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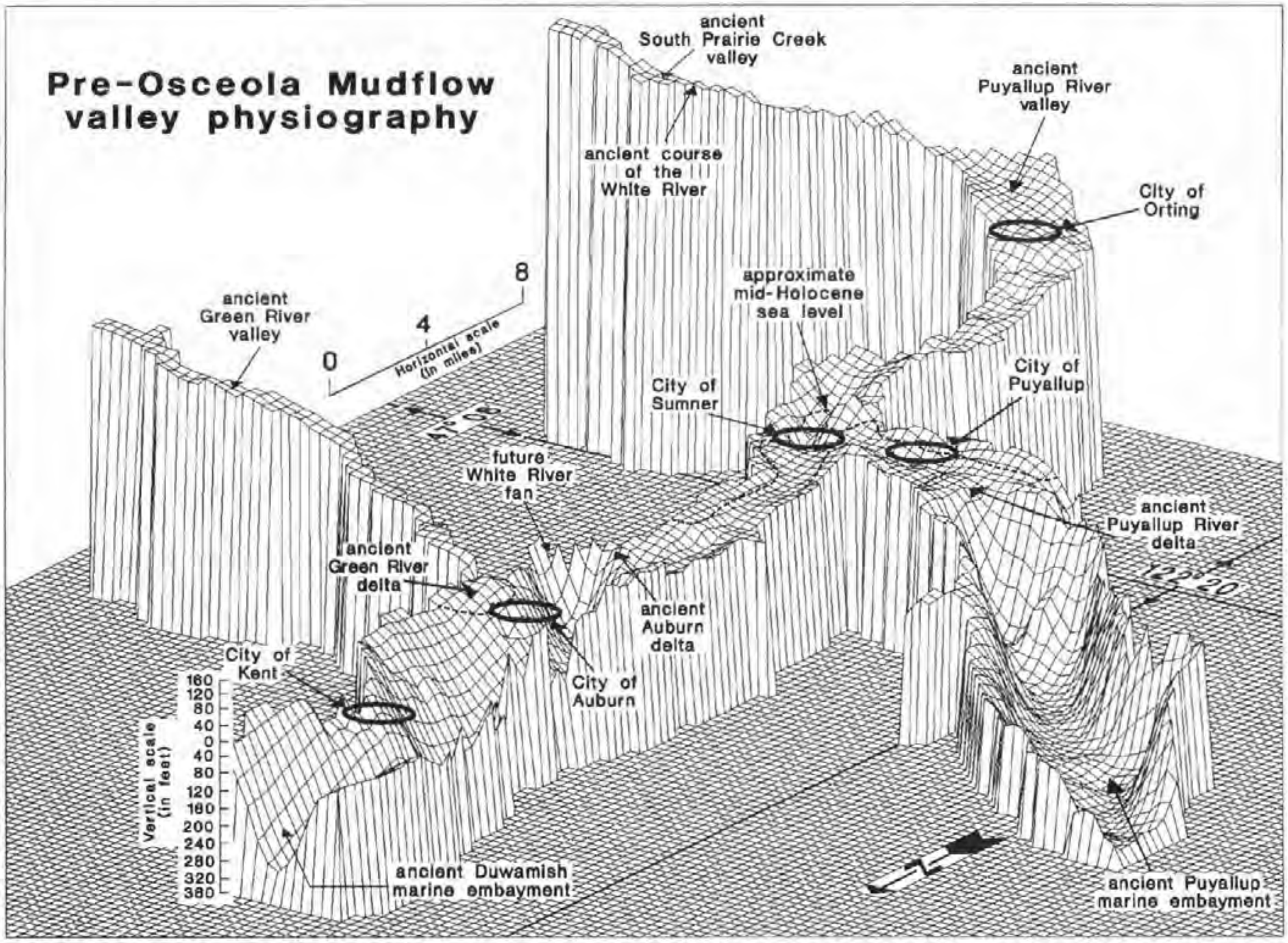
Pre-Osceola Mudflow valley physiography

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Cover Illustration: A view of mid-Holocene pre-Osceola valley topography of an area northwest of Mount Rainier (created using SURFER®). The Osceola Mudflow filled these valleys 5,700 years ago, providing a marker bed that can be used in reconstructing subsurface physiography. Note the position of the presently buried ancient deltas. In this figure, the highest elevation is 450 ft in the South Prairie Creek valley; the lowest point is 320 ft below present sea level. Before the mudflow was deposited, the White River followed the course of South Prairie Creek and the Puyallup River. After the mudflow, the White River cut across the glacial uplands south of the Green River and established its present course and the large fan at Auburn.

The Division's Role in Environmental Regulation

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The Division of Geology and Earth Resources administers the Oil & Gas Conservation Act of 1951, the Surface Mine Reclamation Act of 1970, the Underground Gas Storage Act of 1976, and the Geothermal Resources Act of 1976. Additionally, we regulate aspects of the Underground Injection Act of 1978 and the Metals Mining and Milling Act of 1994 in concert with the Washington Department of Ecology. This article describes recent developments in our regulatory program.

During the past decade, the Division of Geology has constantly reviewed and improved regulatory performance with the goal of assuring that we are fully responsive to public needs while concentrating our efforts on those activities that produce the most cost-effective government. During this period, it became clear that we needed to enhance and improve the effectiveness of these environmental regulatory programs.

In order to meet this goal, we implemented a four-phase program to (1) improve the skills of our regulatory personnel, (2) perform and publish reclamation and other regulatory research, (3) undertake a public outreach and education program, and (4) facilitate improvements in state regulatory laws and the Department of Natural Resources' (DNR) administrative rules with the following actions:

- Since 1986, reclamation specialists have replaced generalists in most of the Department's seven regional offices. This has been the key to marked improvements in mine compliance throughout the state. In addition, the Division trained 140 DNR employees, some representatives of local governments, and many industry personnel in mine reclamation techniques.
- Recognizing that construction aggregates (sand, gravel, and crushed bedrock) are the most important mineral commodities in Washington and that such mining results in the largest cumulative ground disturbance, we concentrated our regulatory effort in this area.

  Aggregate mines present unique reclamation problems, such as a highly porous substrate containing virtually no nutrients for plant life. The literature and programs of other states offered little guidance for appropriate reclamation procedures. Consequently, the Division researched appropriate techniques and wrote ground-breaking papers on their findings (Norman and Lingley, 1992; Norman, 1992). As a result of this work, as well as industry research by companies such as Acme Inc. of Spokane and Lone Star Northwest of Tacoma, we now have access to reclamation technology that establishes stable landforms that harmonize with adjacent topography and a healthy plant/soil ecosystem as the first stage of successional revegetation.
- Washington's laws regulating the extractive industries were written to protect the general public and the environment. However, most laws must be studied in detail to be under-

Continued on p. 48

Extent and Geometry of the Mid-Holocene Osceola Mudflow in the Puget Lowland—Implications for Holocene Sedimentation and Paleogeography

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The Osceola Mudflow (OM) originated on the summit and northeastern flank of Mount Rainier about 5,700 years ago (Table 1). This lahar flowed down the White River drainage and spilled into the Green and Puyallup drainages. It covered an area of *at least* 195 mi^2 (505 km^2), including 71 mi^2 (185 km^2) now buried under more recent valley fills and 124 mi^2 (320 km^2) currently exposed on glacial uplands at higher elevations (Fig. 1 inset). After passing through the White River bedrock gorge upstream of Mud Mountain dam, the OM blanketed the drift valleys and plain with as much as 100 ft (31 m) of clay-rich gravel, cobbles, and boulders (or diamicton). Its average thickness is about 25 ft (8 m).

The OM was originally named the Osceola till by Willis (1898). Crandell and Waldron (1956) later recognized it as an enormous mudflow from Mount Rainier. The high clay content and composition of the clays in the mudflow indicate that it started as a sector collapse—a huge, deep-seated landslide that removed a large part of the mountain and cut into its hydrothermally altered core (Crandell, 1971; Scott and others, 1992). The landslide mass incorporated rock debris, glacial ice, and stream water as it slid and probably began transforming into a lahar before it left the cone. Its fluidity enabled it to cross a significant part of the Puget Lowland.

The OM appears to have been synchronous with volcanism. Tephra layers F (Mullineaux, 1974) and S, F_l, and F_u (J. Vallance, Michigan Technological University, and K. Scott, U.S. Geological Survey, unpub. ms.) can be correlated with the mudflow by their stratigraphic relations, resemblance to the matrix of the mudflow, and radiocarbon (^{14}C) ages. That is, layer F does not lie on top of the OM and thus cannot be younger than the mudflow. Also, organic material beneath layer F has an age of 5,800 years (Crandell, 1971), similar to the age of the OM (Table 1).

Table 1. Radiocarbon ages related to the Osceola Mudflow deposit. Calibrated ages corrected using tree ring data (Stuiver and Reimer, 1993) and reported as [– 1 sigma (age) + 1 sigma] using the calibration of Stuiver and Reimer (1993). Commonly, fluctuations in the calibration curve yield more than one intercept or calibrated age. B.P. (before present) ages are reported with respect to A.D. 1950. (See Coleman and others, 1987, for a discussion of ^{14}C terminologies.) bpsl, below present sea level

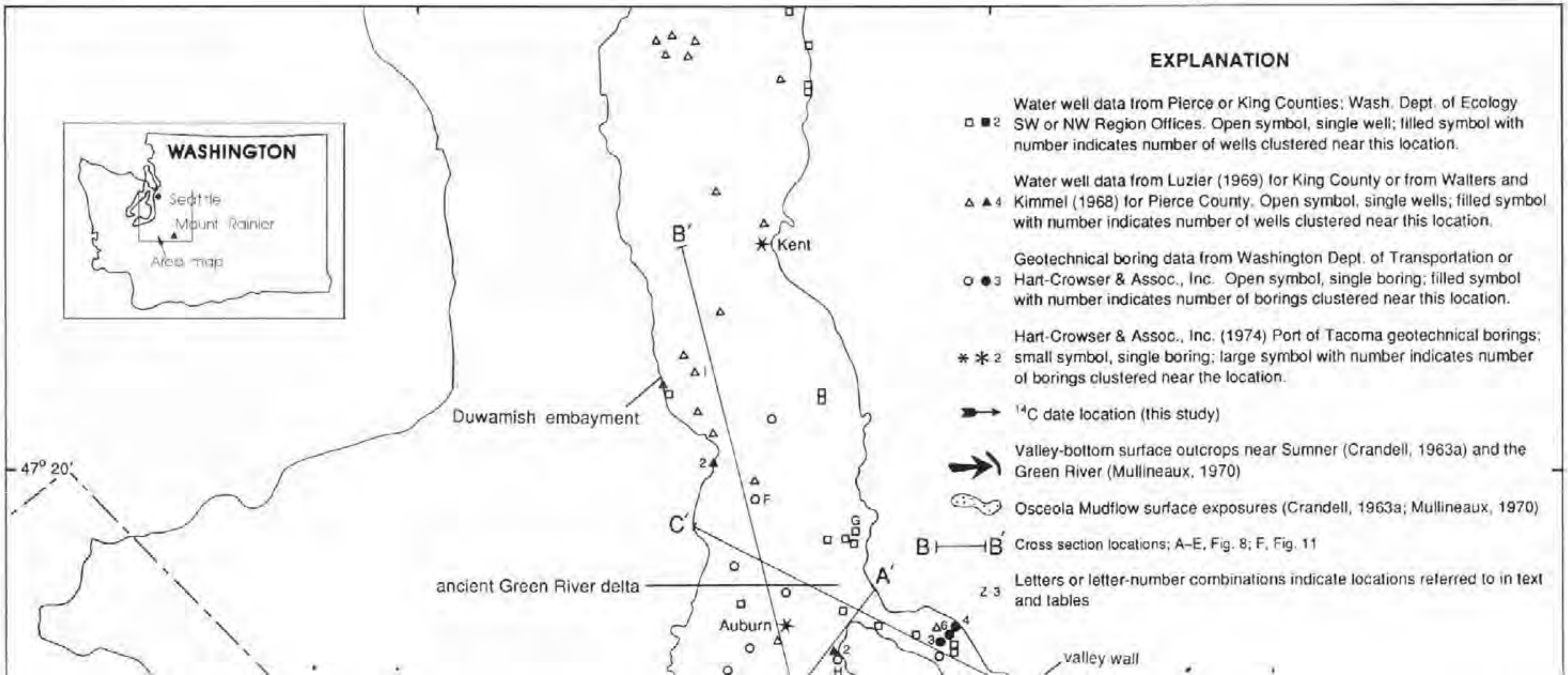
Laboratory number	Uncalibrated ^{14}C age (years B.P.)	Calibrated age (years B.P.)	Calibrated age (years B.C.)	Source of sample
Univ. of Wash. UW-62	5040 ± 150	5931 (5850, 5830, 5750) 5612	3981 (3900, 3880, 3800) 3662	Wood from well hole 22/4-35H2; Osceola Mudflow at 265–280 ft bpsl; Luzier (1969)
U.S. Geol. Surv. W-564	4700 ± 250	5659 (5452, 5365, 5332) 4997	3709 (3503, 3416, 3383) 3047	Wood from Osceola Mudflow (Crandell, 1971)
Lamont Geol. Observ. L-223A	4800 ± 300	5896 (5580, 5503, 5497) 5057	3946 (3631, 3554, 3548) 3107	Wood from Osceola Mudflow (Crandell, 1971)
Lamont Geol. Observ. L-223B	4950 ± 300	5988 (5658) 5322	4038 (3709) 3372	Wood from Osceola Mudflow (Crandell, 1971)
U.S. Geol. Survey W-2053	5020 ± 300	6170 (5741) 5337	4220 (3792) 3387	Peat from above tephra layer N and below layer F at Mount Rainier (Crandell, 1971)
Geochron Lab. 1	4455 ± 355	5584 (5042, 5001, 4998) 4564	3634 (3093, 3052, 3049) 2614	Wood from Osceola Mudflow (Scott and others, 1992)
Geochron Lab. 2	4980 ± 200	5927 (5721) 5489	3977 (3772) 3539	Wood from Osceola Mudflow (Scott and others, 1992)
Geochron Lab. 3	5230 ± 235	6285 (5982, 5974, 5947) 5730	4335 (4033, 4025, 3998) 3780	Charcoal fragments from base of lahar under Osceola Mudflow (Scott and others, 1992)
Beta Analytic 65937	5010 ± 80	5892 (5736) 5652	3942 (3787) 3702	Twigs from WA DOT borehole B-3, 4 km north of Sumner
Beta Analytic 66269	4700 ± 60	5569 (5450, 5370, 5330) 5320	3619 (3500, 3420, 3380) 3370	Wood from Osceola Mudflow at Puyallup River Bridge at Sumner
Beta Analytic 72328	10,160 ± 200	12,258 (11, 870) 11,044	10,308 (9920) 9094	Wood from 235 ft depth at Puyallup Recreation Center well

Our study is the first systematic attempt to map the extent and geometry of the *subsurface* OM. We used 833 geotechnical boring and water-well logs (Fig. 1) and previous subsurface correlations to trace the OM in the valley deposits of South Prairie Creek, the Carbon, Green, and Puyallup Rivers, and Duwamish embayment. Translating OM top and bottom depths into altitudes helped us create an OM isopach map, determine the 3-D geometry of the mudflow, and construct a surface map of the pre-OM topography (cover). The maps and cross sections developed from these data provide a basis for pre- and post-OM paleogeographic and sedimentologic interpretations and a new OM volume estimate. Paleogeographic reconstructions from OM bottom elevations show ancient deltas west of

Figure 1. Locations of geotechnical borings and water wells

Geotechnical boring and water-well drill hole locations used to determine Osceola Mudflow (OM) correlations, thickness, and top and bottom elevations. The stippled pattern shows where the mudflow is exposed on the uplands; it is also found in the valleys below more recent valley fills. (See Figure 8 for cross sections and Tables 3 and 4 for descriptions of delta platform and marine embayment drill holes, respectively.)

Insets: **Top inset** shows the location of study area in relation to the state of Washington. **Bottom inset** shows regional geographic and paleogeographic locations. Box shows study area and area of this figure and Figures 2–5. The OM originated as a large landslide from the northeastern side of Mount Rainier, reducing the old summit elevation by about 0.5 mi (0.9 km) before construction of the post-OM cone. The landslide transformed into a mudflow and entered the White River valley, flowed into the Puget Lowland glacial uplands east of Enumclaw, and spread over a dissected glacial drift plain (stippled). It then flowed into several major valleys, passed over three ancient deltas into former Puget Sound embayments (see Fig. 6), and became channelized along the marine embayment bottoms.



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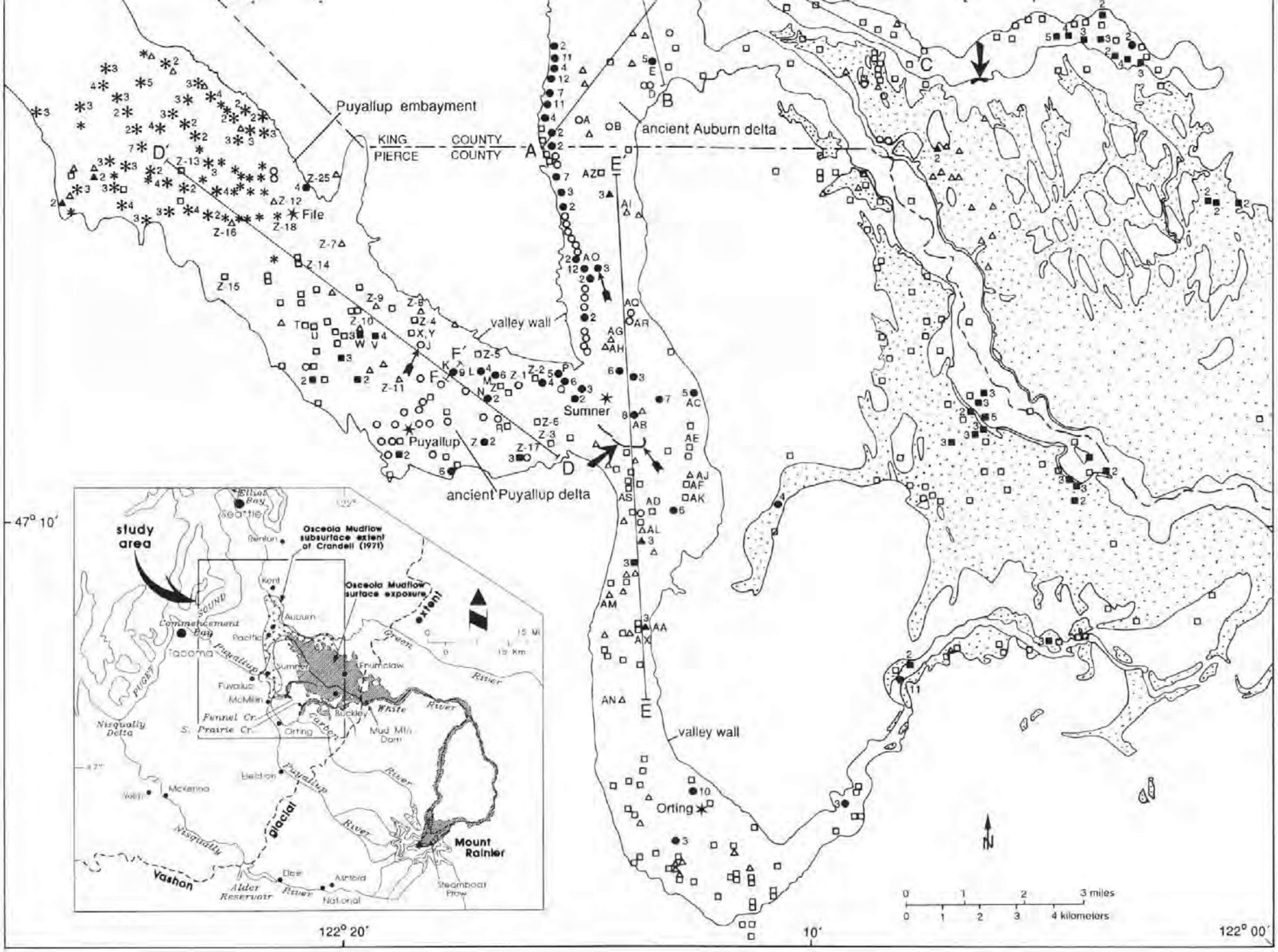
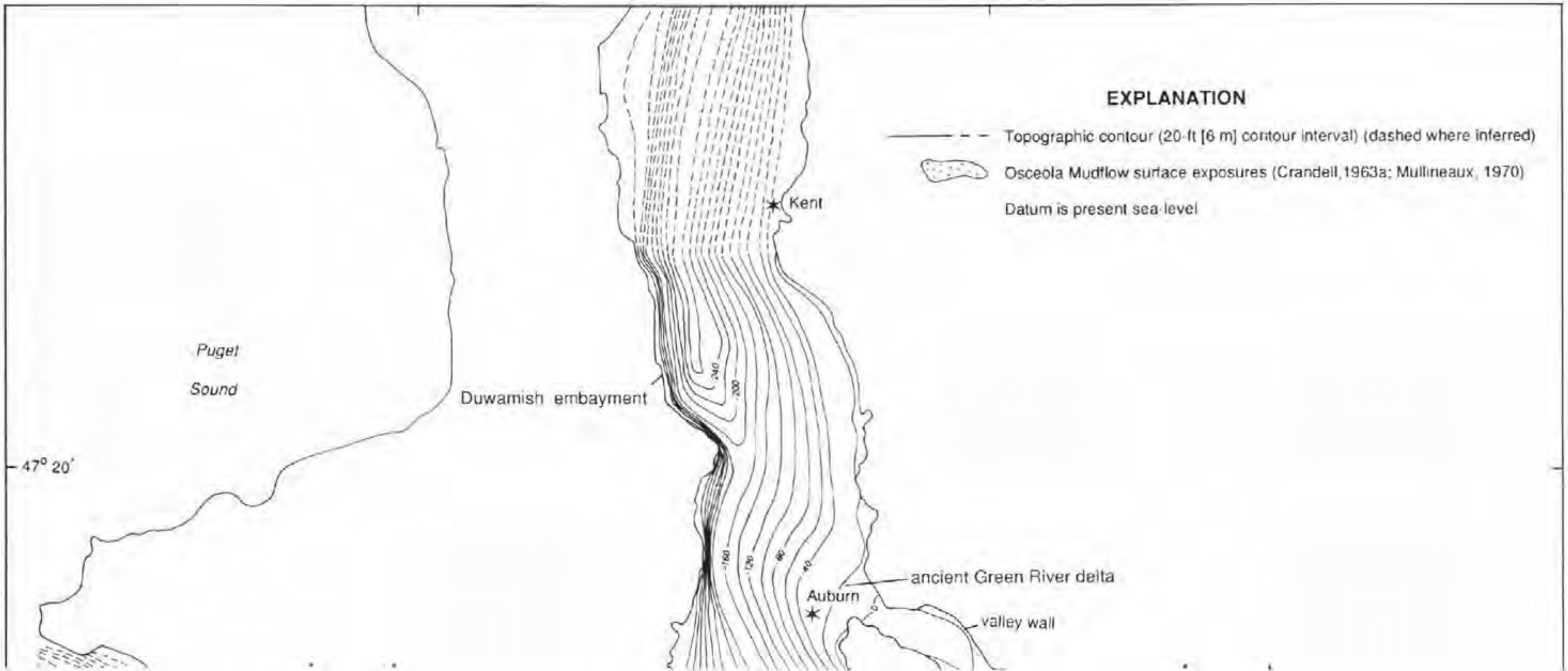
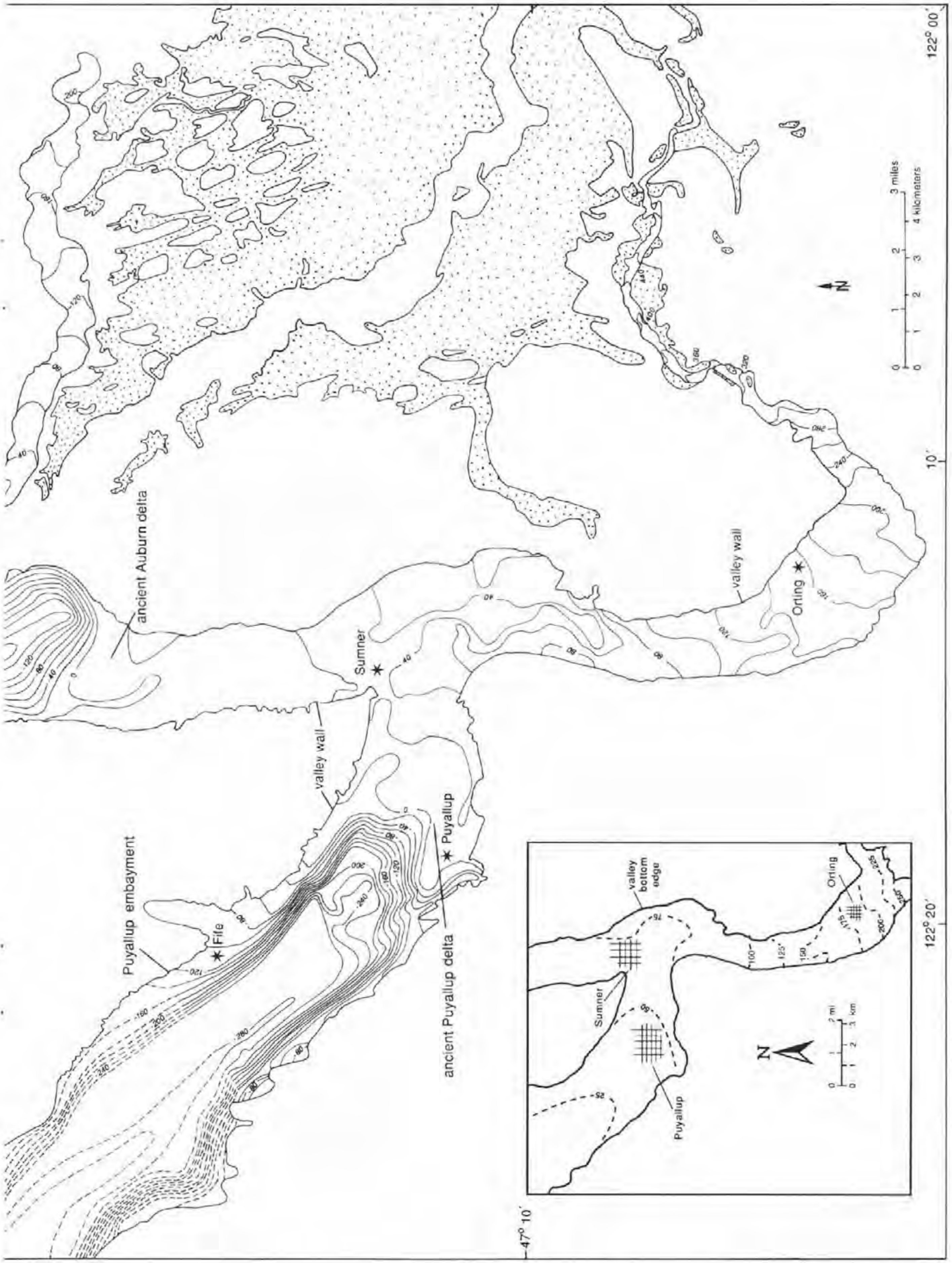

