect aftershocks, listen to radio.
   d. Anticipate tsunamis if you're on the coast.
   e. Answers c and d.
5. When did the last great subduction-zone earthquake and tsunami hit coastal Oregon?
   a. Precisely on January 26, 1700.
   b. About 300 years ago.
   c. Several thousand years ago.
   d. There hasn't been one.
6. When did the last damaging tsunami hit the Oregon coast?
   a. Precisely on January 26, 1700.
   b. About 300 years ago.
   c. March 1964.
   d. There hasn't been one.
7. Are there active faults near you?
   a. Probably yes, but their locations are not well understood.
   b. No, there are none.
   c. I don't know.
   d. There were, but they were voted out of office.
8. To protect against loss of life or damage, do the following:
   a. Vulnerability study.
   b. Risk study.
   c. Prioritize your seismic strengthening needs.
   d. Prepare emergency kit and response plan.
   e. All of the above, and follow through with necessary actions.

(Answers on page 9)

New areas of geothermal potential in southeastern Oregon are being explored

Field and stable isotope indicators of geothermal resource potential, central Lake County, Oregon

by A. Mark Jellinek, Research School of Earth Sciences, The Australian National University, Canberra; Ian P. Madin, Oregon Department of Geology and Mineral Industries; and Robert Langridge, University of Oregon

ABSTRACT

The geothermal resource potential in central Lake County, Oregon, has been known for some time on the basis of active hot springs and hot wells in the Summer Lake Known Geothermal Resource Area, scattered warm springs at the north end of Summer Lake and on the east shore of Lake Abert, and a single published borehole heat-flow measurement at Paisley. We report field and stable isotopic evidence for Quaternary hot springs at the north end of Lake Abert and in the Picture Rock Pass area that indicate the presence of recently active paleogeothermal systems. At the north end of Lake Abert, tufa mounds and travertine vein fillings are possibly associated with a zone of intersecting northeast- and northwest-trending faults. The tufa mounds occur in a narrow elevation range, a feature that suggests their deposition was controlled by the Pleistocene lake level. At Picture Rock Pass, travertine and silica sinter mineralization occurs in fractures, joints, and cavities in basalt bedrock, in Pliocene or Quaternary channel gravels, and in Holocene colluvium associated with the Egli Rim escarpment and an adjacent network of closely spaced northeast- and northwest-trending faults. The $\delta^{18}O$ (SMOW) and $\delta^{13}C$ (PDB) data for samples of travertine from the study areas range from 16.1 to 17.4 per mil and −6.8 to −10.7 per mil, respectively, at Picture Rock Pass and from 24.0 to 28.9 per mil and 1.4 to 4.5 per mil, respectively, at Lake Abert. These data are similar to analogous data from geothermal areas in New Zealand, central Italy, western Germany, southwestern Colorado, and Yellowstone in Wyoming. Surface precipitation temperatures for samples of sinter and travertine from the Picture Rock Pass area are determined with equilibrium oxygen-isotopic thermometry to be 39°–70°C and 30°–49°C, respectively, and are geologically reasonable. The precipitation temperatures for samples of Picture Rock Pass sinter combined with temperature-dependent solubility curves of Rimstidt and Cole (1983) for amorphous silica and quartz indicate geothermal reservoir temperatures of 145°–205°C and suggest that the Picture Rock Pass sinter was precipitated from a hot-water system. The results of the field and stable isotopic studies indicate a significant geothermal resource potential at both sites.

INTRODUCTION

This study is part of a program of the Oregon Department of Geology and Mineral Industries (DOGAMI) to prospect for geothermal resources in southeastern Oregon by looking for geologic evidence of late Quaternary hot spring activity. The program began in 1992 and is funded by the Bonneville Power Administration, the U.S. Department of Energy, and Portland General Electric Company.

Most of the Known Geothermal Resource Areas (KGRAs) in southeast Oregon (Alvord, Crump Geyser, Lakeview, Summer Lake, and Klamath Falls) are spatially associated with major Basin and Range faults (Oregon Department of Geology and Mineral Industries/NOAA, 1982). All of these KGRAs have natural hot springs, and the Alvord KGRA (Hemphill-Haley and others, 1989), Summer Lake KGRA (Pezzopane, 1993), and Klamath Falls KGRA (Sherrod and Pickthorn, 1992) show evidence of Holocene faulting. The program's aim is to use the association of faulting and hot springs to locate new areas of geothermal potential by locating evidence for geologically young but currently inactive hot springs associated with Neogene faulting in southeast Oregon. We report the results of preliminary field and stable isotopic studies from two sites in central Lake County, Oregon (Figure 1). The two areas, Picture Rock Pass and Sawed Horn (at the north end of Lake Abert), were selected for detailed field investigation on the basis of complex and closely spaced faulting observed with photogeologic mapping and in the field. Neither site has a known hot spring or hot well, but both sites showed evidence of late Quaternary or Holocene hot springs in the form of travertine and sinter mineralization precipitated into Miocene basalt bedrock, Pliocene or Quaternary channel gravels, and Holocene colluvium. Both sites were mapped at 1:24,000 scale, and the travertine and sinter were sampled.

Stable isotopic data are presented for samples of travertine and sinter collected from the Picture Rock Pass area and for samples of travertine collected from the Sawed Horn area. Oxygen and carbon isotopic data for the Lake Abert and Picture Rock Pass travertine are compared with similar data from travertine of central Italy, southwest Colorado, western Germany, Yellowstone National Park, and the Broadlands geothermal field in New Zealand. Additionally, surface saturation temperatures for fluids precipitating travertine and surface saturation and geothermal reservoir temperatures for fluids precipitating sinter from the Picture Rock Pass area are determined with oxygen isotope thermometry on the basis of temperature-dependent equilibrium quartz-water and calcite-water isotopic fractionations.

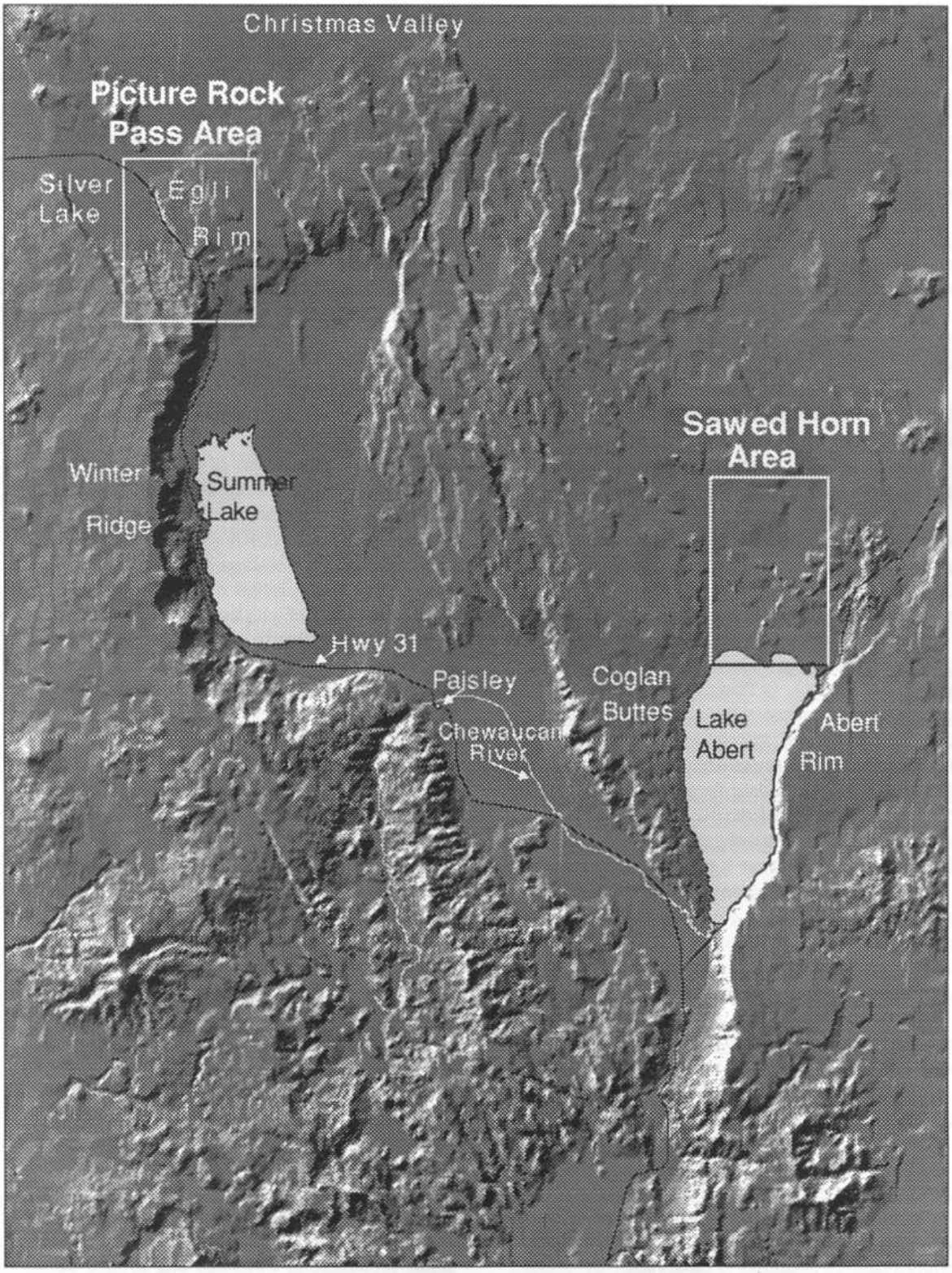

Figure 1. Shaded-relief map of central Lake County showing study areas.

PICTURE ROCK PASS

The Picture Rock Pass study area is located on the Egli Rim 7½-minute quadrangle astride Highway 31 between two major Basin and Range basins, Silver Lake to the north and Summer Lake to the south (Figure 1). The bedrock is predominantly Miocene basalt (Hampton, 1964; Walker and others, 1967; Travis, 1977; Walker and McLeod, 1991). Fiebelkorn and others (1983) report a K-Ar age of 6.9 ± 0.9 Ma for basalt at Picture Rock Pass. Bedrock in the study area is cut by numerous, commonly intersecting, northeast- and northwest-trending faults (Figure 2). Paleochannels follow many of the grabens developed between the intersecting faults, and Pliocene or Quaternary cobble gravel deposits fill the channels. Where the channels are cut by intersecting faults, numerous small Pliocene or Quaternary playa lakes have formed. Quaternary lacustrine deposits fill the Silver Lake basin west of the Egli Rim, and Holocene colluvium mantles the escarpment of the Egli Rim.

Samples of sinter and travertine were collected from the cobble gravel; colluvium; and cavities, fractures, and joints in basalt flows along the Egli Rim (Figure 1). The best exposures of sinter and travertine occur in road-cuts along Highway 31 and the other unimproved roads in the area. The proximity of these exposures to regional faults and fault intersections suggests that the movement of associated geothermal fluids was strongly fault controlled.

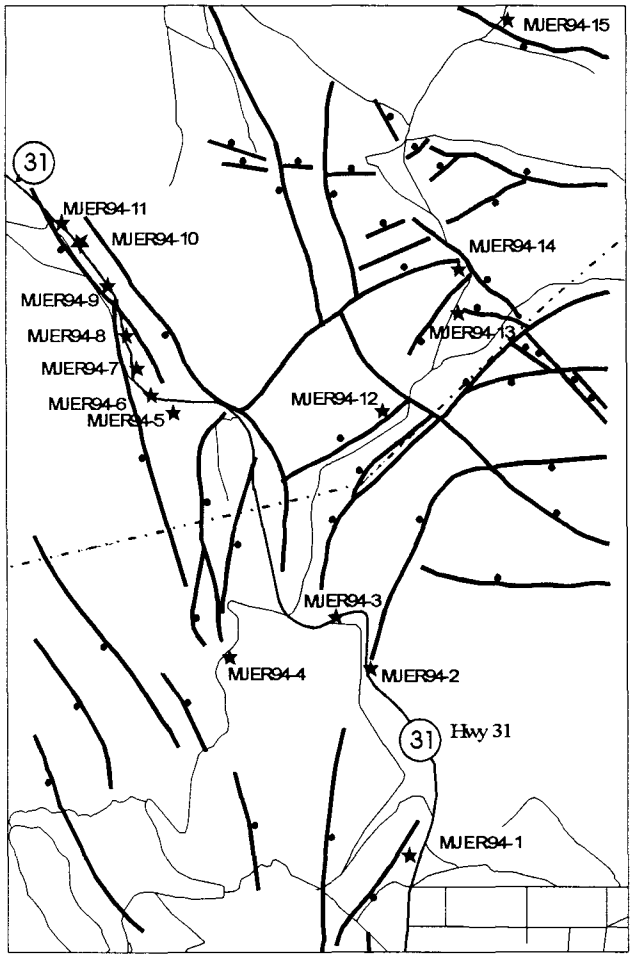

Figure 2. Sketch map of the Picture Rock Pass area, Egli Rim quadrangle. Heavy lines are faults, with ball on downthrown side. Fine lines are unimproved roads; dot-and-dash line is a transmission line. Stars show sample locations.

In most sampled exposures, travertine is a soft, white- to cream-colored rind on typically vitreous, honey-colored to yellow or tan, hard to friable siliceous sinter. The stratigraphic position of travertine on top of sinter indicates that the two phases were probably not syndepositional. In exposures of altered colluvium, sinter is friable, occurs as meter-scale layers or paleoterraces, and can contain internal, centimeter-scale layers that are fine grained to conglomeratic. Packages of centimeter-scale layers can include rhythmic interbeds of sinter and travertine. The pebbles constituting conglomeratic layers are generally well rounded and attributed to the host sediment. The sedimentary appearance of these exposures is similar, for example, to that described for the Beowawe, Nevada, sinter deposit (Rimstidt and Cole, 1983).

In exposures of altered and mineralized cobble gravels, boulders, and basalt flows, sinter occurs as a hard, smooth or rough glaze up to 2 cm thick that is also typically coated by rinds of travertine. Minor brecciation is common, particularly in exposures along Highway 31. Mineralized zones hosted by cobble gravel are typically massive, up to 7 m thick, and stratigraphically confined to gravel horizons of high permeability. Alteration zones in basalt flows are rectangular to prolate and up to 10 m high and can have aspect ratios of 60:1. Mineralization is typically confined to single flows within flow packages, which suggests that certain flows exhibit greater fracture permeability than others.

SAWED HORN

Lake Abert occupies a Basin and Range graben bounded by the Abert Rim to the east and Coglan Buttes to the west (Figure 1). The Sawed Horn study area is an area of faulted bedrock at the north end of the graben and is on the Sawed Horn and Lake Abert North 7½-minute quadrangles. The bedrock consists of Miocene basalt flows overlain by the Miocene Rattlesnake Ash-flow Tuff (Walker and MacLeod, 1991). Quaternary beach, dune, and lacustrine deposits overlie the bedrock along the north shore of the lake. Numerous well-defined northwest- and northeast-trending faults cut the bedrock units (Figure 3). Several travertine mounds overlie the Quaternary deposits at an elevation of about 4,390 ft and may be associated with the projections of faults beneath the alluvium. Travertine also occurs as vein fillings in joints and fractures in the basalt bedrock.

The mounds are oblate to mushroom-shaped, 1–3 m high, and constructed of weakly bedded to massive, spongy, and exceedingly porous carbonate material or tufa (Turi, 1986). The relative proportions of calcite and aragonite are not known. Several mounds have rounded pebbles and cobbles of the host sediment entrained in their bases. Their occurrences at similar elevations suggest a rela-

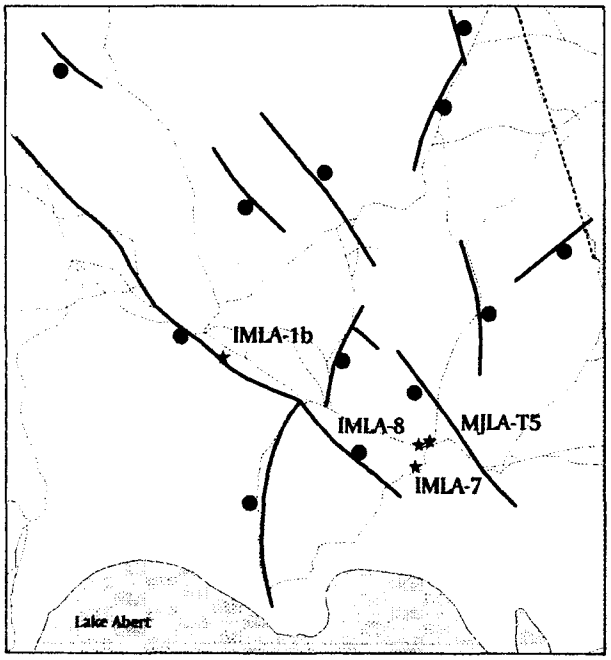

Figure 3. Sketch map of the Lake Abert North and Sawed Horn quadrangles. Heavy lines are faults, with ball on downthrown side. Dashed lines are unimproved roads. Dot-and-dash line is a transmission line. Stars show sample locations.

tionship to paleo-lake level. Samples were collected from tufa mounds and travertine vein fillings in the Sawed Horn area, and one tufa mound was sampled (COGBUT-1) on the shore of Lake Abert, several kilometers southwest of the study area.

OXYGEN AND CARBON ISOTOPES AND THERMOMETRY

Samples of travertine and sinter were collected and analyzed for stable isotopic characterization and comparison with other geothermal areas around the world. Oxygen isotope data are also used with appropriate equilibrium fractionation equations to determine travertine and amorphous silica surface saturation temperatures for the geothermal fluids of Picture Rock Pass in order to evaluate fluid reservoir temperatures (Fournier and Rowe, 1966; Rimstidt and Barnes, 1980; Rimstidt and Cole, 1983). Temperatures determined in this way are generally in good agreement with measured precipitation temperatures (Clayton and others, 1968; Friedman, 1970). The methods of McCrea (1950) and Borthwick and Harmon (1982) were employed to determine $^{18}O/^{16}O$ ratios for siliceous sinter and $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios for travertine. The analyses were performed at the Stable Isotope Laboratory at Washington State University. The $^{18}O/^{16}O$ ratios are reported relative to the standard mean ocean water standard (SMOW) and the $^{13}C/^{12}C$ ratios relative to the PDB (Peedee belemnite) standard as $\delta^{18}O$ and $\delta^{13}C$ values in per mil, respectively.

The $\delta^{18}O$ and $\delta^{13}C$ data are tabulated with comparative analyses from other studies in Table 1. The $\delta^{18}O$ values are not included for all of the comparative studies because global comparison of $\delta^{18}O$ values for hydrothermal travertine and sinter is complicated by latitude-controlled variations in the $\delta^{18}O$ values for meteoric water (Taylor, 1974), from which the two phases acquire most of their oxygen. Shallow geothermal fluids are composed of nearly purely meteoric water (Truesdell and Fournier, 1976; Truesdell and others, 1977; Taylor, 1979). The $\delta^{18}O$ data for travertine of central Italy and southwest Colorado are included because they are from study areas of similar latitude to south-central Oregon. Analogous $\delta^{18}O$ values for sinter are currently unavailable.

The $\delta^{18}O$ data for Picture Rock Pass sinter vary from 17.5 to 21.5 per mil. The $\delta^{18}O$ and $\delta^{13}C$ data for travertine range from 16.1 to 17.7 per mil and –6.8 to –10.7 per mil, respectively. The $\delta^{18}O$ values are similar to those reported by Chafetz and others (1991) for travertine deposited from a warm spring in southwest Colorado and are substantially lighter than values given by Turi (1986) for travertine of central Italy. The $\delta^{13}C$ values are analogous to data of Savelli and Wedepohl (1969) for travertine of the Westerhof, Göttingen, and Iburg areas of western Germany and to data of Blattner (1975) for travertine of the Broadlands geothermal field, New Zealand. The $\delta^{18}O$ values for samples of Lake Abert tufa mounds vary from 24.0 to 28.9 per mil and are similar to values recorded by Turi (1986) for travertine of central Italy. The $\delta^{13}C$ data range from 1.4 to 4.5 per mil and are analogous to data reported by Friedman (1970) for samples of travertine from New Highland Terrace, Mammoth Hot Springs, Yellowstone National Park, and also similar to data of Turi (1986). These $\delta^{18}O$ and $\delta^{13}C$ values are considerably heavier than those of Picture Rock Pass samples.

Precipitation temperatures are determined for sinter and travertine samples from Picture Rock Pass with the assumption that the geothermal fluids and precipitates were in stable isotopic equilibrium at the time of their deposition (Bottinga and Javoy, 1973; O'Neil, 1986; Clayton and others, 1989). We evaluated the equilibrium fractionation temperatures for sinter using the quartz-water fractionation equation of Sharp and Kirschner (1994):

$$\delta^{18}O_{qtz} - \delta^{18}O_{H2O} = 3.65(10^6/T^2) - 2.9 = 1000 \ln\alpha,$$

where T is absolute temperature and α is the fractionation factor. We determined similar temperatures for travertine by combining the quartz-calcite and quartz-water fractionation equations of Clayton and others (1989) and Sharp and Kirschner (1994) into a calcite-water fractionation equation:

$$\delta^{18}O_{Cc} - \delta^{18}O_{H2O} = 3.27(10^6/T^2) - 2.95 = 1000 \ln\alpha.$$

We calculated the $\delta^{18}O_{H2O}$ values for meteoric water of south-central Oregon, which are taken to be equivalent to geothermal fluid values, using the meteoric water line and

Table 1. *Stable isotope data from this and comparative studies along with calculated precipitation temperatures of samples of travertine and sinter from Picture Rock Pass. Values in per mil*

	Sample number	$\delta^{18}O$	$\delta^{13}C$	Tp (–112.5)*	Tp (–13.75)*	Tp (–15)*
Picture Rock Pass						
Sinter	MJER 94–2	17.5	—	60.0	53.8	48.0
	MJER 94–3	21.5	—	41.4	36.2	31.3
	MJER 94–8	18.7	—	54.0	48.1	42.6
	MJER 94–4	21.5	—	41.3	36.1	31.1
	MJER 94–10	19.7	—	49.1	43.5	38.2
	MJER 94–12	15.8	—	68.9	62.3	56.0
Travertine	MJER 94–9	17.3	–8.4	42.6	36.7	31.2
	MJER 94–11	17.7	–7.7	40.9	35.1	29.7
	MJER 94–1	16.8	–10.7	45.2	39.3	33.6
	MJER 94–7	16.1	–6.8	48.9	42.7	36.9
	MJER 94–5	17.0	–8.8	44.4	38.4	32.8
	MJER 94–13	17.4	–6.8	42.5	36.6	31.2
Sawed Horn						
Travertine	IMLA–7	24.9	1.8	—	—	—
	COGBUT–1	24.0	1.4	—	—	—
	IMLA–8	24.8	1.3	—	—	—
	IMLA–1b	28.9	4.5	—	—	—
	MJLA–5	24.8	1.5	—	—	—
Comparative studies						
	Chafetz and others (1991)	16.74 to 16.95	–2.89 to –2.70	33.21	—	—
	Blattner (1975)	—	–5.4 to –10.2	—	—	—
	Friedman (1970)	—	1.7 to 4.3	73 to 30.5	—	—
	Turi (1986)	16 to 26	–4 to 8	—	—	—
	Savelli and Wedepohl (1969)	—	–10 to –7	—	—	—

* Tp (x) is the calculated precipitation temperature in degrees Celsius for the phase in equilibrium with meteoric water that has a $\delta^{18}O$ value of x.

δD values reported by Taylor (1974) for meteoric surface waters of south-central Oregon and northern Nevada. The $\delta^{18}O_{H2O}$ values used in this study are -13.8 ± 1.3 per mil and assume negligible ^{18}O-shifting to higher values as a result of the interaction of hot geothermal waters with their host rocks.

Calculated surface saturation temperatures for fluids precipitating samples of Picture Rock Pass sinter and travertine are tabulated in Table 1. The $\delta^{18}O$ values for samples of Lake Abert tufa were too heavy to allow geologically reasonable temperatures to be calculated with equilibrium isotope thermometry—a feature that may reflect significant evaporation occurring as the tufa was precipitated. For Picture Rock Pass samples, the ranges of precipitation temperatures predicted are 30°–49°C for travertine and 31°–70°C for sinter and are geologically reasonable. Travertine and sinter are typically deposited by waters cooling through 75°–25°C and 100°–50°C, respectively (Friedman, 1970; Rimstidt and Cole, 1983). The consistent stratigraphic position of travertine on top of sinter in outcrops of altered alluvium, colluvium, and basalt suggests that the precipitation of these two phases was sequential and may, in part, reflect changes in the thermal histories of the geothermal fluids. Temperatures predicted for two travertine/sinter sample pairs, ER94–1/ER94–2 and ER94–9/ER94–10, suggest that the precipitation of travertine after sinter correlates with cooling of the geothermal fluids. Finally, assuming that the surface fluids were saturated in amorphous silica, the reservoir fluid equilibrated with quartz, and there was no subsurface boiling, one can use Figure 1 of Rimstidt

and Cole (1983) to evaluate reservoir fluid temperatures on the basis of the different temperature-dependent solubilities of amorphous silica and quartz (see also Truesdell and Fournier, 1976; Rimstidt and Barnes, 1980). Sinter precipitated from fluids saturated in amorphous silica at 30°–50°C indicates geothermal reservoir temperatures of 145°–205°C.

CONCLUSION

The results of the preliminary stable isotope study support three conclusions. The first is that $\delta^{18}O$ and $\delta^{13}C$ data for samples of travertine from Picture Rock Pass and Lake Abert tufa mounds are similar to analogous data for travertine from other geothermal areas around the world. Second, precipitation temperatures for sinter and travertine determined with oxygen isotope thermometry of 31°–70°C and 30°–49°C, respectively, are geologically reasonable. Last, precipitation temperatures for sinter combined with the temperature-dependent solubility curves of Rimstidt and Cole (1983) for amorphous silica and quartz indicate geothermal reservoir temperatures of 145°–205°C. This assessment assumes that the surface fluids were saturated with respect to amorphous silica, that the reservoir fluid equilibrated with quartz, and that there was no subsurface boiling.

These results also suggest that hot springs systems were active at the north end of Lake Abert during the late Quaternary and at Picture Rock Pass during the late Quaternary and Holocene. The combination of geologically recent hot spring activity and extensive faulting in both of these areas indicates that they have significant geothermal resource potential. Further work, including local heat flow measurements, is warranted to better evaluate the resource potential of both areas.

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(Continued from page 2)

Earthquake IQ test answers

1. **Question:** What is generally considered to be a "major" earthquake?
   Answer: b — Magnitude (M) 7. However, smaller magnitude earthquakes can be very damaging. Remember, the M 5.6 earthquake on March 1993 at Scotts Mills ("Spring Break Quake") caused minor damage (about $30 million). The *intensity* scale (expressed in Roman numerals) describes the effects people experienced ("felt effects") from an earthquake and can be associated with damage levels.
2. **Question:** When will the next big earthquake be?
   Answer: b — No one knows. No one can reliably predict "when, where, and how big" the next earthquake will be.
3. **Question:** What do you do *during* an earthquake?
   Answer: d — It really depends on where you are. (1) If you are indoors, ***duck*** or drop down to the floor. Take ***cover*** under a sturdy desk, table, or other furniture. ***Hold*** on to it and be prepared to move with it. Hold the position until the ground stops shaking and it is safe to move. Stay clear of windows, fireplaces, wood stoves, and heavy furniture or appliances. Stay inside. Outside, you may be injured by falling glass or building parts. If you are in a crowded area, take cover and stay where you are. Stay calm and encourage others to do likewise. (2) If you are outside, get into the open, away from buildings, power lines, and trees. (3) If you are driving, stop if it is safe, but stay inside your car. Stay away from bridges, overpasses, and tunnels. Move your car as far out of the normal traffic pattern as possible. Avoid stopping under trees, light posts, power lines, or signs if possible. (4) If you are in a mountainous area, or near unstable slopes or cliffs, be alert for falling rock and other debris that could be loosened by the earthquake.
4. **Question:** What do you do immediately *after* an earthquake?
   Answer: e — Both c and d. Check for injuries, hazards (fire, gas leaks, spills, etc.), clean up, expect aftershocks, listen to radio. Anticipate tsunamis if you're on the coast and quickly go inland or uphill. Also, remember that there very well may be strong aftershocks, that is, additional earthquakes.
5. **Question:** When did the last great subduction-zone earthquake and tsunami hit coastal Oregon?
   Answer: a and b — On January 26, A.D. 1700, **and** about 300 years ago. Scientists have found many lines of evidence for a great (i.e., magnitude 8 and higher) earthquake event about 300 years ago. Evidence includes land subsidence, land uplift, tsunami deposits, liquefaction features, and turbidites, as well as cultural evidence from coastal Native Americans. Studies by a Japanese scientist of the historic record of tsunamis experienced in Japan suggest that a Cascadia event occurred specifically on January 26, 1700. The M 7 Cape Mendocino ("Petrolia") earthquake of April 1992 occurred on the northern Californian coastline about 50 km south of Eureka and was likely a subduction zone earthquake.
6. **Question:** When did the last damaging tsunami hit the Oregon coast?
   Answer: c — March 1964. The M 9.2 Prince William Sound Alaska ("Good Friday") earthquake on this date generated a tsunami that hit coastal Oregon (and California). There were several fatalities at Beverly Beach, Oregon, and in Crescent City, California. Low-lying coastal areas that suffered damage due to flooding included Seaside, which suffered the most damage to structures; Newport's Yaquina harbor; and Cannon Beach, which had a bridge collapse.
7. **Question:** Are there active faults near you?
   Answer: a — Probably yes, but their locations are not well understood. Earth scientists (seismologists and geologists) have identified **some** faults in Oregon, but certainly not **all** of them. Furthermore, faults that have been identified may or may not be *active*, that is, capable of generating earthquakes. A 1995 report titled "Seismic Design Mapping, State of Oregon," and prepared for the Oregon Department of Transportation includes the most comprehensive *active* fault map for the state. Copies are available in the libraries of the DOGAMI offices in Portland, Baker City, and Grants Pass.
8. **Question:** To protect against loss of life, property, and injury, do the following:
   Answer: e — All of the above (vulnerability study, risk study, prioritizing your seismic strengthening needs, and preparing emergency kit and response plan) **and follow through with necessary actions.** □

The development of the Portland, Oregon, Building Code—50 years of evolution, 1945–1995. A comparison of seismic events and structural aspects

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ABSTRACT

Revision to building codes has not always been an action resulting from specific steps taken by specific identities. The growth of a code has often been a very vague process. One factor that could affect a structural design code evolution is the seismic environment in which the code operates. It therefore is of interest to see if the occurrence of seismic events in the geographic area serviced by the Portland Building Code seems to have had an effect on the structural requirements of the code for designing a structure in that area. The tabulation herein shows very little connection between seismic occurrences and code changes from 1940 to 1990. Subsequent changes were made by an entity created to examine the seismicity of Oregon, which reversed a previous disinterest to a highly sensitive interest. Code changes as revealed by the records in the Portland Archives then began to respond to seismic events.

INTRODUCTION

The City of Portland emerged from the days of World War II with a code that had been written during the Depression as a job maker. It specified in detail the materials that could be used in construction in Portland and how they were to be used. The Code did not pretend to address any loading condition that could come from an earthquake. It did address wind, with numbers provided for the pounds per square foot of vertical surface that were to be applied in the design, but no other horizontal loading was mentioned.

Structural engineering as an identified engineering discipline was greatly augmented by the Long Beach, California, earthquake of 1933. That event, causing much loss of life and property, was a surprise to southern California and caused the passage of a state law requiring public buildings to be designed by a structural engineer. It also started the study in California of the effects of earthquakes on buildings.

In 1948, the American Telephone and Telegraph Company (AT&T) was planning to build a central switching building in Portland. AT&T wanted that building to be solid and to survive major events. They became interested in its exposure to earthquakes and thus were responsive to the insistence of a consulting structural engineer named Guy Taylor, who had been preaching about the susceptibility of Oregon to earthquakes ever since his return from service in the Army. His firm, Moffatt, Nichol, and Taylor, now Moffatt, Nichol, and Bonney, was retained to furnish the structural design of this switching building with Pietro Belluschi as the architect. Since I had extensive experience in aircraft design and responding to loads from any direction, he assigned to me the task of designing that building.

In that process I became convinced that Portland should in fact address the probability of having an earthquake and began to talk to the city commissioners about that. There had been for very many years a structural engineer named Miles Cooper who had been, until Taylor came on the scene, virtually the only structural engineer in the state and who had been kept overwhelmingly busy just designing things to take their vertical loads and thus had never thought much about earthquakes. But Guy Taylor and I kept working on the city commissioners to convince them that earthquakes could happen in Portland.

In 1949, we started the Structural Engineers Association of Oregon. The organization had an exceedingly small membership at the beginning, but we were attuned to the activities of the Structural Engineers Associations of both northern and southern California, where seismic design was extremely high on the agenda. We attended their conventions and listened to their theories. We advised the local City Council on the expectations that many engineers were beginning to accept: that we were likely to have earthquakes and needed to be current on designing for them—as was being pursued in California. The Public Works Commissioner then was Bill Bowes. We started talking to him about adopting a code that included earthquake loading. The idea of a performance code was a real problem with Bill. In fact, we had two problems with him: In his view, (1) the old specification code was an Oregon product and thus was just right for Portland, and (2) only California and Washington had earthquakes.

The business community, fearing higher construction costs, was glad to agree with Bowes wholeheartedly.

We were suggesting the adoption of the Uniform Building Code (UBC) by the City of Portland. Bill was sure that no one outside Oregon was qualified to write a proper code for Portland, much less for Oregon. So we did not get far very fast. The earthquake in the Olympia, Washington, area in 1949 that also shook Portland fairly firmly had a slight effect on Bill's thinking. Finally in 1955, after a good shake on December 15, 1953, the City Council became convinced that an improvement was overdue and decided to adopt at least parts of the UBC. But when it came to earthquake loading, the City adopted the code in such a way as to put Portland in a Zone 1 location, even though the UBC suggested it be in Zone 2.

Table 1. *Correlation of Portland, Oregon, building code revisions with seismic events felt in Portland 1940–1995. Comparison of city ordinance and state actions and intent with seismic events magnitude 4.0 or greater. Earthquake data from Bott and Wong (1993). Portland ordinances in City of Portland Archives*

	City and state actions			Seismic design requirements		Seismic events		
Year	Ordinance	Adopted	Provisions	Portland	UBC[1]	Date	Magnitude	Location
1995	168627	03/22/95	Delays retrofitting existing buildings until 1997	Zone 3	Zone 3	—	—	—
1994	—	—	—	Zone 3	Zone 3[1]	—	—	—
1993	(State)	01/01/93	OSSPAC[2] adopts Zone 3 for western Oregon	Zone 3	Zone 2B	09/20/93	6.0	Klamath Falls
						03/25/93	5.6	Scotts Mills
1992	166111	12/23/92	State 1993 Structural Code adopted with UBC 1990 edition	Zone 2B	Zone 2B	—	—	—
1991	—	—	—	Zone 2B	Zone 2B[1]	—	—	—
1990	162695	01/18/90	State 1990 Structural Code adopted with UBC 1988 edition	Zone 2B	Zone 2B	—	—	—
1989	—	—	—	—	—	—	—	—
1988	—	—	—	Zone 2	Zone 2B[1]	—	—	—
1987	—	—	—	—	—	—	—	—
1986	(State)	07/01/86	State adopts 1985 UBC edition	Zone 2	Zone 2	—	—	—
1985	—	—	—	Zone 2	Zone 2[1]	—	—	—
1984	—	—	—	—	—	—	—	—
1983	155104	09/15/83	Replaces City Title 24 regulations with new version. Adopts State Code of 1983	Zone 2	Zone 2	—	—	—
	(State)	08/01/83	State adopts 1982 UBC edition	Zone 2	Zone 2			
1982	—	—	—	Zone 2	Zone 2[1]	—	—	—
1981	—	—	—	—	—	02/13/81	5.5	Mt.St. Helens
1980	(State)	07/01/80	State adopts 1979 UBC edition	Zone 2	Zone 2	—	—	—
1979	—	—	—	Zone 2	Zone 2[1]	—	—	—
1978	(State)	03/01/78	State adopts 1976 UBC edition	Zone 2	Zone 2	—	—	—
1977	—	—	—	—	—	—	—	—
1976	—	—	—	Zone 2	Zone 2[1]	—	—	—
1975	—	—	—	—	—	—	—	—
1974	(State)	07/01/74	State adopts 1973 UBC. Cities' acceptance made mandatory	Zone 2	Zone 2	—	—	—
1973	—	—	—	Zone 2	Zone 2[1]	—	—	—
1972	134654	05/26/72	Replaces Title 24 City Code. Adopts UBC 1970 edition	Zone 2	Zone 2	—	—	—
1971	—	—	—	—	—	—	—	—
1970	130672	03/20/70	An ordinance enacting the "Code of the City of Portland, Oregon" on the regulations and prohibitions relating to public space, health, safety, or public welfare	Zone 1	Zone 2[1]	—	—	—
1969	—	—	—	—	—	—	—	—
1968	—	—	—	—	—	—	—	—
1967	—	—	—	Zone 1	Zone 2[1]	—	—	—
1966	—	—	—	—	—	—	—	—
1965	—	—	—	—	—	—	—	—
1964	—	—	—	Zone 1	Zone 2[1]	—	—	—
1963	—	—	—	—	—	12/27/63	4.5	Banks
1962	—	—	—	—	—	11/05/62	5.5	Scappoose
1961	—	—	—	Zone 1	Zone 2[1]	11/06/61	5.0	Portland
						09/17/61	5.0	Cougar
						09/15/61	4.5	Cougar
						08/18/61	4.5	Mill City
1960	—	—	—	—	—	—	—	—
1959	—	—	—	—	—	—	—	—
1958	—	—	—	Zone 1	Zone 2[1]	—	—	—
1957	—	—	—	—	—	11/16/57	4.5	Tillamook
1956	103415	01/07/56	Replaces Building Code of Ordinance 77435. First to incorporate "Earthquake Regulations" per UBC of 1955. Restricts to Zone 1 loading	Zone 1	—	—	—	—
1955	—	—	—	—	Zone 2[1]	—	—	—
1954	—	—	—	—	—	—	—	—
1953	—	—	—	—	—	12/15/53	4.5	Portland
1952	—	—	—	—	Zone 2[1]	—	—	—
1951	—	—	—	—	—	—	—	—
1950	—	—	—	—	—	—	—	—
1949	—	—	—	—	Zone 2[1]	04/13/49	7.1	Olympia
1948	—	—	—	—	—	—	—	—
1947	—	—	—	—	—	—	—	—
1946	—	—	—	—	Zone 1[1]	—	—	—
1945	—	—	—	—	—	—	—	—
1944	—	—	—	—	—	—	—	—
1943	—	—	—	—	—	—	—	—
1942	77435	May 1942	Specification Code written by Bureau of Municipal Research and Service, University of Oregon/League of Oregon Cities. Funded by Works Progress Administration	None	—	—	—	—
1941	—	—	—	—	—	12/29/41	4.5	Portland
1940	—	—	—	—	—	—	—	—

[1] UBC = Uniform Building Code, which is reissued every three years.
[2] OSSPAC = Oregon Seismic Safety Policy Advisory Commission.

There was no state building code at that time. Outside a city limit, anything could be built with anything to any criteria, if any. So there was considerable concern expressed in the rural areas about the thought of requiring a building to be made expensive to build by requiring earthquake considerations in its design. So the Portland adoption was not a welcome development in the State of Oregon. The majority of the people did not consider Oregon to be subject to earthquakes—California, yes, and maybe Washington, but not Oregon.

Structural designing is taken very seriously by structural engineers. During the 1950s, many of us designed to Zone 2 loading. Even so, very often wind was the major factor, not the light requirement of Zone 2. One thing we did not fully appreciate was the relation between the characteristics of the site and those of the building. We had not thought much about the site—it was just there.

The Oak Street Building of AT&T had been designed with the steel frame taking all the horizontal forces, then the outer concrete shear wall being nearly equal in strength to provide redundancy. In that process was used a method called Moment Distribution that determines the moments and shears acting on the steel frame. This was a method of calculating the moments created in a steel frame with continuous joints and had been developed by Hardy Cross at Yale. Using that moment distribution method was a tedious procedure, requiring calculating moments reflected back and forth, up and down, until the refinement of accuracy presumed to be required by the analyst was reached. So it was a slow process, increasing design costs.

The role of the structural engineer was undergoing a strain in this evolution of the criteria accepted as that which was necessary and proper for use to both safeguard the life and property of the public and do so at minimum cost to that public. That dichotomy still exists. The professional engineer is committed to obtaining a product safe for the public to use—and yet to achieving this at minimum cost to the using public. It is easy to establish high requirements and design to them, but if during the life of a structure this structure is never subjected to conditions that justify those requirements, the cost of providing for them may be considered as a loss or, at a minimum, as the cost of insurance. So the profession has debated and continues to debate how much is enough but not more than needed.

This burden is now being shared with the seismologists. Society is now looking to them for guidance on the probable size of the next earthquake as well as its possible imminence. Both have major impacts on the investment that society decides to make in the environment it builds. The seismologist has joined the meteorologist as a major influence on the structural design of our built environment.

DISCUSSION OF TABLE 1

Table 1 lists all the Portland ordinances adopted by the City Council that affected the structural designing of buildings from 1940 to 1995. It also lists code-related activities that occurred in that time. Such activities were the issuance of a new Uniform Building Code, the adoption of a new city ordinance, or an action of the State of Oregon. Also shown are the dates and magnitudes of earthquakes felt in Portland to the extent that they were deemed to have had a magnitude of 4 or greater.

The table reads chronologically from the bottom up. Each activity is shown with its date. If there was no activity, no information on that year is supplied.

The first code in the State of Oregon that required structures to be designed to resist earthquake forces did so gingerly. The Portland Code 103415, adopted January 7, 1956, incorporated that requirement as an appendix and provided that Portland designs should utilize earthquake Zone 1 forces, even though the UBC of 1955 that was being adopted showed Portland in a Zone 2 location. Portland Code 103415 called for the application of a horizontal loading at each floor, influenced by the number of stories above that floor. The total weight is made up of all the dead load tributary to the point under consideration. It called for foundation ties but did not address the geological characteristics of the site. Stresses were allowed to exceed the allowable working stresses by 33.3 percent. Overturning moment was not to exceed two thirds of the moment of stability. The Force Formula was a simple one of $F = CW$, with C coming from a table wherein the Zone was recognized and W being the contributing weight.

The zone recommended by the UBC for Portland and western Oregon had been Zone 2 since the UBC edition of 1949, which moved Portland from Zone 1 to Zone 2. The reluctance by Portland to accept the Zone 2 designation was primarily a political decision.

The 1961 UBC edition formula for calculating the horizontal force became $V = ZKCW$, with Z coming from the table as before but with K from a new table reflecting the type of framing system and C being a numerical coefficient for base shear calculated to recognize the period of the structure. This lateral force V was distributed over the height of the building by an equation that reflected the mass of the building at the point of application of the force. The structural frame for buildings 13 stories high or higher had to be a moment-resisting ductile space frame capable of resisting not less than 25 percent of the required seismic load for the structure as a whole.

The overturning moment was more fully addressed than previously by the utilization of three formulas that recognized the possible differences in resistance to overturning among various elements of the building—as well as the period of the structure. Story drift was mentioned, but no limitations were established. Reference was made to "accepted engineering practice." Stresses from a combination of vertical and lateral loads could be increased.

Thus this code reflected considerable thought on the structural analysis aspects of an earthquake but did not consider the characteristics of the site that would affect the structure. It was not adopted by the City of Portland.

The 1964 UBC edition was structurally substantially the same as the 1961 edition. The earthquakes of 1961 had not had an opportunity to have an influence on the code.

The 1967 UBC edition required a more careful analysis of the *W* factor (total dead load). It distributed the total lateral load over the height of the structure by a new formula for *V*. It was still interested in the period of the building. The overturning moment analysis was unchanged. There was no reference to site geology.

The 1970 UBC edition was substantially the same as the 1967 code in reference to earthquake designing. It showed Portland as being in Zone 2, with a revised area of southern and western Oregon placed in Zone 1.

On March 20, 1970, City Ordinance 130672 enacted the "Code of the City of Portland, Oregon," revising the makeup of the city codifying and retaining the established structural requirements, which still put the city in Zone 1, while the UBC had it in Zone 2 at that time (1970 edition).

On May 26, 1972, Portland Ordinance 134654 substituted a new Title 24 code for the existing one. It specifically adopted the UBC 1970 edition, moving Portland from Zone 1 to Zone 2 for the first time. Thus, ten years after the last Oregon earthquake—Banks (magnitude 4.5), on 12/27/63—Portland moved up a space from the minimum zone level.

The 1973 UBC edition simplified the determination of the weight *W* but did not change the basic lateral load formula which still reflected the period of the structure. Overturning moment was addressed in Section 2314; and for specific limits, reference was made to Section 2308. Still no comment was made about site relevance. On July 1, 1974, the State of Oregon adopted the 1973 edition of the UBC with its designation of Zone 2 for Portland.

The 1976 UBC edition added to the earthquake design a requirement to consider the "Occupancy Importance Factor" as taken from a table. This factor varied from 1.5 for "Essential Facilities," to 1.25 for buildings of primary assembly for more than 330, to 1.0 for all others. Provisions for consideration of the site characteristics were added to the basic lateral forces formula. The formula $V = ZIKCSW$ thus included the *I* (Importance) and the *S* (Site-structure resonance) in its makeup. The *S* factor reflected *T* the period of the site, which could be determined by geotechnical data or was to be taken as 1.5, if not otherwise established. The minimum *T* as established could be 0.3 seconds, or up to 2.5 seconds. Provisions for ductile design and distribution of lateral loads were more fully addressed.

On March 1, 1978, the State of Oregon adopted the 1976 edition of the UBC—with Portland in Zone 2.

The 1979 UBC edition made structural refinements in some of the equations and addressed the use of concrete shear wall design. It also addressed what had become known as "Exterior Elements" at considerable length. Portland was still in Zone 2, with a Zone 1 area inserted across central and southern Oregon.

On July 1, 1979, the State of Oregon adopted the 1979 edition of the UBC with Portland in Zone 2.

The 1982 UBC edition made no change in the basic lateral force formula as established. It did make some refinements in the loading of bracing members. Portland was unchanged in Zone 2.

On August 1, 1983, the State of Oregon adopted the 1982 edition of the UBC.

On September 9, 1983, with Ordinance 155104, the City of Portland replaced its Title 24 regulations with a revised Title 24, and adopted the Oregon State Building Code of 1983, thus adopting the 1982 UBC edition.

The 1985 UBC edition added a new provision relating to the *S* factor in the horizontal force formula. The factor varied according to the makeup of the site, varying from rock to stiff clay to soft clay. The factor varied from a minimum of 1.0 on rock to 1.5 on soft clay. In sites of unknown characteristics, factor 1.5 was to be used. Refinements were made in structural requirements, but the Zone identities were not changed.

On July 7, 1986, the State of Oregon adopted the 1985 edition of the UBC.

The 1988 UBC edition made major changes. It required that consideration be given in the structural design to zoning, site characteristics, occupancy, configuration, structural system, and height. It introduced a factor *R*, which reflected the type of structural system being used, into the lateral force equation. It mandated that design use the dynamic lateral force procedures for structures 240 ft or more in height, for those having certain vertical irregularities, and, with some exceptions, for any structure over five stories or 65 ft in height in Zones 3 and 4 that did not have the same structural system throughout their height. The code addressed both static and dynamic structural design and their relationships to the site. The soil coefficient *S* varied from 1.0 for rock to 2.0 for a 40-ft depth of clay.

This edition put all of Oregon in a new Zone 2B and added a set of curves to guide the selection of the effect of site on structures of various periods.

On January 18, 1990, the City of Portland, with Ordinance 162695, adopted the State of Oregon Structural Code of 1990 with its 1988 UBC edition, putting Portland in Seismic Zone 2B.

The 1991 UBC edition made extensive revisions to many aspects of structural design but did not revise the basic approach to site characteristics and their possible effects on the structure. The factor *S* was still obtained from a table.

On December 23, 1992, the City of Portland, with Ordinance 166111, adopted the State of Oregon Structural Code of 1993 with its 1990 UBC edition, continuing Portland in Seismic Zone 2B.

On January 1, 1993, the Oregon Seismic Safety Policy Advisory Commission adopted Seismic Zone 3 for western Oregon. This was the result of long analysis and debate among Oregon structural engineers and state geophysicists.

The current 1994 UBC edition contains a major revision of the design requirements for seismic resistance of buildings. It extensively addresses dynamic as well as static de-

sign and relates the structures to the geology. It does not address the identification of the characteristics of sites in the retrofitting of structures less than five stories high. It puts all of western Oregon in Zone 3, along with western Washington and portions of northern California. It puts eastern Oregon in Zone 2B.

CONCLUSION

Thus it is seen that seismic events seem to have had little effect on the determination of seismic structural design of buildings until after the 1991 UBC edition. Portland had ten very quiet years to contemplate its seismic exposure after the Banks event (M 4.5) on December 27, 1963. Subsequent events in California and elsewhere (especially the 1989 Loma Prieta earthquake and its well-publicized effects on the San Francisco area), however, caused the Oregon Seismic Safety Policy Advisory Commission to take a hard look at the potential in Oregon for a major seismic event. With input from geologists of the Oregon Department of Geology and Mineral Industries, the Structural Engineers Association of Oregon, and others, this led to the adoption of Zone 3 as the design loading for all of western Oregon. In response to the adoption by Oregon, the UBC promptly did likewise.

Careful examination of failures of structures in earthquakes in the last ten years or so has revealed a potentially close relationship between the seismic characteristics of the site and the seismic performance of the structure on it. The UBC has increasingly recognized that potential tie. Whether that recognition is sufficiently close now is a matter that deserves much more attention.

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Current practice in seismic design of structures owes a great deal to the obsessed devotion to that matter among many pioneer engineers and geologists. The Earthquake Engineering Research Institute with its worldwide membership has been at the cutting edge of the development of the seismic design technology. Early members like George W. Housner, John Blume, and John Rinne provided imaginative and innovative thinking on a problem that had been recognized for several years but was not appreciated as something that could be conveniently addressed. They and many others were instantly aware that it was a problem that had solutions, and they devoted their professional skills to fully understand the phenomena involved and to provide for their effects.

Response observed after recent earthquakes indicates that considerable progress has been made, but perfection may not yet have been reached. As yet, the vast field of retrofitting is far from being adequately addressed. An economical and effective way to obtain safety for historic or cherished structures at the site on which they happen to be located still deserves much attention.

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EERI offers new slide set: Expected seismic performance of buildings

The Ad Hoc Committee on Seismic Performance of the Earthquake Engineering Research Institute (EERI) has created a slide set to complement the highly popular booklet, *Expected Seismic Performance of Buildings*, which it published in 1994. The booklet and slide set were developed to help building owners, code administrators, and others involved in building maintenance understand how seismic design provisions and quality of construction affect earthquake performance. They describe damage to buildings that may be expected from earthquakes of various magnitudes. The focus is on new buildings in Seismic Zone 4 designed under the 1991 UBC (Uniform Building Code) and on older unreinforced masonry (URM) buildings rehabilitated under the 1991 UCBC (Uniform Code for Building Conservation).

Both booklet and slide set are intended for a nontechnical audience. They can be used by building officials, engineers, and others involved in seismic design, codes, and construction techniques as an easy way to answer questions with the help of a slide presentation. They also provide an excellent educational tool to explain the goals and limitations of seismic provisions in building codes and to dispel some myths that lead to false expectations about building performance.

The new set, *Expected Seismic Performance of Buildings*, consists of 40 slides (including a printed copy of each slide for better reference) and is offered in a package with the 20-page booklet of 1994 for $70 ($60 EERI members). The booklet alone is available for $4. California orders must include 8.25 percent sales tax; orders from outside the U.S. must add 10 percent for shipping.

Orders should be directed to the EERI office at 499 14th Street, Suite 320, Oakland, CA 94612-1934, phone (510 451-0905, FAX (510) 451-5411.

Evaluating the effectiveness of DOGAMI's Mined Land Reclamation Program

by Deborah Gellar, Urban and Regional Planning Program, Michigan State University, East Lansing, Michigan 48824

ABSTRACT

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

INTRODUCTION

Mining is an active industry in Oregon, with the extraction of industrial minerals (e.g., diatomite, limestone, pumice, bentonite, silica), metals (e.g., gold, silver, nickel), and aggregate (e.g., sand, gravel, rock) occurring throughout the state. In particular, the demand for aggregate products continues to rise along with population and urban growth.

Historically, the consequence of mining operations over time has resulted in short-term impacts on natural resources and permanent changes to natural landforms. The state of Oregon has risen to the challenge of responsibly regulating the mineral industry. Comprehensive state requirements regulate the operation and reclamation of active mines. In 1971, legislation was passed which required that operators reclaim surface mine areas to support a second beneficial land use after mine closure. The Oregon Department of Geology and Mineral Industries (DOGAMI) began implementation of the Mined Land Reclamation (MLR) program in 1972. The Oregon Mined Land Reclamation Act exempted lands disturbed prior to July 1, 1972, from the reclamation requirements. However, any acreage mined after 1972 that exceeds minimum production and acreage requirements is subject to state reclamation requirements.

Applications for a mine operating permit must include a reclamation plan. Therefore, the preferred reclamation methods and goals are determined prior to beginning or expanding mining operations. A post-mining land use must be designated during the application process and must be supported by the reclamation plan. Standard information required in the reclamation plan includes designation of second land use, creation of stable landforms, restoration of drainage(s), and identification of specific measures to protect surface-

Healthy stream that was reestablished after mining.

and ground-water quality, sloping and grading, and vegetation establishment. After a site has been reshaped, and revegetation has been successfully established, the site is evaluated by DOGAMI for release from the program.

DOGAMI's six-year plan, *Mission, Goals, and Activities 1991-1997*, states as part of the Department's "vision" that "regulatory programs will ensure that mineral resource extraction is conducted as an interim use of lands that are returned to subsequent beneficial long-term uses." More than 500 surface mine sites in Oregon have been closed since the MLR program began in 1972. Since then, 3,160 acres have been successfully reclaimed and released from the program. Until this project, no comprehensive study had been done to evaluate the condition of these lands years after they were released from the MLR program.

This paper summarizes a 1995 study to evaluate the effectiveness of the MLR program. The study asks the following questions: Is the goal of providing long-term beneficial land use being met? What post-mining uses are these lands supporting? Have the required reclamation practices been effective over a long period of time? Have former mine sites continued their development towards healthy, self-sustaining environments?

SITE SELECTION

The primary goal of the study was to document former mine site conditions and to evaluate the MLR program. This task was addressed through field studies of 47 former mine sites (Table 1). DOGAMI's computer database was used to select sites meeting three basic criteria for the study: (1) Sites were subject to state reclamation requirements. (2) Sites have met all reclamation requirements. (3) Sites have been closed for at least five years (i.e., closed prior to 1990). Selections were further winnowed as sites were sorted by location and mineral commodity to ensure reasonable representation of mine types and geographic coverage.

The selected post-mined sites form a representative sample of lands that have been accepted as reclaimed by DOGAMI. In order to determine the effectiveness of the reclamation program, MLR-managed sites were also compared to sites not subject to reclamation. Ten mine sites exempt from DOGAMI reclamation requirements (pre-law sites[1]) were also included in the study.

Field studies were performed at 17 reclaimed sites in high-precipitation regions, at 20 reclaimed sites in low-precipitation regions, and at ten pre-law sites at scattered locations in Oregon. The commodities represented include rock, sand, gravel, clay, gold, topsoil, shale[2], picture rock, and cinder. Sites were surveyed in remote, rural areas as well as in densely populated, urban regions.

[1] Term for mine sites that are exempt from state reclamation requirements because they began operation prior to 1972 and have not expanded beyond the 1972 perimeter.

[2] In Oregon miner's terminology, shale is almost any fine-grained material that can be mined with a front-end loader and can be used without further processing for such applications as surfacing driveways.

Table 1. *Site Summary*

Site	County	Commodity	Years closed	Precipitation type
0001	Clatsop	Gravel	9	High
0002	Deschutes	Gravel	Inactive	Low
0003	Douglas	Gold	9	High
0004	Douglas	Gold	10	High
0005	Douglas	Gold	9	High
0006	Gilliam	Basalt	7	Low
0007	Gilliam	Basalt	Inactive	Low (pre-law site)
0008	Grant	Gold	10	Low
0009	Grant	Gravel	13	Low
0010	Harney	Cinder	10	Low (pre-law site)
0011	Harney	Basalt	10	Low
0012	Harney	Gravel	7	Low
0013	Hood River	Basalt	12	Low
0014	Jackson	Shale	13	Low
0015	Jackson	Shale	13	Low
0016	Lane	Basalt	8	High
0017	Lane	Basalt	8	High
0018	Lane	Basalt	2	High
0019	Lane	Gravel	13	High
0020	Lincoln	Clay	17	High
0021	Linn	Rock	Inactive	High (pre-law site)
0022	Linn	Rock	Inactive	High (pre-law site)
0023	Linn	Gravel	11	High
0024	Linn	Gravel	10	High
0025	Linn	Basalt	>20	High (pre-law site)
0026	Malheur	Gravel	7	Low
0027	Malheur	Picture rock	5	Low
0028	Malheur	Gravel	9	Low
0029	Malheur	Gold	6	Low
0030	Malheur	Gold	9	Low
0031	Malheur	Gold	9	Low
0032	Marion	Topsoil	13	High
0033	Morrow	Gravel	Inactive	Low
0034	Multnomah	Gravel	5	High
0035	Sherman	Rock	14	Low
0036	Tillamook	Basalt	11	High
0037	Umatilla	Rock	Inactive	Low (pre-law site)
0038	Umatilla	Rock	Inactive	Low (pre-law site)
0039	WalLowa	Gravel	8	Low
0040	Wasco	Rock	>20	Low (pre-law site)
0041	Wasco	Basalt	5	Low (pre-law site)
0042	Wasco	Gravel	8	Low (pre-law site)
0043	Washington	Basalt	8	High
0044	Washington	Gravel	Inactive	High
0045	Wheeler	Gold	12	Low
0046	Wheeler	Gold	13	Low
0047	Yamhill	Rock	10	High

FIELD STUDIES

The state of Oregon has diverse environmental regimes, including mountain ranges, large valleys and basins, coastal regions, and desert. For simplicity in this study, however, the state has been divided into two regions on the basis of annual precipitation rates. Low-precipitation regions are those areas with total annual precipitation of < 40 in./year, which generally describes regions east of the Cascades. There, most sites have a precipitation of < 20 in./year. High-precipitation regions are typically those west of the Cascades, where the

much wetter climate is characterized by annual precipitation rates of 40–100 in./year.

The data collected during the field studies describe the primary site characteristics. These are separated into five categories:

1. The **landform characteristics** describe erosional features such as gullies, slumps, and slides, and identify any overburden piles and whether they were sloped and vegetated. A determination was made whether the final landforms conflict with or support the current land use and whether they blend in with the surrounding topography.

2. Successfully reclaimed lands must support a second beneficial **land use**. Information was gathered to record the type of current use and then compared to the land use proposed in the reclamation plan.

3. Dominant plant and tree species were identified, as well as percentage of ground cover and general species diversity. The **vegetation** identified at the time of closure was compared to that currently supported on site. Volunteer species were identified and their abundance noted, including annual and noxious weeds. Any appearance of overgrazing was also noted.

4. Sites were evaluated for their use as **wildlife habitat**, regardless of the designated end use. Basic indicators included estimates of percent of cover, diversity of vegetation, and visual observations of animals, tracks, scat, game trails, bedding areas, and burrows. These gave a general impression of the usage or potential usage as wildlife habitat.

5. Any **wetlands** created or left were described by size, type of vegetation, and general vigor. **Streams** were examined for stable and vegetated banks. **Ponds** were often created by gravel mining or other excavations below water table, and these were described on the basis of their shape, size, bank stability, and vegetation.

In addition to the preceding list, photographs were taken during the field surveys to document current site conditions. A comparison of historical photographic records with current photos allowed visual evaluation of program effectiveness over an extended period.

Pond in high-precipitation area.

RESULTS

Landform characteristics

The landforms observed at reclaimed mine sites were generally in excellent condition. Soils and slopes were consistently stable, and erosion was not an issue. No safety hazards were noted from unstable or oversteepened areas. One feature occasionally observed was the presence of unvegetated rock piles. This prevented the site from blending in well with the surrounding areas and was aesthetically detrimental. This is not necessarily a reflection on reclamation regulations, as DOGAMI policy permits leaving stockpiles for landowner use after mine closure. Further, no regulations address aesthetics (except in designated "Scenic Areas").

Sloping is critical as a reclamation procedure for safety, topographic continuity, erosion control, and vegetative success. An overly steep highwall/slope may not support vegetation, whether volunteer, planted, or seeded, and is more likely to erode or be unstable. The few small bare areas observed during the study were either rock piles with no cover of topsoil, steep slopes, or highwalls. The lack of vegetation in these cases seemed to be a function of poor landform characteristics rather than failure of revegetation efforts.

Most sites did blend in well with surrounding topography. The regulations regarding final angle of slopes are 3:1 (horizontal to vertical ratio) below water, 2:1 for above-water slopes of fill material, and 1.5:1 for above-water slopes cut into the pre-mine topography. These standard requirements serve to accomplish safety, erosion control, and establishment of vegetation. They have been applied effectively and have resulted in the maintenance of high-quality landforms over time.

Land use

Statutes require that the post-mining (second) land use be declared in the reclamation plan. The planned reclamation techniques must provide the appropriate resources to support the declared land use. Second land uses also must be physically supported by the underlying landform, type and amount of soil resources, vegetation, and appropriate water bodies.

Second uses may be determined by the value of the land for post-mining development. Land in urban areas has relatively high property value, and study sites in these settings

tended to have high-intensity second uses. Reclamation of post-mined land in urban regions can be highly profitable, and this is a strong incentive for operators to reclaim the land for industrial sites, residential developments, or parklands. For those sites that were high in human traffic, negative impacts on natural resources included compacted soils, littering, and trampled vegetation. Therefore, some second uses can have a negative impact on the condition of the land if they are not designed to accommodate high-intensity uses.

Heavily used fishing pond in Lane County.

The sites in rural and remote areas were supporting low-impact land uses. In high-precipitation areas, land uses were often fields and ponds, which also functioned as wildlife habitat. Sites in the low-precipitation areas frequently were reclaimed to rangeland. This is due to the fact that eastern Oregon sites are predominantly located on Bureau of Land Management (BLM) land, where policy generally requires the land to be returned to pre-mine use. At most of these sites, reclamation to grazing conditions was successfully accomplished.

The proposed end use must be clearly stated within the reclamation plan, and this use must have landowner concurrence. The plan is circulated to the appropriate local land use agency for comment. The accepted post-mining land uses can then be used as a goal that will be achieved through supportive reclamation practices. This administrative procedure appears to be successful, as former mining sites consistently support viable second uses, which are sustained by the underlying landforms and vegetation.

Vegetation

In general, post-mining vegetation was well established in all regions. A high percentage of ground cover and good species diversity existed on most sites. The reclamation plantings and seedings did remain healthy at most sites, but with varying degrees of assimilation into much larger, more diverse vegetative communities.

In high-precipitation regions, fast-growing species are selected to assure immediate erosion control through ground cover. The long-term persistence of these species was less important, because growing conditions also favor rapid volunteer growth. The survival rate and percent cover of vegetation is naturally greater in the high-precipitation regions because of the available moisture, topsoil, and adjacent seed sources.

In low-precipitation regions, the seeding mixes are more critical, because survival rates are lower due to the limited moisture and to the poor quality of topsoil. Survival of the planted species may be low due to overgrazing, and therefore volunteer species may come from less diverse, and sometimes less desirable, vegetative communities. This can include noxious weeds, which create undesirable ecosystems that out-compete native vegetative species. Better grazing practices and fencing to exclude cattle can give vegetation time to achieve proper root development and develop into self-perpetuating ecosystems.

Even in cases where percent of ground cover was low, reclaimed low-precipitation sites still fit in well with the surrounding plant communities, in part due to volunteer species. One possible exception is proliferation of aggressive vegetation (e.g., annual/noxious weeds), which induce adjacent native plant communities to encroach. Again, it is critical to determine the appropriate seed mix for each site in low-precipitation regions. The type of vegetation desired should support the second land use and take advantage of proper planting times and ground preparation techniques.

State reclamation requirements include successful revegetation of the site. In low-precipitation regions, delayed germination can result in a longer monitoring period (1–3 years) after seeding has been initiated. While this period appears to be an adequate time frame for establishing vegetative cover, no set standard for vegetative species mix exists.

DOGAMI, working with the BLM and other appropriate natural-resource agencies, recommends specific seed mixes to mine operators. The agencies also provide information about techniques to increase the survival rate of seedings, including tilling, mulching, and use of topsoils. This no doubt contributes towards higher survival rates on low-precipitation lands.

Wildlife habitat

More than 50 percent of the sites were clearly functioning as viable wildlife habitats, and another 25 percent had significant potential (or less obvious usage by wildlife). Wildlife habitat was created in a variety of environments across the state and was not region-specific. Poor landform or aesthetic characteristics may not negatively affect wildlife usage. Many sites with rock piles and highwalls were inhabited by wildlife. A wide diversity of animal species was directly observed, from song and game birds to antelope and deer. Sites with water bodies supported the most vigorous wildlife habitats. Vegetative diversity is also important, and the presence of a wide variety of species usually increased the quality of the habitat.

Many sites did not have wildlife habitat as their designated end use but were functioning as such. Those sites that were not supporting wildlife were in urban areas or areas with high human usage. In eastern Oregon, overgrazing of reclaimed sites was observed to negatively impact both vegetation and soil stability. Cattle will eat selectively, thus affecting the vegetative composition and reducing preferred food for grazing wildlife.

The creation of wildlife habitat is specifically supported by regulations only when this is the second land use designated in the reclamation plan. Otherwise, while DOGAMI encourages seed mixes that foster wildlife habitat, such a requirement is not part of the regulatory framework. Most of the reclaimed and pre-law sites are supporting wildlife habitats, in addition to the primary proposed end use. This suggests that regulatory initiatives are not required to promote post-mining wildlife habitat. While these successes are not a direct function of regulatory requirements, DOGAMI's practice of encouraging diverse seed mixes and variety in landform has resulted in post-mining sites that support a second land use as well as wildlife populations.

Wetlands that were specifically designed to attract wildlife.

Water/wetlands issues

All streams and ponds at the observed sites were well established. Banks were consistently well sloped, stable, and revegetated, and no sedimentation problems existed. Wetlands were created as a fringe effect around ponds created by the mining operations. Ponds are commonly created at former sand and gravel pits, and these consistently had stable, well-vegetated banks. The water bodies supported fish populations and aquatic vegetation and appeared to be healthy environments. Ponds are more common in the regions of abundant precipitation. However, several ponds in low-precipitation areas were of exceptional quality. Reclamation requirements that direct the reestablishment of streams and drainages, including bank restoration, appear to be very effective. Banks were well vegetated and fit in with surrounding environments. The ecosystem established was vigorous and contributed diversity to the surrounding environments.

INCIDENTAL OBSERVATIONS

All surveyed sites had been closed for at least five years. Greater age did not seem to be an important factor in establishment and thickness of vegetation. For vegetation to establish itself and diversify, five years appears to be an adequate period. The four remaining primary site characteristics showed no obvious correlation to age.

The type of commodity mined generally did not have a noticeable effect on the quality of long-term reclamation. The possible exception to this statement may come from rock quarries. Quarries may experience lower percentages of vegetative cover (due to rocky substrates and highwalls) and may be more difficult to blend with surrounding topography. Otherwise, there was no obvious pattern of commodity type affecting overall quality of reclamation.

There were some relative differences in quality between low- and high-precipitation sites. Low-precipitation sites supported lower percentages of vegetative cover than high-precipitation sites. Yet revegetation was considered successful, because low-precipitation regions are characteristically sparsely vegetated. These lands also are impacted by grazing pressure, which prevents plant establishment and increases erosion. A visual impression of lower quality exists due to exposure of bare soil, but often the mine sites blend in well with surrounding topography and vegetation. Therefore they are, for all functional and legal purposes, well-reclaimed sites.

Mine sites operated under the MLR program are reclaimed better than the pre-law sites. Field study

results clearly showed that the pre-law sites consistently had the poorest landforms. However, these lands were often functioning as viable wildlife habitats, which may develop despite landform. Pre-law sites were usually supporting some type of second land use, although in several cases the end use could not be determined. Water quality characteristics scored well on both types of sites. At pre-law sites, vegetation often had a lower percentage of cover and tended to provide less even ground cover. This was most prevalent in low-precipitation regions. In the high-precipitation regions, sites without reclamation seeding/planting were colonized through volunteer species. The most common negative characteristic for both types of sites was the presence of bare rock piles. Most of the problems associated with pre-law sites could have been addressed in a cost- and labor-effective manner, had reclamation occurred at or before the time of closure.

Low-precipitation site that blends well with surroundings.

The overall conclusion from comparing reclaimed sites to pre-law sites is that MLR regulations do have a positive and lasting affect on the quality of primary site characteristics. It is also noteworthy that unlike the pre-law sites, almost all of the sites accountable to the MLR program were indistinguishable from the surrounding area as former mines.

While most of the reclaimed sites were not identifiable as extractive sites, the pre-law sites were obviously former mine sites and were aesthetically unappealing. This suggests that by meeting state reclamation requirements, aesthetics are indirectly affected in an advantageous manner. Therefore, it appears unnecessary to specifically regulate aesthetics.

Some of the reclamation activities were voluntarily in excess of the regulatory requirements. In these cases, the landowners or operators often had taken active roles in the reclamation process and produced reclaimed sites with greatly enhanced aesthetic characteristics. Several sites in the study were nominated for reclamation awards in past years because of the excellent work done by landowners and operators.

CONCLUSIONS

The purpose of the reclamation regulations is "to provide that the usefulness, productivity, and scenic values of all lands and water resources affected by surface mining . . . receive the greatest practical degree of protection and reclamation necessary for their intended subsequent use" (Oregon Mined Land Reclamation Act, Division 30, 1994). Under these regulations, reclamation is defined as any procedure that minimizes the disturbance from surface mining and rehabilitates surface resources adversely affected by mining. Specifically, this includes the use of land-shaping and soil-stabilizing procedures, establishment of vegetative cover, and protection of surface and subsurface water resources, as well as any other measures supporting the second beneficial use of post-mining lands.

The data collected from this study of 47 mine sites strongly suggest that the goal of returning mined lands to subsequent beneficial long-term uses is being met by the MLR program. This means that mineral extraction is, in effect, an interim land use in the life of the site. Regulations applied through the MLR program appear to have a lasting affect on the shape and quality of the land. These reclaimed lands are supporting second beneficial land uses and have continued their development, since their release from the program, as healthy, self-sustaining environments.

The existence of a reclamation plan prior to the mining process has been a positive influence on reclamation success in Oregon. Following an approved reclamation plan makes the requirements readily apparent to operator and regulator, gives guidelines for procedures ranging from vegetation and topsoil stripping to regrading and revegetating, and provides clear goals for the reclamation process.

Successful reclamation is contingent upon site inspection by DOGAMI and the determination that the approved reclamation objective was met. Since each reclamation plan is site specific, final reclamation conditions vary from site to site. In addition, multiple opportunities exist in the Oregon Mined Land Reclamation Act to allow DOGAMI the discretion to permit alternative, site-specific reclamation practices. This allows opportunities for implementing creative reclamation techniques and unique second land uses when they are well supported by a reclamation plan. Mine

Pre-law site with poor quality of landforms and aesthetics.

sites once permitted by DOGAMI are now functioning as raptor habitat, recreational parks, industrial or office parks, fishing facilities, wildlife habitat, and a variety of other second land uses.

Summary points

- DOGAMI's MLR goal, to reclaim mined lands to support long-term, beneficial second land uses, is being met.
- MLR regulations have positive, long-term impacts on the shape and quality of former mine sites.
- Nearly all of the sites from the MLR program are indistinguishable from their surroundings as former mines.
- Former mine sites are consistently supporting second uses that are viable because they are supported by the underlying landforms and vegetation.
- Landforms at reclaimed mine sites are generally in excellent condition.
- Post-mining vegetation at reclaimed sites is diverse and well established in both high- and low-precipitation regions.
- Five years is an adequate period for vegetation to become established and diversify.
- More than 75 percent of the reclaimed and pre-law sites are clearly functioning as viable wildlife habitats or have significant potential in that respect.
- Reclamation requirements directing the reestablishment of streams, ponds, and drainages is highly effective.
- Land values tend to drive reclamation in urban areas.
- Mine sites operated under the MLR program are better reclaimed than the pre-law sites.

FURTHER STUDIES

The objective of this preliminary field study has been to document the general condition of a representative selection of former mine sites from across Oregon. The results of the study reflect positively on both the regulatory agency and the mining industry. In addition to the program evaluation process, this preliminary field study may be used as a reference in future studies where vegetation transects, habitat diversity, and plant community changes are studied in more detail. As an extension of this study, field data are being analyzed as part of a master's thesis in Mined Land Reclamation at Michigan State University. Some of the preliminary objectives include the use of principal component analyses to identify and relate critical site characteristics and the generation of equations to predict wildlife habitat and vegetative compositions.

ACKNOWLEDGMENTS

This work was done as part of an internship with DOGAMI-MLR in Albany, Oregon. The internship was made possible by Gary Lynch, MLR Supervisor, and done under the direction of Allen Throop. The entire MLR staff was supportive of the effort. □

Geology Board plans final adoption of tsunami rules at January meeting

The Governing Board of the Oregon Department of Geology and Mineral Industries (DOGAMI) met December 11 at the Hatfield Marine Science Center in Newport to receive public comment on proposed rules to implement Senate Bill 379. The bill was passed by the last Oregon Legislature and is designed to protect public safety on the Oregon coast by placing restrictions on construction of certain types of emergency and special occupancy structures within the tsunami inundation zone. The Board anticipates final adoption of the rules at its next meeting, which is scheduled for January 22, 1996, in Grants Pass.

The Governing Board is in the process of making long-term plans for DOGAMI programs and welcomes public participation in this process. At the January meeting in Grants Pass, time will be set aside for suggestions from the public as to the role they think DOGAMI should play in the future. People who are unable to attend the meeting but would like to submit written suggestions should send them to Angie Karel, DOGAMI, 800 NE Oregon St. #28, Portland, OR 97232-2162, phone 503-731-4100, FAX 503-731-4066. The following Board meeting is scheduled for April in Bend. □

DOGAMI PUBLICATIONS

Released November 15, 1995:

Relative Earthquake Hazard Maps of the Siletz Bay Area, Coastal Lincoln County, Oregon, by Yumei Wang and George R. Priest. Geological Map Series map GMS–93, 4 maps on 3 sheets, 13 p. text, $20.

The four-map set covers a coastal strip of the Lincoln City-Siletz Bay area, from D River in the north to Gleneden Beach in the south. Three earthquake hazards related to site geology (liquefaction, amplification, and landsliding) were evaluated individually and presented on separate maps. The three were then combined to develop the *Relative Earthquake Hazard Map* (map 4).

