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Main Office: Suite 965, 800 NE Oregon Street # 28, Portland 97232, phone (503) 731-4100, FAX (503) 731-4066.

Baker City Field Office: 1831 First Street, Baker City 97814, phone (541) 523-3133, FAX (541) 523-5992.
Mark L. Ferns, Regional Geologist.

Grants Pass Field Office: 5375 Monument Drive, Grants Pass 97526, phone (541) 476-2496, FAX (541) 474-3158.
Thomas J. Wiley, Regional Geologist.

Mined Land Reclamation Program: 1536 Queen Ave. SE, Albany 97321, phone (541) 967-2039, FAX (541) 967-2075.
Gary W. Lynch, Supervisor.

The Nature of the Northwest Information Center: Suite 177, 800 NE Oregon Street # 5, Portland, OR 97232-2162, phone (503) 872-2750, FAX (503) 731-4066, Donald J. Haines, Manager.

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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).

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-

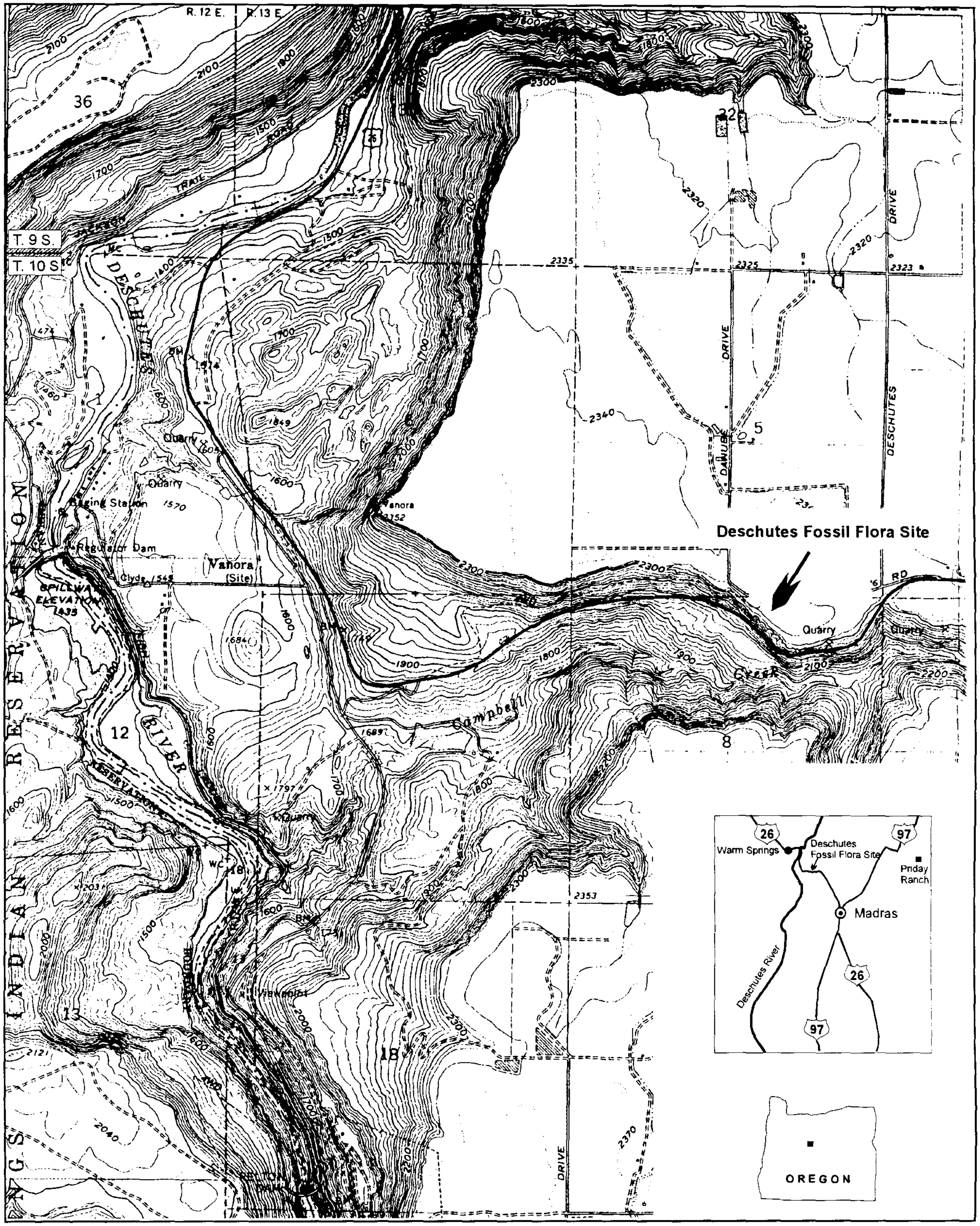

Figure 1. Map showing location of Deschutes fossil locality (NW¼NE¼ sec. 8, T. 10 S., R. 13 E.) on Highway 26 near Madras in Jefferson County.