Puyallup embayment
KING COUNTY
PIERCE COUNTY
A
B
C
D
D′
E
E′
F
F′
ancient Auburn delta
Fife
valley wall
valley wall
Sumner
Puyallup
ancient Puyallup delta
Orting
47° 10′
122° 20′
10′
122° 00′
0 1 2 3 miles
0 1 2 3 4 kilometers
study area
Seattle
Elliott Bay
Renton
Kent
Auburn
Commencement Bay
Tacoma
Pacific
Sumner
Puyallup
McMillin
Enumclaw
Buckley
Orting
Fennel Cr.
S. Prairie Cr.
Mud Mtn Dam
Osceola Mudflow subsurface extent of Crandell (1971)
Osceola Mudflow surface exposure
Puget Sound
Green River
White River
Carbon River
Puyallup River
Nisqually Delta
Nisqually River
Yelm
McKenna
Electron
Alder Reservoir
Elbe
Ashford
National
Steamboat Prow
Mount Rainier
glacial extent
Vashon
0 15 Mi
0 15 Km
122°
47°

Figure 2. Topography of the top of the subsurface Osceola Mudflow

Compared to the topography buried by the Osceola Mudflow (OM) (Fig. 5 and cover), the OM top is generally smoother due to its fluidity during deposition. The OM slopes downvalley and, to a lesser degree, toward the valley axes, mimicking pre-existing topography. (Geographic and paleogeographic locations are shown on Fig. 1 insets.) Stippling shows OM exposed in the uplands. The OM is not represented along the steep marine embayment slopes that funneled the mudflow along embayment bottoms (see Fig. 3, zero isopach).

Inset: General elevation of the water table in the Puyallup valley (modified from Sceva and others, 1955). The subsurface OM is a major aquitard, a continuous layer of low permeability on which ground water perches or by which it is confined. For example, the water table is about 50 ft (15 m) above the OM at Puyallup, 35 ft (11 m) above the OM at Sumner and about 10–20 ft (3–6 m) above it at Orting. Downvalley from Puyallup, the OM is deeply buried and the shallow water table is controlled by other strata. Some contours may mimic the geometry of the OM top; for example, the 50-, 75-, and 150-foot (≈15-, 23-, and 46-m) contours are subparallel to our mapped OM top contours. Additionally, artesian conditions reported in some water wells and boring logs are apparently the result of aquitard confinement by the overlying OM layer (for example, middle boring, Fig. 11). Several deep wells terminating just below the OM (Fig. 8D) appear to have penetrated waters confined by the low permeability of the OM.




Puyallup embayment
Fife
ancient Puyallup delta
Puyallup
valley wall
Sumner
ancient Auburn delta
valley wall
Orting
47° 10'
122° 20'
10'
122° 00'
0 1 2 3 miles
0 1 2 3 4 kilometers
N
0
40
80
120
160
200
240
280
320
360
400
440
valley bottom edge
Orting
Sumner
Puyallup
N
0 1 2 mi
0 1 2 3 km
25
50
75
100
125
150
175
200
225

Puyallup, south of Auburn, and at the confluence of the Green River with the Duwamish valley (Fig. 2, cover). The ancient delta-platform elevations approximate sea level at OM time.

Understanding the extent and geometry of the OM in the subsurface distal portion of the deposit has relevance to several important issues. First, we can better estimate mudflow volume and runout distance. This information is useful for volcanic-hazards planning in the Mount Rainier area. Mudflows probably represent the greatest risk to populations downstream of volcanoes (U.S. Geodynamics Committee, 1994). Second, the OM deposit is an important stratigraphic marker of known age, allowing us to better understand the paleogeography during OM time. For example, the geometry of ancient deltas aids in deciphering the record of mid-Holocene rising sea level and other postglacial processes. Third, the texture of the OM influences ground-water distribution and the engineering properties of soils. The OM has low permeability and is an important aquitard. Additionally, because of its low density, the deposit has very low bearing strength when saturated (Crandell, 1963a) and may be locally liquefiable (Palmer, 1992; Dragovich and others, unpub. data).

Past workers recognized the geometry of the ancient Duwamish marine embayment. Luzier (1969, p. 14) identified the OM in a water well 4 mi (6.4 km) northwest of Auburn. At this site, a wood-rich interval 265–280 ft (77–85 m) below sea level overlying a 22-ft (7 m) -thick bed of gravelly bouldery clay (diamicton) yielded a ^{14}C age of 5,040 ± 150 years before present (B.P.) (about 5,700 calendar years), showing that part of the OM reached ancient Puget Sound along the Duwamish valley.

Mullineaux (1970) postulated that the Green River built a delta into the marine embayment envisioned by Luzier (1969). He thought the existence of older alluvium beneath the buried OM deposits and an OM exposure in a Green River valley terrace indicated that the valley existed prior to deposition of the OM. Geohydrologic studies for the City of Auburn (Hart-Crowser & Associates, Inc., 1982) correlated diamictons identified in six borings at about 240 ft (73 m) below sea level with the OM, supporting Luzier's contention that the OM reached this embayment.

Crandell (1963a) showed that the OM extended in the subsurface to near Sumner, where it is locally 97 ft (30 m) thick. On the basis of elevations of the base of the OM relative to present sea level, he suggested that Puget Sound at that time occupied the Puyallup valley as far upstream as Alderton. Crandell also mapped an important OM exposure in a cutbank of the Puyallup River at Sumner (see arrow and outcrop pattern, Fig. 1).

The present course of the White River upstream of Auburn crosses the glacial drift-plain uplands (Fig. 1 inset). This new course was cut soon after OM deposition when the river abandoned its former South Prairie Creek course. It resulted in abundant supplies of coarse sediment of Mount Rainier provenance being brought to the Duwamish embayment (Mullineaux, 1970) and in the creation of the White River fan at Auburn. Using water-well logs from near Sumner and from Luzier's water well discussed above, Crandell (1971) projected the subsurface OM under Puyallup and Kent (Fig. 1 inset, Crandell's OM limits).

METHODS

Major sources of data for this study include water-well records (archives of Washington State Department of Ecology's Northwest and Southwest regions; Walters and Kimmel, 1968; Luzier, 1969) and geotechnical boring logs obtained from private consultants and the Washington Department of Transportation (DOT). Typically, geotechnical boring logs were of higher quality than those from water wells. In addition, many of these boring logs provided textural, density, or other data that assisted mudflow correlation and Holocene sedimentologic and paleogeographic analyses.

First, we assigned suspected OM layers top and bottom elevations relative to modern sea level for each boring (Fig. 1). We then prepared three maps at 1:24,000: (1) an OM surface elevation topographic map, (2) an OM thickness (isopach) map, and (3) a post-OM alluviation thickness (isopach) map. Figures 2–4 were generated by compiling these maps at 1:100,000 scale. Subtracting (by computer methods) the thickness from the top elevation produced the valley topography prior to catastrophic burial (Fig. 5 and cover). In addition to top and bottom elevations, we also compiled elevations of fossil shell layers and other notable features.

We studied surface exposures of the OM to help us identify and correlate the subsurface deposits. (See also Crandell and Waldron, 1956; Crandell, 1963a, 1971; Mullineaux, 1970.) Diagnostic criteria included:

(1) poor sorting of the gravel, sand, silt, and (or) clay with occasional boulders (diamicton) (Fig. 3 inset),

(2) typical massive texture,

(3) normal grading of material coarser than sand size,

(4) low density as determined from blow-count data (Fig. 11),

(5) dominance and angularity of volcanic clasts of Mount Rainier provenance,

(6) random inclusions of wood and organic debris,

(7) gray color with mottled yellow patches and sulfurous smell,

(8) stratigraphic position expected for the 5,700-year-old mudflow, and

(9) surface gradient, thickness, and elevation ranges consistent with both upstream surface exposures

For most water wells, we made the OM correlation from the presence of a poorly sorted, massive diamicton (criteria 1 and 2) at an expected stratigraphic position (criterion 8) and the dramatic thinning and increasing depth of the mudflow deposits off delta fronts west of Puyallup and north of Sumner (discussed later in this article). Black sands composed mostly of Mount Rainier andesite volcanic fragments and crystals commonly overlie the mudflow where we found it at depth and where it was deposited in ancient Puget Sound.

Water is perched above the OM and locally confined below it. For example, in the Puyallup River valley, the shallow water table overlies and locally mimics the mapped OM surface shape (Fig. 2 inset).

The surface exposure of the OM farthest downstream of Mount Rainier is near the Puyallup River bridge at Sumner (arrow south of Sumner on Fig. 1). To substantiate the existence of the OM in the subsurface, we submitted detrital wood from the deposit for ^{14}C dating. The uncorrected age estimate of 4,700 ± 60 years B.P. (sample Beta-66269) confirms that the unit is the OM and validates an OM date (Crandell, 1963a) from a nearby outcrop (Table 1; ^{14}C ages reported later in this text are uncorrected). We also submitted twigs obtained from a correlative deposit in a DOT drill sample from below the State Route 167/32nd Street interchange north of Sumner (Fig. 1, arrow ≈2.2 mi or 4 km north of Sumner). The ^{14}C age, 5,010 ± 80 years B.P. (sample Beta-65937), is well within the age envelope for the OM (Table 1). Lastly, twigs from a deep geotechnical boring sample west of Puyallup (Fig. 1, J) yielded a ^{14}C age of 10,160 ± 200 years. The number of probable OM layers at the same elevation suggest that some older twig material was incorporated in this OM sample or that the organic material sample was too small to provide an accurate date. Alternatively, this could be an older cohesive lahar deposit.

Evidence for subsurface OM deposits was found in 377 of 745 (51 percent) drilling logs (Fig. 1). In addition, 88 water wells and boring logs were consulted in order to constrain the thickness of the surface OM blanketing the glacial uplands (Fig. 1 stippled area). Ten of 11 geotechnical borings and nine of 29 water wells that penetrated strata below 120 ft (37 m) below present sea level (bpsl) and seaward of ancient deltas (see below) contain a diamicton correlative with the OM. None of the 157 geotechnical borings in the Puyallup valley at the Port of Tacoma (Hart-Crowser & Associates, Inc., 1974, borings in Fig. 1) penetrated more than 180 ft (55 m) below sea level. Even though these holes did not reach the OM, they help constrain its minimum probable depth. Five of nine geotechnical borings and 22 of 49 water wells that penetrated below 250 ft bpsl and seaward of ancient deltas (see below) passed through a diamicton correlative with the OM. The majority of the drill holes that did not contain a correlatable diamicton either were not deep enough or, particularly with water wells, had incomplete or poor sediment descriptions in the logs.

PRE-OSCEOLA MUDFLOW STRATIGRAPHY AND PALEOGEOGRAPHY

The three types of ancient physiographic features that were buried by the OM and are revealed by our stratigraphic and topographic analyses are: (1) former Puget Sound marine embayments occupying the Puyallup and Duwamish valleys (Fig. 6), (2) ancient deltas at the interface between ancient marine embayments and river valleys (Fig. 6), and (3) river valleys. Ancient river valleys are upvalley of the ancient deltas and are generally at a shallow depth below the present river valley (such as South Prairie Creek) (Fig. 5 and cover).

Regionally, deglaciation rapidly raised sea level from about 390 ft (120 m) to about 30 ft (10 m) bpsl between 13 ka and 7 ka (Fig. 7; for example, Clague and others, 1982). Sea level rose more gradually from about 6 ka to 3 ka (Clague, 1989). Sea-level studies in Puget Sound (Biederman, 1967; Booth, 1987; Eronen and others, 1987; Williams and Roberts, 1989; Beale, 1990) and southwestern British Columbia (Clague, 1983, 1989; Clague and others, 1982) are in general agreement and suggest that sea level was about 16 ft (5 m) bpsl about 5,700 years ago (Fig. 8).

Major factors that affected sea level from 13 ka to 9 ka were absolute sea-level rise, isostatic rebound, and probably tectonism (Thorson, 1981; Booth, 1987). There are evidently no stable regions where eustatic sea level can be precisely measured (see, for example, Clark and Lingle, 1979). At the end of Vashon glaciation, sea level apparently stood about 328–394 ft (100–120 m) bpsl, and rapid uplift resulted in emergence of much of the Puget Lowland. Isostatic rebound following recession of the Puget lobe during Vashon deglaciation was about 197–262 ft (60–80 m) for the study area, increasing to the north (Thorson, 1989). Rebound appears to have stopped by 9 ka (Clague, 1989; Thorson, 1989), well before OM time. At about 9 ka (Mathews and others, 1970), worldwide sea-level rise began to drown the early Holocene shorelines (Clague and others, 1982).

Glaciation, Rebound, and Marine Embayments

The Puyallup and Duwamish valleys are relict subglacial meltwater channels cut in advance outwash deposits during recession of the Puget lobe about 14,000 years ago (Crandell, 1963a; Mullineaux, 1970; Booth, 1994; Booth and Goldstein, 1994). The Puyallup and Duwamish troughs join at Sumner and extend to near Orting. Subsequent marine, deltaic, and alluvial deposits partly filled the meltwater troughs before this topography was entombed by the OM.

Glacial-lake conditions prevailed behind (south of) the Puget lobe ice dam until the Puget lobe retreated north to the Strait of Juan de Fuca, opening the Puget Sound to the Pacific Ocean and establishing a conduit to the sea and an oceanic base level. The Vashon Stade ended about 13 ka when ice retreat allowed marine inundation of the Puget Lowland.

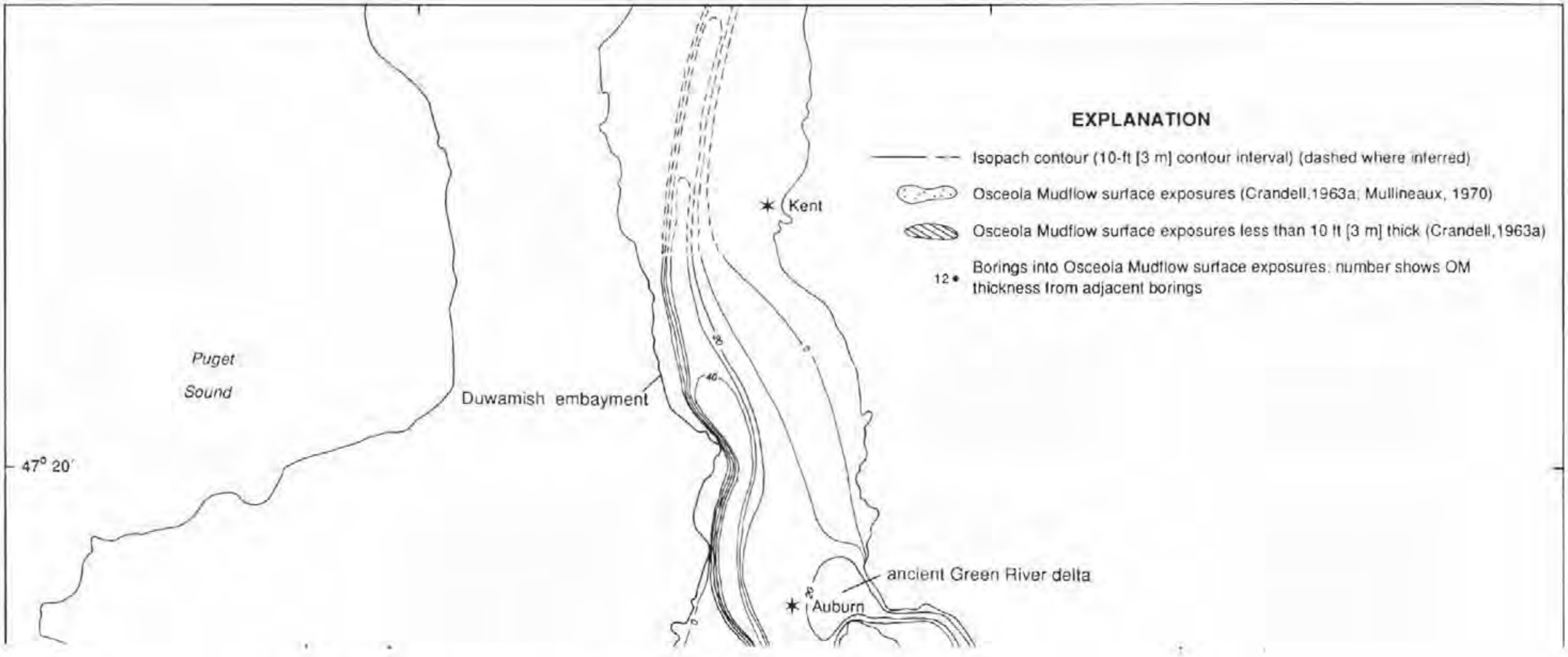
Distal OM deposits directly overlie or lie a few meters above late-glacial Vashon deposits in the Puyallup and Duwamish embayments (Fig. 8). Rapid isostatic rebound of the Puget Lowland from about 13 ka to 9 ka (see Booth, 1987), along with a low early Holocene sea level, resulted in partial to complete emergence of marine embayments in the study area. Little or no marine deposition in the embayments may be due to early Holocene emergence (when nondeposition or erosion would have been operating), possibly followed by slowly accumulating estuarine sediments (see Table 7, p. 24) as the former glacial troughs were inundated by rising marine waters. Thus, the proximity of the OM and glacial deposits in ancient marine embayments reflects slower marine sedimentation and, at least locally, basin emergence, nondeposition, or erosion during periods of lower sea level. Increased stream gradients caused by both a significantly lower postglacial sea level and more vigorous early Holocene erosion of recently deposited unconsolidated glacial drift (see Church and Ryder, 1972) locally increased river sediment loads and deltaic or nearshore sedimentation, but they did not appear to have resulted in significant sedimentation in the marine embayment deeps.

Marine fossils are widespread in postglacial sediments of the Duwamish embayment downvalley and on the platform of the ancient Auburn delta (Fig. 8A; hole A) and in the Puyallup embayment west of Sumner (Fig. 8D; hole Z-10 and west). Also Mullineaux (1970) reported fossils from 40, 50, and 75 ft (12, 15, and 23 m) bpsl from drill holes in Kent, south of Renton, and in northern Renton, respectively. The fossils were

Figure 3. Osceola Mudflow isopachs

Osceola Mudflow (OM) isopachs showing significant thickening of the mudflow on flat delta platforms and along channelized marine embayment bottoms, as well as thinning on steeper delta foreslopes (Figs. 5 and 10). In addition, inundated ancient river channels and terraces upstream of the marine embayments can be detected from thickening and thinning, respectively, of OM in the ancient river valleys.

Inset: Osceola Mudflow grain-size cumulative frequency diagram showing poor sorting. Data are from Crandell (1963a) (lines), Washington Department of the Transportation (DOT) (X's), and this study (X's). Data shown are for matrix samples only. J. Vallance and K. Scott (unpub. ms.) show that average grain size and sorting increase with distance from Mount Rainier due to stream bulking of better sorted alluvial sand and gravel typically lacking appreciable fine material. The general reduction in gravel content in the distal subsurface samples is caused by sampling bias due to the 1.5-in. (3.8 cm) aperture and reduced sample volume of split-spoon drill samples. Sampling bias should affect only the coarsest fractions, suggesting that some downstream sorting in the subsurface samples is real and not due to successive downstream deposition of the coarse tail by basal traction of the mudflow.