The four maps are printed on orthophoto base maps. The liquefaction and amplification maps are at the scale of 1:24,000, the landslide and relative earthquake hazard maps at 1:12,000. Colors depict the three to four different zones of hazard levels. The accompanying 13-page text is written for nontechnical as well as technical readers. An appendix contains two site-specific seismic hazard evaluations.

Released December 11, 1995:

Reconnaissance Geologic Map of the Dora and Sitkum Quadrangles, Coos County, Oregon, by Thomas J. Wiley. Geological Map Series map GMS–98, 1 map, 5 p. text, $6.

The Dora and Sitkum quadrangles cover an area in the east-central part of Coos County around and north of the two towns of the same names along the East Fork Coquille River. The maps represent the final two of a block of maps for eight quadrangles in the southern Coast Range for which geologic maps have been produced by DOGAMI, including also the Camas Valley, Kenyon Mountain, Mount Gurney, Remote, Reston, and Tenmile quadrangles.

The new, two-color geologic map and accompanying cross section were produced at a scale of 1:24,000. A five-page text discussing rock units, structural geology, geologic history, and mineral resources accompanies the map sheet.

Mapping of these quadrangles in the southern Coast Range represents part of DOGAMI's study of the geology of the Tyee sedimentary basin. The study is supported by a consortium of nine corporations and agencies from private industry and federal, state, and county government and by the National Geologic Mapping Program (STATEMAP) administered by the U.S. Geological Survey.

Released December 29, 1995:

Geology and Mineral Resources Map of the Lakecreek Quadrangle, Jackson County, Oregon, by Frank R. Hladky. Geological Map Series map GMS–88, 1 map, 9 p. text, $8.

The publication continues the series of geologic maps planned to aid regional planning in the Medford-Ashland area, which is experiencing rapid population growth. The area of the Lakecreek quadrangle lies on the western margin of the Cascade Range and roughly 15 miles northeast of Medford.

The full-color geologic map is at a scale of 1:24,000 and is accompanied by two geologic cross sections. Innovative mapping techniques allowed detailed mapping of the many lava flows that built up this part of the Western Cascades. A separate sheet contains tabulated analytical data from rock samples collected in the quadrangle. The nine-page text that accompanies the map contains rock-unit explanations and discussions of geologic structure, geologic history, and ground-water and mineral resources.

Geologic Map of the Coos Bay Quadrangle, Coos County, Oregon, by Gerald L. Black and Ian P. Madin. Geological Map Series map GMS–97, 1 map, 6 p. text, $8.

The area of the Coos Bay 7½-minute quadrangle includes most of the city of Coos Bay at its northern edge and the Isthmus and Catching Sloughs. Directly adjacent to the west lies the Charleston quadrangle, for which a geologic map was published recently as DOGAMI map GMS–94.

The full-color geologic map is at a scale of 1:24,000 and is accompanied by three geologic cross sections. A six-page text contains rock-unit explanations and discussions of geologic structure, geologic history, resources, and hazards.

Landslide Loss Reduction: A Guide for State and Local Government Planning, by Robert L. Wold, Jr., Colorado Division of Disaster Emergency Services, and Candace L. Jochim, Colorado Geological Survey. DOGAMI Open-File Report O–95–8, 50 p., $8.

This report was designed to be used as a guide for state and local governments. It has been distributed to all states through the support of the Federal Emergency Management Agency (FEMA). In nine well-illustrated chapters, it describes landslide losses and the benefits of mitigation; causes and types of landslides; hazard identification, assessment, and mapping; transferring and encouraging the use of information; landslide loss reduction techniques; and plan preparation and necessary steps in implementing such a plan.

The 50-page report was published originally by the Colorado Geological Survey for FEMA to provide stimulation and assistance to government agencies, private interests, and citizens throughout the nation to reduce the landslide threat. The preparation of the report was guided by an advisory committee that included Oregon's Deputy State Geologist John D. Beaulieu.

These DOGAMI publications are now available over the counter, by mail, FAX, or phone from the Nature of the Northwest Information Center in Portland (see order information on the back cover of this issue); or the DOGAMI field offices (see page 2 of this issue). Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment except for credit-card orders. □

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VOLUME 58, NUMBER 2 MARCH 1996

IN THIS ISSUE:

Seismically induced water-level oscillations in a fractured-rock aquifer well near Grants Pass.
Earthquake intensity maps, Scotts Mills earthquake (survey evaluation).
Landslides in the West Hills of Portland: A preliminary look.

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Cover photo

"Theme scene" from Portland's SW Council Crest Drive after the disastrous rains in February 1996: The rains caused not only the rivers to rise but also the hills to fall, leaving many Oregonians squeezed somewhere between them. Pages 42–43 of this issue show a preliminary look at some slides that occurred in Portland. Photo Scott F. Burns.

Governor proclaims April 1996 Earthquake and Tsunami Preparedness Month

Office of the Governor, State of Oregon Proclamation

Whereas: Oregon has recently suffered considerable damage from two small earthquakes; and

Whereas: Scientific evidence indicates that Oregon is at risk for much larger earthquakes in the future; and

Whereas: A major earthquake associated with the Cascadia Subduction Zone could, also, generate a destructive tsunami; and

Whereas: The loss of life and property can be greatly reduced if appropriate earthquake preparedness measures are taken BEFORE such an earthquake or tsunami occurs; and

Whereas: Oregon enacted a law in 1995 that requires schools to instruct and drill students on emergency procedures such as those related to earthquakes and tsunamis; and

Whereas: Emergency management agencies, the Department of Geology and Mineral Industries, and the American Red Cross will highlight these preparedness strategies and provide earthquake safety information to citizens during the month of April,

Now,

Therefore, I, John A. Kitzhaber, Governor of the State of Oregon, hereby proclaim April 1996

EARTHQUAKE AND TSUNAMI PREPAREDNESS MONTH

in Oregon and encourage all citizens to increase their awareness of and preparedness for earthquake and tsunami hazards.

In witness whereof, I hereunto set my hand and cause the Great Seal of Oregon to be affixed. Done at the Capitol in the City of Salem in the State of Oregon, on this day, January 22, 1966.

John A. Kitzhaber, Governor

Phil Keisling, Secretary of State

Seismically induced water-level oscillations in a fractured-rock aquifer well near Grants Pass, Oregon

by Douglas Woodcock, Oregon Water Resources Department, Salem, Oregon 97310, and Evelyn Roeloffs, U.S. Geological Survey, Vancouver, Washington 98660

INTRODUCTION

Groundwater data have been collected from water wells in the Grants Pass area for the last several years to assess groundwater conditions and aquifer behavior. Thirteen unused water wells have been monitored with analog water-level recorders to observe short- and long-term responses to precipitation, pumpage, barometric effects, and well interference. One of these monitored wells stands apart from the others for its response to the strain produced by Earth tides but also, more interestingly, for its extreme sensitivity to earthquakes that have occurred locally and at great distances from the well. A digital data logger has expanded the data-recording capabilities at the well and has captured detailed seismic wave trains. These "hydroseismograms" provide an interesting look at how a water well developed in a fractured-rock aquifer responds to earthquakes.

There are practical reasons to study the response of water wells to earthquakes. For example, to ensure the safety of underground waste repositories, it is essential to understand how distant earthquakes could affect subsurface stress or fluid pressure. Distant fluid-pressure changes may also explain why large earthquakes, like the 1992 earthquake at Landers, California, sometimes trigger additional earthquakes as far as several hundred kilometers away.

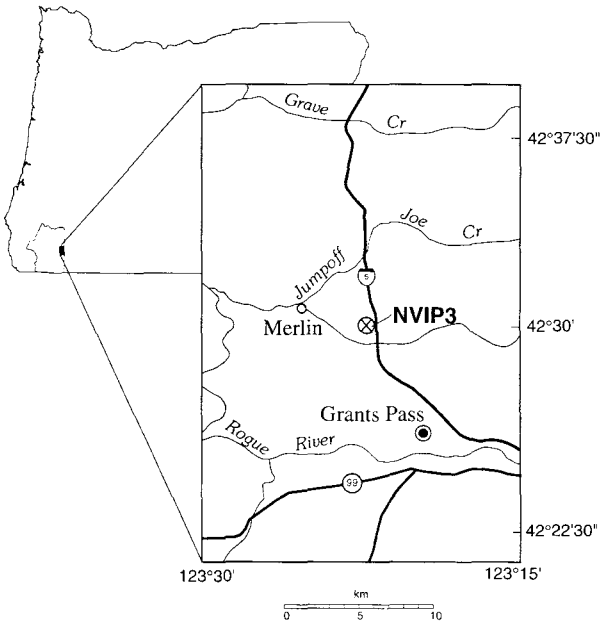

Figure 1. Geographic location of NVIP3 in Josephine County.

THE SETTING

The well of interest is the North Valley Industrial Park #3 well (NVIP3), located about 6 km (3.75 mi) northwest of the city of Grants Pass in Josephine County (Figure 1). It is a 15-cm (6-in.)-diameter well and is 91.4 m (300 ft) deep. The driller's log reports that cement grout was placed to a depth of 36.6 m (120 ft) and casing to 50.9 m (167 ft). The well is open to the formation from 50.9 to 91.4 m (167–300 ft). It was drilled to supply the industrial park with groundwater, but only domestic quantities of water were encountered, so the well has gone unused. The well is developed in fractured granitic rock of the Grants Pass pluton, a 260 km^2 body of granodiorite, quartz diorite, and related intrusives. A down-hole video shows, in the bottom 23 m (75 ft) of the borehole, a fractured, complex intrusive contact between the pluton and a dark metamorphic rock. It is unknown whether the well has fully penetrated the pluton or has only encountered a large block of incorporated country rock.

THE ANALOG DATA YEARS

The Josephine County Water Resources Department recognized the value of using NVIP3 as a long-term observation well and, shortly after completion of the well in 1984, installed a continuous analog water-level recorder. This type of recorder consists of a recording drum attached to a float and counterweight mechanism. As the water level rises and falls in the well, the change in water level is traced on the recording drum. This recorder was maintained until the end of 1993, when it was replaced with a digital unit.

Comparison of the water-level record at NVIP3 to those records collected from shallower wells in the Grants Pass pluton suggests that the deeper, fractured aquifer is confined. That is, the water at depth cannot flow freely to the water table, because the water-bearing zones are bounded by rock of lower permeability. Thus, the aquifer at depth is under a pressure greater than atmospheric pressure and is sensitive to forces that produce small volumetric changes in the rock body.

Figure 2 is an analog chart from NVIP3 showing the diurnal and semi-diurnal water-level response to the strain induced by Earth tides. As with coastal tides, water-level amplitudes reach their maximum and minimum at two-week intervals—when the gravitational attraction of the moon and sun are in alignment (at full and new moon) and when those forces are perpendicular with respect to the

Earth (called "lunar quadrature"). However, in contrast to coastal tides, the water level in a tide-sensitive well declines when the tide-generating force is overhead. This is because the lithostatic pressure on the aquifer is reduced when the gravitational force pulls on the Earth's crust.

Over the period of record, the analog charts also show 155 rapid water-level fluctuations, which are superimposed on the smooth, relatively slow changes due to Earth tides, barometric pressure changes, and groundwater recharge.

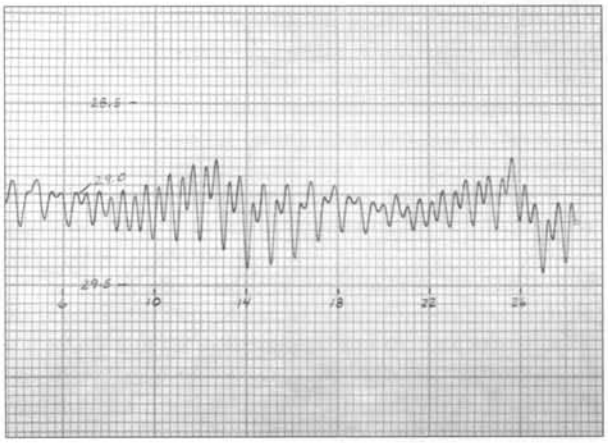

Figure 2. Strong diurnal and semi-diurnal Earth-tide signal dominates the water level in this analog recording for the month of November 1989. The numbers on the left side of the photograph indicate water level in feet below land surface, while the numbers across the bottom indicate days of the month.

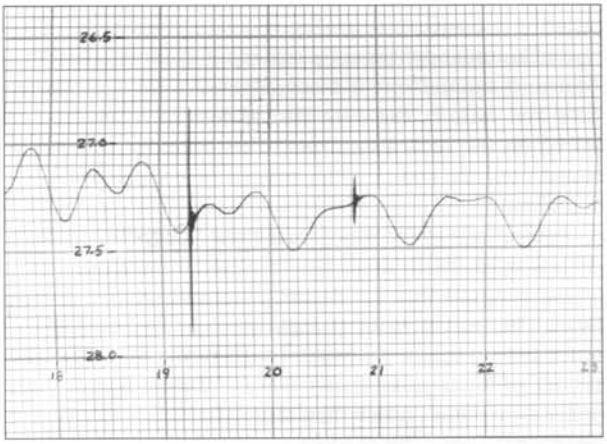

Figure 3. Analog recording of the September 19, 1985, earthquake at Michoacan, Mexico (Ms 7.9) and aftershock (Ms 7.5) superimposed on earth tide signal. The numbers on the left side of the photograph indicate water level in feet below land surface, and the numbers across the bottom reflect days of the month. The main shock caused 32 cm (1.05 ft) of peak-to-peak fluctuation, the aftershock 7 cm (0.23 ft).

These rapid fluctuations correlate with earthquakes. For example, well responses to the 1985 Michoacan (Mexico) earthquakes, with surface-wave magnitudes (M_S) of 7.9 and 7.5, are shown in Figure 3. The peak-to-peak response was 32 cm (1.05 ft) from the main shock and 7 cm (0.23 ft) from the aftershock. Both epicenters were approximately 30 arc degrees (~3,330 km) distant from the well.

We correlated rapid water-level oscillations on the analog charts to earthquakes by matching the event time on the recorder chart with large earthquakes, which are logged in the catalog *Preliminary Determination of Epicenters* (PDE) maintained by the U.S. Geological Survey National Earthquake Information Center. The majority of the water-level charts were recorded at a time scale of 8 h / 2.5 mm, yielding a time resolution of about two hours. Thus the earthquake database was searched for any large earthquakes that occurred within ± 2 h of the recorded oscillation. Occasionally, the database lists more than one large earthquake within this time window, which makes correlation difficult. Furthermore, battery and pen failures and freezing clocks caused either gaps in the record or discrepancies in clock time. Still, of the 155 rapid fluctuations in the analog record, 119 occurred within two hours of an earthquake with a magnitude 6.0 or greater somewhere in the world. An additional 13 of the water-level fluctuations correspond to earthquakes in or offshore Oregon or California with magnitudes 4.0 or greater.

CONVERSION TO DIGITAL DATA ACQUISITION

Detailed responses to earthquakes could not be resolved from the analog records because of their compressed time scale. For this reason, a UNIDATA digital shaft encoder, data logger, and barometric transducer were installed in November 1993 (Figure 4). Like an analog recorder, the shaft encoder utilizes a float-and-counterweight mechanism to track water-level change in the well. The difference

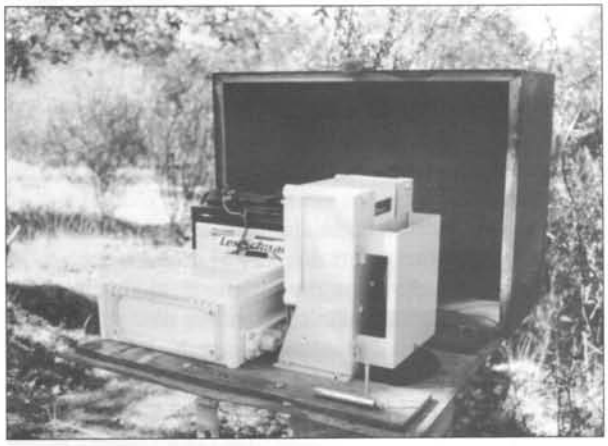

Figure 4. Configuration of UNIDATA instrumentation at NVIP3. Shaft encoder (on right) digitally encodes water-level data for storage in data logger (in weatherproof housing on left).

is that the data are digitally encoded and stored in the data logger for later retrieval. The data logger is configured to record water level and barometric readings every 15 minutes but goes to a high-speed sampling interval—one sample per second—anytime the water-level movement equals or exceeds 0.18 cm (0.006 ft) in a one-second interval. This split sampling scheme provides data for a long-term record and at the same time allows a finer resolution for short-term phenomena.

Since the change to digital instrumentation, 80 additional rapid fluctuations have been recorded. Figure 5 shows the digital record for a portion of January 1994. It includes the response to the Northridge, California, event (M_S 6.8) as well as three other earthquakes. The peak-to-peak response to the Northridge main shock was 22.3 cm (0.73 ft). Figure 6 expands the time scale for this response and compares it to the vertical component of a broadband seismogram recorded at Yreka, California. The comparison shows that the well and recorder are emulating a seismograph, recording the passage of the early arriving *P* and *S* waves and the later arriving surface waves.

Because of the greater detail provided in the record, the digital equipment allows a more accurate determination of the timing of events. Time resolution, now on the order of seconds as opposed to hours, has greatly improved the confidence of correlating earthquakes to fluctuations in the water-level record.

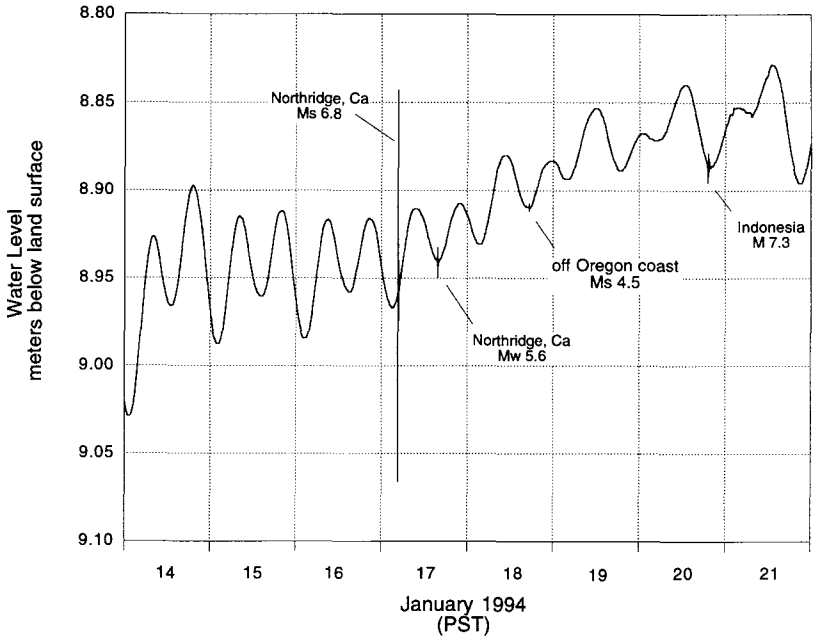

Figure 5. Digital recording of water-level change for 8 days in January, 1994. Local and distant earthquakes are identified in the record.

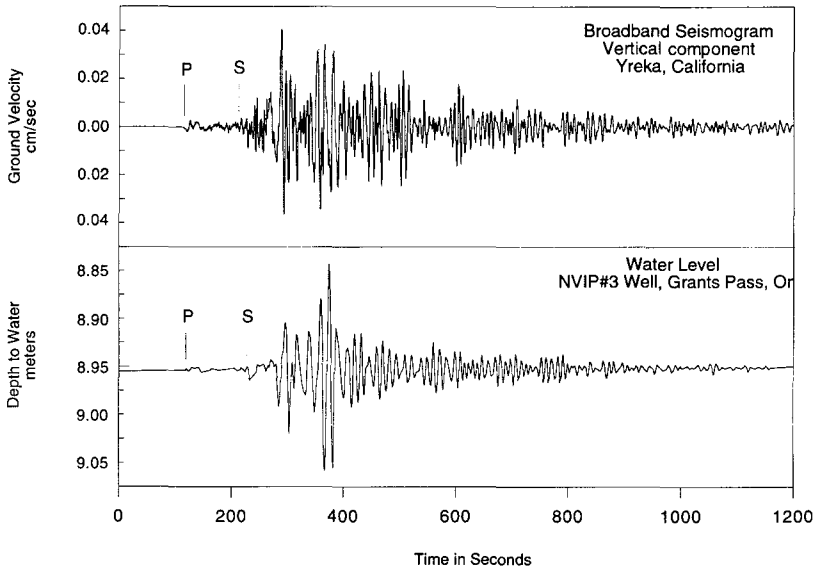

Figure 6. Northridge main shock, January 17, 1994. Comparison of the water-level response observed at NVIP3 and the vertical component broadband seismogram collected at Yreka, California.

OSCILLATORY WELL RESPONSE

As can be seen in the response to the Northridge earthquake, the water level at NVIP3 fluctuates in response to the passage of various seismic waves. This dynamic response is produced by two simultaneous mechanisms: (1) rapid pressure changes in the aquifer as the waves compress and dilate the rock body, and (2) amplification by the momentum of the water column moving in the well.

Early work by Leggette and Taylor (1935) suggested that water wells that employ float recorders, such as NVIP3, are capable of recording only those aquifer pressure changes produced by long-period seismic waves (e.g., Rayleigh waves), because considerable time is necessary for water to flow into and out of the borehole in response to those changes. Eaton and Takasaki (1959) stated that of the different waves produced by an earthquake, it is only waves that produce volume changes in the rock that induce water-level fluctuations in a well. Both *P* waves and the later-arriving Rayleigh waves have this property, but Rayleigh waves would be expected to generate the larger oscillations because of their longer periods. Waves that induce a shear-

ing motion as they propagate through a rock body, such as *S* waves and Love waves, do not dilate the rock as they pass and, theoretically, should not induce oscillations. Rexin and others (1962), however, identified many seismic phases, including Love waves and *S* waves, in expanded time-scale recordings from a well in Milwaukee, Wisconsin.

NVIP3 clearly responds not only to *P* waves and Rayleigh waves but also to the shearing motion of *S* waves. The relative amplitudes of the *S* wave and *P* wave responses cannot be determined at present because the one-second sampling rate is not fast enough to accurately record *P* waves, which have frequencies of several cycles per second. Consequently, the small fluctuations in response to *P* waves are not accurate representations of the pressure changes occurring in the aquifer. That the well responds at all to these higher frequency waves suggests that the hydraulic conductivity in the aquifer surrounding the well must be sufficiently high to allow rapid movement of water in and out of the well in response to the small but rapid pressure changes induced by *P* waves.

The well's response to nondilatational *S* waves is curious. One possible explanation is that hydraulic conductivity within the aquifer is dominated by a single permeable fracture or set of fractures having a preferred orientation. If a fracture is oriented normal to the shearing motion of an *S* wave, then elastic deformation of the fracture aperture—without volumetric change of the rock body—would produce pressure changes in the aquifer, thus inducing water movement in the well-aquifer system.

Cooper and others (1965) derived a mathematical equation for the amplification of water-level oscillations in a well relative to pressure fluctuations in the aquifer caused by seismic waves. The most interesting feature of Cooper's analysis is that, for wells in aquifers with sufficiently high hydraulic conductivity, there is a resonant frequency at which the water-level fluctuation in the well can be amplified orders of magnitude above the pressure fluctuation in the aquifer. The frequency at which resonance occurs is determined by the dimensions of the water column and the aquifer. Hydraulic conductivity is the key parameter governing the amplification. Liu and others (1989) modified Cooper's analysis to improve its agreement with observations for the case of a very thick aquifer. For the well and water column dimensions of NVIP3, Liu's equation suggests that seismic waves with periods of 10–20 s will produce a resonant water-level response. This is supported by the hydroseismograms recorded at NVIP3, which are dominated by oscillations at these periods.

RESPONSES TO LOCAL AND DISTANT EVENTS

The majority of earthquakes inducing a response at NVIP3 occurred along plate margins within the active Pacific rim, but small fluctuations (<1.0 cm) were correlated to large events in China, Sudan, Turkey, and India. Figure 7 shows the worldwide distribution of all earthquakes with magnitudes 6.0 or larger that have occurred since data have been collected at NVIP3. The largest fluctuations recorded at the well have been produced by earthquakes occurring along the western margin of North America, Alaska to Mexico. Local events (earthquakes with epicenters occurring in northern California, southern Oregon, or the near offshore) are responsible for many of these larger oscillations. Table 1 displays the 20 largest responses observed at this well.

Of 27 events in the PDE catalog with surface-wave magnitudes of 7.4 or greater, all but five showed a response in the well, including all such events that have taken place since 1989. All but one earthquake within 20 arc degrees of the well and with a magnitude of M_S 6.0 or greater produced a response. The most distant event to cause a water-level fluctuation (0.91 cm) was a M_S 7.1 event in the Sudan on May 20, 1990. Magnitude and distance being equal, a shallow event is more likely to produce a well response than a deep event. The deepest earthquake to cause a water-level fluctuation (0.18 cm) was a m_b 6.5 event in North Korea on July 21, 1994, at a depth of 471 km. (Here, m_b denotes a magnitude derived from body waves. Earthquakes this deep do not generate strong enough surface waves to calculate a meaningful M_S.) It is unknown whether water-level fluctuations were induced in response to the magnitude 8.2 earthquake 600 km beneath Bolivia on June 8, 1994—the largest earthquake ever documented at that depth—because the water-level recorder was inactive at the time of the event.

An earthquake's surface-wave magnitude and its distance (Δ) in arc degrees from the well can be used to estimate the amplitude (A) of 20-s Rayleigh waves at the well site using the formula

$$\log A = M_S - 1.66 \log (\Delta/20),$$

where Δ is measured in degrees, and A is in millimicrons of ground motion (see, for example, Evernden, 1971). The size of the water-level fluctuation tends to increase with the estimated Rayleigh wave amplitude, as shown in Figure 8. All earthquakes in the PDE catalog that produced Rayleigh waves with estimated peak-to-peak ground motion in excess of 5 mm (0.2 in.) caused water-level fluctuations to occur in the NVIP3 well.

Using long-period seismic waves, Shearer (1994) generated a global image of the Earth's response to seismic energy. Ground motion for a point on the Earth's surface was plotted as a function of time and distance from the earthquake. Among other things, this provides a methodology for identifying wave arrivals many hours after earthquake origin times. This model was used to identify Rayleigh wave arrival times from a great earthquake that occurred off the Kuril Islands, north of Japan. The M_S 8.2 event occurred on October 4, 1994, and produced an 18.9-cm (0.62-ft) response at NVIP3. The well continued to oscillate for over three hours. Early time data show a small but clear *P* wave response and a sharp response to *S* wave arrivals (Figure 9). Subsequent increases in oscillatory amplitude in the well correspond closely to the modeled arrival times of the Rayleigh wave components R1, R2, and R3 for the well

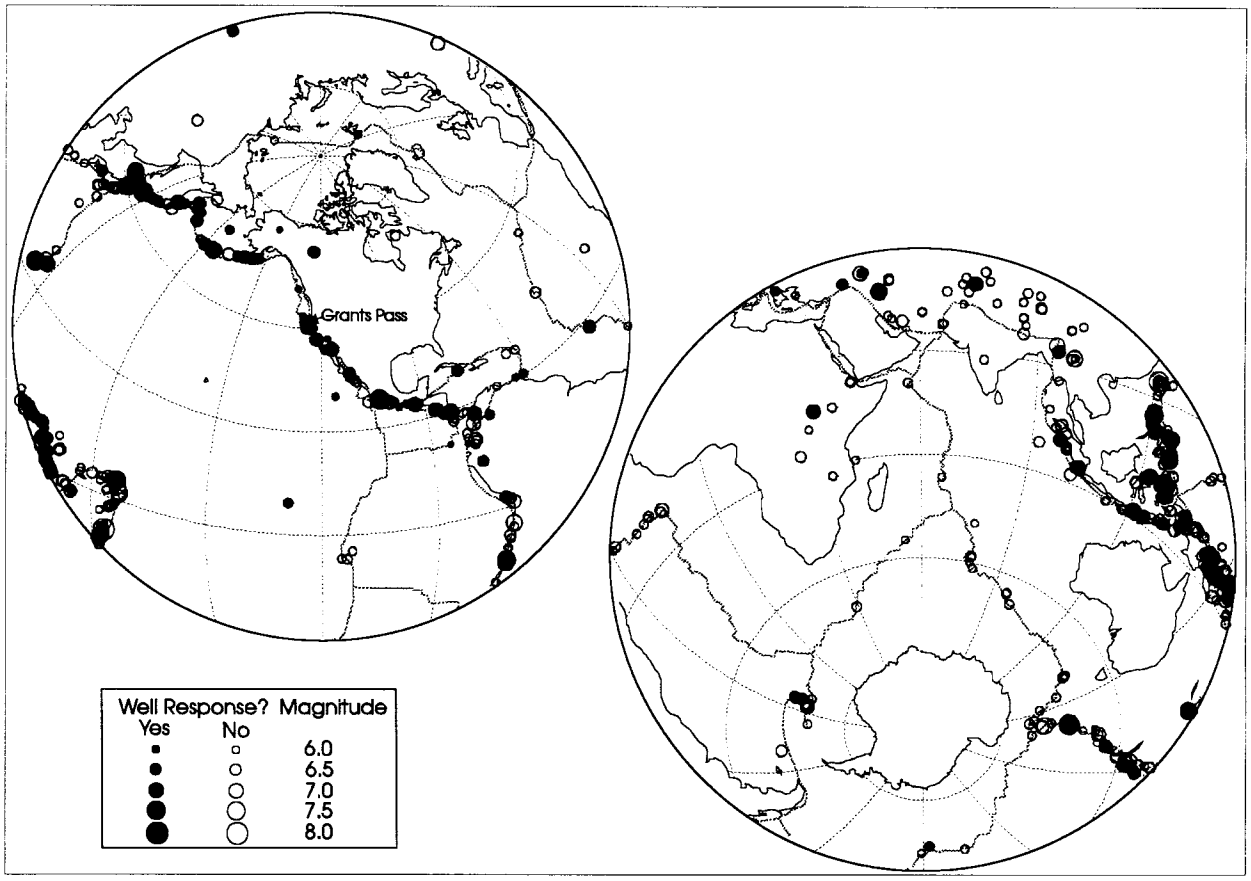

Figure 7. Two views of the Earth displaying earthquakes that occurred over the period of water-level record for NVIP3.

Table 1. Earthquakes generating the 20 largest peak-to-peak responses at NVIP3. Included are any observed coseismic water-level changes.

Location	Event date (GMT)	Magnitude	Depth (km)	Distance (arc degrees)	Well fluctuation (cm)	Well fluctuation (ft)	Coseismic change (cm)	Data format
Cape Mendocino	4/25/92 1806	M_S 7.1	15	2.3	114.3	3.75	21.0 drop	Analog
Landers, CA	6/28/92 1157	M_S 7.6	1	9.9	78.0	2.56	3.1 drop	Analog
Off north CA coast	8/17/91 2217	M_L 6.8	13	1.7	71.6	2.35	15.2 drop	Analog
Offshore Petrolia, CA	9/1/94 1515	M_W 7.2	10	2.7	62.2	2.04	15.2 drop	Digital
Yakutat, AK	11/30/87 1923	M_S 7.7	10	20.2	45.7	1.50	18.3 drop	Analog
Off Oregon coast	7/13/91 0250	M_L 6.7	11	1.7	41.8	1.37	7.0 drop	Analog
Gulf of Alaska	3/6/88 2235	M_S 7.5	10	19.1	36.6	1.20	(Pen skip)	Analog
Loma Prieta	10/18/89 0004	M_L 7.0	18	5.6	36.6	1.20	10.4 drop	Analog
Michoacan	9/19/85 1317	M_S 7.9	27	30.1	32.0	1.05	—	Analog
Klamath Falls	9/21/93 0545	M_D 6.0	12	1.0	29.6	0.97	27.4 drop over 2 shocks	Analog
Cape Mendocino	4/26/92 1118	M_S 6.6	22	2.3	24.4	0.80	—	Analog
Northridge, CA	1/17/94 1230	M_S 6.8	5	9.1	22.3	0.73	—	Digital
Klamath Falls	9/21/93 0329	M_D 5.9	12	1.0	19.8	0.65	27.4 drop over 2 shocks	Analog
Kuril Trench	10/4/94 1322	M_S 8.2	33	61.8	18.9	0.62	—	Digital
Cape Mendocino	4/26/92 0741	M_S 6.6	20	2.3	18.6	0.61	—	Analog
Off north CA coast	2/18/95 0403	M_S 6.6	10	2.6	17.8	0.58	—	Digital
Aleutians	5/7/86 2247	M_S 7.9	33	35.4	15.2	0.50	—	Analog
Off north CA coast	8/17/91 1929	M_L 6.0	12	2.0	15.2	0.50	—	Analog
Guam	8/8/93 0834	M_S 8.2	60	82.6	15.2	0.50	—	Analog
Guatemala	9/10/93 1912	M_S 7.2	34	38.3	15.2	0.50	—	Analog

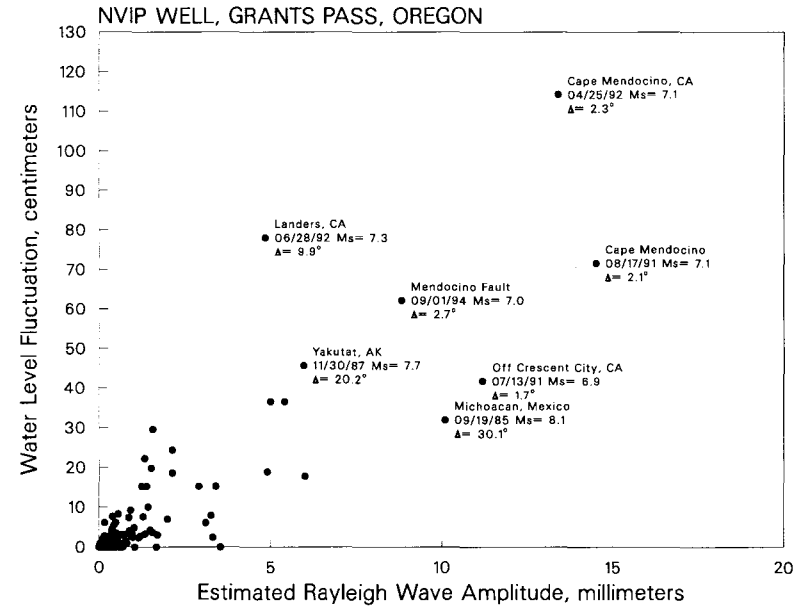

Figure 8. A comparison plot of the observed water-level response recorded at NVIP3 and the calculated Rayleigh wave amplitude at the well site.

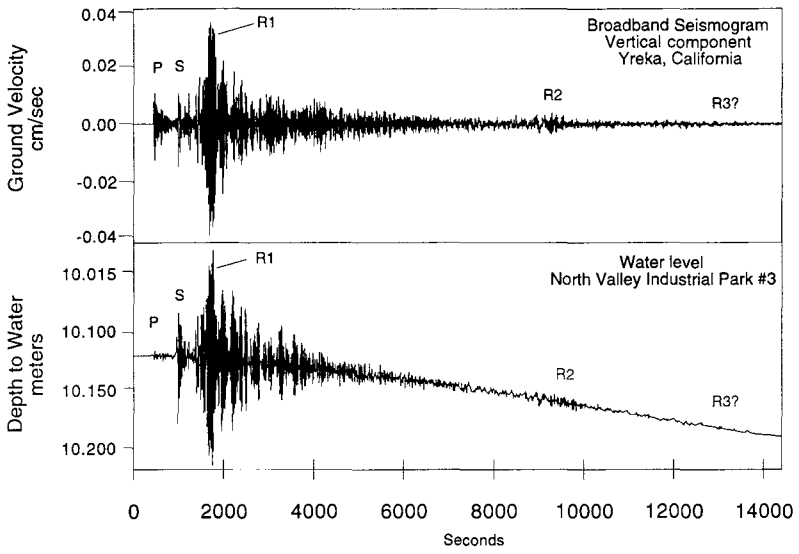

Figure 9. Earthquake east of Kuril Islands on October 4, 1994. Comparison of the water-level response observed at NVIP3 to the vertical-component seismogram collected at Yreka, California. Note strong S *wave response. The water-level data are unfiltered, and the decline is in response to Earth-tide strain.*

location, which is 62 arc degrees from the event origin (P.M. Shearer, personal communication, 1994). The significance of these Rayleigh components is in their travel paths. R1 travels 62 degrees along the shortest great-circle path to the well and should produce the largest water-level oscillations. R2 should produce a smaller set of oscillations—due to the decrease of wave amplitude with distance—as it takes the opposite path along the great circle, traveling a distance of 298 degrees. R3, which represents R1 making its second pass by the well, will have traveled 422 degrees around the Earth. R1 and R2 are clearly evident in the well record and in the seismogram of Figure 9. R3, however, is not as distinct; in the well record, an isolated cluster of low-amplitude (0.18-cm) oscillations occurs at the calculated time and may very well represent the arrival of R3. If R3 was recorded in the vertical seismogram it is not readily apparent.

COSEISMIC WATER-LEVEL CHANGES

An interesting and unexplained phenomenon associated with the larger oscillations in the NVIP3 well is a coseismic drop in water level. The observed water-level declines after large events range from 3.0 to 27.4 cm (0.1–0.9 ft). Figure 10 shows the response to the Mendocino fault earthquake of September 1, 1994, off the coast of northern California and near the town of Petrolia, and the subsequent 15.2-cm (0.5-ft) drop in water level. The degree of water-level decline attributable to the earthquake is evident when water-level oscillations, barometric pressure, and Earth-tide strain are filtered from the record (Figure 11). The coseismic drop begins shortly after the earthquake and continues for approximately 20 hours. It is unknown at this time whether the water-level drop represents permanent or semi-permanent aquifer deformation or some movement or discharge of groundwater from the system or both. Coseismic changes in the NVIP3 well are always water-level drops, decaying over a period of hours. The return to preseismic levels may take weeks. That this phenomenon occurs after very large fluctuations suggests that it is related to the passage of surface waves; however, the water-level losses are not proportional to the amplitude of the oscillation. Also, the large distance to the epicenter for some events (e.g., Yakutat, Alaska, 1987, M_S 7.7) suggests that the mechanism is due to something other than a change in the stress field around the active fault.

Rojstaczer and others (1995) examined reported hydrologic changes in fractured-rock aquifers near the 1989 Loma Prieta, California, earthquake. Increases in stream flow and coseismic drops of water levels in wells were

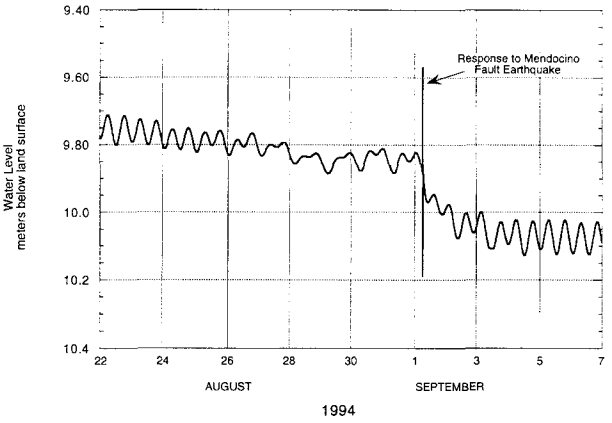

Figure 10. Compressed time-scale recording of the water-level response to the September 1, 1994, Mendocino fault earthquake off the California coast near the town of Petrolia. Note 15.2-cm drop in water level following the event.

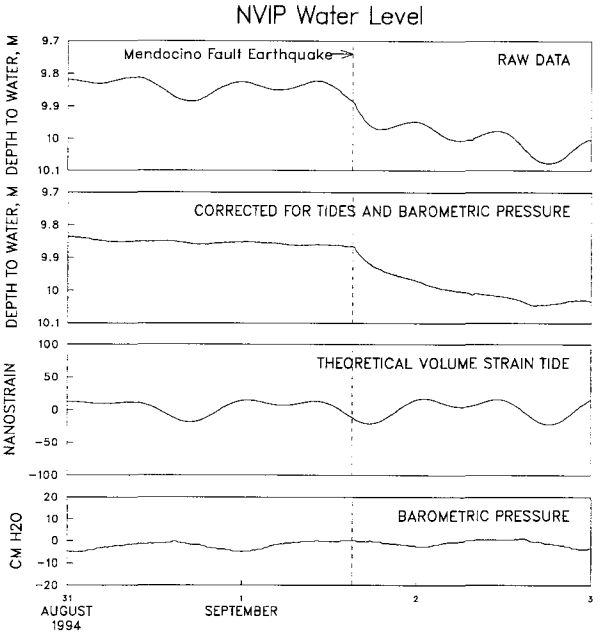

Figure 11. Residual water-level data after removing the oscillatory response, barometric pressure, and Earth tides. Note water-level decline following water-level response to the Mendocino fault earthquake.

found to be consistent with permeability enhancements in the aquifer. The increased permeability allows an increase in groundwater discharge to streams, which can lower the water level in the aquifer, if recharge to the aquifer is not equally enhanced. Surface-water data are not available for the area around the NVIP3 well, so it is unknown whether increases in stream flow accompany the coseismic drops.

SUMMARY

NVIP3 is unusual among wells monitored in the Grants Pass area in that it is highly sensitive to earthquakes generated locally and at great distances from the well. It responds to both dilational and nondilational seismic waves, but the largest amplitude oscillations occur in response to the dilational Rayleigh waves. NVIP3 resonates at wave periods of 10–20 s, producing peak-to-peak water-level fluctuations as large as 114.3 cm (3.75 ft). Over the period of record, all earthquakes that generated more than 5 mm (0.2 in.) of ground motion at the well site produced a well response. In addition to this oscillatory response, persistent water-level drops occur after those earthquakes that induce the larger fluctuations in the well.

The value of NVIP3 and other wells that are developed in strain-sensitive aquifers is their utility for teaching us how earthquakes affect aquifer systems at a distance. It is well documented that water wells respond to the passage of seismic waves, even at teleseismic distances. But there is still much to learn about the movement of groundwater or the aquifer deformation that can result from those waves.

ACKNOWLEDGMENTS

The authors would like to thank Geoff Carrigg of Unidata America for his assistance in configuring the digital recording equipment for high-speed water-level sampling and Norman Daft of the Josephine County Water Resources Department for his diligent collection of data at NVIP3 and other recorder sites in the Grants Pass area. We also thank Jennifer Hughes for her assistance with correlating the earthquake and water-level databases and Andrew Fountain and Karl Wozniak for technical reviews.

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Shaking things up down on the farm

by Bruce Pokarney, Oregon Department of Agriculture, 635 Capitol St. NE, Salem, Oregon 97310, phone 986-4559.

When the big one comes, it won't just be the city folks who will be affected. Their country cousins—including those who represent agriculture in Oregon—will be shaking and rattling, too. Earthquake experts say rural Oregon needs to prepare itself just as much as urban Oregon.

"Earthquakes can occur anytime, anywhere," says Matthew Mabey, an earthquake specialist with the Oregon Department of Geology and Mineral Industries, who himself grew up on a farm. "In fact, the odds are that the epicenter of an earthquake will be in a rural area simply because most of the land mass in Oregon is rural."

It was nearly three years ago that an earthquake measuring 5.6 on the Richter scale shook much of the Willamette Valley. The "Spring Break Quake" was centered in a rural area near Scotts Mills. Extensive damage was reported after a pair of earthquakes in Klamath Falls in 1993. Although a major earthquake measuring perhaps as high as 8.5 is predicted for Oregon some time in the next 200 years, no one can precisely predict where it will be located. Even if it strikes the Portland area, as some expect, its shock waves surely will roll through Oregon farms and ranches.

"Earthquakes, like other natural disasters, could certainly have an impact on our agricultural operations," says Phil Ward, Assistant Director of the Oregon Department of Agriculture.

Everything from production to marketing could be affected, not to mention the daily way of life all residents face, whether they live in the city or the country.

"The collective impact of an earthquake may be less in rural areas where there are fewer people and fewer buildings," says Mabey. "But rural residents still need to think about preparing for an earthquake and its aftermath."

The indirect effects of a major earthquake on agriculture may be greater than those impacts that are felt immediately. The loss of electrical power would cripple many operations. But the loss of the infrastructure could be more damaging.

"Growers need to get the goods to market," says Mabey. "Transportation of those goods could be interrupted. Ports could be affected. The costs of getting the goods to a processor or the end market could be higher."

A look at Kobe, Japan, shows what can happen to commerce. Port facilities were still crippled months after the 1995 earthquake. Agricultural trade suffered, too, of course.

One Oregonian who has thought long and hard about earthquakes and their impact on rural residents is Ralph Richie of Lane County. A transplanted Californian who has experienced a number of big quakes, Richie has written a book entitled *Emergency Procedures for Country Living*, which features an entire section on earthquakes. (The book —nearly 200 pages, $24.95— can be obtained from the author whose address is 90586 Nadeau Road, Mohawk Valley, Springfield, OR 97478, phone 541-741-0794. —*editor*).

His booklet outlines the potential danger spots unique to the farm. It starts out with the rural dwelling itself.

"Wood frame houses move with vibration, so they're more likely to withstand the shock of an earthquake than other structures," says Richie. "Whether a house is tied to a foundation is critical. An outer wall has to move only four inches, and it's off the foundation. Any house off its foundation is headed toward collapse."

Old stone farmhouses are less likely to withstand the shaking. Manufactured homes—common in rural areas—are many times founded on blocks or jacks. Those, too, could be in trouble during a quake and should be secured as well as possible.

Rural homes often rely on propane or butane for heating. The tanks need broad footings to remain standing upright. If they topple, pipes can break, and gas can escape, threatening fire danger. Water pipes can break, and electricity and telephone service can be cut off. Anything on the farm that can be tipped over probably will be.

Then there are those things on a farm or ranch that are not manmade.

"During an earthquake, herd animals will stampede," says Richie. "One of the casualties of earthquakes is fencing. That brings up the point of whether or not all of your animals are identified well enough so they can be brought back home."

Richie advises everyone, city or country, to put together emergency packs that include at least two weeks' worth of water just for human consumption. Farmers with animals will need more. He also urges rural folks to form neighborhood disaster groups, even if homes are separated by miles.

"You can't expect help from city crews," says Richie. "I would expect 911 to be overloaded immediately in the event of a major earthquake. Out here, forget it."

Richie says neighbors can assemble a skills inventory, equipment inventory (especially important is a list of items that don't need electricity), and a feed schedule for each others' animals in case the rightful owners can't make it back to the farm.

Most experts agree that rural folks are generally better suited than their city cousins to handle a major earthquake.

"Living out in the country already is an indication of independence," says Richie. "The rural resident tends to have the ability to face a problem and handle it independently without having to dial 911. I'd rather be out here in the country than in the city where all that help is supposed to be available."

Still, farmers and ranchers in Oregon can't afford to have their heads in the clouds when the ground under their feet starts shaking. Preparing for earthquakes and the damage they can cause is essential when you live in an earthquake zone. □

Earthquake intensity maps for the March 25 1993, Scotts Mills, Oregon, earthquake

by Gerald L. Black, Oregon Department of Geology and Mineral Industries, Portland, Oregon 97232

ABSTRACT

The magnitude 5.6 Scotts Mills, Oregon, earthquake was the largest recorded event in northwest Oregon. Following the earthquake the Oregon Department of Geology and Mineral Industries received nearly 5,000 intensity responses from a variety of sources. The responses were coded according to the Modified Mercalli scale of Wood and Neumann (1931), the data were entered into spreadsheets, and the intensities plotted with MapInfo®, a desktop mapping system. The resulting digital plots were hand-contoured to produce a 1:500,000-scale isointensity map of the felt area and a 1:100,000-scale isointensity map of the Portland-Vancouver (Oregon-Washington) metropolitan area. The felt area map is similar to a previous intensity map by Dewey and others (1994), but it also shows, in several communities, increased shaking that probably resulted from amplification by poorly consolidated sediments. The isointensity map of the metropolitan area shows variations that can be correlated to local geology. Also, where the data density is adequate in the Portland quadrangle, areas of increased shaking correlate fairly well with intensities predicted for bedrock shaking with a peak acceleration of 0.03 *g* (equivalent to a moderate magnitude earthquake at the distance of Scotts Mills).

INTRODUCTION

The Richter magnitude (M_L) 5.7 Scotts Mills earthquake occurred on March 25, 1993, at 5:34 a.m., Pacific Standard Time. It is the largest recorded event in northwest Oregon. The earthquake was felt over an area extending from Roseburg, Oregon, on the south to Seattle, Washington, on the north and from the Oregon coast on the west to Prineville, Oregon, on the east. In the epicentral area, significant damage was done to a large number of unreinforced masonry (URM) buildings. The preliminary damage estimate was $28.4 million (Madin and others, 1993). The final damage figure is certainly higher, though there is no official mechanism for tracking damage.

The epicenter, as located by the Pacific Northwest Seismograph Network (PNSN), was at lat 45.033°N., long 122.586°W. (sec. 19, T. 6 S., R. 2 E.) (Thomas and others, 1996), approximately 3 mi (4.8 km) due east of Scotts Mills, a small community in Marion County near Silverton and Mount Angel (Figure 1). The focal depth was 15.1 km (Thomas and others, 1996).

Initial speculation for the source of the earthquake centered on the Mount Angel fault, a structure first mapped by Hampton (1972) near Mount Angel (Figure 1). Werner and others (1992), working with commercial seismic-reflection data and water well logs, extended the fault to the northwest to Woodburn. They also suggested that the fault might be active, basing this on a series of six small earthquakes that occurred near Woodburn in 1990. Focal mechanisms for these earthquakes indicate that the Mount Angel fault is a right-lateral strike-slip fault with some reverse motion on a steeply north-dipping plane (Werner and others, 1992). The Mount Angel fault is part of the northwest-trending Gales Creek-Mount Angel structural lineament which extends for approximately 150 km across the Willamette Valley (Beeson and others, 1985).

The focal mechanism for the Scotts Mills earthquake was determined by Dewey and others (1994), Nabelek and Xia (1995), and Thomas and others (1996). The preferred fault plane strikes N. 44° W. to N. 56° W. and dips 58° to 63° NE. Movement on this fault plane is approximately equal parts right-lateral and reverse slip, consistent with the findings of Werner and others (1992).

The exact relationship of the main-shock focal mechanism and the Mount Angel fault is uncertain. The strike of the main-shock focal mechanism is identical to the strike of the southern end of the Mount Angel fault. However, a projection of the focal mechanism fault plane intersects the surface southwest of the mapped Mount Angel fault (Dewey and others, 1994; Nabelek and Xia, 1995). One possible explanation is that the dip of the main-shock focal mechanism

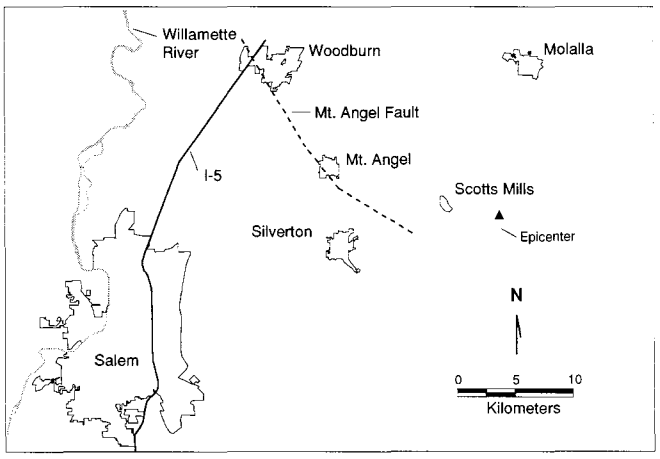

Figure 1. Index map showing the epicentral area of the Scotts Mills earthquake. Large triangle is the epicenter. Dashed line is the trace of the Mount Angel fault (location taken from Werner and others, 1991).

steepens as it nears the surface, so that it intersects the surface at the extended trace of the Mount Angel fault (Nabelek and Xia, 1995). A second possibility is that the Scotts Mills earthquake occurred on one of several parallel en echelon faults (Dewey and others, 1994; Nabelek and Xia, 1995).

PURPOSE OF THIS REPORT

Ideally an earthquake's magnitude is a number that represents the total energy released by that earthquake. Therefore, in theory, an earthquake should have only a single magnitude. In fact, however, several different magnitude scales exist, estimating the released energy on the basis of different parts of the seismic wave spectrum. These different scales give slightly different magnitudes for any given earthquake. For information on various magnitude scales, see Allen (1993) or Bolt (1993).

The intensity is a number that describes the effects of an earthquake on people, manmade structures, and the Earth's surface. The intensity scale most commonly used in the United States is the Modified Mercalli scale of 1931 (Wood and Neumann, 1931). An abridged form of this scale is reproduced in Table 1. The contours on an isoseismal map separate areas of equal seismic intensity.

In 1994, the Oregon Department of Geology and Mineral Industries (DOGAMI) received a grant from the U.S. Geological Survey (USGS) to produce two isoseismal maps for the Scotts Mills earthquake: a 1:500,000 map of the felt area, and a 1:100,000 map of the Portland metropolitan area. The results of that study are described in this paper.

Several previous studies have examined the effects of the Scotts Mills earthquake. Both Madin and others (1993) and Wong and others (1993) described some of the damage associated with the earthquake. Dewey and others (1994) produced small-scale isoseismal maps for the earthquake and described the damage in communities near the epicenter.

The additional isoseismal maps were produced for two reasons: First, the work by Dewey and others (1994) was based on 460 mail questionnaires sent to post offices, police stations, and fire stations in the vicinity of the epicenter. DOGAMI obtained approximately 5,000 additional data points. This greater data density enabled us to correlate areas showing greater than expected shaking with geologic conditions. Second, in 1993 DOGAMI published a set of earthquake hazard maps for the Portland quadrangle (Mabey and others, 1993). Included in this study was a relative ground motion amplification map of the Portland quadrangle (Mabey and Madin, 1993). This map shows areas in the Portland quadrangle where shaking might be worse than expected due to local geologic conditions. The Scotts Mills earthquake gives us an opportunity to see if there is any correlation between predicted amplification and reported intensity resulting from a real earthquake.

METHODS

Immediately after the earthquake, DOGAMI placed a questionnaire in newspapers in the felt area (and in *Oregon Geology*) that asked responders to describe their location during the earthquake, what they felt, and what effects to surrounding objects they observed. DOGAMI received more than 3,500 responses to the questionnaire. An additional 510 responses were collected by Anthony Qamar of the University of Washington, and 700 damage reports were collected by the Oregon Emergency Management Division. Of the nearly 5,000 reports available, 4,774 contained usable information and were entered into Microsoft Excel® spreadsheets. The most common reasons for data to be unusable were a lack of adequate location information—and sound sleepers (i.e., the responder slept through the earthquake). Geology students of Michael Cummings of Portland State University sorted the responses by zip code and assigned preliminary intensities.

Each of the responses was assigned an intensity according to the Modified Mercalli scale of 1931 (Table 1). The assignment of intensities of IV and above was modified by practices described in Stover and Coffman (1993). These

Table 1. *Modified Mercalli intensity scale of 1931 (abridged)*

I	Not felt except by a very few under especially favorable circumstances.
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many are frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage **negligible** in buildings of good design and construction; **slight** to moderate in well-built ordinary structures; **considerable** in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage **slight** in specially designed structures; **considerable** in ordinary substantial buildings, with partial collapse; **great** in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage **considerable** in specially designed structures; well-designed frame structures thrown out of plumb; **great** in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

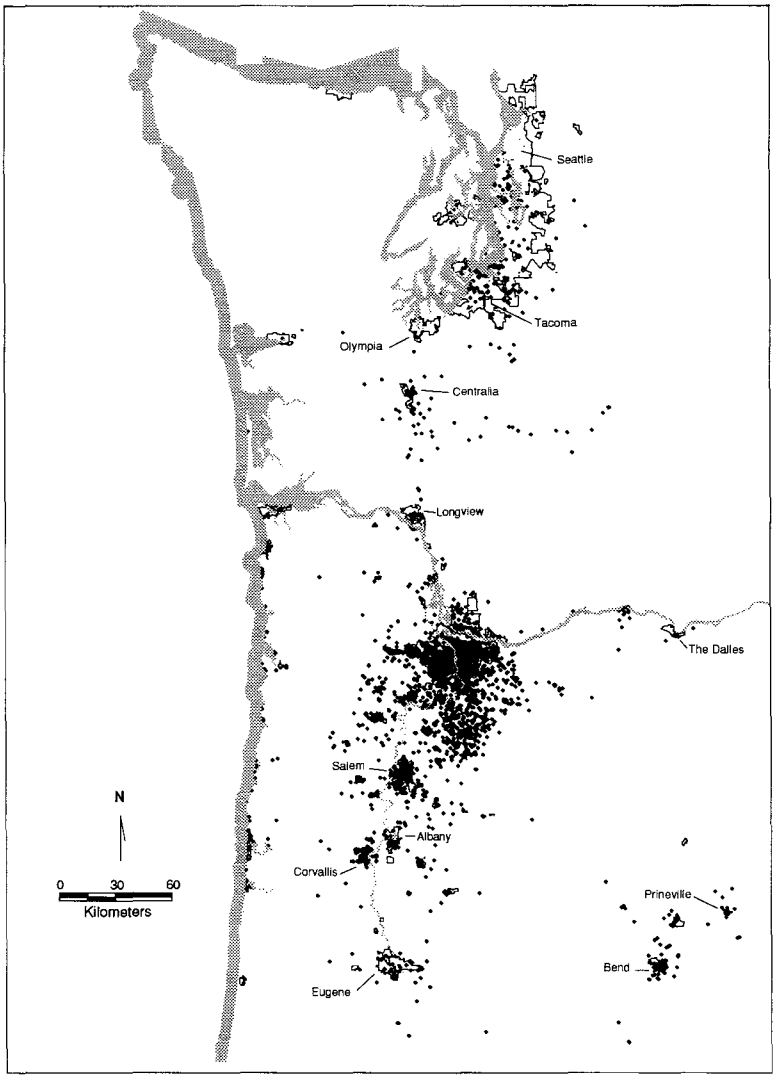

Figure 2. Map of the felt area for the Scotts Mills earthquake showing the distribution of data points used in producing the isoseismal map of Figure 3.

modifications are made because "subjective effects on people described in the MM intensity scale are not reliable considerations for assigning values above the intensity IV level" (Stover and Coffman, 1993). The modifications described below are taken directly from these authors:

IV–Felt by many to all. Trees and bushes were shaken slightly. Buildings shook moderately to strongly. Walls creaked loudly. Observer described the shaking as "strong."

V–'Felt,' 'frightened,' and 'awakened' effects are not used at this or higher intensity levels. Hanging pictures fell. Spilled liquid effects were not used to assign any intensity. Trees and bushes were shaken moderately to strongly. People had difficulty standing or walking. Felt moderately by people in moving vehicles.

VI–At this level, there must be reports of physical damage to manmade structures as described in the MM intensity scale. The only exception is that intensity VI is still assigned if many small objects fell from shelves and (or) many glassware items or dishes were broken.

VII–Only damage to buildings or other manmade structures (as described in the MM intensity scale) is considered.

After intensities were assigned and the data were entered into spreadsheets, MapInfo®, a desktop mapping system designed for personal computers, was used to create plots of the distribution of intensities. Of the 4,774 data points contained in the spreadsheets, all but 205 were successfully located by MapInfo®. More than half of the unlocatable points were in the Portland metropolitan area, where data are abundant The plots were hand-contoured to produce the isoseismal maps discussed below.

RESULTS

Figure 2 shows the distribution of the nearly 4,800 data points used to produce the isoseismal map of Figure 3. Immediately obvious is that most responses were from the Portland metropolitan area, with additional clusters of responses from urban areas, both large and small, in the northern Willamette Valley. What is significant is the lack of data in the Coast Range between the Willamette Valley and the coast.

When an earthquake occurs, the nature of the shaking at any point within the felt area is dependent on several factors, including the size of the earthquake, the distance to the epicenter, the nature of the earthquake source, and variations in local geologic conditions. It is this last factor that can be examined (in a subjective way) with intensity maps. In general, ground shaking is amplified by loose (unconsolidated) sedimentary deposits. Therefore, damage tends to be greater at sites underlain by this type of material than at adjacent sites underlain by bedrock.

Felt area isoseismal map

The isoseismal map of Figure 3 is similar to the map of Dewey and others (1994) with one major exception. Dewey and others (1994) extended the intensity V isoseismal line to the coast, enclosing an area from just south of Tillamook on the north to Newport on the south. In Figure 3, the intensity V isoseismal is closed east of the Coast Range because (1) the small number of data points in the Coast Range are all intensity III, and (2) so are most of the data points along the coast between Newport and Tillamook. Remaining higher intensities (mostly IV and a few V) are associated with the major bays and estuaries. These are interpreted as resulting from amplification in young, unconsolidated estuarine sediments and/or Pleistocene terrace deposits.

Both the intensity IV and V isoseismals of Figure 3 have

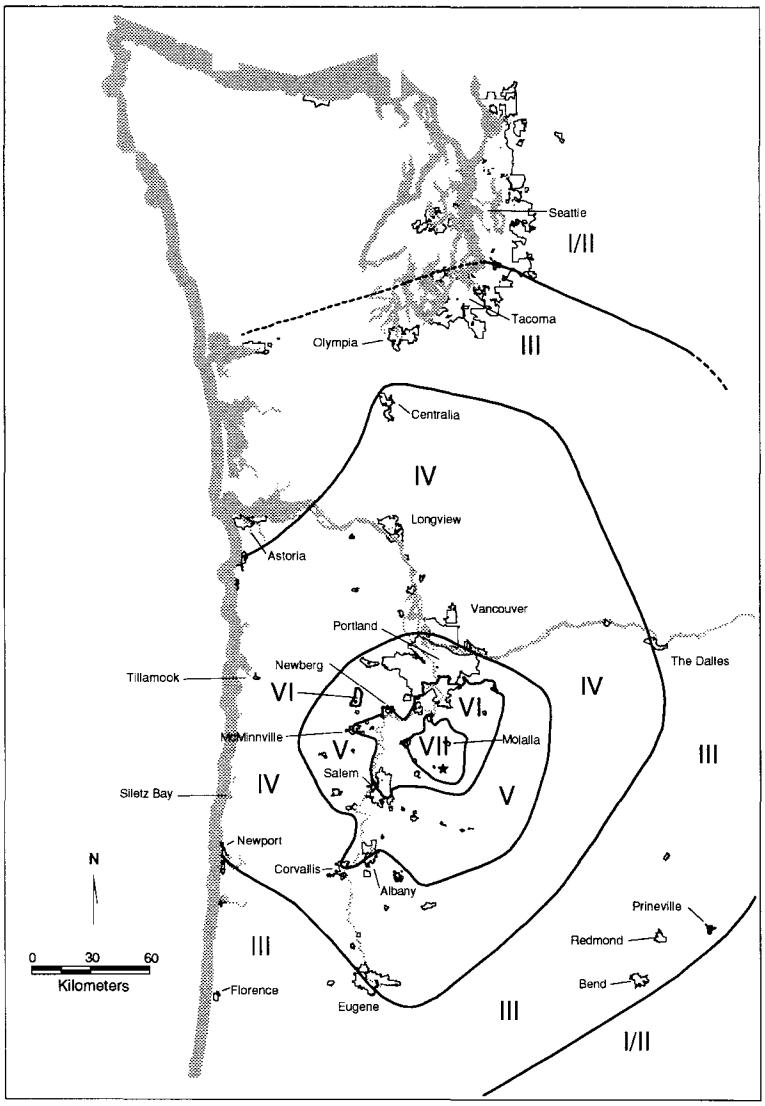

Figure 3. Isoseismal map of the felt area for the Scotts Mills earthquake. Star marks location of epicenter. Contours are isoseismal lines separating areas of equal seismic intensity (dashed where poorly constrained by data). Roman numerals are intensities.

southwest-trending "tails" that follow the course of the Willamette River. These "tails" probably result from increased shaking on poorly consolidated flood plain sediments of the Willamette River.

Newberg and McMinnville suffered damage during the earthquake (intensity VI) that probably resulted from local amplification by unconsolidated flood-plain sediments. Newberg is adjacent to the Willamette River and McMinnville adjacent to the Yamhill River. The small community of Yamhill, due north of McMinnville (see Figure 3), had many intensity VI responses (15 of intensity VI and one VII). Yamhill is located at the junction of Yamhill Creek and the North Yamhill River, and the high-intensity responses are localized along young, unconsolidated alluvium deposited by these streams (as mapped by Schlicker and Deacon, 1967).

In Eugene, at the southern end of the Willamette Valley, most of the responses were intensity III and IV. There was, however, a block of I and II responses from the south end of town, probably reflecting location on a bedrock high.

Farther east, the community of Prineville lies within the intensity III zone, but there were two IV and one V response from the core downtown area. The remainder of the responses were intensity III. Prineville sits at the junction of the Crooked River and Ochoco Creek, and unconsolidated sediments probably caused some ground amplification there. The Bend-Redmond area also lies within the intensity III zone, but more than 70 percent of the responses were I and II. This lower level of shaking, even though slightly closer to the epicenter, reflects the area's location on bedrock basalt flows of the High Lava Plains.

Portland metropolitan area

Figure 4 shows the distribution of data points used to produce the isoseismal map of Figure 5. Notable data gaps are in the Forest Park and industrial areas of northwest Portland, along the east bank of the Willamette River north of the downtown core area, and in north Portland adjacent to the Columbia River. These areas are either unoccupied (Delta Park and the Port of Portland) or zoned for industrial use (i.e., largely unoccupied at 5:34 a.m.).

On Figure 5 are shown seismic intensity zones IV, IV/V, V, and VI. The IV/V zone contains mostly IV responses with about 18 percent III and 10 percent V responses. The adjacent intensity V zone contains only a few III responses and at least 30 percent intensity V responses.

The shape of the intensity VI isoseismal can be explained partially by the fact that the area is closest to the epicenter. It extends slightly farther northward than might be expected, and this probably results from increased shaking on poorly consolidated outburst-flood deposits that underlie much of east Portland and the area around Lake Oswego (Madin, 1990). The shape of the intensity V isoseismal is largely controlled by geology. Increased shaking is evident in the Tualatin Valley, downtown Portland, and northeast Portland, all areas underlain by poorly consolidated outburst-flood deposits, and lesser shaking (intensity IV/V) in the Portland Hills, which are underlain by bedrock basalt. De-

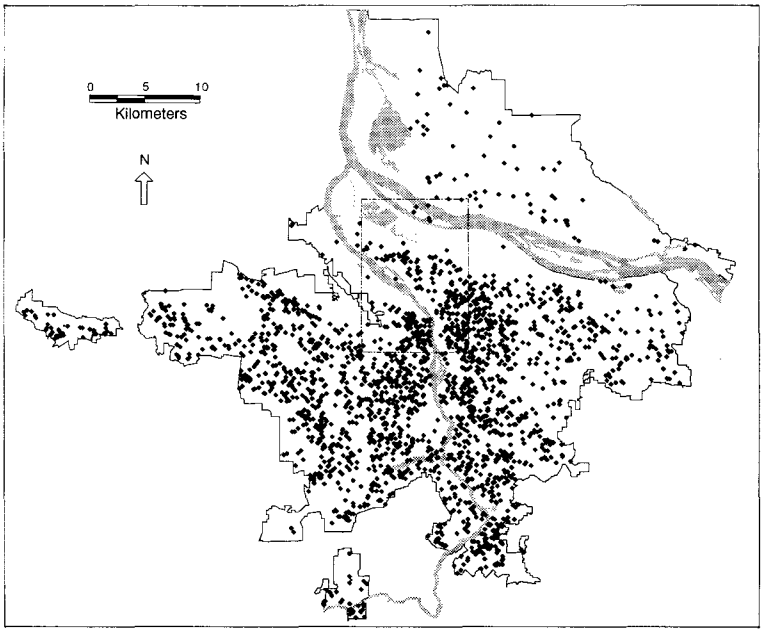

Figure 4. Map of the Portland metropolitan area showing the distribution of data points used in producing the isoseismal map of Figure 5. The boundary shown south of the Columbia River is the urban growth boundary. North of the Columbia River, it outlines the urbanized parts of southern Clark County, Washington. Box outlines the Portland 7½-minute quadrangle.

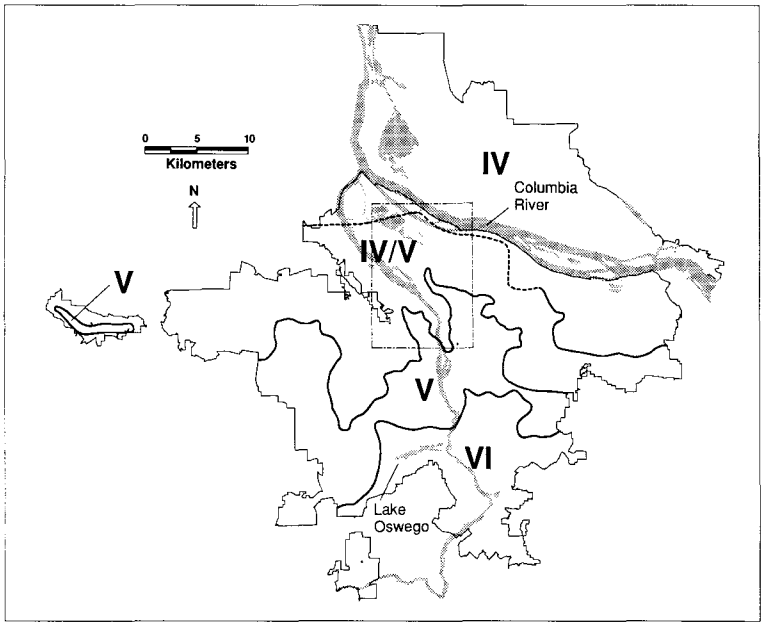

Figure 5. Isoseismal map of the Portland metropolitan area. The boundary shown south of the Columbia River is the urban growth boundary. North of the Columbia River, it outlines the urbanized parts of southern Clark County, Washington. Contours are isoseismal lines (dashed where poorly constrained). Roman numerals are intensities. Box outlines Portland 7½-minute quadrangle.

creased shaking to the north represents increasing distance from the epicenter.

Figure 6 is a map of the Portland 7½-minute quadrangle showing predicted intensities that resulted from bedrock shaking with a peak acceleration of 0.03 *g* (i.e., a moderate magnitude earthquake at the distance of Scotts Mills). The map was prepared by Matthew Mabey of DOGAMI and was constructed in a manner similar to the ground motion amplification map of Mabey and Madin (1993). A three-dimensional model of the geology and its material properties is used with the computer program SHAKE (Schnable and others, 1972). SHAKE performs ground motion analysis, which results in expected average peak accelerations throughout the quadrangle. A detailed description of the above methodology can be found in Mabey and Madin (1993). The average peak accelerations are correlated to intensity on the basis of information from Bolt (1993). The correlation of intensity versus average peak acceleration is reproduced in Table 2. For a variety of reasons, the intensities predicted in Figure 6 are higher than those actually experienced. The correlation between average peak acceleration and intensity (Table 2) is a very crude approximation. Also, the peak acceleration of 0.03 *g* used as the input to SHAKE was a little higher than actual bedrock shaking resulting from the Scotts Mills earthquake (Matthew Mabey, personal communication, 1996). Finally, the assumed bedrock shaking used to create Figure 6 was applied uniformly across the quadrangle. There was no accounting for variations in acceleration due to attenuation at differing distances from the earthquake source, so it is to be expected that the northern portion of the quadrangle would be "overpredicted" by a bit more than the southern portion of the quadrangle. What is most important is not the absolute value of the predicted intensities, but rather the patterns shown in Figure 6.

For a direct comparison of actual intensities with the predicted patterns, the relevant portions of the isoseismal contours of Figure 5 are overlaid on Figure 6. The Roman numerals on Figure 6 represent the intensity zones from Figure 5. Predicted intensities are denoted by the shading pattern. (It should be noted that the predicted intensity map was not examined until the intensities of Figure 5 had been plotted and contoured. No adjustments were made to either map after their initial preparation.)

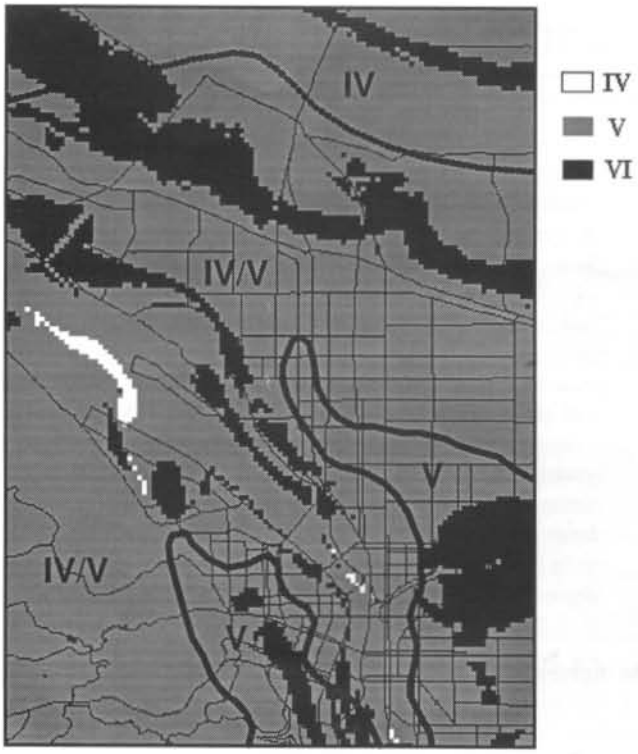

Figure 6. Predicted intensities in the Portland 7½-minute quadrangle as they would result from a magnitude 5.6 earthquake near Scotts Mills, Oregon. Contours are relevant isoseismal lines taken from Figure 5.

There are significant correlations between Figure 5 and Figure 6. West of the Willamette River, Figure 6 predicts increased shaking in the downtown core area, which is underlain by a combination of fill, alluvium, and unconsolidated, fine-grained outburst-flood deposits (Beeson and others, 1991). A north-northwest-trending tongue of intensity V responses confirms increased shaking in this area. Higher intensities are also predicted north of this intensity V tongue (adjacent to the Willamette River and in the northwest Portland industrial area), but they cannot be confirmed because of a lack of data (see Figure 4).

Higher intensities are also predicted to the east of the Willamette River, in areas of northeast Portland underlain by unconsolidated, fine-grained outburst-flood deposits (Beeson and others, 1991). Again, there is a north-northwest-trending tongue of intensity V responses that confirms increased shaking. Higher intensities predicted along the east bank of the Willamette River in fill and alluvium cannot be tested due to lack of data (see Figure 4).

In north Portland and across the Columbia River in Vancouver, Washington, Figure 6 predicts two west-northwest-trending bands of higher intensity. Neither band is evident on the isoseismal map. Data from Washington are sparse and show no obvious trend. This may be due to increased distance to the epicenter. Because the input bedrock acceleration used to create Figure 6 did not take into account distance to the epicenter, the northern part of the quadrangle tends to be "overpredicted" relative to the south part. Also, it is to be remembered that the correlation between intensity and average peak acceleration is crude, so that slight variations in acceleration may not show up as intensity variations.