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 above-mentioned 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

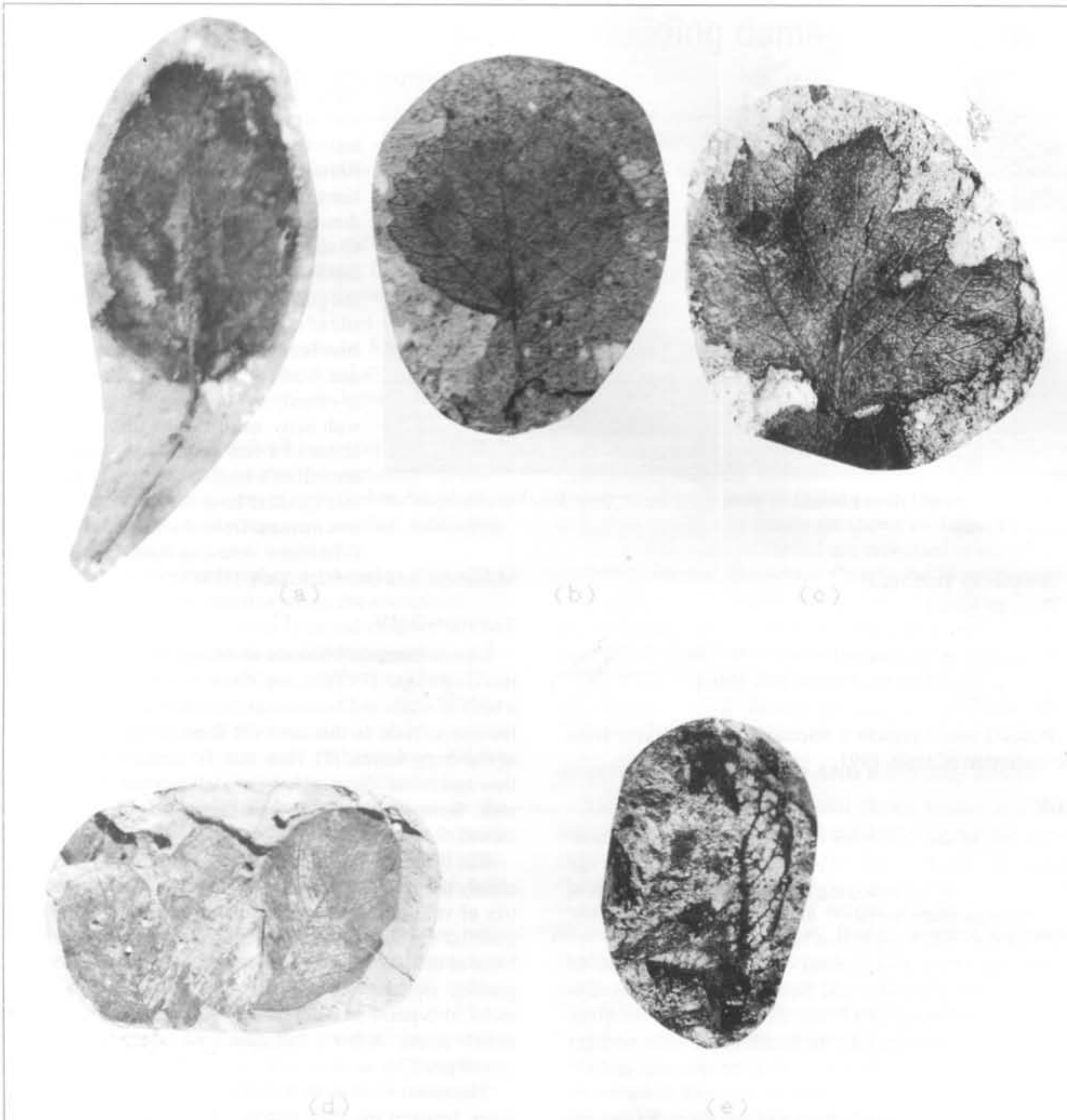

Plate 1. Deschutes flora leaves (MSA/F-14), approximately natural size. (a) Arbutus*? sp. [madrona]; (b)* Populus alexanderi *Dorf (Chaney, 1938) [cottonwood]; (c)* Populus subwashoensis *[cottonwood]; (d) "juvenile leaves" of* Populus alexanderi *Dorf (Chaney, 1938) [cottonwood]; (e)* Rosa *sp. [rose].*