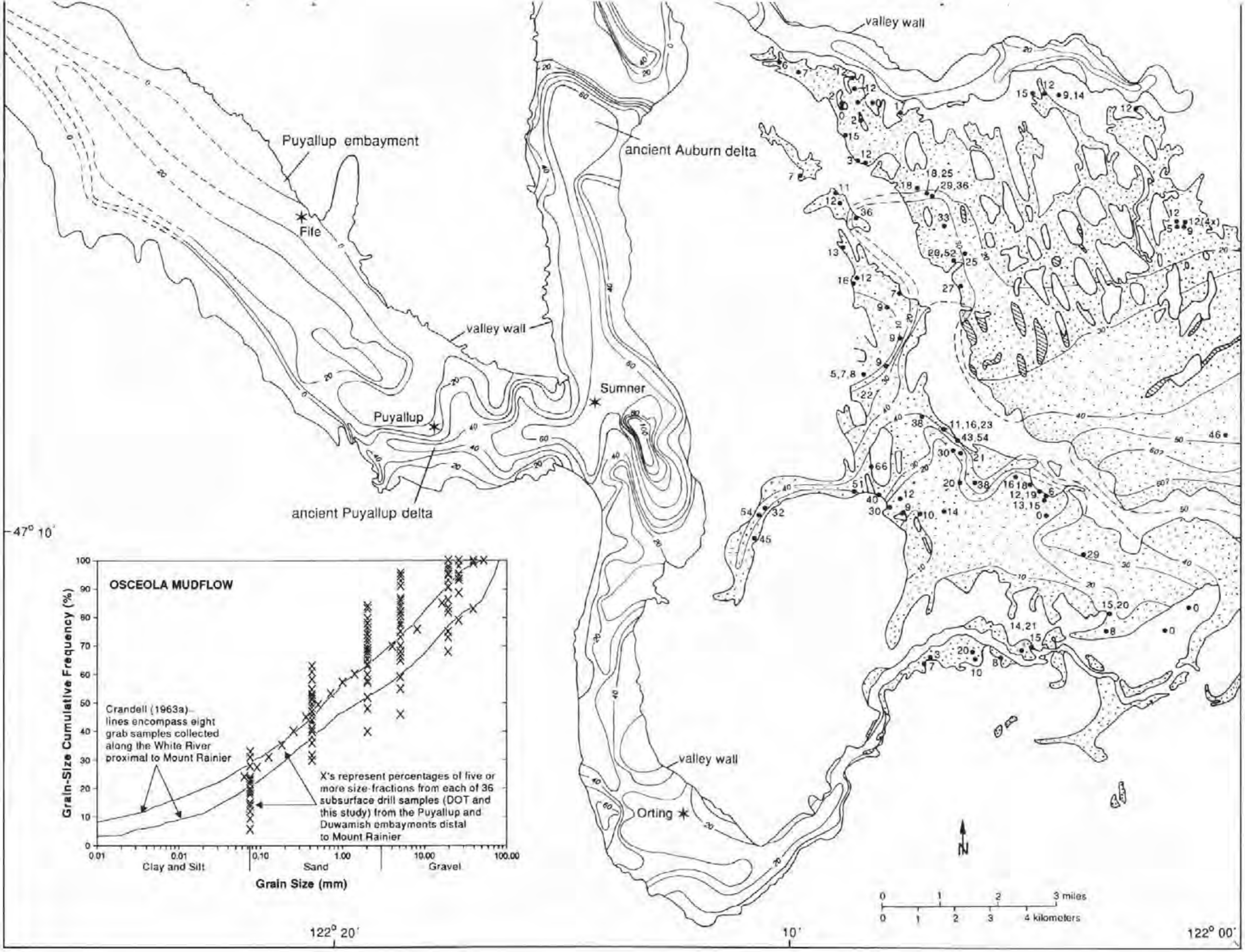
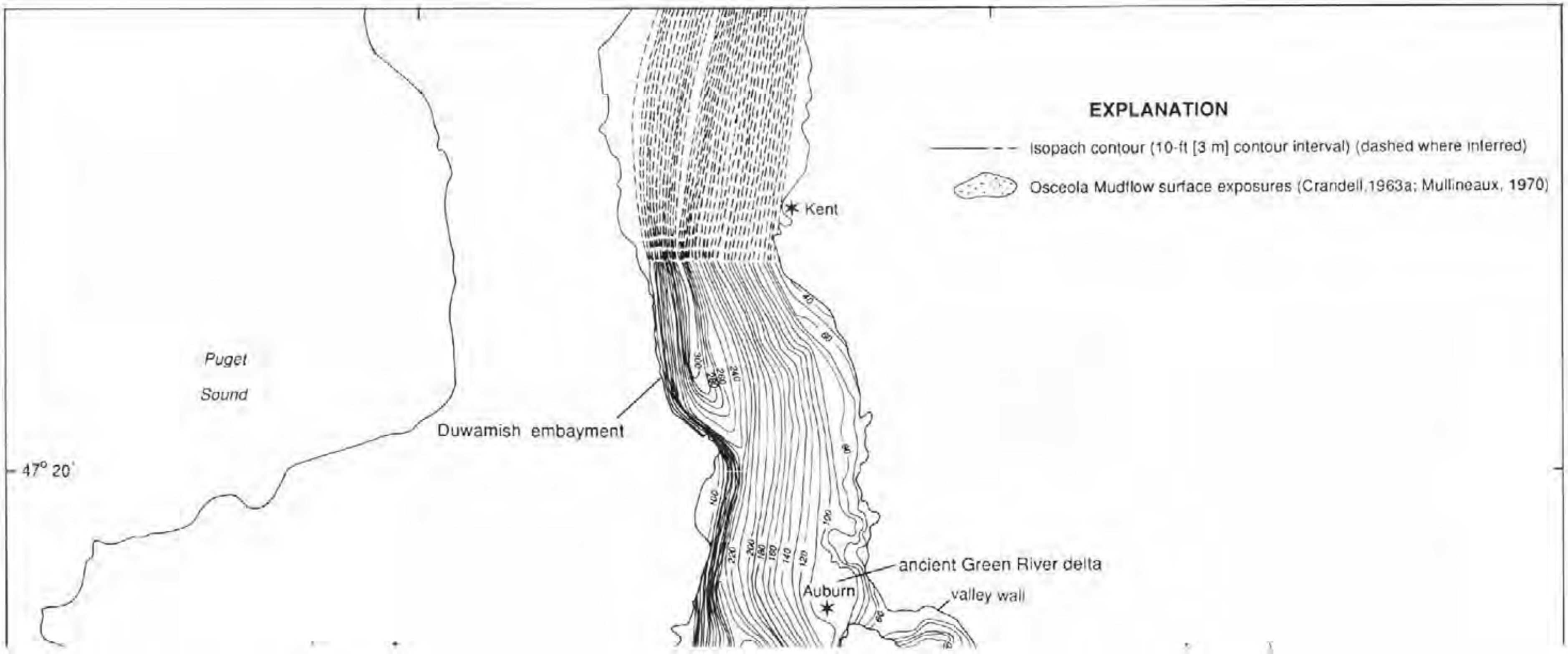
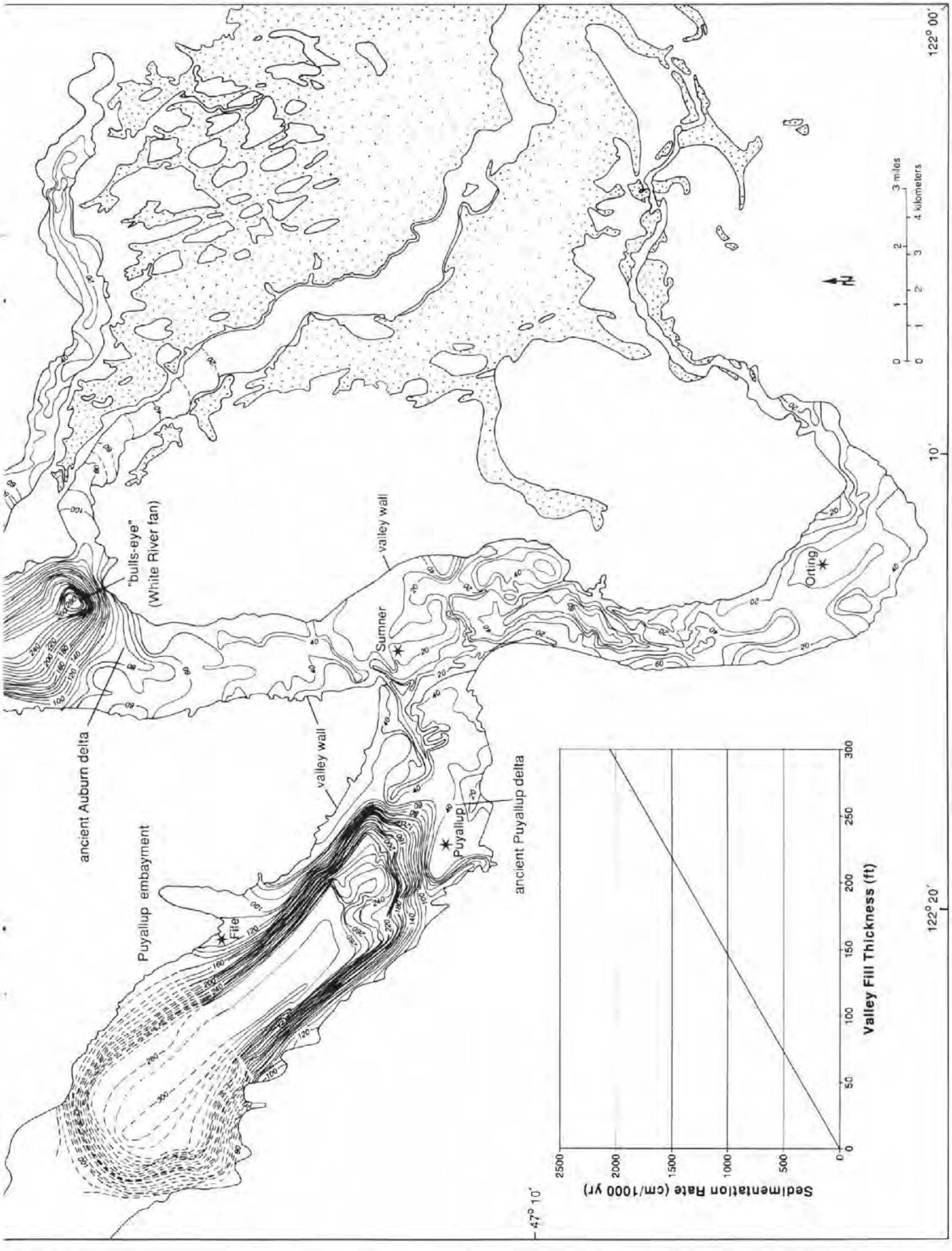

Puyallup embayment
Fife
valley wall
Puyallup
ancient Puyallup delta
ancient Auburn delta
Sumner
valley wall
Orting
valley wall
47° 10'
122° 20'
10'
122° 00'
0 1 2 3 miles
0 1 2 3 4 kilometers
N
OSCEOLA MUDFLOW
Grain-Size Cumulative Frequency (%)
Grain Size (mm)
0.01 0.01 0.10 1.00 10.00 100.00
Clay and Silt
Sand
Gravel
Crandell (1963a)–lines encompass eight grab samples collected along the White River proximal to Mount Rainier
X's represent percentages of five or more size-fractions from each of 36 subsurface drill samples (DOT and this study) from the Puyallup and Duwamish embayments distal to Mount Rainier

Figure 4. Post-Osceola Mudflow (OM) valley-fill isopach (thickness) map

Deltaic, fluvial, and laharic sediments filled the Puyallup and Duwamish marine embayments after OM deposition. Post-OM inception of the White River fan at Auburn and incision of the White River into the glacial drift plain provided abundant sediment for post-OM deltaic progradation down the valleys, accompanied by valley aggradation by river sediments. Post-OM aggradation of about 10–60 ft (3–18 m) in the valleys upstream of the ancient deltas is partially attributed to a rising sea level and laharic deposition.

Inset: Conversion between sedimentation rates and post-OM valley-fill isopachs (thickness) illustrated below. (See Table 7 for sedimentation rates, particularly deltaic, and compare those with information in the map and the inset.) High sedimentation rates in the embayments suggest deposition largely in deltaic regimes.




ancient Auburn delta
Puyallup embayment
valley wall
"bulls-eye"
(White River fan)
valley wall
Sumner
Fife
Puyallup
ancient Puyallup delta
Orting
47° 10'
122° 20'
10'
122° 00'
0 1 2 3 miles
0 1 2 3 4 kilometers
N
Sedimentation Rate (cm/1000 yr)
0
500
1000
1500
2000
2500
Valley Fill Thickness (ft)
0
50
100
150
200
250
300

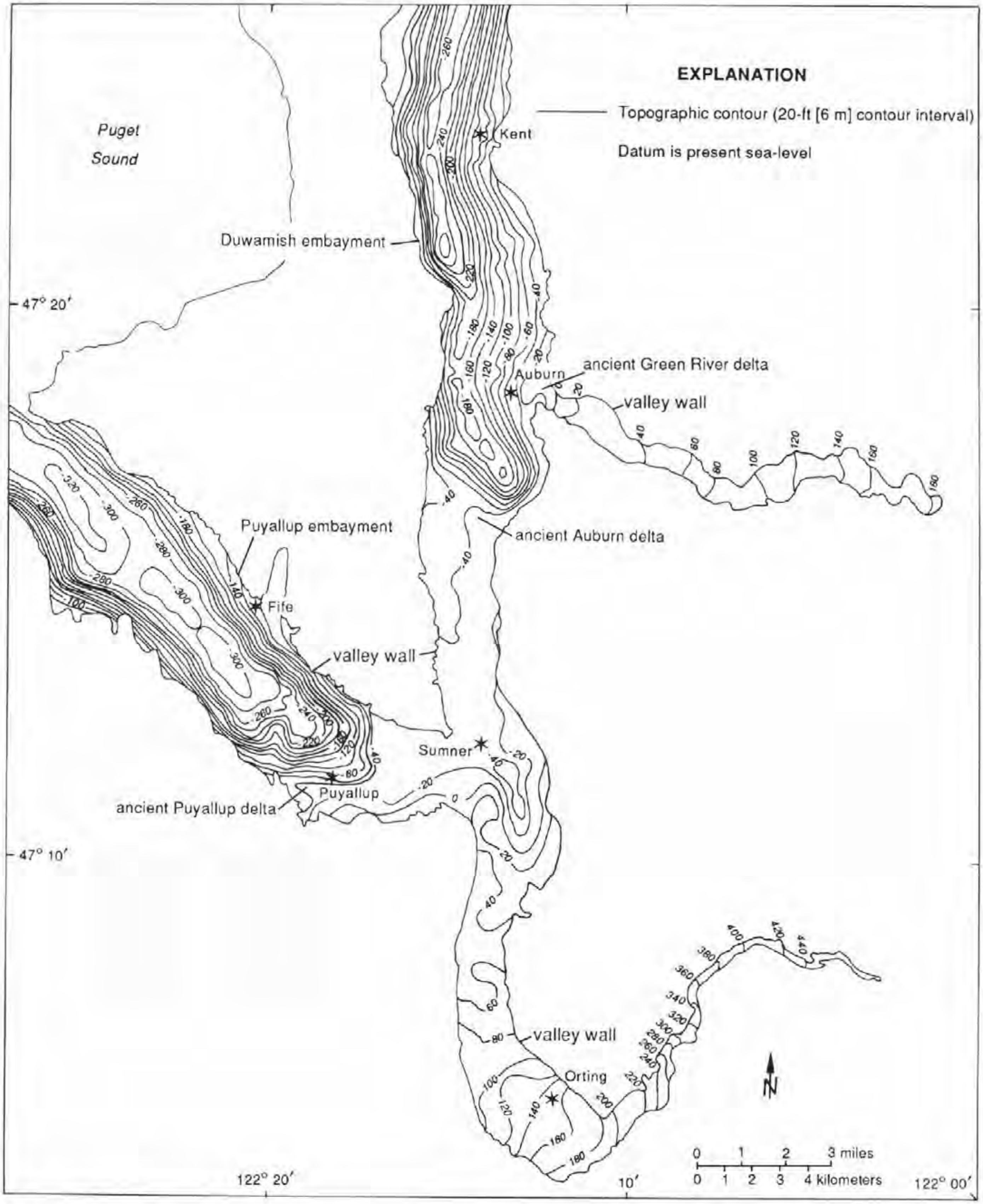
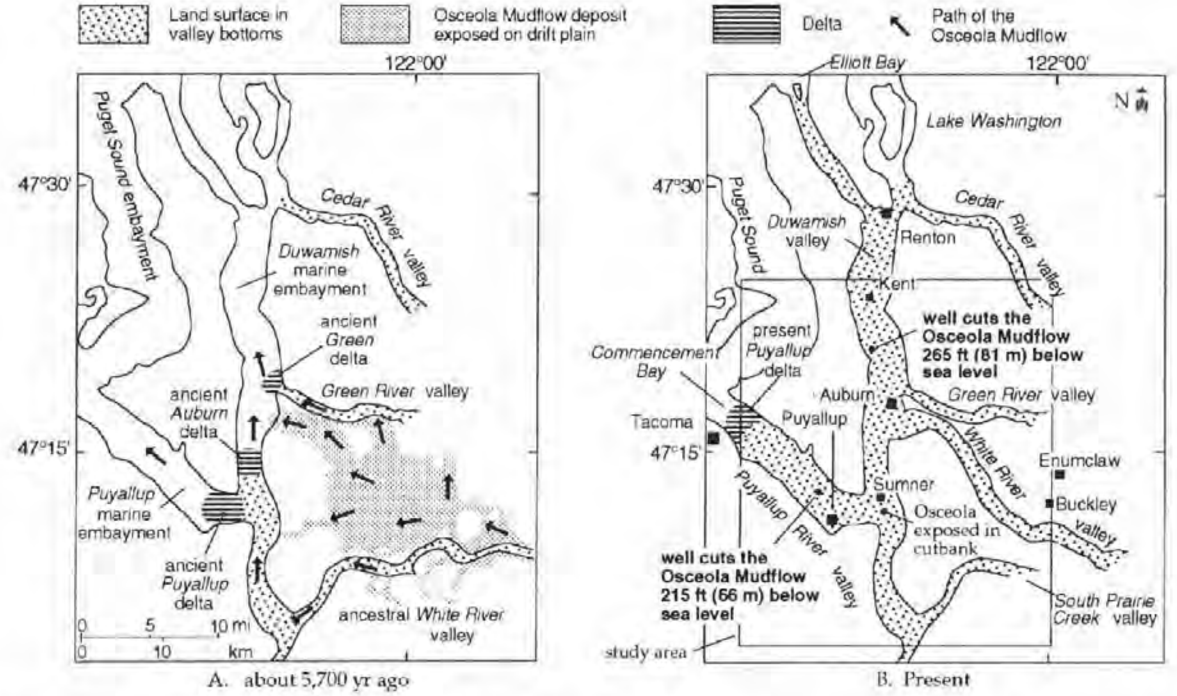


Figure 5. Pre-Osceola Mudflow (OM) topography revealed by contouring the OM bottom altitude as determined by subtraction of data in Figure 3 (OM thickness) from that in Figure 2 (OM top elevation) and using SURFER® software (also see cover for surface map of this data). Notice the flat topography above the delta foreslopes for the ancient Auburn delta (AAD), ancient Puyallup (River) delta (APD), and ancient Green (River) delta (AGD) and similar elevation of the three delta platforms as well as two marine embayment bottoms, lending credibility to the correlations. Sea level was about 26 ft (8 m) bpsl at 5.7 ka, based on these delta platform elevations. Ancient marine shelves, river-valley channels, and terraces are also suggested by the data.



A. about 5,700 yr ago

B. Present

Figure 6. Comparison of the modern shoreline of Puget Sound (B) with that just after deposition of the Osceola Mudflow and burial of the ancient deltas (A). Fine stippling shows distribution of the mudflow deposit as exposed on the surface of the drift plateau. Box in B is study area boundary. (B is modified from Luzier, 1969.)

identified by E. J. Moore (in Mullineaux, 1970) as limpets (*Acmaea*), periwinkles (*Littorina*), mytilid mussels, *Cryptomya*, *Mya*, barnacles, and a few echinoid spines. Moore notes that some of these marine fossils suggest depths of less than a few fathoms and that the limpets, periwinkles, mussels, and barnacles probably lived where they were exposed at low tide, thus suggesting a lower sea level in postglacial times.

Pre-Osceola Deltas in the Puyallup and Duwamish Valleys

A delta is a relatively localized and generally protrusive mass of stream-borne and partly stream-deposited sediment laid down close to the mouth of a stream; part of a delta may be above water (Fairbridge and Bourgeois, 1978) (Fig. 9). The existence of ancient deltas in the study area follows from evidence that marine embayments extended south of Kent (Luzier, 1969; Mullineaux, 1970) and north of Alderton (Crandell, 1971), as suggested by the depth of the OM and locations of fossil shells relative to sea level 5,700 years ago. Generally, rivers carrying large sediment volumes in glacially fed, volcanically active regions would be expected to form sizable delta complexes where they enter open water (for example, Kuenzi and others, 1979).

Ancient deltas in the study area, such as the ancient Green (River) delta (AGD), ancient Auburn delta (AAD)[1], and ancient Puyallup (River) delta (APD) (Figs. 5, 6, and 7), are mapped where there are distinct changes of valley slope gradient. (See Fig. 5 and cover.) The slope changes mark the transition from delta platform to the steeper delta foreslope and coincide with the lowest low-tide levels (mean sea level is typically marked by highest high tide) (Fig. 9B) about 5,700 years ago. Delta-front angles are about 2–3 degrees (184–277 ft/mi or 35–52 m/km) for the AGD, AAD, and APD, similar to those at the modern Puyallup delta at Commencement Bay (Fig. 10), Fraser River delta (Fig. 9B), and other marine deltas worldwide (Table 2).

Approximately uniform coeval delta-top elevations are observed (Table 3), but because we do not correct for compaction, current elevations of those ancient deltas may differ. The general absence of postglacial gravel layers and lenses seaward of the delta platforms (Fig. 8) reflects the loss of river power and termination of river channels on flat delta platforms.

Upstream of the APD, AAD, and AGD, the OM is underlain by older alluvial peats, clays, silts, sands, and gravels in valleys of the Green (Fig. 8C), Puyallup (Fig. 8D), and Carbon Rivers and South Prairie Creek. (Some of these deposits are probably lahars or lahar runouts.) The presence of the OM supports evidence (Crandell, 1963a; Mullineaux, 1970) that these valleys were established by the end of Vashon glaciation.

The APD and AAD were estuarine deltas, confined by their valley walls. This setting is consistent with rising sea level during the mid-Holocene, when glacial troughs were drowned by encroaching seas. In contrast, the smaller AGD may have been more arcuate or lobate or formed where the constricted ancient Green River valley spilled into the broad Duwamish marine embayment.

Local Paleo-Deltas and Sea Level in Puget Sound

Using the OM-time delta geometry, we can help estimate the mid-Holocene sea level relative to present. For simple Gilbert-type freshwater deltas, the slope break between topset and

---

[1] Sedimentation on the early to mid-Holocene AAD (as discussed later) may have been dominantly estuarine (not deltaic) because of sediment starvation or diversion of the ancient Puyallup River toward the APD. The Puyallup River appears to have fed both estuaries at times during the Holocene.