Table 2. Correlation of intensity and average peak acceleration. From Bolt (1993), Appendix D

Intensity value	Average peak acceleration in g (g = gravity = 980 cm/sec^2)
I–III	< 0.015
IV	0.015–0.02
V	0.03–0.04
VI	0.06–0.07
VII	0.10–0.15
VIII	0.25–0.30
IX	0.50–0.55
X–XII	> 0.60

South of the Columbia River, Figure 4 shows a distinct lack of data where higher intensities are predicted. There is, however, a hint that higher intensities may occur there. This area lies within the intensity IV/V zone (Figure 5). Where data for this zone are abundant, they consist of intensities III, IV, and a few V. Along the northern edge of this band of abundant data, however, there are no intensity III reports, only IV and one V. This is not enough to draw separate contours, just a hint that the level of shaking might be higher in the data gap to the north.

CONCLUSIONS

The Scotts Mills earthquake confirms that a significant earthquake hazard exists in western Oregon. It further demonstrates that when an earthquake occurs, one can expect significant damage. The early damage estimates for the Scotts Mills earthquake were $28.4 million (Madin and others, 1993). An earthquake of this size or larger centered under the Portland metropolitan area would do significantly more damage.

Seismic intensity maps, despite their limited precision and resolution, are a useful means of delimiting those areas where greater than expected shaking might occur. An example is the correlation between increased intensity and the presence of underlying alluvium in Figure 4. Intensity maps, however, depend on actual earthquakes.

The degree of correlation between intensities experienced during the Scotts Mills earthquake and intensities predicted by methods utilized in Mabey and Madin (1993) suggest that ground motion amplification maps are a useful means of predicting where excessive shaking will occur. This information can then be utilized to take mitigation steps before the earthquake actually occurs. An even better

degree of hazard identification could be achieved with the aggressive placement of strong-motion instruments throughout the Portland metropolitan area, so that, when another earthquake like Scotts Mills occurs, accelerations throughout the city can be directly measured.

Since the Scotts Mills earthquake, DOGAMI has prepared earthquake hazard maps for an additional four quadrangles in the Portland metropolitan area (Mabey and others, 1995a,b,c,d) and for the Oregon coast at Siletz Bay (Wang and Priest, 1995). The Washington Division of Geology and Earth Resources has produced relative earthquake hazard maps for the Vancouver, Washington, urban area (Mabey and others, 1994). DOGAMI has additional studies in progress in Salem, Eugene, and the Portland metropolitan area.

ACKNOWLEDGMENTS

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Landslides in the West Hills of Portland: A preliminary look

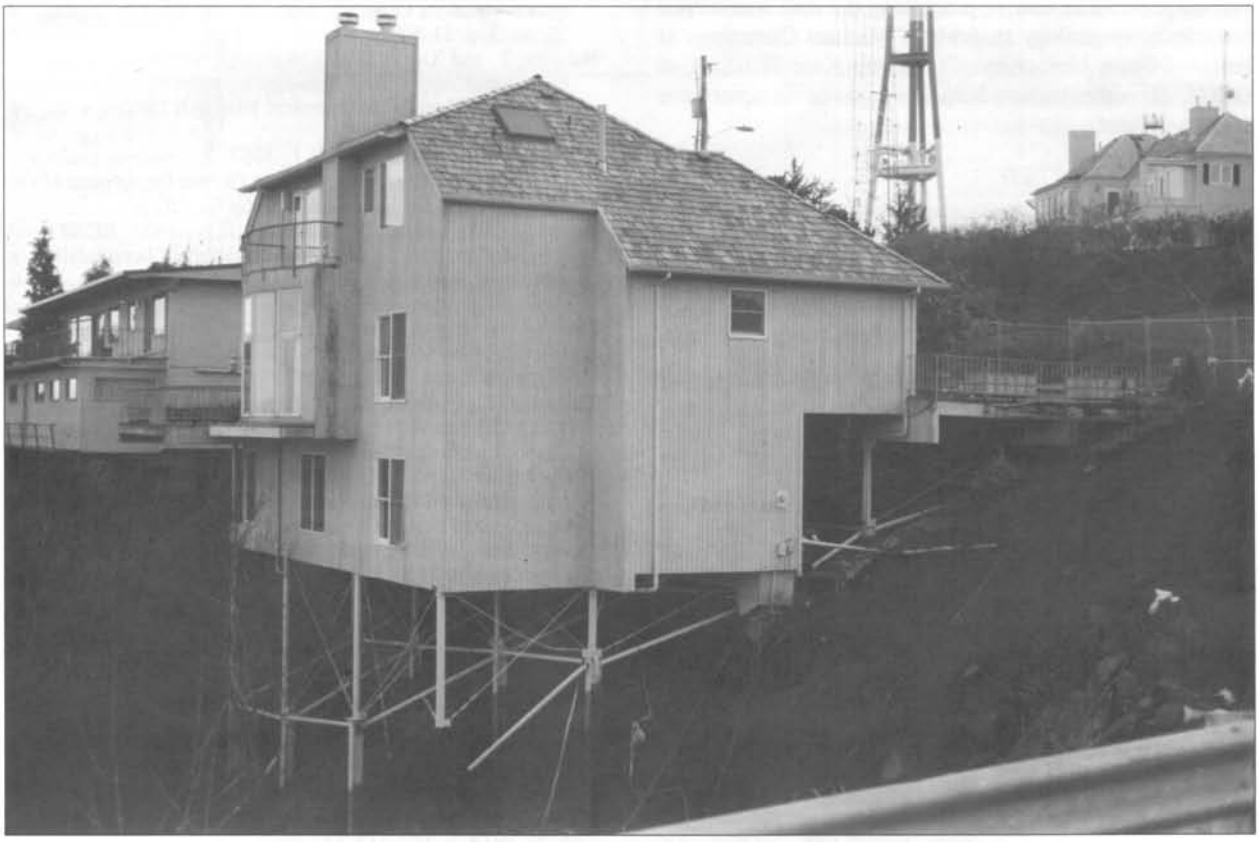
Photographs by Scott F. Burns, Geology Department, Portland State University

The heavy rains during February of 1996 caused not only disastrous flooding but also numerous landslides.

At the time of this writing, the City of Portland estimates 168 slides, of which over 90 percent occurred in the West Hills—and more slides are threatening. As of February 21, the estimate of damage just to public facilities was $32.5 million. By the end of February, 12 slide-affected homes had received red tags, which means that, for safety reasons, they cannot be entered at all. For another 25 homes yellow tags were issued, meaning that they cannot be continuously occupied because of serious problems that must be fixed.

All of the West Hills slides appear to have occurred in the Portland Hills Silt, a loess that mantles the Portland Hills and was deposited there by winds during dry interglacial periods. The Portland Hills Silt is a weak soil when wet. Heavy rainfall of over six inches in three days on soils that were already saturated, the oversteepened slopes of the West Hills, clogged or defective drainage systems, streets without curbs and gutters, and misdirected runoff water led to many of the disastrous slides. □

Asphalt berm placed on edge of SW Council Crest Drive to keep water from running over edge of road and flowing onto landslide below the road.



Slide next to house on 4300 block on SW Council Crest drive.

Slide on 2700 block of SW Fairmont. Plastic covers the slope to keep rainwater away from it.

Slide on 2600 block of SW Fairmont.

ABSTRACTS OF PAPERS

The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.

Properties and depositional characteristics of tsunamis in south coastal Oregon from a paired coastal-lake and marsh study, by Harvey M. Kelsey, Department of Geology, Humboldt State University, Arcata, California; Alan R. Nelson, U.S. Geological Survey, Denver, Colorado; and Eileen Hemphill-Haley, U.S. Geological Survey at Department of Geological Sciences, University of Oregon, Eugene, Oregon.

Through a paired study of two adjacent sites, we are studying the depositional properties of tsunami deposits of presumably the same age but deposited in two markedly different depositional environments. Both sites are on the south coast of Oregon, separated by 28 km of coastline. One site is Bradley Lake, a freshwater lake 0.5 km inland from the coast at an elevation of 5.5 m. The other site is Sixes River marsh, which borders the estuary of the Sixes River.

These two depositional environments both record the same set of great-earthquake-generated tsunami deposits for a period of time extending from the present back to ca. 5,000 years B.P. Individual tsunami events tentatively can be correlated between the Bradley Lake stratigraphy and the stratigraphy in the Sixes River marsh. The tsunami deposits are layers of sand capped by woody detritus. In the lake, eight to nine sand horizons are interlayered with lake sediments. The sands form continuous layers in the lake. In the oceanward portion of the lake, sand horizons attain thicknesses as great as 70 cm. Sand thicknesses decrease landward. For those sand intervals investigated in detail, the sands are overlain by lake mud that is rich in marine or brackish-water diatoms. Therefore, the sand was transported by a pulse of water that entered the lake from the ocean.

The data from the lake setting and the marsh setting together provide a good synoptic view of a tsunami. In the lake setting, a tsunami leaves widespread and well-preserved deposits that thin in a landward direction. In some cores and for some of the tsunami deposits, the tsunami has eroded the lake sediment substrate, preserving rip-up clasts of the substrate in the tsunami deposit. Because the tsunami deposit itself is not eroded, details of the deposit, such as the number and thickness of individual pulses, are preserved. The elevation and position of the lake provide estimates as to tsunami inundation extent and run-up magnitude, but the lake setting provides no information about land-level changes, as inferred from diatom stratigraphic data. In the marsh, tsunami deposits can also be related to incidences of liquefaction,

In conclusion, neither the lake setting nor the marsh setting in south coastal Oregon provides a complete data set to reconstruct a paleotsunami and any accompanying land-level change. However, the two data sets together can potentially give information on land-level change immediately preceding the tsunami, as well as data on inundation extent and run-up magnitude. □

In memoriam: Wally McClung

Wally McClung, volunteer for DOGAMI at the Nature of the Northwest Information Center, died January 25, 1996. Wally was known to all of us for his kindness, generosity, and knowledge and love of outdoor Oregon. He is survived by his wife Eleanor, two sons, and a daughter.

Wally was a past president of the Geological Society of the Oregon Country and a volunteer guide at the Japanese Gardens. His interest in geology led him to DOGAMI, where he provided his own help as well as that of other volunteers he found for us. He periodically brightened our lives by bringing exquisite flower arrangements, the product of another of his hobbies. One of the greatest joys of his life was fishing, and his knowledge of that and geology made him an invaluable help in the Information Center.

We miss him in many ways—his warm friendly smile, his encouragement, and his love of the out-of-doors. This summer, as people talk of fishing, geology, the Japanese Gardens—the things Wally made so vivid to us all—we will remember him and the way he enriched our lives by sharing his time and talents with us. □

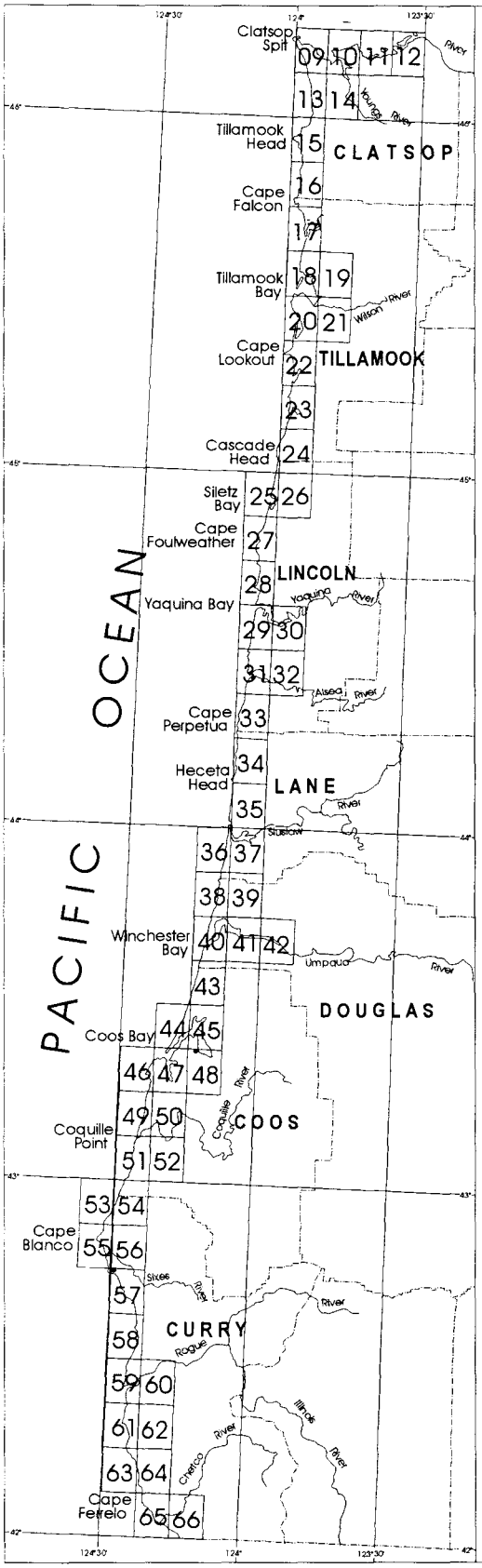
Tsunami hazard maps released

At its January 22, 1996, meeting in Grants Pass, the Governing Board of the Oregon Department of Geology and Mineral Industries (DOGAMI) adopted final rules and maps to implement Senate Bill 379, passed by the 1995 Oregon Legislature, which restricts construction of certain types of essential facilities and special-occupancy structures within the tsunami inundation zone.

The tsunami inundation zone is shown on 58 *Tsunami Hazard Maps*, Open-File Reports O–95–09 through O–95–66. Each map has a line that shows how far inland and uphill a tsunami caused by a magnitude 8.8 undersea earthquake is expected to go. Each of the blueline diazo maps is on a 7½-minute topographic map base, at a scale of 1:24,000. Cost of each map is $3. A complete set of all 58 maps costs $160. See order information on page 48.

An explanatory 100-page text is published separately as Open-File Report O–95–67, and can be purchased for $9.

The index map on the next page correlates the names of the quadrangles with the number of the respective open-file report. Coastal features and county borders on the index map allow for quicker orientation. □



Index map to Senate Bill 379 tsunami inundation zone maps

09 Use the last two digits of Open-File Report number to locate individual tsunami inundation maps

Open-File Report	USGS quadrangle map
O-95-09	Warrenton
O-95-10	Astoria
O-95-11	Cathlamet Bay
O-95-12	Knappa
O-95-13	Gearhart
O-95-14	Olney
O-95-15	Tillamook Head
O-95-16	Arch Cape
O-95-17	Nehalem
O-95-18	Garibaldi
O-95-19	Kilchis River
O-95-20	Netarts
O-95-21	Tillamook
O-95-22	Sand Lake
O-95-23	Nestucca Bay
O-95-24	Neskowin
O-95-25	Lincoln City
O-95-26	Devils Lake
O-95-27	Depoe Bay
O-95-28	Newport North
O-95-29	Newport South
O-95-30	Toledo South
O-95-31	Waldport
O-95-32	Tidewater
O-95-33	Yachats
O-95-34	Heceta Head
O-95-35	Mercer Lake
O-95-36	Goose Pasture
O-95-37	Florence
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O-95-55	Cape Blanco
O-95-56	Sixes
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O-95-58	Ophir
O-95-59	Gold Beach
O-95-60	Signal Buttes
O-95-61	Cape Sebastian
O-95-62	Sundown Mountain
O-95-63	Mack Point
O-95-64	Carpenterville
O-95-65	Brookings
O-95-66	Mount Emily

DOGAMI PUBLICATIONS

Released February 12, 1996:

Best Management Practices for Reclaiming Surface Mines in Washington and Oregon, by David K. Norman, Peter J. Wampler, E. Frank Schnitzer, and Jaretta M. Roloff. DOGAMI Open-File Report O–96–2, var. pag., $8.

This is a manual for landowners, land-use planners, and mine operators that describes reclamation and mining practices for Oregon and Washington.

The approximately 120-page, extensively illustrated manual provides information about planning a surface mine from start-up to final reclamation, incorporating water and erosion control during operation and reclamation, soil salvage and replacement, land shaping, and revegetation. The authors urge miners to use this manual as a resource in developing an environmentally and financially sound mine.

The report was produced cooperatively by members of the Washington Department of Natural Resources, Division of Geology and Earth Resources, and the DOGAMI Mined Land Reclamation Program. It has been released also by the Washington agency as Open-File Report 96–2. The project was supported in part by the U.S. Environmental Protection Agency and conducted under the Tri-State Agreement for Mining between Idaho, Oregon, and Washington.

Coauthor Peter Wampler of the DOGAMI Mined Land Reclamation Program explains that "The term 'best management practices' (BMPs) has generally been used to describe mechanical means of minimizing or eliminating water-quality problems. The BMPs presented here, however, apply as well to reclamation, planning, and specific methodologies to promote an integrated approach to mining." He adds that the manual presents "the most effective and economical reclamation and mining practices known to the issuing Washington and Oregon agencies."

Released March 7, 1996:

Geology and Mineral Resources Map of the Three Creek Butte Quadrangle, Deschutes County, Oregon, by Edward M. Taylor and Mark L. Ferns. Geological Map Series GMS–87, 1 map, 8 p. text, $6.

The Three Creek Butte quadrangle covers part of the eastern margin of the High Cascades geologic province between the cities of Bend and Sisters. The quadrangle map is at a scale of 1:24,000 and is produced in two colors: the brown topographic base is overlain by geologic information in black.

The map identifies rock units, faults, and the outlines of Pleistocene glaciers.The accompanying text describes three stages of geologic history for the quadrangle: Tertiary tectonic and volcanic activity between 7 and 5.5 million years ago, Pliocene-Pleistocene subsidence from about 5.4 million years ago, and Pleistocene volcanism and glaciation beginning about 600,000 years ago.

The text also discusses mineral, geothermal, and groundwater resources and includes geochemical analyses for major and trace elements of 34 samples collected in the quadrangle. Aggregate and building stone are the main mineral resources in the quadrangle. While the geology suggests geothermal energy potential, limited exploration so far has not identified a resource.

The report is one product of a cooperative mapping effort by geologists from Oregon State University, the Oregon Department of Geology and Mineral Industries, and the U.S. Geological Survey. One goal of the project is to provide a detailed geologic framework for Oregon Water Resources Department/U.S. Geological Survey groundwater studies in the Deschutes River basin.

These DOGAMI publications are now available over the counter, by mail, FAX, or phone from the Nature of the Northwest Information Center and the DOGAMI field offices in Baker City and Grants Pass. Addresses are on page 26 of this issue. Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment except for credit-card orders. □

DOGAMI cooperates in earthquake hazard study

Gerald L. Black, geologist with the Oregon Department of Geology and Mineral Industries, was one of the three scientists who jointly studied certain effects of the 1964 earthquake in Alaska. He was joined by Timothy J. Walsh of the Washington Division of Geology and Earth Resources and Rodney A. Combellick of the Alaska Division of Geological and Geophysical Surveys.

The purpose of the study was to examine some of the geologic effects of earthquake-induced liquefaction during the 1964 Alaska earthquake as an analogue for recognizing and interpreting evidence of prehistoric earthquakes in the Pacific Northwest and the Cascadia Subduction Zone.

The 1964 Alaska earthquake—magnitude 9.2, property damage estimated at $311 million—caused much of its damage to railroads and highways by ground failure induced by liquefaction. What the scientists were able to observe in Alaska will help others to recognize such effects in the field and to understand better where to look for them as evidence of prehistoric earthquakes.

The resulting 80-page report has been published by the Washington Division of Geology and Earth Resources as Report of Investigations 32, under the title ***Liquefaction Features from a Subduction Zone Earthquake: Preserved Examples from the 1964 Alaska Earthquake***.

It is available for purchase from the Washington Division of Geology and Earth Resources in Olympia, P.O. Box 47007, Olympia, WA 98504-7007, and also from the Nature of the Northwest Information Center in Portland (see order information on the back page of this issue). The purchase price is $5. □

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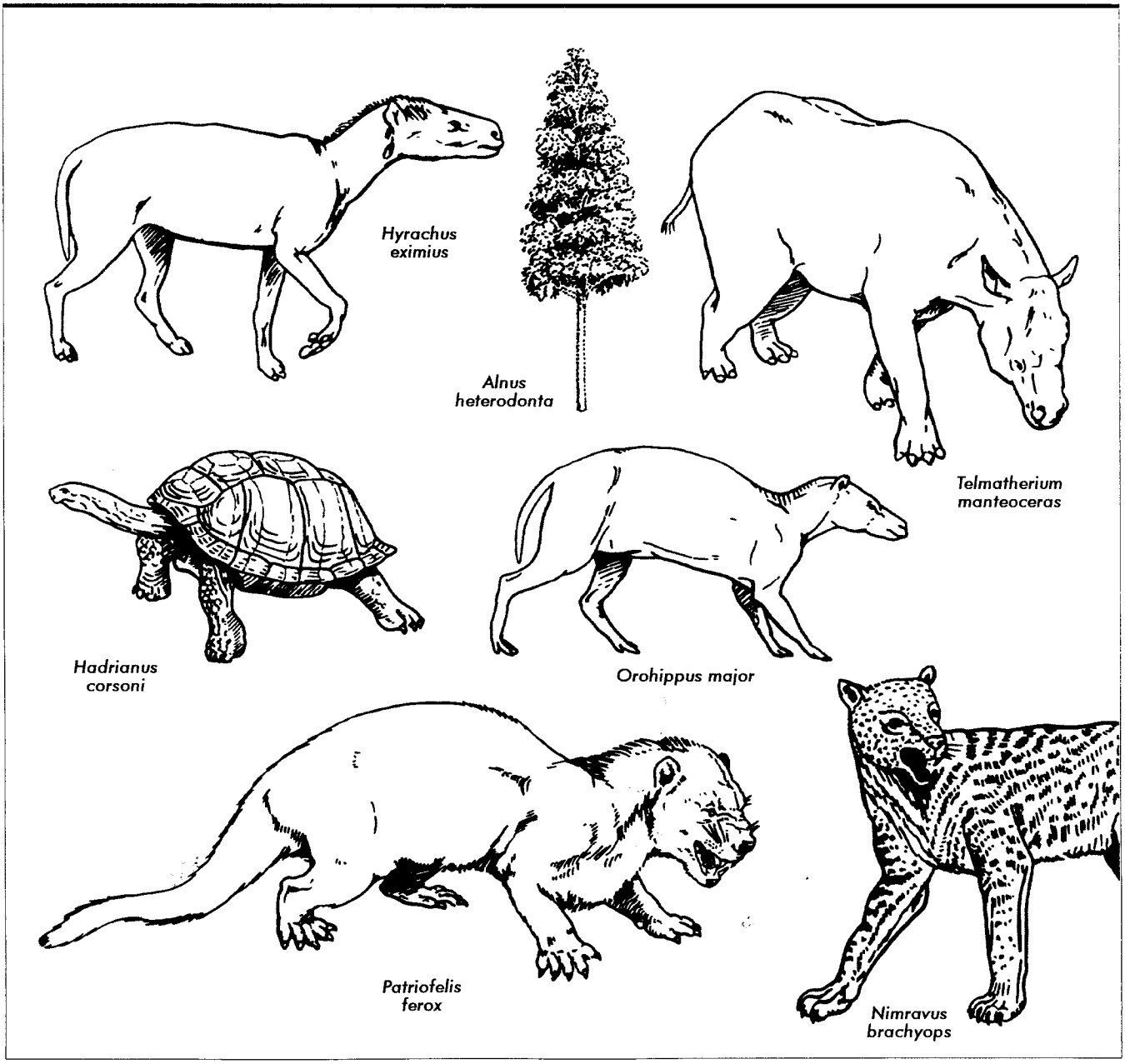

IN THIS ISSUE:

Reconstructions of Eocene and Oligocene Plants and Animals of Central Oregon

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

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).

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Cover illustration

Collage of samples from reconstructions of plants and animals from fossils of the John Day Fossil Beds National Monument. Illustrations and discussion of such reconstructions are contained in the article beginning on next page.

In memoriam: Volunteer Shirley O'Dell

Shirley O'Dell, volunteer at the Nature of the Northwest Information Center, died March 30, 1996.

Born in Minneapolis, Minnesota, she spent most of her life in Portland, Oregon. She was a secretary at Charles F. Berg, at an investment company, and at Columbia Grain Company. After her retirement, she worked as a volunteer at St. Vincent's Medical Center Gift Shop and at the Nature of the Northwest Infomation Center. She was a member of the Geological Society of the Oregon Country (GSOC) for more than 30 years and held various elective and appointive offices, including secretary and auditor.

Shirley was an avid worldwide traveler. She is missed at the Center because she contributed so much as a volunteer—her knowledge about Oregon, interest in geology, and willingness to do careful, meticulous work.

She is survived by one brother and many friends. □

DOGAMI will map tsunami hazard zones at Newport and Seaside-Gearhart

The Oregon Department of Geology and Mineral Industries (DOGAMI) has received support to produce tsunami hazard maps for the Yaquina Bay area of Newport and for the cities of Seaside and Gearhart. The Seaside-Gearhart project is funded by a grant of $132,000 from the Petroleum Antitrust Grant Program administered by the Oregon Department of Justice. The Newport project is funded by a grant of $85,000 from the National Earthquake Hazard Reduction Program of the U.S. Geological Survey.

Both projects will produce maps of expected tsunami flooding from undersea earthquakes on the nearby Cascadia subduction zone fault system. Great (magnitude 8–9) earthquakes on this fault system have caused large tsunamis to strike the Oregon coast every 300 to 500 years, the last one being 300 years ago. Such tsunamis strike the coast within 30 minutes or less after the earthquake, so evacuation guided by accurate knowledge of possible flooding zones is essential.

DOGAMI is working in collaboration with the Oregon Graduate Institute of Science and Technology and the Geology Department of Portland State University to generate the necessary data for these maps. For information about the projects, contact George Priest at the Portland office of DOGAMI, phone 503-731-4100. □

DOGAMI now has Internet home pages

The Oregon Department of Geology and Mineral Industries (DOGAMI) can now be found on the Internet with its own home pages:

The general Department address
http://sarvis.dogami.state.or.us
The Nature of the Northwest Information Center:
http://www.naturenw.org
The Mined Land Reclamation Program:
http://www.proaxis.com/~dogami/mlrweb.shtml □

Reconstructions of Eocene and Oligocene plants and animals of central Oregon

by Gregory J. Retallack, Erick A. Bestland, Department of Geological Sciences, University of Oregon, Eugene, OR 97403-1272, and Theodore J. Fremd, John Day Fossil Beds National Monument, HC 82 Box 126, Kimberly, OR 97848-9701

ABSTRACT

Tertiary fossil plants and mammals of the Clarno and Painted Hills units of the John Day Fossil beds have now been placed within a stratigraphic framework created by excavating trenches through poorly exposed parts of the sequence. The middle-late Eocene Nut Beds locality in the Clarno Formation of the Clarno area is at the top of a sequence of volcanic mudflows, that include fossil plant localities near the Hancock Tree and the Fern Quarry of about the same geological age. Reconstructions are presented here of an extinct tree *(Meliosma beusekomii)*, a tortoise *(Hadrianus corsoni)* and a variety of fossil mammals *(Telmatherium manteoceras, Hyrachyus eximius, Orohippus major, Patriofelis ferox)* from the Nut Beds, and of an extinct plane tree *(Macginitiea angustiloba)*, from near the Hancock Tree. Also reconstructed are late Eocene mammals *(Protitanops curryi, Plesiocolopirus hancocki, Teletaceras radinskyi, Haplohippus texanus, Diplobunops crassus, Hemipsalodon grandis)* similar to those from the Mammal Quarry of the uppermost Clarno Formation. Newly discovered in the Clarno area but in the lower John Day Formation are fossil plants and mammals of late Eocene age. Early Oligocene lake beds of the middle Big Basin Member of the lower John Day Formation in the Painted Hills include a variety of plants, dominated by an extinct alder *(Alnus heterodonta)*, reconstructed here. Lignites stratigraphically higher within the middle Big Basin Member have yielded mostly remains of dawn redwood *(Metasequoia occidentalis)*, also reconstructed here. Late Oligocene fossil mammals *(Diceratherium annectens, Miohippus quartus, "Entelodon" calkinsi, Hypertragulus hesperius, Eporeodon occidentalis, Nimravus brachyops)* from the Turtle Cove Member of the John Day Formation also are reconstructed.

INTRODUCTION

Our impressions of the prehistoric past are based less on illustrations of fossil bones and leaves than on the work of such artists as Charles Knight, Bruce Horsfall, Zdenek Burian, Jay Matternes, Frank Knight, and Peter Murray. Their restorations of past landscapes are more powerful coherent images than fragmentary fossils scattered in museum drawers and published in technical journals. Their artistry also makes obvious testable hypotheses of the nature of past life, hypotheses that can prod the search for deeper understanding. In this spirit, we offer new reconstructions of some fossil plants and animals from the Eocene-Oligocene parts of the Clarno and John Day Formations of central Oregon.

Central Oregon has long been known as an important region for Cenozoic nonmarine fossils now conserved in the John Day Fossil Beds National Monument (Figure 1). Fossil leaves were discovered in the Painted Hills by soldiers using the military road from John Day to The Dalles in the 1860s. Thomas Condon, then a missionary in The Dalles, made the first scientifically useful collections of plant and mammal fossils from the region in 1865 (Clark, 1989) and shipped them east for expert description (Marsh, 1873, 1874, 1875; Newberry, 1898; Knowlton, 1902). Expeditions from the University of California at Berkeley revisited these sites at the turn of the century and discovered plant fossils in the Clarno area (Merriam, 1901a,b, 1906; Sinclair, 1905; Merriam and Sinclair, 1907). The most significant sites in the Clarno area were first developed by amateurs, the Nut Beds by Thomas Bones, beginning in 1943 (Stirton, 1944; R.A. Scott, 1954; Bones, 1979; Manchester, 1994a), and the Mammal Quarry by Lon Hancock in 1955 (Mellett, 1969; Hanson, 1973, 1989; Pratt, 1988). The fossil riches of the area are far from exhausted, and paleontological research is still active (Retallack, 1991a,b; Manchester and Kress, 1993; Manchester, 1994a,b, 1995; Manchester and others, 1994; Meyer and Manchester, unpublished data, 1995; Fremd, 1988, 1991, 1993; Fremd and Wang, 1995). John Day fossils present striking evidence of paleoclimatic and evolutionary change on a 50-million-year time scale (Chaney, 1948a; Ashwill, 1983; Wolfe, 1992; Bestland and others, 1994). Emphasis of this paper is on their diversity and quality of preservation that allows an unusually detailed view of plants and animals on land in the distant geological past.

EOCENE FOSSILS OF THE CLARNO AREA

The geological sequence of fossil localities in the type area of the Clarno Formation near Clarno has remained unclear until recently because of the complicating effects of a local dacite intrusion and poor outcrop of clayey strata in badlands and grassy slopes. We addressed both problems by digging trenches to improve exposure and found, for example, that the dacite intrusion has a capping paleosol, so that it was a volcanic hill onlapped by fossiliferous rocks of the upper Clarno Formation (Bestland and Retallack, 1994a; Bestland and others, 1994, 1995). Such stratigraphic data, together with recent single-crystal $^{40}Ar/^{39}Ar$ radiometric dates (by C.C. Swisher for Bestland and Retallack, 1994a) have enabled us to establish the stratigraphic order of fossil localities near Clarno (Figure 2).

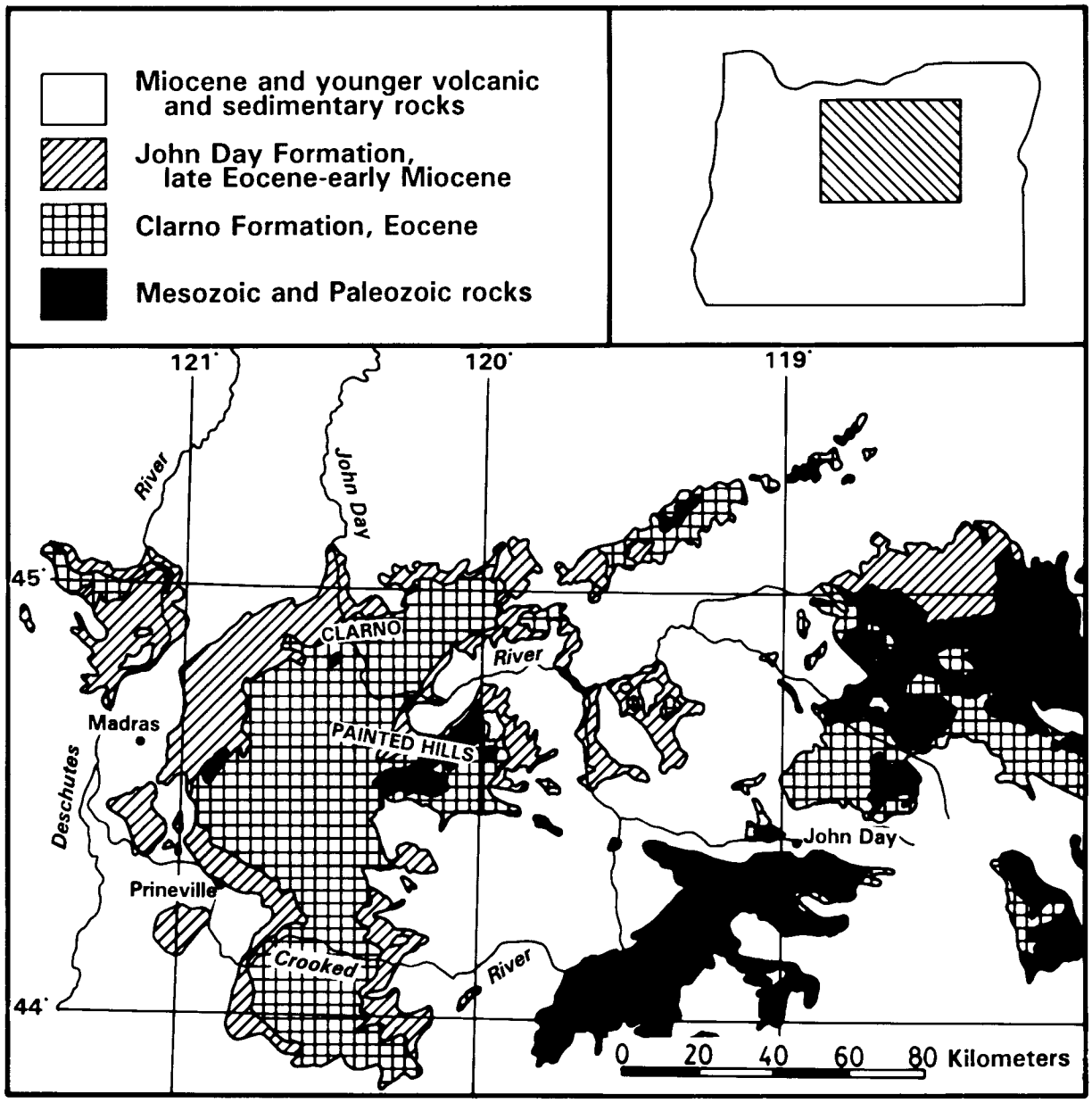

Figure 1. Location map for Painted Hills and Clarno Units of the John Day Fossil Beds National Monument, showing distribution of Clarno and John Day Formations and older rocks (after Walker, 1977; Walker and Robinson, 1990).

The best known fossil locality in this area is one known as the Clarno Nut Beds, named for an extraordinary diversity of 173 species of fossil fruits and seeds (Manchester, 1994a), fossil wood, leaf impressions, and insects (R.A. Scott, 1954, 1955, 1956; R.A. Scott and Barghoon, 1956; R.A. Scott and others, 1962; Gregory, 1969; Manchester, 1977, 1979, 1980a,b, 1981, 1983, 1987, 1988, 1991; Manchester and Kress, 1993). The diversity of the flora, its vines, bananas, palms, and other taxa, has been regarded as evidence of multistratal rain forest (Manchester, 1994a). However, associated paleosols are Ultisols (Smith, 1988; Bestland and Retallack, 1994a) rather than the Oxisols typical under equatorial rain forest or "high evergreen selva" (of Gómez-Pompa, 1973). A better modern analog considering the palms, cycads, tree ferns, oaks, planes, and laurels in the fossil flora may be the "high semi-evergreen montane selva of Lauraceae" of tropical Mexico (Gómez-Pompa, 1973). Vertebrate fossils found in the conglomerates of the Nut Beds include tortoise (*Hadrianus* sp. indet.), crocodilian, titanothere (*Telmatherium* sp. indet.), four-toed horse (*Orohippus major*), extinct rhino (*Hyrachyus eximius*), and lionlike extinct carnivore (*Patriofelis ferox*)

(Hanson, 1973; Pratt, 1988). Such a fauna is compatible with a forested habitat and middle Eocene (Bridgerian) age. Late Eocene (Uintan) is indicated by recent radiometric determinations of 43.6 and 43.7 Ma by Vance (1988), using fission tracks, and of 43.7 Ma by Turrin (for Manchester, 1994a), using single-crystal laser-fusion $^{40}Ar/^{39}Ar$ on plagioclase crystals. Most of the fossil mammals listed are known also from the Uintan, and there remain problems with the Uintan-Bridgerian boundary (Prothero and Swisher, 1992; Evanoff and others, 1994). A more precise determination than "Bridgerian-Uintan" will have to await further studies of the Wyoming type section and the Clarno fossils.

The relationship of the Nut Beds to other nearby localities has been problematic (Retallack, 1981). On the basis of our correlation of rhyodacitic ashes, unusually thick lahars, and a distinctive amygdaloidal basalt, we place the Nut Beds at the top of the volcanic mudflows in the Clarno Formation. These thick lahars with few and weakly developed paleosols accumulated rapidly, so that the numerous fossil plant localities now known to underlie the Nut Beds are not much different in geologic age. This idea is supported by fission track dates of 44 Ma for the Muddy Ranch tuff and of 44.3 Ma from a dacite cobble in a lahar above the Fern Quarry (Vance, 1988). The dacite cobble was probably derived from the onlapped local dacite dome, which is older than any known Eocene fossil locality in this area. The Muddy Ranch tuff is within a clayey sequence of paleosols between the conglomerates of the Palisades and the overlying conglomerates of Hancock Canyon, which are capped by the Nut Beds.

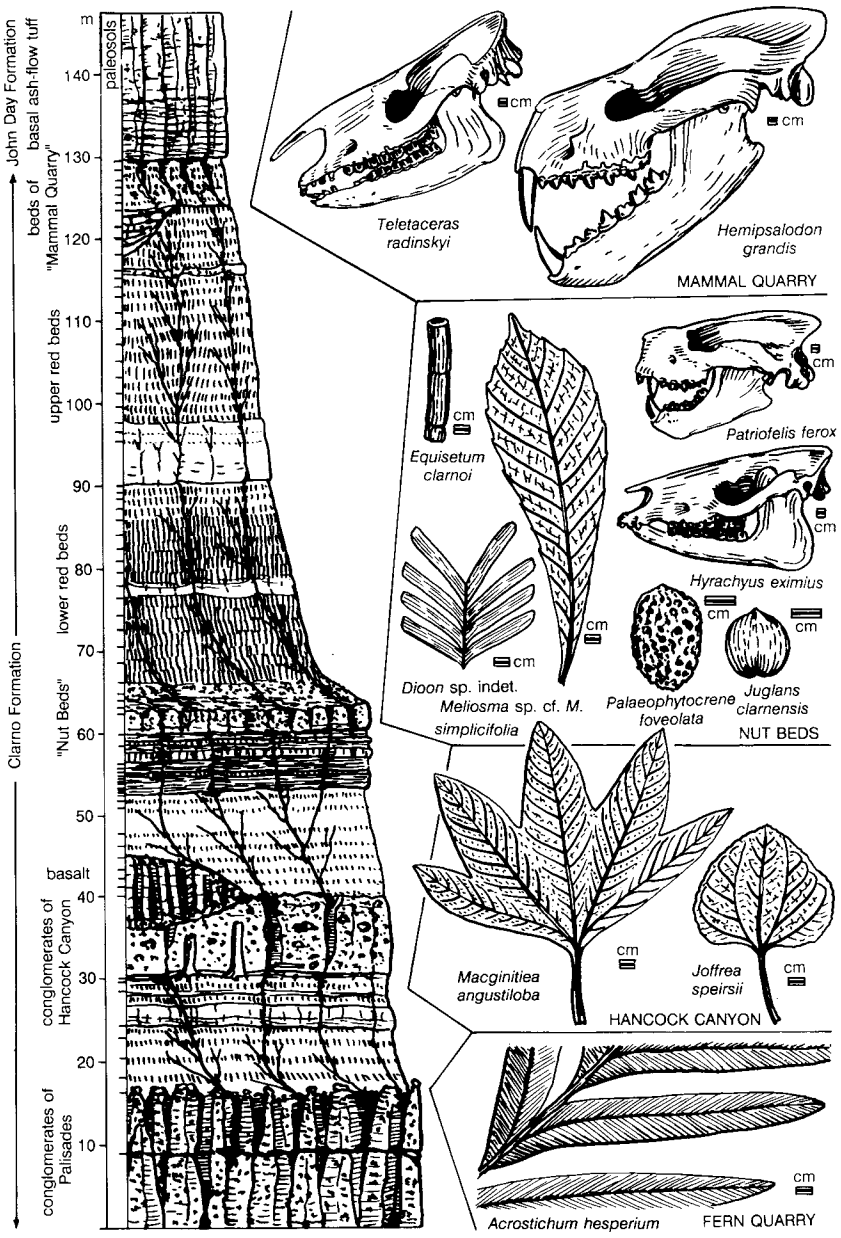

Figure 2. Geological section and fossil assemblages of the upper Clarno Formation in the Clarno Unit of the John Day Fossil Beds National Monument (illustrations adapted from Chaney, 1937; R.A. Scott, 1954; MacGinitie, 1969; Mellett, 1969; Brown, 1975; Manchester, 1981, 1986; Crane and Stockey, 1985; Savage and Long, 1986).

A newly discovered locality for lignites is within the lahar sequence, buried within the slope beneath the amygdaloidal basalt, 1 km northeast of the Oregon Museum of Science and Industry (OMSI) Hancock Field Station (Bestland and Retallack, 1994a). The thick, peaty surface horizon, associated fossil logs, and tabular systems of thick carbonaceous fossil roots are evidence of swamp forest dominated by dicotyledonous angiosperms. These are preserved in the paleosols as leaf compressions and include laurels (*Litseaphyllum presanguinea*, *Cinnamomophyllum* sp. cf. "*Cryptocarya*" *eocenica*) and aguacatilla (*Meliosma* sp. cf. *M. simplicifolia*), as well as fragments of a broad-leaved grass or sedge (*Graminophyllum* sp.) and a fern (*Anemia grandifolia*). The dominance of this swamp by dicots is most like swamps of central America south of Mexico (Breedlove, 1973; Porter, 1973; Hartshorn, 1983). In northern Mexico and the United States, in contrast, swamps are dominated

by conifers such as bald cypress (*Taxodium distichum*) (Best and others, 1984). The dominance of swamps of temperate to subtropical climates by taxodiaceous conifers can be traced back in the fossil record at least into Late Cretaceous times (Retallack, 1994b).

The Fern Quarry also is within the lahar sequence of the upper Clarno Formation. Its fossil plants include mainly ferns (*Acrostichum hesperium*) with lesser horsetails (*Equisetum clarnoi*) and dicots (*Joffrea speirsii*, *Quercus* sp., *Cinnamomophyllum* sp. cf. "*Cryptocarya*" *eocenica*). Ferns and horsetails are in growth position, dicots in leaf litters of very weakly developed volcaniclastic paleosols. This herbaceous and shrubby vegetation may have been early in the ecological succession to colonize volcanic ash (Burnham and Spicer, 1986).

The Hancock Tree is a local landmark in Hancock Canyon and is part of an extensive fossil forest within the lahars of the upper Clarno Formation (Manchester, 1986). It is 39 cm in diameter and shows a 279-cm length of exposed trunk above a concealed basal portion of 115 cm to the base of the lahar and 28 cm to the top of the paleosol in which it is rooted: a total preserved length of 422 cm. The Hancock tree has 59 annual rings as well as another 12 mm too deformed to count in its 39-cm diameter. Six other prone fossil logs within the lahar had diameters of 32, 9, 7, 6, 6, and 3 cm. These were thus tall colonizing forests, intermediate between secondary regrowth and old-growth forest. Fossil leaf litters have been recovered from paleosols supporting the permineralized trunks; they include mainly temperate elements such as sycamore (*Macginitiea angustiloba*), katsura (*Joffrea speirsii*), and alder (*Alnus clarnoensis*), with few tropical elements such as laurel (*Cinnamomophyllum* sp. cf. "*Cryptocarya*" *eocenica*). In contrast, leaf litters of a weakly developed paleosol in conglomerates underlying the Nut Beds to the east yielded mainly tropical elements such as aguacatilla (*Meliosma* sp. cf. *M. simplicifolia*) and magnolia (*Magnolia* sp. cf. *M. leei*) with less common walnut (*Juglans* sp. indet.) and sycamore (*Macginitiea angustiloba*). Similarly, paleosols so weakly developed that bedding has persisted within the Nut Beds include aguacatilla (*Meliosma* sp. cf. *M. simplicifolia*), moonseed (*Diploclisia*), icacina vine (*Goweria dilleri*), magnolia (*Magnolia leei*), laurels (*Litseaphyllum praesanguinea*, *L. praelingue*, *L.* sp. cf. "*Laurophyllum*" *merrilli*, *Cinnamomophyllum* sp. cf. "*Cryptocarya*" *eocenica*), tree fern (*Cyathea pinnata*), horsetail (*Equisetum clarnoi*), walnut (*Juglans* sp.), maple (*Acer clarnoense*), alder (*Alnus clarnoensis*), katsura (*Joffrea speirsii*), and sycamore (*Macginitiea angustiloba*). Again, to the east, very weakly developed paleosols have leaf litters of temperate climatic affinities, including leaves of sycamore (*Macginitiea angustiloba*), katsura (*Joffrea speirsii*), alder (*Alnus clarnoensis*), laurel (*Litseaphyllum presanguinea*), and horsetail (*Equisetum clarnoi*). These leaf litters of both weakly and very weakly developed paleosols in the two areas represent an ecotone between two distinct kinds of ancient colonizing forest. *Meliosma* today includes species of colonizing forests (van Beusekom and van de Water, 1989), as do living sycamore (*Platanus*) (Peattie, 1991; Manchester, 1986) and alder (Burger, 1983). Vegetation comparable to the *Macginitiea*-dominated fossil assemblages in the eastern part of the OMSI Hancock Field Station is deciduous tropical forest dominated by *Liquidambar macrophylla* found at elevations of 1,000–2,000 m on volcanoes in tropical Mexico (Gómez-Pompa, 1973). *Meliosma*-dominated assemblages in the western part of the OMSI Hancock Field Station were probably comparable to pioneering forests of lowland evergreen rain forest of Mexico ("selva" of Gómez-Pompa, 1973). Such a reconstruction of deciduous forest on volcanic footslopes to the east and semi-evergreen forest on volcanic toeslopes to the west is compatible with a reconstructed Clarno paleogeography of an andesitic stratocone source for lahars to the east of the study area (White and Robinson, 1992). High-elevation deciduous Eocene plants became increasingly important for the evolution of Oligocene and younger cool-temperate deciduous floras of North America (Wolfe, 1987).

The Mammal Quarry is close to the upper contact of the Clarno Formation with the basal ash-flow tuff (member A) of the John Day Formation, which has now been radiometrically dated at 39.22±0.03 Ma, using single-crystal $^{40}Ar/^{39}Ar$ dating (Bestland and Retallack, 1994a). Thus it includes the oldest known mammalian fauna of the Duchesnean North American Land Mammal "Age" (Lucas, 1992). Very weakly developed paleosols and closely associated fluvial deposits in the quarry have yielded crocodilians, creodont carnivores (*Hemipsalodon grandis*), sabre-tooth cats (Nimravidae gen. et sp. indet.), rodents (gen. et sp. indet.), anthracotheres (*Heptacodon* sp. indet), oreodons (*Diplobunops* sp. indet.), rhinoceroses (*Teletaceras radinskyi* and cf. "*Procadurcodon*" sp. indet.), tapirs (*Plesiocolopirus hancocki* and *Protapirus* sp. indet.), and horses (*Epihippus gracilis* and *Haplohippus texanus*) (Mellett, 1969; Hanson, 1973, 1989; Schoch, 1989; Lucas, 1992). Some of these creatures, particularly the common small rhinoceros (*Teletaceras radinskyi*), evidently died locally, because they are represented by moderately complete though disarticulated specimens. Their carcasses accumulated on a fluvial point bar as isolated elements or groups of bones still united by flesh (Pratt, 1988).

Also found in the Mammal Quarry was a fossil flora of fruits and seeds (McKee, 1970; Manchester, 1994a), including tropical vines (*Odontocaryoidea nodulosa*, *Diploclisia* sp. indet., *Eohypserpa* sp. indet., *Iodes* sp. indet., *Iodicarpa* sp. indet., *Palaeophytocrene* sp. cf. *P. foveolata*, *Ampelocissus* sp. indet., *Vitis* sp. indet., *Tetrastigma* sp.), sycamores (*Platananthus synandrus*), dogwoods (*Mastixioidiocarpum oregonense*), alangiums (*Alangium* sp. indet.), cashews (*Pentoperculum minimus*), and walnuts (*Juglans clarnensis*). Late Eocene mammals here evidently lived in forests, but Luvisol paleosols in association with these fossils are evidence for a cooler and drier climatic

regime than during deposition of the Nut Beds (Bestland and Retallack, 1994a).

New fossil localities were also discovered within the lower John Day Formation in footslopes of Iron Mountain, stratigraphically below a distinctive thick tuff radiometrically dated (using the single-crystal laser-fusion $^{40}Ar/^{39}Ar$ technique) at 38.4±0.07 Ma (C. Swisher for Bestland and Retallack, 1994a). This is still within the late Eocene and Duchesnean (Swisher and Prothero, 1990). From a red paleosol described by Getahun and Retallack (1991) immediately below the dated tuff came a fragment of a tusk, probably of the extinct family of hoglike Entelodontidae, and a molar of the small Clarno rhino *Teletaceras radinskyi*. Brown lake beds with fish scales some 5 m below the tuff have yielded winged fruits of walnutlike plants (*Cruciptera simsoni*, *Palaeocarya clarnensis*), fruits of eucommia (*Eucommia* sp. indet.), extinct malvalean flowers (*Florissantia ashwillii*), seeds of cigar-tree (*Catalpa* sp. indet.), and leaves of elm (*Ulmus* sp. indet.), Oregon grape (*Mahonia* sp. indet.), and dawn redwood (*Metasequoia occidentalis*) (Bestland and Retallack, 1994a; S.M. Manchester, oral commun., 1995). This flora and associated Luvisol paleosols are evidence for forests of lesser stature, more open and deciduous than earlier in the Eocene.

The "Slanting Leaf Beds" is a well-known locality higher within the John Day Formation in the Clarno area and now radiometrically dated at 33.62±0.19 Ma (Swisher for Bestland and Retallack, 1994a), which is very early in the Oligocene (Swisher and Prothero, 1990). These tuffaceous lacustrine beds have yielded a very different fossil flora dominated by alder (*Alnus heterodonta*) and dawn redwood (*Metasequoia occidentalis*). This is one of the many Bridge Creek floras especially well known near Fossil and in the Painted Hills (Manchester and Meyer, 1987; Kvacek and others, 1991; Manchester, 1992; Meyer and Manchester, unpublished data, 1995). The dramatic floral change from floras of tropical to those of temperate climatic affinities is reflected in a change in paleosols from red Luvisols to a mix of Inceptisols, Vertisols and Luvisols (Bestland and Retallack, 1994a), also seen in the Painted Hills.

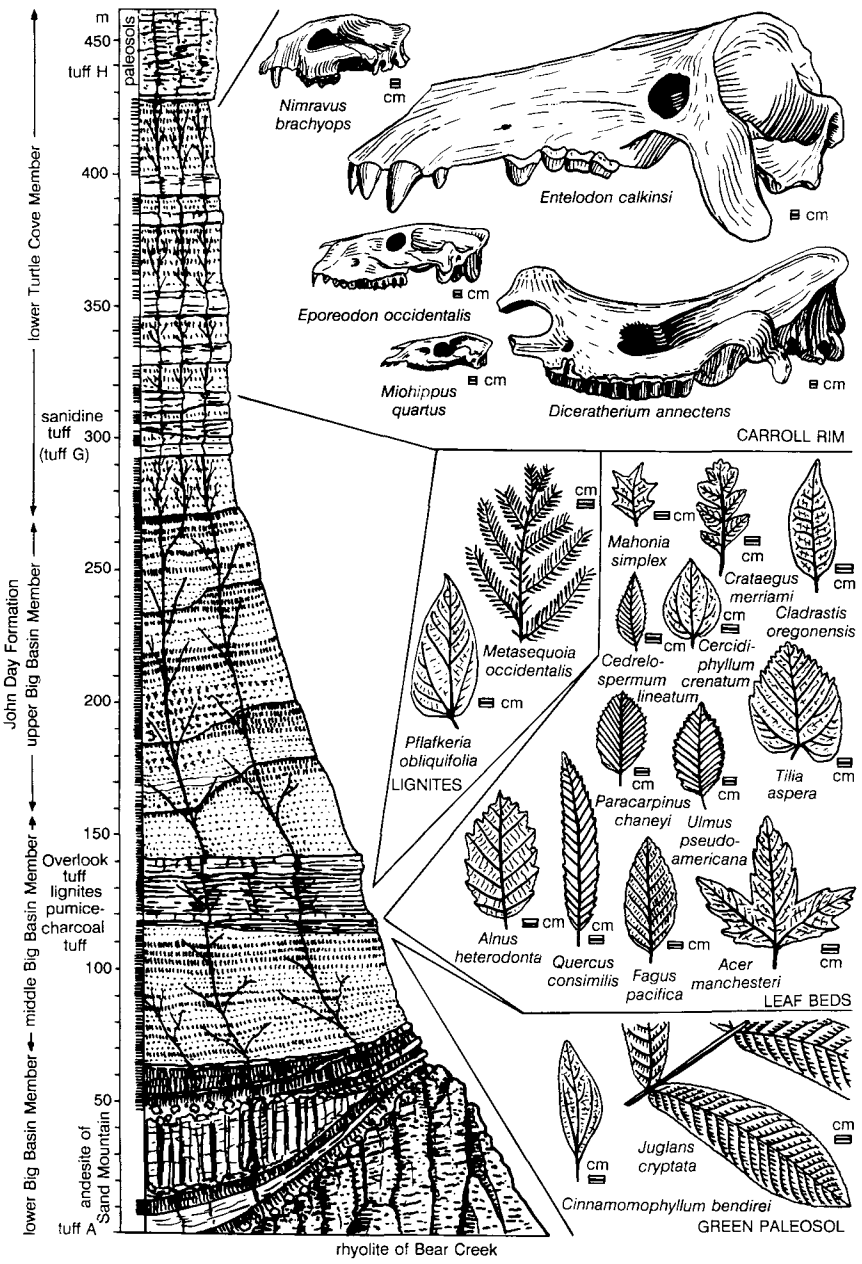

Figure 3. Geological section and fossil assemblages of the lower John Day Formation in the Painted Hills Unit of the John Day Fossil Beds National Monument (illustrations adapted from Knowlton, 1902; Sinclair, 1905; Osborn, 1918; Peterson, 1920; Toohey, 1959; Lander, 1977; Tanai and Wolfe, 1977; Wolfe and Tanai, 1987; Meyer and Manchester, unpublished data, 1995).

OLIGOCENE FOSSILS OF THE PAINTED HILLS

The principal fossil resources protected by the Painted Hills Unit of the John Day Fossil Beds are the lake beds with leaves of the Bridge Creek flora (Figure 3), first col-

lected by Thomas Condon in 1865 for Newberry (1898) and Knowlton (1902) and then made famous by pioneering papers in quantitative paleoecology by Chaney (1924, 1925a). Dominance of these shales by plants of temperate climatic affinities such as oak (*Quercus consimilis*), alder (*Alnus heterodonta*), and dawn redwood (*Metasequoia occidentalis*) is in striking contrast to the tropical affinities of fossil plants in the Clarno Formation (Chaney, 1948a). At first, Chaney (1924, 1938) compared the assemblage with that of redwood forests of California. When it was discovered in 1941 that dawn redwood was still living in China, Asian mixed mesophytic forests became a better model (Chaney, 1948a,b, 1952, Wolfe, 1981, 1992; Manchester and Meyer, 1987). In contrast, our new collections indicate that *Metasequoia* was a swampland tree.

One problem with leaves in lake beds is the way in which elements of different plant communities are mixed with and overwhelmed by deciduous lake-margin species. We have been able to demonstrate such biases in the Bridge Creek flora with new collections of plants from leaf litters of paleosols associated with the lake beds (Bestland and Retallack, 1994b). A small fossil flora of leaves found in the surface horizon of a weakly developed green paleosol underlying the lake beds included dawn redwood (*Metasequoia occidentalis*), nutmeg tree (*Torreya* sp. indet.), grass (*Graminophyllum* sp. indet.), laurel (*Cinnamomophyllum bendirei*), and walnut (*Juglans cryptata*). Remains of walnuts were most common, followed by the laurels. The dawn redwood is represented by only one foliar spur. The paleosol and plants combined indicate semi-evergreen mesophytic forest of bottomlands. A very different assemblage was found in a manganese-stained shale overlying a very weakly developed paleosol within the lake beds: mainly leaves of alder (*Alnus heterodonta*) with oak (*Quercus consimilis*) and yellowwood (*Cladrastis oregonensis*). Alders in particular are well-known pioneer plants of disturbed ground, both in tropical and temperate regions (Burger, 1983), and this interpretation is supported by the minimal development of the fossil soil. Lignitic paleosols overlie a pumice-charcoal tuff above the lake beds. These ancient soils of swamps are overwhelmingly dominated by dawn redwood (*Metasequoia occidentalis*), associated with rare bracken fern (*Pteridium calabazensis*), grass (*Graminophyllum* sp. indet.), alder (*Alnus heterodonta*), and extinct basswood (*Plafkeria obliquifolia*). These paleosol assemblages indicate that the Bridge Creek flora of lacustrine shales is a mix of at least three distinct plant communities: semi-evergreen lowland laurel forest, dawn redwood swamp, and deciduous alder pole woodlands.

The age of the Bridge Creek flora in the Painted Hills is constrained by new single-crystal laser-fusion $^{40}Ar/^{39}Ar$ radiometric dates of 32.99±0.11 Ma for a biotite tuff below the lake beds and 32.66±0.03 Ma for tuffs above the lake beds and lignites, both within the middle Big Basin Member of the John Day Formation (C.C. Swisher for Bestland and Retallack, 1994b). Like the "Slanting Leaf Beds" of the Clarno area, these also are earliest Oligocene in age. At some time between 33 Ma and the 38-Ma fossil flora from the Clarno area discussed above, there was a climatic deterioration from mean annual precipitation of 1,500 mm to 1,000 mm (Leopold and others, 1992), from mean annual temperature of 20°C to 12°C, and from mean annual range of temperature of 10°C to 25°C (Wolfe, 1992). A comparable deterioration to temperate climate is indicated by the transition from kaolinitic and iron-rich, red, lateritic Ultisol and Luvisol paleosols of the lower Big Basin Member of the John Day Formation, which are erosionally truncated and abruptly overlain by smectitic and tuffaceous Inceptisol, Vertisol, and Luvisol paleosols of the middle Big Basin Member (Bestland and others, 1994, 1995, 1996). The erosional contact probably corresponds to the Eocene-Oligocene boundary now recognized at 34 Ma (Swisher and Prothero, 1990), judging from radiometric dates from underlying units: a new $^{40}Ar/^{39}Ar$ single-crystal radiometric date of 39.72±0.03 Ma for the basal ash-flow tuff of the John Day Formation (C.C. Swisher for Bestland and Retallack, 1994b) and a date of 37 Ma for the andesite of Sand Mountain (Hay, 1963; Evernden and James, 1964). Our correlation of these units and assessment of the degree of development of lateritic paleosols of the lower John Day Formation suggest that the Eocene-Oligocene climatic deterioration was abrupt (Retallack, 1992; Rice, 1994; Bestland and others, 1996).

The badlands of Carroll Rim in the Painted Hills and the nearby footslopes of Sutton Mountain have yielded only sparse and fragmentary mammal fossils from the Turtle Cove Member below the massive ash-flow tuff of Carroll Rim ("Picture Gorge tuff" or Member H of Robinson and others, 1984). The Turtle Cove Member here is dated by new determinations of 29.75±0.02, 29.70±0.06, 28.65±0.05, and 28.65±0.07 Ma on tuffs and the cliff-forming ash flow (last two dates), respectively (C.C. Swisher for Bestland and Retallack, 1994b). Comparable late Oligocene (early Arikareean) fossil mammals are more abundant and better known from the Turtle Cove Member in the John Day Valley south of Kimberly (Fremd, 1988).

Fossil mammal fragments were mainly found in paleosols and can be grouped by paleosol type. Some of these have brown, finely structured, near-mollic surface horizons over a subsurface horizon of calcareous nodules, as in soils now supporting grassy woodland and wooded grassland. Fossil mammals in these paleosols include mouse deer (*Hypertragulus hesperius*), oreodonts (Merycoidontidae gen. et sp. indet.), and rhinoceros (*Diceratherium* sp. cf. *D. annectens*). Other paleosols are comparable in their brown, finely structured surface horizons, but lack nodules, which indicates a shorter time for formation but comparable vegetation. Mammals of these paleosols include an unidentifiable mammalian navicular, a distal phalanx of an oreodont (Merycoidodontidae), and a cuboid similar to that of a giant, hoglike entelodon (cf. *Entelodon* sp. indet.). Very weakly developed paleosols probably supported streamside grassy

vegetation early in ecological succession to communities represented by the other paleosols. Mammals of these transient communities include extinct squirrel-like rodent (Eutypomyidae gen. et sp. indet.), oreodon (*Agriochoerus* sp. indet., *Eporeodon* sp. indet.), three-toed horse (*Miohippus* sp. cf. *M. quartus*), and two-horned rhinoceros (*Diceratherium* sp. cf. *D. annectens*). Other paleosols are green and clayey with subsurface calcareous nodules and probably supported seasonally wet alluvial grassy woodland. Comparable paleosols near Foree to the east have yielded oreodont (*Eporeodon occidentalis*), three-toed horse (*Miohippus* sp. cf. *M. anceps*), and foxlike dog (*Mesocyon coryphaeus*). No red, clayey paleosols were seen in the Turtle Cove Member of the Painted Hills, but red paleosols in Rudio Creek canyon near Kimberly yielded three-toed horse (*Miohippus equiceps*). Although endocarps of hackberry (*Celtis willistoni*) (Cockerell) Berry 1928 (Chaney 1925b) are the only plant fossils found in the Turtle Cove Member, paleosols indicate a mosaic of woodland in hills and footslopes, wooded grassland and grassy woodland in valley bottoms, and local grassy woodlands in seasonally wet bottomlands. Mammalian collections from particular paleosols are as yet inadequate to demonstrate their ecological preferences. Nevertheless, the paleoenvironmental reconstruction from paleosols is compatible with the mix of arboreal squirrels, browsing horses and oreodonts, and grazing rhinos, similar to assemblages in the Great Plains regarded as adapted to grassy woodland and wooded grassland (Webb, 1977; MacFadden, 1992; Prothero and others, 1996).

Paleosols of the Turtle Cove Member indicate much drier and probably also cooler paleoclimatic conditions than earlier in the Oligocene. Depth to the calcareous nodules is strongly correlated with mean annual rainfall in modern soils (Retallack, 1994a), and application of these relationships with allowances for compaction of paleosols in Carroll Rim gives mean annual rainfall of 614±141 mm to 911±141 mm (Bestland and Retallack, 1994b). This range of about 500–1,000 mm for the Turtle Cove Member can be compared to 800–1,000 mm for the upper Big Basin Member and 1,000–1,200 mm for the middle Big Basin Member, derived by comparison with comparable soils in Mexico (Bestland and Retallack, 1994b). Paleoclimatic drying continued into the early Miocene, judging from our reconnaissance observations of the upper John Day Formation on Sutton Mountain. The John Day Formation preserves a long-term paleoclimatic record that complements and correlates well with the geological record of global change in deep-sea cores (Bestland and Retallack, 1994b).

RECONSTRUCTED FOSSIL PLANTS

An outstanding advantage of preservation of plants in paleosols is the lack of mixing and separation of different parts of different plants. The leaves, fruits, flowers, and wood are preserved near their place of growth, little mixed by transport in streams or drifting off into lake beds. Such fossiliferous paleosols are known in the lower part of the Clarno Nut Beds and within the lignites and lake beds of the Painted Hills, and they make easier the difficult task of reconstructing ancient plants from a jumble of different plant remains (Manchester, 1981). Physical attachment of one part of a plant to another, such as fruits on leafy twigs, is the most compelling, but unfortunately rare, evidence for reconstructing fossil plants. Comparison with modern plants is also useful, particularly if there is only one fossil species of fruit, wood, flower, and leaf comparable to a particular modern plant. In this way, it is hoped to gain a complete concept of particular ancient plants and their evolution. As this work proceeds, it is revealing that some parts of plants such as fruits and seeds evolve at rates different from others such as wood and leaves (Manchester, 1986, 1987; Manchester and Wheeler, 1993). This mosaic evolution not only explains differing interpretations of ancient vegetation based on wood, fruits, and leaves but is of interest for understanding the evolutionary process itself.

Meliosma beusekomii

Meliosma beusekomii Manchester (1994a) is a middle Eocene fossil species named for fruits common in the Clarno Nut Beds of the Clarno Formation (Figure 4). The fruits are drupes, but the preserved parts are characteristically dimpled stones or endocarps (Manchester, 1994a). *Meliosma beusekomii* endocarps are very similar to those of living species such as *M. pinnata* and *M. simplicifolia*. Leaves comparable to *M. simplicifolia* also are common in the Nut Beds and in other fossil leaf litter assemblages of the upper Clarno Formation (Manchester, 1980b). Our reconstruction of the shoot with fruits and leaves is based on that of *M. simplicifolia* (van Beusekom and van de Water, 1989). Wood of *Meliosma* has also been found in the Nut Beds (Manchester, 1980b) and was sketched from photomicrographs generously supplied by Steven Manchester.

The large leaves (up to 21 cm long) of this extinct Eocene species of *Meliosma* have a pronounced drip tip, as is typical for plants of tropical rainy climates. *Meliosma* today is widespread in the humid tropics and subtropics of eastern Asia, Indonesia, Central America, and the West Indies (Gentry, 1980; van Beusekom and van de Water, 1989). *Meliosma* includes both shrubs and trees, and its family Sabiaceae includes vines (Gentry, 1980). Permineralized fossil wood of *Meliosma* is known only as waterworn fragments but is evidence that *M. beusekomii* was a tree. It probably was not a large tree, because its leaves dominate the litters of very weakly developed paleosols that lack large root traces or differentiated soil horizons. These paleosols in the Nut Beds and elsewhere are associated with fluvial facies (Retallack, 1991a), so that *M. beusekomii* can be envisaged a pole tree of woodlands early in ecological succession of recovery from stream flooding.

Macginitiea angustiloba

Macginitiea angustiloba (Lesquereux) Manchester

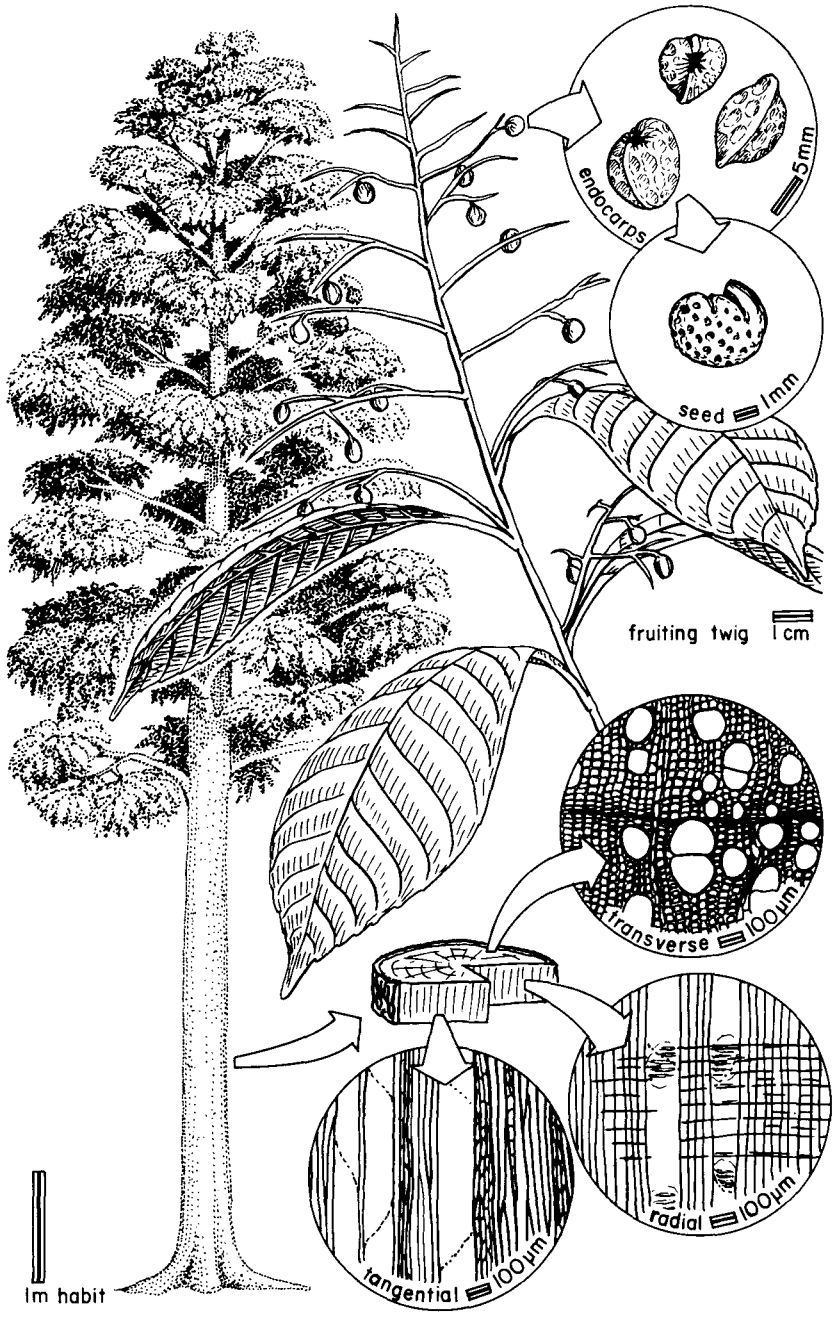

Figure 4. Reconstruction of a fossil aguacatilla (Meliosma beusekomii) *from the middle-late Eocene "Nut Beds" of the Clarno Formation at Hancock Field Station (data from Bones, 1979; Manchester, 1981, 1994a; van Beusekom and van de Water, 1989).*

(1986) is the name of a palmately lobed leaf common in lahars of Hancock Canyon and elsewhere in the Eocene Clarno Formation (Figure 5). The leaf is similar to those of living sycamores and planes (*Platanus*). The Hancock tree is a well-known local landmark in Hancock Canyon and is a katsura (*Joffrea speirsii*) (Retallack, 1991a), but the other common species within the same paleosol is *Macginitiea angustiloba*. Stumps of *Macginitiea angustiloba* are recognizable in hand specimen by their characteristic wide rays, and this wood has been referred to *Plataninium haydenii* (Wheeler and others, 1977; R.A. Scott and Wheeler, 1982). The globose pistillate and staminate heads and isolated anthers of this plant have also been given separate names, *Macginicarpa glabra*, *Platananthus synandrus*, and *Macginistemon mikanoides*, respectively (Manchester, 1986), in the widely used organ–generic procedure of paleobotany. There is little doubt from their joint association in numerous localities, including lake beds and fluvial sandstones as well as the paleosols of Hancock Canyon and the Nut Beds, that these represent parts of the same extinct species of sycamore-like plant (Manchester, 1986).

Like modern sycamores, *Macginitiea angustiloba* had leaves with abscission scars, indicating it was deciduous. Its separate pistillate and staminate flowering heads produced abundant small (16–18 µ) pollen and small (6–8 mm), hard fruits, which are indications that it was pollinated and dispersed by wind and water (Manchester, 1986). *Macginitiea angustiloba* had slightly smaller pollen, better developed perianth, and more consistently pentamerous flowers than modern sycamores, which may indicate facultative unspecialized insect pollination or an evolutionary legacy of insect pollination. *Macginitiea angustiloba* also lacked hairs that facilitate wind dispersal of fruits of living sycamores. This combination of largely wind and water pollination and dispersal with some hints of facultative animal involvement are common in plants that colonize disturbed ground. Like living sycamores (*Platanus*), many comparable fossils as old as Cretaceous also were trees of disturbed streamsides (Retallack and Dilcher, 1981). Such an ecology for the Clarno plant is indicated in Hancock Canyon, where trunks attributed to *Macginitiea angustiloba* are rooted in a weakly developed paleosol capping fluvial deposits interbedded with lahars (Bestland and Retallack, 1994a). *Macginitiea angustiloba* is the most prominent of several plants in the Clarno For-

mation that were deciduous, wind and water pollinated and dispersed, and with cool-temperate climatic affinities. Unlike diverse assemblages of the Nut Beds, low diversity fossil forests of Hancock Canyon may represent a flora of higher elevations on the volcanic cone, like the *Liquidambar* forests of San Martin Volcano in Veracruz, Mexico (Gómez-Pompa, 1973).

Metasequoia occidentalis

Foliage, cones, and seeds of the dawn redwood *Metasequoia occidentalis* (Newberry) Chaney (1951) are common in the Bridge Creek flora of the middle Big Basin Member of the John Day Formation at many localities, including the Painted Hills, the Slanting Leaf Beds of the Clarno area, and the well-known bank behind the High School in Fossil (Manchester and Meyer, 1987). In the Painted Hills, foliage of this plant is found in nearly monospecific assemblages with permineralized coniferous wood in a sequence of lignites. Exceptionally well preserved permineralized wood, cones, and foliage of *Metasequoia* also are known from the middle Eocene Princeton chert of British Columbia (Rothwell and Basinger, 1979; Basinger, 1981, 1984), which is a permineralized peat swamp. Although these Eocene fossils have been referred to the species *Metasequoia milleri*, they are externally identical to living dawn redwood *M. glyptostroboides*, which cannot be readily distinguished from the fossil species for leaf impressions, *M. occidentalis*. *Metasequoia milleri* differs from *M. glyptostroboides* in its higher wood rays and two additional resin canals in the distal portion of the microsporophyll of the pollen cone (Rothwell and Basinger, 1979; Basinger, 1981). Plants of peat swamps are known to evolve very slowly; for example, many species known from permineralized remains range through the entire 30 Ma of the Pennsylvanian with little evolutionary change (DiMichele and others, 1987). Similarly, *M. occidentalis*, *M. milleri*, and *M. glyptostroboides* may all represent the same long-lived species. *Metasequoia* has long been known as a living fossil, because it was discovered alive in China after description as a fossil (Chaney, 1948a). This raises the interesting procedural problem of a living genus with a fossil type specimen (Schopf, 1948).