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

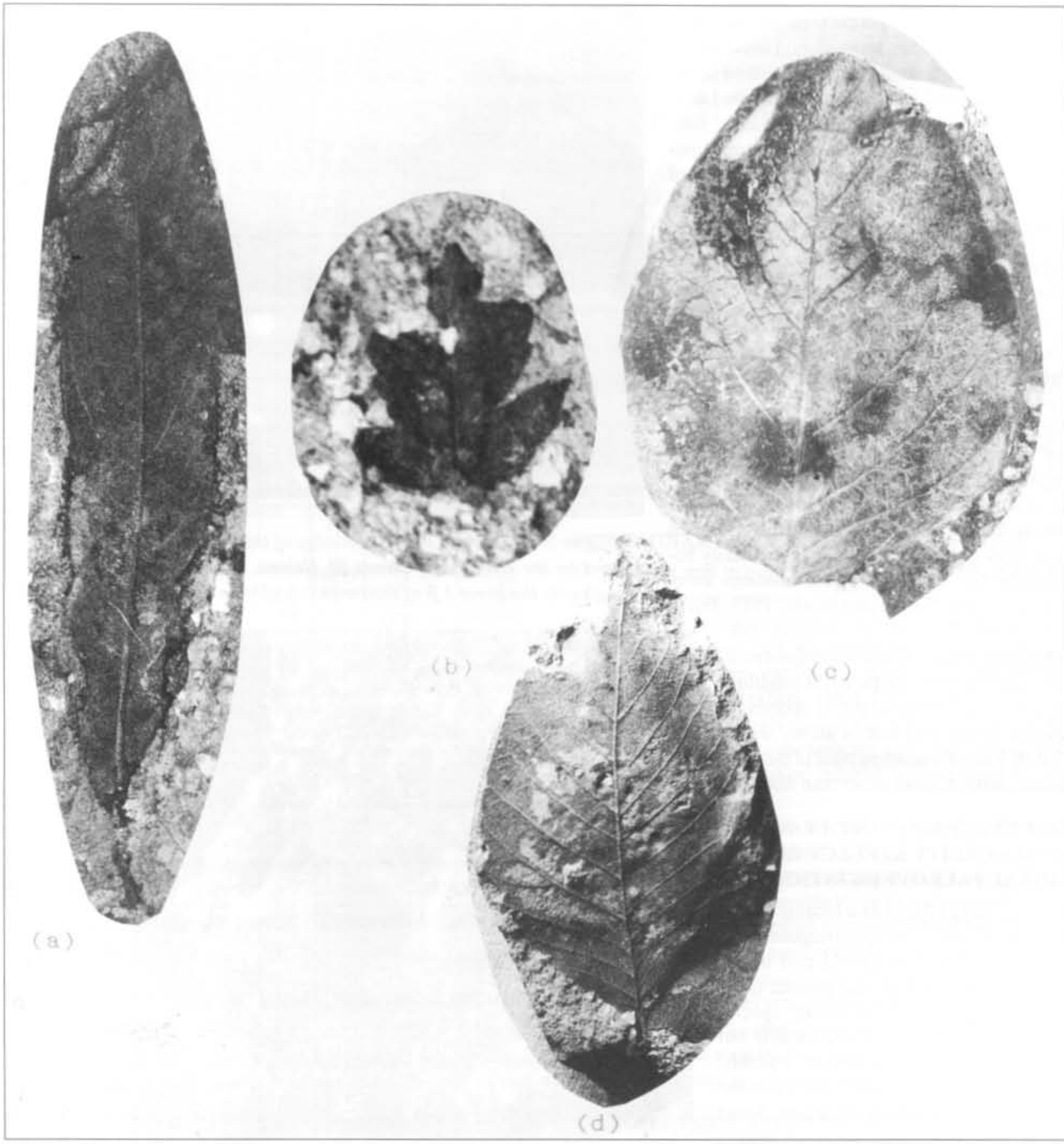

Plate 2. Deschutes flora leaves (MSA/F-14), approximately x1.25: (a) Salix florissanti *Knowlton and Cockerell [willow]; (b)* Crataegus *sp. [hawthorn]; (c)* Populus pliotremuloides *Axelrod [quaking aspen]; (d)* Ulmus *sp. [elm].*

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, leaving 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.