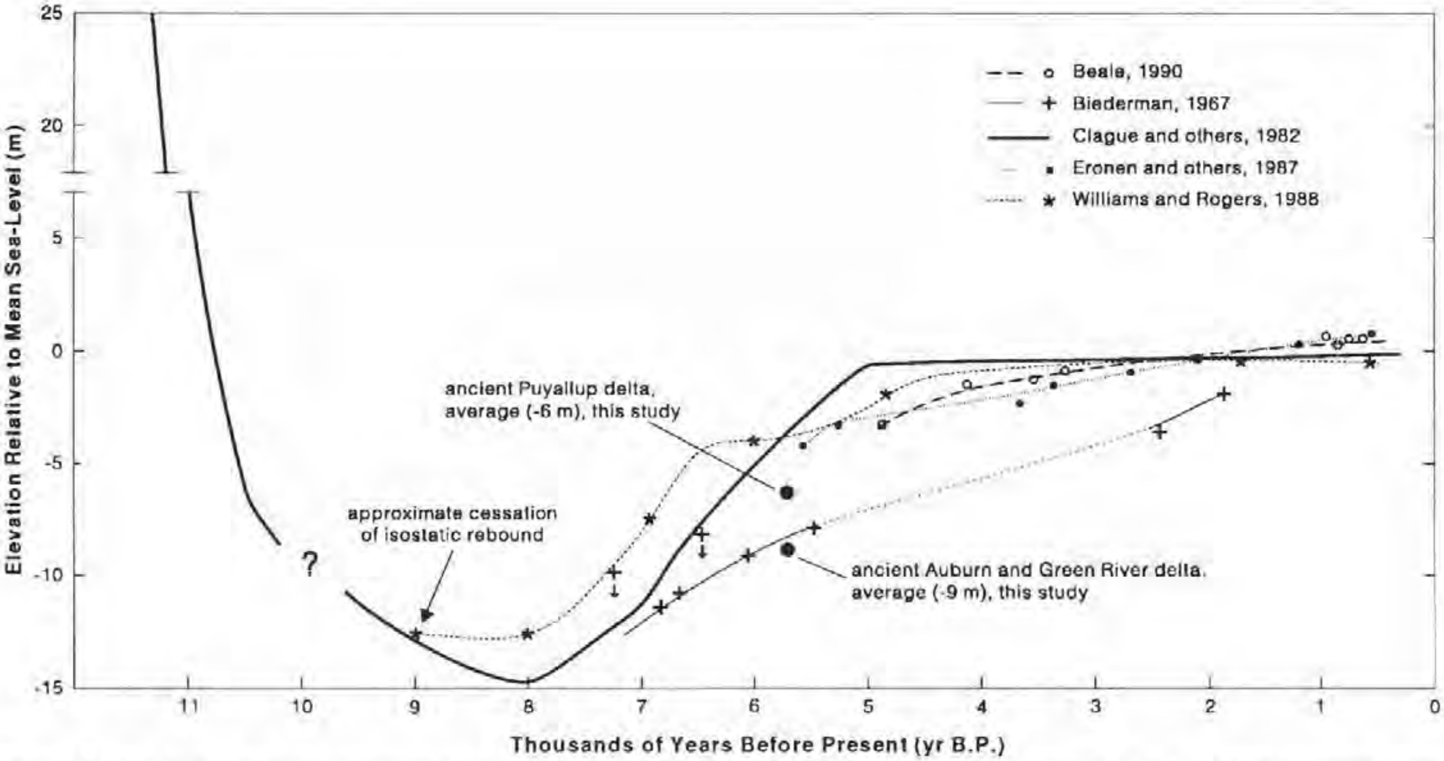


Figure 7. Mid- to late Holocene sea-level curves using data of Biederman (1967), Clague and others (1982), Eronen and others (1983, 1987), Williams and Roberts (1989), and Beale (1990). Cessation of glacial rebound at about 9 ka somewhat simplifies sea-level comparisons. Higher relative sea level prior to deglaciation occurred during a time of eustatic sea-level rise at a rate of up to a few centimeters per year at about 14 to 13 ka (time not shown). Over the following several thousand years, isostatic rebound elevated the lowland areas at average rates of several centimeters per year, typically several times faster than concurrent rates of sea-level rise (see, for example, Booth, 1987). The studies indicate that sea level stood about 16–33 ft (5–10 m) below present sea level (bpsl) at Osceola Mudflow (OM) time (5.7 ka). Localized tectonic movements and other variables that influence sea level, such as compaction of sediments (particularly peats), can cause paleo-sea-level estimates to differ locally and regionally. Our sea-level estimate is derived from the elevation of delta platforms in 22 drill holes, which systematically increases with distance from the delta foreslope in the study area (Table 3). In a marine setting, the delta platform adjacent to the foreslope is below mean high high tide (HHT, Fig. 9B), which is commonly taken as sea level and is at the landward edge of the tidal flats. Our elevations probably span HHT (or are concentrated on the delta platform, skewing the data toward a slightly lower sea level), and thus our average value of 25 ft (8 m) bpsl for all the ancient deltas is low. Other factors would work to lower the present ancient delta platform elevations, suggesting that our estimates are in line with a -16 ft (-5 m) sea level 5,700 years ago as suggested by most studies. The few excessively low AAD and AGD platform elevation values (Table 3) are probably the result of increased compaction due to the abundance of peats and sediment starvation (estuarine setting) prior to OM deposition. Also, the AAD and AGD averages (Table 3) generally contain less well constrained elevation data (from wells rather than geotechnical borings)—thus we are more confident in the APD average.

foreset beds (Fig. 9A) typically lies slightly below water level. For marine deltas, sea-level estimates have to account for uncertainties in tidal range, particularly in estuary settings where ranges can be many meters greater than on an open shoreline. Our data for these paleodeltas suggest that sea level was about 25 ft (8 m) bpsl as estimated by averaging our delta platform elevations, which slope toward the marine embayments and appear to span the delta platform and mean sea level (Table 3; Fig. 9). This level is somewhat lower than the 16 ft (5 m) bpsl estimated for 5.7 ka by most studies (Fig. 7). However, both post-OM sediment compaction and the common occurrence of mean sea level or mean high high water (highest tide level) above the delta platform (Fig. 9B) make many of our individual platform elevations low and thus our sea-level estimate appears low. Therefore, we get confirmation of our ancient delta platform elevations from modern published sea-level curves (Fig. 7).

The pre-OM Puyallup River supplied sediment to both the APD *and* the AAD—the paleo-Puyallup slopes toward both deltas (Fig. 5 and cover) and bifurcates at Sumner, distributing the sediment load to both deltas. The number and thickness of sand and gravel layers in the uppermost parts of the APD (Fig. 11) signal high-energy (river channel or beach facies) conditions during much of the Holocene. Apparently the APD was receiving most of the Puyallup River sediment before OM time. In contrast, the AAD was not an active delta in the mid-Holocene—it had a broad, shallow, submerged platform that appears to have been a few feet lower than the APD or AGD (Table 3). There is little evidence of high-energy fluvial sedimentation, and apparently sedimentation did not keep up with sea-level rise in the mid-Holocene (Table 3). AAD clays, silts, peats, and some fine sands (Fig. 8A) record lower energy conditions and probably less vigorous sedimentation, implying that the delta complex was left open to significant wave and tidal reworking and the resulting geomorphic modifications. In addition, the presence of many peat layers below the AAD platform indicates both local swampy conditions and increased compaction, thus lowering the platform elevations, over the APD. We therefore envision coastal marshlands giving way to broad tidal flats where periodic shifts in Puyallup River sedimentation into this embayment resulted in renewed deltaic sedimentation.

As suggested by earlier researchers, the OM may have been associated with an eruption. Records for a few wells

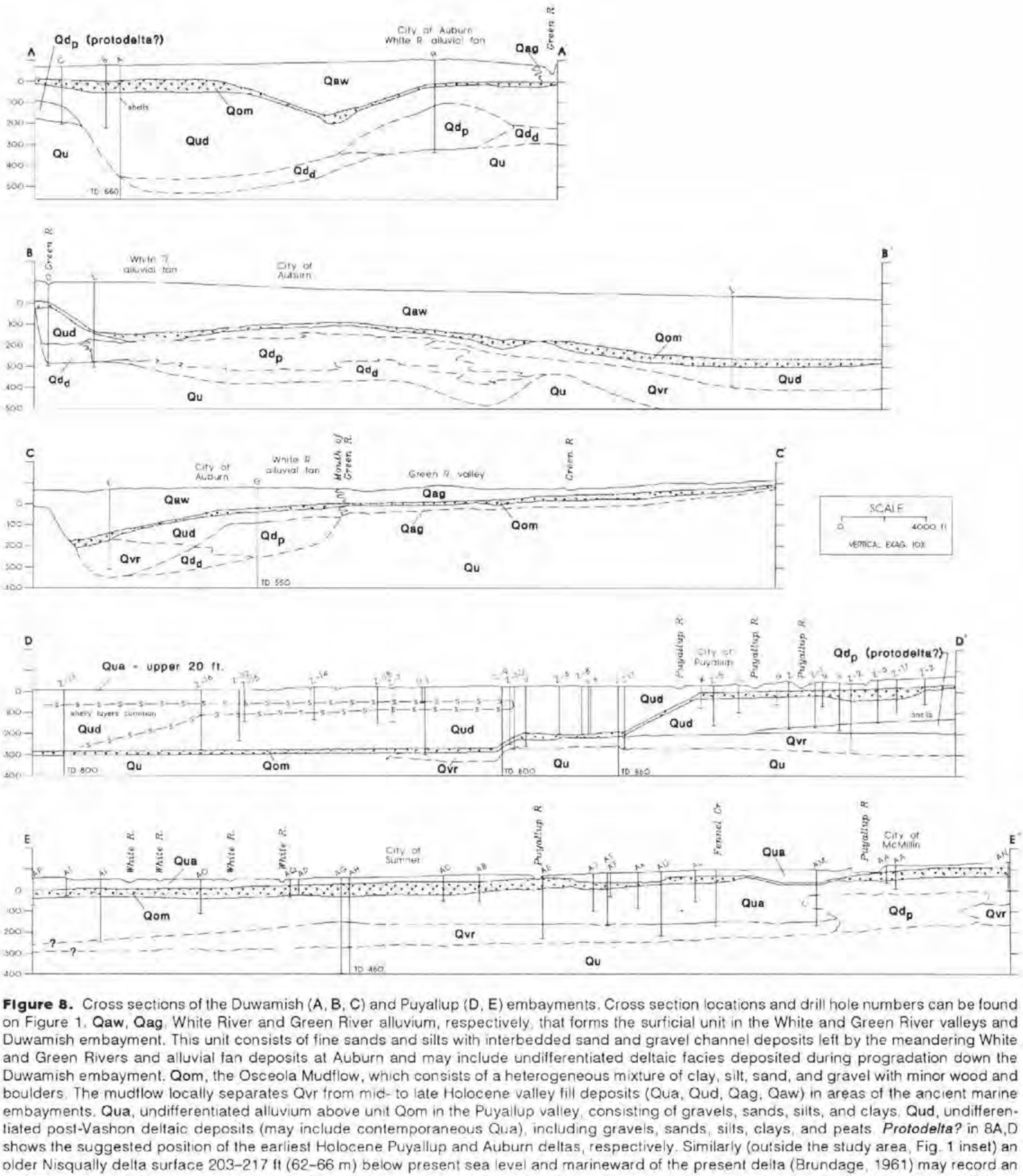


Figure 8. Cross sections of the Duwamish (A, B, C) and Puyallup (D, E) embayments. Cross section locations and drill hole numbers can be found on Figure 1. **Qaw**, **Qag**, White River and Green River alluvium, respectively, that forms the surficial unit in the White and Green River valleys and Duwamish embayment. This unit consists of fine sands and silts with interbedded sand and gravel channel deposits left by the meandering White and Green Rivers and alluvial fan deposits at Auburn and may include undifferentiated deltaic facies deposited during progradation down the Duwamish embayment. **Qom**, the Osceola Mudflow, which consists of a heterogeneous mixture of clay, silt, sand, and gravel with minor wood and boulders. The mudflow locally separates Qvr from mid- to late Holocene valley fill deposits (Qua, Qud, Qag, Qaw) in areas of the ancient marine embayments. **Qua**, undifferentiated alluvium above unit Qom in the Puyallup valley, consisting of gravels, sands, silts, and clays. **Qud**, undifferentiated post-Vashon deltaic deposits (may include contemporaneous Qua), including gravels, sands, silts, clays, and peats. ***Protodelta?*** in 8A,D shows the suggested position of the earliest Holocene Puyallup and Auburn deltas, respectively. Similarly (outside the study area, Fig. 1 inset) an older Nisqually delta surface 203–217 ft (62–66 m) below present sea level and marineward of the present delta (Brundage, 1961) may record an approximate early Holocene sea-level position. **Qdp**, sands, gravels and cobbles of proximal Vashon recessional elevated deltas at Auburn (Mullineaux, 1965) and McMillin (Crandell, 1963a) deposited behind ice-dammed lakes. Qdp associated with *protodelta?* are suggested post-glacial (lake) marine delta deposits. Glacial-lake water levels were controlled by perched meltwater spillways—water discharged through successively lower spillways as they were uncovered by retreating ice, ultimately seeking the Black Lake spillway and Chehalis River to the south and west of the retreating Puget lobe (see Thorson, 1981). Lakes occupying the newly created troughs intercepted these channels, forming Gilbert-type deltas (Fig. 9A). In the study area, a glacial-lake delta was first formed at McMillin; after ice retreated to Auburn, the glacial-lake delta above Auburn formed (Mullineaux, 1970; Thorson, 1981). **Qdd**, silts and clays of distal Vashon recessional deltas at Auburn (distal facies are not apparent around the recessional delta at McMillin). **Qvr**, sands and gravels deposited by Vashon recessional meltwater channels (location modified from Hart-Crowser & Associates, Inc., 1985). **Qu**, undifferentiated glacial and interglacial deposits, commonly capped by till.

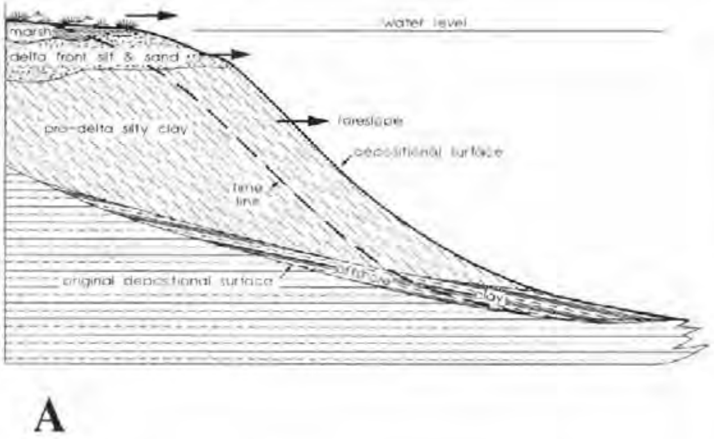
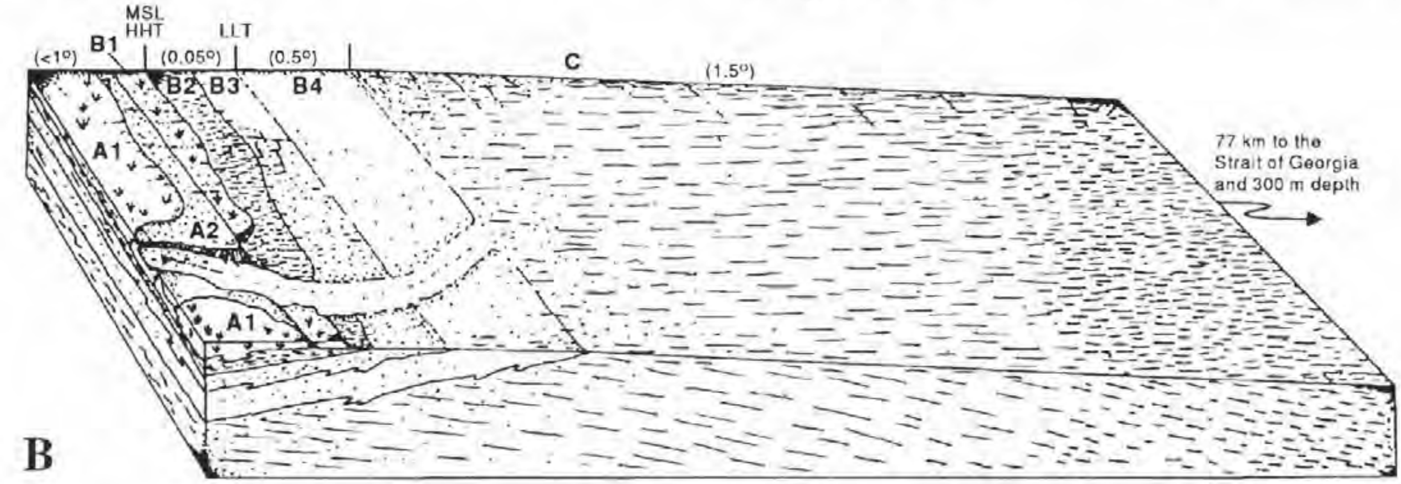


Figure 9. **A**, Schematic diagram of a fresh-water Gilbert-type delta showing the steep foreslope and constant water level–sediment interface. **B**, Block diagram of a marine-type delta (based on data of Williams and Roberts, 1989, for the Fraser River delta [FRD], British Columbia). Angles, delta province average slope (conversion: 1°≈90 ft/mi or 17 m/km). **A**, subaerial upper deltaic plain: **A1**, peat bog; **A2**, flood plain. **B**, subaqueous lower deltaic plain: **B1**, upper tidal marsh; **B2**, mid-tidal silts and sands; **B3**, lower tidal sands; **B4**, subaqueous delta platform. A and B constitute the delta platform. The mean sea level (MSL) corresponds to the highest high tide (HHT) between the tidal plain (B) and subaerial upper delta (A). **C**, delta foreslope, which grades from silty fine sands and sandy silts to silts to clayey silts with increasing water depth. The response of the FRD to mid-Holocene sea-level rise included both vertical accretion and continued seaward progradation due to abundant river sediment input (Williams and Roberts, 1989). In the study area, mid- to late Holocene progradation of deltas was likely enhanced by abundant volcaniclastic and laharic sediment input and a waning sea-level rise.



penetrating the ancient marine embayments mention ash deposits above the OM. We observed but could not identify a thin buff-gray layer of very fine volcanic ash that contained diatoms and apparently was preserved on the OM in the low-energy AAD delta platform environment (Fig. 8E, hole AO). OM-time delta platforms provide low-energy swampy areas suitable for localized preservation of tephras associated with past eruptions.

Early to Middle Holocene Deltaic Sedimentation

Marine waters filled the embayments as sea level rose throughout the early Holocene and isostatic rebound ceased after about 9 ka (Fig. 7). Marine incursion into the study area resulted in renewed deltaic sedimentation. Early Holocene deltaic deposition in the Puyallup valley (Fig. 8D) is constrained *vertically* by subjacent glacial deposits flooring the valley, *upvalley* by the ancient glacial-lake delta below McMillin (Fig. 8E) that probably formed a barrier to marine incursion, and *downvalley* by the general lack of pre-OM postglacial deposits seaward of the APD. Geohydrologic studies near Puyallup (Fig. 8D) and Auburn (Figs. 8A,B,C) (Hart-Crowser & Associates, Inc., 1982 and 1985, respectively) identified recessional outwash deposits below about 180 ft (45 m) bpsl in the Puyallup valley. A sand and gravel body on glacial outwash appears to dip downvalley (see Fig. 8D, *protodelta?*) and may be the early Holocene position of the APD. Coarse deltaic sedimentation could have been a consequence of (1) the erodibility of recently deposited loose, coarse glacial sediments and (2) the increased carrying capacity of rivers while gradients were steeper during lower stands of sea level. Higher in the section and below the OM-time APD platform, shelly fossils above this postulated early delta at 46 ft bpsl (Fig. 8D, hole Z-17) indicate marine conditions there and provide evidence for some APD progradation in the mid-Holocene prior to the OM inundation.

Mid-Holocene slowing of sea-level rise probably allowed sediment accumulation rates to exceed sea-level rise (see Davis and Clifton, 1987), promoting downvalley migration of the delta complexes. The early history of the APD resembles that recorded in the early Holocene stratigraphy of the Snohomish (Fuller and others, 1989) and Fraser River deltas (Williams and Roberts, 1989) where coarser basal sequences and rapid postglacial progradation coincided with the cessation of glacial rebound and a lowered base level.

Because mid-Holocene sea level (base level) was lower, gradients from mountains to shore were steeper and streams carried more sediment. For example, the current average gradient for the Green River above the confluence with the Duwamish valley is 20 ft/mi or ≈3 m/km (0.2°) (Mullineaux, 1970); the gradient from the South Prairie Creek Bridge downstream to southeast Sumner (State Route 410 & Pioneer Way) is 21 ft/mi (≈4 m/km). The approximate mid-Holocene gradient was 27 ft/mi (≈5 m/km) for the equivalent valley traverse (estimated using OM bottom elevations from borings) (Fig. 2). Progradation of the early to middle (pre-OM) Holocene AAD and AGD into the Duwamish embayment was probably controlled by reduced sedimentation concurrent with a rising base

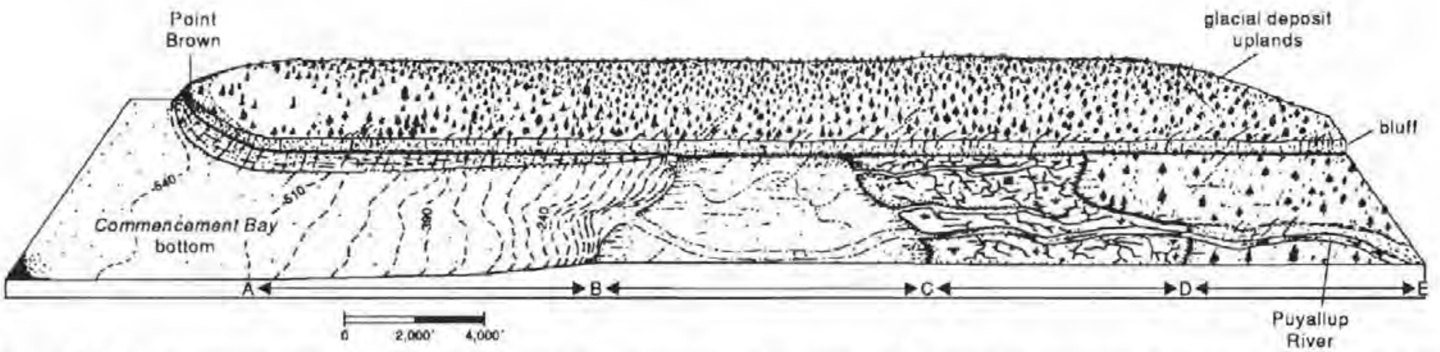


Figure 10. Block diagram of the modern Puyallup delta at Commencement Bay showing the gross physiographic features of an estuarine delta (based on pre-urbanization physiographic data of Bortleson and others, 1980). A–B, delta foreslope with calculated angles of 2.8, 2.8, and 2.6 degrees along three parallel longitudinal profiles, similar to estimated delta foreslope angles of the ancient deltas (Table 2). B–C, delta platform tidal flats. C–D, delta platform subaerial wetlands (salt marsh). D–E, Puyallup River flood plain and river channel. The ancient estuarine deltas at Puyallup (8 mi or 13 km upriver) and Auburn probably displayed similar physiography, including significant delta platforms constrained between prominent glacial bluffs. Delta progradation will slow as the present delta foreslope moves into the more open Puget Sound west of Point Brown.

level from 9 ka to 6 ka and by the increased delta foreslope depositional area as a result of the incursion of the AAD and AGD into the wide Duwamish embayment. Sea-level rise slowed during the late Holocene, delta sedimentation outpaced inundation, and deltas prograded to their present positions.

Former positions of the AAD are poorly constrained. Deltaic sedimentation shifted from the glacial-lake delta east-southeast of Auburn (see Mullineaux, 1970; Thorson, 1989) to the lower elevation of the AAD when marine water re-entered the embayments. Below the mid-Holocene AAD platform, gravels and sands (80–190 ft, 24–58 m, bpsl) above till (Fig. 8A, hole C, *protodelta?*) may represent early fluvial-deltaic channels; coeval marine conditions are suggested by shelly horizons from 80 to 160 ft (24–49 m) bpsl basinward (Fig. 8A, hole A). Similarly, sands and gravels on proglacial delta deposits (Fig. 8C) may reflect fluvial dissection of the emergent glacial delta at Auburn during isostatic rebound/sea-level fall and robust sedimentation along the AGD delta front in the early Holocene.