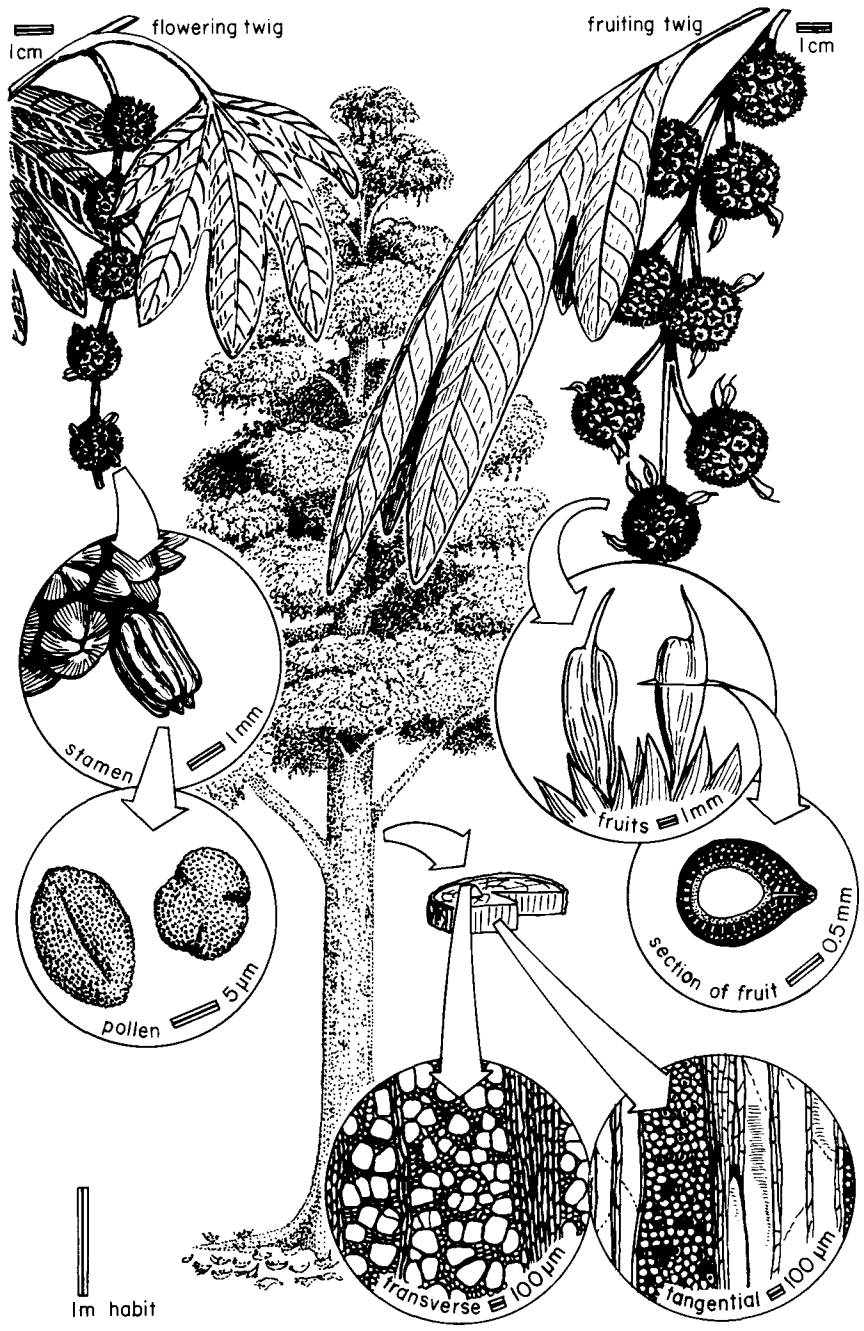

Figure 5. Reconstruction of a fossil plane (Macginitiea angustiloba) *from the middle-late Eocene conglomerates of Hancock Canyon of the Clarno Formation at Hancock Field Station, Oregon (data from Wheeler and others, 1977; R.A. Scott and Wheeler, 1982; Manchester, 1986).*

Metasequoia has been extinct in North America since

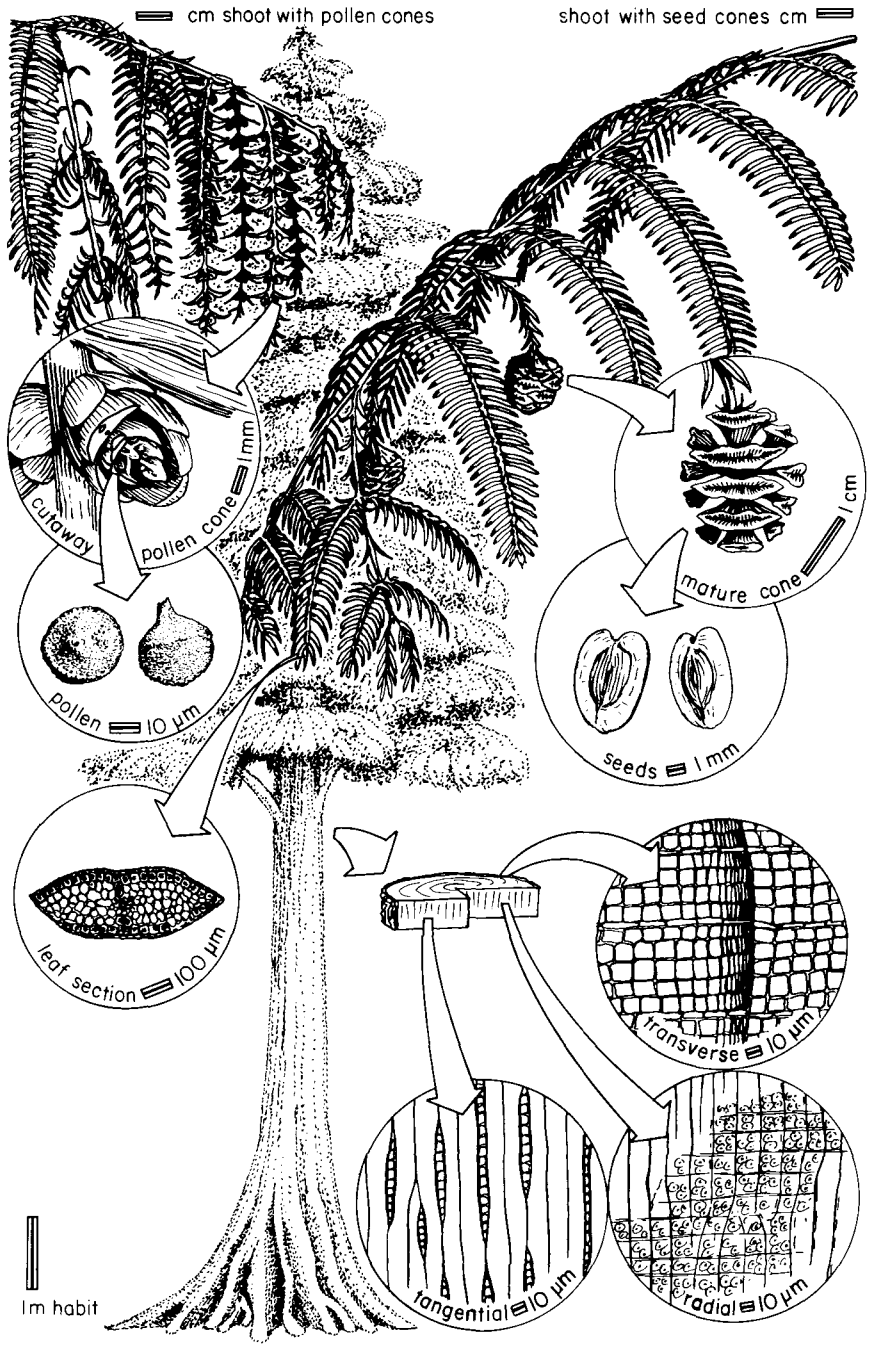

Figure 6. Reconstruction of a fossil dawn redwood (Metasequoia occidentalis) *from the early Oligocene middle Big Basin Member of the John Day Formation in the Painted Hills, Oregon (data from Merrill, 1948; Manchester and Meyer, 1987; Meyer and Manchester, unpublished data, 1995; additional details from the probably conspecific* M. milleri *of Rothwell and Basinger, 1979; Basinger, 1981, 1984).*

late Miocene time (Chaney, 1948a), and the geologically youngest fossils found anywhere are Pliocene (Miki, 1941). Several hundred *Metasequoia* trees now growing in Oregon are descended from seeds distributed by Ralph Chaney in 1950. During his visit to China in the spring of 1948, he was unable to obtain seeds, but he distributed seeds purchased from China by E.D. Merrill (1948) of Harvard's Arnold Arboretum. A particularly fine tree grown from Chaney's original distribution grows near Cascade Hall on the University of Oregon campus. It stands under the gaze of a bronze bust of Thomas Condon, who first discovered these Oregon fossils. Sketches of this tree were used for our reconstruction (Figure 6).

Metasequoia is seasonally deciduous like larch (*Larix*) and differs in this respect from most conifers, which are evergreen. The pollen cones are formed with the soft, light-green spring leaves, and the seed cones do not mature until late in the fall. Like most conifers it is wind pollinated, and seed is dispersed by wind and water. *Metasequoia occidentalis* has long been regarded as a dominant of a mixed conifer–angiosperm flora (Chaney, 1924, 1925a; Wolfe, 1981, 1992), and this has been regarded as confirmed by its occurrence in China (Chaney, 1948a, Chu and Cooper, 1950; Hu, 1980). However, this small area of northwest Hupei Province has been greatly disturbed by agriculture. *Metasequoia glyptostroboides* was found in ravines and embankments around paddy fields that have submerged at least two hundred trunks of a relatively pure stand of these plants (Bartholomew and others, 1983). Its common occurrence with angiosperm leaves in the various Bridge Creek floras could be a result of mixing in lake deposits. A new view of the natural habitat of *Metasequoia* emerges from its dominance in the lignites of the Painted Hills (Bestland and Retallack, 1994b) and permineralized peats of British Columbia (Rothwell and Basinger, 1979, Basinger, 1981, 1984). *Metasequoia occidentalis* and the likely conspecific *M. milleri* can now be seen as swamp cypresses comparable with living bald cypress (*Taxodium distichum*) of Okefenokee Swamp and the Florida Everglades (Best and others, 1984). Both *Taxodium* and *Metasequoia* are in the family Taxodiaceae, and Newberry (1883) may not have been far off the mark when he included fossils now called

Metasequoia in *Taxodium*. These modern swamps have a low diversity complement of angiosperms, and some angiosperm fossils also have been found with *Metasequoia* in the fossil peats of the Painted Hills (Bestland and Retallack, 1994b) and British Columbia (Stockey, 1987; Cevallos-Ferriz and Stockey, 1988a,b, 1989, Erwin and Stockey, 1989a,b, 1994; 1990a,b, 1991; Stockey and Pigg, 1991; Cevallos-Ferriz and others, 1993). However, these cannot be taken as representative of forests of well-drained soils away from the swamps. Much has been made of the climate of relict populations of *Metasequoia* in Hupei to infer Oligocene paleoclimate of Oregon (Chaney, 1948a). As a swamp plant, however, its paleoclimatic significance is limited, because it lived in soils isolated from regional climate by local waterlogging. Its temperature tolerances in the past were probably also cool-temperate to subtropical, like swamp cypresses today, which dominate swamps as far south as northern Mexico but are replaced by angiosperm swamps in the Central American tropics (Breedlove, 1973; Porter, 1973, Hartshorn, 1983).

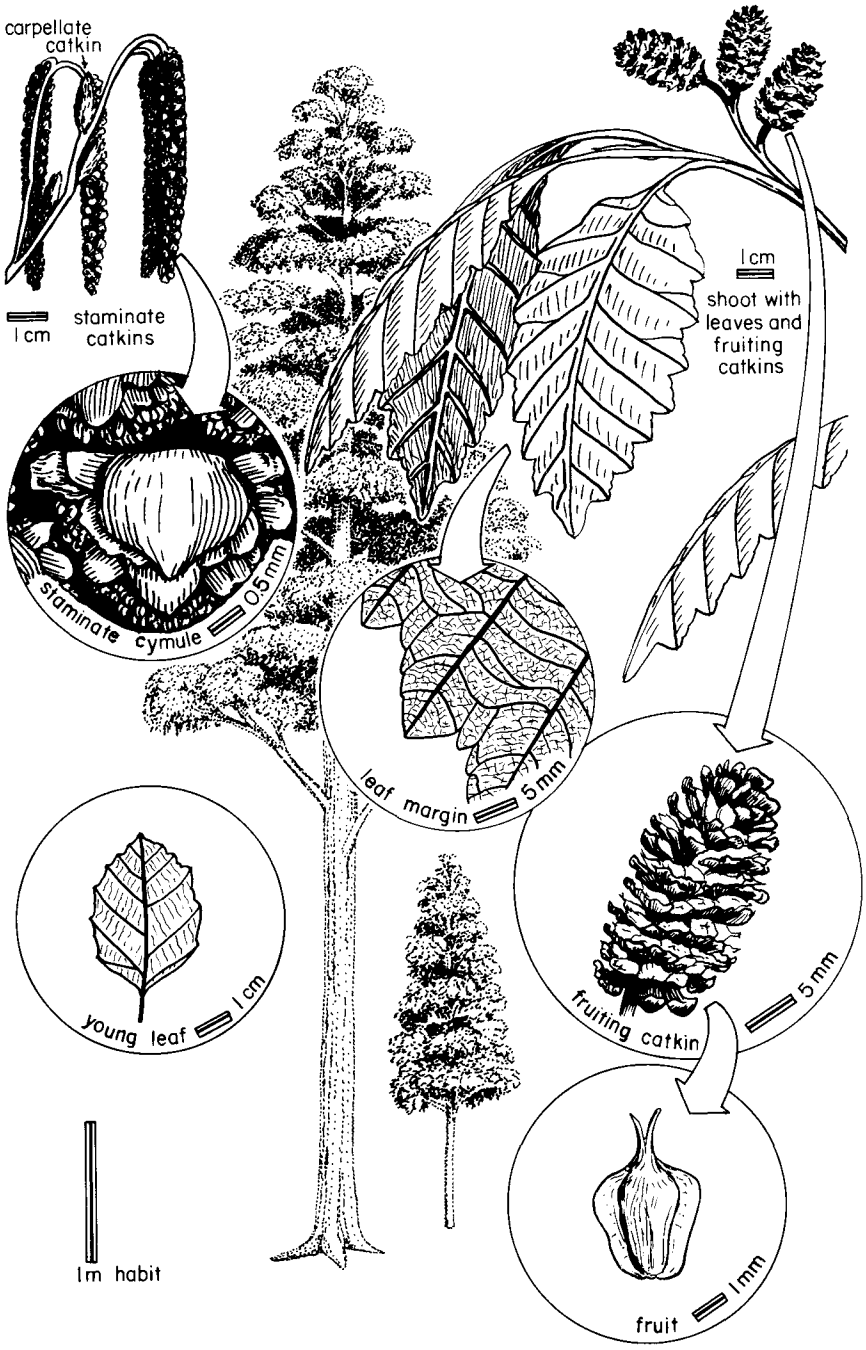

Figure 7. Reconstruction of a fossil alder (Alnus heterodonta) *from the early Oligocene middle Big Basin Member of the John Day Formation in the Painted Hills, Oregon (data from Klucking, 1956; Wood, 1974; Manchester and Meyer, 1987; Meyer and Manchester, unpublished data, 1995).*

Alnus heterodonta

Alder leaves and catkins are among the most common fossils in Bridge Creek floras of the middle Big Basin Member of the John Day Formation (Manchester and Meyer, 1987; Meyer and Manchester, unpublished data, 1995). Several species of alder have been recognized, even within single localities (Klucking, 1956), but *Alnus heterodonta* is the most common leaf in the Painted Hills (Figure 7). Young leaves, seeds, and staminate and fruiting catkins also are found occasionally (Meyer and Manchester, unpublished data, 1995). The attribution of all these remains to one plant is based on association and comparison with living alder.

The inconspicuous flowers, small, flattened seeds, and leaf abscission scars of the fossils are evidence that this extinct species was wind pollinated and dispersed and seasonally deciduous like living alder and others of the family Betulaceae in cool-temperate climatic regions of the northern hemisphere. Because these leaves dominate the leaf litter of a very weakly developed paleosol in the lake beds of the Painted Hills (Bestland and Retallack, 1994b), it is likely that they were plants of pole woodlands early in the ecological succession to recover disturbed ground. Such an oppor-

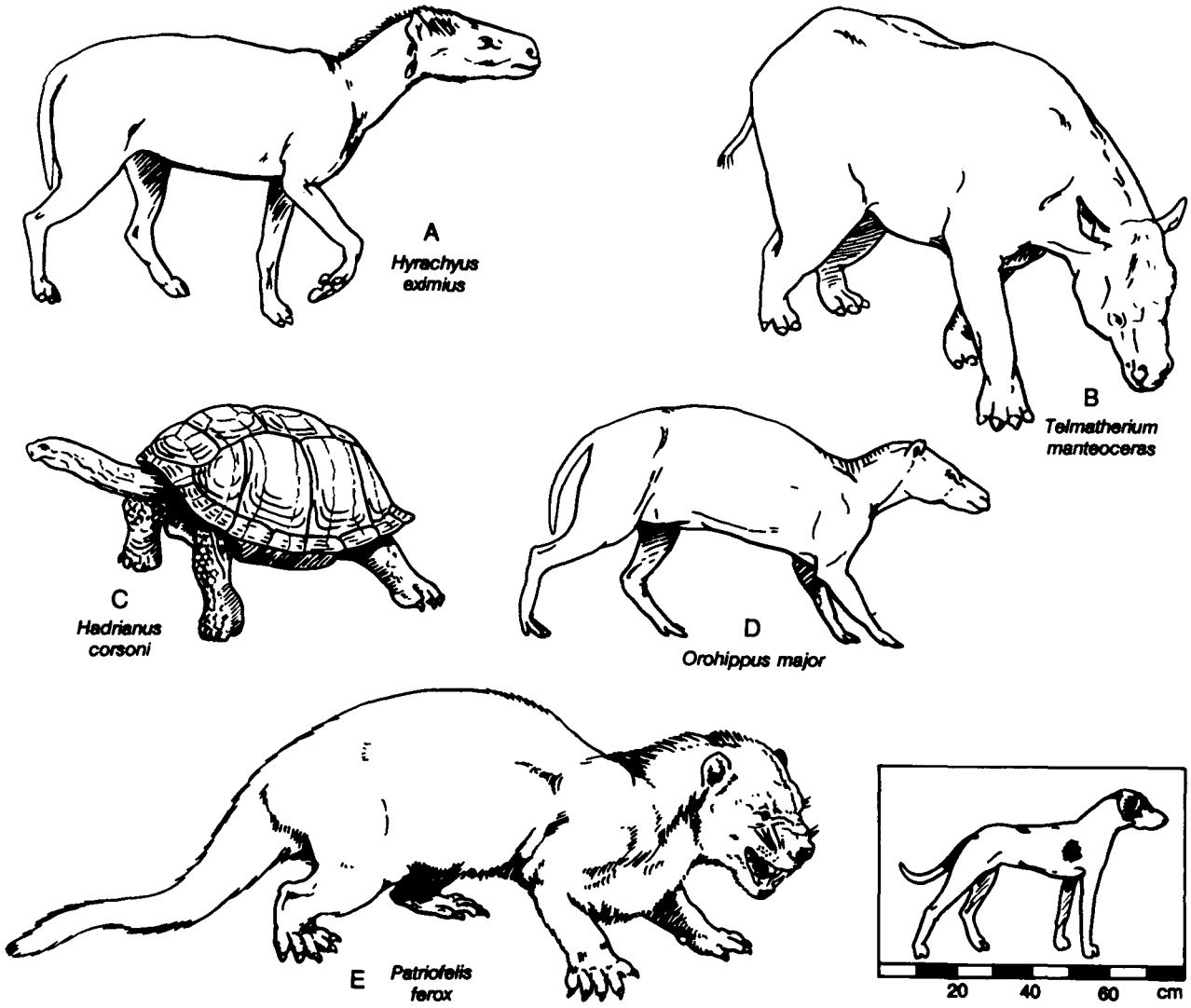

Figure 8. Reconstructions of middle-late Eocene (Bridgerian-Uintan) animals from the Nut Beds of the Clarno Formation at the OMSI Hancock Field Station, Oregon (A and scale from R.B. Horsfall for W.B. Scott, 1913; B from E.M. Fulda for Osborn, 1929; E from C.E. Knight for Osborn, 1910; others original with data from Hay, 1908).

tunistic ecology is characteristic of many alder species (Burger, 1983), including the red alder (*Alnus rubra*) of Oregon, which forms roadside and streamside pole woodlands, and extensive stands for some 50–80 years after clear-cutting or fire (Peattie, 1991). Neither the swamp-bound *Metasequoia occidentalis* nor the ephemeral *Alnus heterodonta* are likely to have been abundant in well-drained soils during Oligocene time, despite their dominance of lacustrine leaf accumulations.

RECONSTRUCTED FOSSIL ANIMALS

Complete skeletons or natural mummies of extinct animals are ideal for reconstructing their appearance and lifestyle (Savage and Long, 1986). Few of these have been found in the John Day Fossil Beds, where fleshing out the fragments must rely on more complete skeletons from other parts of North America and inferences from comparable modern mammals. Fortunately, there is a long tradition of fossil vertebrate reconstruction (Osborn, 1910; W.B. Scott, 1913). More than ever before, we have the resources to conjure up visions of extinct beasts from isolated teeth and bones.

Hadrianus corsoni

Only a fragment of this thick-shelled tortoise has been found in the middle Eocene Clarno Nut Beds, and it is not referable to a particular species. The reconstruction offered here (Figure 8C) is *Hadrianus corsoni* (Leidy) Cope (1873), represented by complete carapaces and limb bones from middle Eocene (Bridgerian) rocks south of Fort Bridger, Wyoming (Hay, 1908). The genus *Hadrianus* ranges through much of the Eocene (Wasatchian to Uintan)

(Hutchinson, 1992). These were land tortoises of the family Testudinidae, which are all herbivores and include the well-known Galapagos tortoises (*Geochelone*) (Carroll, 1988).

Telmatherium manteoceras

Molars of this brontothere are the most common vertebrate fossils in the middle Eocene Clarno Nut Beds and may represent a new species of *Telmatherium*. Our reconstruction (Figure 8B) is based on one by E.M. Fulda (for Osborn, 1929) of *Telmatherium manteoceras* (Hay) Mader (1989), known from good skulls and partial skeletons of middle Eocene (Bridgerian-Uintan) age in the Washakie and Bridger Basins of Wyoming (Osborn, 1929; Eaton, 1985). Painted reconstructions by Charles Knight (for Osborn, 1910, 1929) are very similar to this sketch. Brontotheres (also called titanotheres) are extinct perissodactyls of North America and Asia and represent a distinct evolutionary lineage from rhinoceroses which they vaguely resemble. *Telmatherium* had the low-crowned teeth of a browser, like most bronthotheres. It was small for this group, which evolved from dog-sized animals in the early Eocene to massive rhino-sized animals in the latest Eocene (Carroll, 1988).

Hyrachyus eximius

A variety of skull fragments and teeth in the Clarno Nut Beds belong to *Hyrachyus eximius* Leidy (1871), well known from relatively complete skeletons in middle to late Eocene (Bridgerian to Uintan) deposits of the Bridger and Washakie Basins of Wyoming (W.B. Scott, 1913). Our reconstruction (Figure 8A) is based on the sketch of Bruce Horsfall (for W.B. Scott, 1913), which we prefer to more stocky reconstructions by Zdenek Burian (for Spinar and Burian, 1972), Jay Matternes (for Smithsonian Institution mural, see Dott and Batten, 1981), Michael Long (for Savage and Long, 1986), and Graham Allen (for Dixon and others, 1992). Its low-crowned teeth are those of a browser, but it had padded feet like those of a tapir rather than hooves like modern ungulates. Primitive features of *Hyrachyus* include four toes on the rear limbs and prominent canine teeth. It belongs to an extinct group of mammals (Helatetidae or Hyrachyidae) allied to both tapirs and rhinos and possibly ancestral to both.

Orohippus major

The small, primitive horse *Orohippus major* Marsh (1874) is represented by several teeth and jaw fragments from the Clarno Nut Beds, but good skeletons have been found in the middle Eocene (Bridgerian) of the Bridger Basin of Wyoming (Kitts, 1957). Our reconstruction (Figure 8D) is based on one by Charles Knight (for Osborn, 1910), although others have been done by Zdenek Burian (for Spinar and Burian, 1972) and Jay Matternes (for Smithsonian Institution mural, see Dott and Batten, 1981). With its low-crowned teeth of a browser and four toes on the front limbs and three toes in the rear, this very small horse is far removed from our modern concept of a horse (MacFadden, 1992). These early forest-dwelling ancestors of modern Equidae lack exact modern analogs.

Patriofelis ferox

Patriofelis ferox (Marsh) Marsh (1878) is represented by a single jaw fragment from the middle Eocene Clarno Nut Beds. A complete skeleton is known from the middle Eocene (Bridgerian) of the Bridger Basin of Wyoming, and this was the basis for our reconstruction (Figure 8E), which is close to that of Charles Knight (for Osborn, 1910). More gracile reconstructions have been made by Bruce Horsfall (for W.B. Scott, 1913), Michael Long (Savage and Long, 1986), and William Scheele (1955). Although it had the appearance of a big cat, *Patriofelis ferox* lacked the precisely bladed carnassial teeth of modern carnivores and belonged to an extinct group of catlike carnivores (Oxyaenidae, Creodonta) (Carroll, 1988).

Protitanops curryi

A variety of limbs and skull fragments of a large brontothere have been found in the late Eocene (Duchesnean) Mammal Quarry of the upper Clarno Formation. Although referred to *Protitanops* (Lucas, 1992), there is doubt about this generic assignment (Mader, 1989). Our reconstruction (Figure 9F) is based on the generally similar *Protitanops curryi* Stock (1936) from the late Eocene (Chadronian) Titus Canyon Formation, east of Death Valley, California. Like *Telmatherium* (Figure 8B), *Protitanops* was a brontothere and a browser. It was much larger than *Telmatherium* and probably had a significant impact in destroying trees and other browse—like modern megaherbivores such as elephants and rhinos (Owen-Smith, 1988). The horns of this and geologically younger brontotheres were probably sexual display organs of male animals.

Plesiocolopirus hancocki

Several skull fragments and teeth of *Plesiocolopirus hancocki* (Radinsky) Schoch (1989) have been found in the Mammal Quarry of the upper Clarno Formation. Radinsky (1963) envisaged this species as intermediate between the earlier *Helaletes nanus* from the middle Eocene (Bridgerian) of Wyoming and the later *Protapirus* from the early Oligocene (Orellan and Whitneyan) Brule Formation of South Dakota (W.B. Scott, 1941)—which he regarded as the first true tapir. Our reconstruction (Figure 9C) was influenced by reconstructions of *Helaletes nanus* by Jay Matternes (see Dott and Batten, 1981) and Bruce Horsfall (for W.B. Scott, 1913) and by those of early Miocene *Miotapirus* by Graham Allen (for Dixon and others, 1992). The Clarno fossils have a large nasal incision and reduced nasal bones. These bones are not so modified as in living tapirs, so the proboscis of *P. hancocki* may not have been so large and flexible. Tapirs are forest browsers, and the teeth of *P. hancocki* are compatible with a similar diet.

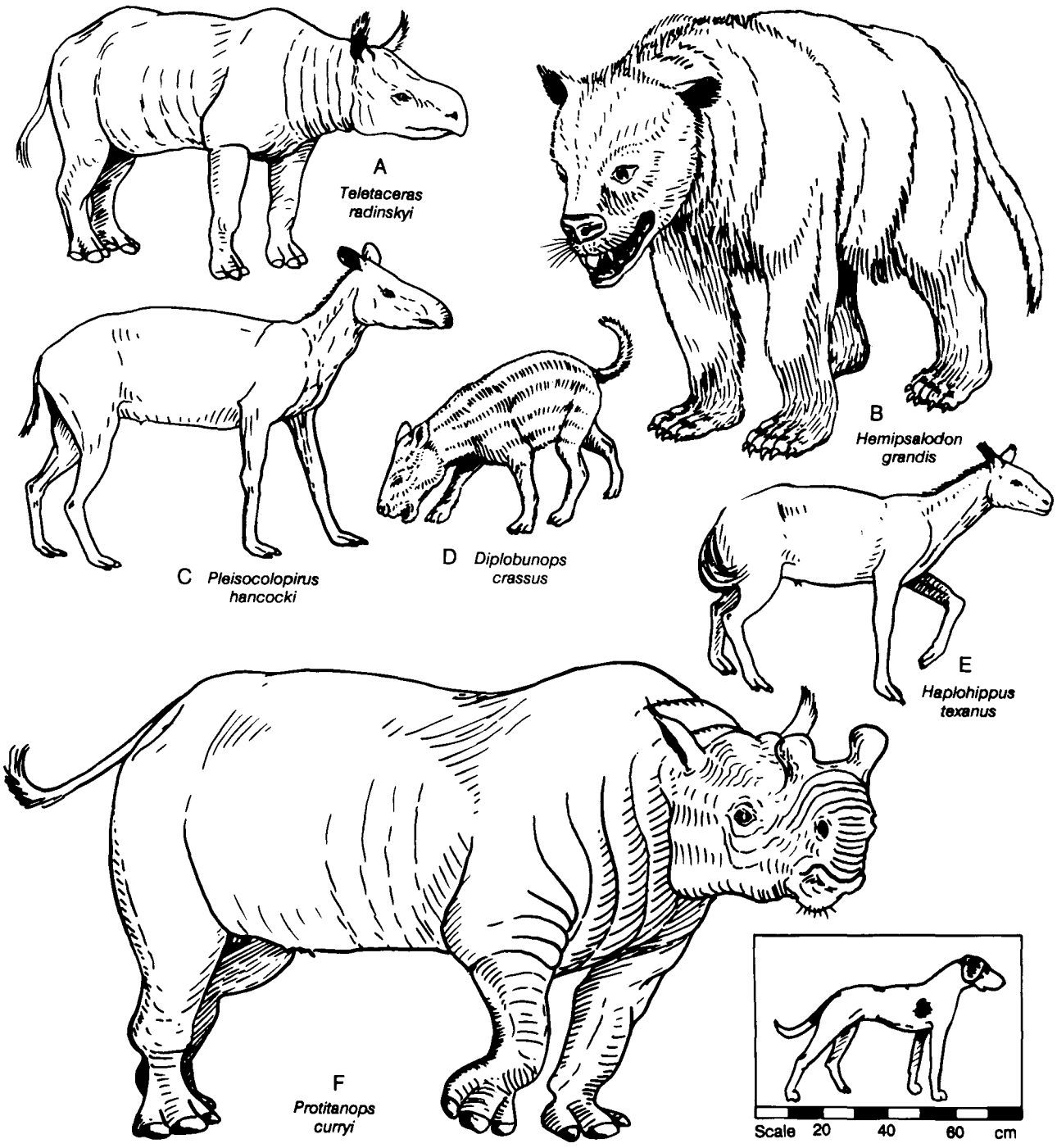

Figure 9. Reconstructions of late Eocene (Duchesnean) animals from the Mammal Quarry of the upper Clarno Formation at the OMSI Hancock Field Station, Oregon (scale from R.B. Horsfall for W.B. Scott, 1913; others original with inspiration from Stock, 1936; Russell, 1938; W.B. Scott, 1945; McGrew, 1953; Radinsky, 1963; Mellett, 1969; Savage and Long, 1986; Hanson, 1989; Dixon and others, 1992).

Teletaceras radinskyi

Teletaceras radinskyi Hanson (1989) was a small rhino, represented by skulls and a variety of other bones from the Mammal Quarry of the upper Clarno Formation. Hanson (1989) compared it with *Trigonias osborni* from the Late Eocene (Chadronian) Chadron Formation of South Dakota, a species reconstructed by Irving Biehn (for W.B. Scott, 1913) and Graham Allen (for Dixon and others, 1992). Compared with this geologically younger rhino, the Duchesnean *Teletaceras radinskyi* was a smaller and more gracile animal (Figure 9A). The Clarno rhino may have evolved from immigrant *Teletaceras* from Asia and represents an early true rhino (Rhinocerotidae). As with most rhinos, its teeth are those of a browser.

Haplohippus texanus

The primitive horse *Haplohippus texanus* McGrew, 1953, is represented by a variety of skull fragments and teeth from the Mammal Quarry of the upper Clarno Formation, as well as the late Eocene (Duchesnean) Porvenir local fauna of the Vieja Formation of Texas. The teeth of *Haplohippus texanus* ally it with primitive, forest-browsing horses such as *Orohippus* (Figure 8D), from which it differed by being larger, yet more gracile (Figure 9E). Another horse found in the Clarno Mammal Quarry, *Epihippus gracilis*, on the other hand, is even more gracile and cursorial and has more complex and larger molars, perhaps reflecting a preference for slightly more open habitats. *Haplohippus* was the last of the primitive hyracotheriine horses, but *Epihippus* was in the lineage giving rise to later three-toed horses (McGrew, 1953). Although horse evolution has been portrayed as a unidirectional trend, this and other examples indicate a luxuriant bush of evolutionary branches (MacFadden, 1992).

Diplobunops crassus

A skull of *Diplobunops* from the Mammal Quarry of the upper Clarno Formation is crushed and extensively cracked and may belong to a new species. Our reconstruction (Figure 9D) is based on better preserved material of *Diplobunops crassus* W.B. Scott (1945) from the late Eocene (Uintan) of the Uinta Basin, Utah, and on reconstructions of the allied genus *Agriochoerus* by Bruce Horsfall (for W.B. Scott, 1913). *Diplobunops* and *Agriochoerus* were part of a now-extinct group of creatures grouped into the family Agriochoeridae, which were primitive artiodactyls similar to the extinct but more familiar oreodons common in Oligocene and Miocene parts of the John Day Formation (Carroll, 1988). Their prominent canines and postcranial skeleton are superficially similar to those of dogs, although the tarsus is that of an artiodactyl. The cheek teeth, however, are low crowned and those of a browser.

Hemipsalodon grandis

The large carnivore *Hemipsalodon grandis* (Cope) Russell, 1938, is represented by a crushed but complete skull and lower jaws from the Mammal Quarry of the upper Clarno Formation (Mellett, 1969). This species is known from a variety of localities of late Eocene (Duchesnean and Chadronian) age from Saskatchewan in the north to near the Mexican border of Texas but remains very incompletely known. The bearlike reconstruction offered here (Figure 9B) is based partly on a facial reconstruction by Russell (1938) from Canadian specimens and on an associated astragalus of a plantigrade animal (Mellett, 1969). Although perhaps frugivorous to carnivorous like bears, *Hemipsalodon* was not closely related to them but rather belongs in an extinct group of creodont carnivores (Hyaenodontidae) (Carroll, 1988). *Sarkastodon* from the late Eocene of Mongolia is another bearlike creodont for which a reconstruction is available (by Graham Allen for Dixon and others, 1992).

Diceratherium annectens

Only molar fragments of the rhino *Diceratherium annectens* Marsh (1873) have been found in the late Oligocene (early Arikareean) Turtle Cove Member of the John Day Formation on Carroll Rim and the footslopes of Sutton Mountain, but excellent skulls and postcranial remains continue to be found at the same stratigraphic level in and around the Sheep Rock Unit of the John Day Fossil Beds near Dayville (Peterson, 1920). Our reconstruction (Figure 10A) is based on a hornless reconstruction by Bruce Horsfall (for W.B. Scott, 1913). This Oregon rhinoceros should not be confused with a Nebraskan Miocene rhino, formerly regarded as congeneric but now assigned to *Menoceras cooki* (Prothero and others, 1989) and reconstructed by Bruce Horsfall (for W.B. Scott, 1913). *Diceratherium annectens* had hypsodont teeth and was one of the earliest grazing mammals (Webb, 1977).

Miohippus quartus

The three-toed horse *Miohippus quartus* Osborn (1918) is represented only by fragmentary teeth in the late Oligocene (Arikareean) Turtle Cove Member of the John Day Formation in the Painted Hills area but by fine skulls in the same stratigraphic horizon to the east near Dayville. Other species of *Miohippus* represented by skulls and complete skeletons are known from the Oligocene (Orellan and Whitneyan) Brule Formation of South Dakota (Prothero and Shubin, 1989). These and a reconstruction by Charles Halgren and associates (for Simpson and Beck, 1963) were used to prepare our version (Figure 10B). *Miohippus* like the co-occurring *Mesohippus* was a three-toed horse with the low-crowned teeth of a browser. Nevertheless, both taxa, and *Miohippus* more than *Mesohippus*, have more complex, wider, and higher crowned teeth and more elon-

gate limbs than geologically older forest horses such as *Haplohippus*, *Epihippus*, and *Orohippus*. These indicate adaptation to more open country. The distribution of fossil horses in paleosols of Oligocene age in South Dakota has suggested to MacFadden (1992), that *Mesohippus* preferred streamside woodlands, whereas *Miohippus* lived in more open, grassy vegetation of interfluves, an idea supported to a limited extent by our discovery of *Miohippus* in paleosols in Oregon (Bestland and Retallack, 1994b).

"Entelodon" calkinsi

The large, hoglike *"Entelodon" calkinsi* (Sinclair) Trox-

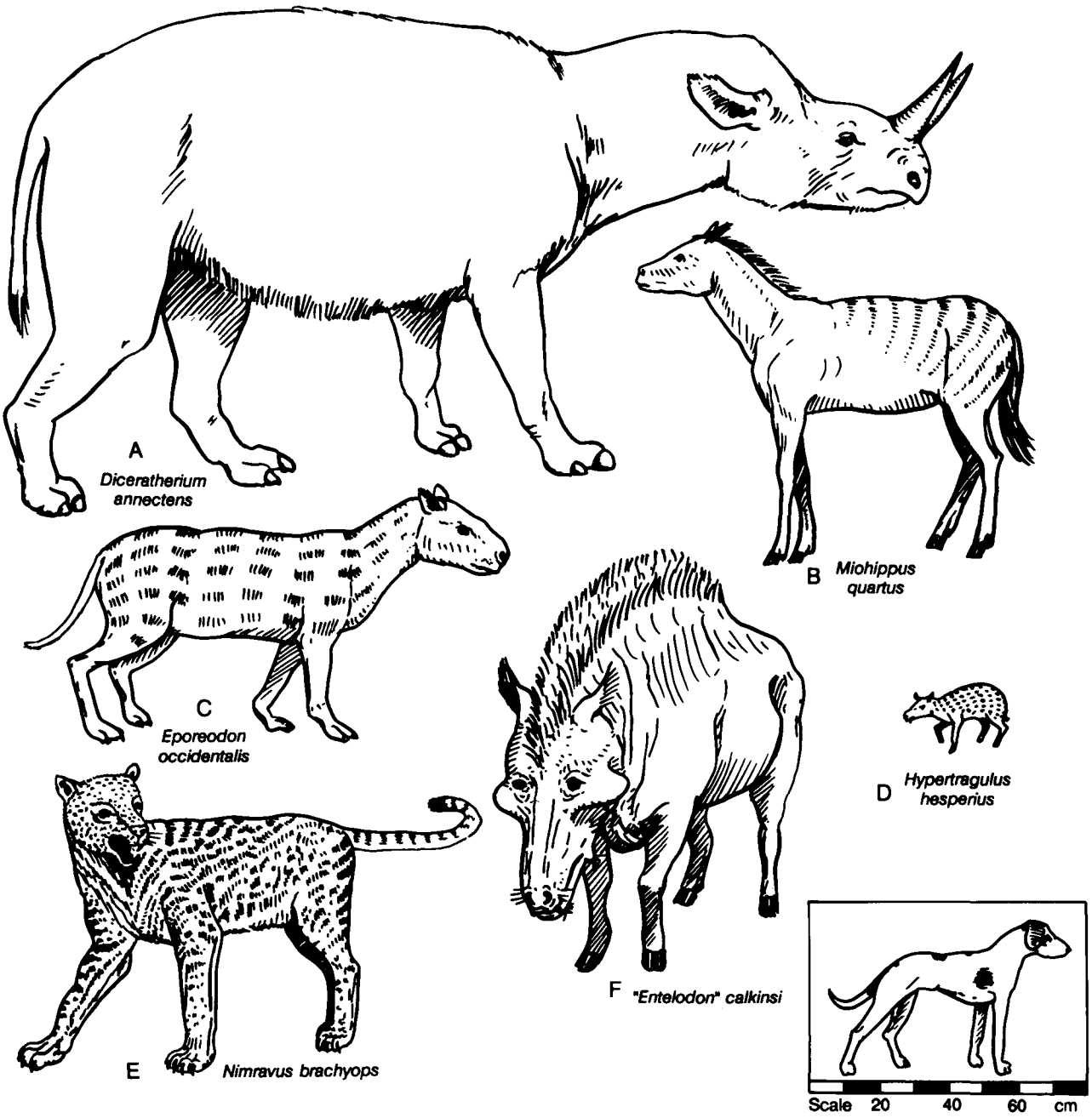

Figure 10. Reconstructions of fossil mammals known from the late Oligocene lower Turtle Cove Member of the John Day Formation in the Painted Hills area (A and scale by R.B. Horsfall for W.B. Scott, 1913; D from Dixon and others, 1992; others original with inspiration from Sinclair, 1905; Merriam, 1906; Osborn, 1918; Peterson, 1920; W.B. Scott, 1940; Simpson and Beck, 1963; Czerkas and Glut, 1983).

ell (1920) is represented by very fragmentary remains in the late Oligocene (Arikareean) Turtle Cove Member of the John Day Formation in the Painted Hills area but by a large and complete skull at comparable stratigraphic level in the Dayville area. *Entelodon* and allied genera belong to an extinct group (Entelodontidae), distinct from but allied to pigs (Carroll, 1988). Other species of entelodons have been widely reconstructed (W.B. Scott, 1913; Czerkas and Glut, 1982; Savage and Long, 1986; Dixon and others, 1992), but our version (Figure 10F) emphasizes the distinctive pattern of bony knobs on the jaw and cheeks of the skull described by Sinclair (1905). Entelodons are unique in many ways but were probably omnivore-scavengers (Joeckel, 1990).

Hypertragulus hesperius

The small mouse deer *Hypertragulus hesperius* Hay (1902) is one of the most abundant fossil mammals in the Turtle Cove Member of the John Day Formation but is represented mainly by fragmentary remains. Good skeletons of other species of *Hypertragulus* and the similar *Leptomeryx evansi* are known from the Brule Formation of South Dakota (W.B. Scott, 1940). These and the reconstructions of *L. evansi* by Charles Knight (for Osborn, 1910) have influenced our reconstruction of *Hypertragulus hesperius* (Figure 10D). *Hypertragulus* and *Leptomeryx* are placed in separate families (Hypertragulidae and Leptomerycidae) of extinct primitive ruminants allied to the living mouse deer (Tragulidae) of Southeast Asia and Africa. Like living mouse deer, the extinct ones were probably forest browsers.

Eporeodon occidentalis

Good skulls, including the holotype of *Eporeodon occidentalis* Marsh (1873), have been found in the late Oligocene (Arikareean) Turtle Cove Member of the John Day Formation in the Painted Hills area (Thorpe, 1921). The taxonomy of these abundant Oligocene mammals remains confused (Prothero and others, 1996). *Eporeodon occidentalis* was similar to though slightly more gracile and shorter limbed than the common *Merycoidodon culbertsoni* of the Badlands of South Dakota, which has been reconstructed by Bruce Horsfall (for W.B. Scott, 1913), Charles Knight (for Osborn, 1910), and Andrew Robinson (for Dixon and others, 1992). Both the local skeletons and these reconstructions influenced our reconstruction (Figure 10C). Oreodonts are a completely extinct group of endemic North American early artiodactyls (Merycoidontidae or Oreodontidae of Carroll, 1988). They have a sheeplike appearance but are unrelated to these domestic bovids. They have also been called ruminant hogs, but pigs were a separate lineage. And although part of the larger ruminant clade, living ruminants all evolved after oreodonts. Oreodonts have a limb structure that includes feet more like paws than hooves and teeth that are low crowned. They were probably browsing animals (Bakker, 1983).

Nimravus brachyops

Only a talonid allied to these early sabre-tooth cats (Nimravidae) has been found in the late Oligocene Turtle Cove Member of the John Day Formation in the Painted Hills area, but good skulls and limb bones of *Nimravus brachyops* (Cope) Cope (1879) are known from this stratigraphic level near Dayville to the west (Toohey, 1959). The reconstruction of Graham Allen (for Dixon and others, 1992) inspired our version (Figure 10E). Nimravidae were among the earliest of the true carnivores that began to replace archaic creodont carnivores in the late Eocene. The sabre-tooth specialization of these carnivores developed independently in several different lineages of cats, the last of which became extinct at the end of the Pleistocene. *Nimravus brachyops* did not have such exaggerated canines as many later sabre-tooth cats. Its limbs were elongate and toes reduced, more like a pursuit than ambush predator, though not so cursorial as the living cheetah (Merriam, 1906).

CONCLUSION

The John Day Fossil Beds National Monument conserves a fossil record of life and landscapes in central Oregon that continues to intrigue amateur and professional paleontologists. The quality of preservation and diversity of fossil plants and animals enables an unusually detailed view of Eocene and Oligocene life on land. Associated fossil soils allow paleoecological interpretations of the fossil assemblages, and abundant volcanic rocks allow their precise radiometric dating. With our reconstructions and supporting notes, we have attempted to introduce a few of the common extinct fossil plants and animals of central Oregon. In distilling 130 years of scientific study of these fossils we are keenly aware that much more remains to be done. John Day fossils will continue to amaze and inspire for years to come.

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John Day Fossil Beds National Monument has a home page on the Internet

Those interested in finding out more about the John Day Fossil Beds and ready to get on the Internet can find the home page of the John Day Fossil Beds National Monument under the address **http://www.nps.gov/joda**.

Without the final "joda" this address is for the National Park Service home page, which can lead you to many other sources of information on National Parks. □

BOOK REVIEWS

Fruits and Seeds of the Middle Eocene Nut Beds Flora, Clarno Formation, Oregon, by Steven R. Manchester. Ithaca, N.Y., Paleontological Research Institution, Palaeontographica Americana 58, August 24, 1994 , 205 p., including 70 plates, $65.00.

Reviewed by Ted Fremd, Paleontologist, John Day Fossil Beds National Monument, HCR 82 Box 126, Kimberly, OR 97848, e-mail Ted_Fremd@NPS.GOV

The predominantly volcaniclastic Clarno Formation, first recognized and described around the turn of the century (Merriam, 1901), covers a huge expanse of eastern Oregon. Manchester's excellent new monograph focuses on only a tiny portion of the record preserved in these strata. The Nut Beds flora is found in 44-million-year-old deposits at a minuscule site within the boundaries of what is now the Clarno Unit of John Day Fossil Beds National Monument. Ever since its discovery, this peculiar locality has puzzled and delighted many botanical workers. In 1942, a fossil enthusiast named Thomas Bones (who did not work with vertebrates) began diligently working these beds. By 1954, when the first monograph on the flora appeared (Scott, 1954), Bones had laboriously collected and painstakingly prepared microscopic specimens of fossil seeds and fruits from over 10 tons of material. Bones continued collecting for another 30 years, providing a classic example of the role "amateurs" can have in paleontology. He amassed significant collections housed today in major repositories where they are available for study, and he published a photographic atlas of his specimens (Bones, 1979).

Steve Manchester's new publication is an exhaustive and thorough summary of the Nut Bed fossil seeds and fruits. It is based on new examinations of over 20,000 specimens, most of them from Bones' collections. Manchester's effort is unique in the North American paleobotanical literature and has produced a huge success, particularly since the Nut Beds site has produced extraordinarily well preserved fruits, flowers, pollen, leaves, stems, roots, and other tissue systems in association.

A marvelously complex picture of a diverse (145 genera), paratropical flora emerges from Manchester's work. Vines or other climbing plants make up nearly half of the flora for which the growth habit can be deduced. A puzzling mix of palms, ferns, cycads, and numerous types of flowering plants is described (with only one herbaceous angiosperm, the banana Ensete, detailed in Manchester and Kress, 1993). For years, we have been comparing the Clarno rain forest to habitats such as those found in modern southeast Asia, but comparisons with modern forests fail to do justice to the diversity and degree of difference of the Clarno rain forest: it appears here much more bizarre than anybody had thought so far. If modern botanists could somehow walk through the Clarno jungle, they would not just see alien species—they would be unable to assign over half of the plants to any of the modern families!

A small but equally odd suite of vertebrates is also known from the Nut Beds, including crocodilians, primitive horses, and brontotheres, some of which undoubtedly feasted on the fruits and helped to disperse the plants.

Professionals and amateurs alike will be delighted with the great number and quality of the photographic plates in Manchester's book. I counted 1,155 clear, crisp images of 170 species with excellent descriptions, including whole-rock specimens, acetate peels, stereopairs, and beautiful scanning-electron microscopy. Incidentally, these photographs would be very useful on a CD-ROM linked to the text descriptions and illustrations, as several publishers are finding. The bulk of the text (90 of 120 pages) is concerned with descriptions of the taxa, including dozens of new species and/or combinations, following standard systematic procedure. The descriptions are accompanied by discussions, clear text figures, and well-designed tables that do an excellent job of clarifying synonymies.

Among the figured specimens are some that may correspond to insect reproductive structures rather than plants. Plate 66, for example, includes illustrations of "seeds" that I had assumed were brood chambers of one or more species of burrowing hymenopteran that are also found in younger John Day Basin strata. In recognizing the possibility of incorrect identification, Manchester decided that, "Rather than exclude taxa that could possibly be construed as insect eggs, I believe it is useful to document all of the structures because of the possible importance for biostratigraphy and/or future insect work" (p. 18). Still, the consequence is somewhat odd: One may have to consult botanical descriptions of micropyles, seed coats, and endosperm cavities for what may be entomological features.

Incidentally, paleobotanists are not the first organisms tempted into thinking that some of the little shapes we find today in Clarno muds are plant seeds. Modern species of "stick insects," of which the oldest known fossil eggs are found in the Nut Beds (Sellick, 1994), have evolved a complex mimicry: They succeed in fooling some ants into thinking the stick insect eggs are a type of plant seed. The ants carry these "seeds" into their nests, unwittingly assisting the reproductive efforts of the stick insects—as presumably their Eocene counterparts did.

Not much can be found that detracts from the excellence of Manchester's work. Among some minor flaws is the erroneous location in text figure 3 of the Hancock Quarry, placed in an outcrop rather far from the actual site. The pages devoted to the geology contain several antiquated interpretations of what is admittedly a puzzling stratigraphic sequence, and they are only partially corrected by "Notes added in proof." For example, instead of the earlier identification of the Nut Beds as "predating an andesitic plug" (p. 9), it is now clear that the Nut Beds actually are high in a section of lahars that accumulated on top of the plug (which is actually dacite) (Bestland and others, 1994). Manchester dismisses the long-standing "lake delta" hy-

pothesis and rightly points out that the evidence is more consistent with a flood/slurry deposit associated with a lahar.

Unfortunately, the binding is pathetically inadequate for a book of this caliber. Since it will often serve as a reference, users will have to reinforce the binding to guard against losing individual pages.

Fruits and Seeds of the Middle Eocene Nut Beds Flora is a major contribution to paleobotany and an indispensable reference tool that belongs on the shelves of every paleobotanist and worker who deals with any aspect of the terrestrial Tertiary.

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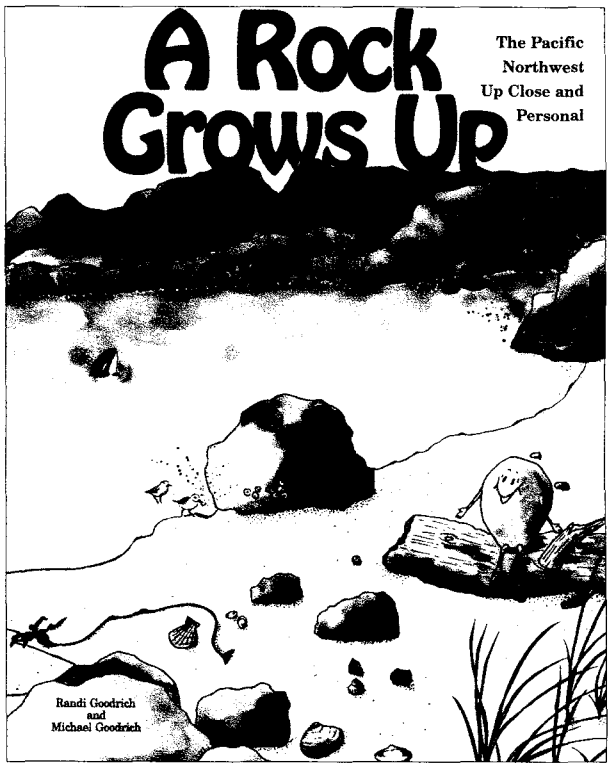
A Rock Grows Up, by R. and M. Goodrich. Lake Oswego, Oreg., GeoQuest Publishing, 56 p., $9.95.

A Rock Grows Up is the title of a children's book, created by Lake Oswego high school teacher Michael Goodrich and his wife Randi and delightfully illustrated by Michele Han, honor student at Lake Oswego High School. The book introduces earth science concepts in such a way that they become appealing and easily comprehensible to children at the elementary school level.

Following the story of Barry Basalt, the rock that grows up, young readers of the large-print book meet a dozen characters—family members and neighbors—that represent rocks and rock-forming minerals, such as Larry Gneiss and Annie Augite. They all participate in the great geologic cycle of rock formation and decomposition that starts in the asthenosphere below a sea-floor spreading ridge and leads through plate subduction, volcanism, weathering, sedimentation, and metamorphosis—from formlessness into form and back.

The whimsical pictures of the characters in the story are accompanied by schematic block diagrams that illustrate the geologic processes as they occur in the earth from the Juan de Fuca Plate to the Cascade Range—once even to Picture Gorge. In this sense, the book addresses children of Oregon and, to a lesser extent, the Pacific Northwest, conveying the framework of basic geology these children can experience at home.



Cover of *A Rock Grows Up*

The about fifty pages of the book include also a glossary of geologic terms and an index, also a list of significant technical books that introduce the teacher to the geology of the Pacific Northwest and to the major processes touched upon in the story of Barry Basalt. A bit of caution is advised in following the pronunciation aids given throughout the text and the glossary. A teacher may want to try them out before introducing them to children of the Northwest.

A Rock Grows Up is conceived as a teaching tool and thus accompanied by more teaching aids: a curriculum guide for student activities in lab exercises, coloring, and creative writing and with more materials for the use of the teacher ($7.95). The authors also offer a kit containing tagged samples of the rocks and minerals of the story ($14.95).

The book and accompanying materials are available from the publishers, GeoQuest Publishing, P.O. Box 1665, Lake Oswego, OR 97035, phone (503) 635-4420; or from the Nature of the Northwest Information Center on the ground floor of the State Office Building in Portland (see address on last page of this issue).□

Offshore volcanic activity reported

The Nature of the Northwest Information Center has received numerous inquiries about volcanic activity off the Oregon coast. Internet users can find up-to-date information on this subject in the U.S. Department of Commerce NOAA/PMEL/VENTS Program under the address **http://www.pmel.noaa.gov/vents/eruption.html**. □

Oil and gas exploration and development in Oregon, 1995

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

ABSTRACT

Oil and gas leasing activity was about the same during 1995 as it was in 1994. Four U.S. Bureau of Land Management (BLM) lease sales were held, and offers were received on three tracts comprising 8,250 acres located in Jefferson County, Oregon. A total of 11,760 federal acres were under lease at year's end. The State of Oregon conducted no lease auctions during the year. A total of 16 State of Oregon tracts were under lease at year's end and consisted of 25,520 acres, which is the same as 1994. Columbia County held no lease sales during 1995.

During 1995, no exploratory wells were drilled in Oregon, primarily due to the fact that the operator of Mist Gas Field, Nahama and Weagant Energy Company, had filed for bankruptcy during 1994. The field was put for sale, and Enerfin Resources was the successful bidder and will become operator of the majority of the wells at the field upon finalization of the ownership transfer. Oregon Natural Gas Development Company acquired ownership of 10 wells and certain leases at Mist Gas Field.

At the Mist Gas Field, 18 wells were productive during 1995. A total of 2.5 Btu of gas was produced with a total value of $1.8 million during the year. This is a significant decline from the 4.2 Bcf of gas with a total value of $6.4 million produced during 1994. Reasons for the decline in production during 1995 include the normal decline in the wells at the field; the record low of prices paid for gas, which discouraged exploration and production activities; and the decommissioning of the Nitrogen Rejection Unit during 1995, which caused several low-Btu wells to be suspended.

Final reports on the DOGAMI five-year study of the oil, gas and coal resource potential of the Tyee Basin should be published during 1996. No changes to statutes and administrative rules were made during the year.

LEASING ACTIVITY

There was little oil and gas leasing activity in Oregon during 1995. This is a continuation of a generally declining trend in leasing activity that began during the late 1980s. Activity included four public sales by the BLM at which a total of three offers were received for oil and gas leases on lands in Jefferson County. Robert F. Harrison, Seattle, Washington, applied for 8,250 acres during December 1995. He and other individuals have held leases on a block of federal land comprising about 11,680 acres in this general area since 1977. This acreage, plus an 80-acre parcel located in Columbia County in the vicinity of Mist Gas Field, are the only federal lands presently under lease in Oregon. Total rental income to the BLM was $11,760 during 1995. Applications were pending on 13,103 federal acres at the end of 1995, which is a decrease from applications pending on 39,942 acres at the end of 1994 because the majority of such offers were withdrawn during the year.

The State of Oregon held no lease sales during 1995, and no State oil and gas leases were issued during the year. With no changes during the year, a total of 16 State of Oregon tracts comprising a total of 25,250 acres were under lease at year's end, and total rental income was $25,250—the same as in 1994.

Columbia County held no lease sales during 1995.

DRILLING

For the second consecutive year, no exploratory oil and gas wells were drilled in Oregon. Before this, exploratory wells for oil and gas had been drilled in Oregon each year from 1974 until 1993. The lack of drilling during 1995 is largely attributed to the fact that Nahama and Weagant Energy Company, the operator of Mist Gas Field, had filed for bankruptcy during 1994. A court-appointed trustee was assigned to sell the assets of Nahama and Weagant Energy Company, including the Mist Gas Field. During 1995, Enerfin Resources of Houston, Texas, was the successful bidder for the Mist Gas Field and will become the operator of the field. It was reported that negotiations were completed during December 1995, which transferred ownership of ten wells and certain leases to Oregon Natural Gas Development Company (ONGD) of Portland, Oregon. ONGD is now the operator of the following wells: CC 13–34, CC 43–33–75, CC 23–22, CC 43–22, CC 31–27–65, CC 14–23, CC 44–27–65, CC 31–34–65, CC 21–35–65, and LF 12B–35–65. All other wells at Mist Gas Field are operated by Nahama and Weagant Energy pending finalization of the transfer of ownership to Enerfin Resources.

During 1995, DOGAMI did not issue any permits to drill, while four incomplete applications were withdrawn. Permit activity is listed in Table 1.

Table 1. Oil and gas permit activity in Oregon 1995

Permit number	Operator, well, API number	Location	Permit activity
440	Norwestco, Inc. 1–29 36–069–00009	SW¼ sec. 29 T. 9 S., R. 23 E. Wheeler County	Incomplete application, withdrawn.
485	Carbon Energy Menasha 28–1 36–001–00025	SW¼ sec. 28 T. 26 S., R. 13 W. Coos County	Incomplete application, withdrawn.
498	Carbon Energy Menasha 1–16 36–011–00028	SE¼ sec. 16 T. 26 S., R. 13 W. Coos County	Incomplete application, withdrawn.
499	Carbon Energy Menasha 1–16 36–011–00028	SE¼ sec. 32 T. 26 S., R. 13 W. Coos County	Incomplete application, withdrawn.

PRODUCTION

Despite the bankruptcy of Nahama and Weagant Energy Company, the Mist Gas Field operated normally during the year. The field had a total of 18 wells that were productive during the year, which is a decline from 21 wells productive during 1994. The wells produced 2.5 Bcf of gas, a significant decrease from the 4.2 Bcf of gas produced during 1994. This decrease was largely the result of the three factors. The first is the normal decline of the existing wells at the field. The second factor is the record low price received for gas at the Mist Gas Field since it was discovered during 1979, which discouraged exploration and production at the field. The gas prices paid during 1995 ranged from 4 cents to 11 cents per therm during the year until December, when they increased to 22 cents per therm for the month. During 1994, gas prices ranged from 11 to 23 cents per therm. The final reason for the production decline during 1995 was the decommissioning of the Nitrogen Rejection Unit (NRU) that was installed during 1994. The NRU enabled three low-Btu wells at Mist Gas Field to go on production by separating the methane gas from noncombustible nitrogen gas. However, due to the cost to run the NRU, decline in production of the low-Btu wells, and other factors, the NRU was decommissioned during the year and the three low-Btu wells were shut in. As a result of the low production volume and low gas prices during 1995, the total value of the gas produced at Mist Gas Field was $1.8 million, a significant decline from the $6.4 million during 1994. Cumulatively, the Mist Gas Field has produced about 56.5 Bcf of gas with a total value of $112.8 million since it was discovered in 1979.

GAS STORAGE

The Mist Natural Gas Storage Project remained fully operational during 1995. The gas storage project has nine injection-withdrawal service wells, five in the Bruer Pool and four in the Flora Pool, and thirteen observation-monitor service wells. The two pools have a combined storage capacity of 10 Bcf of gas. This allows for the cycling of about 6 Bcf of gas in the reservoirs at pressures between approximately 400 and 1,000 psi and will provide for an annual delivery of 1 million therms of gas per day for 100 days. During 1995, about 4,469,288 cubic feet of gas was injected, and 3,566,865 cubic feet was withdrawn at the Mist Storage Project. Plans are underway by ONGD to develop additional storage pools at the Mist Gas Field during 1996.

OTHER ACTIVITIES

DOGAMI has completed a five-year study of the oil, gas, and coal resource potential of the Tyee Basin located in Douglas and Coos Counties in the southern Coast Range. The study, which was funded by landowners in the study area and by county, state, and federal agencies in a public-private partnership, is an investigation of source rock, stratigraphy, and structural framework for those character-

(Continued on page 74)

ABSTRACTS OF PAPERS

The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.

A paleohydraulic reconstruction of 300-year old tsunami deposits at Willapa Bay, Washington State, by Mary Ann Rinehart, GeoEngineers, Inc., Redmond, Wash.; and Joanne Bourgeois, Department of Geological Sciences, University of Washington

Sand sheets about 300 years old along the southern Washington coast can be explained by a tsunami generated at the Cascadia Subduction Zone but not by storm setup or seiching. These sand sheets, preserved in many parts of the interiors of Willapa Bay and Grays Harbor estuaries, overlie a buried peaty soil indicating abrupt subsidence. They are composed of one to five horizontal laminae of sandy silt or silty sand, alternating with laminae of mud. The character and sedimentology of the deposits indicate that (1) the depositional mechanism was a single, landward-directed event comprising multiple pulses; (2) each lamina was deposited rapidly from a high concentration of suspended sediment; (3) velocities and boundary shear stresses generated during each pulse were high enough to entrain and suspend sufficient volumes of sand and silt into the overbank part of the flow from tidal-channel floors; (4) overbank velocities were sufficient to transport sand up to about 200 m across marsh surfaces; and (5) a period of quiet water followed deposition of each sandy lamina.

As a test of the tsunami hypothesis we used a simple sediment-transport model to reconstruct the conditions necessary to deposit sandy laminae on marshes along the Niawiakum River, an arm of Willapa Bay. We assumed (conservatively) steady-flow conditions and uniform distribution of sand and silt throughout the overbank part of the water column. Discharge and suspended-sediment concentrations were reconstructed with a simple advection model applied to the lateral distribution of grain sizes in the basal sandy lamina. We then constrained the rate of lamina deposition, overbank flow depth, and pulse period by matching the component concentrations (estimated from the overbank trajectory model) to concentrations generated within the channel as calculated from the Rouse equation. The results of the reconstruction indicate overbank flow depths of 1–2 m, pulse periods of 18–30 min, and in-channel velocities of 340–400 cm/s.

A tsunami wave train provides the best fit to results of the reconstruction, based on wave period, number of pulses, water velocity, and distribution of the sand sheet around

Willapa Bay and Grays Harbor. The calculated wave periods are consistent with known tsunami periods and inconsistent with the calculated seiche period for Willapa Bay (1.5–2 hrs.)

The number of pulses is also improbable for a seiche, as it is unlikely the bay could seiche the required number of times, given its shallow, irregular bathymetry. Storms are unlikely to have produced the calculated flow velocities, maximum combined storm/tidal current velocities at the entrance of Willapa Bay are not known to exceed 250–300 cm/sec, and channel-flow velocities of that magnitude would not be maintained in protected tidal channels such as the Niawiakum River. Finally, the regional extent of the deposit, as well as its characteristics and local variation, can be explained by tsunami wave behavior. □

(Continued from page 73)

istics that are needed to generate and trap oil and gas. The final data, reports, and maps are expected to be published by DOGAMI during 1996. A series of maps and preliminary reports that present a revised understanding of the geologic framework of the Tyee Basin have already been published. Contact DOGAMI for a complete publication list including those for the Tyee Basin study.

The Northwest Energy Association, formerly the Northwest Petroleum Association, remained active for the year and has over 100 members. At its regular monthly meetings, speakers give talks generally related to energy matters in the Pacific Northwest. The 1995 symposium was held at Astoria, Oregon, on underground natural gas storage and energy-related matters of interest in the region. Plans are now underway for the 1996 symposium, which will be held in the Seattle, Washington, area. For information, contact the NWEA, P.O. Box 6679, Portland, OR 97228.

During 1996, no legislative or rule changes were made to DOGAMI statutes and administrative rules related to oil and gas drilling exploration activities. Copies of current statues and administrative rules can be obtained from DOGAMI. □

In memoriam: Barbara Jacob, Cliff Speaker

The Oregon Department of Geology and Mineral Industries (DOGAMI) mourns the death of two former staff members, both retired.

Barbara Ann Jacob died March 4, 1996, at age 75, in Portland. She was a native of Tacoma and lived most of her life in Portland. She was a secretary for DOGAMI for 15 years until her retirement in 1986 and specialized in the regulatory work of the oil and gas section. Barbara leaves a son, R. Larry, in Vancouver, Washington; a daughter, Carolyn Harmon, in Olympia; a sister, Gloria Kingsley, in Milwaukie; a brother, Dee Swayze, in Santa Clara, California; and three grandchildren.

Clifford Drake Speaker died March 6, 1996, at age 82. He was born in Parkrose and lived in Vancouver, Washington, from 1983 until his death. He was an accountant for Publishers Paper Company and then worked as business manager for DOGAMI from 1970 until his retirement in 1978. His surviving family includes his wife, Rachel C.; a daughter, Marylou S. Churchill, in Boston; sons Paul, in Upland, California, and Michael, in Portland; stepsons Roger Cole, in Vancouver, and Douglas Cole, in Bellingham, Washington; and three grandchildren. □

DOGAMI PUBLICATIONS

Released May 1, 1996:

Tsunami Hazard Map of the Siletz Bay Area, Lincoln County, Oregon, by G.R. Priest, M. Qi, A.M. Baptista, C.D. Peterson, and M.E. Darienzo. Geological Map Series GMS–99, $6.

This map of the area between Lincoln City and Gleneden Beach outlines five tsunami hazard zones for elevations between sea level and about 100 ft (30 m). The map was produced by the joint efforts of scientists from DOGAMI, the Oregon Graduate Institute of Science and Technology, and Portland State University and is intended primarily for planning for evacuation in the event of a tsunami.

The tsunami hazard map shows a black-and-white airphoto image of the coastal zone with elevation contours superimposed. The scale of 1:12,000 (1 inch = 1,000 feet) allows identification of streets and medium-sized structures. Three different types of red lines mark tsunami runup elevations that serve to separate risk zones: extreme risk, high risk, moderate risk, and low risk; the fifth category, negligible risk, is identified as those lands above 100 feet (30 m) in elevation. The map also identifies drill sites where cores revealed buried soils and, in some cases, tsunami sand layers from prehistoric events.

For evacuation planning, the new tsunami map should be used in conjunction with the relative earthquake hazard maps of the area published earlier by DOGAMI as Geological Map Series map GMS–93 ($20).

Explanation of Mapping Methods and Use of the Tsunami Hazard Map of the Siletz Bay Area, Lincoln County, Oregon, edited by G.R. Priest. DOGAMI Open-File Report O–95–05, 69 p., $6.

This 69-page paper contains detailed discussions of the map mentioned above and of its use. It also describes the development of the methods used to produce the map and the geologic evidence of prehistoric earthquakes and tsunamis on the coast.

These DOGAMI publications are now available over the counter, by mail, FAX, or phone from the Nature of the Northwest Information Center and the DOGAMI field offices in Baker City and Grants Pass (addresses on p. 50). Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment. □

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Separate price lists for open-file reports, tour guides, recreational gold mining information, and non-Departmental maps and reports will be mailed upon request.

GMS maps marked with an asterisk (*)are available in digital form on diskette (geological information only).

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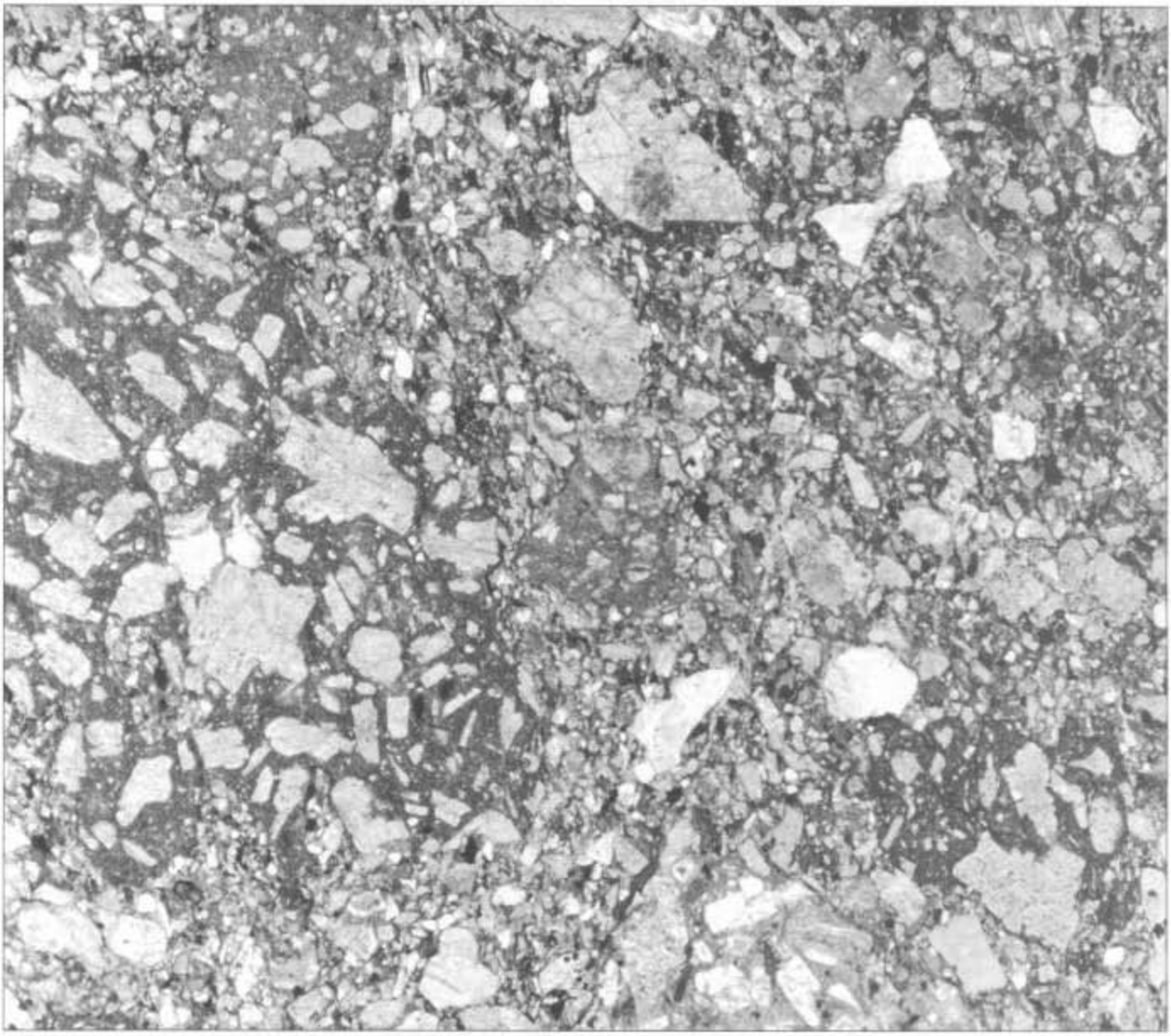

IN THIS ISSUE:

The Enigmatic Applegate Group of Southwestern Oregon: Age, Correlation, and Tectonic Affinity.
Geothermal Exploration in Oregon, 1994–1995.
Mined Land Reclamation Program Honors Outstanding Mine Operators of 1995.

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Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).

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Cover photo

Photomicrograph of a poorly sorted volcaniclastic litharenite from the Western Hayfork terrane near Applegate Dam, Jackson County. Hornblende separated from this rock has provided the first radiometric age constraints for the Applegate Group: around 173 million years. Largest distinguishable mineral fragment is approximately 3 mm in diameter. Related article on the Applegate Group begins on next page.

Educator Christensen joins DOGAMI Governing Board

Donald W. Christensen of Depoe Bay has been appointed by Governor John Kitzhaber and confirmed by the Oregon Senate for a four-year term as member of the Governing Board of the Oregon Department of Geology and Mineral Industries (DOGAMI). He succeeds Ronald K. Culbertson of Myrtle Creek, whose term expired June 30.

Donald W. Christensen

Don Christensen is a retired educator who holds degrees from the University of Oregon (B.S. and M.S.) and Oregon State University (Ed.D.). For 34 years, Christensen taught Communication Skill subjects, the last 30 at North Salem High School. He also served as volunteer public boating instructor in Salem and Lincoln City and as Marine Deputy Sheriff for Linn County. Since his retirement in 1990, he has been active as a volunteer in various civic organizations in Depoe Bay. He is currently serving as volunteer tutor in the Oregon Literacy Program at Taft High School.

Serving with Christensen on the three-member board are Jacqueline G. Haggerty of Enterprise, Chair, and John W. Stephens of Portland.

Geologists sought for National Parks

The National Park Service has announced a new Geologist-in-the-Parks program and seeks earth scientists to work with park staff in the areas of interpretation, education, resource management, and research. The positions, which are available for university faculty, graduate students, researchers, and teachers, run from two to six months in the summer and during off-seasons. Most offer housing and a nominal stipend. Some positions, open primarily to university professors, provide salary, sick leave, and vacation time.