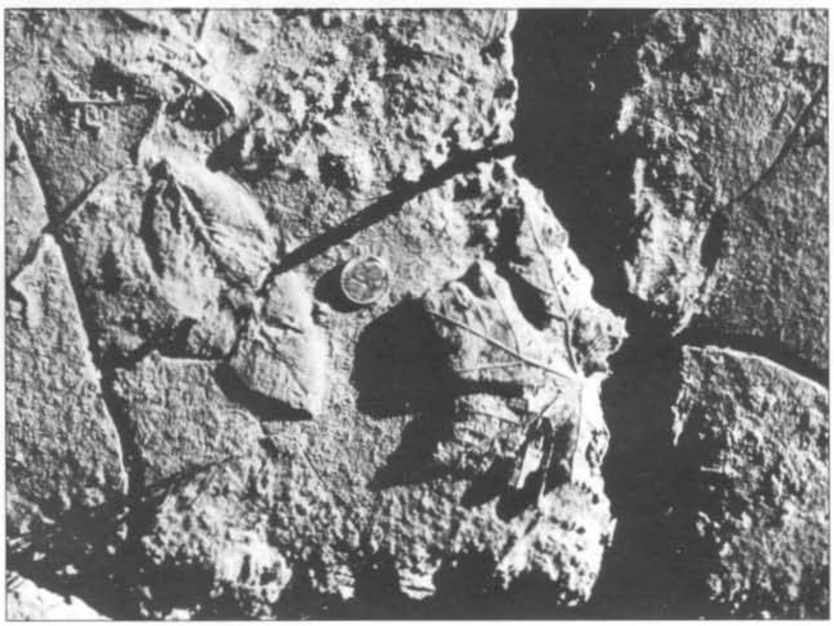

Figure 6. Flat lying leaves on the rain-etched surface of the Toutle River mudflow near Interstate Highway 5 at Castle Rock, Washington, one year after the Mount St. Helens eruption.

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.

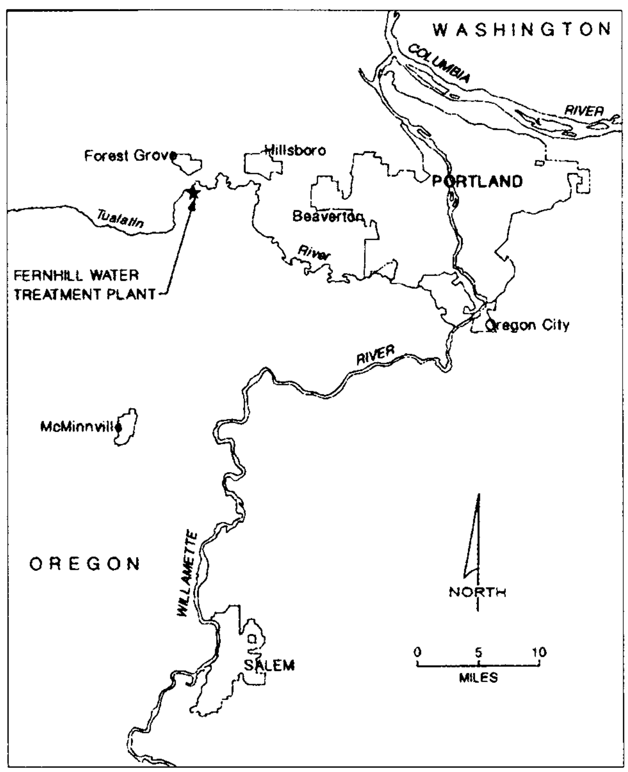


Figure 1. Sketch map showing location of the Fernhill water treatment plant, the site discussed in this paper.