THE SUBSURFACE OSCEOLA MUDFLOW

Crandell (1971) stated that

> *"....forty miles downvalley from Mount Rainier, just inside the Cascade Mountain front, the White River passes through a bedrock gorge that is now blocked by Mud Mountain Dam. The gorge lies at the south edge of the White River valley, which is about 3 miles [5 km] wide in this vicinity. A long, narrow, flat topped ridge (Mud Mountain) several hundred feet high, which extends southward across the broad [post-OM] White River valley, is made up largely of Pleistocene unconsolidated deposits. The [OM] was temporarily at least 450 feet (137 m) deep in this part of the valley and cascaded in a sheet nearly a hundred feet deep down the west slope of Mud Mountain into the Puget Sound lowland."* (See Fig. 1.)

The OM then spread widely on a plain of Vashon till and recessional meltwater deposits. There, the OM is only a few feet thick on some scarps and drumlins, but elsewhere it is as much as 75 ft (23 m) thick (Crandell, 1963a, 1971; Mullineaux, 1970). The mudflow cascaded off the drift plain into the ancient valleys occupied by the Green River and South Prairie and Fennel Creeks, burying older alluvial deposits. The OM flowed down South Prairie Creek to the Carbon River, and then down the Puyallup River below Orting and on to the ancient deltas at Puyallup and Auburn. The OM reached the AGD via the Green River.

The elevations of the top of the OM (Fig. 2) and the isopach map (Fig. 3) document the shape and extent of the OM that we derived from drill hole information. (Figure 1 inset shows a previous OM map from Crandell, 1971.) Subsurface correlations are strengthened by the regularity of the top and bottom elevations in nearby drill holes. OM thickness varies with buried geomorphic features. For example, bottom contours (or pre-OM topography, Fig. 5) show that the OM is thicker where the paleoslope decreased. OM thicknesses in the ancient river valleys (Fig. 3) range from 10 to 100 ft (3 to 30 m), averaging about 25 ft (8 m). Both the bottom and top of the OM slope downvalley (Figs. 2 and 5) and generally toward ancient valley axes.

We attribute local thinning against valley walls to tapering of the mudflow against buried alluvial terraces or side slopes. However, significant thicknesses of OM in borings located less than 100 ft (30 m) from valley walls demonstrate that the mudflow filled river-valley segments from wall to wall.

The cross-valley profile of the OM bottom is less regular than the fairly flat to broadly concave-upward OM top (Fig. 11). The OM would have come to rest with a fairly level upper surface due to its behavior as a viscous liquid. Where the lowermost parts of the ancient valleys terminated at flat delta plat-

Table 2. Modern and ancient delta foreslope angles measured along the longitudinal profile of a delta. (Conversion: 1°≈90 ft/mi.) Exceptions, like the high delta-front angles off the modern Nisqually delta, are the result of extreme conditions. Strong tidal currents through Nisqually Reach tangential to the delta foreslope winnow fines, erode the delta front, and produce a slope composed of medium sands that stand at steeper angles of repose.

ANCIENT DELTAS	
Puyallup delta	1.6°, 1.8°, 2.7°
Auburn delta	2.9°, 2.2°, 1.3°, 2.8°
Green delta	2.1°, 1.6°, 1.3°, 1.3°
MODERN DELTAS	
Puyallup delta at Commencement Bay (Fig. 10)	2.8°, 2.6°, 2.8°
Mississippi Delta (Busch, 1974)	1.0°
Fraser Delta, BC, (Williams and Roberts, 1989) (Fig. 9B)	1.5°
Nisqually delta (Brundage, 1961; Scott, 1982)	7° to 20°

Table 3. Delta platform elevations (Osceola Mudflow [OM] bottom elevations). The occurrence of fine tidal-flat or delta-front sediments over distributary channel sands and (or) beach facies deposits may be due to transgression during sea-level rise or to subaqueous platform sediments encroaching over diverse upper deltaic environments (such as beaches, distributary channels, marshes). Hole ID, boring location identification on Figure 1 or Figure 8. *, multiple borings at site, average values for elevation and distance. Second column gives elevation of the OM bottom below present sea level. Distance, map distance of boring from the seaward edge of delta platform. Platform elevation increases with distance from the seaward edge of the delta platform. Paleogeographic and other reconstructions are discussed in the text. /, sediment contact; ww, water well [remainder are geotechnical borings]). *Italics* indicate a single-layer, multiple layers are in normal type.

Hole ID	Delta platform elevation	Distance (ft)	Sediments under the Osceola Mudflow
ANCIENT AUBURN DELTA			
A	-54 ft (-16 m)	5,750	*sandy silt* / sands, shells & peats
B	-47 ft (-14 m)	5,800	*silty sand* / silty sands, sandy silts, silts
C	-31 ft (-9 m)	9,000	*silt & cobbles* / gravels, sands
D	-54 ft (-16 m)	0	*thinly laminated fine sandy organic silt* / silty fine sands & fine sandy silts
AB*	-8 ft (-2 m)	28,600	*sand & sandy silt* / silty clays & clayey silts
AC*	-9 ft (-3 m)	26,900	*silty clay & fine sandy silt* / silty clays, clayey silts, silty sands, peats
AE	+6 ft (2 m)	31,600	*gravelly coarse sand* / silts, sands, gravels
AG	-34 ft (-10 m)	22,000	*sand & mud*
AO	-46 ft (-14 m)	15,400	*fine sandy silt with organics* / fine sandy silts, silty fine sands, sands, silts
AQ	-24 ft (-7 m)	20,000	*fine sand*
AR	-24 ft (-7 m)	19,800	did not penetrate OM bottom
Avg.	-30 ft (-9 m)	16,805	---
ANCIENT GREEN RIVER DELTA			
G	-31 ft (-9 m)	0	*silty gravel & sand with cobbles* / sands, gravels, occasional silt & clay layers
ANCIENT PUYALLUP RIVER DELTA			
K*	-25 ft (-8 m)	0	*silt & sandy silt or silty clay (3–11 ft)* / sands, gravels
L*	-23 ft (-7 m)	2,300	*silty fine sand & sandy silt, silt (6 ft), organic silt & clay (3 ft)* / sands, silts, clays
M*	-20 ft (-6 m)	3,700	*silty fine sand with thin layers of silt or clayey silt (8 ft)* / silty fine sands, gravelly silty sands, gravels
N*	-23 ft (-7 m)	2,750	*silty fine sand, minor gravel* / gravels, sands, silts
O*	-22 ft (-7 m)	7,800	*sandy silt or sandy silt with some fine sand (12 ft) & peat* / silty sandy gravels & clays
P*	-20 ft (-6 m)	9,100	*silty clay or silt with lenses of peat & traces of sand (12–24 ft)* / silty gravelly sands
Q*	-13 ft (-4 m)	10,000	*sandy silt, silt, clayey silt with thin silty sand layers (13 ft)* / silty sands (silt interbeds) / sandy gravels & gravelly sands with some silt
R*	-17 ft (-5 m)	3,500	*silty fine sand & sandy silt or silt lenses (15 ft)* / sands, clays, silts
S	-36 ft (-11 m)	3,100	*sand and gravel* (ww)
Z3	11 ft (3 m)	10,700	*sand and gravel* / sands, clays / sands, gravels (ww)
Avg.	-19 ft (-6 m)	5,296	---

forms (<0.2° degree slope), mudflow speed was reduced, deposition was promoted, and OM thicknesses increased. On the AAD platform OM thickness commonly exceeds 60 ft (18 m) and locally reaches 100 ft (30.5 m), representing a significant hidden OM volume, discussed below.

The OM probably regained speed as it streamed off the deltas into Puget Sound; here, the significant amount of clay in the flow promoted sediment cohesion and immiscibility with water and thus impeded significant entrainment of water (Scott and others, 1992; J. Vallance and K. Scott, unpub. ms.). Logs enclosed in the OM in a distal Duwamish valley boring (Fig. 8B, hole I) and ^{14}C dated by Luzier (Table 1) show that the OM remained cohesive enough during submarine flow to transport large, light, woody debris to the bottom of the marine embayment (J. Vallance and K. Scott, unpub. ms.).

The OM thinned to less than 20 ft (6 m) (Fig. 3) on delta foreslopes. For areas farther downstream, our 3-D mapping of the OM shows that embayment slopes funneled the mudflow toward the embayment axis, channelizing the flow. The OM deposits rethicken on the bottom due to reduced paleoslopes and a more constricted pathway.

The inferred minimum distal extent of the OM in the embayments (dashed contours, Figs. 2 and 3) is based on the significant OM thickness observed in the most distal holes penetrating the deposit. (See Table 4 for descriptions.) We can confidently extend the OM in the Puyallup embayment to southeastern Fife and probably to Commencement Bay (Figs. 2 and 3). The marine bottom geometry in the Puyallup embayment is defined by seven water wells and two borings that penetrated a distinctive clayey or silty sandy gravel diamicton having a consistent thickness of 10–30 ft (3–9 m) and a top elevation of about 220–240 ft (67–73 m) bpsl. Also, diamictons present in two of four City of Fife water wells at about 120 ft (37 m) bpsl appear to be OM correlatives (Fig. 1, hole Z-25), suggesting that it traveled along a shallow marine shelf in the northeastern part of the Puyallup embayment. Correlative strata are diamictons in water wells around the Port of Tacoma at Commencement Bay; here, a 3–13-ft (1–4 m) -thick, poorly sorted gravel or diamicton has top elevations of 252–264 ft (77–81 m) bpsl. Although we are not certain these diamictons represent one event, the significant thickness of the diamictons at the same level in the embayment suggests that the OM flowed along the Puyallup embayment at least to the Port of Tacoma and possibly farther.

In a water well 4 mi north of Auburn and 1 mi south-southwest of Kent (Fig. 8B, hole I), wood above a diamicton containing clasts of Mount Rainier origin at 265 ft (81 m) bpsl yielded an uncorrected ^{14}C age of 5,040 ± 150 years (Table 1), indicating that an arm of Puget Sound extended into the Duwamish embayment at that time (Luzier, 1969). Additional correlations by Hart-Crowser & Associates, Inc., (1982) and this study (Table 4) constrain the extent and geometry of the OM in this embayment south of Kent (Figs. 2–4). The significant thickness of the OM observed in these most distal wells suggests that it traveled along the embayment bottom past the present location of Kent.

Volume and Origin

Our new estimates from isopachs revise the total volume upward from that of Crandell (1971) to *at least* 0.89 mi^3 (3.8 km^3) (Table 5), making the OM one of the largest known landslides resulting from the collapse of a volcanic edifice (Table 6; Lee Siebert, Smithsonian Institution, written commun., 1994). Computer-generated volume estimates and our isopach map (Fig. 8) provide a subsurface OM volume of *at least* 0.36 mi^3 (1.50 km^3) covering a subsurface of at least 71

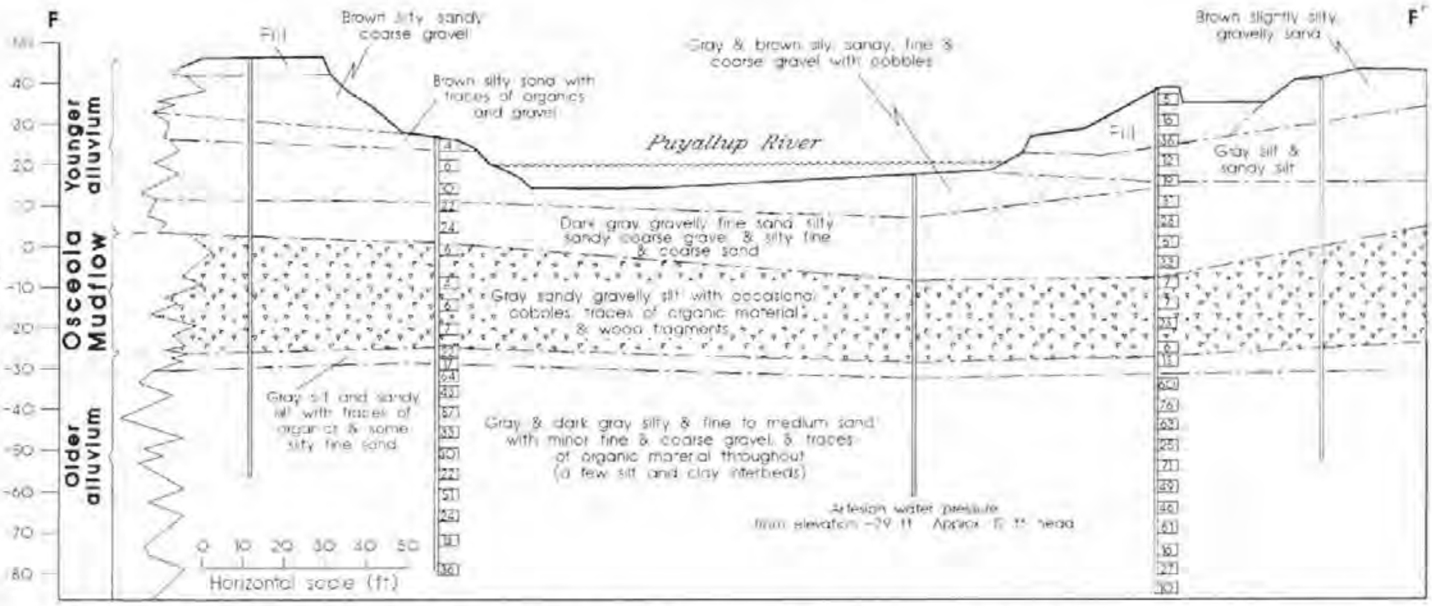


Figure 11. Detailed cross-section transverse of the Puyallup valley and ancient Puyallup delta showing the Osceola Mudflow (OM) deposit above deltaic silts, sands, and gravels. Note the slope of the mudflow toward the present basin axis (location K, Figs. 1 and 8D). Numbers in boxes are standard penetration test blow counts; the low density of the OM is reflected in the low penetration resistance. Our interpretation that tidal silts overlie beach or distributary-channel sands and gravels (Table 3) may indicate marine transgression prior to OM deposition or facies changes (such as distributary channel migration) with time. Artesian water pressure in the middle boring is the result of water confinement below the OM aquitard. (1 ft = 0.3048 m) (Modified from Washington Department of Transportation, 1968.)

mi^3 (185 km^2). This is the first OM subsurface volume estimate based on systematic compilation of mudflow thicknesses. The inferred distal areas and thicknesses of OM accumulation appear reasonable. From the distal thickness projected from boring data, additional OM deposits are inferred to have flowed along the marine embayment bottoms beyond the study area or to have been eroded. For example, assuming an average thickness of 25 ft (7 m), 0.54 mi^3 (6.19 km^3) is estimated to have been eroded from the post-OM course of the White River between the White River fan and Mud Mountain dam (Table 5).

The OM increased its volume during flow by scouring and entraping stream and other sediments. Scott and others (1992) estimated at least 50 percent bulking of the OM in the gravel size range within 25 mi (40 km) of the mountain (where bulking is significant due to addition of clean gravels from overridden river sediments). However, for tens of years after OM deposition, the loose, bare mudflow deposit would be prone to severe erosion by surface processes (for example, by rilling) or landsliding (for example, by stream incision and undercutting) (see Kuenzi and others, 1979), thus decreasing the OM volume. The few to tens of feet of black (volcanic lithic and crystal) sands that commonly overlie the OM at depth in ancient marine embayments may largely represent eroded and reworked OM deposits transported to the marine embayments.

The clay minerals of the OM link it to clays in hydrothermally altered rocks now exposed high on Mount Rainier—strong evidence that the OM originated as avalanches and (or) slumps that removed part of the Mount Rainier edifice. (See also Crandell, 1971; Scott and others, 1992.) Additionally, the presence of the OM high on the flank of the volcano at Steamboat Prow (Fig. 1 inset) indicates that the flow started above that point. Previously Crandell (1971) separated the OM from the Greenwater lahar (deposited on terraces in the upper White River), but Scott and others (1992) provided evidence that the Greenwater and the OM are separate facies of the same mudflow. In the latter view, the Greenwater represents the less clay-rich outer carapace of the collapsed mountain sector, whereas the OM originated as a later clay-rich sector collapse involving rock hydrothermally altered within the volcano. J. Vallance and K. Scott (unpub. ms.) estimate the volume of the Greenwater lahar at 0.12 mi^3 (0.5 km^3).

Several authors (Russell, 1898; Matthes, 1914; Coombs, 1936; Crandell, 1963b; Fiske and others, 1963) have noted that Mount Rainier must have been much higher at one time. The present summit of Mount Rainier is a small, post-OM lava cone constructed in a still-discernible circular depression whose diameter is about 1.5 mi (2.4 km) (Fig. 12). Assuming a cone height of 2,950 ft (900 m) and a cone frustum geometry (Van Haveren, 1986) similar to the shape of the present cone, the missing summit has a volume of 1.10 mi^3 (4.6 km^3), slightly greater than the minimum of 0.89 mi^3 (3.8 km^3) we estimated for the OM (Table 5). Cone-method calculations underestimate the original volume because an edifice collapse typically leaves an elliptical depression. The total volume can best be described by adding the volume of the cone to the volume of the underlying inclined spoon-shaped mass. For comparison, the missing summit at Mount St. Helens has a cone frustum volume of only 30 percent of the 0.6 mi^3 (2.5 km^3) of its 1980 debris avalanche; this was calculated by placing a cone frustum on the present crater rim and incorporating the old cone height. Therefore, to accurately model the volume of the missing summit of Mount Rainier, we need more information about the geometry and location of the original sector-collapse failure plane. These estimates suggest that additional OM deposits await identification. Erosion and reworking of the OM deposit and flow of the deposit outside the study area along the marine embayment bottoms are plausible sources for additional volume.

POST-OSCEOLA MUDFLOW VALLEY FILL

The geologically instantaneous deposition of the OM provides a subsurface time line for studying rates of post-OM valley sedimentation (Fig. 8). Isopachs that show the amount of post-OM valley filling by a combination of fluvial, deltaic, and laharic processes are shown in Figure 4. Inception of the modern course of the White River and its fan complex at Auburn are dominant late-Holocene events resulting from OM deposition in the Puget basin.

Inception of the Modern White River

The OM profoundly changed the lower course of the White River (WR). Crandell (1963a) provided convincing evidence that before the mudflow, the WR turned south after exiting the Cascade mountain front and flowed through what is now the South Prairie Creek valley to join the Carbon and Puyallup Rivers (Fig. 1 inset). When the mudflow exited the Cascade Mountains (Fig. 1), one lobe extended down South Prairie Creek (old WR valley) and another flowed across the broad, undulating drift plain, mantling all but the highest hills. Within days or weeks the WR cut into the drift plain, initiating its modern valley as well as the alluvial fan at Auburn where the river debouched into the ancient Duwamish embayment. The steep gradient and straight path of the modern WR (where it cuts into the drift plain) allowed the river to transport the coarse bedload supplied by the OM deposit (and underlying glacial drift), which is perched along the newly exposed valley walls (Mullineaux, 1970).

A significant part of the Holocene fill in the Duwamish and Puyallup valleys postdates the OM and can be attributed to sedimentation by the WR fan (Mullineaux, 1970). The Green and Cedar Rivers had already cut their valleys to the present depth and built fans into the Duwamish embayment prior to the OM. Post-OM deposition, enhanced by lahars down the WR, filled and aggraded that embayment above sea level, burying the Green River fan and the southern part of the Cedar River fan. The dominance of post-OM sands and gravels (minor silt or clay, and no peat) in the Duwamish Valley, particularly in the upper 95 ft (29 m) (Mullineaux, 1970) north and south of the ancestral WR fan (Figs. 8A,B,E), reflects energetic WR sedimentation. South of Auburn and north of Sumner, deposition of the WR fan locally reversed the valley slope from north to south in this part of the Duwamish embayment, burying the AAD and enabling the present WR to eventually flow south (Figs. 1, 8A,B), contrary to the former course of the Puyallup River, which feeds the north-facing AAD (Fig. 6A).

Delta Progradation Rates and Valley Sedimentation

Post-OM river aggradation and delta progradation eventually filled the ancient Puyallup and Duwamish arms of Puget Sound to their present positions—aided by a stagnant or slowly rising sea level, elimination of tidal flushing due to shoaling, erosion of the OM deposit, and high Mount Rainier erosion rates (including lahars). For example, immediately after OM deposition, the WR at Auburn probably built a delta directly into the Duwamish marine embayment. Rapid incision and erosion of the OM resulted in increased sediment loads, delta progradation (primarily by the new WR delta), and burial of the AAD as the WR delta advanced. Although most of the sediments above the OM are shown as undivided alluvium (unit Qua) in Figure 8, these deposits are chiefly deltaic at depth. For example, most of the silt and clay is probably material deposited along or distal of the delta foreslope (Fig. 9B).