Position announcements and application materials are available via the Internet at the Internet address http://www.aqd.nps.gov/grd. You may also contact Vera Smith, National Park Service, Geologic Resources Division, Denver Service Center, 12795 W. Alameda Parkway, Denver, Colo. 80225, phone (303) 969-2011, e-mail address geologic_resources_division@nps.gov. □

The enigmatic Applegate Group of southwestern Oregon: Age, correlation, and tectonic affinity

by Mary M. Donato, U.S. Geological Survey, Water Resources Division, 230 Collins Road, Boise, Idaho 83702, and Calvin G. Barnes and Susan L. Tomlinson, Department of Geosciences, Texas Tech University, Lubbock, Texas 79409

ABSTRACT

There are long-standing questions about the composition, age, and geologic affinities of the Applegate Group of the Klamath Mountains of southwestern Oregon. Our recent geologic mapping and geochemical and geochronologic studies indicate that the southernmost part of the Applegate Group consists of (1) greenschist- to amphibolite-facies metamorphosed ophiolitic mélange containing amphibolite, greenstone, argillite, quartzite, marble, and serpentinite and (2) overlying greenschist-facies volcanic graywacke, argillite, and minor volcanic conglomerate. On the basis of lithologic similarity, structural style, and geochemistry of the metabasites, we correlate the ophiolitic mélange unit with the rocks of the Late Triassic to Early Jurassic Rattlesnake Creek terrane of northern California. We correlate the structurally higher unit with the rocks of the Middle Jurassic Western Hayfork terrane, as evidenced by strong lithologic similarities, identical geochemical signatures, and Middle Jurassic $^{40}Ar/^{39}Ar$ isotopic ages of detrital igneous hornblende separated from volcanic sandstones. These data demonstrate that the Western Hayfork terrane extends from California into the Klamath Mountains of southern Oregon, at least as far north as about 42°15'N., for a total distance along strike of more than 200 km (125 mi). This work also provides an example of the utility of geochemical data in terrane interpretation and correlation.

INTRODUCTION

The Klamath Mountains geologic province extends northward from California into parts of Josephine, Jackson, Curry, and Douglas Counties in southwestern Oregon (Figure 1). Although significant headway has recently been made in understanding the geologic history and tectonic evolution of the Klamaths in California (e.g., Ernst, 1990; Saleeby and Busby-Spera, 1992; Hacker and others, 1993; Harper and others, 1994), progress toward this goal has been slower in the Oregon Klamaths. Indeed, "state-line" correlation problems between Oregon and California still exist (e.g., compare adjacent parts of Wagner and Saucedo's [1987] geologic map of the Weed, California, 1°×2° quadrangle with Smith and others' [1982] map of the Medford, Oregon, 1°×2° quadrangle). A thorough understanding of the geology of this region is important to an integrated tectonic synthesis of the Klamath Mountains province. Furthermore, a substantial number of Oregon's active mines and exploration sites occur in the Klamath Mountains (see Figure 2 *in* Hladky, 1993), and understanding the thermal, structural, and magmatic evolution of the region enhances our ability to identify favorable sites for future minerals exploration.

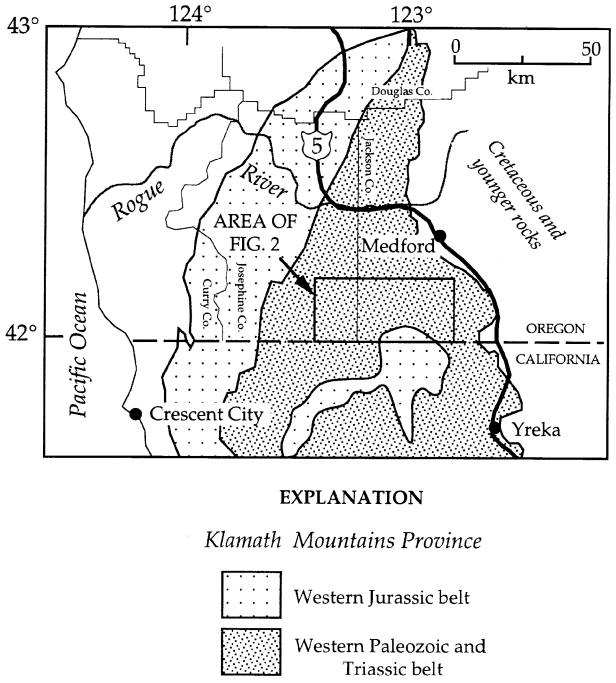

Figure 1. Map showing the northern part of the Klamath Mountains province in southwestern Oregon. Two of the four lithologic belts of Irwin (1966) occur in the Oregon Klamaths: the western Jurassic belt and the western Paleozoic and Triassic belt. In Oregon, the rocks composing the western Paleozoic and Triassic belt are known as the Applegate Group.

Two of Irwin's (1966) four lithotectonic belts of the Klamath Mountains province are present in Oregon: the western Jurassic belt and the western Paleozoic and Triassic belt (Figure 1). Some attempts have been made to place parts of Oregon's western Jurassic belt in a larger regional context (Blake and others, 1985), and the age and tectonic setting of these rocks are quite well known (Saleeby and Harper, 1993; Harper and others, 1994). However, only a limited number of recent studies have focused on mapping and interpretation of the western Paleozoic and Triassic belt rocks to the east (see, for example, Blair and others, 1981; Donato, 1991a,b, 1992a,b; Kays, 1992).

The rocks of the western Paleozoic and Triassic belt in southwestern Oregon are known as the Applegate Group,

an extensive unit that includes a wide variety of volcanic, sedimentary, and crystalline rocks. These rocks were originally described, but not named, by Diller (1914), who believed, on the basis of poorly preserved fossils in limestone, that they were Devonian and Carboniferous in age. The rocks were later named the Applegate Group by Wells and others (1949), who assigned them a Triassic(?) age. Later reconsideration of fossil collections caused the age of the Applegate to be revised to Late(?) Triassic (Wells and Peck, 1961). Still later revision of the age of the Applegate to Late(?) Triassic and Jurassic by Wardlaw and Jones (1979) was based on Jurassic radiolarians from the western part of the Applegate Group as reported by Irwin and others (1978). The presence in the Applegate of both Late Triassic conodonts and Jurassic radiolarians is difficult to interpret, however, because the fossil localities are widely scattered, and the areal extent of the units they represent is not well understood. Furthermore, until this study, no direct radiometric age determinations had been made on rocks in the low- and medium-grade parts of the Applegate. Thus, the uncertainty about the age of the Applegate has been exacerbated by the paucity of geochronologic and paleontological data for this region and the lack of an adequate regional context for the existing scant data. Nevertheless, Irwin (1994) tentatively correlated parts of the Applegate Group with two well-known terranes in the northern California Klamath Mountains: the Western Hayfork terrane and the Rattlesnake Creek terrane.

In an attempt to resolve long-standing questions about the age, composition, and makeup of the southern part of the Applegate Group, we have undertaken geologic mapping and related petrologic and geochronologic studies in three areas in the western Paleozoic and Triassic belt of southernmost Oregon: the Bolan Lake area, the Applegate Dam area, and the Observation Peak area (Figure 2). We confirm Irwin's (1994) interpretation that these rocks bear strong lithologic similarities to the Western Hayfork and Rattlesnake Creek terranes, and we present new geochemical data and the first direct radiometric age determinations of rocks in the Applegate Group to substantiate these correlations.

Our study (Figure 2) focuses on the western Paleozoic and Triassic belt between about 42°00'N. and 42°15'N., within parts of the Ruch, Talent, and Oregon Caves 15' quadrangles. We exclude both the Condrey Mountain Schist and the May Creek Schist from the Applegate Group. The Condrey Mountain Schist consists of actinolite schist and graphite schist and is exposed through a structural window in the Applegate Group that straddles the Oregon-California border (Figure 2). It is distinguished from rocks in the overlying plate by relatively high-pressure, low-temperature metamorphic assemblages and distinctive lithologies. Although its protolith and tectonic affinities are still controversial (Saleeby and Busby-Spera, 1992) and its history may well be linked with one or more terranes in the western Paleozoic and Triassic belt, it should not be included in the Applegate Group. The May Creek Schist (not shown in Figure 2) and underlying amphibolite, which occur in the northernmost part of the western Paleozoic and Triassic belt in Oregon, have already been stratigraphically excluded from the Applegate Group mainly on the basis of their middle-amphibolite-facies metamorphic

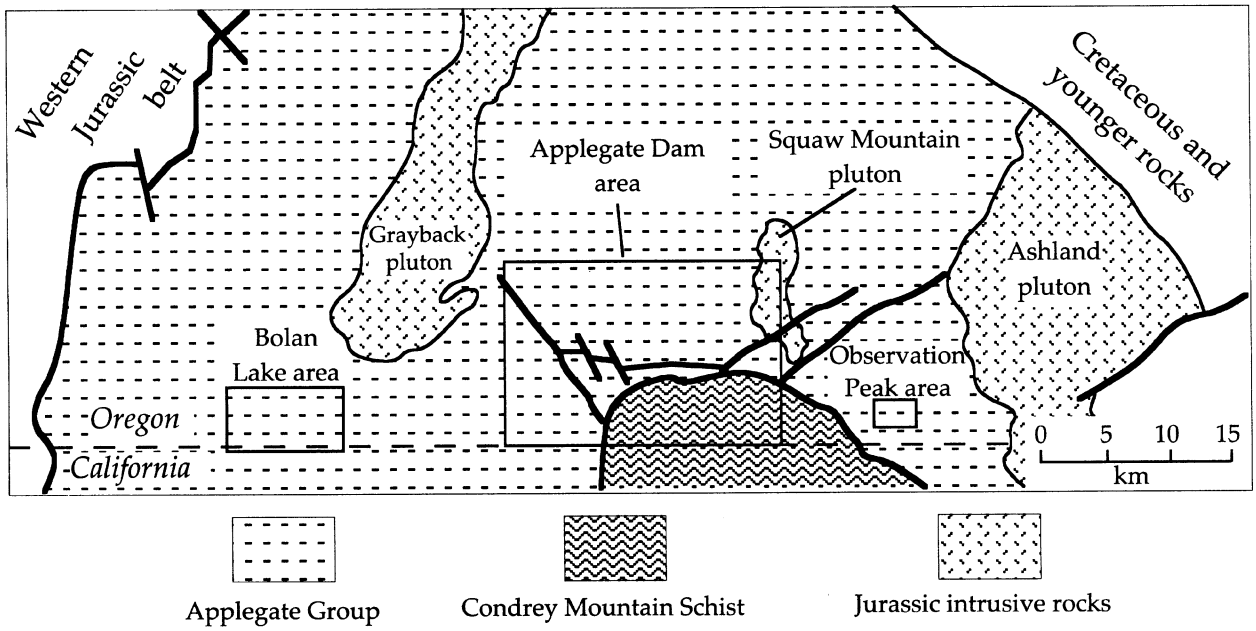

Figure 2. Index map of part of the Applegate Group, showing locations of detailed geologic mapping and investigation. Heavy lines indicate faults.

grade and their distinctive lithologies (Donato, 1991b). That assemblage was interpreted as remnants of a Middle Jurassic back-arc basin; its tectonostratigraphic terrane affinities are not certain.

WESTERN PALEOZOIC AND TRIASSIC BELT IN CALIFORNIA

The nomenclature of terranes of the western Paleozoic and Triassic belt in California has undergone considerable revision since Irwin's original (1966) work. In this report we use the terrane nomenclature for the western Paleozoic and Triassic belt outlined by Irwin (1972) and modified by Wright (1982) and Hacker and others (1993). From west to east, structurally lowest to highest, the terranes are the Rattlesnake Creek, Western Hayfork, Sawyers Bar, and Stuart Fork terranes. They are separated by east-dipping thrust faults. The two structurally lowest units, the Rattlesnake Creek and the Western Hayfork terranes, are of interest in this report.

The Rattlesnake Creek terrane in California consists of two parts: (1) a serpentinite-matrix mélange containing blocks of greenstone, amphibolite, metadiorite, harzburgite, metachert, siliciclastic metasedimentary rocks, and limestone, which is unconformably overlain by (2) a cover sequence of interbedded volcanic, hemipelagic, and clastic sedimentary rocks of Late Triassic to Early Jurassic age (Gray, 1985; Wright and Wyld, 1994). The mélange has a polygenetic and multistage origin, developing first in an oceanic fracture zone and subsequently evolving in a subduction zone or forearc environment. The overlying cover sequence, in contrast, clearly reflects a volcanic arc source. The entire sequence was deformed and metamorphosed during Middle to Late Jurassic accretion to the North American continental margin.

It is generally accepted that the Rattlesnake Creek terrane is the basement for the Middle Jurassic Western Hayfork arc terrane, discussed below. The metamorphic grade of the Rattlesnake Creek terrane is generally greenschist facies or lower in the southern Klamaths and increases northward to middle and upper amphibolite facies near the Condrey Mountain window, where these rocks are known as the Marble Mountain terrane. Norman and others (1983) showed that in the western part of the belt, the Rattlesnake Creek terrane extends at least as far north as the Oregon-California border.

The Western Hayfork terrane in California consists of a lower volcaniclastic unit and an upper mixed volcaniclastic, epiclastic, and hemipelagic unit (Wright and Fahan, 1988). A limestone breccia unit is present locally above the upper unit. The lower volcaniclastic unit contains interlayered volcanic breccias, crystal-lithic tuff, and argillite with minor lava, conglomerate, and radiolarian chert. At least 80 percent of these rocks are volcanic derived, but the presence of siliceous argillite and argillaceous clasts in conglomerate suggest a terrigenous source as well. The volcaniclastic rocks, which range from unstratified massive breccias to finely layered crystal-lithic tuffs, exhibit partial Bouma sequences that suggest deposition by turbidity currents. The upper mixed volcaniclastic, epiclastic, and hemipelagic unit is interpreted to rest depositionally on the lower unit. A characteristic of the upper unit is the presence of polylithologic conglomerate lenses that contain clasts of argillite, metachert, limestone, and quartzite, along with porphyritic volcanic rocks identical to those found in the underlying volcaniclastic unit. Also, radiolarian chert, argillite, chert-pebble sandstone, and tuffaceous argillite, crystal-lithic tuff, and rare quartzose sandstone are found. The age of the Western Hayfork terrane has been well established by Wright and Fahan (1988). They report conventional K-Ar ages on hornblendes from crystal tuffs and from a clast in volcanic breccia as ranging from 168 to 177 Ma. Hornblende gabbro bodies that intrude the terrane are about 169 and 171 Ma. The Western Hayfork rocks are interpreted by Wright and Fahan (1988) to represent a Middle Jurassic arc terrane constructed across older Klamath Mountains terranes, including the Rattlesnake Creek terrane. The arc was built above an east-dipping subduction zone that was part of a west-facing arc system.

WESTERN PALEOZOIC AND TRIASSIC BELT IN OREGON

Bolan Lake area

The Bolan Lake area (Figure 3) is underlain by two distinct tectonostratigraphic units, both of which were ascribed to the Applegate Group by Smith and others (1982). The structurally lower unit is an ophiolitic mélange, and the structurally higher unit is a sequence of weakly to strongly metamorphosed interbedded volcanogenic arenite and argillite. These units are separated by a probable thrust fault that was subsequently modified by high-angle faults.

On the west, north, and east sides of the area, the ophiolitic mélange unit consists of meter- to kilometer-scale blocks of metamorphosed serpentinite, gabbro, massive and pillowed lavas, volcaniclastic rocks (predominantly keratophyric), chert, siliceous argillite, and marble (Tomlinson, 1993). The lack of serpentinite matrix suggests that the unit is a block-on-block mélange. Some of the metasedimentary blocks contain well-bedded sequences that include chert, siliceous argillite, volcaniclastic rocks, and, rarely, ironstone. Late Triassic (Norian) conodonts have been recovered from marble blocks to the west of Bolan Lake (Irwin and others, 1983; J. Barrick, Texas Tech University, oral communication, 1985), and chert blocks collected northwest of our study area contain Middle Jurassic radiolarians (Smith and others, 1982).

Mélange rocks in the western and northern parts of the area were metamorphosed under regional greenschist-facies conditions after mélange formation. Typical assemblages in metabasic rocks are albite + chlorite + quartz ± actinolite. Relict andalusite in argillitic samples indicates metamorphic pressure less than about 4 kb (Bohlen and others, 1991). On the east side of the area (east of the

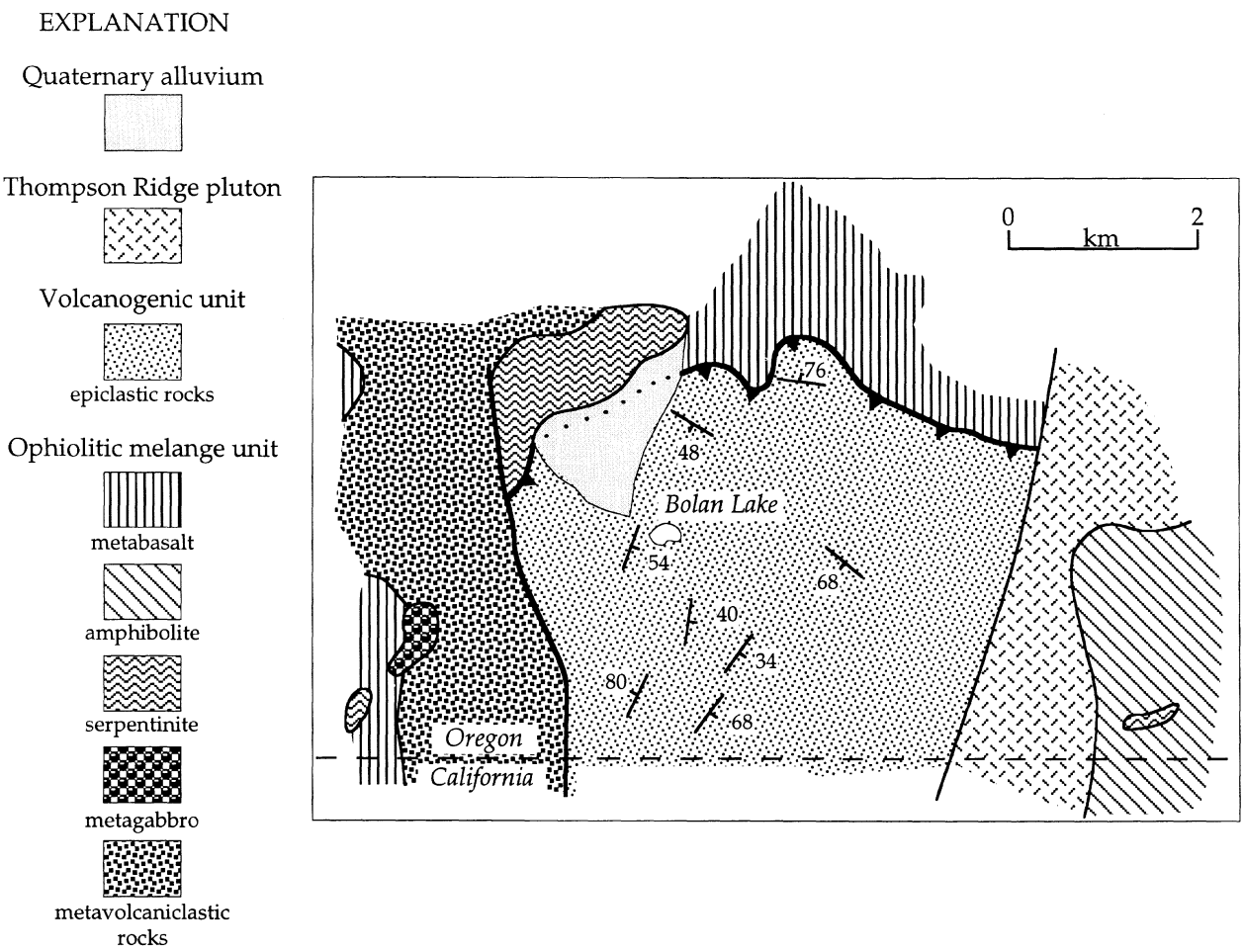

Figure 3. Simplified geologic map of the Bolan Lake area, after Tomlinson (1993). An east-west-trending probable thrust fault separates metabasalt of the ophiolitic mélange unit from epiclastic rocks of the volcanogenic unit. On the west, the contact between the mélange unit and the volcanogenic unit is a high-angle fault, whereas the eastern contact, inferred to be a high-angle fault, has been obliterated by the Thompson Ridge pluton.

Thompson Ridge pluton; Figure 3), the mélange was metamorphosed to amphibolite facies; metabasic rocks typically contain plagioclase + hornblende ± quartz.

The upper volcanogenic unit consists predominantly of well-bedded to massive, crystal-lithic meta-arenite interbedded with fine-grained, black to dark-gray, faintly bedded to massive argillite. Siliceous argillites that characterize fine-grained metasedimentary rocks in the ophiolitic mélange are absent in this unit. Conglomeratic channel deposits occur locally in the upper unit.

The arenite consists of volcanic rock fragments (predominantly augite andesite), rare diorite, plagioclase, augite, and brown hornblende. Argillitic rip-up clasts are sparse. Cobbles in the conglomeratic units are porphyritic andesite, with phenocrysts of plagioclase, augite, and brown hornblende. A conglomeratic channel deposit just above the base of the upper unit north of Bolan Lake contains, in addition to andesitic metavolcanic rocks, clasts of diabase, pumiceous siliceous metavolcanic rocks, plagiogranite, crushed metadiorite, marble fragments, and chlorite schist. These rocks are absent in the upper unit but are common in the lower mélange unit. We interpret their presence in this conglomerate to indicate a proximal source in the lower mélange unit, which probably had considerable topographic relief.

The upper unit was incipiently metamorphosed to greenschist-facies conditions, as exemplified by the assemblage albite + actinolite ± quartz ± chlorite in the volcanic clasts. No break in metamorphic grade was observed between the upper unit and rocks of the lower ophiolitic mélange unit to the west or north.

The low-angle contact (probable thrust fault) that separates the two units is inferred on the basis of solutions to three-point problems and on the observation that bedding in the upper unit is at high angles to the contact (Tomlinson, 1993). A prominent northwest-striking high-angle fault cuts the area, separating the mélange on the west side of the area from the upper unit (Figure 3); on the basis of topo-

graphic expression, it is thought to be a normal fault. On the east side of the upper unit, a second north-trending high-angle fault has been inferred on the basis of palinspastic removal of the Thompson Ridge pluton, the Sucker Creek pluton, and related dikes. In this reconstruction, greenschist-facies rocks of the upper unit would be juxtaposed against amphibolite-facies rocks of the lower unit. This abrupt increase in metamorphic grade suggests that a high-angle fault was present but was obliterated by intrusion of the Thompson Ridge pluton and related magmas.

Metamorphic rocks in the Bolan Lake area are cut by the Thompson Ridge pluton, which is the southernmost of a chain of three plutons: the Thompson Ridge, Sucker Creek, and Grayback plutons. Dike swarms occupy the area between these plutons. The plutons consist of medium- to coarse-grained gabbro, diorite, quartz diorite, tonalite, and rare olivine pyroxenite. Late-stage granitic dikes are widespread but in the Thompson Ridge pluton are common only in its northern part. In a later section we present new Pb-U isotopic ages for zircon from the Grayback pluton. Hornblende $^{40}Ar/^{39}Ar$ cooling ages for the Grayback (157.3 ± 1.4 Ma) and Thompson Ridge plutons (153.9 ± 0.8 and 154.1 ± 0.5 Ma) were previously reported by Hacker and others, 1995.

Applegate Dam area

Much of the previous geologic work in the Applegate Dam area near the Oregon-California border was carried out prior to the construction of the Applegate Dam, which was begun in 1976 and completed in 1980 by the U.S. Army Corps of Engineers. The construction has facilitated access to the area and has created new exposures of bedrock. An early study by Engelhardt (1966) focused on the contact between "Paleozoic schist" (now known as the Condrey Mountain Schist) and the overlying "Triassic rocks of the Applegate Group." Heinrich (1966) described the geologic relationships in the Kinney Mountain area and identified the lithologies as "argillite, feldspathic graywacke, and lithic graywacke, all of probable volcanic origin."

Recent geologic mapping at a scale of 1:24,000 in the vicinity of Applegate Dam has identified two dominant units in the western Paleozoic and Triassic belt: (1) a structurally lower mélange unit that consists of tectonically disrupted and regionally metamorphosed greenstone, amphibolite, quartzite, siliceous argillite, and metaserpentinite, and (2) an overlying unit composed predominantly of interbedded volcaniclastic sandstone and argillite (Figure 4). Together these units constitute the upper plate of a structural dome caused by the Tertiary uplift of the Condrey

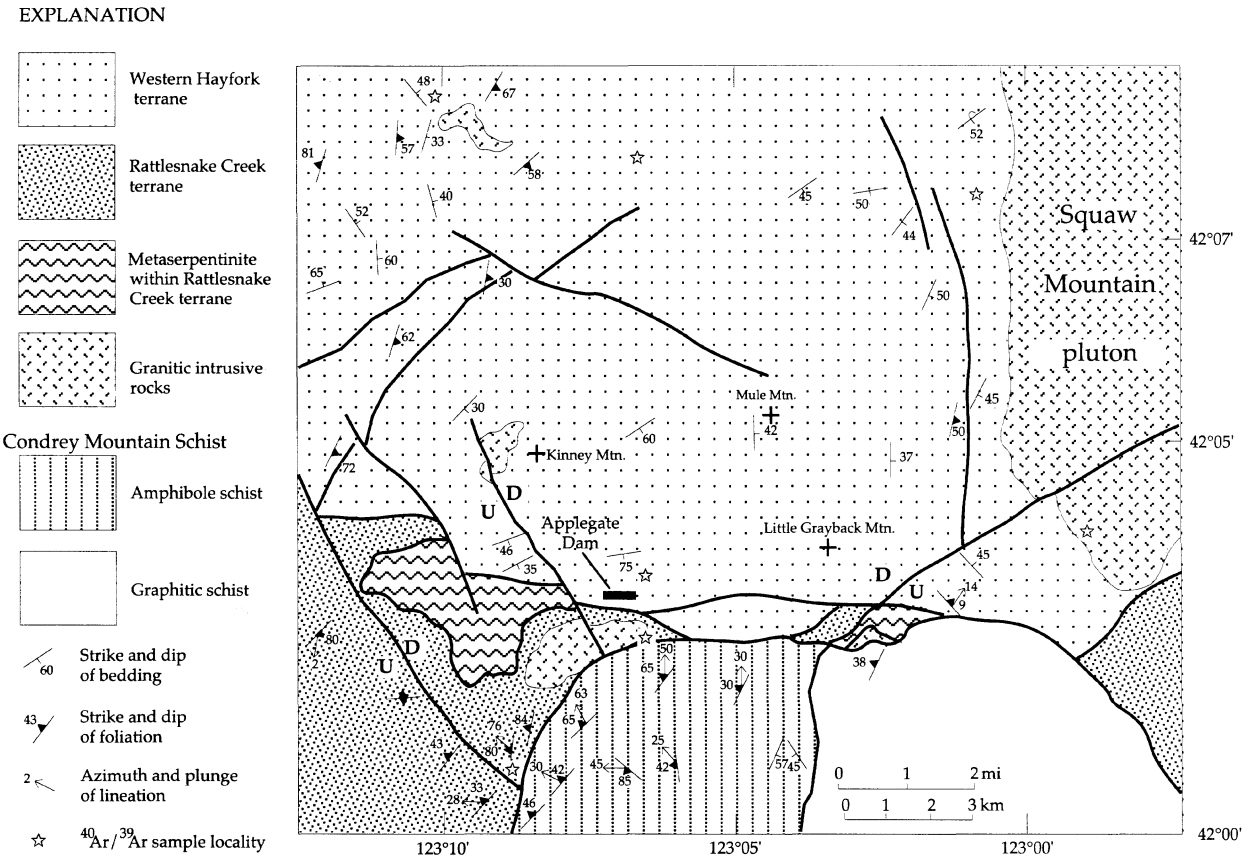

Figure 4. Simplified geologic map of the Applegate Dam area, after Donato (1992c, 1993). Heavy lines indicate faults.

Mountain Schist (Mortimer and Coleman, 1984). On the northern flank of the dome, the upper plate is dropped down in a broad, northward-widening graben bounded on the east and west by northeast- and northwest-trending high-angle fault systems, respectively (Figure 4). In the graben, volcaniclastic rocks predominate in the upper plate, whereas they are absent southeast and southwest of the graben. The graben-bounding faults are interpreted as part of a system of radial faults that accommodated doming (Donato, 1992c; 1993).

The lower mélange unit is lithologically diverse, consisting predominantly of amphibolite-facies metabasic rocks (greenstone and amphibole schist), metamorphosed siliceous argillite, quartzite, and metaserpentinite. Metachert, volcaniclastic metasedimentary rocks, semipelitic metasedimentary rocks, and marble are also present. Metavolcanic and metasedimentary rocks appear to be depositionally interlayered, but continuous units within the mélange are difficult to map due to rapid lithologic changes and poor exposure. Metaserpentinite bodies are fault bounded and were tectonically emplaced. Chlorite-talc-magnetite reaction rinds (blackwalls) are present at many serpentinite contacts and indicate post-emplacement metasomatism during regional metamorphism. Textures of serpentinite, including antigorite pseudomorphs of bladed olivine, and the presence of high-temperature metamorphic assemblages (e.g., olivine + enstatite + tremolite) indicate that the serpentinite and the surrounding metasedimentary and metavolcanic rocks underwent synchronous regional metamorphism. A moderate degree of deformation is indicated by the outcrop-scale structures in the mélange unit. Most rocks except serpentinites display well-developed metamorphic foliation, and locally this foliation has been isoclinally folded. Argillites locally display a strong lineation defined by intersection of compositional layering with cleavage, causing the rock to break into pencil-like rods.

The upper volcaniclastic unit consists predominantly of greenish-gray volcanogenic sandstone with lesser amounts of interbedded grayish-brown argillite and conglomerate. Some units exhibit graded beds and partial Bouma sequences, suggesting deposition by turbidity currents. Sandstone is well sorted, fine to coarse grained, and composed dominantly of plagioclase, clinopyroxene, brown to greenish-brown hornblende, and variable amounts of mafic to intermediate volcanic and volcaniclastic lithic fragments. Plagioclase and clinopyroxene are the dominant phenocrysts in volcanic lithic fragments, but hornblende also occurs. Interbedded subaqueous volcanic rocks, including weakly metamorphosed pillow breccia and hyaloclastite (glassy material is replaced by chlorite, but shardlike textures remain), constitute a minor part of the sequence (estimated <5 percent). They are interbedded with poorly sorted, altered volcanic arenites, volcanic conglomerate, and calcareous metasedimentary rocks. Arenites contain detrital quartz in rare cases. Rocks interpreted as hyaloclastite contain irregular subrounded fragments of amygdaloidal and porphyritic volcanic rock, which in rare cases contain calcite or chlorite pseudomorphs of olivine phenocrysts. Primary igneous hornblende and clinopyroxene are commonly partially or completely replaced by actinolite but are preserved locally. Weak flattening foliation and cleavage are locally developed, but in general the unit is relatively undeformed.

Observation Peak area

Amphibolite-facies ophiolitic mélange underlies the east and northeast flanks of the Condrey Mountain dome in the vicinity of Observation Peak (Figure 2). The upper volcaniclastic units that occur in the Bolan Lake and Applegate Dam areas do not occur south of the northeast-trending fault north of the Observation Peak area. Detailed mapping in the mélange (e.g., Hotz, 1979; Kays and Ferns, 1980; Thompson, 1988) shows that it consists of metaserpentinite, metagabbro, amphibolite, siliceous metasedimentary rocks, and marble. Metamorphic grade ranges from middle to upper amphibolite facies and increases toward the Condrey Mountain dome (Kays and Ferns, 1980; Rice and Ferns, 1980).

In the Observation Peak area, the intrusive and structural relationships among intrusive bodies provide chronological constraints on the relative timing of metamorphism, intrusion, and deformation (Thompson, 1988). Isotopic data for key intrusive bodies, presented below, allow absolute time frames to be established. The mélange is cut by dikes and small stocks of mafic through felsic compositions and by the much larger, composite, Ashland pluton. The earliest intrusions into the mélange were gabbros to quartz diorites. These were followed by mafic dikes and by coeval or slightly younger tonalitic dikes that are commonly hybrid (Thompson, 1988). All of these intrusions were deformed during amphibolite-grade metamorphism as shown by isoclinal folding of the amphibolitic and tonalitic dikes. However, the dikes lack the polyphase deformation displayed by amphibolitic blocks in the mélange; therefore, we interpret the timing of intrusion to be during the waning stages of regional metamorphism and deformation. The youngest dikes at Observation Peak are undeformed granodiorite. These dikes are compositionally similar to the nearby Ashland pluton (Thompson, 1988; Gribble and others, 1990) in that they display anomalously high concentrations of P_2O_5 and Y.

Lithologic similarities

Thus, in the Bolan Lake, Applegate Dam, and Observation Peak areas, we recognize the clear lithologic similarities in the lower mélange unit to the well-described serpentinite-matrix mélange of the Rattlesnake Creek terrane in California. Blocks of gabbro, marble, and metamorphosed serpentinite are particularly distinctive and are completely comparable to those found to the south. Likewise, the volcanogenic units in the Bolan Lake and Applegate Dam areas compare favorably with the lower volcani-

clastic unit of the Western Hayfork terrane in the southern Klamath Mountains. Note that in both Oregon and California the structural/stratigraphic juxtaposition of the two units is identical, further validating the comparison.

GEOCHRONOLOGIC STUDIES

Bolan Lake and Applegate Dam areas

Isotopic $^{40}Ar/^{39}Ar$ ages were determined for two hornblende separates from the mélange unit and two separates from metagraywackes within the volcaniclastic unit. In addition, cooling age determinations were made for hornblende from six samples of various intrusive rocks within the upper volcaniclastic unit in the Applegate Dam area, including the Squaw Mountain pluton (Figure 4; see sample RU–372–92 in Figure 5 and Table 1). For all but two of the determinations, incremental heating techniques were used; the remainder are total fusion experiments (see Table 1 for analytic details). The two samples from the mélange unit are (1) a hornblende-plagioclase schist from near the contact with the Condrey Mountain Schist and (2) a boudinaged hornblende metadiorite sill intruding metasedimentary rocks near Applegate Dam (Figure 4).

The two samples from the volcaniclastic unit (one each from the Bolan Lake and Applegate Dam areas) are weakly metamorphosed volcanic graywacke containing detrital igneous hornblende. The hornblende constitutes olive-green grains or grain fragments that optically appear to be essentially unaltered by regional metamorphism. A few grains are weakly zoned from reddish-brown cores to olive-green rims, features that indicate an igneous origin. The six intrusive rock samples are mainly taken from hornblende-phyric dikes and represent a variety of lithologies and apparent magmatic sources. All show clear cross-cutting relationships with the volcaniclastic rocks. The cooling ages obtained for all samples are summarized in Table 1; age spectra are shown in Figure 5.

Observation Peak area

Hornblende from an amphibolite-facies, weakly deformed, garnet-bearing quartz diorite (sample KM113A) that intrudes the mélange unit near Red Mountain gives a $^{40}Ar/^{39}Ar$ plateau age of 149 ± 2 Ma (Table 1). A single split of zircon (nonmagnetic, coarse fraction) gave discordant Pb-U ages (Table 2). We interpret this body to be among the relatively early generation of dioritic intrusive bodies. Its cooling age is similar to most hornblende cooling ages from the high-grade mélange in Oregon and California (Hacker and others, 1995), including the amphibolite from the mélange in the Applegate Dam area cited above.

Zircon was also separated from a folded, amphibolite-facies tonalitic dike at Observation Peak and from two samples from the Ashland pluton (Table 2). Two size fractions from the dike yielded discordant results, with $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages near 150 and 153 Ma and $^{207}Pb/^{206}Pb$ ages of 165 and 167 Ma. Zircon from the Ashland pluton yielded concordant ages of 152 and 151 Ma.

Discussion of geochronology

Applegate Dam/Bolan Lake

The ages obtained by the $^{40}Ar/^{39}Ar$ method represent the elapsed time since the hornblende cooled below its closure temperature for diffusion of Ar, estimated to be about 500° to 550°C (McDougall and Harrison, 1988). The results from the mélange unit are somewhat puzzling, because the cooling age of the deformed metadiorite (158 ± 1 Ma) appears to be significantly older than that of amphibolites (151 ± 2 and 149 ± 2 Ma) considered to be part of the metadiorite's "host rock." Why should an intrusive body in a regionally metamorphosed (metamorphosing) terrane appear to have cooled more quickly than its surrounding host rock? This apparent paradox has been observed previously in the Marble Mountain terrane of California. Most metamorphic rocks from this terrane yield hornblende $^{40}Ar/^{39}Ar$ cooling ages around 150 Ma (Donato, 1992d; Hacker and others, 1995), whereas many plutons interpreted as "syntectonic" or "posttectonic" give hornblende cooling ages older than 150 Ma (e.g., Wooley Creek pluton; Hacker and others, 1995). In many cases, U-Pb isotopic dating of zircon confirms that the pluton's igneous age is indeed older than 150 Ma. We have no satisfactory explanation for this disparity except to speculate that the systematics of argon diffusion in igneous hornblende are different from those in metamorphic hornblende, perhaps due to fundamental crystal-chemical differences in the two types of amphibole or to the effects of fluids on argon diffusion in magmatic vs. metamorphic situations.

In the case of detrital hornblende from the volcaniclastic unit, the $^{40}Ar/^{39}Ar$ age is interpreted as the cooling age of the volcanic rock source, since there is no petrographic evidence that the temperature of the volcanic graywacke exceeded hornblende closure temperature during regional metamorphism. Therefore, the sediments were probably derived from a Middle Jurassic volcanic source. Note that the age of each of the graywackes is based on the isotopic composition of several hundred simultaneously heated detrital grains; thus the ages represent the average isotopic composition of the grain population, not necessarily the age of any single grain. It is conceivable that the source terrane of the arenites contained multiple volcanic centers of widely different ages averaging 173 Ma. However, the composition of the volcanic sediments is remarkably uniform, and there is no petrographic, field, or compositional evidence to suggest that detritus was derived from multiple sources. Indeed, the presence of relatively fresh clinopyroxene, plagioclase, and hornblende grains in graywackes suggests derivation from nearby active volcanic centers. Therefore, we interpret the age to represent a uniform source terrane and the depositional age of the volcaniclastic unit to be no older than Middle Jurassic.

The cross-cutting intrusive rocks in the volcaniclastic unit provide a minimum age constraint for sediment deposition: the metasediments cannot be younger than the oldest cross-cutting dike. The oldest dike (175 ± 2 Ma), a weakly

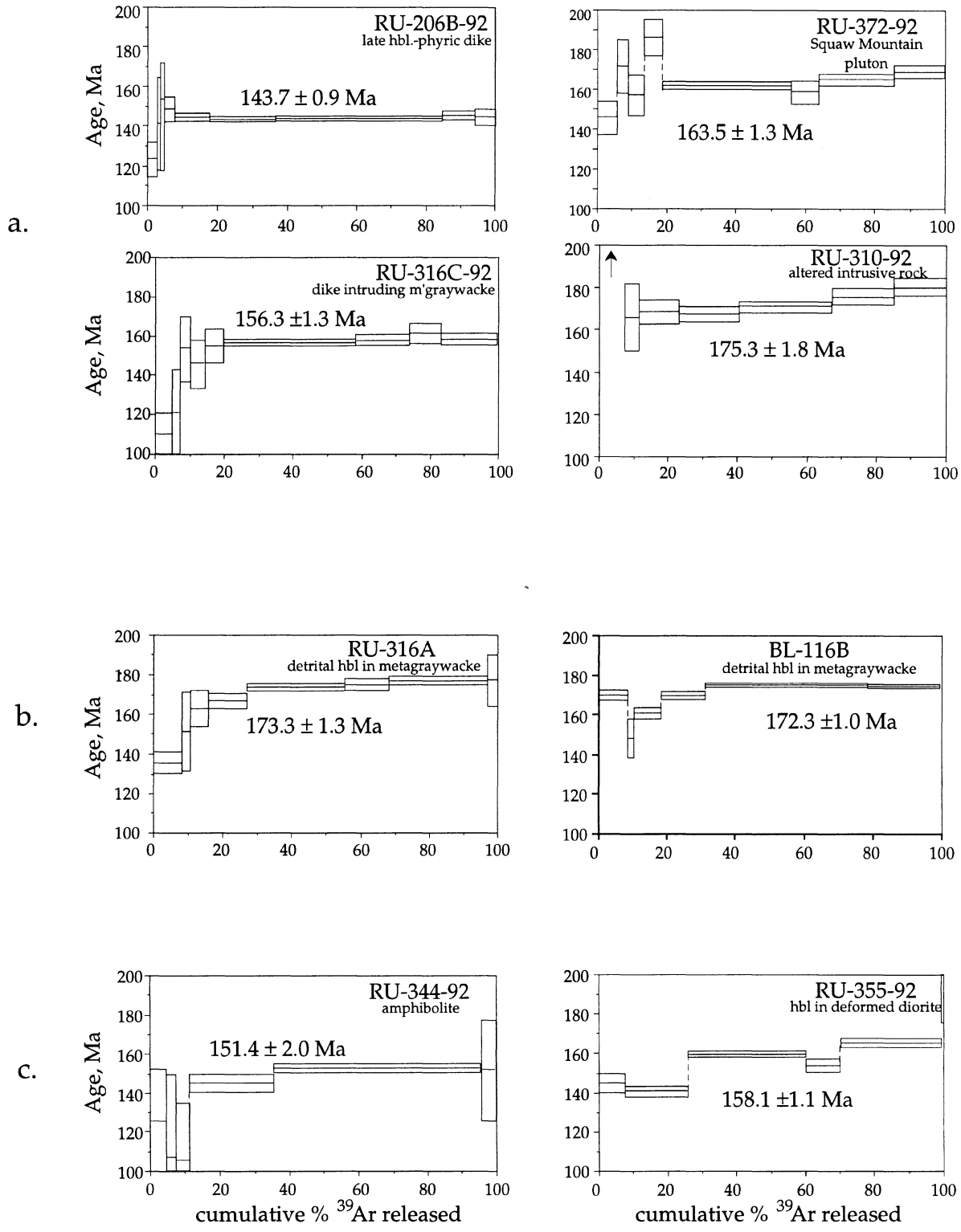

Figure 5. $^{40}Ar/^{39}Ar$ age spectra for samples from the Applegate Dam and Bolan Lake areas. Ages shown are weighted mean plateau ages based on 100 percent of the ^{39}Ar released (see Table 1 for details). a = Intrusive rocks in volcanogenic unit; b = volcaniclastic unit; c = ophiolitic mélange unit.

recrystallized and altered hornblende-plagioclase diorite body, contains olive-green hornblende that strongly resembles the detrital hornblende in the host arenites. Two other intrusive rocks gave Middle Jurassic cooling ages (171 ± 4 Ma and 167 ± 3 Ma), indicating that they are roughly synchronous with the Middle Jurassic volcanism that provided detrital hornblende to the arenites. Two other dikes are significantly younger (156 ± 1 Ma and 144 ± 1 Ma). The former is consistent with the cooling age of the nearby Grayback pluton, previously dated by $^{40}Ar/^{39}Ar$ (hornblende) at 156 ± 3 Ma (Hacker and others, 1995). Early Cretaceous plutonism in the region is recorded by the nearby Gold Hill pluton (K-Ar, hornblende; recalculated with new decay constants, 145 Ma; Hotz, 1971).

Together, the ages of the detrital hornblende (172 ± 1 and 173 ± 1 Ma) and the oldest cross-cutting dike (175 ± 2

Table 1. *Results of $^{40}Ar/^{39}Ar$ geochronologic investigations of hornblende separates from the Applegate Group, Oregon*

Sample no.	Area	Lat/Long	Method	Rock type	Mineral	No. of steps	$^{40}Ar_{rad}/^{39}Ar_K$	Irradiation parameter (J)	Age (Ma)
Volcaniclastic unit									
BL-116B	Bolan Lake	42°00'35"N. 123°27'00"W.	IH	Graywacke	Hornblende	8	10.622890	0.0093498	172 ± 1
RU-316A	Applegate Dam	42°03'12"N. 123°06'43"W.	IH	Graywacke	Olive-green hornblende	8	7.749319	0.01276	173 ± 1
Mélange unit									
RU-344	Applegate Dam	42°02'27"N. 123°07'09"W.	IH	Amphibolite	Green hornblende	7	6.777371	0.01255	151 ± 2
RU-355	Applegate Dam	42°00'46"N. 123°08'57"W.	IH	Metadiorite	Olive-green hornblende	6	7.339332	0.012386	158 ± 1
KM 113A	Observation Peak	42°03'05"N. 122°49'52"W.	IH	Garnet-bearing metadiorite	Green hornblende	8	7.245217	0.011887	149 ± 2
Intrusive rocks									
RU-65D	Applegate Dam	42°09'33"N. 123°10'16"W.	TF	Hornblende-phyric dike	Brown hornblende	1	10.894460	0.00913276	171 ± 4
RU-167A	Applegate Dam	42°08'38"N. 123°06'37"W.	TF	Hornblende-phyric dike	Green hornblende	1	10.785980	0.00898374	167 ± 3
RU-372-92 (Squaw Mountain pluton)	Applegate Dam	42°03'50"N. 122°59'03"W.	IH	Hornblende quartz diorite	Green hornblende	8	7.849332	0.012129	164 ± 1
RU-206B	Applegate Dam	42°11'47"N. 123°08'23"W.	IH	Hornblende-phyric dike	Brown hornblende	9	6.466213	0.012818	144 ± 1
RU-310	Applegate Dam	42°08'07"N. 123°00'57"W.	IH	Altered dioritic intrusive rock	Green hornblende	7	8.157141	0.0127137	175 ± 2
RU-316C	Applegate Dam	42°03'12"N. 123°06'43"W.	IH	Hornblende-phyric dike	Brown hornblende	10	6.995931	0.01267	156 ± 1

All analyses were performed at the U.S. Geological Survey, Menlo Park. Separated minerals were irradiated in the U.S. Geological Survey TRIGA reactor in Denver, Colorado (Dalrymple and others, 1981). Sample sizes ranged from approximately 200 to 250 mg. Grain size was 80 to 100 mesh in most cases. Irradiation flux was monitored by using the MMhb-1 hornblende and Taylor Creek sanidine standards. Incrementally-heated (IH) samples were heated in a resistance-furnace in one-hour intervals, using from 6 to 10 temperature steps. Total fusion (TF) experiments consisted of a single step in which the mineral was fused at 1,400°C. Temperatures were monitored by thermocouple and are accurate to about ±5°C. Isotopic analyses were made using a 60°-sector, 15.2-cm-radius, Nier-type mass spectrometer. Sample handling procedures and corrections for Ca- and K-derived isotopes are as described in Dalrymple and Lanphere (1971). For IH samples, age given is weighted mean plateau age based on 100 percent of ^{39}Ar released. Additional analytical data are available from the authors upon request.

Table 2. *Pb-U isotopic data for zircon from samples from the Observation Peak area*

Sample no.	Fraction[3]	Mass (mg)	^{238}U (ppm)	^{206}Pb (ppm)	Observed ratios $\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	Ages (Ma) $\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	Rock type
OP 8[1]	F, NM	5.3	2,864	58.37	6,386	0.05170	0.1373	150	151	167	Folded metatonalite
OP 8[1]	C, NM	3.3	2,479	51.25	4,158	0.05290	0.1272	152	153	165	Folded metatonalite
KM113A[2]	C, NM	1.0	2,272	48.8	10,204	0.05082	0.1901	158.0	158.0	169±17	Garnet metadiorite, Wrangle Gap

[1] Analyses performed by Nick Walker, mineral separates by Mark Helper, University of Texas at Austin.

[2] Analyses performed by R. Tosdal, U.S. Geological Survey, Menlo Park, California. Common Pb correction assumed to be 208 : 207: 206 : 204 = 38.622 : 15.610 : 18.927 : 1.

[3] F = fine, C = coarse, NM = nonmagnetic.

Ma) provide a narrow constraint on the age of the volcaniclastic unit. The data suggest that volcanism, sedimentation, and dike intrusion were essentially synchronous at around 173 Ma.

Observation Peak

Isotopic $^{40}Ar/^{39}Ar$ ages of hornblende from the Ashland pluton (Hotz, 1971; Hacker and others, 1995) indicate that the pluton and, by implication, its host rocks, cooled below about 500°C soon after its emplacement at approximately 152 Ma. If the distinctive undeformed P_2O_5- and Y-rich granodioritic dikes at Observation Peak are related to Ashland pluton magmatism, then the deformed tonalitic dikes must predate the Ashland pluton. This suggests that the ~166-Ma Pb-Pb age of the deformed tonalite (Table 2, sample OP 8) is a closer approximation to the igneous age than its Pb-U ages are. This interpretation is consistent with previously determined ages for regional high-grade metamorphism of >161 Ma, which were determined on the basis of U-Pb data for cross-cutting plutons (e.g., Barnes and others, 1986; Coleman and others, 1988).

GEOCHEMICAL STUDIES

We have drawn upon our extensive database of geochemical data for metavolcanic and volcaniclastic rocks of the western Paleozoic and Triassic belt (Barnes and others, 1995) for criteria to evaluate possible correlatives to the distinctive units of the Applegate Group described above. Because volcanogenic sedimentary rocks in the Western Hayfork terrane bear strong lithologic similarities to parts of the Applegate, they are obvious candidates for comparison. Likewise, we compare the chemical characteristics of known samples of the Rattlesnake Creek terrane to those of the mélange unit.

Most lavas and volcanic cobbles from the known Western Hayfork terrane in California have a relatively narrow range of SiO_2 (47–55 percent) and FeO*/MgO (0.7–1.3 percent) (Barnes and others, 1995). Mafic samples are characterized by Zr and P_2O_5 enrichment at approximately constant Ti (Figure 6a). Their generally low Ti/Zr and low FeO*/MgO indicate a calc-alkaline affinity. Multielement diagrams ("spidergrams") presented in Figure 7a show that Western Hayfork samples are enriched in light rare-earth elements (LREE) and are depleted in Nb, characteristics typical of calc-alkaline arc rocks. In Figure 8a, the Western Hayfork data fall mainly in the island arc basalt field (IAB) in the Ti-V plot of Shervais (1982).

Most metabasaltic rocks of the Rattlesnake Creek terrane fall in the compositional range between 46 percent to 55 percent SiO_2 (Wyld and Wright, 1988; Wright and Wyld, 1994; Barnes and others, 1995) . They display a wide range of FeO*/MgO values and, as a result, plot in both tholeiitic and calc-alkaline fields. However, the wide range and generally high values of TiO_2 in these rocks (Figure 6b) are typical of tholeiitic rather than calc-alkaline suites. This characteristic is particularly useful in distinguishing Rattlesnake Creek metabasites from Western Hayfork metabasites. Wright and Wyld (1994) showed that mélange blocks in the Rattlesnake Creek terrane are geochemically similar to ocean floor basalt (both enriched mid-ocean ridge basalt [EMORB] and normal mid-ocean ridge basalt [NMORB]). Rare blocks of ocean island basalt composition are also present; this feature appears to be a characteristic of the Rattlesnake Creek terrane mélange (Wright and Wyld, 1994). Multielement diagrams for the Rattlesnake Creek rocks are generally similar to those for the Western Hayfork samples but lack the characteristic LREE enrichment pattern (Figure 7b), a subtle, but effective distinction. Figure 8b displays the dispersion of the Rattlesnake Creek metabasites in the MORB field of Shervais' (1982) Ti-V diagram.

We plotted samples of metabasite from the volcaniclastic and mélange units of the Applegate Group along with the

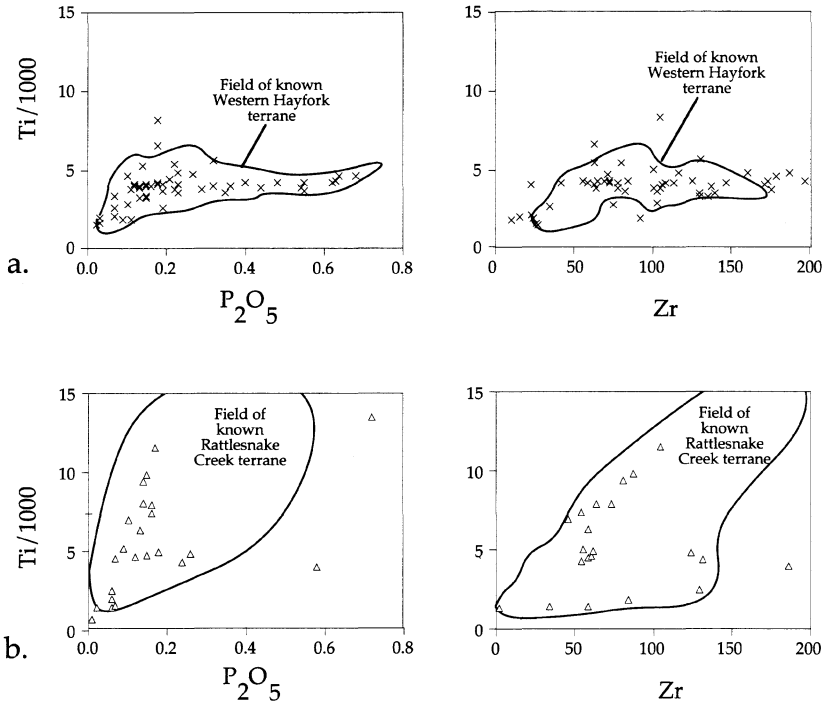

Figure 6. Ti/1000 plotted as a function of P_2O_5 and Zr. × = volcaniclastic rocks of Applegate Group; triangle = Applegate Group mélange. Note relatively narrow range of TiO_2 values for the Western Hayfork terrane (a) compared with that of the Rattlesnake Creek terrane (b). The volcaniclastic and mélange units of the Applegate Group compare favorably with the rocks forming the Western Hayfork and Rattlesnake Creek terranes, respectively.

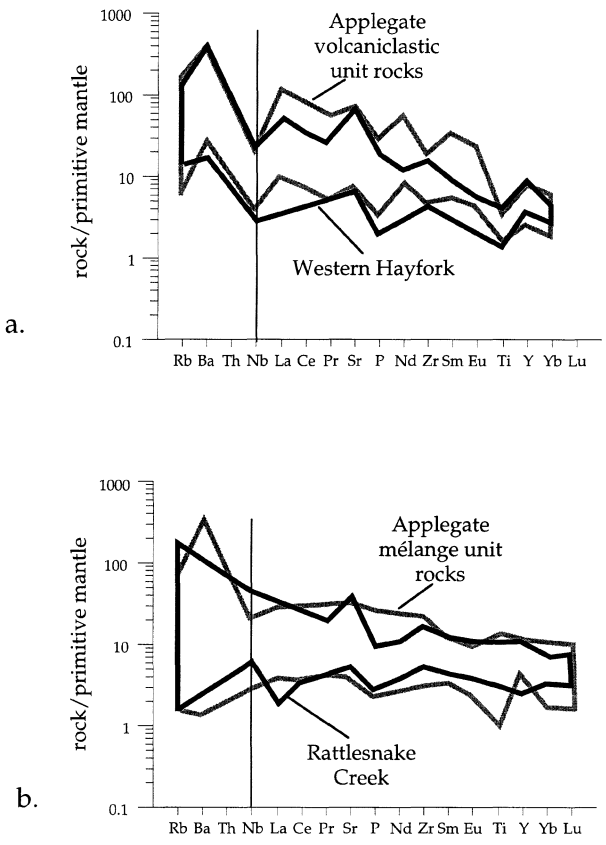

Figure 7. Multielement diagrams ("spidergrams") comparing generalized range of patterns of Western Hayfork (a) and Rattlesnake Creek (b) terranes with patterns for volcaniclastic and mélange units of Applegate Group, respectively. Note contrast between Western Hayfork and Rattlesnake Creek patterns in the range of LREE (light rare earth elements, La through Nd): enrichment pattern in the former vs. relatively flat pattern in the latter. Normalization factors from Sun and McDonough (1989).

fields for the Western Hayfork and Rattlesnake Creek terranes, respectively, in Figures 6 through 8. Overall, these diagrams highlight the remarkable geochemical similarities between the Applegate metabasites and the corresponding rocks of the California terranes and strongly support our proposed correlations. In Figure 6, there is nearly complete overlap of the corresponding terranes in terms of P_2O_5 and Zr vs. Ti. Multielement diagrams (Figure 7) demonstrate that volcaniclastic samples from both Oregon and California display the characteristic LREE-enriched pattern of the Western Hayfork terrane. Likewise, metabasites from the mélange unit show the distinct flat REE pattern characteristic of ocean floor basalts and compare favorably with patterns of known Rattlesnake Creek samples from California (Figure 7). The Ti-V tectonic discrimination diagram (Figure 8) not only highlights the differences between the Rattlesnake Creek terrane and the Western Hayfork terrane in terms of tectonic regime but also reinforces the proposed similarities between the Oregon units and the corresponding California terranes.

CONCLUSIONS

We recognize virtually identical lithologic assemblages in the Bolan Lake and Applegate Dam areas in southwestern Oregon: a structurally lower mélange unit overlain by a more stratigraphically coherent volcaniclastic unit. In the Observation Peak area, only the mélange unit occurs. The striking lithologic and structural similarities of these units to the Rattlesnake Creek and Western Hayfork terranes in northern California suggest that the Oregon terranes are their northward extensions. Two additional lines of evidence support such a correlation: age equivalence and compositional identity.

The application of geologic mapping, geochemical analysis, and $^{40}Ar/^{39}Ar$ geochronology has allowed us to begin to unravel the mystery of the origin and affiliation of the Applegate Group. In addition, we have demonstrated the usefulness of geochemical (especially trace-element) analysis in terrane correlation and interpretation. We now know that parts of this region are related to an important arc and forearc system recognized in California, which dominated the continental margin during Late Triassic through Middle Jurassic time. Additional studies of this nature may eventually allow the entire Applegate Group to be fully understood in a larger geologic and tectonic context. Perhaps our goal should be to gain a complete enough understanding that the catch-all name "Applegate Group" may be abandoned in favor of more meaningful appellations.

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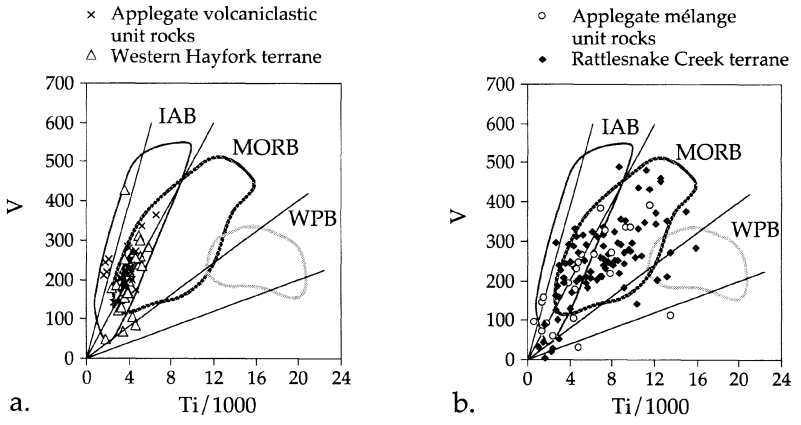

Figure 8. Tectonic discrimination diagram for Western Hayfork (a) and Rattlesnake Creek (b) terranes from Oregon and California. IAB = Island arc basalt; MORB = mid-ocean ridge basalt; WPB = within-plate basalt. Outlines identify basalt fields defined by Shervais (1982).

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DOGAMI PUBLICATIONS

Released June 7, 1996:

***Mist Gas Field Map*, 1996 edition.** Released as Open-File Report O–96–01. Price $8.

The map of the Mist Gas Field in Columbia and Clatsop Counties has been updated through December 1995 and is accompanied by a production summary for 1993–1995.

The *Mist Gas Field Map* is also available in digital form (price $25). It is offered in three different CAD formats (.DGN, .DWG, and .DXF), all on one 3½–inch high-density diskette formatted for DOS, for use by different software systems.

The cumulative report of past production at the Mist Gas Field during 1979–1992 is available in a separate 40-page release: *Mist Gas Field Production Figures, 1979–1992*, Open-File Report O–94–06, (price $5).

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Geothermal exploration in Oregon, 1994–1995

by Dennis L. Olmstead, Oregon Department of Geology and Mineral Industries

ABSTRACT

No geothermal lease sales were held in 1994 or 1995. However, geothermal drilling activity occurred in two areas of the state: Newberry Caldera Known Geothermal Resource Area (KGRA) and Vale Hot Springs KGRA. A Final Environmental Impact Statement was issued by the USDA Forest Service for the Newberry Caldera project site proposed by CE Exploration. At the state level, the Energy Facility Siting Council received an application for a site certificate for the Newberry Caldera project and issued the site certificate. In addition, preparation started on an environmental impact statement for a development drilling and power plant project in the Alvord KGRA.

New publications and inventories appeared dealing with direct use of geothermal resources. The Department of Geology and Mineral Industries (DOGAMI) issued a report on the low- and moderate-temperature resources in the state (Black, 1994a,c). The U.S. Geological Survey conducted studies in the state and published results of some of the work. The 1995 legislature passed a bill raising the level of bonding for geothermal drilling in the state.

LEASING

No geothermal lease sales were held during 1994 or 1995, although there were some filings for acreage. Table 1 shows leasing trends for these years. In November 1994 and September 1995, suspension was lifted on 68,673 leased acres that were suspended in 1990 due to formulation of the Newberry National Volcanic Monument legislation and disputes over some lease interests in the Federal geothermal unit. A total of 1,200 acres remains suspended.

DIRECT-USE PROJECTS

The Oregon Institute of Technology (OIT) in Klamath Falls recently completed a resource study of the 10 western states as a participant in the Low-Temperature Resource Assessment project funded by the U.S. Department of Energy, Geothermal Division. The purpose was to update the inventory of the nation's low- and moderate-temperature geothermal resources in 10 western states and to encourage development of these resources. The inventory of geothermal resources for Oregon is discussed in the DOGAMI section below.

OIT contributed by studying the location of low- and moderate-temperature resource sites relative to potential direct-use sites. A potential direct-use site was considered to be a town or other end user with significant consumption of electricity that could be offset through the use of geothermal resources in a geothermal heating district. Potential resource sites were considered if (1) fluid temperatures were greater than 10°C above the mean ambient air temperature, (2) sites were located outside environmentally sensitive areas such as National Monuments, or (3) sites had fluid temperatures greater than 50°C and were located within 8 km (5 mi) of a community. The following Oregon communities were recommended as potential direct-use sites: Paisley, Lakeview, Burns/Hines, La Grande, and Vale. OIT developed geothermal energy/cost evaluation software to determine the cost of geothermally supplied heat to these communities in comparison with the cost of heat supplied by natural gas.

In Klamath Falls, the municipal heating district has expanded over the past two years to include a theater, two large churches, a bank, laundry, and an 80,000-ft^2 retirement center added to the hospital. Altogether 27 buildings are now on the district system. Three blocks of sidewalks in downtown Klamath Falls have recently been fitted with pipes for snow melting, and a total of eight blocks is planned.

The Liskey Farms Greenhouses operation outside Klamath Falls now sends warm-water effluent to a tropical-fish farmer who provides fish to a national market. All effluent in Klamath Falls is now injected; no surface discharge is allowed.

OIT now monitors the freshwater aquifer under the campus and nearby hosptial via six monitor wells to detect im-

Table 1. *Geothermal leases in Oregon, cumulative, 1994 and 1995*

Types of leases	Numbers	Acres
Cumulative leases issued since 1974:		
Noncompetitive, USFS	385	718,867
Noncompetitive, USBLM	274	415,778
KGRA (competitive), USFS	18	18,388
KGRA (competitive), USBLM	66	125,740
Cumulative leases relinquished since 1974:		
Noncompetitive, USFS	320	653,256
Noncompetitive, USBLM	273	415,156
KGRA (competitive), USFS	8	11,925
KGRA (competitive), USBLM	61	114,080
Federal leases issued during 1994, USFS	0	0
Federal leases issued during 1994, USBLM	0	0
Federal leases closed 1994, USFS and BLM	50	81,354
Federal leases issued during 1995, USFS	0	0
Federal leases issued during 1995, USBLM	0	0
Federal leases closed 1995, USFS and BLM	21	30,992
Federal leases in effect 12/31/95:		
Noncompetitive, USFS	65	65,610
Noncompetitive, USBLM	1	623
KGRA (competitive), USFS	10	6,463
KGRA (competitive), USBLM	5	11,660
Federal income from geothermal leases, estimated 1994		$105,000
Federal income from geothermal leases, estimated 1995		$100,000

pacts on the aquifer by geothermal withdrawal and injection. Reports of the monitoring, including water levels and temperatures, go to the Oregon Water Resources Department (WRD).

OREGON DEPARTMENT OF ENERGY (ODOE)

On June 28, 1995, ODOE received application for an energy facility site certificate from CE Exploration for a proposed geothermal plant on the west flank of Newberry volcano in Deschutes County. The application is for a 33-megawatt (MW) plant adjacent to Newberry National Volcanic Monument. The review process was carried out, including agency reviews and a request to CE Exploration for additional information. The application was found to be complete on December 5, 1995. ODOE issued a draft proposed order and held a public hearing in January 1996. The Energy Facility Siting Council (EFSC) met and prepared a draft proposed order and subsequently a proposed order. No one asked for a further hearing, and by the deadline in February 1996 there were no objections to the issuance of a site certificate, which was then approved in March.

OREGON WATER RESOURCE DEPARTMENT (WRD)

The WRD has jurisdiction over low-temperature geothermal resources, primarily including groundwater used for its thermal characteristics and encountered in wells with bottom-hole temperatures less than 250°F and depth of less than 2,000 ft. This program is presently not very active due to the switch in Klamath Falls to injection of spent geothermal effluent. Over the past two years, only a few requests for low-temperature geothermal injection wells have been received. Staff from the City of Klamath Falls, the WRD, and the Department of Environmental Quality met recently in an effort to streamline the process of obtaining the necessary permits for reinjection.

Table 2. *Geothermal permits and drilling activity in Oregon, 1994-1995*

Permit no.	Operator, well, API number	Location	Status, proposed or actual total depth
G-157	Trans-Pacific Geothermal ESI-A-S Alt 36-045-90008	NE¼ sec. 33 T. 18 S., R. 45 E. Malheur County	Drilled and abandoned, TD not released.
G-174	CE Exploration 88-21 TCH 36-017-90035	SE¼ sec. 21 T. 21 S., R. 12 E. Deschutes County	Permitted, drilled and suspended, TD not released.
G-175	CE Exploration 76-15 TCH 36-017-90036	SE¼ sec. 15 T. 21 S., R. 12 E. Deschutes County	Permitted, drilled and suspended, TD not released.
G-176	CE Exploration 76-15 36-017-90037	SE¼ sec. 15 T. 21 S., R. 12 E. Deschutes County	Permitted, PTD 9,000 ft.
G-177	CE Exploration 47-15 36-017-90038	SW¼ sec. 15 T. 21 S., R. 12 E. Deschutes County	Permitted, PTD 9,000 ft.
G-178	CE Exploration 23-22 36-017-90039	NW¼ sec. 22 T. 21 S., R. 12 E. Deschutes County	Permitted, drilled and suspended, TD not released.
G-179	CE Exploration 86-21 36-017-90040	SE¼ sec. 21 T. 21 S., R. 12 E. Deschutes County	Permitted, drilled and suspended, TD not released.
G-180	Trans-Pacific Geothermal TGC 61-10 36-045-90025	NW¼ sec. 10 T. 19 S., R. 45 E. Malheur County	Permitted, drilled and abandoned, TD not released.
G-181	Trans-Pacific Geothermal TGC 24-11 36-045-90026	NW¼ sec. 11 T. 19 S., R. 45 E. Malheur County	Permitted, expired and canceled.
G-182	CE Exploration 88-21 36-017-90041	SE¼ sec. 21 T. 21 S., R. 12 E. Deschutes County	Permitted, drilled and suspended, TD not released.

Note: An additional 17 permits to Trans-Pacific Geothermal from 1993 in the Vale area expired and were canceled in 1994. Call DOGAMI for details.

OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES (DOGAMI)

In 1991, the U.S. Department of Energy began an evaluation of low- and moderate-temperature geothermal resources. Participants included state agencies and universities in 10 western states, including Oregon. The Low-Temperature Geothermal Database for Oregon (Black, 1994a,c) is completed and contains nearly 2,200 wells and springs (mostly 20° to 100°C), with over 200 thermal areas identified. This more than doubles the number of known geothermal resource sites in the state over the previous inventory done in 1982. Spring and well data include site name, county, type (spring or well), township, range, section, subsection, latitude, longitude, temperature (°C), depth in meters, flow rate in liters per minute, and remarks. Chemical data include site name, county, type (spring or well), location, date of analysis, pH, conductivity, total dissolved solids, major cations, major anions, and a reference code. Geothermal fluids are used by business, homeowners, and government for heating over 625 buildings. In addition, greenhouses, aquaculture sites and industrial processes are also using geothermal heat. This database, published as DOGAMI Open-File Report O–94–09 (one 3½-in. disk), is available from DOGAMI for $12.00.

REGULATORY ACTIONS AND INDUSTRY DRILLING ACTIVITIES

Regulatory activity and drilling during 1994 and 1995 showed a big increase, with action in three geographic areas of the state: Newberry volcano, Vale, and Pueblo Valley. These areas are all Federal leases in KGRAs.

At Newberry volcano, CE Exploration drilled two temperature-gradient wells and three production wells to test the resource on the west flank of the volcano, outside the Newberry National Volcanic Monument. No results have been released by the operator on this project. An environmental impact study (EIS) for field development and power plant is already in place (see USDA Forest Service section of this report) as well as a state site certificate for

the construction of the project.

At Vale, TransPacific Geothermal drilled 17 shallow temperature-gradient holes (in 1993) and followed them with two deep exploration wells that were subsequently abandoned. Results have not been released, but the company has relinquished all its Federal leases in the area.

Anadarko Petroleum has had no new activity in the past two years but still has three suspended wells in its Pueblo Valley project area in Harney County. An EIS is in preparation for the development and power plant at the site.

Table 2 shows active state geothermal permits during 1994 and 1995, including wells permitted and drilling activity that occurred.

U.S. GEOLOGICAL SURVEY (USGS)

USGS work in Oregon included publication of work done on samples from a deep well in the Breitenbush area (Bargar, 1994). Work still in progress at this time includes mapping and resource assessment of the Crater Lake area. This will be published soon in the USGS Open-File Report series. Other ongoing work includes hydrothermal alteration studies on Newberry volcano rocks and microprobe analyses of zeolites from well and outcrop samples in the Cascades.

Dave Sherrod has contributed to the Eastside Ecosystem project conducted by the Bureau of Land Management (BLM). This project will produce a document for the management of National Forests of the interior Columbia River basin. Sherrod prepared a geothermal assessment for BLM as part of a minerals and energy resource assessment of the Malheur and Jordan resource areas of the Malheur District. The geothermal assessment showed areas favorable or permissive for the presence of geothermal resources.

In addition, Patrick Muffler has produced and contributed to several technical papers of note dealing with the Cascade Range (Muffler and Guffanti, 1995; Muffler and Tamanyu, 1995; Guffanti and Muffler, 1995).

USDA FOREST SERVICE (USFS)

Over the past two years, the USFS has produced environmental documents on the Newberry volcano area in preparation for geothermal development. One set of documents makes up the Newberry National Volcanic Monument Comprehensive Management Plan. The purpose was to meet the legislative requirement to develop a management plan for the Monument and adjacent areas. These documents describe five alternatives for managing the Monument and adjacent special areas. The study covered 16 issues ranging from recreation to vegetation, fire, air and water quality, roads, and wildlife. The "Record of Decision" part of the document includes the choice of alternative to be used and reasons for the decision.

The USFS, with cooperation from BLM, and the Bonneville Power Administration, has also prepared an EIS for the Newberry Geothermal Pilot Project. This is in response to a proposal from CE Exploration Company of Portland to build and operate a geothermal pilot project and supporting facilities to generate 33 MW of power. The project would consist of four phases: exploration, development, utilization, and decommissioning. The project would be located on the west flank of Newberry volcano on Federal geothermal leases. The EIS analyzes three alternatives for this project. An alternative was chosen that provided siting flexibility to make the most efficient use of the geothermal resources while minimizing negative impact on the environment. The Final EIS was issued in July 1994.

U.S. BUREAU OF LAND MANAGEMENT (BLM)

BLM has continued its monitoring of Borax Lake since 1991. Measurements include three deep and two shallow temperature probes, a pressure probe, and air-temperature, solar-radiation, wind, rain, and relative-humidity monitoring. The agency has also provided funding to support the USGS seismic recording station near Andrews, Harney County, to detect seismicity that may affect geothermal features such as hot springs.

The agency funded a study by Michael Cummings of Portland State University of the geothermal aquifer in the Alvord basin. Strontium isotopic ratios, Sr and Rb concentrations, and major- and trace-element compositions of fluids and rocks were determined for three hot spring areas and cold groundwater in stratigraphic units that are exposed in the ranges surrounding the Alvord basin. Analyses were conducted to better constrain the location and possible extent of the geothermal aquifer in the Alvord basin.

MHA Environmental Consulting, Inc., conducted four scoping meetings in preparation for the EIS to be written for the Anadarko Petroleum project in the Pueblo Valley on BLM leases. Meetings were held in Fields, Burns, Bend, and Portland. The EIS will be prepared for the proposed geothermal production and construction of a 22.9 MW power plant.

The agency also cooperated in writing the EIS for the Newberry Geothermal Pilot Project (see Forest Service section above).

BONNEVILLE POWER ADMINISTRATION (BPA)

The CE Exploration project on the west flank of Newberry volcano was in part the result of the BPA Geothermal Pilot Project Program. The agency also cooperated in writing the EIS for the project (see Forest Service section above). Through special agreements for buying power, the BPA encouraged the project with its 1991 Request for Proposals. CE Exploration, in partnership with the Eugene Water and Electric Board, was one of the successful applicants.

RELATED ACTIVITIES

The 1995 regular session of the Oregon Legislature passed house bill HB 2101, authorizing an increase in the bonding levels for drilling geothermal wells in the state. The bond levels are now the same as for oil and gas wells:

*(Continued on page 98—**Geothermal**)*

Outstanding mine operators rewarded by MLR

The Mined Land Reclamation Program of the Oregon Department of Geology and Mineral Industries announced the 1995 Reclamation Award winners at the Oregon Concrete and Aggregate Producers Association (OCAPA) annual meeting on May 18, 1996.

The awards recognize mine operators who go beyond the basic requirements of planning, operation, and reclamation at Oregon mine sites. The awards program continues to increase awareness within the industry to insure that reclamation is successful and is achieved in a cost-effective manner. Innovative mine management can reduce off-site impacts as well as operating costs.

The Reclamation Award winners were selected by a committee consisting of Dorian Kuper, David Newton Associates, Portland; Bill Levens, LTM (Rogue Aggregates), Medford; David Haight, Oregon Department of Fish and Wildlife, Central Point; Diane Stone, Linn County Planning Department, Albany; and Cole Gardiner, Oregon Trout, Portland.