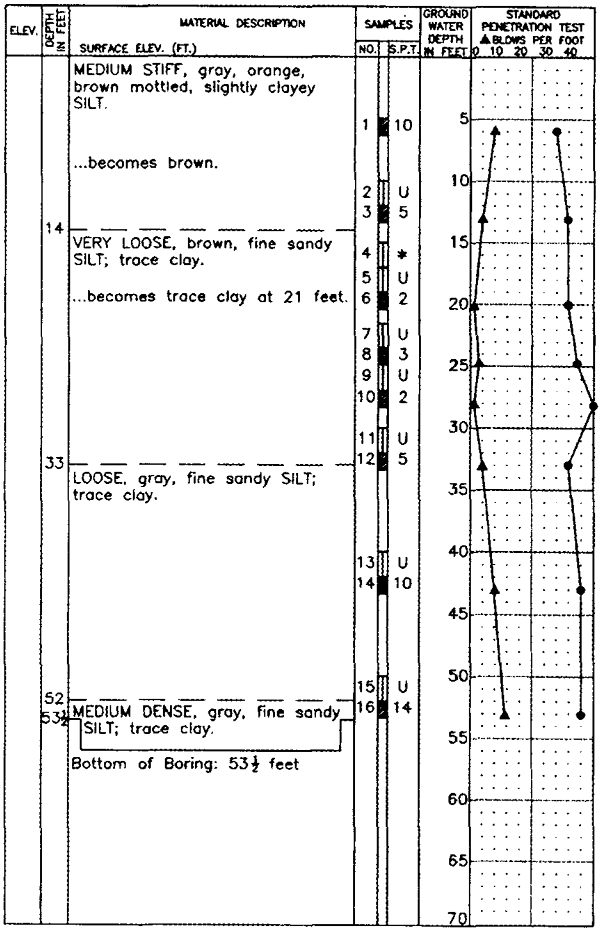


Figure 2. Representative boring log. U *=Shelby tube sample; * = no sample recovered; curve on extreme right marked by circles shows moisture content in percent.*

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,

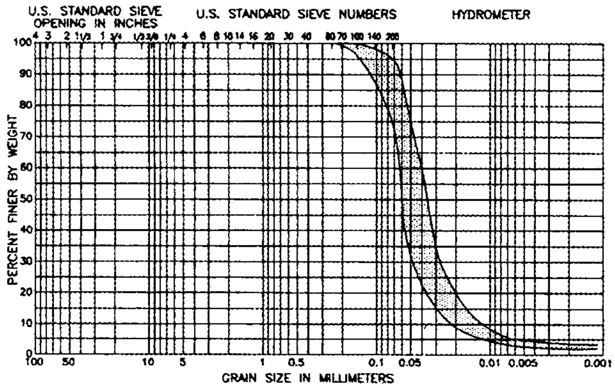


Figure 3. Range of particle size for 5 cyclic triaxial specimens.

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.

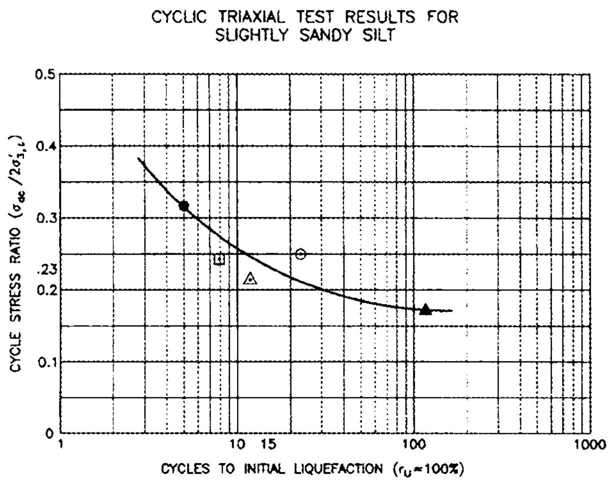
Table 2. *Results of cyclic triaxial testing of Willamette silts*

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-



TEST NO.	SYMBOL	SAMPLE DEPTH (FT)
CC-4, 7T	⊙	22
CC-4, 7M	●	22½
CC-4, 7B	△	23
CC-4, 9T	▲	26
CC-4, 11T	⊡	31

INITIAL EFFECTIVE CONFINING STRESS, ($\sigma'_{3,i}$) = 1,500 psf

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

[1] Current address: ECONorthwest, Pioneer Tower, Suite 1460, 888 SW Fifth Avenue, Portland, OR 97204-2028.
[2] Current address: Geology Department, Brigham Young University, P.O. Box 25111, Provo, UT 84602-5111

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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Whelan, R.M., 1995, An economic analysis of construction aggregate markets and the results of a long-term forecasting model for Oregon: Oregon Department of Geology and Mineral Industries Special Paper 27, 123 p. □

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

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