Table 4. Description of distal water-well and geotechnical borings containing a correlative OM diamicton from the ancient Puyallup and Duwamish Puget Sound embayment bottoms. Some drill hole locations given to the 16th section, U.S. Geological Survey well location convention. Hole ID, boring location identification on Figure 1 or Figure 8. Distance to delta foreslope: *, from ancient Auburn delta; **, from ancient Green River delta. Sources: 1, Walters and Kimmel, 1968; 2, Luzier, 1969; 3a, Dept of Ecology (Southwest Region) water-well record; 3b, Dept of Ecology (Northwest Region) water-well record; 4a, Hart-Crowser & Associates, Inc., 1985; 4b, Hart-Crowser & Associates, Inc., 1982. Confidence values in parentheses: 1, high; 2, moderate; 3, moderate to low; 4, low. Sediment abbreviations: *ash*, ash fragments or layers noted; *tight* indicates low permeability, which suggests that significant fine sediment fills pore space, implying a diamicton

Drill hole location: township-range-section (hole ID)	Sediment description (diamicton top and bottom elevations below present sea level in feet)	Distance to delta foreslope (ft)	Source (Confidence)
ANCIENT PUYALLUP MARINE EMBAYMENT			
20-4-21 SE NW (J)	silty sandy gravel (188–199)	50	4a (1)
20-4-20	gravel, sand, silt (246–252)	5,000	3a (1)
20-4-20 NE NW (W)	muddy sand & gravel (231–281)	6,000	3a (1)
20-4-20 NW NE (V)	sand, gravel, heavy silt (230–245)	6,000	3a (1)
20-4-20 C1	clayey sand & gravel (259–262)	6,000	1 (1)
20-4-19 NW SE	fine to medium sand & silt with trace of gravel (227–248)	6,100	1 (2)
20-4-18 NE NW	silty sandy angular gravel (188–199)	7,100	3a (1)
20-4-20 NW NW	black sand & gravel	8,000	3a (3)
20-3-3 L1 (Z-13)	*tight* sand and gravel (257–260)	29,000	3a (2)
20-3-4 J2	boulders cemented with clay (250–344)	31,000	1 (4)
20-3-4 J3	cemented gravel	31,000	1 (4)
20-3-4 H2	clay and boulders (264–277)	32,000	1 (3)
20-3-4 NE SW	sand, gravel, clay (252–263)	32,000	3a (2)
20-3-4 H2	clay & boulders (264–277)	32,000	1 (3)
20-3-4	sand, clay, gravel (252–265)	33,000	3a (3)
21-3-27 J1	cemented gravel (252–256); gravel & loose boulders (256–294)	34,000	1 (3)
ANCIENT DUWAMISH MARINE EMBAYMENT			
21-5-30 NW NE	silty gravelly sand with clay (118–156)	0*	4b (2)
21-5-30 NE SW	silty sandy gravel (138–145)	0*	4b (1)
21-5-30 NE SW	silty sandy gravel (146–158)	0*	4b (1)
21-4-12 SE SW	silty gravelly sand (143–168), *ash*	0**	4b (1)
21-4-12 SE SW	silty gravelly sand (143–163)	0**	4b (1)
21-4-14 NW NE	silty gravelly sand (175–182)	0**	4b (1)
21-4-1 D1	sand, gravel, clay (170–188)	4,100*	2 (2)
22-4-35 H2	wood (265–280); gravel & clay (280–290); boulders & clay (290–302)	10,000*	2 (1)

By comparing the APD, AAD, and AGD and present delta-platform edge positions in the Puyallup and Duwamish valleys, we calculate average progradation rates for the last 5,700 years of about 8.2 ft (2.5 m)/yr for the Puyallup valley and 22.6 or 19.6 ft (6.9 or 6.0 m)/yr for the Duwamish valley. The advance of the (approximate) ancient shoreline near Sumner (Fig. 5 and cover) to its present position in Elliott Bay

Table 5. Osceola Mudflow (OM) area, depth, and volume estimates. Crandell (1971) estimated the subsurface extent of the OM (Fig. 1 inset). We enlarge this area (see Fig. 2) because we recognize the OM in the Puyallup valley below the confluence of the Puyallup and Carbon Rivers and as far west as Fife. Crandell speculated that if the subsurface and surface thicknesses of the OM are the same, the subsurface volume would be about 660 million yd^3 (0.5 km^3). We add 0.2 mi^2 (0.5 km^3) to the exposed OM by assuming an average OM *exposed* area depth of 25.1 ft (7.6 m) and enlarged its area. Our average subsurface area depth was obtained from averaging values obtained from a kilometer grid placed on the OM isopach (Fig. 3). Our subsurface volume was obtained using SURFER® computer software. Our exposed area was calculated using AutoCAD® and the OM surface map boundaries of Crandell (1971). Scott and others (1992) include the Greenwater lahar with the OM. The estimated volume of the Greenwater lahar is from J. Vallance and K. Scott (unpub. ms). Miscellaneous, an additional volume of 0.05 mi^3 (0.19 km^3) for the OM that was eroded by the post-OM course of the White River

Study	Exposed Area	Subsurface Area	Thickness (average)	Exposed volume	Subsurface volume	Greenwater lahar volume	Miscellaneous volume	Total volume
Crandell (1971)	100 mi^2 259 km^2	27 mi^2 70 km^2	20.0 ft 6.1 m	0.36 mi^3 1.5 km^3	0.12 mi^3 0.5 km^3	— —	— —	0.48 mi^3 2.0 km^3
This study	128 mi^2 330 km^2	71 mi^2 185 km^2	25.1 ft 7.6 m	0.48 mi^3 2.0 km^3	0.36 mi^2 1.5 km^2	0.01 mi^3 0.05 km^3	0.05 mi^3 0.19 km^3	0.89 mi^3 3.8 km^3

Table 6. Volumes of Quaternary debris avalanches from volcanoes, as compiled by Lee Siebert of the Smithsonian Institute (Siebert, 1984; Siebert and others, 1987; and newer data from Siebert, written commun., 1994). The Osceola Mudflow probably originated as a debris avalanche. Volumes exclude the much larger debris avalanches emanating from submarine Hawaiian Island volcanic slopes. *, contact Siebert for information about data source

Volcano (location)	Debris avalanche volume (km^3)	Source of volume data
Shasta (California)	48	Crandell (1984)
Popocatepetl (Mexico)	28	Robin and Boudal (1984)
Colima (Mexico)	22–33	Stoopes and Sheridan (1992)
Socompa (Chile)	>25?	*
Avachinsky (Kamchatka)	16-20	*
Meru (Tanzania)	10-20	Cattermole (1982)
Antuco (Chile)	15	*
Fuego (Guatemala)	15	Siebert and others (1994)
Wrangell (Alaska)	>12.6	*
Orizaba (Mexico)	11	*
Sheveluch (Kamchatka)	9.5	Bogoyavlenskaya (1985)
Yatshgatake (Japan)	>9	Mimura and others (1982)
Peteroa (Chile)	9	MacPhail (1973)
Colima (Mexico)	6–12	Stoopes and Sheridan (1992)
Egmont (New Zealand)	>7.5	Palmer and others (1991)
Mawenzi (Tanzania)	7.1	Downie and Wilkinson (1972)
Drum (Alaska)	>7	*
Egmont (New Zealand)	5.8	Palmer and others (1991)
Kamen (Kamchatka)	5	*
Fuego (Guatemala)	5	Siebert and others (1984)
Rainier (Washington)	**>3.8**	**this study**

averaged about 29 ft (9 m)/yr over the last 5,700 years*. This compares with about 9.8 ft (3 m)/yr progradation of the Fraser Delta from 1859 to 1919 (Johnson, 1921) and 1–2 ft (0.3–0.5 m)/yr for the modern Mississippi delta. The Fraser River delta prograded 21.3 ft (6.5 m)/yr from 9 ka to 8 ka, but only 12.4 ft (3.8 m)/yr between 6.2 ka and 5.8 ka, then 7.8 ft (2.4 m)/yr from 2,250 years ago to the present. Early rapid rates reflect progradation in a laterally restricted embayment (Williams and Roberts, 1989). Another analog is the Samala delta (Guatemala), which has prograded 3.9 mi (6.4 km) or about 295 ft (90 m)/yr seaward as a result of catastrophic input of sediment (Kuenzi and others, 1979) after the very large 1902 Santa Maria eruption.

Additionally, Williams and Roberts (1989) show that lateral progradation and vertical accretion rates of the Fraser River delta during the Holocene are inversely related; that is, more vertical accretion onto the delta platform occurred than lateral deposition onto the delta foreslope as sedimentation kept pace with rapidly rising sea level. Therefore, both massive input of eroded OM sediment and slowly rising or stable sea level during the mid- to late Holocene (Fig. 7) would result in rapid delta progradation and lesser aggradation.

Such initially rapid post-OM progradation is also inferred for the ancient deltas by the apparent dilution of shelly material immediately after OM deposition in the Puyallup valley (Fig. 8D). Shelly material was flooded by (diluted with) clastic material from a rapidly prograding delta front that inhibited recolonization until sedimentation waned. The tapered profile of shell occurrences in adjacent drill holes (Fig. 8D) in the Puyallup valley may record the delta profile that existed with recolonization. Deep-water shelly horizons may reflect expansion of habitat with reduced sedimentation and turbidity or transport of shallow-water shelly material to depth. In the Duwamish valley, the break in documented fossil occurrences from a pre-OM position 120 ft (37 m) bpsl (Fig. 8A, hole A) to a post-OM 40 ft (12 m) bpsl at Kent (Mullineaux, 1970) defines a similar pause in documented shell deposition. Shells at 75 ft (23 m) bpsl at Renton (Mullineaux, 1970) mirror the deepening of post-OM downvalley fossil occurrences that we observed in the Puyallup valley. The deepening of fossil occurrences may indicate the re-establishment of benthic fauna with reduced post-OM sediment reworking and marine deposition over time. Post-OM largely deltaic sedimentation of at least 790 in. (2,000 cm)/1,000 yr downvalley of the ancient deltas compares favorably with high deltaic vertical sedimentation rates worldwide (Table 7 and Fig. 4 inset). Early Holocene (pre-OM) sedimentation rates of about 275 in. (700 cm)/1,000 yr were estimated (1) using 180 ft (55 m) of unit Qua underlying the OM and overlying late-glacial recessional deposits (unit Qvr, Fig. 8D) and (2) assuming about 8,000 years between glacial retreat and OM deposition. (Lower calculated early Holocene sedimentation may attest to partial to complete basin emergence and resultant erosion or nondeposition during early Holocene uplift, thus reducing the *overall* sedimentation rate.)

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* Greater delta progradation down the Duwamish embayment is largely attributed to the high sediment load of the White River (see Mills, 1976; J. Vallance and K. Scott, unpub. ms.), supplemented from time to time by lahars

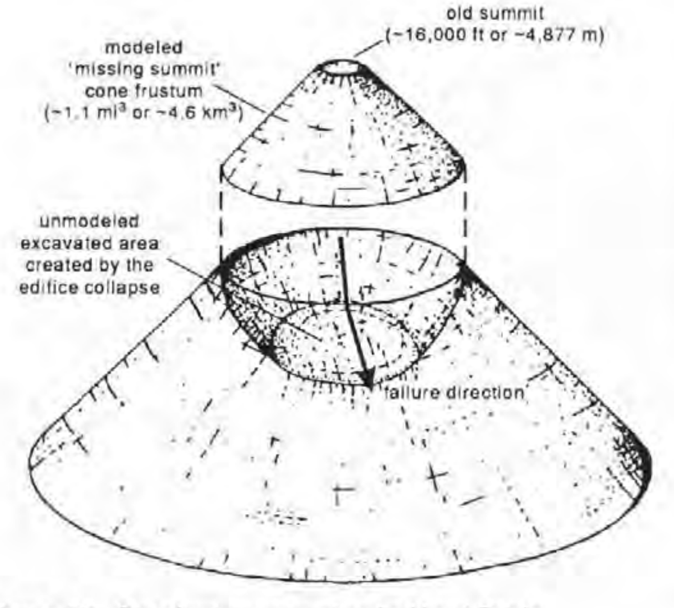

Figure 12. Cone frustum parameters for Mount Rainier.

Mullineaux (1970) reported about 120 in. (305 cm)/1,000 yr accumulation for Cedar River alluvium at Renton since about 7 ka (Mazama ash), similar to accumulation rates in the lower Green River and Puyallup valley south of Sumner since 5.7 ka (Table 7 and Fig. 4). The lower post-OM valley-fill sedimentation rates, which ranged from 0 to about 79 in. (200 cm)/1,000 yr (Table 7) in the White, Green, Carbon Rivers and Prairie Creek may reflect OM-induced stream congestion or aggradation in these restricted channels after catastrophic OM input and subsequent reworking in an attempt to reach graded river conditions.

Post-OM lahars and lahar runouts from Mount Rainier further aggraded the lower valleys (Crandell, 1971; Scott and others, 1992; J. Vallance and K. Scott, unpub. ms.). For example, the Round Pass Mudflow probably reached the Puget Lowland about 2,600 ^{14}C years ago. Deposits of many other lahars have been documented in both the White and Puyallup River valleys, and many of these inundated the lowlands (for example, see Pringle and Palmer, 1992), although their stratigraphic positions are not well known.

Erosion rates on Mount Rainier were estimated by Mills (1976) using dissection of the original landform, volumes of glacial and lahar deposits, present sediment loads of meltwater streams, reservoir sedimentation rates, and super-glacial debris loads. Erosion rates of 118–315 in. (300–800 cm)/1,000 yr suggested by the Nisqually and White River sediment loads and Alder Lake reservoir sedimentation are very high relative to values determined in similar studies in volcanic environments, demonstrating that high sediment loads, rapid delta progradation, and localized stream aggradation are normal consequences of the high denudation rates at Mount Rainier throughout the Holocene.

SUMMARY

We constructed the contour map of the upper surface of the Osceola Mudflow and the thickness (isopach) map from boring and well data. The regular nature of the top and thickness contours indicate that Figures 2 and 3 reasonably portray the extent and geometry of the Osceola Mudflow deposit in the subsurface. Later Holocene laharic, alluvial, and deltaic deposits in Puget Lowland rivers have subsequently filled the former marine embayments.

Table 7. Sedimentation rates in various depositional environments

Environment	Location (reference)	Rate (cm/1000 yr)
Fluvial	Nile River flood plain (Kukal, 1971)	900
	Ohio River flood plain (Moore, 1971)	450
	Cedar River (WA) (Mullineaux, 1970)	305
Deltaic	Alamo River delta (US) (Arnal, 1961)	5,000
	Fraser River delta (Canada) (Kukal, 1971)	5,000–30,000
	Mississippi River delta (US) (Kukal, 1971)	6,000–45,000
	Orinoco River delta (Venezuela) (Kukal, 1971)	1,000
	Tama River delta (Japan) (Ambe, 1972)	3,000–7,000
Estuarine	Great Bay Estuary (US) (Capuzzo and Anderson, 1973)	160-780
Bays, gulfs, lagoons, sounds	Corpus Christi Bay (US) (Shepard, 1953)	380
	Kiel Bay (Germany) (Kukal, 1971)	150–200
	Gulf of California (US) (Kukal, 1971)	60–100
	Gulf of Paria (Venezuela) (Kukal, 1971)	0–100
Tidal flats, marshes, peat bogs	Tidal flats (Netherlands) (Kukal, 1971)	1,000–2,000
	Peat bogs (North America) (Kukal, 1971)	550
	Swabian high moors (Germany) (Kukal, 1971)	150–180

Using 833 geotechnical boring and water-well logs, we systematically traced the subsurface OM to Kent in the Duwamish valley and Fife in the Puyallup valley, both more than 62 mi (100 km) channel distance from Mount Rainier. We constructed pre-OM topographic, as well as OM and post-OM valley-fill isopach maps using top and bottom elevations to calculate volumes of sediment deposited. The mudflow overrode ancient deltas just west of Puyallup, south of Auburn, and along the present mouth of the Green River valley and flowed down delta foreslopes. Delta platform elevations suggest sea level was no more than about 26 ft (8 m) bpsl at about 5 ka.

The OM originated as a huge sector collapse from the northeastern flank of Mount Rainier about 5.7 ka. Provisional estimates from our isopachs revise the total OM volume upward to at least 0.89 mi^3 (3.8 km^3), including 0.48 mi^3 (2.0 km^3) (average 25 ft [8 m] thick over 128 mi^2 [330 km^2]) for the surface OM and 0.36 mi^3 (1.5 km^3) (average 25 ft [8 m] covering 71 mi^2 [185 km^2]) for the subsurface OM. This estimate triples Crandell's (1971) estimate of 0.12 mi^3 (0.5 km^3) for the subsurface OM. We increase the average surface OM depth to 25.1 ft (7.1 m) from Crandell's (1971) previous 20-ft (6.1 m) estimate. Accelerated post-OM sedimentation was initially dominated by reworking of this sediment pulse (and by subsequent smaller lahars). Delta progradation of 8 and 22 mi (13 and 35 km) in the Puyallup and Duwamish valleys, respectively, over the following 5,700 years is indicated by our data.

The OM was an enormous event in the Holocene history of the Duwamish and Puyallup valleys, yet later valley filling, dominantly in a deltaic environment, was about four times the volume of the mudflow. This tremendous sedimentation was due to laharic floods from Mount Rainier as well as post-OM channel readjustments, including a shortening of the channel length and increase in gradient of the White River to accommodate the massive input of laharic sediment to the system.

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Correction

The photo of the lahar at Nevado del Ruiz, Colombia, in the last issue of *Washington Geology* (v. 22, no. 3, fig. 2, p. 27) was taken by Dick Janda. His last name was accidently omitted during printing.

The Eocene Orchards and Gardens of Republic, Washington

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Washington State leads the nation in the production of several kinds of fruits and berries: apples, cherries, and red raspberries. The state's climate allows us to grow a wide variety of ornamental trees and shrubs (rhododendron, dogwood, mountain ash, holly, honeysuckle, juniper, laurel) and herbs (thyme). And the timber industry (fir, pine, spruce, cedar) is an important element of our economy.

What few people realize is that a great many of the plants we choose to cultivate were here about 50 million years ago—albeit looking a little different. The fossil beds at Republic and across the border to the north in British Columbia (Fig. 1) continue to show us that Washington's agricultural economy is firmly rooted in this region's geologic past. For that reason, we have nicknamed the Okanogan Highlands, and the Republic fossil beds in particular, the Eocene orchards and gardens of the Northwest.

The botanical heritage of the Okanogan Highlands has made some significant paleontological contributions. The presence during the middle Eocene of more than 450 fossil species of plants is a record of diversity unmatched by any other known fossil locality in western North America. Nearly 250 species have been identified from Republic and Princeton, BC, and an additional 200+ taxa that likely represent new species and new genera have also been found in these localities. (See Table 1.) Many of these fossils are on display at the University of Washington's Burke Museum in Seattle, Stonerose Interpretive Center in Republic, and Princeton Museum and Archives in Princeton, BC.

Additionally, the world's oldest well-documented fossil records for our economic staples—apple (*Malus*), cherry (*Prunus*), and red raspberry (*Rubus*)—come from Republic and Princeton. Most of the other fossil leaves and fruits illustrated in this article (Plates 1–3; see also Table 2)—wild currants and gooseberries (*Ribes*), mulberries (*Morus*), elderberries (*Sambucus*), madrona (*Arbutus*), Saskatoon berries or serviceberries (*Amelanchier*), and the citrus family (Rutaceae)—also represent some of the oldest known fossil records for these genera.

Some Fundamentals of Paleobotany

The study of fossil plants depends primarily upon accurate radiometric dates for associated volcanic rocks and strata and competent identifications of well-preserved fossil material. Recent ^{40}Ar-^{39}Ar dating of the Klondike Mountain Formation, in which the Republic fossil flora occurs, has provided new information about the age of the flora and its closely associated volcanic rocks: "Adularia in the Golden Promise vein, which marks the termination of Sanpoil volcanism in the district, is 50.1 ± 0.1 Ma and a feeder dike for the basalt on top of Klondike Mountain is 48.8 ± 1 Ma. These dates limit the deposition of the Klondike Mountain Formation in the district to between 50 and 49 Ma" (Byron Berger, U.S. Geological Survey, Denver, written commun., 1992). This age is essentially consistent with and confirms earlier radiometric dating of coeval British Columbia floras (48 ± 2 Ma, Matthews, 1964).

When examining fossil plants, it is important to consider whether the plants grew close to where they were incorporated in sediments or are examples of materials transported from farther away and therefore represent a different flora—perhaps one at a higher elevation or a more arid site. Long-distance transport generally results in both fewer and less complete specimens. For example, fossil pollen from spruce and hemlock appears in the Eocene Burrard Formation at Vancouver, BC. However, because of its scarcity and poor quality, paleobotanists conclude that the pollen was carried from outside the local area and does not represent the flora surrounding the depositional site. In contrast, the excellent condition of many examples of types of foliage in the Okanogan floras indicate that the source of these specimens was close by.

As we have said, many of the Okanogan Highlands fossil leaves and plants are superbly preserved. This allows paleobotanists to compare them in microscopically fine detail with modern leaves of close affinity. However, some earlier identifications of fossil leaves were made from poorly preserved material that had only a superficial resemblance to the modern plants to which they were compared. Some of these fossil plants were assigned not only to the wrong species and genera but to the wrong families and even orders as well. This would

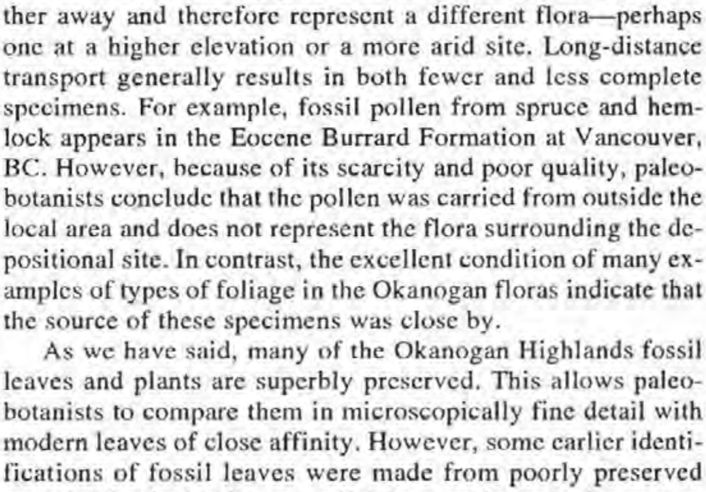

Figure 1. Location of Republic, Washington, and Princeton, British Columbia. The Okanogan Highlands physiographic province encompasses northeastern Washington and eastern British Columbia.

Table 1. Plants from middle Eocene localities in the Okanogan Highlands of Washington and British Columbia. The Republic and British Columbia early middle Eocene localities contain more than 450 species of fossil plants, many of which have yet to be identified. At least 61 families of dicots and 8 families of monocots are recognized, in addition to fossil conifers, fungi, mosses, lycopods, ferns, and quillworts. This list covers 83 families and 177 genera. Many of the identifications in this list will be found in publications by Jack A. Wolfe, Howard E. Schorn, Ruth A. Stockey,

CONIFERS AND OTHER GYMNOSPERMS

- **Ginkgoaceae** (ginkgo family)
  - *Ginkgo* (maidenhair fern tree)
- **Taxaceae** (yew family)
  - *Amentotaxus* (Chinese yew)
  - *Taxus*? (yew)
  - *Torreya* (California nutmeg)
- **Cephalotaxaceae** (plum-yew family)
  - *Cephalotaxus* (plum-yew)
- **Taxodiaceae** (redwood family)
  - *Cryptomeria* (Japanese cedar)
  - *Metasequoia* (dawn redwood)
  - *Sequoia* (redwood)
  - *Sciadopitys* (umbrella pine)
- **Pinaceae** (pine family)
  - *Abies* (true fir)
  - *Picea* (spruce)
  - *Pinus* (pine)
  - *Pseudolarix* (Chinese golden larch)
  - *Tsuga* (hemlock)
- **Cupressaceae** (cedar family)
  - *Chamaecyparis* (false cypress)
  - *Juniperus* (juniper)
  - *Thuja* (arborvitae)

FLOWERING PLANTS OR ANGIOSPERMS

- **Magnoliaceae** (magnolia family)
  - *Liriodendroxylon* (tulip tree) (wood)
  - *Talauma*
- **Schisandraceae**
  - *Kadsura*
- **Lauraceae** (laurel family)
  - *Lindera* (allspice)
  - *Litseaphylla*
  - *Ocotea*
  - *Phoebe*
  - *Sassafras*
- **Nymphaeaceae** (water lily family)
  - *Nuphar* (water lily) (fruit)
  - *Allenbya* (extinct genus) (fruits, seeds)
- **Ranunculaceae**
  - *Clematis*
- **Trochodendroid Group**
  - *Trochodendron*
  - *Tetracentron*
  - *Cercidiphyllum* (katsura)
- **Trochodendroid Group** *(Continued)*
  - *Nordenskioldia* (extinct genus)
  - *Joffrea* (extinct genus)
  - *Eobaileya* (extinct genus)
  - genus unknown (extinct)
- **Hamamelidaceae** (witch-hazel family)
  - *Corylopsis*
  - aff. *Fothergilla* (extinct genus)
  - aff. *Hamamelis* (extinct genus)
  - *Langeria* (extinct genus)
  - *Liquidambar* (sweet gum) (seed)
  - genus unknown (extinct)
- **Hollickiaceae** (extinct family)
  - 'Princeton taxon' (extinct genus)
- **Eucommiaceae**
  - *Eucommia* (fruit)
- **Platanaceae** (sycamore family)
  - *Macginicarpa* (extinct genus) (fruits)
  - *Macginitiea* (extinct genus) (leaves)
  - *Platanus* (sycamore)
- **Theaceae** (tea/camellia family)
  - *Cleyera*?
  - *Gordonia* (Carolina bay)
- **Flacourtiaceae**
  - *Idesia*?
  - extinct genus
- **Cucurbitaceae** (gourd/pumpkin family)
  - genus unknown
- **Salicaceae** (willow family)
  - *Populus* (cottonwood, poplar)
  - *Salix* (willow)
- **Ericaceae** (heath family)
  - aff. *Arbutus* (madrona)
  - aff. *Leucothoe*
  - *Rhododendron*
- **Styracaceae** (storax/silverbell family)
  - cf. *Styrax*
  - genus unknown
- **Tiliaceae** (linden family)
  - *Craigia*? ("*Koelreuteria*") (fruit)
  - *Plafkeria* (extinct genus)
  - *Tilia* (linden)
- **Sterculiaceae** (cocoa tree family)
  - aff. *Eriolaena* (extinct genus)
  - *Florissantia* (extinct genus) (flower)
  - extinct genus
- **Malvaceae** (mallow family)
  - *Hibiscus*
- **Moraceae** (mulberry family)
  - *Morus* (mulberry)
- **Ulmaceae** (elm family)
  - *Ulmus* (elm)
  - aff. *Ulmus* (extinct genus)
  - *Zelkova* (Chinese elm)
- **Thymeleaceae** (thyme family)
  - aff. *Dirca* (extinct genus)
- **Fagaceae** (oak family)
  - *Castaneophyllum* (chestnut)
  - *Fagopsis* (extinct genus)
  - *Fagus* (beech)
  - *Quercus* (oak)
- **Betulaceae** (birch/alder family)
  - *Alnus* (alder)
  - *Betula* (birch)
  - *Corylus* (hazelnut)
  - *Paleocarpinus* (extinct genus) (fruit)
- **Myricaceae** (wax myrtle/sweet fern family)
  - *Comptonia* (sweet fern)
- **Juglandaceae** (walnut family)
  - *Pterocarya* (wingnut)
  - *Cruciptera* (extinct genus) (fruit)
  - *Palaeocarya*? (extinct genus) (fruit)
- **Hydrangeaceae** (hydrangea family)
  - *Hydrangea*
- **Iteaceae** (Virginia willow family)
  - *Itea* (Virginia willow)
- **Philadelphaceae** (mock orange family)
  - *Deutzia*?
  - *Philadelphus* (mock orange)
- **Grossulariaceae** (currant family)
  - *Ribes* (wild currant, gooseberry)
  - genus unknown (extinct)
- **Rosaceae** (rose family)
  - *Spiraea* (bridal wreath)
  - aff. *Spiraea* (extinct genus)
  - *Physocarpus* (ninebark)
  - aff. *Physocarpus* (extinct genus)
  - *Stonebergia* (extinct genus)
  - *Paleorosa* (extinct genus) (flower)
  - *Amelanchier* (Saskatoon berry or serviceberry)
  - *Hesperomeles*
  - aff. *Potentilla*? (extinct genus)
  - *Crataegus* (hawthorn)
  - aff. *Crataegus* (extinct genus)
  - aff. *Sorbus* (mountain ash)
  - *Malus* (apple)
  - *Photinia*
  - *Crataegus/Pyrus* (hawthorn/pear)

be analogous to identifying a fossil fly as a bee, or a fossil butterfly as a wasp. Paleobotanical literature abounds with theories about origins, evolution, and biogeographical dispersals of plant lineages that were based on such misidentifications. "Gross picture-matching", a common approach to fossil leaf identification in the not too distant past, was often oblivious to these crucial differences between vegetational and floristic diagnostic features. As a consequence, many fossil leaf identifications now need critical review.