The 1995 award winners are as follows:

Special Recognition Award: The winner of this first annual award was Bracelin-Yeager Excavation and Trucking, Inc., Coos Bay.

This award category was created new this year—a cash award to be presented to the "best of the best" and made up entirely of contributions from industry suppliers, consultants, and publications. The recipient company is encouraged to present this award to those of its individual members most responsible for the work recognized as outstanding. The cash award was made possible through the generous donations of David J. Newton Associates, Inc., Portland; North Santiam Paving Company, Stayton; Pape Brothers, Inc., Eugene; Richard and Ann Hensley, Medford; and Valley Equipment Company, Salem.

Outstanding Operator: Canby Sand and Gravel, Div. of Parker NW Paving, Oregon City, Robert Traverso, operator.

The award is in recognition of the work performed to protect the Molalla River and adjacent salmon spawning beds, the development of wildlife habitat, and the opening-up of reclaimed areas to public access. The hauling of material from the pit to the processing area by off-road trucks across a temporary river crossing was eliminated. The operator installed a free-standing, enclosed conveyor system that reduced dust, noise, and adverse impacts to the river. Complex wildlife habitat was created at reclaimed mine ponds. Considerable effort went into creating irregular shorelines, islands, and gentle slopes that allowed sensitive wetland plant communities to establish. The reclaimed ponds were stocked with fish and opened to public access.

Outstanding Reclamation: Bracelin-Yeager Excavating and Trucking, Inc., Coos Bay, Keith Yeager, operator.

This site north of Port Orford was nominated because of the aggressive and innovative approach to reclamation the operator brought to this site. Bracelin-Yeager acquired this existing mine site in the mid-1980s and immediately began reclamation that soon reduced the area of disturbance by one-half. By practicing concurrent reclamation (performing reclamation on mined-out areas as mining expands to new ground) and by utilizing "live top-soiling" (stripping soil from new ground and immediately placing this soil on a final-grade mined-out area), agricultural lands are taken out of production for only 12 months. The company was also recognized for its past record of reclamation above and beyond the requirements of its permit.

Outstanding Operator of a Small Mine: Teague Mineral Products, Adrian, Glen Teague, operator.

Teague Mineral Products operates numerous small bentonite mine sites in eastern Oregon, where reclamation is always a challenge because of normally scarce precipitation. Bentonitic soils make the job all the harder due to poor nutrient availability, excessive water retention, and structural damage from swelling and shrinking. Glen Teague decided to use the materials at hand for revegetation efforts. Seeds from native plants on adjacent undisturbed ground were collected by hand and dried. The seeds were germinated and then hand-planted during final reclamation. During site inspections in 1995, the ultimate goal of reclamation was realized: mined areas could not be distinguished from adjacent unmined areas.

Good Neighbor: LTM-Rogue Aggregates, Inc., Medford, William Levens, operator.

Rogue Aggregates, Inc., completed mining on a 40-acre parcel adjacent to the Rogue River in 1994. Rather than completing reclamation—which would have decreased the company's bonding liability and operational expenses—Rogue Aggregates joined the School Reform Act program with Crater High School and created a living laboratory for high school students. This program creates a "school within a school" that focuses studies in one discipline. Students learn about water quality, wildlife habitats, surveying, natural and introduced vegetation, planning, and real-world economics. This program is an excellent example of how a mine operator can get involved in the community by providing a learning experience in business and the environment. Rogue Aggregates has demonstrated that mining can take place in an environmentally sound manner, meeting growing resource needs while developing a stable and productive wetland area.

Outstanding Reclamation after Exploration: Malheur Mining, Huntington, Alan Glaser, operator.

Exploration for gold at this site 17 mi north of Ontario, Oregon, was completed in 1994. The operator reduced the need for exploration roads on steep slopes by using a track-mounted drill rig for fifty separate drill holes. Grading of

drill pads and exploration roads, coupled with successful revegetation efforts, once again realized the pinnacle of mine reclamation: During a 1995 on-site visit, many of the exploration road cuts across the hillside were not readily apparent even to the trained eye.

Outstanding Reclamation by a Government Agency: Oregon Department of Transportation, Region IV, Bend, Randy Davis and Russ Frost, Geology Section.

The award was given for a sand and gravel extraction site located 1 mi south of Service Creek, adjacent to the John Day River which, in this area, is designated a scenic waterway. The project was completed and the site was reclaimed in 1992. Since then, this site has been inundated by flood waters three separate years. After a 30-year flood event in 1992, a 2- to 3-ft depression was scoured out of the extraction area and acted as a fish trap when the water receded. The area was repaired and survived high water in 1995 and 1996. The site has been developed into a boat launch and day-use area with restrooms and picnic tables. The agency was also commended for exemplary interagency cooperation at Federal, State, and local levels. □

Oldest fossil turtle discovered

On May 14, a prehistoric turtle carapace was collected from rocks of the Oregon Coast Range between Scottsburg and Reedsport by William Orr, professor of geology at the University of Oregon and curator of the Department of Geological Sciences Condon Museum of Geology, and his wife Elizabeth Orr. The turtle remains include the plastron or bottom plates of the shell along with about 30 percent of the top of the carapace. The animal was originally about 18 in. long and is a distant relative of the modern green turtle. Bits and pieces of limb bones and appendages were also recovered but not the skull.

This turtle represents the oldest marine (salt-water) turtle found to date in Oregon. It was entombed in what is known as the Tyee Formation, deposited during the Eocene Epoch roughly 48–50 million years ago in a huge delta structure that was developing along the proto-Oregon coast area under semitropical conditions.

Recent floods in the vicinity of the site had exposed the fossil-bearing rock. Gary J. Schulz and John H. Seward of the Oregon Department of Forestry made the discovery during a road building project on land of Roseburg Forest Products, Inc. Together with Carey Weatherly of Roseburg Forest Products, Inc., they directed the Orrs to the collecting site and assisted in the extraction and retrieval of some 80 lb of fossil-bearing rock. The specimens are presently undergoing preparation in the Condon Museum laboratory. The preparation includes impregnating the bone with a rapidly hardening polyvinyl-acetate plastic solution and removing much of the rock matrix.

—University of Oregon news release

ABSTRACTS OF PAPERS

The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.

Paleotsunami barrier-overtopping: One piece of the puzzle, by Curt Peterson, Portland State University, and George Priest, Oregon Department of Geology and Mineral Industries.

Geologic records of barrier-overtopping by paleotsunamis provide independent measures of Cascadia tsunami hazard. Several different types of information are available from such records including (a) minimum inundation distance, (b) minimum runup elevation, and (c) minimum number of surge events. Differential overtopping might also permit some estimates of maximum runup height (corresponding to along-shore variation in barrier height) and event scaling (corresponding to selective overtopping of different events).

Interpretations of paleotsunami runup from these records require constraints on paleobarrier morphology, stability, and elevation. The barriers can be divided into hard and soft features, depending on their relative stability. The uplifted marine terraces at Crescent City, California, provide an example of a hard barrier that has been repeatedly overtopped by Cascadia tsunamis. Beach cobble-ridges in Seaside, Oregon, partly diverted paleotsunami surges and represent barriers of intermediate stability. Dune flats and ridges of bay mouths and bay spits are examples of soft barriers, as are tidal-channel levees in back-bay environments. The stability of soft barriers, such as barrier-spit dune fields, must be evaluated by mapping and radiocarbon dating of paleosols in the barrier stratigraphy. For example, late Holocene forest paleosols were mapped and dated in the Salishan spit of Siletz Bay, Oregon, and in the Long Beach Peninsula (Loomis Lake area), Washington, to establish the paleosurface elevations of these barriers during prehistoric Cascadia tsunami events. A new dune-coring tool now permits rapid mapping of dune paleosurfaces.

Paleotsunami barrier-overtopping must be discriminated from other flood-depositional events by indicators of surge origin. For example, marine-surge overtopping is demonstrated by deposit isopachs, grain mineralogy, grain-size distribution, and microfossil indicators of direct marine-surge origin. Back-barrier bay marsh sites permit testing of correspondence between overtopping surges and paleosubsidence (near-field tsunami origin). Interdune ponds and terrace wetlands provide more numerous sites for preserving barrier-overtopping records, but care needs to be taken

to discriminate between chronic storm surge and catastrophic tsunami surge origins. The two types of sites should be used together to maximize the runup-record coverage along the coast. Most importantly, the paleotsunami barrier-overtopping records are required to verify/calibrate numerical models of tsunami excitation and runup in the historically aseismic Cascadia margin. Credible runup-model results can then be extrapolated well beyond the geologic record sites to predict site-specific tsunami inundation hazards.

Sand and gravel mine operators donated sand, equipment, and time to fight February floods

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

Without the assistance of aggregate producers, many of the volunteer efforts to protect homes and businesses would not have been possible. DOGAMI would like to recognize the following firms for their commitment and service to the community:

Burch West, Inc., McMinnville
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Viesko Redi-Mix, Inc., Keizer
Walling Sand and Gravel, Salem □

BOOK REVIEW

Geology of the Pacific Northwest, by Elizabeth L. and William N. Orr. McGraw-Hill, 8½11 in., paper, 1996, 409 p., $40.

Reviewed by Allen F. Agnew, Courtesy Professor, Oregon State University, Corvallis, Oregon 97331

This book presents a welcome new look at the landscapes described a quarter of a century ago by Bates McKee (*Cascadia*, 1972). Spiced with 96 excellent maps and block diagrams, it tells the geologic story of the Pacific Northwest in great detail.

The expansion of the authors' purview from their *Geology of Oregon* (Orr, Orr, and Baldwin, 1992) to include British Columbia, Washington, and Idaho has enabled them to relate subduction to features we see today in the landscape and to help us understand how they got that way. The book "explains the role of tectonic plate movements and particularly accretionary events as fundamental processes of northwest geologic history," dividing the region into a dozen physiographic areas ("superterranes") and almost 50 smaller terranes and geologic provinces.

The 10 chapters beyond the first, introductory one can be read separately but are also organized in a sequence that can be read continuously as a skein of geologic evolution.

Like earlier "double-Orr" books, this one contains many excellent sketches of fossils—but they are not keyed to the text, so the reader is left to wonder if they are included merely as decorations. Such wondering is compounded by the 200 photographs, which are likewise not keyed to the text—and which the printer did a poor job of reproducing.

Thus the reader must search from the text back through the illustrations to find one that shows the feature discussed in the text. It is a strenuous job of reading and searching—but then, the geologic story of the Pacific Northwest is both complex and challenging to decipher, so it is also a rewarding job.

Unfortunately, the introductory chapter, called "Cornerstones of Pacific Northwest Geology," is rather harder to digest than the rest of the book. On 20 pages, with roughly half of that space filled with illustrations, the Orrs have attempted to equip the reader not only with sufficient basic knowledge of geologic science and the elements of plate-tectonic processes but also with the complex plate-tectonic setting and development of the Pacific Northwest region.

This reader felt that the result is an unsatisfying taste of what the following 10 chapters say in detail—and say very well. The complicated matters of subduction and plate movement, together with the resulting volcanism and sedimentation in basins through 550 million years of geologic time, cannot be easily or lucidly told in only 20 pages of introduction (of which only half is the printed word). Thus the introduction threatens to confuse the reader. Furthermore, the text throws numerous geographic names at the reader—which caused even this reviewer (who likes to

think he is familiar with the Pacific Northwest) to hurry to various reference books for enlightenment.

Readers are thus well advised in not getting bogged down in the introductory chapter; in fact, they may leap over it completely and begin the book with the second chapter, called "Omineca-Intermontane British Columbia."

The Orrs have included a very full bibliography at the end, and each chapter ends with a selection from that bibliography as "Additional Readings." Seventy percent of the references are less than 15 years old; only 15 percent are pre-1970, and those older ones are classics. An illustrated glossary of 230 terms, a complete index, and a metric conversion chart round out this volume.

One of the pleasant surprises in the book is the attention paid in almost every chapter to geologic hazards and mineral production as results of the overall geologic history.

Nevertheless, the worth of the book as a whole overwhelms my criticisms. In sum, then, *Geology of the Pacific Northwest* is an excellent book and one that we geologists—and many other folks—will be happy to own and to use. □

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*(**Geothermal**—Continued from page 94)*

for prospect wells (< 2,000 ft deep) bonds are not less than $10,000 per well or $50,000 for a blanket bond, and for geothermal wells (≥ 2,000 ft deep) bonds are not less than $25,000 per well or $150,000 for a blanket bond. Geothermal operators active in the state supported the legislation.

The Pacific Northwest Section of the Geothermal Resources Council has been relatively inactive the past two years and has been invited to merge with the Northwest Energy Association, a regional organization composed of members in the energy field from both private and public sectors. No decision has yet been made on the proposed merger.

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Poster shows 1996 Willamette Valley Flood

The Nature of the Northwest Information Center offers a new poster entitled *Willamette Valley Flood of 1996*. It shows two images of the northern Willamette Valley. The size of each image is 8.516 in., and the scale is 1 in. = 6 mi.

One image shows the "before" condition from EOSAT photos taken in the summers of 1992 and 1994; the other EOSAT image, taken on February 11, 1996, shows the extent of the flooding. The EOSAT satellite images are reproduced in "false color" on the poster, showing intensity of vegetation by shades of green and of bare land by shades of pink, while water bodies stand out in darker purplish-blue. The price of the poster is $25 plus $3 for shipping. □

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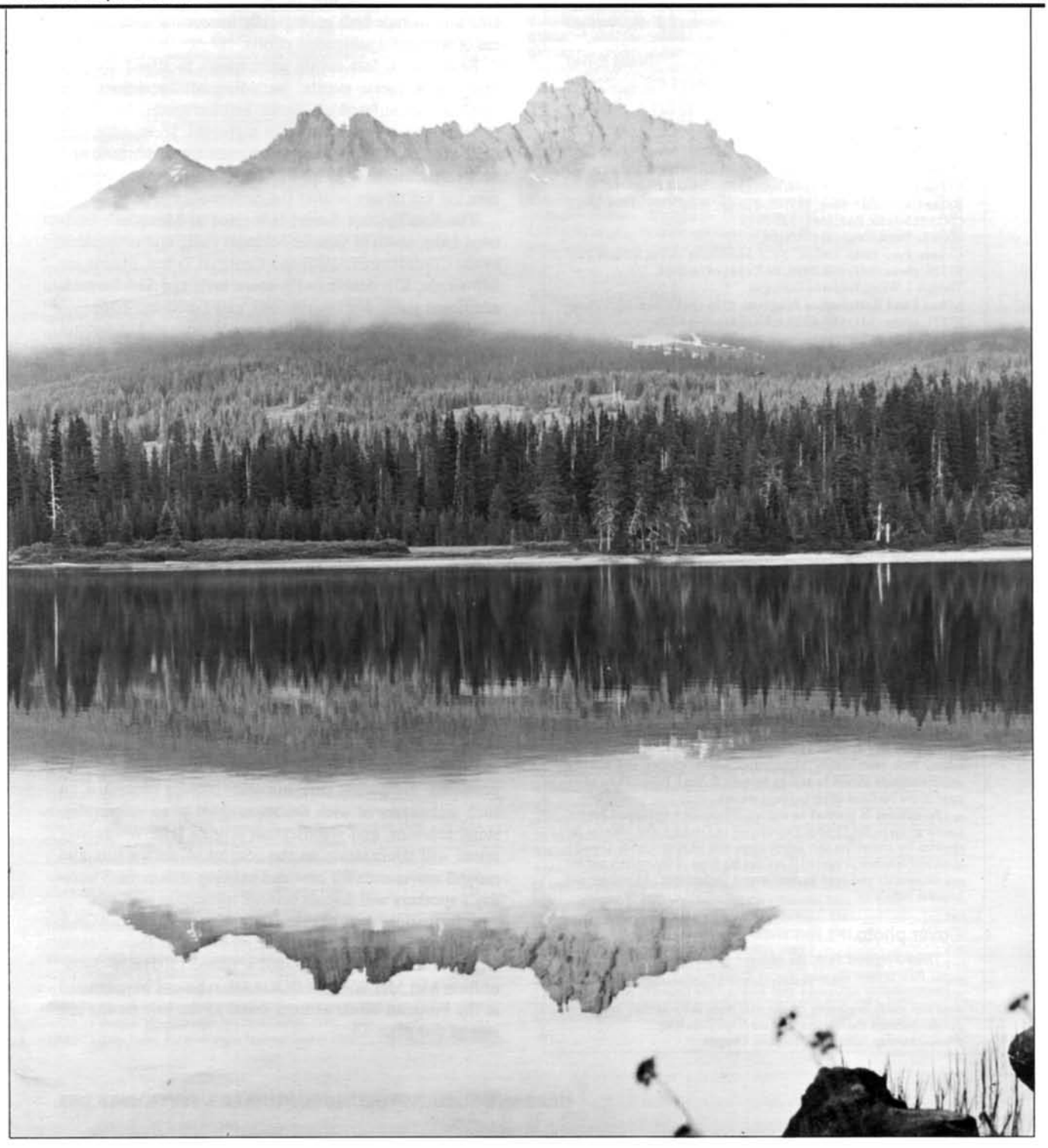

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Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).

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Cover photo

Three Fingered Jack, the remains of a Pleistocene shield volcano. View is from the west, across Santiam Lake. This is one of the relatively young volcanoes that built up the Cascade Range. The field trip guide beginning on the next page leads largely along the border between the Western and the High Cascades.
Photo courtesy John Blum, Stayton, Oregon.

Seismic Policy Council to meet in Montana

The Western States Seismic Policy Council (WSSPC) will hold its annual conference September 18–21, 1996, at the KwaTaqNuk Resort in Polson, Montana. Conference sessions will deal with such topics as geology, earthquake information, preparedness, mitigation, emergency response, and partnerships. A field excursion will offer visits to interesting seismic sites in the Mission fault area of Montana and include both geologically interesting sites and areas of successful mitigation efforts.

Registration fees entitle participants to attend all programs and social events, including all breakfasts and lunches, the conference banquet, and the vendor fair. Early registration by August 1 is $210 registrant, $60 spouse, $25 field excursion; later registration costs are $240, $90, and $25, respectively. WSSPC will invoice prior to the conference but not on site or after the conference.

The KwaTaqNuk Resort is located at Montana's Flathead Lake, south of Glacier National Park, and is operated by the Confederated Salish and Kootenai Tribes. Rooms are $48 single, $78 double (+4% room tax), and $10 for each additional guest. For reservations, call 1-800-882-6363.

WSSPC receives conference registrations at 121 Second Street, 4th Floor, San Francisco, CA 94105, or by FAX at (415) 974-1747, or e-mail at wsspc@wsspc.org. The organization can also be reached by phone at (415) 974-6422 or at its web site http://www.wsspc.org. □

Engineering seminar focuses on ground stabilization and seismic mitigation

The Oregon Section Geotechnical Group of the American Society of Civil Engineers (ASCE) and the Oregon Department of Geology and Mineral Industries (DOGAMI) will sponsor a seminar that presents the latest information on ground stabilization techniques and methods for reducing seismic liquefaction hazards. The seminar will be held Wednesday and Thursday, November 6–7, 1996, in Room 120C of the Oregon Building (State Office Building), 800 NE Oregon Street, in Portland.

Speakers from industry and universities will present a mix of recent research and its applications to engineering problems. Numerous case histories will be presented on such techniques as wick drains, tangent piles, micropiles, stone columns, and stabilization pilings. The Wednesday series will concentrate on the control of settlements and ground movements for new and existing structures. Thursday's speakers will discuss seismic mitigation methods.

Information is available from Wesley Spang, AGRA Earth and Environmental, Inc., 7477 SW Tech Center Drive, Portland, OR 97223–8025, phone (503) 639–3400; or from Mei Mei Wang of DOGAMI, who can be contacted at the Portland office address listed in the box on the left side of this page. □

Water, rocks, and woods—A field excursion to examine the geology, hydrology, and geothermal resources in the Clackamas, North Santiam, and McKenzie River drainages, Cascade Range, Oregon

by David R. Sherrod[1], Steven E. Ingebritsen[2], John M. Curless[3], Terry E.C. Keith[4], Nancy M. Diaz[5], Thomas G. DeRoo[5], and Sanford L. Hurlocker[6]

This guide was prepared for a field trip conducted in conjunction with the Geological Society of America Penrose Conference on fluid-volcano interactions, Kahneeta, Oregon, October 4–9, 1992. Please be sure to read the warning notice at the end of this article.

INTRODUCTION

Water—how it travels through the upper crust, how it is heated in hydrothermal systems above or adjacent to magma, how it alters rocks to reduce their permeability, how it disperses geothermal energy in the near-surface environment—these aspects of hydrogeology are the focus of a field trip that preceded an October 1992 Penrose Conference on fluid-volcano interactions. In the Cascade Range, some uncertainty still surrounds the interpretation of heat-flow data. Anomalously high heat measured in the Western Cascades may be an expression of localized deep magmatic heat sources. Or it may result from groundwater flowing laterally, flushing heat westward from beneath Quaternary volcanoes in the High Cascades to reappear at diffuse sites in the Western Cascades or locally focused at hot springs in valley floors there. These divergent interpretations have important implications for the assessment of geothermal resource potential and exploration of geothermal energy.

This trip covers 140 road miles from Estacada in Clackamas County to Santiam Pass on the border between Linn and Jefferson Counties (Figure 1). The route traverses parts of the Western and High Cascades, and the text emphasizes how topographic contrasts between these physiographic subprovinces influence hydrogeologic conditions in the Cascade Range. Two major hot-spring systems, Austin and Breitenbush, are passed along the route (Stops 2 and 4); and a third system, the McKenzie River group of springs, is discussed at the last stop (Stop 6). Driving time is about 3¾ hr plus the time taken for the 6 or 7 stops, which can vary from 30 minutes to 60 minutes each.

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[6] U.S. Forest Service, Willamette National Forest, HC–73, Box 320, Mill City, OR 97360.

MILEAGE DESCRIPTION

(interval/cumulative)

0.0/0.0 Estacada, traffic signal at intersection of Broadway Street and State Highway 224. **Follow Highway 224**. Route leads southeast towards Ripplebrook Ranger Station (Figure 1). The first 5.7 mi are along new road alignment built since 1985.

3.9/3.9 **Optional stop,** viewpoint. Top of grade (crest of hill) with room to pull out on right, as road begins descent into Clackamas River valley.

From this vantage, on a clear day, the traveler can look southeast along the V-shaped Clackamas River canyon and southward along the western slope of the Cascade Range. Strata are gently west dipping in this area, and the view southeast from here has hints of that bedding orientation. Like many parts of the Cascade Range, however, topographic expression of bedding is difficult to discern, owing to thick forest cover, high rates of mechanical erosion, and myriad landslides that disrupt the development of ledges along some of the more continuous units.

More obvious are the clear-cuts that pattern the forest cover as we look east and south across the 1.1-million-acre Mount Hood National Forest. In the last 50 years, 0.18 million acres of this National Forest have been clear-cut, and an additional 0.1 million acres have had partial cuts. Wilderness and watershed preserves constitute about 0.26 million acres (Tom Ortman, USDA Forest Service [USFS], oral communication, 1992). Elsewhere in Oregon, clear-cutting has been shown to modify the timing and magnitude of peak streamflow (Fredriksen, 1970). Clear-cutting also is associated with increased sediment discharge, although this may be more a function of road building than greatly increased erosion of logged areas (e.g., Fredricksen, 1970; Swanson and Dyrness, 1975).

A subtle relationship exists between landforms, forest fires, and subsequent forest growth. Imagine a fire contained within the river valley, for example. Such fires tend

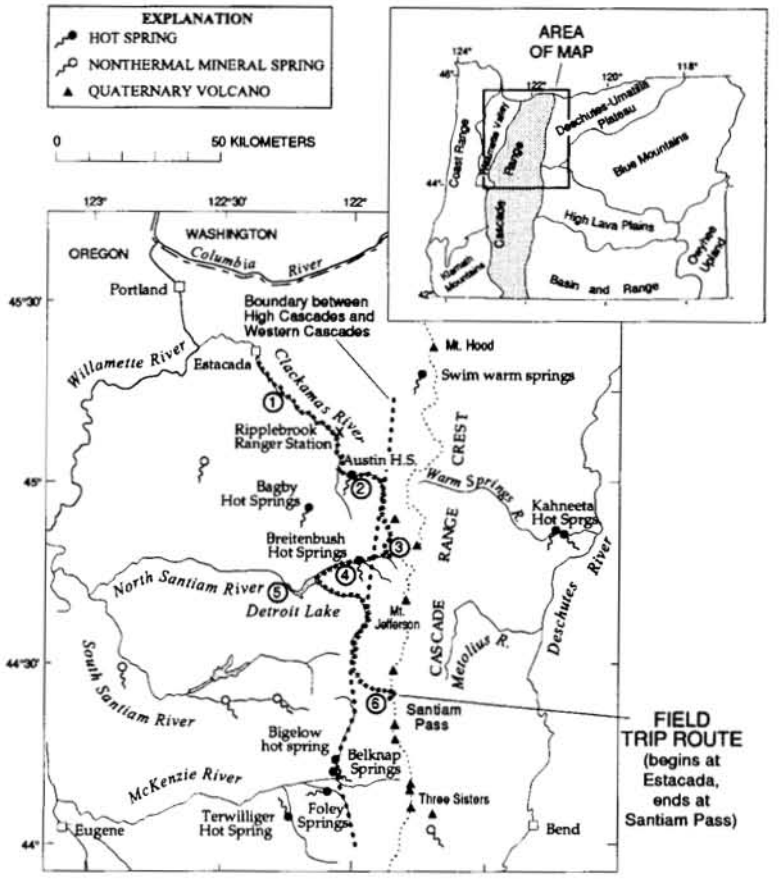


Figure 1. Trip route from Estacada to Santiam Pass. Inset shows physiographic provinces of Oregon. Encircled numerals are field-trip stops. Naming of hot springs follows conventions on published topographic maps; names in lower case are informal.

to be spotty, because wind patterns and wood supply work to minimize rampant burning. Natural reforestation afterwards results in a diverse, intricate pattern of forest species. In contrast, a fire on the broad upland slopes and flattish regions at higher elevations can burn quickly across large areas. Subsequent reforestation creates even-aged, homogeneous stands of timber. Wildlife is tied to habitat, and the fire-modified landscape will see changing use and (or) migration patterns, especially of large mammals and birds.

1.8/5.7 Route joins old road alignment, which may be the only road shown on many maps. Road to right leads back (west) to dam.

0.7/6.4 Mount Hood National Forest sign (entering National Forest lands).

3.3/9.7 **Stop 1—Big Cliff.** At road level are excellent exposures of Grande Ronde Basalt (Prineville chemical type), a formation in the Columbia River Basalt Group.

Our purpose at this stop is to consider the role that lithologic variation plays in some temperature profiles. The Columbia River Basalt Group here consists of nearly flat-lying lava flows and interflow breccia (Figure 2A). Most lava flows of the Columbia River Basalt Group were erupted between 17 and 13.5 Ma from dike swarms located 400 km east of the Cascade Range; they flowed west across the area of the present-day Columbia Plateau and lapped against older rocks of the Cascade Range (Figure 3). Some lava flooded through low gaps in the range in northern Oregon and southern Washington and progressed as far as the Pacific Ocean. The flows in the Clackamas River area have been mapped and described in detail by Anderson (1978).

Contrasts in permeability between massive lava and breccia are responsible for the stepped geothermal gradient seen in a hole drilled in the Columbia River Basalt Group across the Clackamas River from Estacada (Figure 2B). Slight differences in hydraulic head between breccia zones cause flow between zones when they are connected by the drill hole. Steep temperature gradients (subhorizontal steps on Figure 2B) are associated with each permeable zone, whereas low gradients (near-uniform temperatures over a large depth range) characterize the intervening massive flows.

The Columbia River Basalt Group, although not part of Cascade Range volcanism, forms an easily identified stratigraphic marker—and one well exposed in many localities because its lava is erosion resistant. Along the Clackamas River, the lava flows form cliffs and open sunny bluffs that support unique biological communities. Scorpions, poison oak, and perhaps rattlesnakes, while not common in the western part of the Cascade Range at this latitude, are found sporadically among outcrops of the Columbia River Basalt Group, especially the south-facing exposures. So, too, is found the Oregon white oak, a species far more common in the Willamette Valley and on eastern slopes of the Cascade Range, where the hotter, drier summers favor its growth. Note how the deciduous trees grow in shaded clefts and fractures.

0.7/10.4 Bridge, Memaloose Road to right. **Continue on main highway**. "Memaloose" is Chinook jargon for "dead" or "death." ("Jargon" used in its linguistic sense as a language group comprising words from several separate languages.) Folk legend holds that an Indian chief is buried along ridge at headwaters of Memaloose Creek (Beth Walton, USFS, oral communication, 1992).

Although not visible from our route along the canyon bottom, Pliocene basalt caps canyon walls on the northeast. These lava flows were emplaced along a broad paleovalley, before the ancestral Clackamas River began to carve its deep narrow gorge. The basalt flows along the Clackamas River are not directly dated, but they can be traced nearly to the High Rock area of the Cascade Range, where petrographically similar rocks form the lowest part of a conformable sequence of lava flows as young as 2.78±0.09 Ma (Sherrod and Conrey, 1988). For this reason, we assign the entire sequence an age between about 3 and 2 Ma. The modern gorge has been cut since that time.

0.4/10.8 Lazy Bend Campground (USFS).

0.8/11.6 Oak plant communities thrive on south-facing slopes above road.

3.4/15.0 Big Eddy picnic ground (USFS).

At Big Eddy, the northwest-trending channel of the Clackamas River turns abruptly northeast, forcing the main current to the outside of its bend. Outcrops of lava further constrict the channel. A short distance beyond the constriction, the channel width increases from 8 to 20 m and channel depth increases from 1 to 5 m or more. These increases combine to create two large ovoid eddy cells 6×15 m and 4.5×9 m. Many intermittent local vortices migrate in the larger eddy.

1.2/16.2 Carter Bridge picnic ground (USFS).

0.5/16.7 Highway bridge over Clackamas River.

0.2/16.9 Fish Creek Road to right. **Continue on main highway**. Temperature measurements from shallow wells in campgrounds nearby provide the only conductive heat-flow data for an area of about 300–400 km^2 centered here (holes no. 11, 12, 14, and 15 in appendix to Ingebritsen and others, 1991).

2.5/19.4 Roaring River Campground (USFS).

1.8/21.2 Road cuts on left show sedimentary interbeds that are lithostratigraphic equivalents of the Vantage Member of the Ellensburg Formation in eastern Washington (Anderson, 1978; Hammond and others, 1980) and separate Grande Ronde Basalt and overlying Wanapum Basalt, both units part of the Columbia River Basalt Group. Overall lack of volcaniclastic interbeds among Oregon Cascade Range exposures of the Grande Ronde and Wanapum Basalts indicates relative quiescence of arc volcanism from 17 to 14.5 Ma.

0.9/22.1 Quaternary terrace and talus deposits exposed in road cuts on left.

0.3/22.4 Three Lynx Road junction. **Continue ahead on main highway**.

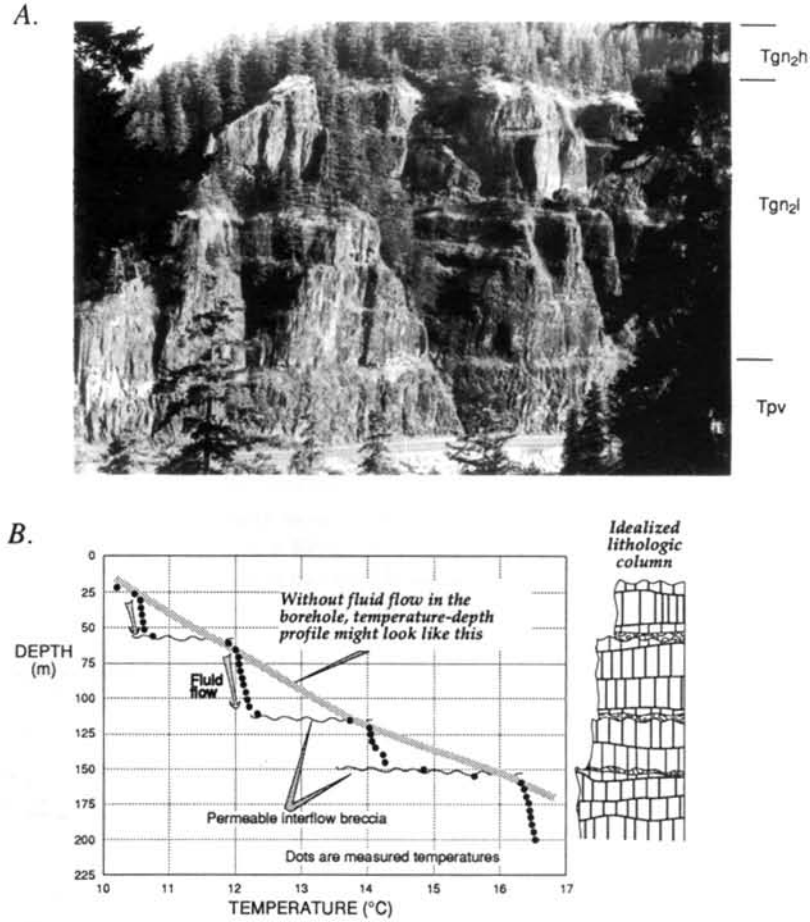


Figure 2. Comparison of Big Cliff stratigraphic section (Stop 1) and disturbed temperature profile from heat-flow hole drilled into Columbia River Basalt Group: A—Informally named Prineville basalt of Nathan and Fruchter (1974) at road level (unit Tpv) overlain by low- and high-magnesium chemical types of normally polarized Grande Ronde Basalt (units Tgn_2l and Tgn_2h, respectively). Photograph and stratigraphic interpretation from Anderson (1978). B—Temperature profile for hole drilled near Estacada (northwest corner of sec. 29, T. 3 S., R. 4 E.) with lithologic layering probably similar to that exposed at Big Cliff (from Ingebritsen and others, 1988).

1.1/23.5 Bridge, Indian Henry Road to right. Trip has been in narrow gorge carved in gently west-dipping lava flows of the Columbia River Basalt Group. Our southeast-directed travel has taken us downsection, and at this point we pass into Oligocene and lower Miocene volcanogenic rocks. The narrow gorge abruptly widens upstream (southeast) from here because of widespread landsliding, a consequence of slope failure in the altered tuffaceous volcanogenic rocks of the Western Cascades.

At about this point we enter a westward "bulge" in the map pattern of some geophysical features. For example, the apparent Curie point isotherm, which in the High Cascades is located at depths of 6–9 km, extends at similarly shallow depths into the Western Cascades here, although most of the Western Cascades have isotherm depths greater than 9 km (Figure 4). The concept "depth to apparent Curie point isotherm" is more correctly described as depth to the base of the magnetic layer, a geophysical property resulting from hydrothermal alteration or high temperature. Heat-flow contours for 60- and 80-mW/m^2 (milliwatts per square meter) also extend westward to enclose this area before sweeping back east toward the High Cascades (Figure 4).

1.1/24.6 Chronically rough road with sunken grade as a consequence of landsliding. As much as 6 m (20 ft) of asphalt reportedly has built up over the years, as the roadbed is continually relayered along this curve.

0.6/25.2 Boggy wetland. On warm days in late spring and summer the smell of skunk cabbage is unmistakable. (Try not to catch the eye of someone sitting near you!)

2.7/27.9 Timber Lake Civilian Conservation Corps work center.

A sawmill was built near this site toward

⇒

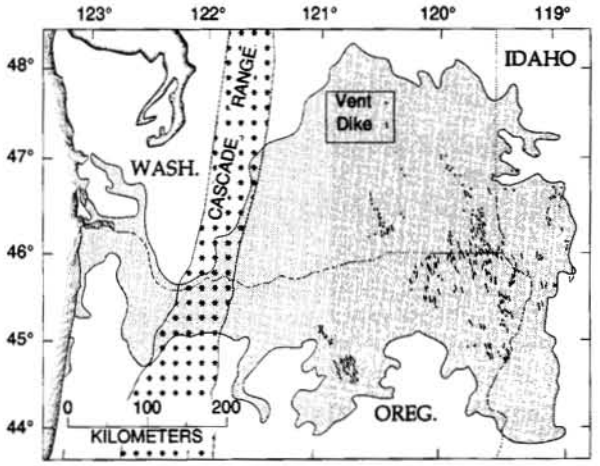


Figure 3. Distribution of Columbia River Basalt Group and location of volcanoes and dikes that fed the lava flows in it. Generalized from Tolan and others (1989).

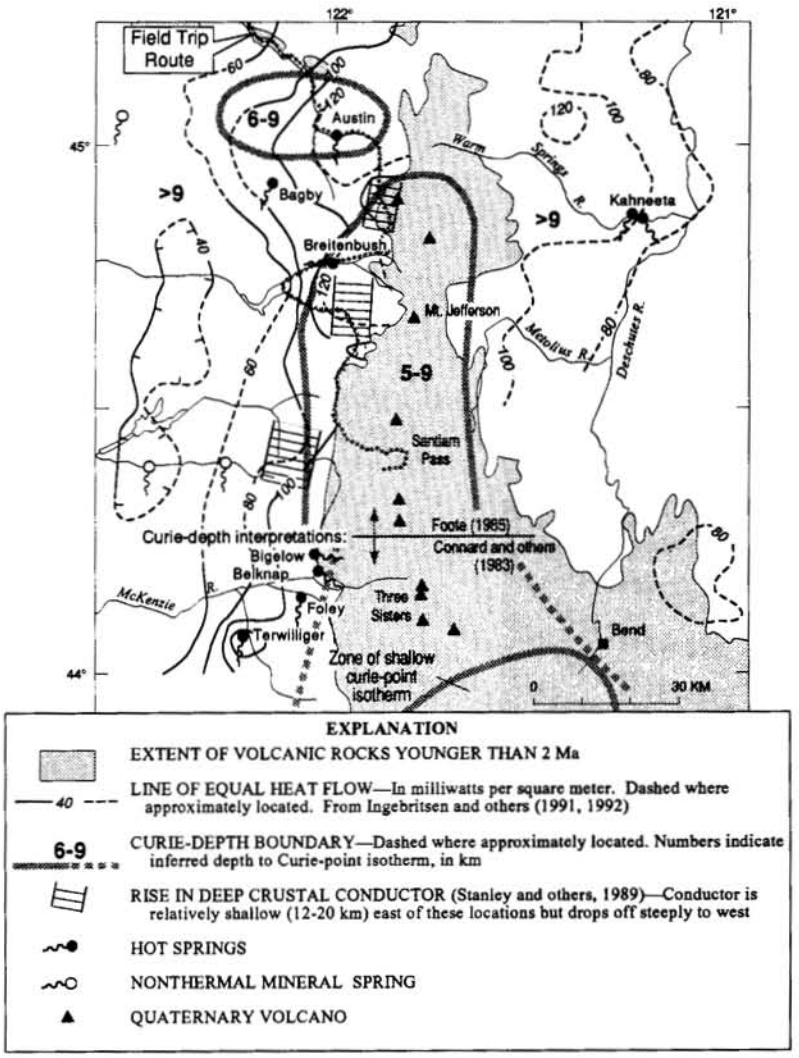


Figure 4. Map showing relation between near-surface heat flow, apparent Curie-depth boundaries (Connard and others, 1983; Foote, 1985), and rise in deep crustal conductor (Stanley and others, 1989, 1990). Note westward "bulge" in heat-flow contour for 80 mW/m^2 and its approximate coincidence with shallow Curie-depth boundary in area of Austin Hot Springs. From Ingebritsen and others (1991, 1992).

the end of World War II, the time when large-scale logging began to open up slopes along the Clackamas River drainage. With the development came attempts to drain bogs that dot the surface of this landslide. Forest planners presently are minimizing logging to preserve the landslide-prone area for the rich habitat it possesses. Bogs and moving water on the landslide surface create diverse openings favorable for wildlife. Wetlands here provide important winter forage for deer and elk.

1.0/28.9 Ripplebrook Ranger Station. Wilderness permits, pay telephone. Highway 224 becomes Forest Road 46. **Continue ahead.**

0.5/29.4 Junction, Forest Road 57 to left. **Keep right on Road 46**. The road not taken, Road 57, leads east to Timothy Lake along the Oak Grove Fork Clackamas River.

As discussed by Ingebritsen and others (1991), the watershed of the Oak Grove Fork encompasses relatively permeable lava flows of chiefly Pliocene and Pleistocene age. In contrast, the watershed of the main stem of the Clackamas River encompasses a wide area of relatively impermeable, altered Oligocene and Miocene tuffaceous strata. A hydrologic consequence of increased permeability is a much higher unit baseflow or recharge rate—26×10^{-9} m/s (~1 m/yr), nearly three times that for the Clackamas River downstream between Three Lynx and Estacada (Figure 5). Unit baseflow is an estimate of the minimum groundwater recharge rate per unit area. Thus, the Oak Grove Fork has a proportionately higher groundwater (baseflow) contribution to stream flow (50 percent of annual precipitation) and a much flatter hydrograph (less seasonal variation) than the main stem of the Clackamas River (baseflow 20 percent of annual precipitation).

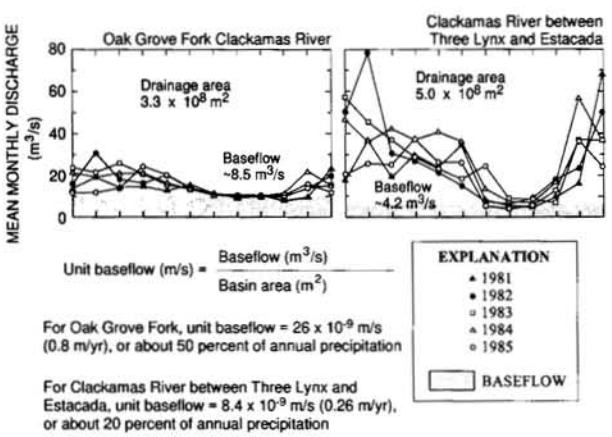


Figure 5. Hydrographs showing contrasts in seasonal stream flow as a consequence of rock permeability in watersheds (from Ingebritsen and others, 1991). Oak Grove Fork Clackamas River encompasses relatively permeable Pliocene and Pleistocene lava flows.

3.0/32.4 Riverside Campground.

0.7/33.1 Junction, Forest Road 63 (Collawash River Road) to right. **Keep left on Road 46.**

Although not part of our trip, the Collawash River Road is the way to Bagby Hot Springs, located about 10 km south of here on the Hot Springs Fork of the Collawash River. The Bagby Hot Springs site is unique among the Western Cascades hot springs for its dilute, high-pH, Na-mixed anion waters and its geographic setting isolated from the Quaternary arc by major drainage divides. Its location, chemical composition, and a relatively low $^3He/^4He$ ratio suggest that Bagby is the product of local, relatively deep circulation. The Na-mixed anion waters are similar to thermal waters associated with granitic rocks of the Idaho batholith (Mariner and others, 1980). Tertiary granitic or dioritic rocks are locally exposed in the Bagby Hot Springs area (Walker and others, 1985) and may be more widespread at depth.

The dilute Bagby Hot Springs water contributes negligible chloride flux to the Clackamas River. Anomalous chloride flux (50 grams per second [g/s]) at the Three Lynx gage downstream from the confluence of the Collawash and Clackamas Rivers is almost entirely from Austin Hot Springs (also about 50 g/s).

WHAT'S IN A MEGAWATT?

At current U.S. rates of electrical power consumption, one megawatt (MW) is sufficient power for about 1,000 people. The Clackamas River power network creates 170 MW of electrical power (MW_e) through its series of 5 dams and 16 generators. In the Pacific Northwest, hydroelectric power supplies about 16,600 MW_e or 74 percent of the average electrical energy use (J.C. King, Northwest Power Planning Council, written, communication, 1992). In contrast, geothermal energy presently is used only for space heating in a few scattered locations. Nationwide, geothermal energy ranks third behind hydroelectric energy and energy from biomass burning in the renewable energy scheme, and these energy sources rank far behind electricity generated from power plants fueled by coal, gas, or nuclear fission. About 2,800 MW_e of electric power generating capacity has been installed since the early 1960s at about 20 geothermal sites in the western United States, and it is projected that 7,000 MW_e of geothermal power will be installed by the year 2010 (Bush, 1992). The Geysers field in northern California is the largest geothermal complex in the United States, producing about 1,500 MW of electricity from 25 operating units. The Geysers field is eminently successful because the wells produce pure steam, whereas other producing geothermal fields commonly yield hot liquid or mixtures of steam and relatively saline liquid.

0.5/33.6 Gabbro sill forms cliffs at left. Its age is known only as younger than the lower Miocene strata that bound it. At this point, we are on the east limb of a broad arch, and our travel eastward begins taking us up through the stratigraphic sequence.

0.5/34.1 This stretch of the Clackamas River is an outdoor biological laboratory. The logs seen spanning the river just below water level have been placed purposely to create riffles, pools, and gravel beds in an attempt to diversify the habitat for fish.

0.2/34.3 Austin slide.

This prehistoric landslide was reactivated after the toe was removed by a 1964 flood. The landslide has obstructed traffic on Road 46 and, at one time, partially dammed the river. Timber was removed from the slide in 1972. Another flood in 1974 caused further erosion and renewed landslide movement. In 1976, after an extensive geotechnical investigation, a large rock fill was placed at the toe to improve slope stability. The rock fill, which is keyed below the slide plane, is 175 m long, 11 m wide, and ranges in height from 16 to 25 m. Total weight of the fill is about 37,000 tons, or about 7 percent of the total weight of the lower part of the slide. The rock fill functions not as a gravity-resisting buttress but as a shear key.

Total cost of the rock fill was approximately $1 million. Periodic monitoring indicates that the rock fill has not moved since its installation in 1976, although some parts of the slide are moving at a rate of 5–7 cm/yr.

1.4/35.7 Road 46 crosses private lands of Austin Hot Springs.

0.6/36.3 **Stop 2—Austin Hot Springs. Stop at east end of area, in view of the main orifice, which is located on south bank of river.** Other springs seep from river bottom. Hot-spring aficionados have built many small, stone-lined pools in the river.

Austin Hot Springs is the largest hot-spring system in the Cascade Range. It discharges 120 liters per second (L/s) of fluid (Table 1) at an orifice temperature of 86°C; heat discharge amounts to 90 MW_t (megawatts of thermal energy), calculated using a geothermometer temperature of 186°C. The heat, if being swept westward by lateral flow from the High Cascades, represents the heat generated by magmatism along 30 km of arc length. Alternatively, the heat could be supplied by a single, large magmatic system, either locally or in the High Cascades.

Like nearly all hot springs in the Western Cascades, Austin is positioned in a canyon floor between 460- and 760 -m (1,500- and 2,500-ft) elevation; its elevation is 510 m (1,680 ft). The springs emerge ~400 m below the top of the Breitenbush Tuff, a widespread sequence of Oligocene and lower Miocene tuff, lapilli tuff, and minor lava flows. These rocks are stratigraphically equivalent to the Little Butte Formation (Peck and others, 1964) elsewhere in the Oregon Cascade Range and to units such as the Skamania Volcanic Series, Ohanapecosh Formation, and Stevens Ridge Formation in Washington. The overlying middle Miocene rocks of the Columbia River Basalt Group are exposed at an elevation of about 850–910 m (2,790–2,990 ft), 370–400 m above us in the canyon walls.

Early visual estimates grossly underestimated the discharge of Austin Hot Springs. For example, U.S. Geological

Table 1. *Chemical composition, geothermometer temperatures, and discharge data for hot springs in the field-trip area (from Ingebritsen and others, 1991). Dashes indicate absence of data. Acidity (pH) in standard units. Temperatures (T) are in degrees Celsius (°C). Concentrations are in milligrams per liter (mg/L) and were determined as follows: cations by inductively coupled plasma; bicarbonate by acid titration; chloride by colorimetry or mercurimetric titration; bromide by ion chromatography; sulfate by turbidimetry; silica by atomic adsorption and molybdate blue*

Name	pH	Ca	Mg	Na	K	HCO_3	Cl	Br	SO_4	SiO_2	T_d*	T_g**	Q_t***	$^3He/^4He$
		(mg/L)									(°C)		(L/s)	(R/R_a)****
Austin	7.4	35	0.10	305	6.4	36	390	1.2	130	81	86	186	120±6	5.7
Bagby	9.4	3.3	<0.05	53	0.7	69	14	—	42	74	58	52	1	1.2
Breitenbush	7.0	95	1.1	745	31	137	1,200	4.2	140	163	84	174	13±2	6.5
McKenzie River Group														
Bigelow	7.8	195	0.53	675	15	22	1,250	3.8	140	73	59	155		—
Belknap	7.6	210	0.34	660	15	20	1,200	3.9	150	91	73	152	20±3	—
Foley	8.0	510	0.08	555	8.7	20	1,350	4.0	510	63	79	100	11±4	—
Terwilliger	8.5	215	0.07	405	6.1	21	790	2.2	240	47	46	135	5	—
Kahneeta	8.1	13	0.05	400	11	603	240	0.8	31	78	83	137	50±5	—

* Discharge temperature.

** Chemical geothermometer temperatures based on anhydrite saturation except for Kahneeta and Bagby, which are based on silica (quartz) and cation geothermometers. Solubility of anhydrite ($CaSO_4$) provides a geothermometer indicating maximum temperature (Ellis and Mahon, 1977). Anhydrite saturation values for the Na-Cl and Na-Ca-Cl waters that discharge in the Western Cascades correlate well with sulfate-water isotope temperatures (Mariner and others, 1993). Temperatures listed for Kahneeta and Bagby are averages of the quartz and cation geothermometers. These and other geothermometers are discussed by Fournier (1981).

*** Discharge (Q_t) based on chloride-flux measurements except for Bagby Hot Springs, where discharge was measured directly.

**** Isotopic ratio of ^3He to ^4He reported as the measured ratio (R) normalized by atmospheric ratio (R_a).

KEY OBSERVATIONS AND POSSIBLE INTERPRETATIONS OF THE AUSTIN HOT SPRINGS SYSTEM

Observation	Interpretation
High heat discharge (90 MW_t)	Capture of regional heat flow over large lateral-flow area (100 mW/m^2 over 900 km^2) and (or) lateral flow from a known magmatic heat source (for example, the Mount Jefferson area); alternatively, a local magmatic heat source with no surface expression
Isotopically depleted with respect to local meteoric water	Holocene recharge at a relatively high elevation (about 1,500 m) or alternatively, local recharge during colder times (glacial epochs) of the Pleistocene (more than 10,000 years ago). Pleistocene recharge unlikely if current discharge rate (120 L/s) is typical for the system
High $^3He/^4He$ ratio (5.7 times atmospheric ratio)	Input of magmatic ^3He, either from localized magmatic sources or from beneath the High Cascades
Elevated Cl content (390 mg/L)	May indicate Cl leached from marine rocks below the volcanic arc. Chlorine content of these and similar waters correlates with ^{15}N content (R.H. Mariner, written communication, 1992). Iodine-129 in Na-Ca-Cl waters to the south indicates an Eocene-age source
No $CaCl_2$ component	May indicate relatively little water-rock interaction (owing to relatively short residence time?). In Austin Hot Springs waters, Cl is ionically balanced by Na. In other NaCl hot-spring waters of the Western Cascades, a $CaCl_2$ component is present, perhaps derived from the albitization of plagioclase
Relatively low SiO_2 (like most Na-Cl and Na-Ca-Cl hot springs in the Cascade Range). Geothermometer temperatures $T_{K\text{-}Mg}$ (118°C) and T_{quartz} (126°C) much lower than $T_{SO4\text{-}H2O}$ (186°C) and $T_{anhydrite}$ (188°C)	Probably indicates appreciable water-rock reaction in a long outflow structure. $T_{K\text{-}Mg}$ and T_{quartz} indicate temperatures in the outflow structure. $T_{SO4\text{-}H2O}$ and $T_{anhydrite}$ indicate maximum system temperatures at considerable distance from the hot springs (R.H. Mariner, written communication, 1992)

Survey (USGS) Circular 790 (Brook and others, 1979) cites a value of 16 L/s. More recent measurements, using the solute inventory method, indicate discharge of 120±6 L/s (six sets of measurements from 1984 to 1989; see Figure 6). The solute inventory method measures downstream increases in Na and Cl loads of streams and has proven reliable for the Cascade Range because most of its thermal waters are rich in Na and Cl, whereas the streams are generally very dilute (Mariner and others, 1990). Visual estimates of hot-spring flow rates fail to measure diffuse discharge or multiple orifices that leak directly into streams.

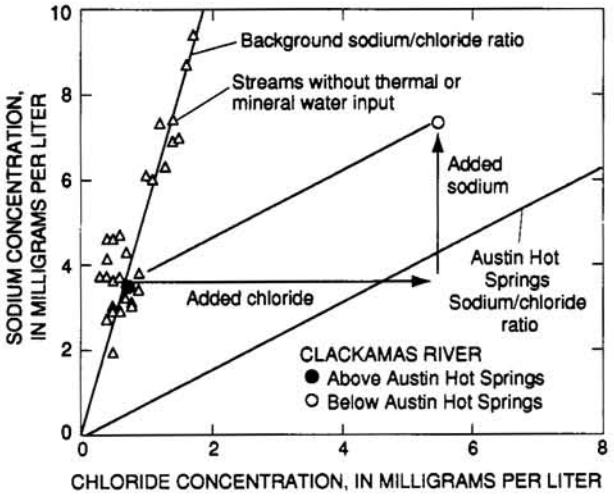


Figure 6. Example showing how hot-spring discharge is calculated by a solute-flux method. Discharge of Clackamas River was 9,400 L/s; hot-spring discharge was 120 L/s determined by Na increase, 120 L/s determined by Cl increase (from Ingebritsen and others, 1991).

The signs posted in this area to warn of scalding temperatures are a result of people's trespassing to the orifice, badly burning themselves, and then seeking legal redress by suing the landowner. A limited population of thermophilic algae and perhaps some bacterial organisms live in the orifice of Austin Hot Springs.

Resume travel eastward on Road 46.

2.5/38.8 Dating locale, 13-Ma andesite. The Columbia River Basalt Group has pinched out and is absent south of here, so we ascend through the stratigraphic sequence without seeing it. (It would crop out about here.)

4.7/43.5 Hydrothermally altered hornblende dacite (middle or upper Miocene) in road cut on left.

0.6/44.1 Bridge on right, Road 4650.

0.2/44.3 Junction, Road 4660 to left. **Continue ahead (right) on the main highway**. Road enters Big Bottom area of the Clackamas River. This is the western limit of late Pleistocene glacial advances, and the river floodplain broadens upstream as a consequence.

Rhododendron becomes a common shrub upslope beginning at about this elevation. Rhododendron seems to like coarser textured soils and soils with low nitrogen levels, both of which characterize the middle-elevation slopes in the snow zone of the Cascades. A well-developed understory of rhododendron is a nightmare to anyone conducting traverses through the woods. Surprisingly, rhododendron diminishes abruptly in the Cascades near the Columbia River and is nearly absent northward in Washington to about the Nisqually River on the west side of Mount Rainier.

3.1/47.4 Junction, Road 42 (Skyline Road) to left. **Continue ahead on main highway**. The road proceeds on Pleistocene outwash gravel that forms several terrace levels; the active Clackamas River floodplain is nested among these terrace deposits.

5.8/53.2 Bridge over Clackamas River.

1.1/54.3 Junction, Road 4690 (to Olallie Lake) on left. **Continue ahead**.

Olallie Lake is one of many lakes in the glacially scoured lavas of the High Cascades north of Mount Jefferson. It shares its name with Olallie Butte, a late Pleistocene basaltic andesite shield volcano. The lake is a popular summer fishing area with rustic setting. In winter, Olallie Lake Resort boasts excellent cross-country skiing. Guests and their equipment are transported to the snowbound lake by Sno-Cat.

0.8/55.1 **Stop 3—Clackamas-Breitenbush divide.**

If the weather is clear, attention turns quickly to the dramatic views of Mount Jefferson and several silicic domes that dominate the skyline southeast at the headwaters of the North Fork Breitenbush River. Our present knowledge of the Mount Jefferson area comes from mapping and geochemical study by Richard M. Conrey during the 1980s (Conrey, 1991). Mount Jefferson is a composite volcano built mainly in the last 100,000 years. Main-cone silicic andesite lava (62-63 percent SiO_2) sits atop an older mafic andesite volcano (57–58 percent SiO_2), and as many as six volcanoes can be distinguished within the entire edifice. Age of oldest lava ascribed to the eruption of Mount Jefferson proper is about 280 ka (see also age of 290±170 ka reported by Priest and others, 1987). The bulk of the cone, however, is composed of units emplaced about 70 ka.

Although an earlier interpretation held that Mount Jefferson was an isolated andesitic cone built entirely upon a basaltic field (Sutton, 1974; McBirney and White, 1982), Conrey's exhaustive mapping and more than 600 chemical analyses indicate that Mount Jefferson is part of a much larger, long-lived field of chiefly Quaternary andesite and dacite (Figure 7). Dacite and rhyodacite domes form the prominent bulbous hills visible in the middle distance; most high-temperature hydrothermal systems worldwide are related to Quaternary silicic rocks like these. Silicic volcanic rocks are probably erupted from upper-crustal storage chambers, whereas mafic volcanic rocks commonly arise from deeper rooted, more diffuse magmatic systems (Figure 8). The Cascade Range has one of the lowest extrusion rates for volcanic arcs worldwide, 3–6 km^3/km/m.y. (Sherrod and Smith, 1990), and the magmatic systems that supply most

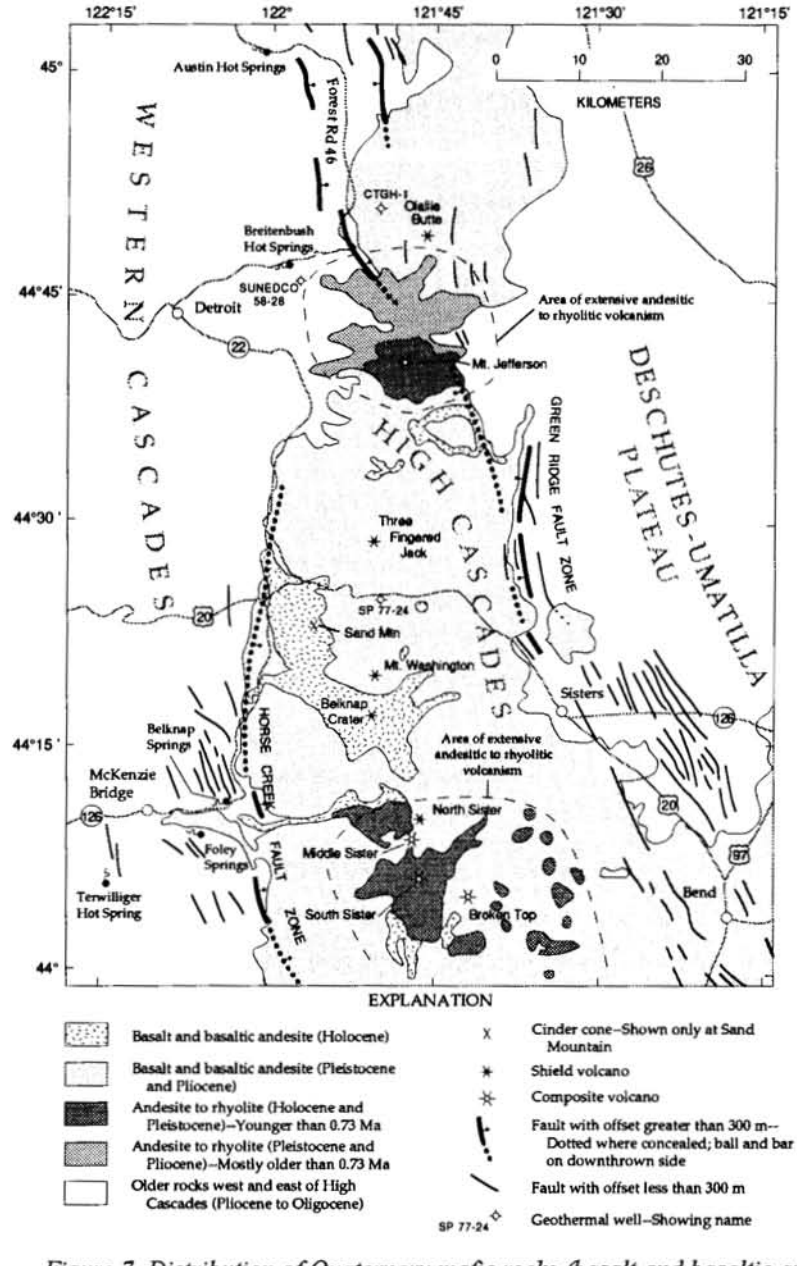


Figure 7. Distribution of Quaternary mafic rocks (basalt and basaltic andesite) and andesitic to rhyolitic rocks in the High Cascades (generalized from Sherrod and Smith, 1989). Note similar size of the andesitic to rhyolitic fields in the Mount Jefferson and Three Sisters areas. Figure 8 compares probable magmatic systems associated with mafic and andesitic to rhyolitic volcanism.

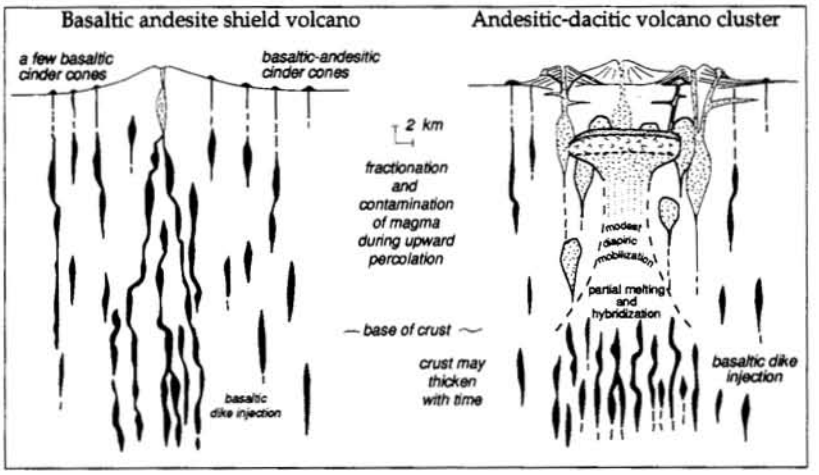


Figure 8. Contrasting volcano-structural setting of mafic shield volcano and andesitic-dacitic volcano cluster (from Hildreth, 1981).

Cascade mafic shield volcanoes are probably insufficient to focus heat and create an economic geothermal resource potential. In contrast, the longer lived Quaternary andesitic-dacitic volcano cluster and its associated crustal melting and magma storage are capable of sustaining a hydrothermal system of economic proportion (Smith and Shaw, 1975).

From this stop, we can view the pronounced physiographic differences between Western and High Cascades. Eastward, the High Cascades form a broad ridge with gentle slopes. Volcanic construction has kept pace with erosion in most areas; strata are late Pliocene and younger in age. Nearly every circular hill is a vent of some kind (cinder cone, dome, shield volcano, composite volcano), and many vents are younger than 0.73 Ma (formed in Brunhes Normal-Polarity Chron). Westward, the Western Cascades form a moderately incised terrane with steep slopes (commonly 70-percent slopes, as any Western Cascades field geologist will quickly point out). Lower Pliocene basalt flows cap several of the rudely concordant ridge tops near the margin with the High Cascades, and underlying strata are volcanogenic in origin and Oligocene or Miocene in age. Canyon cutting has occurred in the last 3 million years, and most of the canyons had their present form (and two-thirds or more of their depth) by 2 Ma.

This physiographic divide is a good place to ponder the location of heat sources and origin of hot springs in the Western Cascades (Breitenbush Hot Springs is 7 km west in valley floor of the Breitenbush River). The High Cascades physiographic subprovince, which terminates the orographic slope, forms a broad catchment area for precipitation. Rates of groundwater recharge are high; as much as 50 percent of precipitation infiltrates to recharge groundwater systems (Figure 5 and discussion at milepoint 29.4 apply equally here). Groundwater recharge in the Western Cascades, where rocks are older and less permeable, generally amounts to between 1 and 10 percent of precipitation. Groundwater moves along hydraulic gradients into the Western Cascades, some of it going deep enough to be heated by magmatic sources in the High Cascades and to reappear at hot springs in the Western Cascades. Total hot-spring discharge in the Western Cascades is less than 0.2 percent of inferred groundwater recharge in the High Cascades (Ingebritsen and others, 1991). Breitenbush Hot Springs is readily explained by lateral flow of water heated in the Mount Jefferson area. In contrast, Austin Hot Springs, located 25 km north-northwest of here (41 km from Mount Jefferson), is separated from Mount Jefferson by this major topographic divide. Its hydraulic connection to the Mount Jefferson area is more tenuous.

Perhaps the single feature common to hot springs of the Western Cascades is their location at the bottom of major stream valleys and between elevations of 460 and 760 m (1,500 and 2,500 ft) (Figure 9). Stratigraphic and structural controls are more difficult to define. Most hot springs in the Western Cascades are located near the top of a widespread sequence of altered tuff and tuffaceous strata of Oligocene to Miocene age, which suggests some stratigraphic control resulting from permeability contrasts. The McKenzie River group of springs, however, is in relatively permeable middle Miocene lava flows. Structural control by major faults seemingly applies to several hot springs, notably the McKenzie River group, but the majority of springs are at some distance from major faults.

Resume southerly travel on Road 46 into the valley of the Breitenbush River. Long downgrade ahead. Power lines overhead were installed by Bonneville Power Administration in the 1950s to bring power into western Oregon from the Columbia River power network.

4.9/60.0 Road 4685 to left. **Stay on Road 46.**

Road parallels a stretch of the Breitenbush River (on left or south in woods) that was reamed out by floods of 1964. At that time, it was thought that large logs in the stream acted as battering rams to speed streambank destruction; therefore logs were removed. Forest practice has changed since 1979, and now logs are maintained in the streams for habitat (see milepoint 34.1 for example). Downstream log migration is monitored in this stretch of the Breitenbush River to better understand the interactive processes of downed vegetation and stream flow (G.E. Grant, USFS, written communication, 1989).

Road 46 is a proposed scenic byway, part of a USFS program to engender economic diversity and tourism by promoting passenger-car travel along the more accessible and paved parts of the logging road network. Another part of

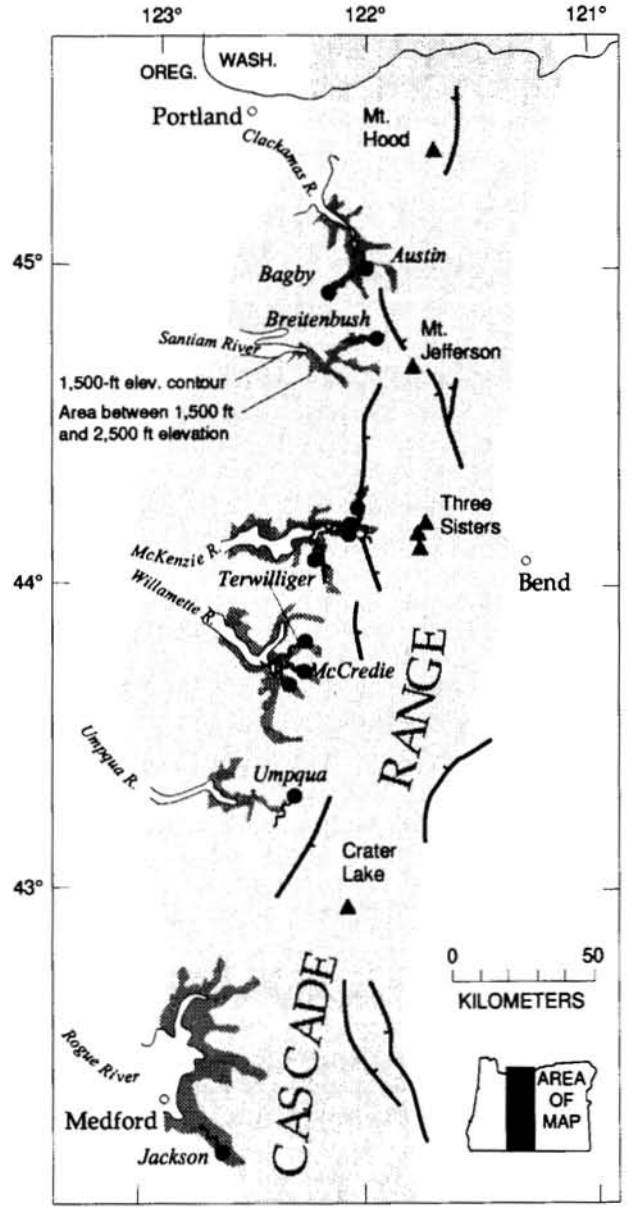
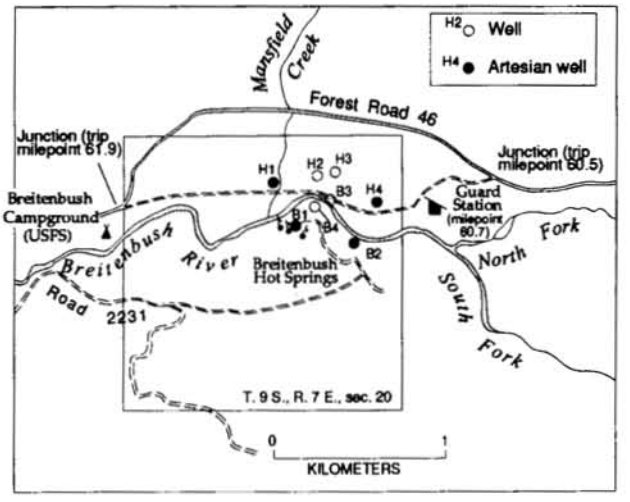


Figure 9. Hot springs in Western Cascades of Oregon lie between 1,500-ft and 2,500-ft elevation, with exception of Umpqua Hot Springs (2,650 ft). Dark shading shows areas in major stream drainages bounded by 1,500- and 2,500-ft contours. Major faults shown by bold line; tick on downthrown side (from Sherrod and Smith, 1989).

the program will display new perspectives in forest practices through the use of numbered stops and printed road guides.

0.5/60.5 **Obscure junction, be alert. Turn left** from pavement onto dirt Road 4600-050. This road passes near Breitenbush Hot Springs before reconnecting with main road.

0.2/60.7 Breitenbush Guard Station (USFS). The station was built in 1935 and is now listed on the National Register of Historic Places. A fire-



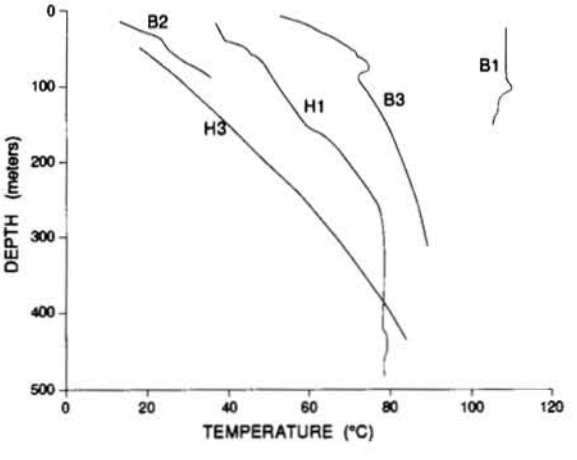


Figure 10. Temperature profiles for Breitenbush Hot Springs area; data from Ingebritsen and others (1988).

prevention technician lives on-site during fire season from June until autumn rains have begun in earnest.

0.2/60.9 Artesian well north of road (H4 on Figure 10) can produce 20–40 L/s, which is double or triple the output of nearby Breitenbush Hot Springs (10–11 L/s). Water from the well, about 85°C, is chemically similar to Breitenbush thermal waters.

0.2/61.1 Breitenbush Hot Springs and Breitenbush Community, a spiritual conference center, across river. We will pause long enough to glimpse the setting but will not stop here out of courtesy to landowners, instead discussing the hot springs while at Stop 4.

0.8/61.9 Dirt road rejoins pavement (Road 46) near Breitenbush Campground. **Continue straight ahead on pavement.**

0.7/62.6 Cleator Bend. Outcrops of altered pumiceous tuff, whose pale-grayish-green colors result from celadonite, a K-Fe illite-structured clay mineral formed by alteration of glass.

This unit, known as the Cleator Bend Tuff of Hammond and others (1982) or part of the quartz-bearing tuff in the Breitenbush Tuff of Priest and others (1987), has a plagioclase K-Ar age of 20.3±0.2 Ma (Sutter, 1978; sample DMS-43 recalculated, using new decay constants). This age may be too young, inasmuch as overlying rocks in this area have ages as old as 24.9±0.3 Ma (see Priest and others, 1987, for summary).

0.9/63.5 **Stop 4—Quarry in quartz-bearing ash-flow tuff.**

This tuff is one of many small- to moderate-volume ash-flow tuffs (a few tens of cubic kilometers) found in the Cascade Range. It is rhyolitic in composition (72.6 percent SiO_2, recalculated water-free) (White, 1980, sample BX–102) and contains abundant plagioclase crystals and lithic and pumice fragments. Quartz crystals are locally abundant in the tuff, and altered ferromagnesian crystals, probably originally orthopyroxene and clinopyroxene, are present in minor amounts throughout. Ash-flow tuffs in the Oregon Cascade Range generally lack quartz as a phenocryst phase; sanidine is always absent, and biotite is found only in rare instances.

Hydrothermal alteration is pervasive in this tuff, with the once-glassy pumiceous lapilli and matrix replaced by zeolite (mainly mordenite and heulandite) and clay minerals (celadonite and smectite). This mineralogy indicates alteration temperatures between 90°C and 150°C (Figure 11). The nearly isochemical alteration of glass in the tuff has reduced pore volume and interstitial permeability. Thin veinlets of celadonite, zeolite, opal, and (or) calcite occur locally. A K-Ar celadonite age of 17–18 Ma was recently obtained from the Cleator Bend sample locality (milepoint 62.6), and an age of about 20.5 Ma was obtained from fine-grained illite in silicified tuff on Boulder Ridge, 8.5 km southwest from here (M. Shafiqullah and T. Keith, unpublished data, 1992). Thus, the zeolite-clay alteration greatly predates the present hydrothermal system.