When identifying fossil leaves, it is essential to distinguish between certain kinds of features. For example, leaf shape and size and the character of the leaf margins (toothed or entire) [smooth] and tips (long and sharp drip tips or blunt tips) are features that can merely reflect a plant's responses to climatic changes and environmental stress. Other leaf features, such as venation and tooth type, are not influenced by environmental factors; they indicate phylogenetic relations. These latter morphological characteristics separate superficial resemblances between fossil leaves from those that are phylogenetically diagnostic.

The willow family (Salicaceae), as an example, includes two well-known genera: *Salix* (willow) and *Populus* (cottonwood and aspen). Superficially, willow leaves and cottonwood leaves don't look at all alike. Cottonwood leaves look more like *Katsura* leaves than they look like willow leaves. Willow leaves can look more like some forms of extinct oak family

Steven R. Manchester, Victor B. Call, and Wesley C. Wehr. Some of the unpublished determinations are provisional and require further study. Other determinations have been provided by Jack A. Wolfe (angiosperms), Howard E. Schorn (Conifers), M. A. Gandolfo and William L. Crepet (Fagaceae), Charles N. Miller, Jr., and Gar W. Rothwell (conifers and filicales), David L. Dilcher, and Kathleen B. Pigg

Rosaceae (rose family) *(Continued)*
  'Pyracantha'
  aff. *Vauquelinia*?
  Neviusia
  Rubus (blackberry, raspberry, salmonberry)
  Prunus (cherry, plum, peach)
  aff. *Prunus* (extinct genus)

Lythraceae (loosestrife family)
  Decodon (loosestrife)

Melastomataceae
  genus unknown

Myrtaceae (myrtle family)
  Paleomyrtinaea (extinct genus) (fruit)

Leguminosae (legume family)
  genus unknown

Rutaceae (citrus family)
  genus unknown

Anacardiaceae (cashew family)
  Comocladia?
  Rhus (sumac)
  Schmalzia?

Meliaceae (mahogany family)
  aff. *Chukrasia* (extinct genus)

Burseraceae (torchwood family)
  Barghoornia (extinct genus)

Sapindaceae (soapberry family)
  Allophylus
  Bohlenia (extinct genus)
  Deviacer ('Acer' arcticum) (extinct genus)
  Koelreuteria
  Paullinia
  Sapindus (soapberry)
  Serjania
  Wehrwolfea (extinct genus) (flower)

Aceraceae (maple family)
  Acer (maple)

Hippocastanaceae (horse chestnut family)
  Aesculus (horse chestnut)

Davidiaceae (Chinese dove tree family)
  Tsukada (extinct genus)

Mastixiaceae
  Mastixia?

Cornaceae (dogwood family)
  Cornus (dogwood)

Aucubaceae (Japanese laurel family)
  Aucuba (Japanese laurel)

Helwingaceae
  Helwingia? (fruit)

Araliaceae (ginseng family)
  Aralia?

Aquifoliaceae (holly family)
  Ilex (holly)

Celastraceae (spindle tree family)
  Celastrus?

Icacinaceae (moonvine family)
  Palaeophytocrene (extinct genus) (fruit)

Rhamnaceae (buckthorn family)
  Ceanothus?
  Hovenia (Chinese raisin tree)
  Paliurus? (Christ's thorn) (fruit)
  Rhamnus (buckthorn)
  genus unknown

Vitaceae (grape family)
  'Cissus'
  Vitis (grape)
  Ampelocissus (grape) (seeds)

Olacaceae (olax family)
  Schoepfia

Loranthaceae (mistletoe family)
  extinct genus

Oleaceae (olive family)
  Fraxinus (ash) (fruit)

Rubiaceae (gardenia/coffee/quinine family)
  genus unknown (fruit)

Caprifoliaceae (honeysuckle family)
  Sambucus (elderberry)
  Viburnum?

Bignoniaceae (catalpa family)
  genus unknown (fruit)

Unknown Affinity
  Republica (extinct genus)
  Pteronepelys (extinct genus) (fruit)
  Calycites ('*Abelia*') (flower)

MONOCOTS

Alismataceae (water-plantain family)
  Heleophyton (extinct genus)

Liliaceae (lily family)
  Soleredera (extinct genus)

Smilacaceae (greenbriar family)
  Smilax (greenbriar)

Juncaceae/Cyperaceae (rush/sedge family)
  Ethela (extinct genus)

Arecaceae (palm family)
  Uhlia (extinct genus)

Typhaceae (cattail family)
  Typha (cattail)

Araceae (arum lily/calla lily family)
  Keratosperma (extinct genus) (fruits, seeds)

FUNGI

Ustilaginaceae (smut fungus)
  cf. *Microbotryum*

BRYOPHYTES (MOSSES AND LIVERWORTS)

Musci (mosses)
  Aulacomnium (extant genus)
  Muscites (form genus)
  Ditrichites (form genus)
  Palaeohypnum (form genus)

FILICALES (FERNS)

Osmundaceae
  Osmunda

Schizaeaceae?
  genus unknown

Aspleniaceae
  cf. *Cystopteris*

Polypodiaceae (common fern family)
  Dennstaedtiopsis
  cf. *Diplazium*

Salviniaceae (water-fern family)
  Azolla (water fern)

EQUISETALES (HORSETAILS AND SCOURING-RUSHES)

Equisetaceae (horsetail family)
  Equisetum (horsetail)

LYCOPODIOPHYTA

Selaginellaceae (spikemoss family)
  Selaginella (spikemoss)

ISOETALES (QUILLWORTS)

Isoetaceae (quillwort family)
  Isoetites (extinct genus)

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leaves (*Dryophyllum*, for instance) than like cottonwood and aspen leaves. This is exactly where leaf architecture comes in. What *Populus* and *Salix* have in common, rather than similar vein patterns, is that they both have a highly characteristic diagnostic type of leaf tooth (termed salicoid) that indicates their close phylogenetic relation. But only in well-preserved fossil material can scientists clearly discern these critical diagnostic features.

The beautiful preservation of many Republic fossil leaves, especially the examples of the rose family (Rosaceae), and the application of leaf architectural criteria to distinguish between vegetational and phylogenetic features has recently led to the recognition that many middle Eocene flowering plant (angiosperm) genera actually represent extinct ancestral genera. This would indicate that the middle Eocene warm-temperate to subtropical climates in the Okanogan Highlands forests, thought to be a result of higher altitudes than those in the coeval coastal lowland forests, were significant influences in the rapid evolution and diversification of many groups of plants, especially the rose family group.

Origins of the Rose Family

The rose family (Table 1) has many Eocene representatives in the Okanogan floras. This diverse family offers some real challenges to paleobotanists because the origins of the Rosaceae are difficult to establish. There appear to be several

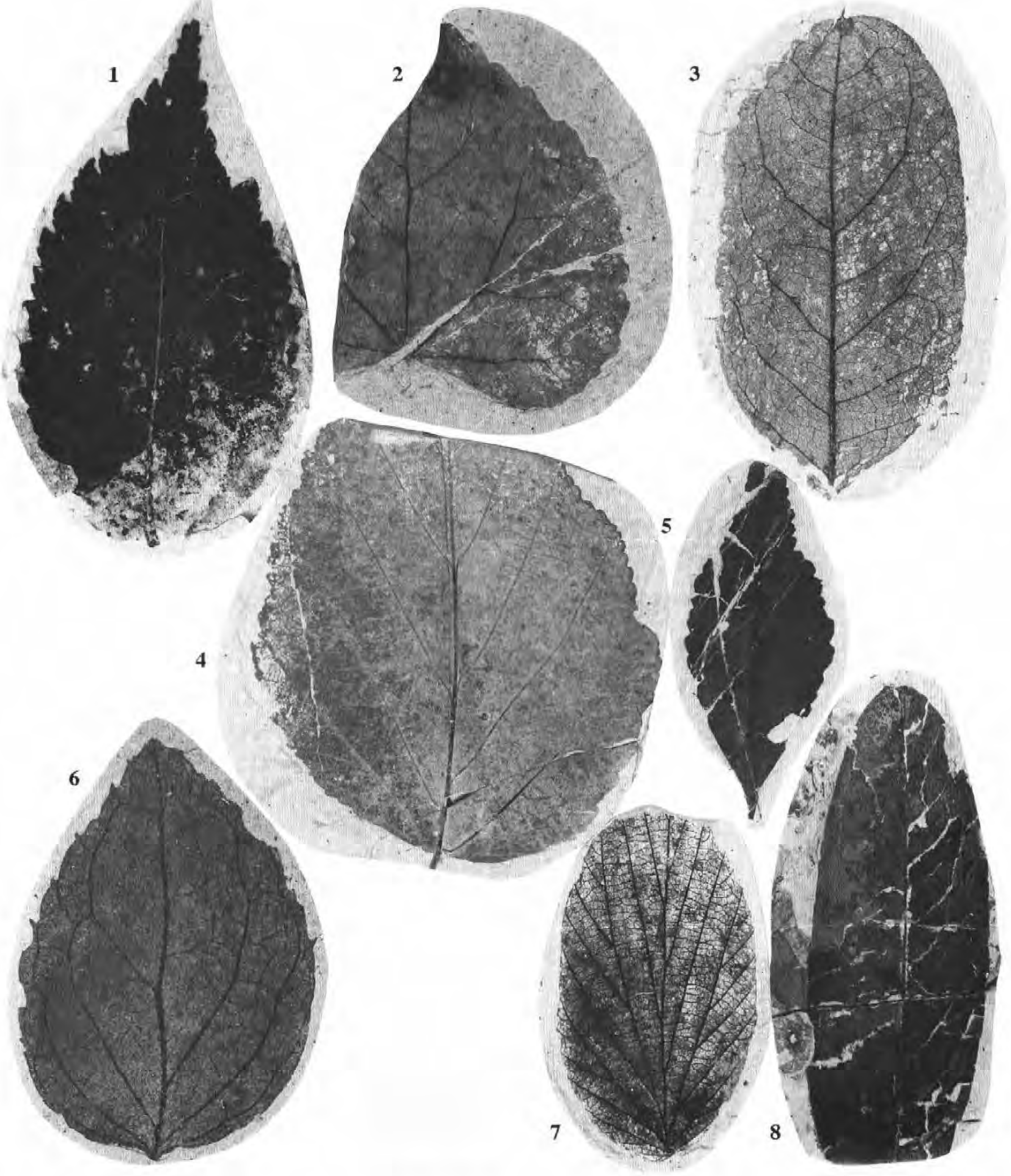

Plate 1. Fossil leaves from middle Eocene trees and shrubs, Republic, Washington. SR, Stonerose Interpretive Center collection; UWBM, Burke Museum (Univ. of Wash.) collection. Locality numbers are those assigned by the Burke Museum. **1.** *Rubus* (raspberry, etc.), UWBM 36840, loc. B2737, x 1.65. **2.** *Vitis* (grape), SR 94-2-4B, loc. B2737, x 1.65. **3.** Rutaceae (citrus family), SR 94-2-2B, loc. B4131, x 1.65. **4.** *Hibiscus* (unlobed leaf), UWBM 26011, loc. B4131, x 1. **5.** aff. *Arbutus* (madrona), UWBM 76520, loc. B2737, x 0.85. **6.** *Philadelphus* (mock orange), UWBM 71381, loc. B2737, x 3. **7.** *Corylopsis* (winter hazel), UWBM 71085, loc. AO307, x 2. **8.** *Talauma* (magnolia), SR 93-7-4B, loc. AO307, x 0.65.

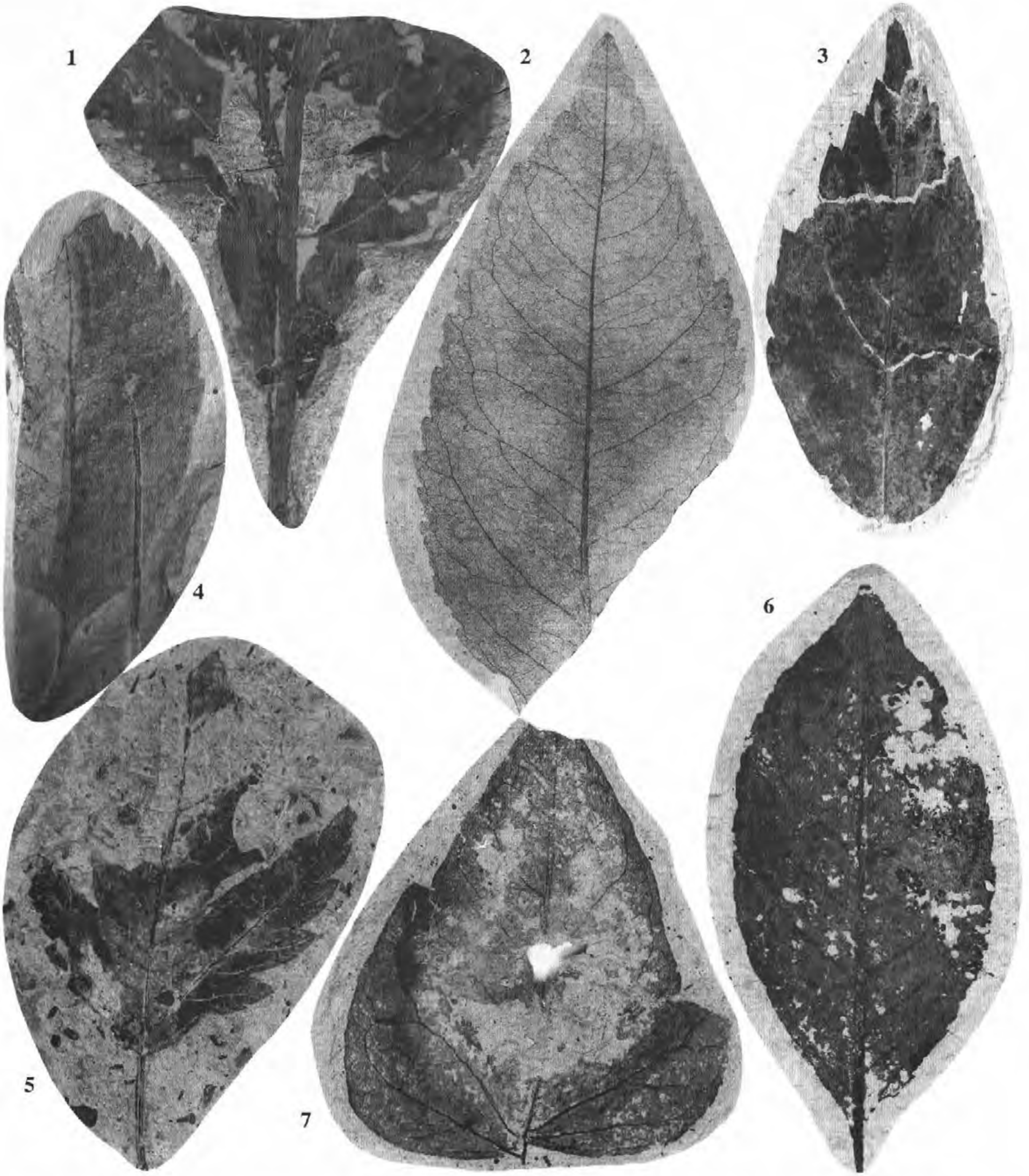

Plate 2. Fossil leaves from middle Eocene trees and shrubs, Republic, Washington, and Princeton, British Columbia. SR, Stonerose Interpretive Center collection; UWBM, Burke Museum (Univ. of Wash.) collection. Locality numbers are those assigned by the Burke Museum. 1–6. Rosaceae (rose family): **1.** aff. *Prunus*, UWBM 76828, loc. B4600, x 0.6. **2.** *Malus* (apple), SR 93-7-2B, loc. B2737, x 1.6. **3.** *Neviusia*, UWBM 56622, loc. B4131, x 1.3. **4.** *Amelanchier* (Saskatoon berry), UWBM 54168, loc. B3389 (Princeton), x 1.6. **5.** *'Crataegus/Pyrus'* (hawthorn/pear hybrid?), UWBM 36860, loc. B4131, x 1.3. **6.** *Prunus* (cherry), UWBM 78006, loc. B4131, x 1.3. **7.** *Clematis*, SR 94-2-5B, loc. B2737, x 2.

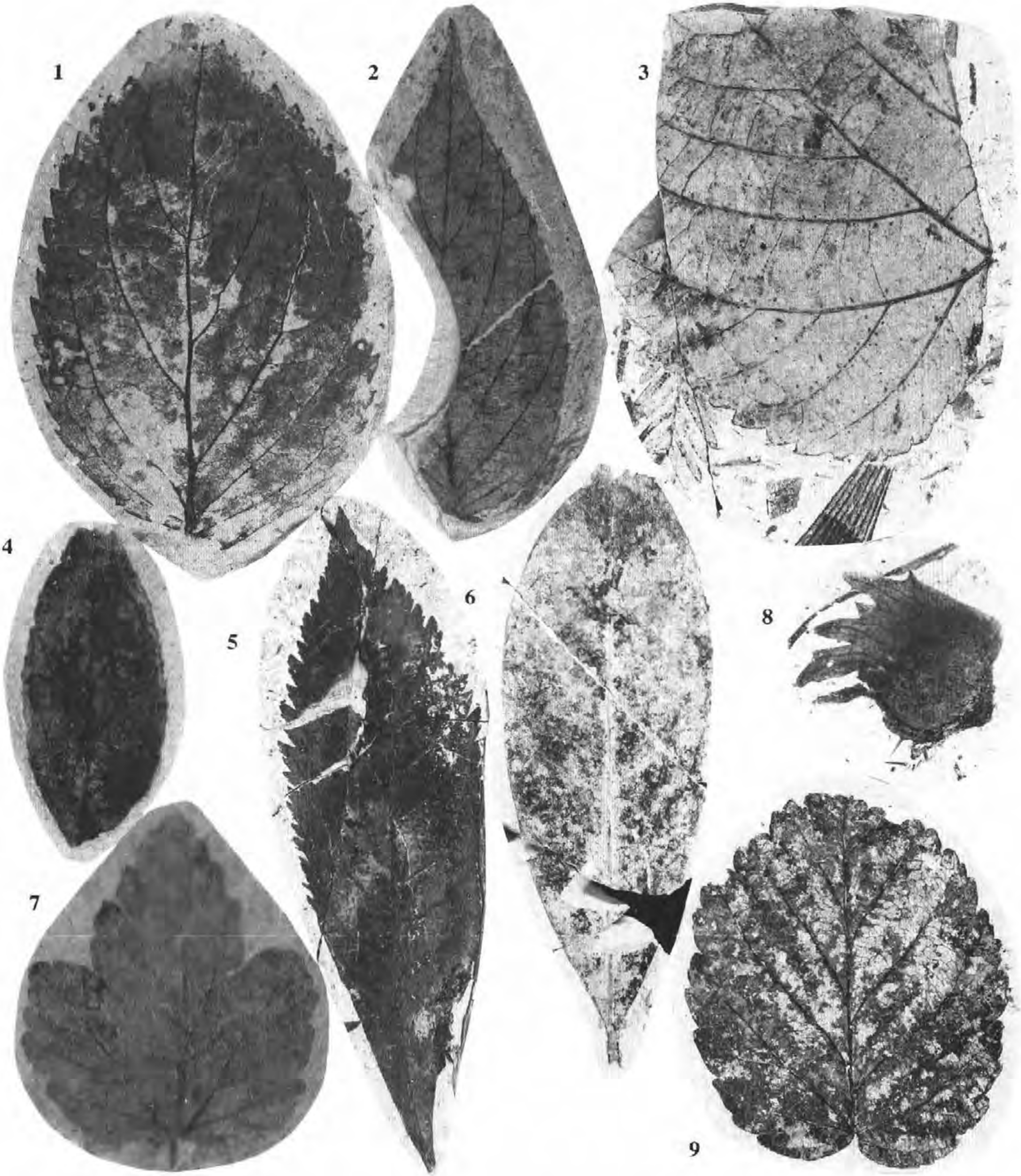

Plate 3. Fossil leaves and fruit from middle Eocene trees and shrubs, Republic, Washington, and Princeton, BC. SR, Stonerose collection; UWBM, Burke Museum (Univ. of Wash.) collection. Locality numbers are those assigned by the Burke Museum. **1.** *Hydrangea* (type I), UWBM 36835A, loc. B4131, x 2. **2.** *Hydrangea* (type II), UWBM 56594, loc. B4131, x 1.3. **3.** *Morus* (mulberry), UWBM 56633, loc. B4131, x 2. **4.** aff. *Leucothoe* (*Andromeda*), UWBM 71129, loc. B2737, x 1. **5.** *Sambucus* (elderberry), UWBM 57488A, loc. B3389 (Princeton), x 1.65. **6.** *Rhododendron*, UWBM 54858, loc. AO307B, x 0.75. **7.** *Ribes* (wild currant), SR 91-5-10, loc. B4131, x 2. **8.** *Corylus* (hazelnut involucre), UWBM 71062A/B, loc. AO307, x 1.65. **9.** *Corylus* (hazelnut leaf), SR 94-2-3B, loc. AO307, x 2.