This quartz-bearing tuff is exposed near the orifices at Breitenbush Hot Springs and is believed to be the same unit that hosts a thermal aquifer at the depth from 752 to 782 m in the SUNEDCO 58–28 drill hole south of the hot springs (Priest and others, 1987). The 115°C of measured temperature in the SUNEDCO thermal aquifer and the projected bottom-hole temperature of approximately 140°C are too low to modify the previously developed zeolite-clay alteration. Fluid-inclusion homogenization temperatures measured from late-formed calcite and anhydrite in the SUNEDCO drill cuttings are generally within 15°C of measured temperatures except in the thermal aquifer, where homogenization temperatures in calcite are all hotter than

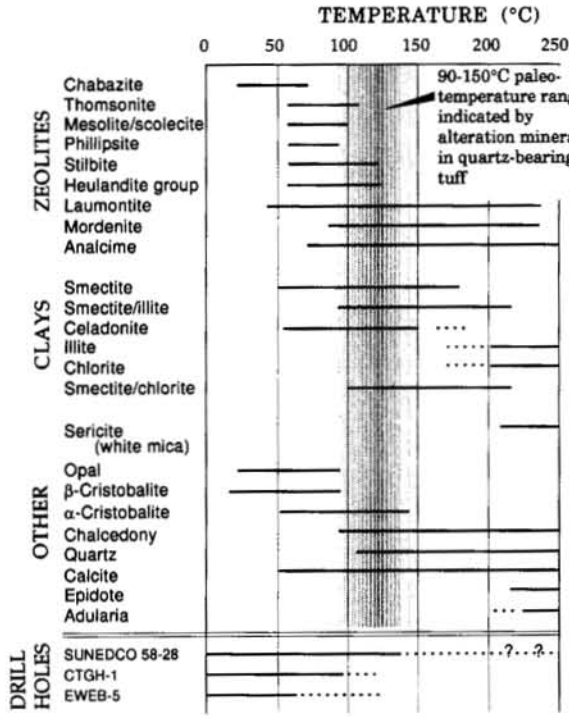


Figure 11. Selected hydrothermal minerals found in Breitenbush-Austin Hot Springs area plotted against temperatures of occurrence in well-defined active geothermal systems. Dashed lines indicate uncertain temperature range. Shown at bottom are inferred maximum temperature ranges for three drill holes from this part of Cascade Range; present maximum temperature (measured) shown by solid line, and past possible maximum temperature (inferred from alteration mineralogy) shown by dashed line. Gray shading shows paleotemperature indicated by alteration minerals in quartz-bearing tuff of Stop 4. Figure modified from Keith (1988); see that reference for sources of mineralogical information.

measured temperatures and reach as much as 150°C (K.E. Bargar, USGS, oral communication, 1992).

Why this particular ash-flow tuff would serve as a thermal aquifer remains unclear, inasmuch as similar, stratigraphically adjacent tuff layers are not aquifers. Primary permeability of partially to moderately welded tuff is low (Winograd, 1971), and the alteration seen here further reduces primary permeability. Secondary permeability owing to fracturing may enhance water-carrying capacity of the unit.

In general terms, rock fracturability and secondary permeability are enhanced by higher temperature minerals (>200°C), which are anhydrous (quartz, epidote) or nearly so (chlorite, actinolite, or biotite) relative to lower temperature minerals (zeolites, clays). Pervasive alteration to higher temperature minerals results in rock that is hard, brittle, and more readily fractured than rock from lower temperature minerals, which tends to tear and compress rather than fracture cleanly. Rocks that have undergone

high-temperature alteration tend to sustain open fractures. Those fractures, however, can be filled subsequently by secondary minerals precipitating from fluids.

Fracturing is spatially variable in this quartz-bearing ash-flow tuff because of variable alteration. At the quarry of Stop 4, alteration of glass is complete, and pore spaces are filled. Much of the tuff contains open vertical fractures suitable for sustaining an aquifer. A short distance away on either side of the quarry exposure, however, the same tuff is more pumiceous, contains open pore spaces, and is much softer than the quarry rock.

The Breitenbush Hot Springs lie within an electrically conductive zone, identified from telluric data, that comprises either two linear, electrically conductive structures (Figure 12) or curvilinear intertwined structures that splay and converge along a broadly northeast trend (H. Pierce and colleagues, USGS, written communication, 1989). The conductive zone also encompasses two unusual low-discharge Na-HCO_3 mineral springs. The conductive zone may represent fractures that channel thermal water to the surface or a relatively impermeable barrier that blocks lateral movement of thermal water (Ingebritsen and others, 1992). The 100°C isotherm, whose broad upwarp in the Breitenbush area may be further evidence for a stratigraphically controlled thermal aquifer, deepens abruptly northwest of the conductive zone (Figure 12).

A 6- to 7-km-deep integrated-finite-difference grid (Figure 13) was used to simulate groundwater flow and heat transport in the Breitenbush section (Figure 14) (Ingebritsen and others, 1992). Simulations using only conductive heating, with either narrow or wide basal heat-flow anomalies, failed to reproduce the low, near-surface conductive anomaly in the Quaternary arc or the elevated heat flow between Breitenbush Hot Springs and the Quaternary arc: some permeability is required. We simulated a 1-km-wide section of arc length. With appropriate permeability, most of the groundwater recharged in the Quaternary arc (303 kg/s) discharges locally in topographic lows (301 kg/s) but carries little heat. Simulated discharge in the Breitenbush Hot Springs area (~1 kg/s) is a small fraction of total recharge in the Quaternary arc, but this relatively small mass flux transports substantial amounts of heat from the Quaternary arc to the Western Cascades. Using the permeability values shown in Figure 13, the ratio of hot-spring discharge to recharge in the Quaternary arc (0.003) is similar to the ratio (0.002) estimated from measured groundwater recharge and hot-spring discharge rates (Ingebritsen and others, 1992).

0.2/63.7 View upslope ahead (across Breitenbush River) of area burned in the 1967 Eagle Rock fire. That fire began after a several-year drought period.

0.9/64.6 Eagle Rock, on left at 11:00 o'clock, is a tholeiitic basalt plug (White, 1980; Priest and others, 1987).

2.5/67.1 Junction, Road 4696 to right, Humbug Creek Campground on left. **Continue ahead toward Detroit.**

View ahead of rocky bluff at skyline is area of Canyon Creek fire, another major fire of the 1960s. The blocky lava flows that form the rimrock were erupted from the Battle Ax shield volcano, one of the few Quaternary volcanoes in the Western Cascades physiographic subprovince. Battle Ax volcano was active some time between 0.73 and 2.4 Ma (Matuyama Reversed-Polarity Chron) (White, 1980). Youngest lava is reversely polarized. Potassium-argon ages range from 1.2 to 1.8 Ma but are poorly constrained owing to low contents of radiogenic argon. Most lava issued from a vent complex near Battle Ax Mountain (White, 1980).

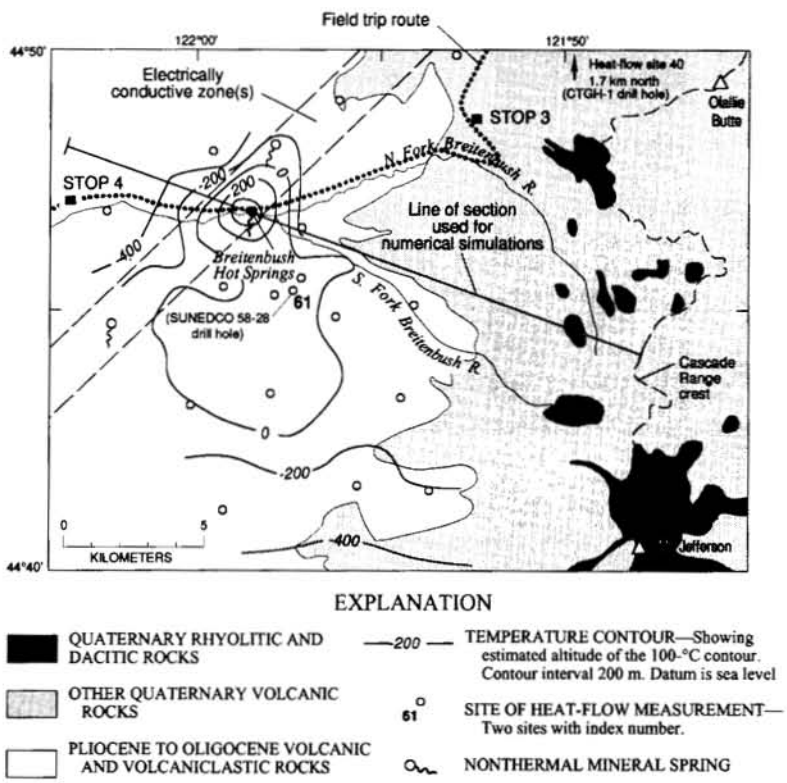


Figure 12. Map of Breitenbush Hot Springs area showing line of section used in numerical simulations, electrically conductive structures identified by H. Pierce and colleagues (written communication, 1989), and estimated elevation of the 100°C isotherm. Geologic data from Priest and others (1987) and from D.R. Sherrod and R.M. Conrey (unpublished data, 1988). This figure appeared originally in Ingebritsen and others (1991, 1992).

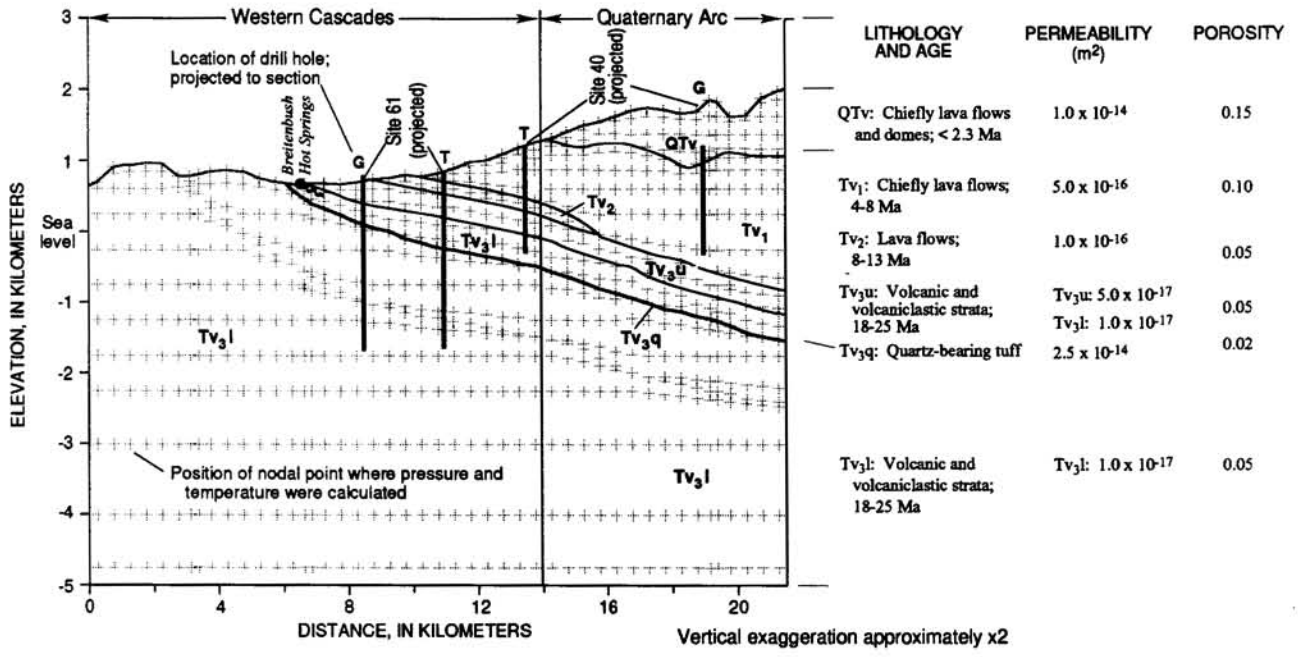


Figure 13. Cross section used for numerical simulation of the Breitenbush Hot Springs system (from Ingebritsen and others, 1992). Heat-flow site 40 (drill hole CTGH–1) and site 61 (hole SUNEDCO 58–28), which lie off the section (Figure 12), are projected in two different ways to indicate their appropriate contexts: G = geologic projection locating the holes relative to stratigraphic contacts; T = topographic projection putting the collar elevation at land surface.

4.5/71.6 Junction, U.S. Highway 22, town of Detroit. **Turn right (west) for side trip** (Stop 5) to view propylitic alteration and shallow plutonic rocks.

1.5/73.1 Ranger Station, Detroit Ranger district, on right. On left is Detroit Lake, a reservoir completed in 1953 by the U.S. Army Corps of Engineers.

The Detroit Lake project was designed chiefly for controlling runoff and providing flood control. Total electrical generating capacity is 118 MW, with most of that (100 MW) coming from the two generator units in Detroit Dam. Big Cliff Dam, a reregulating dam placed below Detroit Dam to control daily downriver variations in stream flow, has a single generator capable of producing 18 MW.

5.8/78.9 Detroit Dam. **Turn left onto road that crosses dam**. The prominent double notch in the road cut (well above road level and visible from a distance) was introduced during dam construction to provide a base for the aerial tracks that carried the concrete bucket. The straight-faced dam (no joking) fills slots cut into bedrock abutments.

0.3/79.2 Road turns left (southeast on south side of dam). This is Forest Road 2212; **continue ahead**.

0.1/79.3 Small turnaround area marked by pavement paint. **Park near here** and walk south ~30 m farther along road to road cut above the Cumley Creek arm of Detroit Lake.

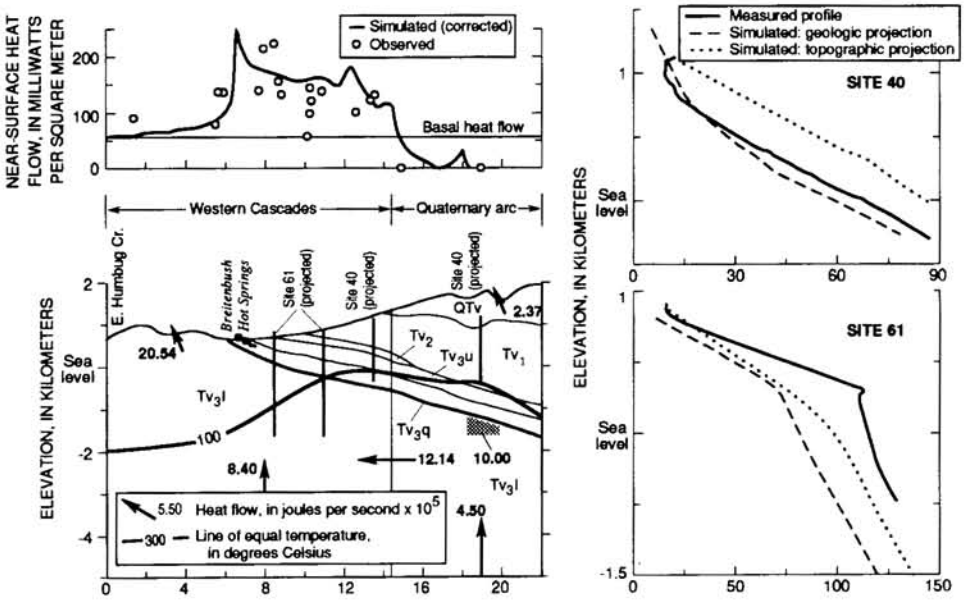
Stop 5—Intrusive phases of the Detroit stock.

Road cut exposes four intrusive phases of the Detroit stock, a composite intrusion covering about 9 km^2 (Figure 15). Lithologic features and alteration seen at this stop are characteristic of the small intrusive masses associated with hydrothermal mineralization in the Western Cascades of Oregon. Fine-grained quartz diorite is the earliest, most widespread phase. Cutting it are coarser grained, lighter colored rocks such as hornblende-bearing quartz diorite and hornblende granodiorite. The hornblende granodiorite contains visible quartz. Porphyritic andesite, thought related to the stock, forms a dike at the northwest end of the road cut. Sparse tonalitic aplite veins cut all rocks. Chemical analyses from the stock are listed in Table 2; modal analyses are shown in Figure 16.

The Detroit stock has a whole-rock K-Ar age of 9.94±0.18 Ma (Sutter, 1978; recalculated using new decay constants), but the rocks are altered, and the age may be too young. Intrusions in the Western Cascades range in age from 22 to 8 Ma (Bikerman, 1970; Sutter, 1978; Power and others, 1981; Keith and others, 1985).

Potassic alteration is indicated by hydrothermal biotite, which forms pseudomorphs after hornblende and pyroxene, especially in the hornblende granodiorite. Other minerals in the potassic assemblage of the Detroit stock are magnetite, potassium feldspar, pyrite, and chalcopyrite (Curless

A. Advective model, with a localized heat source in Quaternary arc



B. Advective model, with a wider, more intense deep heat-flow anomaly

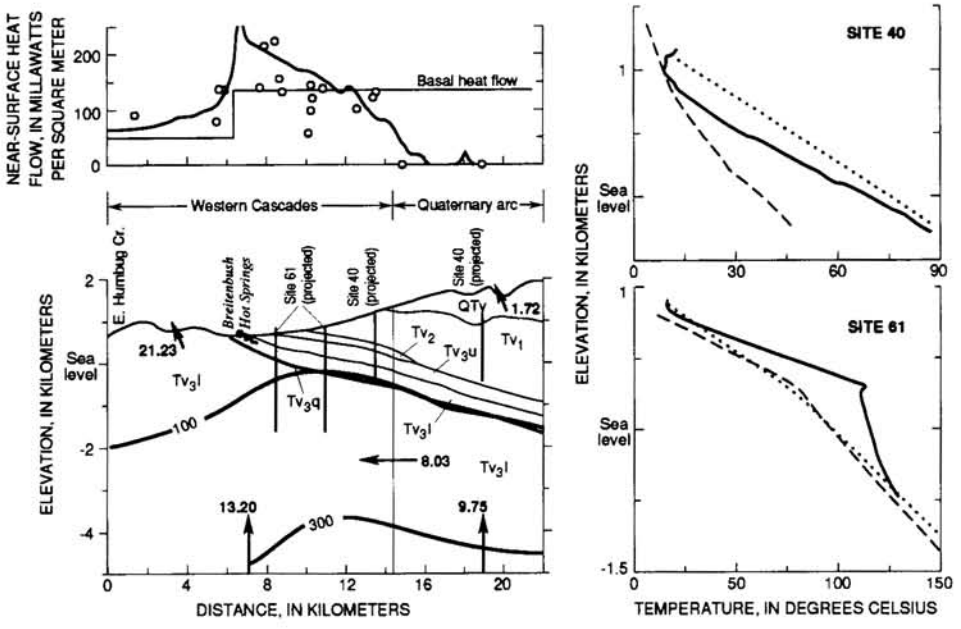


Figure 14. Numerical simulations for area of Breitenbush Hot Springs, showing that the thermal observations can be produced reasonably well with two very different deep thermal structures (from Ingebritsen and others, 1992): A, advective model with localized heat source in Quaternary arc, which corresponds to lateral-flow model (Ingebritsen and others, 1989, 1992). B, advective model with a wider, more intense deep heat-flow anomaly, which corresponds to the midcrustal heat source model (Blackwell and others, 1982, 1990). Map-unit symbols same as for Figure 13.

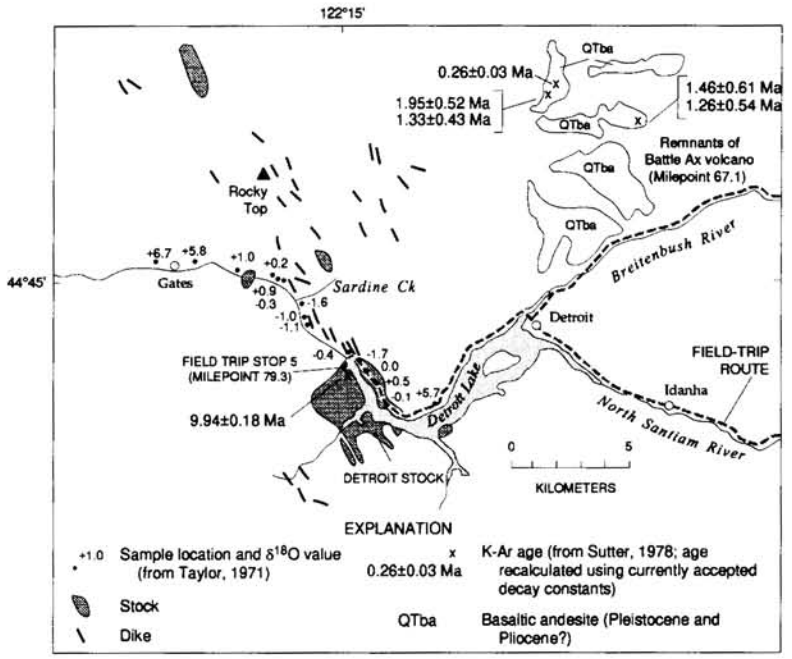


Figure 15. Detroit stock and pattern of oxygen-isotope depletion. Geologic data from Pungrassami (1970), Walker and Duncan (1989), and Curless (1991); isotope data from Taylor (1971).

and others, 1989, 1990). Potassium silicate selvages associated with quartz-magnetite veinlets may be as wide as 2 cm but locally coalesce to form zones of pervasive wall-rock alteration. Magnetite is the dominant opaque mineral; it is present as disseminated crystals in the groundmass, as intergrowths with secondary biotite, and in quartz veinlets. Pyrite and to a lesser extent chalcopyrite are also present in veinlets and as widespread disseminations. Potassic alteration grades outward into weak propylitic alteration, with weak sericitic alteration of plagioclase phenocrysts and hornblende phenocrysts surrounded by reaction rims of chlorite and magnetite. The rocks here are propylitized, characterized by a secondary mineral assemblage of epidote + chlorite + quartz + sericite ± calcite ± albite ± hematite ± pyrite. Veinlets of magnetite-quartz and epidote-quartz cut all rocks. Late-stage sericitic and argillic alteration are structurally controlled and overprint earlier alteration with sericitization of secondary K-feldspar and chloritization of secondary biotite.

Oxygen isotope values are lowered in the vicinity of the Detroit stock, owing to exchange with meteoric water during hydrothermal circulation (Taylor, 1971). Samples from a traverse along Highway 22 at the north edge of the stock shows $\delta^{18}O$ values as low as −1.7 per mil (Figure 15); whereas unaltered intermediate plutonic and volcanic rocks commonly have values ranging from +6 to +8 per mil. These data correlate poorly with early depictions of northeast-trending regional propylitic alteration and a broad syncline (Peck and others, 1964), which had been based on rapid reconnaissance work. Subsequent mapping and isotopic dating have challenged the theorized northeast-trending syncline (Walker and Duncan, 1989; Curless, 1991), but the accurate depiction of regional alteration surrounding the Detroit stock remains undetermined.

A 5-km-wide zone of dikes and faults extends northwest from the Detroit stock through Rocky Top (Figure 15). Intrusive rocks within the adjacent Sardine Creek and Rocky Top areas have mineralogical, textural, and chemical features similar to the Detroit stock. The main stocklike bodies of hornblende granodiorite were emplaced at a minimum depth of 1 km, whereas older quartz diorite may have been emplaced as shallow as 500 m, depending on the thickness of coeval middle or late Miocene volcanic rocks at the time of emplacement. (Elevation at the base of the volcanic sequence is ~1,350 m, whereas granodiorite stocks are as high as 480 m, and quartz diorite is as high as 1,000 m.) Dikes of coarse-grained intrusive rocks were emplaced at even shallower depths.

Mineralized samples from Detroit Dam to Rocky Top are zoned with respect to copper, lead, and zinc. The samples display a trend from Cu-rich porphyry- and breccia-type mineralization at Detroit Dam to Pb-Zn vein-type mineralization at Rocky Top. The trend is probably related to lateral and vertical distance from the Detroit stock (Curless, 1991). Most mining districts in the Western Cascades were developed in vein deposits and are located

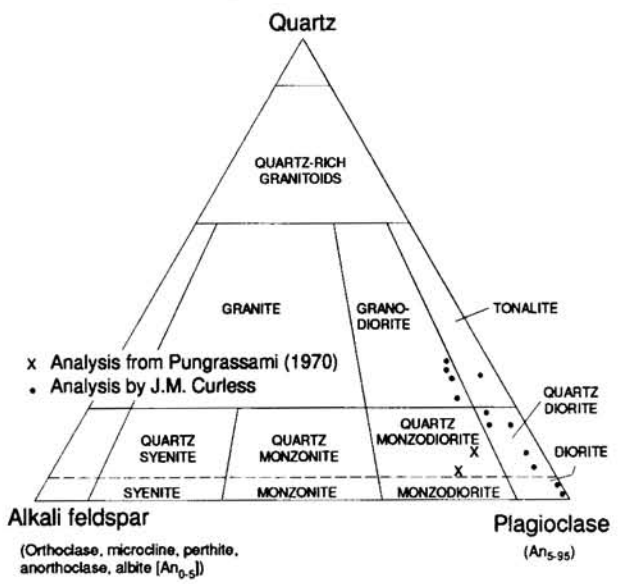


Figure 16. Classification of plutonic rocks from Detroit stock (after Streckeisen, 1976). Modal analyses from Pungrassami (1970) and Curless (unpublished data, 1991).

from 600 to 1,000 m higher on ridges than the associated intrusive masses exposed in adjacent canyon floors.

Return to cars and retrace route across dam. View to northwest from dam is toward the Rocky Top area of the Western Cascades; see Curless (1991, section A-A') for cross section corresponding to this view. **Turn right (east) onto State Highway 22 after crossing dam**. Route continues east toward Detroit, Oregon.

5.4/84.7 View of Mount Jefferson to right (east) across Detroit Lake.

2.1/86.8 Detroit. **Continue east on main highway**. Last auto services until Sisters, Oregon (55 mi).

4.1/90.9 Idanha town limit.

Idanha probably originated as the upstream terminus of the Corvallis and Eastern Railroad, a railroad started in the late 1800s to connect the Oregon coast with rail lines near the Idaho border at Ontario, Oreg. Tracks were laid from Toledo (near Newport, central Oregon coast) through Albany in the Willamette Valley and into the North Santiam River valley as far as here (Mills, 1950).

Table 2. *Major- and trace-element analyses of plutonic rocks from the Detroit stock (Curless 1991). n.d. = not determined; LOI = loss on ignition.*

Rock name	Quartz diorite	Hornblende quartz diorite	Hornblende granodiorite	Tonalite
Sample no.	MV-13	MV-32	MV-70	MV-31
Major-element analyses (weight percent)				
SiO_2	55.70	59.14	67.21	74.80
Al_2O_3	18.32	15.97	15.36	13.37
Fe_2O_3	4.18	2.90	1.69	0.40
FeO	3.16	2.91	2.00	0.37
MgO	3.16	3.63	1.55	0.64
CaO	6.43	5.97	3.33	1.26
Na_2O	3.48	3.90	3.77	5.85
K_2O	0.65	0.84	3.30	0.66
TiO_2	0.86	0.80	0.51	0.43
P_2O_5	0.30	0.29	0.22	0.13
MnO	0.16	0.09	0.10	0.02
LOI	4.05	4.10	1.60	3.74
Total	100.45	100.54	100.64	101.71
SiO_2 water-free	57.8	61.3	67.9	76.4
Trace-element analyses (parts per million)				
Rb	23	40	88	25
Sr	431	378	326	269
Cs	1.8	2.2	1.5	0.4
Ba	335	376	564	239
Th	1.9	4.3	9.1	11.0
Sc	19.9	16.8	8.5	6.5
Cr	54	155	29	103
Co	25.8	20.2	10.2	3.3
Ni	56	80	n.d.	16

1.1/92.0 Green Veneer lumber mill. A 210-m-deep well at the Green Veneer plant produces water enriched in sodium (120 mg/L), bicarbonate (158 mg/L), and chloride (89 mg/L) relative to local shallow groundwater (typically Na <5 mg/L, HCO_3 <60 mg/L, Cl <1 mg/L).

Upstream from Idanha, the North Santiam River is eligible for consideration as a National Wild and Scenic River by virtue of its recreational values. Under provisions of that act, eligible rivers are examined to identify the remarkable values possessed— recreation, scenic, or wild. Rules for management become increasingly stringent along the scale from recreation to scenic to wild. The intensity of development, bridge crossings, and other characteristics limit the rating for this stretch of river.

5.5/97.5 Junction, Whitewater Creek Road to left.

0.4/97.9 Road cut on left exposes block-and-ash (pyroclastic flow) deposit erupted from Mount Jefferson 15 km to the east.

Although once interpreted as Holocene in age (Hammond and others, 1982) or Pleistocene and Holocene (Priest and others, 1987), the deposits characteristically are deeply weathered, older than those of the Fraser glaciation, and entirely late Pleistocene in age. This particular deposit is overlain by a biotite-bearing tephra thought to be the Mount St. Helens set C, which is about 50,000 yr old (W.E. Scott and R.M. Conrey, unpublished data, 1989). The pyroclastic flow could be thousands of years older because a soil representing thousands to tens of thousands of years of development formed prior to deposition of the biotite-bearing tephra (W.E. Scott, written communication, 1992).

3.3/101.2 Riverside Campground.

2.1/103.3 Marion Creek. Marion Forks restaurant on right. Last food services until Sisters (40 mi).

9.4/112.7 Cross North Santiam River. River is eligible for consideration as a wild and scenic river by virtue of its administratively defined scenic values upstream from here.

4.6/117.3 Highway crosses Holocene basaltic andesite lava flows erupted from Little Nash Crater.

1.4/118.7 Santiam Junction, end of State Highway 22 at its junction with State Highway 128 (from Eugene, along McKenzie River) and U.S. Highway 20 (from Corvallis, along South Santiam River). **Continue ahead (east) on Highway 20** toward Santiam Pass.

1.3/120.0 The road rounds a curve built against a Holocene cinder cone, one of three in the Lost Lake chain of cones. These cinder cones dammed Lost Creek, creating shallow Lost Lake (ahead 1 mi on left). As the highway crosses the Lost Lake valley, views at 10:00 o'clock are of craggy Three Fingered Jack, the central pyroclastic cone of a Pleistocene basaltic andesite shield volcano.

The brownish to grayish color of the forest on the slopes above Lost Lake results from extensive tree damage by the spruce budworm. The budworm is a 1-cm-long caterpillar that has attacked about 7 million acres of trees in the Pacific Northwest during the past decade (Bella, 1992a). The pest prefers a climate drier than characterized by Cascade Range slopes but has expanded its range during the last seven years of drought. Trees stressed by drought are less able to survive predation by the budworm; budworm-devastated trees become easy prey for western bark beetle and other insects.

2.8/122.8 Hogg Rock, a flat-topped andesite dome. The dome has a K-Ar whole-rock age of 0.09 Ma (Hill and Priest, 1992). Hogg Rock is named for Colonel T.E. Hogg, promoter of the long-defunct Corvallis and Eastern Railroad. A short section of grade was prepared near Hogg Rock before the project's demise (Mills, 1950).

1.3/124.1 Summit of Santiam Pass. **Turn right at junction with road to Hoodoo ski area** (Road 2690, Big Lake Road). Hayrick Butte, another flat-topped andesite dome similar to Hogg Rock, is directly ahead (south).

Santiam Pass drill hole (SP 77-24) is located 1.6 km east of the Hoodoo junction and a few meters south of U.S. Highway 20 on a narrow dirt road. The hole, drilled to a depth of 929 m, was completed in two phases. The upper 140 m were drilled by rotary method during November 1990, and the remaining 789 m were completed by diamond-core drilling during August and September 1991 (Hill and Benoit, 1992). Basaltic andesite lava flows constitute 95 percent of the core, whereas cinders and volcaniclastic strata constitute the remaining 5 percent; core recovery was 99.7 percent. A K-Ar age of 1.81±0.05 Ma was obtained from a sample at 928-m depth, which indicates that most or all of the core is Pleistocene in age (Hill, 1992). Bottom-hole temperature was 25°C when last measured on September 3, 1991. Temperature gradients are about 50–60°C/km at 700- to 900-m depth and 103–116°C/km below 910 m (Blackwell, 1992). Average thermal conductivity is 1.66 W/m/K, a value that characterizes sequences of lava flows in other parts of the Cascade Range. Heat-flow values from lower parts of the hole range from 86 to 204 mW/m^2 (Blackwell, 1992).

0.9/125.0 **Veer left on Big Lake Road (Rd 2690).**

The road straight ahead leads a short distance into the Hoodoo ski area. Hoodoo Butte, with ski lift tower at its summit, is a geomorphically youthful, late Quaternary cinder cone. The basaltic andesite lava flows that issued from it have been glaciated, an indication that their age is late Pleistocene, not Holocene.

0.2/125.2 Big Lake Road rounds the east flank of Hayrick Butte.

0.6/125.8 View of Mount Washington, a basaltic andesite shield volcano.

Although undated by isotopic methods, Mount Washington has an erosional form characteristic of shield volcanoes ranging in age from about 0.3 to 0.5 Ma and located at the Cascade Range crest. Farther east, older volcanoes are better preserved because of their position in the Cascade Range rain shadow.

1.3/127.1 Minor road intersection. **Keep right on main road toward Big Lake.**

0.1/127.2 **Turn right, leaving the paved road for cinder Road 2690-810 to Sand Mountain.** Note the gently rolling constructional topography, an extreme contrast to the steep, dissected slopes of the Western Cascades. This contrast will become even more obvious from the summit of Sand Mountain.

2.4/129.6 Obscure junction, one of several as this road anastomoses westward. **Continue west, following the small, orange, diamond-shaped tags nailed to trees,** which are the snowmobile route indicators for this same road.

This large area across Santiam Pass was burned by the Airstrip fire of 1967; see Jones and Johnston (1968) for graphic description of the fire. Reforestation is almost entirely with lodgepole pine.

0.5/130.1 **Turn left to remain on Road 2690-810.** Do not continue straight ahead on the poorly maintained spur Road 2690-866.

1.7/131.8 **Parking area at end of Sand Mountain Road;** locked gate bars vehicle passage beyond this point. The summit viewpoint can be easily reached by foot.

Stop 6—Sand Mountain.

A short trail leads to the summit of Sand Mountain. The Sand Mountain Natural Research area was once open range for off-road vehicles but has since been preserved, thanks to the almost single-handed efforts of Don Allen and the Sand Mountain Society. Allen spent part of his youth on Sand Mountain as the son of a fire lookout. The trail (an abandoned road) ascends above the crater of Sand Mountain,

which is still scarred by off-road vehicle tracks. The lookout tower at the summit survived the Airstrip fire of 1967 but burned accidentally in 1968. It has since been replaced by an architecturally authentic grange-hall style lookout (gabled roof is diagnostic). Windows and some of the framing for the replacement structure came from a tower that once sat on Whiskey Peak in the Siskiyou National Forest; restoration has been completed in the last five years. An historic outhouse (diagnostic criteria uncertain) was being relocated to Sand Mountain from Black Butte in the summer of 1992. Presumably some equally historic part of the outhouse remains at Black Butte.

Sand Mountain is the highest geographic feature of the Sand Mountain chain of 23 cinder cones and associated lava flows. Eruptions occurred in two principal episodes, approximately 3,800 and 3,000 years ago, and the composition of lava ranges from subalkaline basalt to basaltic andesite (Taylor, 1981, 1990). Figure 7 shows the extent of Holocene lava flows in vicinity of Santiam Pass. The mountain's summit affords excellent views of prominent peaks in the central Oregon High Cascades—from the Three Sisters on the south to Mount Jefferson on the north—and on a clear day it is possible to pick out Diamond Peak, 110 km south-southwest. Santiam Pass, the low divide between Mount Washington and Three Fingered Jack, has been a major Cascade crossing throughout recorded history. Directly east 24 km is Black Butte, a 1.4-Ma basaltic andesite shield volcano (Hill and Priest, 1992), spared the ravages of glaciation by its position in the Cascade Range rain shadow.

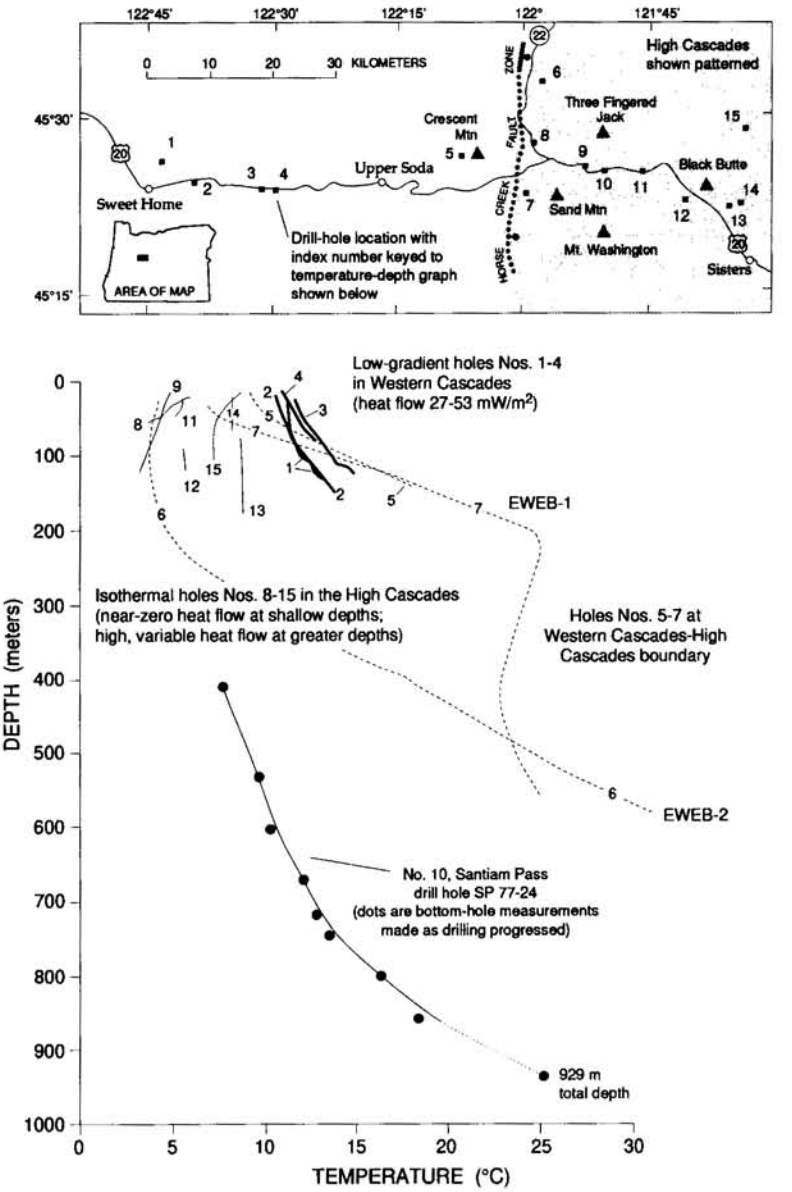


Figure 17. Map showing geothermal-gradient holes located along east-west transect crossing Santiam Pass. Note how temperature-depth gradients are grouped according to geographic position: bold lines show low-gradient holes from Western Cascades; dotted lines show high-gradient holes at Western Cascades-High Cascades boundary; and thin lines show isothermal holes in High Cascades. The 929-m-deep hole SP 77–24 at Santiam Pass (no. 10 on map and graph) penetrated so-called "rain-curtain" that results from large amounts of groundwater infiltrating in the High Cascades. That hole was isothermal above about 400-m depth.

Three geothermal drill holes at least 500 m deep have been sited in the area (Figure 17). Eugene Water and Electric Board (EWEB) drilled two geothermal prospect holes on the western slope of the High Cascades during 1979 (Youngquist, 1980). The first, EWEB–1, was drilled to a depth of 560 m and is located 4.5 km west of Sand Mountain near Clear Lake (Keith and Boden, 1981a). The second, EWEB–2, was drilled to a depth of 587 m and is located 18 km north-northwest of Sand Mountain near Twin Meadows (Keith and Boden, 1981b). During 1990–91, a third, 929-m-deep scientific observation hole SP 77–24 (see milepoint 124.1), was drilled 7 km northeast of Sand Mountain at Santiam Pass to assess the geothermal resource potential along the axis of the High Cascades (Hill and others, 1991; Hill and Benoit 1992).

The geomorphic contrast between Western and High Cascades is strikingly visible from Sand Mountain: the broad volcanic ridge of the High Cascades contrasts with deeply incised canyons of the Western Cascades. Also visi-

ble here is a marked structural contrast between Western and High Cascades not present everywhere along the arc. From south of Mount Jefferson to nearly the Three Sisters, the High Cascades are in a distinct graben that formed after about 4.5 Ma (Taylor, 1981; Smith and Taylor, 1983). The eastern graben-bounding faults form the Green Ridge fault zone (Figure 7). The western graben-bounding faults form the Horse Creek fault zone, which coincides with the topographic boundary between High Cascades and Western Cascades from about McKenzie Bridge northward nearly to Mount Jefferson (Figure 7). Hot springs south-southwest of Sand Mountain are found in the McKenzie River valley (Belknap and Foley Springs, and the Bigelow hot spring). Farther west, Terwilliger Hot Spring is separated from potential magmatic heat sources in the High Cascades by topographic barriers resulting from eastside-down offset on the Horse Creek fault zone and by the canyon of the South Fork McKenzie River.

Displacement on the Green Ridge and Horse Creek fault zones took place in late Miocene and early Pliocene time. Motion along the Green Ridge fault zone isolated the Deschutes basin from now-buried volcanic centers in the High Cascades beginning about 5.4 Ma (Smith and others, 1987). Rocks as young as about 5 Ma are exposed at the top of the 650-m escarpment of Green Ridge (Armstrong and others, 1975), whereas the downthrown block is mantled by Pliocene and Quaternary sedimentary deposits. Displacement is at least 1 km, on the basis of an age of 1.81 Ma from the base of drill hole SP 77–24 at Santiam Pass (Hill and Priest, 1992).

The Horse Creek fault zone has displaced 5- to 6-Ma strata as much as 670 m down along one fault trace north of the McKenzie River (Brown and others, 1980); cumulative mapped offset is as much as 850 m south of the McKenzie River (Priest and others, 1988). An additional 400 m of offset may be indicated by a steep unconformity perhaps resulting from lava buttressing a fault escarpment in the vicinity of Scott Creek (Priest and others, 1988). Thus, demonstrable graben subsidence is on the order of about 1.4 km. Headward erosion by the McKenzie River breached the escarpment by late Pliocene time, and the basalt of Roney Creek flowed from a source in the High Cascades westward across the fault trace and along the McKenzie River valley at about 1.7 Ma (Priest and others, 1988). The fault has been inactive since the emplacement of the basalt of Roney Creek.

COCORP (Consortium for Continental Reflection Profiling) seismic reflection experiments were conducted across the Cascade Range between lat 44°10′ and 44°15′. The seismic line has high noise-to-signal ratios and fails to establish the magnitude of offset on the Horse Creek fault zone (Keach and others, 1989). The line ends eastward near the town of Sisters, where offset on the Green Ridge fault zone may have decreased to less than 100 m.

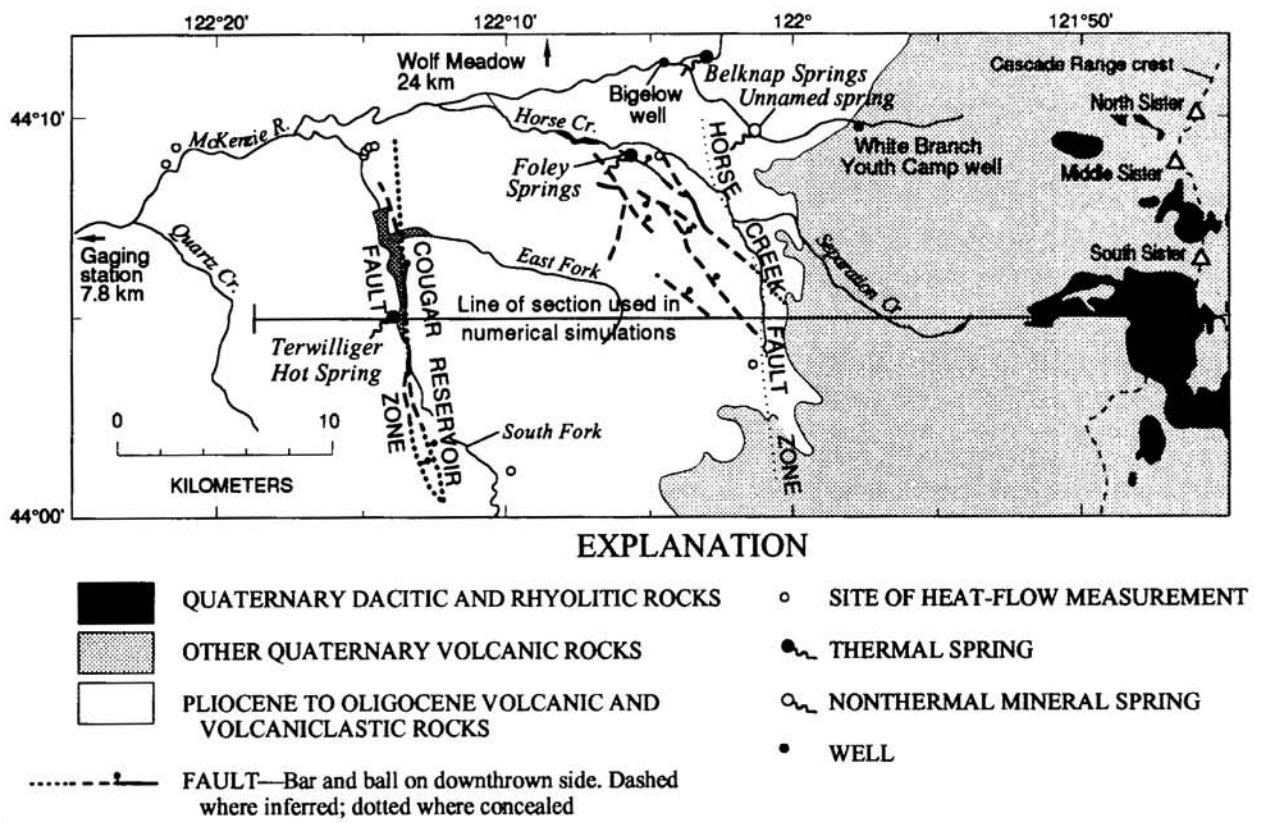


Figure 18. Map and line of section for numerical simulation of McKenzie River area (from Ingebritsen and others, 1992).

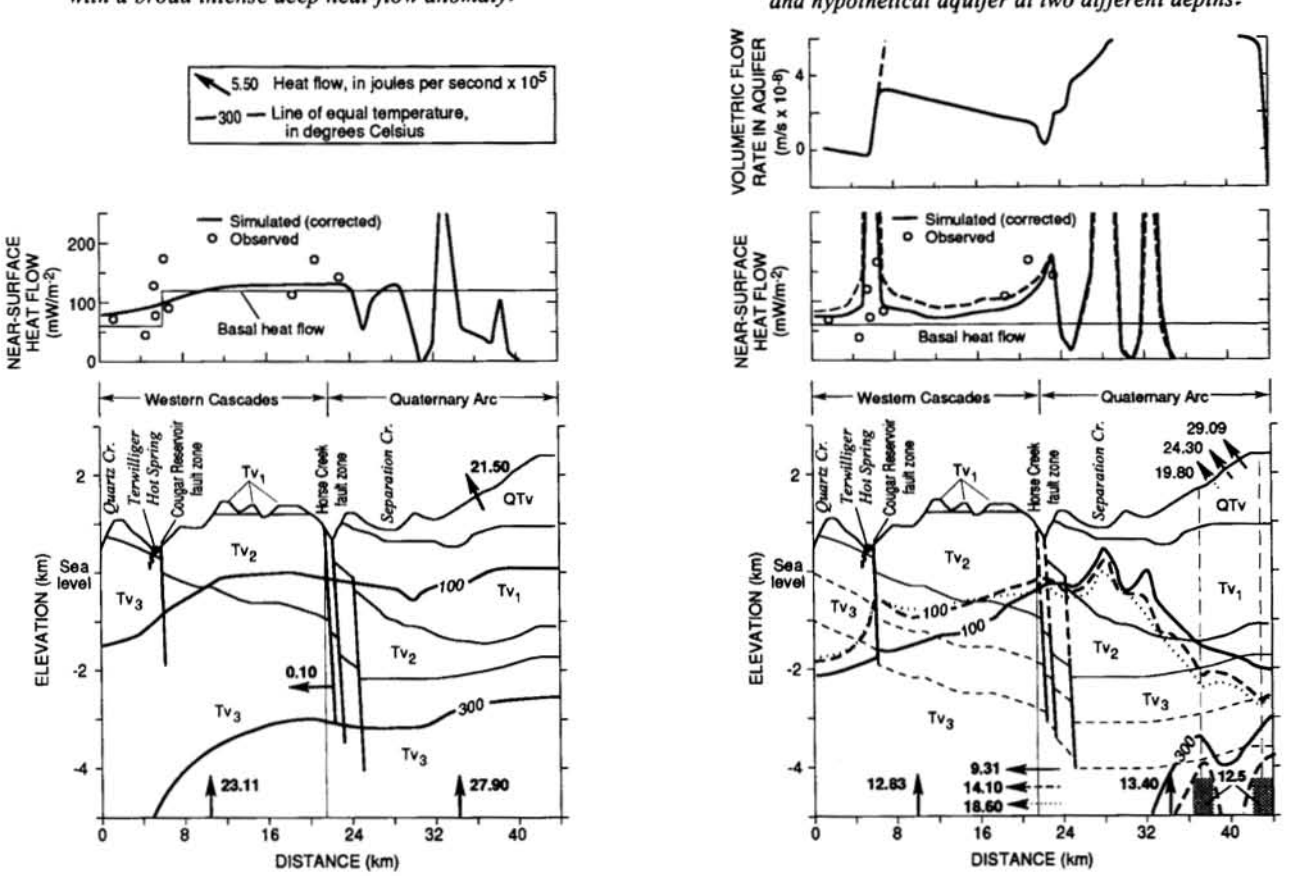


Figure 19. Numerical simulations for area of McKenzie River group of springs, showing matches to the sparse near-surface heat-flow observations (from Ingebritsen and others, 1992): A—Conduction-dominated model involving fluid flow only in shallow volcanic rocks. B—Advection-dominated model with localized heat sources. Map-unit symbols same as Figure 13.

Numerical simulations of a cross section through Terwilliger Hot Spring (Figures 18 and 19) show that any flow across topographic and structural barriers between the hot springs and the High Cascades must be at depths of several kilometers (Ingebritsen and others, 1992). At shallower depths, lateral flow is interrupted by faults and (or) topographically low areas. For example, the simulation models predicted substantial discharge of heated groundwater in the topographically low area along Separation Creek in the Three Sisters Wilderness (Figure 19). Subsequent measurements identified an anomalous Cl flux near the predicted location; the flux, about 10 g/s, is larger than the fluxes from some of the known hot springs in the McKenzie River group. Thus, the predictive value of the numerical simulations was established in at least this limited respect.

Retrace route back to Big Lake Road (pavement) and then north to U.S. Highway 20.

7.7/139.5 Junction, Highway 20. **This ends the field trip.** For a field-trip guide that continues east or west, the traveler is referred to Taylor (1981).

GEOTHERMAL POWER IN PERSPECTIVE

Investigations of geothermal energy resources led to much of the research reported in this guide. High petroleum prices in the 1970s prompted a surge of such studies, but interest in alternative power sources sagged during the energy-easy 1980s. The Pacific Northwest has lived through a decade of power surplus, but the next decade may find the region in an energy deficit. Indeed, in July 1992, the Bonneville Power Administration (BPA) announced plans to build its first new power plant since the completion in 1983 of Washington Public Power Supply System's nuclear plant in Richland, Washington (Koberstein, 1992). The new plant, to be built near Tacoma, Washington, will burn natural gas in combustion turbines to produce an average 240 MW_e, enough power for a city of 150,000 (slightly larger than Eugene, Oreg.). An additional 1,380 MW_e of power is needed by the year 2003 to avoid building any expensive nuclear or coal-fired power plants for at least the next 20 years (Bella, 1992b). BPA reportedly can obtain 780 MW_e (the equivalent of one nuclear plant or Portland's energy use for 16 months) from increased energy conserva-

tion and improved efficiency of transmission lines and turbine generators at dams. Another 50 MW_e would come from major electricity users who find ways to shave their loads in exchange for billing credits. The agency also has agreed to purchase 300 MW_e of power from producers of renewable energy, such as geothermal wells and windmills (Bella, 1992b). Portland General Electric (PGE), a northwest power company, is involved in more than a dozen programs that focus on both residential and commercial energy saving. In 1991, the programs accounted for 5 MW_e of energy saved, enough energy to run about 3,500 homes. For example, low-flow showerheads distributed by PGE are expected to save more than 1 MW_e by the end of 1992, enough energy saved to serve 800 residences (Christensen, 1992).

Given the magnitude of projected energy needs, renewable energy sources will only slightly satisfy our insatiable desire for power. The promise of geothermal energy from the Cascade Range remains cloaked by hydrogeologic problems that make exploration and development a challenge.

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Important notice on this issue's field trip

We have learned from the Oregon Department of Transportation (ODOT) that the stretch of Highway 224 between this trip guide's cumulative milepoints 23.5 and 28.9 is **closed indefinitely**. Access to the point of continuation, milepoint 29.4, from the north (Portland) would be via Highway 26, Forest Road 42 (Clear Lake to Timothy Lake), and Forest Road 57. From the south, access to Forest Road 46 is from Highway 22 at Detroit (including part of the field trip in reverse direction).

ODOT offers telephone information on highway conditions for a charge of 30 cents at (503) 976-7277 and (541) 889-3999. National Forest Ranger Stations may provide similar (but less official) information. □

ABSTRACTS OF PAPERS

The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.

Tsunami disaster planning in Clatsop County, Oregon, by Paul Visher, Tsunami Coordinator.

The Clatsop County oceanfront extends south from the mouth of the Columbia River for about 40 mi to Tillamook County. It includes four incorporated cities and two oceanfront communities.

On first impression, one might consider a common disaster plan for all, but, on more detailed analysis, the actual plan varies from location to location, depending on bridges and local topography. [The following discussion proceeds] from north to south:

The City of Warrenton is protected from tsunamis by a major foredune system having a 50-ft elevation and by the south jetty of the Columbia River. This jetty was initially built in the 1880s and extended in the 1930s. According to the Corps of Engineers, the jetty was built with major rocks of 3–6 ft in diameter with seismic considerations. What will happen to this structure during a magnitude 8+ quake? No one knows for sure, but the best guess would postulate a pile of rocks at a lower elevation but still high enough to significantly restrict the flow of water into the mouth of the Columbia from the projected 16-ft-high tsunami. This projected elevation comes from the Alaska Tsunami Warning Center (ATWC), whose studies indicate a residual 3- to 4-ft wave at Warrenton. Of equal concern in Warrenton is the failure of the 14-ft-high dikes that protect the city from tidal flooding. None of these dikes was engineered to any seismic standards. Warrenton's major threat appears to come from flooding due to dike failure, not a tsunami velocity threat.

Surf Pines is the next area south. Homes are constructed on two parallel dunes—a coastal frontal dune about 30 ft high and a landward dune of 50-ft elevation. The ATWC computer model indicated a 16+ ft wave. Prudence indicates an evacuation to the 50-ft elevation.

At Gearhart, the primary dune, about 600 ft landward of the oceanfront, varies in elevation from 60 to 70 ft. There are large areas of residential construction along lower areas to the east. Much of this construction is at 14 ft, which is the FEMA 100-year storm flood elevation. There is evidence of tsunami deposits at higher elevations. The general evacuation route is to move people to the 60 ft dunetop elevation.

The next town south, Seaside, provides the most complex disaster-planning challenge. The town is located on two sand dunes running parallel to the ocean. The frontal dune is about 20 to 25 ft high and is protected from ocean erosion by a 20 ft-high seawall that was constructed in the 1920s. The second dune varies from 18 to 25 ft in elevation. These dunes are separated by a river crossed by several bridges, none of them designed with seismic consideration. They are assumed to fail. Major motels are located on the forward dune system that can act as a breakwater against the tsunamis, which are projected by the ATWC to be 17 ft high during a magnitude 8.8 quake. Behind the second dune system is a 5,000+ acre storage sump for water below the 18-ft elevation. The tsunami "inundation" area is defined by the in- and out-flow of water that passes the 1,000-ft gap in the dunes between Gearhart and Seaside. The difference in the input and output flows will define the amount of water that must be stored by the sump and raise its water level. There is a reasonable chance that the second dune would provide an island of safety except for the most severe tsunami.

Seaside is planning to reinforce some of the bridges between these lower dunes, as well as some of the bridges from the east dune to the foothills. When these bridges are reinforced, the evacuation route should clearly go to the 40+ ft elevations on the hills east of town.

In Cannon Beach, the next town south, the computer model from ATWC indicates a 17-ft wave from a magnitude 8.8 event. The school and the major downtown area are located at about 12-ft elevation. Fortunately, the town has 40+ ft elevations within 15 minutes walking distance. People in parts of the city can easily walk to the 50- and 60-ft elevations. A bond issue was recently passed to build a new fire station at 40-ft elevation, and a bond issue is being discussed to move the school to a "tsunami-safe" location.

Further south, the area of Arch Cape is confronted by a computer model of a 18 ft wave and walking evacuation routes of 15 minutes or less to reach 50-ft elevations away from the beach.

Except for Seaside, every person in Clatsop County can walk, in 20 minutes or less, to an elevation 10 ft or more above the computer-model tsunami for a magnitude 8.8 subduction zone earthquake event. How good is the model?

Dr. Peterson is using core borings, landward of barriers, to measure the sand deposited in past events. This will bound some of the uncertainties. Dr. Baptista is inputting some of Dr. Peterson's data to revise the model.

At the present time, the disaster planning is based on the ATWC model and the subsidence event occurring at the highest tide, about a 10-ft maximum range; the measured subsidence of about 5 ft, different from the 2 ft in the model; and a time of arrival of about 25 minutes after the event. To me, the most unexpected information from the computer program is the long period, four to five hours, that people should stay away from the lower areas because of repetitive waves.

The computer model from the ATWC, modified by measured subsidence information from Dr. Peterson, is the best information that we now have for planning. When better data are available, the tsunami disaster plan will be modified.

In the meantime every coastal resident in Clatsop County has been provided with instructions as to action he or she should take in case of an earthquake. Programs are being developed to strengthen the bridges, change the locations of the schools and fire stations, and design them to survive a magnitude 8+ event.

We hope it doesn't happen during our lifetimes, but it could happen tomorrow. □

Unusual landscapes and geologic problems in the Pacific Northwest

by John Eliot Allen, Emeritus Professor of Geology, Portland State University, P.O. Box 751, Portland, OR 97207–0751

Geologists and laypersons alike are familiar with the chain of High Cascade volcanoes (Williams, 1953; Allen, 1984), which reach from British Columbia to northern California, the most prominent being Mount Rainier in Washington, Mount Hood in Oregon, and Mount Shasta in California. Most of us are also familar with the two great collapsed volcanoes known as "calderas," Crater Lake (Williams, 1942) and Paulina or Newberry Crater (Williams, 1935).

There are, however, at least five other unusual and remarkable landforms in the Pacific Northwest that are less familiar and may have origins that are of interest, since there are still questions to be answered and alternate hypotheses to be considered. These are the Channeled Scablands, the Mima Mounds, coastal and Willamette Valley terraces, great landslides, and great Tertiary rivers.

I. Channeled Scablands: Areally, the most widespread landform, the Scablands cover nearly 16,000 mi^2 of eastern Washington and affect the Columbia River Gorge, Willamette Valley, and a small area north of Newberg, Oregon, known as the "Tonkin Scablands." J Harlen Bretz first suggested in 1923 that these dry valleys were cut in the loess and underlying basalt by a gigantic flood. Later authors have proposed at least 40 and perhaps a hundred floods, occurring between 15 and 12 thousand years ago at the end of the Pleistocene (Allen, 1986; O'Connor and Waitt, 1995).

II. Mima Mounds: One of the still puzzling landscapes in the Pacific Northwest consists of "Mima Mounds", whose type locality is south of Tenino, Washington. More than a dozen hypotheses have been advanced to explain the fields of hundreds of mounds, which are about a yard high and 4-5 yards in diameter. Similar mounds occur in Oregon in such places as upon the basalt of Tom McCall State Park in the Columbia River Gorge. Hypotheses include gophers, earthquakes, glacial deposits, and wind erosion of volcanic ash over depressions in basalt. It is highly probable that Mima Mounds have multiple origins, but although many papers have been published, the issue is still moot.

III. Terraces: Most of the coastal towns along Highway 101 are located upon the lowermost (50-foot) of a series of marine terraces first described by Diller in 1902. These are wave-cut platforms resulting from upper Tertiary and post-Pleistocene changes in sea level, and so far few of their ages and locations have been mapped. Little attention has been paid to the terraces, first noted by Condon and later by Allison (1936). (Madin and others [1995] mapped such terraces in the Charleston quadrangle. —ed)

IV. Landslides: Great landslides have recently been recognized as having been caused by great earthquakes. The 14-mi^2 Cascade Landslide in the Columbia River Gorge at Bonneville has been dated at about 800 to 1,000 years ago. The mud slide that buried an Indian village on the Olympic Peninsula coast west of Ozette occurred about 400 years ago. Landslides that formed Triangle and Loon Lakes in the southern Coast Range have yet to be dated.

V. Great Tertiary rivers of eastern Oregon: High-level gravel deposits, many of them gold-bearing, have been found high on the summits of the Wallowa Mountains and on the crests of many other ridges (Allen, 1991). They contain numerous and sometimes very large boulders of quartzite and other metamorphic rocks from the Rocky Mountains and must represent at least one very large Tertiary river, either an ancestral Columbia or Snake River. Little has been published as yet on these rivers.

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BLM offers grace period for mining claims

The U.S. Bureau of Land Management (BLM) is urging mining claim holders to apply for a one-year "grace period" that will give them extra time to comply with a new rule published in July 1996 that is intended to stop squatters from illegally occupying land on mining claims they are using for nonmining purposes.

Current claimants may continue their occupancies for one year, provided they fill out and sign a simple form available from any BLM office. The forms must be received in a BLM office or postmarked by October 15, 1996. □

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Cover photo

Northward view toward Pelton Dam on the Deschutes River. Article beginning on next page discusses recently found fossil flora from a locality nearby. Tcr = Columbia River basalt ;Td = Deschutes Formation ;Ts = Simtustus Formation; dashed line = unconformable contact. Photo prepared by Gary A. Smith.

DOGAMI receives WSSPC award for earthquake mitigation work

At its annual conference in Polson, Montana, the Western States Seismic Policy Council (WSSPC) honored the Oregon Department of Geology and Mineral Industries (DOGAMI) with two Awards in Excellence for its mitigation and public-information activities for earthquakes in the Portland metropolitan area and tsunami hazards on the Oregon coast

State Geologist Donald A. Hull explained, "The Award of Excellence was given to DOGAMI because the results of its scientific research were applied across traditional agency boundaries to a real-world hazard in a timely way to reduce risk to people and property."

DOGAMI geologists and engineers, in cooperation with Metro, the Portland regional government agency, developed ground-response data that were used in a variety of ways, for instance, for relative earthquake hazard maps.

For the entire Oregon coast, scientists from DOGAMI, the Oregon Graduate Institute, and Portland State University developed maps showing the areas expected to be inundated by a tsunami from a moderate-sized earthquake. These maps are now being used to guide development of critical buildings on the coast. DOGAMI's public education program includes historical markers about tsunamis, tsunami warning and evacuation signs, and brochures. □

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Klaus K. Neuendorf, Editor

The Pliocene Deschutes fossil flora of central Oregon: Additions and taphonomic notes

by Melvin S. Ashwill, 940 Southwest Dover Lane, Madras, Oregon 97741

ABSTRACT

The 1990–1991 widening project on Oregon State Highway 26 about 8 mi (13 km) northwest of Madras, Oregon, exposed numerous well-preserved, earliest Pliocene leaf and seed compressions and impressions from a locality known and studied since 1935. In the excavation, more than 40 large boulders holding over 8,000 fossil leaf specimens were recovered. The specimens provide new data on the taxonomic composition, relative species abundance, and taphonomy of the Deschutes flora. Taphonomic interpretations are related to the author's observations of leaf deposition in the Toutle River mudflow associated with the 1980 eruption of Mount St. Helens. Considered along with data from several other local florules, the data from the Deschutes locality indicate that a significant geologic event took place somewhere around 6 or 7 million years ago to alter the climate of central Oregon in a relatively short time to a considerable degree.

INTRODUCTION

Located in the rain shadow of the central Oregon Cascade Mountains, the Pliocene Deschutes flora preserved a record of plant life during a time when the regional climate was being altered by two major factors. The first was the rather abrupt decrease in temperature and precipitation that took place about six or seven million years ago. The second factor was structural geologic change, including both a region-wide crustal uplift and a continuation of the elevation of the High Cascade Mountains. These two events led to an enhancement of continental weather characteristics in the area: wider temperature extremes and decreased precipitation, particularly less summer rainfall.

When the present grade for Highway 26 from the Deschutes Canyon to Agency Plains ("Vanora Grade" in Chaney, 1938) was first laid in 1935, fossil leaves were discovered and studied (Chaney, 1937, 1938, 1948b). During the 1990–1991 widening of the road, a much more extensive collection was made, consisting of more than 40 boulders. This paper discusses the new fossil evidence.

Fossil localities of the author are identified with the prefix "MSA" and are registered with the Florida Museum of Natural History, Gainesville, Florida.

OCCURRENCE

The fossil leaves at the Deschutes flora locality were found in a road cut on the north side of Highway 26 about 8 mi northwest of Madras in Jefferson County, Oregon (Figure 1). The fossiliferous material is about 66 ft (20 m) west of milepost 110 and is about 180 ft (59 m) below the top of the rimrock. The exposed cliff face shows a thick layer of black sand at road level (Figure 2). Above this are the gray rocks of the mudflow that engulfed a riverside grove of trees there about 5.3 million years ago. With close inspection, limb molds can be seen. The locality coordinates are NW¼NE¼ sec. 8, T. 10 S., R. 13 E.

AREA GEOLOGY

The fossils are in rocks that were formed by a series of mudflows as part of the upper Deschutes Formation (Smith, 1987, 1991). On some maps and in some literature this formation has been referred to as the Madras Formation and sometimes has been considered to be part of The Dalles Formation.

The oldest rocks in the area are of the Oligocene-Miocene John Day Formation. It is exposed in the Deschutes Canyon near the fossil locality, at the foot of the road grade. The youngest lavas were erupted from Round Butte, a basaltic shield volcano about 7 mi (11 km) west of Madras, Oregon. Flows of the Round Butte member of the Deschutes Formation have been dated at 3.9 Ma and were erupted onto the Agency Plains flow of the Tetherow Butte member that has been dated at approximately 5.3 Ma (Smith, 1987) and forms the rimrock of Agency Plains, the mesa to which Highway 26 ascends at the fossil locality. The Round Butte and Agency Plains lavas, as well as some underlying pyroclastic material, sediments and lavas, make up the upper Miocene to lower Pliocene portion of the Deschutes Formation here, including the lowest basalt flow in the formation, the approximately 7.4-Ma Pelton basalt member (Smith, 1987). All of the rocks exposed in the upper levels of Campbell Creek canyon at the fossil locality are part of this formation.

The lower portions of the canyon walls expose the middle Miocene Simtustus Formation (Smith, 1986a). These rocks are also exposed in the lower parts of the Deschutes Canyon near Pelton Dam, a few miles southwest of the fossil locality (cover photo), and in the lower parts of some valleys around Gateway, Oregon, about 8 mi (12.9 km) to the northeast. In the Deschutes Canyon, near the fossil locality, the Simtustus Formation overlies flows of the Columbia River Basalt Group, Prineville chemical type. This basalt type is exposed in places from near Bowman Dam, south of Prineville, Oregon, along ancient valleys of the ancestral Crooked and Deschutes Rivers and interfingers with the major part of the Columbia River Basalt Group east, north, and northwest of the Mutton Mountains. The relationship of the Prineville chemical type flows with the Columbia River Basalt Group is currently being reeval-

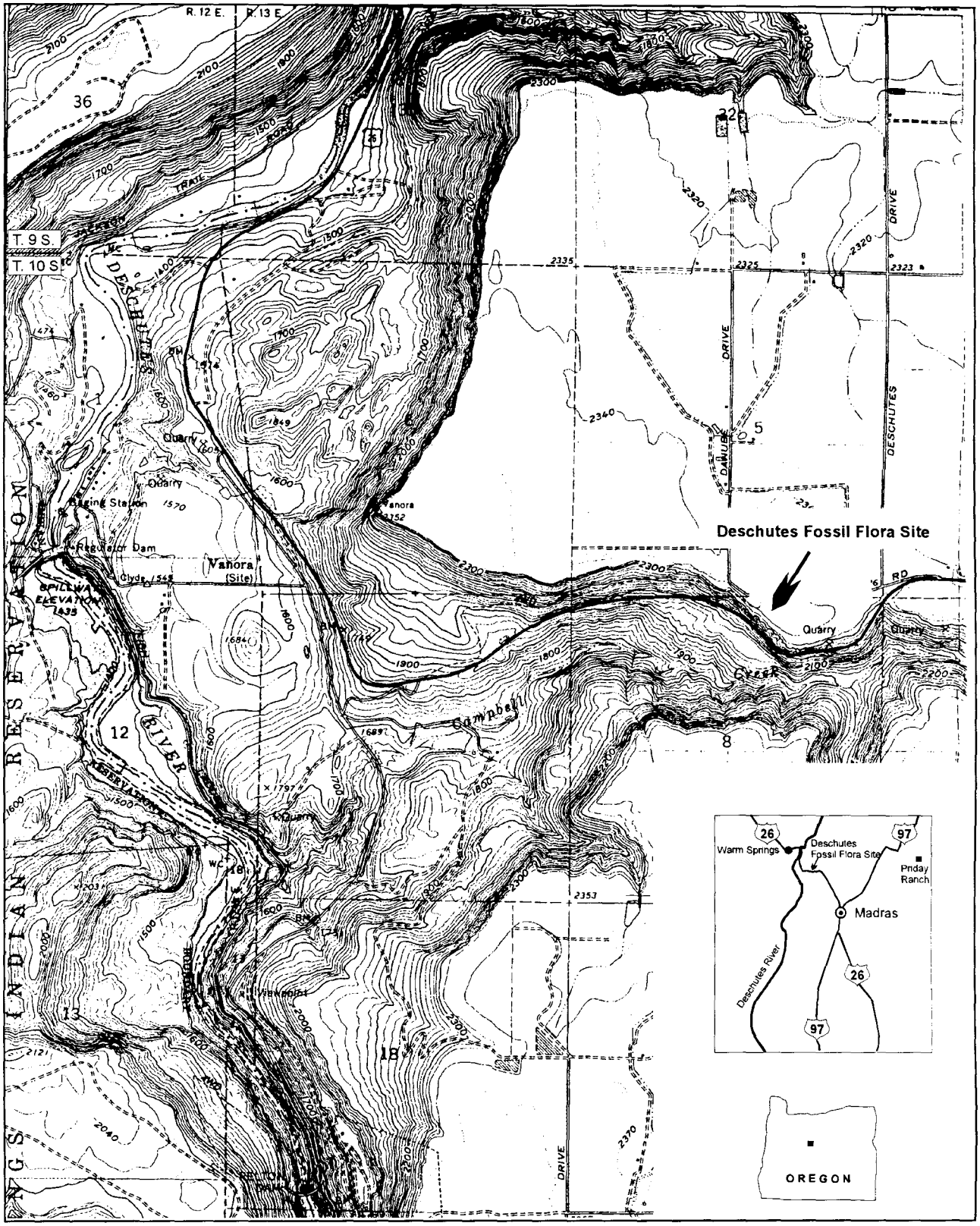

Figure 1. Map showing location of Deschutes fossil locality (NW¼NE¼ sec. 8, T. 10 S., R. 13 E.) on Highway 26 near Madras in Jefferson County.

Figure 2. Views of the Deschutes fossil locality before (top) and after (bottom) the 1990–1991 excavation. "Before" photo still shows remnants of vertical tree-trunk molds.

uated (e.g., Hooper and others, 1993). Pelton Dam is anchored in Columbia River basalt.

The above-mentioned rocks as well as some younger rocks in the Redmond/Lower Bridge area together comprise valley fill for the central part of the Deschutes Basin. The middle Deschutes River basin is a broad depression between the mainly Oligocene and Eocene Ochoco Mountains to the east and the younger volcanic rocks of the High Cascades to the west.

Below the formations mentioned lies the John Day Formation, Oligocene and Miocene in age (Smith, 1987). It extends eastward from the Ochoco Mountains, eventually disappearing beneath the Deschutes Formation and possibly extending under the eastern part of the Cascade Range in the vicinity of the study area. It is exposed below the Columbia River basalt in the lower parts of the Deschutes Canyon at the foot of the grade near the fossil locality and can be viewed for some distance to the north in the lower parts of the canyons. It is also extensively exposed north in the Mutton Mountains and east toward Ashwood, Oregon.

PAST WORK

The occurrence of fossil leaves at the Deschutes flora locality was first reported in 1935. L.S. Cressman, anthropologist and archaeologist at the University of Oregon, visited the locality and made a collection of the leaf impressions, which still remains housed at the University of Oregon Museum of Natural History. R.W. Chaney along with Phil Brogan and Lewis Irving of Madras visited the locality during the summer of 1936 and collected specimens. Chaney also collected that same year with C. Condit of Berkeley and A.W. Hancock and A.D. Vance of the Geological Society of the Oregon Country, Portland, Oregon (Vance, 1936). A thorough study of the fossils recovered was published in 1938 (Chaney, 1938). At that time, only a very small number of collections of Pliocene fossil floras were known worldwide, which represented a weak basis for conclusions about paleoclimate. The new collection of specimens has strengthened that basis.

1990–1991 COLLECTION

Approximately 40 boulders of different sizes were removed from the mudflows that had filled the old river valley here to a depth of more than 25 ft (7.6 m), covering the old river bed and the areas on both paleobanks (Figure 3). Rocks taken from directly above the old river bed did not produce much fossiliferous material. Those from the riversides, however, were a treasure trove. Many single blocks as large as 10 ft (3 m) in diameter contained hundreds of excellently preserved leaf impressions per block. Almost all of the impressions were on a single parting layer, a flat surface that had lain exposed horizontally long enough for a rain of leaves to accumulate, before another surge of the mudflow covered it.

Fifteen of the boulders are now at the Warm Springs Indian Reservation. They are being used there in the landscaping of The Museum at Warm Springs. Two are displayed at the Jefferson County Library in Madras. Two are on display at the home of the author (Figure 4). One is on display at the Jefferson County fairgrounds in Madras. Three were placed in the State Highway Division compound at the top of the grade near the fossil locality, where an interpretive display is planned. The rest are being used in construction of an impressive display wall at the new Juniper Hills Park on the east side of Madras. Thousands of specimens are thus available for viewing by the public and study by scientists.

DISCUSSION

On the approximately 40 large blocks of stone that were saved, it is estimated that between 8,000 and 10,000 specimens were found. Most of these are duplicates of the species

Figure 3. Top: Author standing among field of large boulders from Deschutes fossil locality, each boulder holding dozens to hundreds of leaf fossils. Bottom: Loading fossiliferous boulders on truck for transport to display site.

originally listed by Chaney (1938). Cottonwood (*Populus alexanderi*) remains the overwhelmingly dominant taxon among the fossil leaves at this locality.

Chaney's (1938) study listed five species from this locality as known at the time:

Salix florissanti Knowlton and Cockerell [willow]
Populus pliotremuloides Axelrod [quaking aspen]
Populus alexanderi Dorf (Chaney, 1938) [cottonwood]
Prunus irvingi Chaney [cherry/plum genus]
Acer negundoides MacGinitie [box elder]

The *Prunus* identification was based on only two leaf impressions. In a later publication, Chaney and Axelrod (1959) concluded that of the two earlier identifications one was actually *Populus alexanderi* Dorf (Chaney, 1938) and the other probably *Salix*. This left a floral list numbering four. A later find by this author of a partial Quercus (white oak) leaf once more raised the total to five (Ashwill, 1983).

In the 1990–91 collection, a large number of leaf impressions compared favorably with the two abovementioned specimens originally identified as *Prunus* but later rejected by Chaney and Axelrod (1959). Axelrod examined some of those fossils and identified them as juvenile-growth leaves of *Populus alexanderi*.

The anomalous morphology known as "juvenile leaves" occurs either when seedlings put out their first leaves or when especially intense growth that often occurs after damage reduces the tree to little more than a stump ("breaking back") and leaves the plant with a root system that produces a great deal of nutrient for a small amount of growth. The structure of such "juvenile leaves" does not closely resemble that of mature leaves of the species, whereas leaves that develop later do so. Some botanists feel the juvenile leaves may bear a resemblance to their evolutionary progenitors.

Several specimens of *Quercus* (white oak) were found, which confirms the validity of the single specimen found earlier by Ashwill (1983).

Elm (*Ulmus* sp.), madrona (*Arbutus* sp.), Oregon grape (*Mahonia* sp.), horsetail (*Equisetum* sp.), *Spiraea* sp., rose (*Rosa* sp.), black oak (*Quercus* sp.), hawthorn (*Crataegus* sp.), and juvenile leaves of cottonwood (*Populus alexanderi*) can now be added to the Deschutes flora plant list. In addition, a second species of cottonwood was recovered: *Populus subwashoensis* Axelrod, with extremely large teeth. This brings the number of identified taxa to 14. There are also specimens not yet identified that appear to represent at least two additional species. A few impressions of grasses along with winged fruits of box elder were also found.

The willow leaves may represent two species. They exhibited a very wide range of size: Some were as long as 4.5 in. (11.4 cm), while a sizable group was in the range of 1.5–2 in. (3.8–5 cm). Since size difference alone usually is not sufficient evidence to support identification of a separate species, this question awaits further study.

Not all of the material has as yet been examined, and thus this paper is preliminary. Recognizing this, we can present the following, newly revised plant list for the Deschutes flora:

Equisetum sp. [horsetail]
Mahonia marguerita Smiley? [Oregon grape]
Ulmus sp. [elm]
Quercus sp. [black oak]
Quercus sp. [white oak]
Salix florissanti Knowlton and Cockerell [willow]
Populus pliotremuloides Axelrod [quaking aspen]
Populus subwashoensis Axelrod [cottonwood]
Populus alexanderi Dorf (Chaney, 1938) [cottonwood]

Figure 4. Fossiliferous boulders from Deschutes flora locality displayed at author's home.

Arbutus sp. [madrona]
Rosa sp. [rose]
Spiraea? sp. [spiraea]
Crataegus sp. [hawthorn]
Acer negundoides MacGinitie [box elder]
Incertae sedis [unidentified species]: 2

Plates 1 and 2 present a selection of fossil leaves from the collection of 1990–1991.

AGE

The age of the Deschutes Formation mudflow unit containing the fossil locality is bracketed by the 5.3-Ma age (Smith, 1987) of the overlying Agency Plains basalt flow of the Tetherow Butte member and the 7.4-Ma age (Smith, 1987) of the underlying Pelton basalt member.

The age of the fossiliferous rocks received two K-Ar measurements (Evernden and James, 1964). One measurement produced an age of 4.3 Ma, the other of 5.3 Ma. Since the 4.3-Ma age would make the fossiliferous rocks younger than the overlying strata, it appears to be spurious, and the age accepted here is 5.3 Ma. That the rimrock lies some 66 ft (20 m) above the fossiliferous rocks and yet the two are thought to be correlative in age can be explained. The ancient Deschutes River had eroded a low valley into the paleolandscape. When the Agency Plains lava covered the surface it also flowed down into the river valley where the riparian deposits were the same age as the plains overlooking them.

CORRELATIVE ANIMAL LIFE

As is usual with leaf fossil localities, no vertebrate fossils were found. Documentation from other sources makes it clear, however, that the groves of trees along this portion of the old Deschutes River were surely frequented by an array of animals that would in general seem familiar to us today. Horses and members of the wolf, bear, and cat families lived at the time, also deer and antelope and birds of many types. In addition, animals that would now seem out of place were alive in central Oregon 5.3 million years ago: Rhinoceroses, abundant for many millions of years, were still around, but in diminishing numbers. Camels continued to abound. Bison were present. A mammoth may readily have walked through the groves before they were inundated. Fossils of all of these and many more animals have been found in central and eastern Oregon. Many of the exotic species lasted until as recently as 4,000 years ago and coexisted with early man. Carpal and metacarpal bones of a very large camel were recovered from a mudflow at nearly the same stratigraphic level across the canyon and downstream from the fossil leaf locality (Ted Fremd, John Day Fossil Beds National Monument, oral communication, 1988).

TAPHONOMY

Leaves commonly become fossilized as a result of one of two conditions: (1) They may come to rest at the bottom of a body of water and become covered with silt that over time hardens to rock. In this case, the impressions are generally of flat-lying leaves. (2) They may be caught up in a mudflow and rolled along with the mud that eventually becomes rock. Such fossils tell of their origin because they lie in curved or rolled positions.

The host rocks at the Deschutes fossil floral locality were clearly the result of a mudflow. The gray, fine-grained matrix of volcanic ash contains abundant poorly sorted rock material varying in size from sand to occasional boulders. Most of the inclusions are angular pyroclastic fragments of pumice, cinders, and lava. Branch and tree molds in the rocks also point to their mudflow origin. The molds are mostly empty. A few small ones hold a bit of poorly preserved petrified wood.

The mudflow stratum is at least 20 ft (6 m) thick. For 55 years, between the 1935 and the 1990 road work, the road cut here displayed several cross sections of vertical tree-trunk molds (Figure 2). Unfortunately, they were mostly lost in the latest excavation process. A number of horizontal parting layers from <3 ft (1 m) to >6 ft (2 m) apart vertically show that the mud came down the paleovalley in a series of pulses.

The lowest of these parting layers (and therefore the initial pulse of the mudflow) is about 2 ft (0.7 m) thick. The bottom part of this layer hosts a number of fossil leaves in rolled positions, which indicates that they were picked up from the surface litter and carried a short distance. The surface of this parting layer is, in the area of the vertical tree

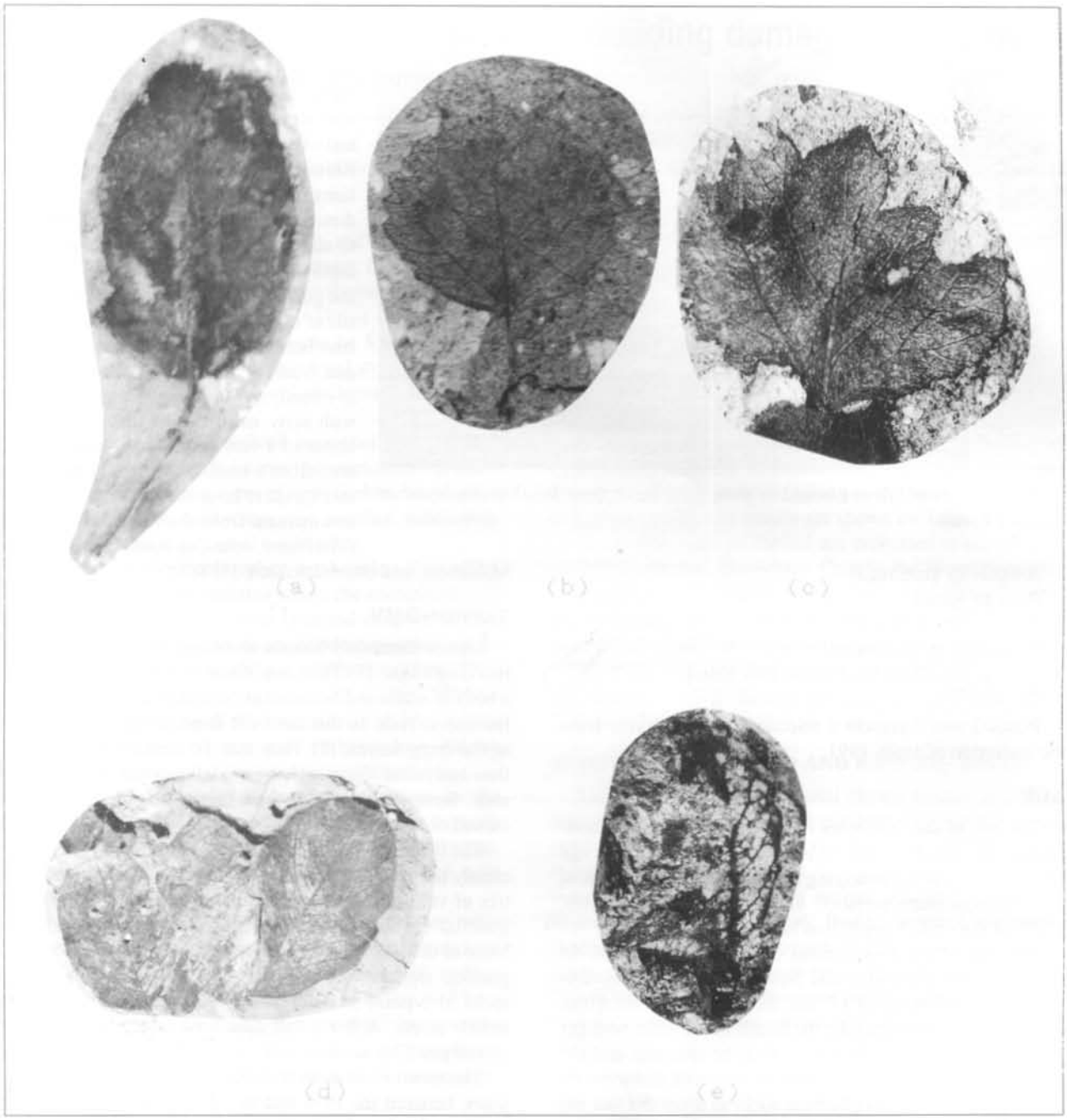

Plate 1. Deschutes flora leaves (MSA/F-14), approximately natural size. (a) Arbutus*? sp. [madrona]; (b)* Populus alexanderi *Dorf (Chaney, 1938) [cottonwood]; (c)* Populus subwashoensis *[cottonwood]; (d) "juvenile leaves" of* Populus alexanderi *Dorf (Chaney, 1938) [cottonwood]; (e)* Rosa *sp. [rose].*

molds, covered with thousands of leaf impressions. In places, the leaves are deposited several layers thick.

This type of leaf-impression-rich parting layer has been noted in other volcanic mudflow deposits (Burnham and Spicer, 1986). These authors concluded that vegetation partially drowned in a volcanic mudflow might suffer stress that would initiate the leaf-abscission process and that a later air fall of pumice might cause a rain of leaves on the mud surface. Conditions observed at the Deschutes fossil flora locality tend to substantiate this conclusion. The lower parting plane with the thick carpet of leaf impressions also includes a centimeter-thick layer of air fall pumice fragments.

Confirmation of this concept was noted by the author in 1981 during the collection of leaves incorporated into the Toutle River mudflow that was caused by the 1980 eruption of Mount St. Helens. Muddy "high-water" marks on tree

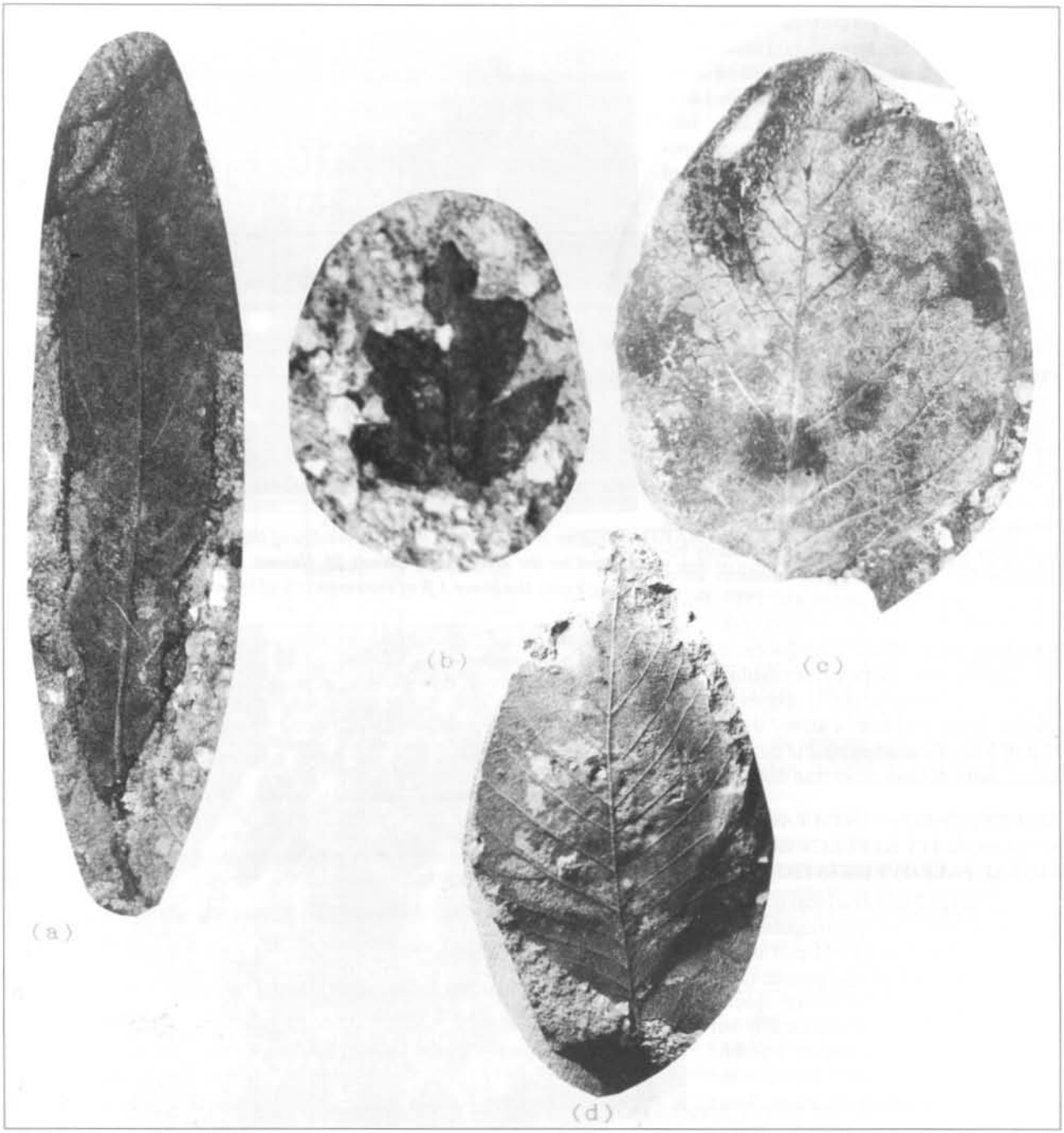

Plate 2. Deschutes flora leaves (MSA/F-14), approximately x1.25: (a) Salix florissanti *Knowlton and Cockerell [willow]; (b)* Crataegus *sp. [hawthorn]; (c)* Populus pliotremuloides *Axelrod [quaking aspen]; (d)* Ulmus *sp. [elm].*

trunks on the outer edges of the mudflow in many places indicate that after reaching an apex, the mudflow subsided by about 3 ft (0.9 m). At this point, the mud solidified on draining and drying. Of course, all of the inundated trees had been killed. Interestingly, great numbers of trees standing free and clear of the consolidated flow but showing a 3-ft coating of mud on their bases had also died (Figure 5). Byron Johnson, landowner at one of the collecting localities, pointed out that the cambium layer of the drowned portions of tree trunks appeared "cooked." The author measured mudflow temperatures in excess of 55°C (131°F) at that time.

Some support of the Burnham and Spicer (1986) hypothesis of accelerated abscission was also noted at the Byron Johnson place: The final upper surface of the mudflow was littered with fallen leaves "in relief" (Figure 6): Rainfall had eroded away about ¼ in. (6.4 mm) of the surface, leav-

ing each fallen leaf perched on its own tiny pedestal. Had another surge of mud covered this surface at that time, the strata would have included (1) a ground-covering layer of mud with rolled leaf inclusions, (2) a parting layer with large numbers of leaves in a flat horizontal position, and (3) the late-surge layer of mud—conditions as they are found at the Deschutes flora locality.

Figure 5. Dead alder trees at the edge of the 1980 Toutle River mudflow caused by the eruption of Mount St. Helens. These trees were killed, although only the lower 3 ft of their trunks had been covered by the mudflow.

HOW FAR FROM THE SOURCE TREE ARE FOSSIL LEAVES?

Having sometimes seen leaves floating down a stream, one wonders how far most fossil leaves travel from their source tree before being deposited. It turns out, not far. Studies show that angiosperm leaves that have traveled for any considerable distance become ragged or fragmented (Spicer and Wolfe, 1987). A number of studies of modern vegetation have shown that by far the greater portion of leaves fallen from trees come to rest either immediately beneath the tree or at a very short distance away (Chaney, 1924; Spicer and Wolfe, 1987; Burnham, 1989). In the preliminary (unpublished) study of the entombment of leaves in the 1980 Toutle River mudflow, the author noted that of the 11 species recovered in the mud matrix all lay within 27 ft (8.2 m) of a standing plant of the same species, many of them closer than that.

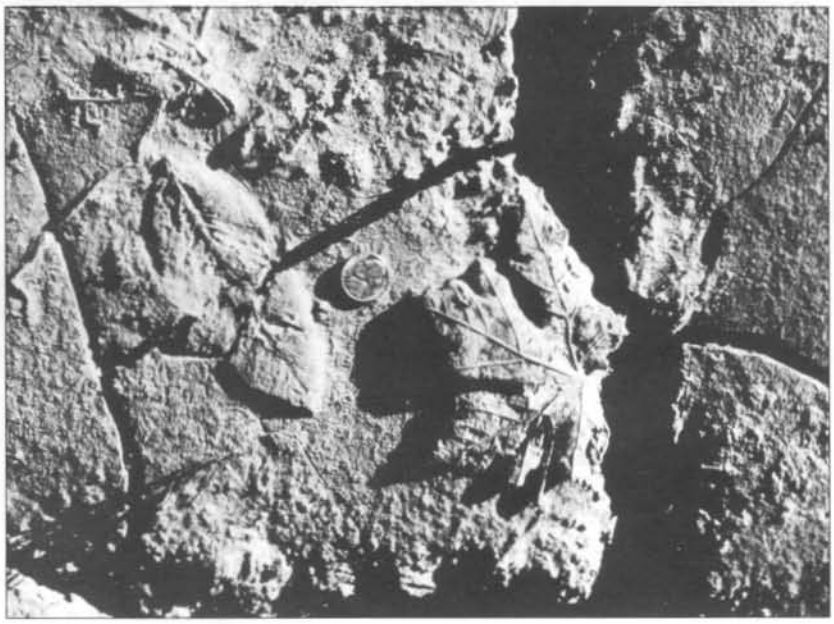

Figure 6. Flat lying leaves on the rain-etched surface of the Toutle River mudflow near Interstate Highway 5 at Castle Rock, Washington, one year after the Mount St. Helens eruption.

HOW FULLY DO FOSSIL LEAVES AT A LOCALITY REFLECT REGIONAL PALEOVEGETATION?

Fossil leaves found at a locality tell an incomplete story of the paleovegetation of a fossil locality. The untold part of the story is a blank left by the absence of an unknown number of additional species that may have grown at the locality but are not known to the collector. Possibly, some trees had not leafed out when the mudflow arrived to bury the leaves. Some plants may have been growing only a short distance away and are therefore not represented in a collection. Some plant fossils may be present but have not yet been found by the collector.

Chaney, in a classic study of leaf entombment at Muir Woods in California's redwood country, found that only 70 percent of the 27 species seen growing in the study area were found in the stream sediments studied (Chaney, 1924). In the Simtustus Formation near Gateway, Oregon, fossilized shells of hackberry (*Celtis*) seeds are so abundant that they were used as a marker fossil during mapping of those rocks (Smith, 1986a). The remarkable deposit of these seeds over a wide area of more than 30 mi^2 (78 km^2) indicates that hackberry trees must have been extremely abundant during the deposition of the rocks of that formation. However, in the only presently known Simtustus Formation fossil leaf locality, the Pelton locality, MSA/F-15, hackberry leaves have not been found (Ashwill, 1990).

As discussed in the previous section, we can feel sure that the plants that produced the fossil leaves lived nearby. And although often a degree of uncertainty remains when a fossil leaf is added to a fossil leaf floral list, nevertheless, the data can confidently be added as a taxon that grew in the region.

HOW NEAR WAS THE VOLCANIC EVENT THAT CONTRIBUTED TO THE BURIAL OF THE GROVES AT THE LOCALITY?

Chaney's (1938) study of the Deschutes flora material found in 1935 included a discussion of the "tuffs" hosting the fossils and their possible source. He puzzled about the flat-lying attitude of the leaves at the parting layer as a possible indicator that they may have been water lain. He noted that other such flat-lying leaf deposits had been usually found in fine sediments rather than in the coarse sediments found at the Deschutes locality. Speculating on a volcanic source for the pumice and vitrophyre incorporated in the mudflow, he suggested a possible nearby silicic volcanic vent.

In response to a request for some comments, in view of more recent work, on the notes made by Chaney (1938) more than fifty years ago on the taphonomy and rocks at the locality, the following was contributed by G.A. Smith, whose 1986 doctoral study included this area:

"Your 'mudflow' term is really quite adequate. This is a very fine-grained rock. The other conspicuous feature is the abundant pumice lapilli and bombs which, as you note, come in pretty big sizes at this outcrop.—I had forgotten the comparison he [Chaney] made to Katmai. There are no vents any closer than the Cascades, and there is nothing about the deposit that requires a source in closer proximity. The idea of the deposition of the flora-bearing beds having closely followed an eruption is reasonable.—The overall impression, therefore, is of serial emplacement of several mudflow units with more dilute-flow phases between them. Because of the upright [tree] trunks, presumably rooted in situ, I don't see this as a lake but rather a flood plain to the ancestral Deschutes River that was inundated by mudflows; I do not recall any evidence that would make me feel strongly that the leaves themselves had been deposited in standing water as Chaney subscribes. I have an analysis of one of the big black pumices in my dissertation; it is andesitic in composition. Besides the rounded cobbles that you mentioned, I also noted a fair number of angular, black glassy clast (vitrophyre). These are common among the ledge forming debris-flow deposits that are so conspicuous northward from Campbell Creek canyon along the east side of the [Deschutes] River and also in places on the [Warm Springs] Reservation, especially north of Seekseequa Junction. I never analyzed the clasts at Chaney's locality, but others collected along the Vanora Cliff are dacitic in composition"(G.A. Smith, University of New Mexico, Department of Earth and Planetary Sciences, written communication, 1995).

GEOLOGICAL SECTION OF LOCALITY

Smith (1986b) measured a geologic section at the Warm Springs/Agency Plains highway grade using collective data taken from road cuts at and near the Deschutes fossil flora locality. Total thickness from the John Day Formation/Deschutes Formation contact to the top of the rimrock was determined to be 338 ft (103 m).

The upper 21.3 ft (6.5 m) consists of coarse-grained, diktytaxitic, high-alumina, olivine tholeiitic basalt (Agency Plains flow of the Tetherow Butte basalt member).

Below this, Smith documented 64 ft (19.5 m) of medium- to coarse-grained sandstone varying from gray to light brown in color and including pumice lapilli. Layers of this sandstone from 2 ft (0.6 m) to 20 ft (6 m) thick are interspersed with lapillistone layers from 1.6 ft (0.5 m) to 4.6 ft (1.4 m) thick.

At the base of the sandstone/lapillistone unit is a dacitic, unwelded, pink to gray ignimbrite layer that is 28 ft (8.5 m) thick.

The section of the Deschutes Formation that lies below the ignimbrite layer is 225 ft (68.5 m) thick and consists of layers of fine- to coarse-grained light-gray to light-brown sandstone with thicknesses between 6.2 ft (1.9 m) and 50 ft (15.2 m) interspersed with lapillistone layers 0.6 ft (0.2 m) to 6.2 ft (1.9 m) thick.

The portion containing the leaf fossils discussed in this paper is about 120 ft (36.6 m) below the top of the rimrock at the locality.

TWO GROVES RECORDED BY THEIR FOSSILS

The ancient river bed is revealed in the road cut by a thick sequence of dark crossbedded sands. The paleoriver is thought to have been flowing in a northerly or northeasterly direction. The east-west road cut gives us a view of a cross section of the riverbed and its valley. The massive mudflow rests on the old riverbed sands and fills its valley deep enough to have partly drowned trees growing at the time on both east and west banks. Over 95 percent of the fossil leaves found came from the area of the drowned grove on the east bank. This is the locality uncovered in 1935. The mudflow section over the center of the river bed is mostly barren of fossils. A few small concentrations of leaf fossils were found on the west bank, mainly of the juvenile *Populus* type.

PALEOCLIMATE AND CORRELATION WITH OTHER FOSSIL FLORAS

Fossil plants are important indicators of past climatic conditions, and the data obtained from the Deschutes fossil flora are quite significant in this respect. Fossil studies of both plant and animal life of the northern hemisphere document a climatic trend from tropical, through warm-temperate to cool and more arid climate in mid-latitude interior areas of the continents, beginning early in the Tertiary and culminating in the Pleistocene "Ice Age." This process during the time interval from the Eocene through

the Pliocene has been especially completely recorded in the richly fossiliferous strata of central Oregon.

The "deterioration" of the climate, though generally gradual, was punctuated by at least two rather sudden (in geologic time) changes. One of these events was the change from tropical to warm-temperate conditions at approximately 33 Ma. Fossil assemblages older than that (e.g., Arbuckle Mountain, MSA/F-34; Denning Spring, MSA/F-35 [also Gordon, 1985]; East Birch Creek, MSA/F-36; Wildwood Campground, MSA/F-54; West Branch Creek, MSA/F-57; Dietz, MSA/F-86) commonly include palms, cycads, and lianas. Even banana has been found in the rocks of central Oregon (Manchester and Kress, 1993; Manchester, 1994a).

Lower John Day Formation floras and others somewhat younger than 33 Ma (e.g., Canal, MSA/F-8; Knox Ranch, MSA/F-32; Fossil High School, MSA/F-33; Twickenham, MSA/F-39; Gray's Ranch, MSA/F-51) produce none of the above-mentioned tropical plants but instead a cooler climate assemblage including dawn redwood, maple, alder, birch, evergreen oaks and other associated plants. These assemblages, along with the classical Bridge Creek flora near Mitchell, Oregon, are all part of a large number of lower John Day Formation fossil localities often collectively referred to as "Bridge Creek flora."

Middle to upper John Day Formation floras and others in the area associated with the Columbia River basalts with ages from 22 Ma to 15 Ma (Heath Ranch, MSA/F-16; Foreman Point, MSA/F-17; Mascall Road Cut, MSA/F-27) still indicate a rather moist paleoclimate. They produce fossils of swamp cypress, walnut, lobed oak, birch, alder, and sweet gum, to name a few.

The second climatic event was a change from moist-temperate to semi-arid conditions that occurred sometime around 7–6 Ma.

The Vibbert fossil locality of Ashwill (1983; MSA/F-12) and the Deschutes fossil assemblage discussed here bracket this abrupt climatic change. They are both within the Deschutes Formation, one at the top, the other at the bottom, and are laterally separated by a distance of only 7 mi (11 km).

The late Miocene Vibbert fossil locality in the lower Deschutes Formation at Gateway, Oregon, 12 mi (19 km) north of Madras is the youngest in the area that has an assemblage of considerable diversity (27 species). Although the abundance of lobed oak, hawthorn, and cottonwood and the impression of a single twig of juniper suggest a trend toward a drier, harsher regime, sycamore, spruce, live oak, ash, and huckleberry, along with the diversity of the flora, point to a climate with milder winters and more summer precipitation than that of today.

Several fossil localities in the Madras area that are younger than the Vibbert flora vary in age from an estimated 6 Ma or late Miocene (Juniper Canyon, MSA/F-7; Round Butte Dam, MSA/F-49; Dry Hollow, MSA/F-92) to approximately 5 Ma or earliest Pliocene (Deschutes, this paper, MSA/F-14; Rehermann, MSA/F-24; Kahneeta, MSA/F-68). These fossil localities correlate well in age and content with the Pliocene flora from the Rattlesnake Formation near John Day, Oregon (Chaney, 1948a).

Some of these assemblages are small and would have little significance individually, but a view of their combined content helps to visualize the ecosystem of the time. Their composition contrasts markedly with that of the Vibbert locality and others somewhat older. Missing are the plants that require considerable summer moisture for survival, including swamp cypress, spruce, and sycamore. At present, the fossil localities younger than 7 Ma record only one conifer species, a large-coned pine in the Dry Hollow locality of the Bridge Creek flora in the western part of the study area. This locality is on the west side of the Deschutes River, where Ponderosa pines still can occasionally be found at streamside in the deep canyons.

The significance of the Deschutes flora, then, is the indication of a severe and abrupt change of climate around 7 Ma, expressed in the bold contrast between its semi-arid-climate plants, and the more diverse, moist-climate flora of the Vibbert assemblage, which is only 2.5 million years older

SUMMARY

The data obtained from thousands of fossil leaves found during the 1990–1991 excavation at the Deschutes fossil locality have enabled us to add to and build upon Chaney's (1938) classic study.

The new and more complete list of plants for the locality documents a more diverse flora than previously known. However, it is still a short list and restricted to plants growing in a paleoclimate bordering on the semi-arid. In this respect the new picture of early Pliocene ecology in central Oregon is not greatly changed by the new finds.

The data from the Deschutes locality, considered along with data from several other local fossil assemblages, contrast strongly with data from the Vibbert locality at Gateway, Oregon, which is only 2.5 million years older and only 7 mi (11 km) distant. The more diverse flora of the Vibbert locality records a moister climatic regime. The indication is that a significant geologic event took place some time around 6 or 7 million years ago to alter the climate of central Oregon to a considerable degree and in a relatively short time.

ACKNOWLEDGMENTS

The conservation of this large volume of fossiliferous material was accomplished by a most remarkable cooperative effort of a number of concerned individuals and agencies. Personnel and equipment were loaned by the various agencies for the effort. Public acknowledgement and many thanks are due to the following, who generously worked together to save the fossils for the public and for science: J.C. Compton, Inc., the contractor, and employees Bob McNary, Bob Pitrak, and George and Edna Lemmon; landowners Jim, Diane, and Jerold Ramsey; Oregon De-

partment of Transportation employees Jim Davenport, Art Steele, and Patty Jo Waters; the Confederated Tribes of the Warm Springs Reservation of Oregon and tribal Museum Planning Committee members Dick Souers and Dale Parker; Jefferson County Commissioner Rick Allen; Don Wood, head of the Public Works Department of Jefferson County; and naturalist Gary Clowers.

Thanks are also due for helpful suggestions to reviewers Steven R. Manchester and Wesley C. Wehr.

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State Seismic Rehabilitation Task Force summary report is now available

The Seismic Rehabilitation Task Force created by the 1995 Oregon Legislature to make recommendations to the Legislature by September 30, 1996, on the seismic rehabilitation of existing buildings in Oregon has completed its work. According to Task Force Chair Paul Lorenzini, "The Task Force met, studied the problem, listened to the public and other affected groups, developed its recommendations, and delivered them as a report to the Legislature for its consideration. The Task Force believes that the program it is recommending will assure that the people of the State of Oregon will ultimately be better protected from earthquakes."

The Task Force report summarizes the findings and recommendations of the Task Force and contains additional information and materials developed by the Task Force. Copies of the report may be purchased for $7 from the Nature of the Northwest Information Center, 800 NE Oregon St. #5, Portland, OR 97232, phone 503-872-2750, fax 503-731-4066. □

OSU to offer earthquake course

Oregon State University will offer a new course, GEO 380, "Earthquakes of the Pacific Northwest," as part of its Baccalaureate Core Curriculum dealing with Science, Technology, and Society. The course will focus on all aspects of the earthquake issue in the Northwest, including geologic evidence, forecasting, earthquake engineering, insurance, and government's role in legislation and disaster preparedness.

The 3-credit course is designed for a general audience and will be taught by Dr. Robert Yeats, OSU Geosciences Department. The Department can be reached by phone at (541) 737-1201. □

PSU to offer evening geology classes

The Geology Department of Portland State University will offer the following courses as evening classes:

Clay Mineralogy (Michael Cummings), MW 5:15–6:30.
Chemical Hydrogeology (Dennis Nelson), M 6:40–9:20.
Well Dynamics (Ansel Johnson), TR 4:40–6:30.
Physical Hydrogeology (Alan Yeakley), TR 4:00–5:50.
Volcanic Hydrologic Hazards (Assessing and mitigating surficial hydrologic hazards at volcanoes; Tom Pierson, U.S. Geological Survey), T 6:40–9:20.

For information, call the Department at (503) 725-3022. □

Liquefaction susceptibility of soft alluvial silts in the Willamette Valley

by D. Andrew Vessely, Cornforth Consultants, Inc., 10250 SW Greenburg Road, Suite 111, Portland, Oregon 97223; Michael Riemer, Department of Civil Engineering, 440 Davis Hall, University of California, Berkeley, California 94720; and Ignacio Arango, Bechtel Corporation, P.O. Box 193965, San Francisco, California 94119.

ABSTRACT

The Tualatin and Portland basins of the Willamette Valley contain vast deposits of very soft to very loose alluvial silts. Large sections of Portland, Hillsboro, Beaverton, and Forest Grove have numerous structures and civil works situated on these flood-plain deposits. Due to the recent upgrading of potential seismic ground motions in western Oregon, the question arises: "Can these saturated silt deposits liquefy?" The behavior of sands and silty sands to earthquake shaking is well understood, and there are widely used, simple empirical charts to evaluate the liquefaction potential for sands, using standard penetration test (SPT) blowcount data. There is not, however, a similar comprehensive knowledge of the seismic behavior of predominantly silty material.

This paper describes the results of cyclic triaxial laboratory tests performed on relatively undisturbed samples of nonplastic, alluvial and flood-deposit silts from a site in the Tualatin basin near Forest Grove in Washington County. Five specimens were tested under various cyclic stress ratios to evaluate the response of the silt to cyclic motions. The test results indicated that all specimens developed a state of initial liquefaction and that four of the five specimens "liquefied," i.e., developed excess pore-water pressures equal to the initial effective confining stress, under cyclic stress ratios and number of uniform cycles representative of postulated earthquakes from crustal and subduction sources.

The results of this study clearly indicate that nonplastic alluvial silts can liquefy under design-level earthquakes. However, the results are site specific, and one must exercise care and judgment before using these results at other sites throughout the Willamette Valley. For example, the effects of increasing plasticity, which is common in many alluvial deposits in the valley, has not been addressed. Much research is needed before the overall seismic behavior of these alluvial materials is fully understood.

INTRODUCTION

The Fern Hill Water Treatment Plant is located about 2 mi south of Forest Grove on the Tualatin River flood plain (Figure 1). The plant is currently being expanded to accommodate increased water-supply needs for several Washington County communities, including Hillsboro and Forest Grove. Current geotechnical studies for the expansion project included a review of existing geotechnical reports from the original plant construction in 1974, the drilling of several borings to evaluate subsurface conditions for specific foundation locations, and a site-specific seismic hazard evaluation.

According to the previous geotechnical information and current borings, the subsurface material at the site consists of 80–85 ft of fine-grained deposits, which are predominantly silts originating from Quaternary catastrophic flood deposits and alluvium. The upper 30–50 ft of this deposit consists of very loose to medium-dense silt, with Standard Penetration Test (SPT) blowcounts[1] ranging from 2 to 21 blows per foot (bpf), with an average blowcount of 8.5 bpf. Groundwater is typically within 5–10 ft of the ground surface. Classification tests indicated that the material is essentially nonplastic. Due to the low blowcounts and low plasticity, the design team became concerned that these silts were potentially liquefiable under current design-level earthquakes. A representative boring log is shown in Figure 2.

[1] Standard penetration test blowcount is the number of blows (of a 140-lb hammer falling freely through a height of 30 in.) to drive a standard sampling tube 12 in. into the ground.

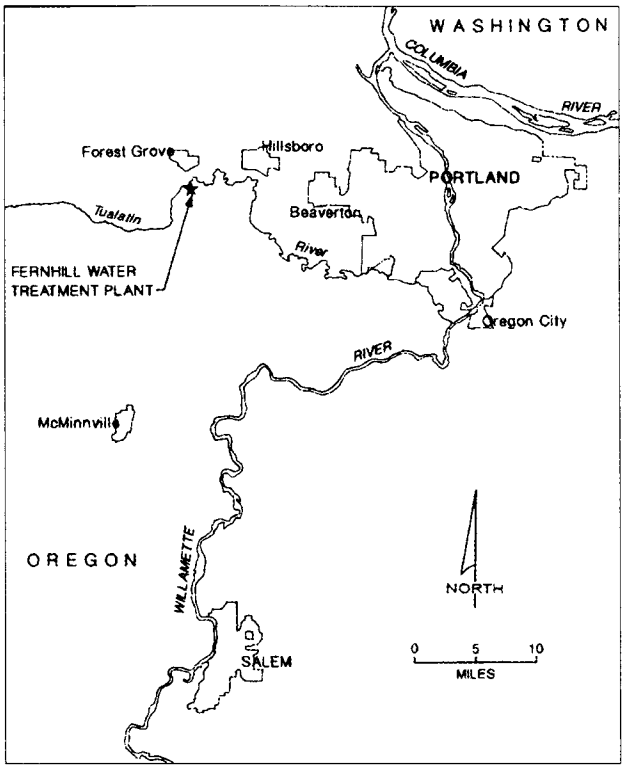

Figure 1. Sketch map showing location of the Fernhill water treatment plant, the site discussed in this paper.

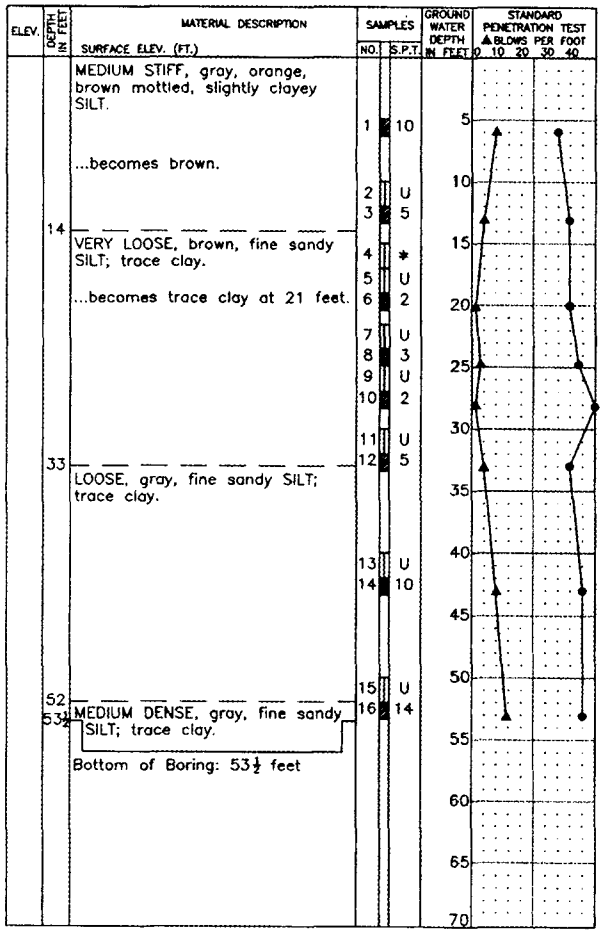

Figure 2. Representative boring log. U *=Shelby tube sample; * = no sample recovered; curve on extreme right marked by circles shows moisture content in percent.*

DESIGN GROUND MOTION

Representative ground motions were developed for several potential seismic sources including crustal earthquakes and intraplate and interface subduction earthquakes. The ground-motion parameters were developed from a comprehensive seismic hazard evaluation performed for the Barney Reservoir expansion project located 15 mi west of the site (Cornforth Consultants, 1994). That study assessed bedrock motions on a probabilistic and deterministic basis and developed synthetic acceleration-time histories for each source.

For the Fern Hill site, the peak rock-acceleration values from Barney Reservoir were attenuated by averaging several empirical relationships for crustal earthquakes (Joyner and Boore, 1982; Idriss, 1991; and Sadigh and others, 1993) and by using relationships developed by Youngs and others (1988) for the subduction earthquakes. Synthetic time histories were scaled to match the attenuated peak ground acceleration. The deterministic ground motions used at the site are presented in Table 1.

Table 1. Deterministic ground motion (bedrock)

Source	Maximum credible earthquake (MCE)	Minimum distance (mi)	Peak bedrock acceleration mean (g)
Portland Hills fault zone	6.8	16	0.16
Intraslab	7.3	30	0.22
Interface	8.5	40-55	0.14

The seismic response of the alluvial soils overlying the bedrock was calculated by use of the program SHAKE91 (Idriss and Sun, 1992). A generalized stratigraphy of the site was developed from the boring logs. Representative shear-wave velocity data for similar soil types were obtained from a review of geophysical testing by DOGAMI on 30 drill sites in the Portland basin (Mabey and Madin, 1995). The results of the dynamic analysis indicate that cyclic stress ratios induced by the earthquakes $(CSR)_{eq}$ would range from 0.18 to 0.29 from the ground surface to a depth of 45 ft.

PRELIMINARY LIQUEFACTION EVALUATION

As a first step in evaluating the susceptibility of the silts to seismic ground motions, the factor of safety against initial liquefaction (FS_l) was calculated in a simplified empirical procedure using SPT blowcount data (N) corrected for overburden pressure, earthquake magnitude, and hammer efficiency (Seed and others, 1983). For corrected SPT blowcounts—expressed as $(N_1)_{60}$—in the range of 4–11, the empirical data for silty sands indicate that cyclic shear stress ratios of 0.12–0.23 must be induced in the ground to cause liquefaction.

Comparing the cyclic stresses induced by the earthquakes with the cyclic shear strength from the empirical chart indicated that the loose deposits of the silt in the upper 50 ft would be susceptible to earthquake-induced liquefaction. However, the design team questioned the validity of the results, since they were obtained from a procedure that was originally developed for sands and silty sands, not for fine-grained silts. Do silts exhibit similar seismic behavior as sands? It was decided to test undisturbed samples of the silt in a cyclic triaxial test apparatus to evaluate the response under simulated earthquake loading.

SOIL CLASSIFICATION PROPERTIES

Three relatively undisturbed (Shelby tube) samples were obtained from the site from depths between 21.5 and 32 ft. Several classification tests were performed on these samples, including natural water content, grain size distribution, and Atterberg limits. Grain size analyses were performed for all five test specimens. On average, the specimens contained 15 percent fine sand, 83 percent silt fraction, and 2 percent clay (Figure 3). The plasticity index (PI) for the five specimens ranged from 0 to 3, with an average of 1.6, which is essentially nonplastic. SPT blowcounts obtained immediately below each tube sample were 3, 2, and 5,

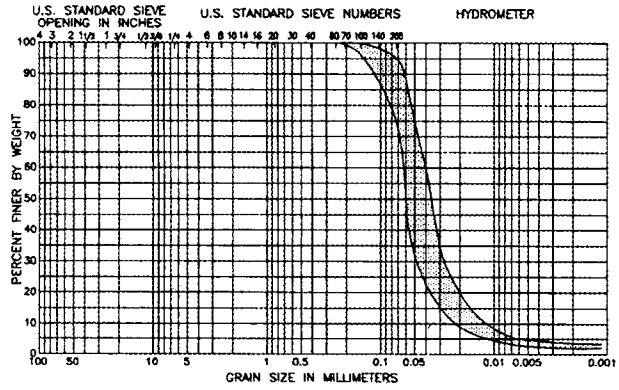

Figure 3. Range of particle size for 5 cyclic triaxial specimens.

respectively, and the corrected average blowcount SPT $(N_1)_{60}$ was 4. Natural water content ranged from 35 to 55 percent and was fairly uniform in the upper 50 ft.

SAMPLE TRANSPORTATION

Cyclic triaxial testing was performed at the Geotechnical Laboratory at the University of California at Berkeley. To help minimize sample disturbance prior to transporting the samples to Berkeley, the end caps of the tubes were removed, and the tubes were left on end with moist filter cloth to allow the sample to drain excess water, thereby mobilizing capillary tension within the sample. As a further precaution, the tube samples were carefully packaged, then hand-carried on a commercial flight to Oakland, California.

SPECIMEN PREPARATION

Triaxial specimens (nominally 2.8 in. in diameter and 6 in. in height) were extruded from segments of the Shelby tubes with a modified hydraulic jack. Capillary stresses in the partially saturated silts were sufficient to maintain free-standing specimens after extrusion. Following placement of the top cap and the latex membrane, each specimen was vacuum saturated and measured, and the triaxial cell was assembled around it. An effective confining stress of approximately half an atmosphere (1,000 pounds per square foot [psf]) was maintained throughout the vacuum and back-pressure saturation processes. The specimens were then consolidated to an isotropic stress of 1,500 psf prior to undrained cyclic loading. Volume changes during both the saturation and consolidation phases were closely monitored and were observed to be small, which satisfied the intent of reconsolidating relatively undisturbed specimens.

CYCLIC TRIAXIAL TESTING

The triaxial tests were performed by use of the CKC e/p pneumatic loader, under the control of Georobot software (version 5.2). Instrumentation included an externally mounted, 500-pound-capacity load cell, a 1.00-in. Collins LVDT, and three differential pressure transducers of varying sensitivities. All of the instrumentation and other components of the systems were calibrated prior to testing.

The cyclic testing consisted of uniform, stress-controlled, sinusoidal loading under undrained conditions at a frequency of 1 cycle/second. The cyclic stress ratios (CSRs), which are a measure of the amplitude of loading, were chosen to span the range expected to result from the design seismic events at the project site. Throughout this report, the cyclic stress ratio is defined as the peak cyclic deviatoric stress (σ_{dc}) divided by two times the initial effective consolidation stress (σ'_{con}):

$$CSR = \frac{\sigma_{dc}}{2\sigma'_{con}}$$

Cyclic loading was applied to all of the isotropically consolidated specimens until they had reached axial strains in excess of 8 percent. In all cases, this occurred after the specimens reached a state of initial liquefaction (at which the effective confining pressure, 3, first reaches a value of zero).

RESULTS OF TESTING

The data from the five cyclic tests are summarized in Table 2. Initial conditions for each specimen include the original depth and the dry density (γ_d) immediately prior to cyclic testing. The results of each test are described by the cyclic stress ratio (CSR), and the number of cycles required to reach "initial liquefaction," defined as the achievement of a pore pressure ratio of $r_u = \Delta u/\sigma'_{con} = 100\%$, where Δu is the change in pore-water pressure.

Table 2. *Results of cyclic triaxial testing of Willamette silts*

Test	Sample depth (ft)	Blow-count $(N_1)_{60}$	In situ dry density, γ_d (pcf)	Cyclic loading (CSR)	Number of cycles ($r_u = 100\%$)
7T	22	4	81.7	0.250	22
7M	22.5	4	80.9	0.327	5
7B	23	4	79.3	0.220	12
9T	26	3	82.5	0.177	105
11T	31	5	83.2	0.247	8

As has been frequently observed in cohesionless soils, the onset of substantial cyclic straining (greater than 5-percent axial strain) roughly coincided with initial liquefaction. The values of CSR versus the number of cycles to initial liquefaction are plotted for the five tests in Figure 4.

CONCLUSIONS

The laboratory testing performed on the samples of alluvial silt during the current study generally confirmed the results of the simplified empirical procedure based on SPT blowcount data. Despite the low percentage of sand-sized particles, these materials are prone to liquefaction when subjected to moderate cyclic loading. Due to the lack of co-

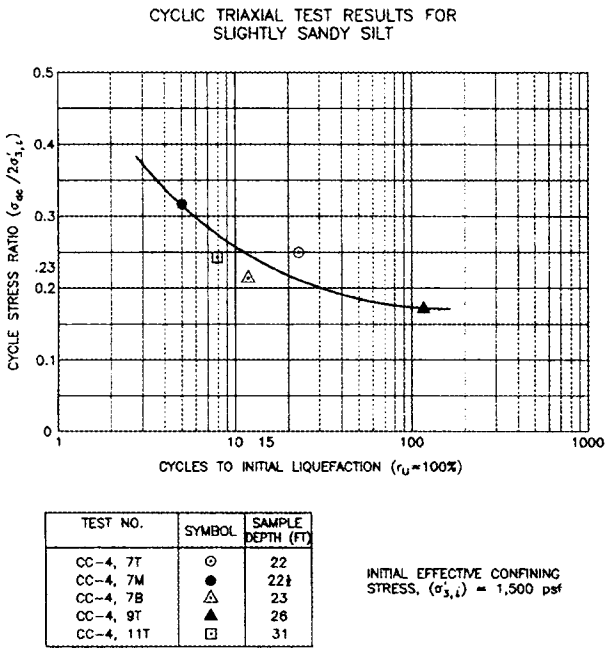

Figure 4. Cycles to initial liquefaction for slightly sandy silt.

hesive fines in the material, and low SPT values indicating a very loose structure, it is likely that the samples retrieved from the field were at least slightly disturbed during the sampling process. This disturbance would be expected to densify the material and, as a result, increase the liquefaction resistance of the specimens tested in the lab; therefore, the data plotted in Figure 4 are suspected of representing levels of liquefaction resistance that are greater than those available in equivalent deposits in situ.

In light of the difficulties in evaluating the degree of disturbance and the magnitude of its possible effects, it seems unreasonable to attempt to quantify them and subsequently "correct" for these effects. The cyclic and static test results can probably best be considered as "upper bound" values on the liquefaction resistance and post-liquefaction strengths, respectively, of the rather low-density silt deposit from which the specimens were obtained.

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Wang to head DOGAMI earthquake hazard reduction efforts

Yumei (Mei Mei) Wang has been appointed to lead the earthquake hazard activities for the Oregon Department of Geology and Mineral Industries (DOGAMI).

Wang, an earthquake engineer with DOGAMI since 1994, will lead a team of geologists and scientists who specialize in studying earthquake hazards in Oregon. She will also work with local, state, and national earthquake groups in forming partnerships for mitigation efforts to reduce loss of life and property.

Wang recently authored the earthquake hazard maps for the Salem area (DOGAMI Geological Map Series GMS–105, 1996). She and other scientists are now working on similar maps for the Eugene-Springfield area.

The hazard maps are part of a larger project to protect Oregonians from earthquake damage. Through Wang and other earthquake professionals, DOGAMI is increasing its efforts to promote earthquake awareness and preparedness.

Wang earned her master's degree in civil engineering with a geotechnical emphasis from the University of California at Berkeley in 1988. Before coming to DOGAMI, she had her own geotechnical engineering consulting firm in Oakland, California. She is an officer for the American Society of Civil Engineers and a member of the Earthquake Engineering Research Institute, the Association of Women Geoscientists, and the Association of Engineering Geologists (AEG). She is chairperson for the AEG's 1997 earthquake symposium.

Wang replaces Matthew Mabey, who left DOGAMI this summer to accept a teaching position at Brigham Young University. □

The expected financial losses due to building damage caused by severe earthquakes in Oregon

by Robert M. Whelan[1], Mineral Economist, and Matthew A. Mabey[2], Earthquake Specialist, Oregon Department of Geology and Mineral Industries

INTRODUCTION

The Oregon Department of Geology and Mineral Industries (DOGAMI) has estimated the direct financial losses from buildings damaged by severe earthquakes in Oregon over the next 55 years. The analysis shows that, over that period, the average annual loss would be $108.6 million. This conclusion is based on a county-level study of building stocks, construction outlooks, and earthquake recurrence rates.

A severe earthquake is defined here simply as one that causes ground shaking of 0.3 times the acceleration of gravity (0.3 *g*) or more. Three types of earthquakes can produce such violent motion: subduction-zone interface, subduction-zone intraplate, and large crustal earthquakes.

The subduction-zone interface earthquakes that affect Oregon occur along the margins where the continental and oceanic plates meet. This zone is found deep below the ocean floor off the Oregon coast. Subduction-zone earthquakes in Oregon are powerful yet infrequent events. They are often characterized by long periods of shaking that occur over extensive areas. A subduction-zone interface earthquake off the northern Oregon coast could produce shaking of 0.3 *g* as far away as the Portland metropolitan area.

Subduction-zone intraplate earthquakes occur as the downgoing, or subducted, oceanic plate breaks beneath North America. The memorable and fatal earthquakes occurring in the Puget Sound region in 1949 and 1965 were of this type.

Crustal earthquakes are more common. They are more localized events, but they can also be quite destructive near their source. Crustal earthquakes are caused by sudden movements between different sections of bedrock. These movements occur along faults that are typically near the surface. Ground shaking of 0.3 *g* or more is not uncommon in crustal earthquakes of magnitude 6 or 7 (Geomatrix, 1995).

RECURRENCE RATE

How often are there earthquakes that cause 0.3 *g* of ground shaking or more? The power and frequency of crustal earthquakes largely depends on local geological conditions. For subduction zone earthquakes, distance from the epicenter is a crucial factor in determining how much ground shaking occurs in an area.

By examining the geologic record, it is possible to estimate the historical frequency of earthquakes in different parts of the state. For this analysis, estimates of the frequencies of large crustal and the subduction-zone earthquakes were used. These estimates were derived from the seismic design mapping project of the Oregon Department of Transportation (Geomatrix, 1995). The frequencies of earthquake occurrence were used to calculate how often these seismic events resulted in ground shaking of 0.3 *g* or more. This was done for the main population center of each county. As a necessary simplification, it is assumed that the frequency of 0.3 *g* ground shaking is the same in all parts of a given county. The results are shown on Table 1.

The probabilities on Table 1 are expressed in recurrence rates. For instance, for Benton County, the recurrence rate is calculated for Corvallis. It is the main population center for the county. In Corvallis, seismic events that cause at least 0.3 *g* of ground shaking happen about once every 1,750 years. The chance that such an event will occur in any one year is 1:1,750, or a little less than 0.06 percent. This probability is applied to all parts of Benton County.

BUILDING STOCK DATA AND DAMAGE RATES

The building stock is the total square footage of buildings in place. To compute the expected future losses from seismic events, a forecast of the building stock of every county was needed. With the exception of the Census of Housing, building stock data are not collected. The construction statistics firm of F.W. Dodge, however, estimates the building stock of each county as part of its regular program of monitoring construction contracts and permits. This is the most reliable source of building stock data.

F.W. Dodge provided 1995 county building stock estimates for 15 categories of structures. These included categories such as retail buildings, schools, and offices. The 1995 data were used as a base for the building stock forecast.

In connection with a study of aggregate demand, DOGAMI built construction forecasting models for each county (Whelan, 1995). The models forecast the number of square feet for over a dozen categories of buildings on an annual basis through the year 2050.

The forecasts were consolidated into categories common to both F.W. Dodge and the county aggregate models. This yielded a projection of additions to the building stock for different types of structures. It was then assumed that a certain percentage of buildings are removed each year from the building stock. Removals happen because of demolition, abandonment, and obsolescence. A removal rate of 0.0111

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Table 1. *The probability of a seismic event causing at least 0.3 g of ground shaking in a county*

County	Population center	Recurrence rate (years)
Baker	Baker City	4,250
Benton	Corvallis	1,750
Clackamas	Portland area	1,250
Clatsop	Astoria	500
Columbia	St. Helens	1,250
Coos	Coos Bay	350
Crook	Prineville	7,250
Curry	Gold Beach	125
Deschutes	Bend	4,500
Douglas	Roseburg	1,500
Gilliam	Condon	5,000
Grant	John Day	7,500
Harney	Burns	25,000
Hood River	Hood River	3,125
Jackson	Medford	1,250
Jefferson	Madras	7,250
Josephine	Grants Pass	1,000
Klamath	Klamath Falls	1,500
Lake	Lakeview	1,500
Lane	Eugene	1,750
Lincoln	Newport	300
Linn	Albany	1,750
Malheur	Ontario	3,500
Marion	Salem	1,500
Morrow	Boardman	5,000
Multnomah	Portland	1,250
Polk	Dallas	1,075
Sherman	Moro	5,000
Tillamook	Tillamook	400
Umatilla	Pendelton	5,000
Union	La Grande	4,250
Wallowa	Enterprise	4,250
Wasco	The Dalles	5,000
Washington	Portland area	1,250
Wheeler	Mitchell	25,000
Yamhill	McMinnville	825

was used for school buildings. A rate of 0.0167 was used for all other nonresidential buildings. For housing, a slightly different approach was used.

Housing data for this analysis came directly from the aggregate models. The total square footage of single and multifamily housing in 1995 came from F.W. Dodge. For manufactured homes, which are not reported in construction statistics, an estimate was made for the total square footage in 1995 by multiplying the number of units by 1,300. The forecasts of additions and removals are part of the aggregate models, and these were used in the forecasts of building stocks.

The square footage of buildings by type was converted into dollar values. The interest here is in the replacement cost of structures. In other words, if a retail building is destroyed in an earthquake, how much would it cost to rebuild it? The concern here is not the market or assessed value, but rather replacement cost.

Construction cost estimates were made with data used in the development of the aggregate models. F.W. Dodge provided construction cost and square footage statistics for 1978 to 1993. These figures exclude the costs of land and of some of the site improvements. They are a fair representation of what it would cost to rebuild a structure after an earthquake. DOGAMI used the F.W. Dodge data to calculate costs per square foot for each major building category. For manufactured homes, which F.W. Dodge does not report, it was assumed that replacement costs equal 60 percent of the replacement cost of single-family site-built houses.

Construction costs tend to be higher in the three counties that make up the Portland metropolitan area. For all building types, construction costs per square foot in Clackamas, Multnomah, and Washington Counties were 4.3 percent higher than the 1978–1992 state average. One reason for this is the prevalence of high-rise multifamily housing in and around Portland. High-rise units historically cost 29 percent more per square foot to build than low-rise units. Approximately 87 percent of the high-rise multifamily construction done in Oregon from 1978 to 1992 took place in the three Portland area counties. Those counties accounted for only 51 percent of the total square footage of building construction during that period. For the other 33 counties in Oregon, average construction costs were 4.6 percent less than the state average.

Construction costs were converted into 1996 dollars, using an index of building costs (Kiley and Moselle, 1993). The average 1996 cost per square foot was calculated for the 1978–1993 period for each building type. The replacement value of the building stock was then estimated by multiplying the square footage for each year in the forecast by the 1996 cost per square foot.

The value for the whole state for 1996 was estimated at $144.3 billion. The forecast shows the value of the building stock rising as the state's population and income level grows. In 2050, the building stock reaches a value of $275.6 billion (1996 dollars). This is equivalent to a 1.2-percent compound annual growth rate over the forecast period.

Damage rates in the analysis are measured as a percentage of the replacement value of buildings. These damage rates, shown in Table 2, come from a preliminary analysis for Multnomah County in the case where buildings are subjected to an approximately 0.3-*g* seismic event (for purposes of this paper, from here on simply referred to as "0.3-*g* event"). Direct losses to buildings equal 15.43 percent of the replacement value of the building stock. Related losses, which include building contents, lost wages, and business interruptions, are 44.55 percent of the building stock's value. Seismic events resulting in weaker ground shaking

Table 2. *Direct economic losses due to building damage from 0.3-g seismic events expressed as a percentage of building replacement value*

Type of loss	Percent of value
Damage to buildings:	
Building support structure	3.83
Other building features	11.60
Total building damage	15.43
Losses related to building damage:	
Building contents	10.47
Inventory losses	0.25
Relocation costs	5.95
Lost wages and business income	27.46
Rental income loss	1.42
Total losses related to building damage	45.55
Total direct economic loss	60.98

would obviously result in lower losses; likewise, stronger ground shaking would cause higher losses.

EXPECTED VALUE OF LOSSES

The expected value of losses due to buildings damaged in 0.3-*g* seismic events equals $75.4 million in 1996. It rises over time as the building stock increases. The expected value of losses in 2050 is forecast at $143.8 million (in 1996 dollars). The average expected value for the 55-year period is $108.6 million.

Expected value is a probability-weighted estimate. It measures the average annual loss due to 0.3-*g* earthquakes. That average combines the zero loss years when no destructive earthquakes occur with the infrequent, yet catastrophic losses from years when large earthquakes hit. For example, if an earthquake would cause $100 million in losses, but has a probability of occurring only once every 50 years, the expected value of losses would be $100 million divided by 50 years or $2 million a year.

The expected values of losses were calculated for each county. These are shown in Table 3. The losses are higher in urbanized and coastal counties and lower in eastern Oregon counties. The actual loss in a year will range from zero to several hundred or thousand times the expected value.

The expected value was calculated for each year for each county. The value of the building stock was multiplied by the damage rates shown on Table 2. The result was then divided by the recurrence rate shown on Table 1.

WHAT DOES THIS ALL MEAN?

We noted that if we factor in all our expectations about the frequency, destructiveness, and locations of 0.3-*g* earthquakes and combine them with a forecast for Oregon's building stock, we find that losses from damaged buildings will average $108.6 million a year. At first blush, that may seem like a manageable loss. Is it, then, really worth spending much money to mitigate building damage from potential earthquakes? It depends, in part, on the remaining life of a building.

Table 3. *Expected value of losses due to building damage from 0.3-g seismic events for the period 1996–2050 (in millions of 1996 dollars per year)*

County	Average expected value of losses (millions of $)
Baker	125
Benton	1,396
Clackamas	11,421
Clatsop	2,297
Columbia	1,149
Coos	6,021
Crook	82
Curry	7,744
Deschutes	1,080
Douglas	1,952
Gilliam	35
Grant	30
Harney	8
Hood River	207
Jackson	4,921
Jefferson	88
Josephine	2,426
Klamath	1,363
Lake	145
Lane	6,756
Lincoln	5,784
Linn	2,053
Malheur	245
Marion	6,542
Morrow	59
Multnomah	21,532
Polk	1,750
Sherman	17
Tillamook	2,538
Umatilla	386
Union	170
Wallowa	58
Wasco	163
Washington	14,484
Wheeler	4
Yamhill	3,534
State total	108,565

The expected value of losses is an annual figure. However, most of the work done to a building and its contents to make them more resistant to earthquake damage will last for the lifetime of the structure. The cost of these efforts must be measured against the losses we expect for the life of the building.

A typical building today has a remaining life of about 55 years. The expected value of losses for the next 55 years in Oregon totals $5,971.2 million. About $1,510.7 million of that amount will be damage to the buildings themselves.

The remaining $4,460.5 million will come from lost incomes, building contents, and other items.

From our analysis, we estimate that in any given year losses equal 0.0522 percent of the value of buildings in the state. A building with a remaining life of 55 years can expect a loss of 2.87 percent of its current value. If an earthquake mitigation plan could reduce expected losses by 50 percent, then one might expect a building owner to be willing to pay up to 1.44 percent of the building's value for mitigation work.

For the purposes of this paper we used an example that is oversimplified. One should consider the characteristics of buildings and their locations. Also, the data here represent an average for the whole state. Some parts of Oregon are very unlikely to suffer a major earthquake, while others are quite vulnerable. For example, if we consider similar buildings in Burns and Portland, much greater expenditure on mitigation would be justified in Portland because the annual loss would be greater there, since earthquakes occur more frequently than in Burns. We also did not factor in loss of life, insurance tradeoffs, and the time value of money. For example, depending on the value placed on a life, the cost of the earthquakes considered here could increase as much as ten times the value of the damage considered in this study.

Perhaps most importantly, we showed the economic costs of 0.3-*g* earthquakes only. We neglected the losses due to weaker ground shaking events, as well as the potential for far greater loss rates than those used here that comes with ground shaking stronger than 0.3 *g*.

A similar analysis based on 0.2-*g* crustal earthquakes gave us very high loss figures. For some counties, the expected value of losses from 0.2-*g* earthquakes is greater than for 0.3-*g* earthquakes. While these smaller quakes cause far less damage, they occur at a much greater frequency. In some places, the frequency is so high that buildings are more likely to suffer losses from 0.2-*g* events than from 0.3-*g* earthquakes.

Much more work needs to be done so that the expected losses from earthquakes can be fully assessed. This preliminary analysis helps place an order of magnitude to the risks to property and commerce from seismic events. Further research will allow us to consider the full spectrum of seismic events and their impact on different building types. This analysis can also be used to place a financial value on mitigation efforts and earthquake insurance.

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DOGAMI PUBLICATIONS

Released October 8, 1996:

Relative Earthquake Hazard Maps of the Salem East and Salem West Quadrangles, by Yumei Wang and William J. Leonard. Geological Map Series map GMS–105, scale 1:24,000, 4 full-color maps and 10 p. text, $12.

The four maps include three maps showing liquefaction susceptibility, ground motion amplification susceptibility, and landslide susceptibility. The fourth, relative hazard map, combines the results of those three to determine the relative earthquake hazards.

In preparation for the Salem maps, engineering studies were made of the local soil and rock to determine how they would respond to an earthquake, and that information was used to develop the relative hazard maps.

Released November 7, 1996:

Geologic Map of the Steelhead Falls Quadrangle, Deschutes and Jefferson Counties, Oregon, by Mark L. Ferns, Donald A. Stensland, and Gary A. Smith. Geological Map Series map GMS–101. Scale 1:24,000, full-color map and 13 p. text, $7.

The Steelhead Falls quadrangle covers an area of about 53 square miles in northern Deschutes and southern Jefferson Counties, where the Crooked and Deschutes Rivers have carved 800-foot-deep canyons into a volcanic basin that is 6 million years old.

The full-color map and 10-page text provide information on the geologic history and resources of this highly scenic part of central Oregon. The map gives both technical and nontechnical people information on how the geology influences groundwater and surface water flow.

Released November 12, 1996:

Earthquake Hazard Maps for Oregon, by Ian P. Madin and Matthew A. Mabey. Geological Map Series map GMS–100. Four full-color maps on one sheet, $8.

GMS–100 provides the most up-to-date and complete information on earthquake hazards in Oregon currently available. It allows users to compare hazards in one part of the state to another and to evaluate the likelihood of damaging earthquake shaking at a particular locale.

The new map was based on data from a report *Seismic Design Mapping, State of Oregon*, prepared by Geomatrix Consultants, Inc., for the Oregon Department of Transportation, and on a 1993 UO dissertation, *Active Faults and Earthquake Ground Motions in Oregon* by Silvio K. Pezzopane.

These DOGAMI publications are now available over the counter, by mail, FAX, or phone from the Nature of the Northwest Information Center and the DOGAMI field offices in Baker City and Grants Pass. Addresses are on page 130 of this issue. Orders may be charged to Visa or Mastercard. Orders under $50 require prepayment. □

Index to *OREGON GEOLOGY*, volume 58, 1996

Numbers refer to issue and beginning page of entry. Most subject entries include cross-references to author entries (in parentheses).

Abstracts of papers 2:44; 3:73; 4:96; 5:125
Agnew, A.F., Geology of the Pacific Northwest (review) 4:97
Allen, J.E., Unusual landscapes and geol. problems in Pac. NW 5:126
Applegate Group (Donato and others) 4:79
Arango, I., coauthor, Vessely and others 6:142
Ashwill, M.S., The Pliocene Deschutes fossil flora of central Oregon: Additions and taphonomic notes 6:131
Barnes, C.G., coauthor, Donato and others 4:79
Bestland, E.A., coauthor, Retallack and others 3:51
Black, G.L., Earthquake intensity maps, Scotts Mills earthquake 2:35
Bourgeois, J, coauthor, Rinehart and Bourgeois 3:73
Burns, S.F., Landslides in the West Hills of Portland (photos) 2:42
Cascade Range: Geothermal field trip (Sherrod and others) 5:103
Christensen, D.W., joins DOGAMI Governing Board 4:78
Clarno Formation: Nut Beds flora (Manchester, rev. by Fremd) 3:70
Clatsop County: Tsunami disaster planning (Visher) 5:125
Curless, J.M., coauthor, Sherrod and others 5:103
DeRoo, T.G., coauthor, Sherrod and others 5:103
Diaz, N.M., coauthor, Sherrod and others 5:103
DOGAMI news 1:21; 2:44; 3:50; 4:78, 95, 97; 6:130,145
Donato, M.M., Barnes, C.G., and Tomlinson, S.L., The enigmatic Applegate Group of SW Oregon: Age, correlation, and tectonic affinity 4:79
Earthquakes: Governor's Preparedness Month proclamation 2:26
———Development of Portland building code (Kennedy) 1:10
———Expected seismic performance, slide set by EERI 1:14
———Intensity maps for Scotts Mills earthquake (Black) 2:35
———Liquefaction susceptibility of silt (Vessely and others) 6:142
———Losses from building damage (Whelan and Mabey) 6:146
———Seismic water-level oscillations (Woodcock and Roeloffs) 2:27
———Shaking things up down on the farm (rural preparedness) 2.34
———What's your earthquake IQ? (Wang) 1:2
Field trip guide: Cascade Range, north (Sherrod and others) 5:103
Fremd, T.J., coauthor, Retallack and others 3:51
———Fruits and seeds of the Nut Beds flora (review) 3:70
Gellar, D., Evaluating the effectiveness of MLR program 1:15
Geothermal energy: Central Lake County potential (Jellinek and others) . 1:3
———Exploration in Oregon, 1994–1995 (Olmstead) 4:92
Governing Board of DOGAMI: Christensen joins as new member 4:78
———To adopt tsunami rules 1:21
———Tsunami rules and maps adopted (SB 379) 2:44
Grants Pass: Water-level oscillations (Woodcock and Roeloffs) 2:27
Hurlocker, S.L., coauthor, Sherrod and others 5:103
Ingebritsen, S.E., coauthor, Sherrod and others 5:103
Jacob, B.A., in memoriam 3:74
Jellinek, A.M., Madin, I.P., and Langridge, R., Field and stable isotope indicators of geothermal resource potential, central Lake County 1:3
Keith, T.E.C., coauthor, Sherrod and others 5:103
Kelsey, H.M., Tsunamis in south coastal Oregon (abs.) 2:44
Kennedy, R.E., Development of Portland building code 1:10
Klamath Mountains: Applegate Group (Donato and others) 4:79
Lake County: Geothermal resource potential (Jellinek and others) 1:3
Landforms, Unusual landforms in the Pacific Northwest (Allen) 5:126
Landslides: From February 1996 floods, Burns (Portland photos) 2:42
Langridge, R., coauthor, Jellinek and others 1:3
Mabey, M.A., coauthor, Whelan and Mabey 6:146
Madin, I.P., coauthor, Jellinek and others 1:3
McClung, W., in memoriam 2:44
Mined land reclamation: Evaluating effectiveness of program (Gellar) 1:15
———MLR program honors outstanding reclamation of 1995 ..... 4:95
Mineral industry: Mine operators recognized for flood help 4:97
O'Dell, S., in memoriam 3:50
Oil and gas exploration and development, 1995 (Wermiel) 3:72
Olmstead, D.L., Geothermal exploration in Oregon, 1994–1995 ..... 4:92
Paleontology: Deschutes fossil flora (Ashwill) 6:131
———Oldest fossil turtle discovered (UO announcement) 4:96
———Reconstructions, central Oregon (Retallack and others) 3:51
Peterson, C., and Priest, G., Paleotsunami overtopping (abs.) 4:96
Pokarney, B. Shaking things up down on the farm 2:34
Portland: Development of Portland building code (Kennedy) 1:10
———Landslides in the West Hills of Portland (Burns) 2:42
Priest, G., coauthor, Peterson and Priest (abs.) 4:96
Publications by DOGAMI, announced:
GMS–87, Three Creek Butte quadrangle, Deschutes County 2:46
GMS–88, Lakecreek quadrangle, Jackson County 1:22
GMS–93, Earthquake hazards, Siletz Bay area 1:22
GMS–97, Coos Bay quadrangle, Coos County 1:22
GMS–98, Dora/Sitkum quadrangles, Coos County 1:22
GMS–99, Tsunami hazard map, Siletz Bay area 3:74
GMS–100, Earthquake hazards maps for Oregon 6:149
GMS–101, Steelhead Falls quad., Deschutes/Jefferson Co. 6:149
GMS–105, Earthquake hazards, Salem East/West quadrangles 6:149
O–95–05, Explanation of methods and use of GMS–99 ..... 3:74
O–95–08, Landslide loss reduction, guide for government 1:22
O–95–09, Warrenton quadrangle, Clatsop County through .....
O–95–66, Mount Emily quadrangle, Curry County (58 quadrangle maps for tsunami inundation zones) 2:44
O–95–67, Explanatory text for tsunami inundation zone maps 2:44
O–96–01, Mist Gas Field map, 1996 edition 4:91
O–96–02, Best management practices in reclamation 2:46
O–96–04, Geothermal resources, SE Oregon (library only) see 1:3
Publications by others, announced and reviewed:
A rock grows up (R. and M. Goodrich) 3:71
Expected seismic performance of buildings, slide set by EERI 1:14
Fruits and seeds of the middle Eocene Nut Beds flora (S.R. Manchester, reviewed by T.J. Fremd) 3:70
Geology of the Pacific Northwest (E.L. and W.N. Orr, reviewed by A.F. Agnew) 4:97
Liquefaction features from a subduction zone earthquake: Preserved examples from the 1964 Alaska earthquake (Washington Div. of Geology and Earth Resources RI 32) 2:46
Report of the State Seismic Rehabilitation Task Force 6:141
Retallack, G.J., Bestland, E.A., and Fremd, T.J., Reconstructions of Eocene and Oligocene plants and animals of central Oregon 3:51
Riemer, M., coauthor, Vessely and others 6:142
Rinehart, M.A., and Bourgeois, J. Tsunami deposits, Willapa Bay (abs.) 3:73
Roeloffs, E., coauthor, Woodcock and Roeloffs 2:27
Scotts Mills 1993 earthquake: Intensity maps (Black) 2:35
Sherrod, D.R., Ingebritsen, S.E., Curless, J.M., Keith, T.E.C., Diaz, N.M., DeRoo, T.G., and Hurlocker, S.L., Water, rocks, and woods—A field excursion to examine the geology, hydrology, and geothermal resources in the Clackamas, North Santiam, and McKenzie River drainages, Cascade Range, Oregon 5:103
Speaker, C.D., in memoriam 3:74
Tomlinson, S.L., coauthor, Donato and others 4:79
Tsunamis: South coastal Oregon (Kelsey) 2:44
———Deposits at Willapa Bay (Rinehart and Bourgeois) 3:73
———Paleotsunami barrier-overtopping (Peterson and Priest) 4:96
———Disaster planning in Clatsop County 6:140
———Governor's Preparedness Month proclamation 2:26
———Rules to implement Senate Bill 379 ..... 1:21; 2:44
Vessely, D.A., Riemer, M., and Arango, I., Liquefaction susceptibility of soft alluvial silts in the Willamette Valley 6:142
Visher, P., Tsunami disaster planning in Clatsop County (abs.) 5:125
Wang, Y., to head DOGAMI earthquake hazard reduction efforts 6:145
———What's your earthquake IQ? 1:2
Wermiel, D.E., Oil and gas exploration and development, 1995 ..... 3:72
Whelan, R.M., and Mabey, M.A., The expected financial losses due to building damage caused by severe earthquakes in Oregon 6:146
Woodcock, D., and Roeloffs, E., Seismically induced water-level oscillations in a fractured-rock aquifer well near Grants Pass 2:27

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