Table 2. Broad-leaved plants of the flora of the Okanogan Highlands shown in Plates 1–3. Rare, 1–3 examples; scarce, 4–10 examples; common, more than 10 examples

Family and genus	Fossil abundance	Present distribution of genus
Magnoliaceae (magnolia family)		
Talauma (magnolia)	rare	S Asia, N&S America, Caribbean
Ranunculaceae (buttercup family)		
Clematis	rare	north & south temperate
Hamamelidaceae (witch-hazel family)		
Corylopsis (winter hazel)	rare	Bhutan to Japan
Ericaceae (heath family)		
Rhododendron	rare	northern hemisphere, southeast Asia
aff. *Arbutus* (madrona)	rare	extinct
aff. *Leucothoe* (*Andromeda*)	rare	extinct
Malvaceae (mallow family)		
Hibiscus	rare	warm temperate to tropics
Moraceae (mulberry family)		
Morus (mulberry)	rare	north temperate & subtropical
Betulaceae (birch/alder family)		
Corylus (hazelnut)	scarce	north temperate
Hydrangeaceae (hydrangea family)		
Hydrangea	scarce	north temperate
Philadelphaceae (mock orange family)		
Philadelphus (mock orange)	rare	north temperate
Rosaceae (rose family)		
Amelanchier (Saskatoon berry, serviceberry)	rare	north temperate
Malus (apple)	rare	north temperate
Crataegus/Pyrus (hawthorn/pear)	rare	north temperate
Neviusia	rare	Alabama & northern California
Rubus (blackberry, raspberry, salmonberry)	rare	north temperate
Prunus (cherry)	common	north temperate
aff. *Prunus* (cherry)	common	extinct
Rutaceae (citrus family)		
genus unknown	rare	extinct
Vitaceae (grape family)		
Vitis (grape)	rare	tropic & subtropic temperate cultivated
Caprifoliaceae (honeysuckle family)		
Sambucus (elderberry)	rare	temperate & subtropical

valid occurrences of the family in the Paleocene of Alberta, notably *Spiraea* and a precursor of *Prunus*. Other reliable early records of the Rosaceae include *Vauquelinia* in the middle Eocene Chalk Bluffs flora of Nevada and *Prunus* fossil wood and leaves from the middle Eocene of Wyoming.

The Okanogan Highlands fossil floras at Republic and Princeton, however, record the first major appearance of the Rosaceae, represented by genera of all four of its subfamilies. At least 50 species of Rosaceae occur in these montane assemblages, represented by 20 identified genera, 36 identified species, and at least 16 taxa of rosaceous affinity that have yet to be identified. *Prunus*, for example, occurs in this region: fossil leaves of five species of *Prunus* and the leaves of an extinct genus of primitive cherry have been found at Republic. More significantly, cherts at Princeton contain—in close association—fossil *Prunus* fruits, seeds, and wood, and the Princeton One Mile Creek flora contains leaves of three species of *Prunus*.

Even though the rose family was obviously undergoing major diversification in the middle Eocene, fossil evidence for the presence in the Okanogan Highlands of several rosaceous genera (for example, *Malus*, *Rubus*, *Amelanchier*, *Neviusia*, *Hesperomeles*, *Stonebergia*, and *Physocarpus*) typically consists only of rare leaves and leaflets. Other rosaceous genera (especially *Prunus* and extinct precursors of *Sorbus*, *Spiraea*, and *Crataegus*) are more common in the Republic and Princeton fossil deposits.

Because many rosaceous genera are closely related, they can be difficult to differentiate in fossil form, especially when only the fossil leaves or leaflets are available. Rosaceous hybrids at the genus level (termed bigeneric hybrids) occur both naturally and as cultivars today. Some of the middle Eocene rosaceous foliage, such as '*Crataegus/Pyrus*' in the Republic flora, suggest intergeneric affinities. Modern botanical identifications are routinely based on complete plants. In contrast, many fossil identifications are based on isolated plant elements, typically foliage and wood, simply because that is all that is available for study. The presence in the Republic and Princeton floras of *Prunus* leaves, fruits, seeds, and wood provides a much better basis for attempting to reconstruct the original entire plants and thereby their relations to other similar forms.

Especially important among the early well-documented Rosaceae is a *Paleorosa* blossom from the Princeton cherts. This flower from an extinct genus is unique in the rosaceous fossil record, not only for the remarkable anatomical detail preserved, but also because it contains the earliest known fossil rosaceous pollen preserved in a rosaceous flower. The Rosaceae, with the exception of Sanguisorbeae, are pollinated by insects, not by wind. The flowers have only small amounts of pollen, and rose pollen is indeed sparsely represented in the fossil record.

Biogeography and Disjunct Distributions

As we have seen, the middle Eocene, especially in the Okanogan Highlands, saw the rapid appearance and diversification of many important groups of flowering plants—notably in the rose, maple, heath, saxifrage, and soapberry families. Nearly 50 million years later, we are witnessing a similarly rapid appearance and diversification of theories about their origins, botanical affinities, and geographical distributions. The fossil finds in the Okanogan Highlands give us new clues to old questions about the origins and modern habitats of angiosperms. However, many of these finds don't resolve old questions so much as they confront us with new ones about the floristic history of North America.

Alabama snow-wreath (*Neviusia alabamensis*), for instance, is a modern rosaceous shrub that grows wild only in the southeastern part of the United States. It is closely related to *Kerria japonica*, a rosaceous shrub native to Japan and China, and to *Rhodotypos*, another Japanese rosaceous shrub. A second species of *Neviusia* (*N. cliftonii*) was recently discovered near Mount Shasta in northern California. This is a very strange distribution for a living plant! Plants that grow wild only in widely separated areas, like these species of *Neviusia*, are said to have disjunct distribution.

To make *Neviusia*'s geographical history even more complicated, fossil leaves of *Neviusia* have been found at both Republic and Princeton. *Neviusia* has no other fossil record. However, just because its oldest fossil record comes from the Okanogan Highlands, we can't assume that this is where *Neviusia* originated. And we need to know what happened to the genus during the nearly 50 million intervening years to produce the modern distribution.

There are still other examples of disjunct rosaceous genera among those that grew in the Okanogan Highlands during the middle Eocene, but that are no longer native (presumably because of later climatic changes). *Photinia*, for instance, occurs at Republic and Princeton as a fossil and now grows wild only in Sumatra, Japan, and the Himalayan mountain range. *Hesperomeles*, another rosaceous genus found at Republic is now confined to Peru and Central America. *Stonebergia*, an extinct genus that may be ancestral to the rosaceous shrubs *Chamaebatia* and *Chamaebatiaria*, occurs as a fossil only at Princeton. *Chamaebatia* is now confined to California, *Chamaebatiaria* to arid intermontane areas from the Sierras to the Rockies.

The rose family, however, is not the only example of disjunct distributions. Winter hazel (*Corylopsis*) fossil leaves have been found at Republic and Princeton and in Eocene rocks of Alaska. Today *Corylopsis* ranges only from Bhutan to Japan. Chinese wingnut (*Pterocarya*) fossil leaves occur at Republic and Princeton, and they are fairly common in many fossil localities of various geologic ages throughout the world. Chinese wingnut is now native only to southeastern Asia and the Caucasus. *Hibiscus* fossil leaves occur at Republic; this genus is now confined to warm-temperate and tropical regions. Still another example of disjunct distributions is the occurrence at Republic of fossil *Talauma* leaves, a genus in the magnolia family that grows today in southern Asia, South America, and the Caribbean. Additionally, many of the Okanogan Highlands middle Eocene gymnosperms and conifers are confined to China and Japan today: Ginkgo, Chinese yew (*Amentotaxus*), dawn redwood (*Metasequoia*), and golden larch (*Pseudolarix*). The Republic flora has no close modern analog. In fact, to see a modern forest that resembles the 50-million-year-old forest of Republic and Princeton, you would have to visit the uplands of Taiwan. Such modern Asian forests, however, contain many trees and shrubs that are either not found or are poorly represented in the Okanogan Highlands.

Conclusion

The Okanogan Highlands flora represents a very early stage in the development of modern temperate forests such as those of the Pacific Northwest—forests dominated by such conifers as pine, spruce, cedar, fir, and hemlock that constitute the basis of our timber industry, as well as the many 'Eocene garden or orchard' fruits and berries that now provide an important basis for Washington's agricultural economy. The older temperate floras (such as the Eocene Arctic flora and northern temperate Paleocene flora [Wolfe and Wehr, 1991]) known from the fossil record differ greatly from the Republic flora, both floristically and vegetationally. We cannot use these temperate floras to explain the Republic flora in terms of descent from any known earlier northern flora.

The Okanogan Highlands fossils show us that, in the middle Eocene, temperate trees such as spruce, fir, and hemlock grew alongside members of such tropical groups as mahogany, magnolia, cashew, pistacia, and tropical laurel. How can we explain this mixture of plants that are today, in essence, mutually exclusive climatically, vegetationally, and floristically? The answer to the mystery of the appearance of the Republic flora may depend on future discoveries.

Fossils show us that many temperate plants were present in the ancient lowland floras as minor elements—representatives of birch, elm, maple, and dogwood lineages. For example, in the Eocene lowland Puget Group rocks are alder, elm, and hydrangea. In the middle Eocene lowland tropical Roslyn Formation, there is an elm. Because of tectonic uplift, the altitude of the Okanogan Highlands became higher with time. Consequently, the climate became more temperate, and the broad-leaved evergreens (laurels, magnolias) that are typical of lowland tropical forests (preserved in some deposits in the Puget Sound area) began to disappear, leaving the broad-leaved deciduous plants (alders, birches, maples, and elms) to flourish. By the time the lake bottom near Republic was incorporating both volcanic ash and the leaves and fruits of the 'Eocene orchards and gardens', many lowland broad-leaved evergreens were apparently only minor elements in the flora. Many types of temperate-climate plants appear for the first time in the Republic fossil beds. Some descendants of deciduous plants that grew at Republic now live beside streams and belong to communities that colonize areas that have been swept bare by natural disasters (such as volcanic eruptions) or human activities.

The interaction between geological and biological processes is well documented in the Republic and Princeton fossils. The flora records the tectonic forces that shaped the topography of the Pacific Northwest and reveals the profound impact these forces had on the development of the Northwest's agricultural base.

Acknowledgments

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Radon Report Now Available

Radon in Washington, a special report by the Environmental Radiation Program of the Washington State Department of Health, was published in June. This 102-page report covers the health effects of radon, its geographic distribution, and radon testing and mitigation. For more information or to obtain copies of this report, contact the Division of Radiation Protection, Airdustrial Center, Building 5, PO Box 47827, Olympia, WA 98504-7827; Phone: (206) 586-8948; Fax: (206) 753-1496.

Earthquake Preparedness—When You're Not at Home

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The small earthquakes of June 1994 in western Washington are another reminder that we live in earthquake country. Most of us have received some training and advice about what to do in our homes and offices. But many of us travel to the mountains and beaches for weekends and vacations, and many tourists come to see Washington's Cascade and Olympic ranges and our coast.

Our playgrounds offer potential earthquake hazards that differ from those at home or in the workplace. When a major earthquake hits, thousands of people will share the 'ride', but many will be exposed to hazards unlike those they may have prepared for and that are unique to their setting as of that moment. The fact that we don't need to worry about falling bricks and glass or other hazards of civilization doesn't mean that we can just clean up the mess and continue the picnic. In outdoor settings in our tectonically active state, ground shaking itself will likely be our only warning to quickly assess the situation. We can't expect a loudspeaker-equipped helicopter to tell us what to do.

If you experienced shaking so strong that it was difficult to stand, it was a major earthquake, and you should expect some major events to follow. Depending on your location, some may occur before the shaking stops, and other hazards may take hours to develop. This article suggests some hazards to be aware of and offers some ways to avoid or cope with them, just in case.

Coastal Locations

A serious potential hazard for the ocean coasts is sea waves (sometimes gigantic) termed tsunamis. Triggering mechanisms for tsunamis are massive submarine landslides on the continental slope, abrupt vertical motion of the continental shelf, or both. The resulting wave action on the coast would be unpredictable. The first arrival might be as a trough, with the sea receding far offshore and 'out' for possibly 10 minutes or more. Furthermore, the first tsunami wave is not necessarily the largest, and the subsequent waves may arrive many minutes after the first. On the open coast there might not even be a wave, just a rapidly rising 'tide' that keeps rising and rising!

Unlike the tsunami that hit our coast about 3.5 hours after the 1964 Alaska earthquake, a tsunami originating along the Pacific coast of Washington could reach the beaches in minutes.

Tsunamis can also travel considerable distances up coastal rivers and estuaries, and they commonly increase in height in these places because the same volume of water is moving in a narrower space as they progress upstream. Almost all the damage from the 1964 tsunamis in the Pacific Northwest was along such inlets.

There are sedimentary records consisting of telltale sand layers left by geologically recent tsunamis in several estuaries on the Pacific Coast, so we know that these areas have been subjected to such waves in the past (Atwater and Yamaguchi, 1991). Depositional patterns also record at least one tsunami in Puget Sound (Fig. 1).

Tsunamis can be extremely powerful and destructive. Possibly the most dangerous part of the tsunami is the debris carried along with the rushing water—driftwood, parts of buildings, rail cars, boats, literally anything moveable will batter everything in the wave path. The bridge across the Copalis River was badly damaged in 1964 by logs hurled against the pilings, and much of the destruction in coastal towns of Washington and Oregon was caused by the floating debris. (One of the few injured along Washington's coast in 1964 was a motorist who drove off a tsunami-damaged bridge).

Tsunami waves generated in the Pacific Ocean would diminish as they travel along the Strait of Juan de Fuca and through narrower inlets. They might be insignificant in Hood Canal or along the shores of Puget Sound. Also, the camper, clam digger, or hiker along such inland shorelines will have more time to get to high ground than those along ocean

Figure 1. Tsunami researchers have found a sand layer along the treeline in the drained salt marsh (near center, background). The sand appears to have been deposited by a wave(s) that swept into Cultus Bay (southern Whidbey Island) about 1,000 years ago.

beaches. However, because it is not immediately possible to tell where an earthquake originated or where a local wave-causing event might occur, you should get ready to leave low ground as soon as possible after any warning, even along inland shorelines.

The potential for dangerous waves to originate in inland waters comes from a variety of sources. The tsunami recorded by tidal marsh sediments at West Point in Seattle and Cultus Bay on Whidbey Island (Fig. 1) probably was caused by abrupt vertical movement of the floor of Puget Sound between Alki Point and Bainbridge Island (Atwater and Moore, 1992). Such waves can also be caused by quake-triggered submarine landslides, most commonly on the relatively steep slopes of loose, saturated sediments that make up delta fronts. Slides on deltas may even include portions of the adjacent shore or uplands. Backfill waves, water that rushes to fill the void left by the drop of the head of the slide, may reach the adjacent shore in seconds. A far-shore wave from such an event can be nearly as damaging. In these instances, too, there is very little time to move safely away from the shore.

Safety Suggestions:

If you are at an ocean beach and you feel strong ground motion or you notice a sudden change of the sea (at night the sound of the surf might abruptly cease), immediately begin to prepare for a calm but quick retreat to higher ground. Time spent hooking up the trailer (Fig. 2) or folding the tent could, in some areas, mean being farther back in the traffic jam. Some bridges across coastal rivers are in locations vulnerable to tsunamis (Fig. 3), and you should try to avoid routes across these bridges if you need to leave the coast or river banks.

You can plan ahead for safety while you are at the beach by getting familiar with the area. Find possible evacuation routes and locate higher ground you can reach in a matter of minutes.

Figure 2. Beach communities such as this one south of Ocean City near Grays Harbor could be vulnerable to a tsunami. Campers would have little time to evacuate a site like this in the event of a locally generated tsunami. Accounts of the impact of the 1964 Alaska tsunami report "mobile campers overturned" (Lander and Lockridge, 1989) and driftlogs flying like matchsticks.

Figure 3. The bridge in the center background at Pacific Beach was damaged by the 1964 tsunami that originated in Alaska. Damage from that event was more common along estuaries than along the open coasts of Oregon and Washington.

Whether evacuating in response to local strong shaking or in response to official warnings of a tsunami from distant quakes, do not return to the beach or low-lying area until you have official word that it is safe to do so.

Never wait along the beach or shoreline estuary to watch a tsunami come ashore. These waves move much faster than you can run or even drive, and runup elevations are unpredictable.

Mountainous Locations

Campers and hikers in a mountain valley may face different, but no less urgent problems after an earthquake. Many of these situations were illustrated by events during and following the 1959 Hebgen Lake earthquake, which was centered north of Yellowstone Park. Rockslides buried some campgrounds, and rolling boulders damaged other sites. Along one lake, segments of the shoreline were repeatedly flooded by the to-and-fro sloshing of the lake water (waves called seiches).

A landslide into a lake can also cause violent wave action. For example, the 1946 Vancouver Island quake triggered a slide that generated an 80-foot wave on one lake there. The prehistoric landslide that separated the single ancestral lake into Lakes Sutherland and Crescent on the north side of the Olympic Peninsula (Tabor, 1987) no doubt created similar havoc.

Landslide dams commonly result from major earthquakes. Drainages can be blocked by rock and debris that collapse into narrow valleys from adjacent slopes. The Hamma Hamma River, in the eastern Olympic Mountains, was blocked in prehistoric times by a landslide that may have been quake-triggered (Schuster and others, 1992). The 1959 Hebgen Lake earthquake triggered a very large landslide that dammed the Madison River, and campers had to flee the rapidly rising backed-up water.

If you are camped near a stream and, after experiencing a quake, you notice significant changes in its flow, slide damming has almost certainly occurred. Flooding above such a landslide dam may be relatively slow and is seldom as dangerous as the sudden downstream flooding that occurs if (or, more properly, when) such a dam is overtopped or breached. Dam-break floods can cause devastation for miles downstream.

Safety Suggestions:

If you feel an earthquake when in the mountains, your urge to flee the area must be tempered with an assessment of your particular situation. What are the current and potential hazards where you are? Could they be worse at your destination or along the way? For example, one family, fleeing in the dark after the Hebgen Lake quake, drove off a slide scarp that had cut the highway. (They were able to walk back to their motel.) Whether you are on a mountain logging road or U.S. Highway 101, car travel after a major earthquake will require caution. Sections of road may be gone (Fig. 4), others covered by slides and boulders. Aftershocks could bring more of the same, possibly trapping travelers in a worse location than that from which they fled.

Are the bridges safe? Some bridges may ride out a quake undamaged, but spreading and settlement of adjacent fills may leave concrete walls or 'launching ramps' at either approach (Fig. 5). Don't assume that highway crews have been able to reach the area and place warnings! They will have plenty of other problems, and yours will be of low priority compared to those in and near population centers.

Figure 4. Road damage like this is typical of the aftermath of an earthquake. Four-wheel drive is seldom of benefit in such a setting. Travel at night in these situations can be especially hazardous.

Figure 5. Bridge-approach fills commonly compact and settle during an earthquake, even though the bridge itself may be undamaged. Here, settlement has created a 'launching ramp' for cars. Elsewhere, settlement can create vertical concrete walls. This example is from the 1971 San Fernando, California, earthquake.

General Safety Preparations

Some of the best preparation for an earthquake in coastal or mountainous areas is in your head—you will never know where you will be when one happens. Review emergency plans with your companions when you get to your recreation destination. Especially for children, this can be an exercise in natural history, like the local geology, plants, and animals. It needn't be frightening. Remember, no one has ever been shaken to death by an earthquake—it is the side-effects of the shaking that you need to be concerned about.

Bring along some emergency supplies and leave some in your vehicle: first aid equipment, food, water, and warm clothing, battery-operated radio, flashlights. And if you have one along, a bicycle can be useful for getting past damaged sections of road or fallen trees. Monitor your car or portable radio to get information, but don't expect much the first day. Plan on being on your own for as long as three days.

A better understanding of what happens during earthquakes and awareness of what may happen next in any setting can go a long way toward dispelling irrational fears or avoiding spoiling your trip.

Selected References

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Atwater, B. F.; Yamaguchi, D. K., 1991. Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington State: Geology, v. 19, no. 7, p. 706-709.

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Manson, C. J., 1994, Tsunamis on the Pacific Coast of Washington State and adjacent areas—An annotated bibliography and dictionary: Washington Division of Geology and Earth Resources Open File Report 94-5, 18 p.

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Tabor, R. W., 1987, Geology of Olympic National Park: Pacific Northwest National Parks and Forests Assoc. [Seattle], 144 p. ■

This article was developed from an article in *The Port Townsend Leader* (Nov. 11, 1992).

Northwest Mining Association CONVENTION, SHORT COURSE, AND TRADE SHOW

Spokane, Washington
Nov. 28–Dec. 2, 1994
Sheraton Hotel

Convention (Nov. 29–Dec. 2):
NWMA-1994, the Northwest Mining Association's 100th annual convention will consider the progress of mining during the past century, and where it is going in the next century, with many timely topics, practical authorities, and an international flavor.

Short Course (Nov. 28 & 29):
Hydrothermal Alteration in Base and Precious Metals
Contributors will present the geology, geochemistry, geophysics, and recent case histories of this internationally important subject.

Exposition (Nov. 30–Dec. 2):
The exposition will have more than 100 exhibitors of products and services for the mining industry.

Guest Program Events: Activities planned for the spouses of participants include two special tours: Historic Spokane's 'Age of Elegance', which will take you on a tour of the rich history and attractions of Spokane, and the Art and Wine Tour, which will visit several local art galleries and wineries.

Registration: Registration deadline is Nov. 11, 1994.

For more information, contact: NWMA, N. 10 Post, Suite 414, Spokane, WA 99201. Phone: (509) 624-1158; Fax: (509) 623-1241.

Geoscience Information Society 1994 Annual Meeting

The Geoscience Information Society (GIS) will hold its 29th annual meeting in conjunction with that of the Geological Society of America (GSA) in Seattle, Oct. 23–27.

In 1994, GSA will be looking at geology at 'the leading edge'. In its symposium "Changing Gateways: The Impact of Technology on Geoscience Information Exchange", GIS will consider not only technological changes, but how they impact the individuals, societies, and organizations that deal with the exchange of geoscience information.

Steve Park (Southern California Earthquake Center, UC Riverside) will discuss geographic information systems as they relate to earthquake hazard mapping for use by public agencies.

Invited speakers will discuss geoscience publishing philosophy and the future, policy changes for government information access, the changing nature of bibliography compilation and of information centers, effects of technology on the information-seeking behavior of geoscientists, electronic journals and electronic publishing issues, and the balance between technology and scientific creativity. GIS will also sponsor a volunteered paper session and a poster session.

The annual Database Forum covers current developments in digital geoscience resources, including online, tape, floppy, and CD-ROM products. The GIS exhibit booth will provide an interactive Internet demonstration featuring earth science resources.

During the Collection Development meeting, Celia Wagner of Blackwell North America will discuss science monograph publishing trends and pricing. The GeoRef Users Group will sponsor a workshop on the new Windows version of the GeoRef Silver Platter CD-ROM product, in addition to its usual GeoRef Users Group meeting.

The Geoscience Information Society is an international nonprofit professional society established in 1965 to improve the exchange of geocience information. To achieve this goal, GIS encourages interaction and cooperation among scientists, librarians, editors, cartographers, educators, and information professionals. GIS is a member society of the American Geological Institute and an associate society of the Geological Society of America.

For more information, contact:

Barbara Haner, 1994 GIS Program Chair,
Physical Science Library
University of California
Riverside, CA 92517-5900
Phone: (909) 787-3511
Internet: haner@ucrac1.ucr.edu.

Progress on the State Geologic Map

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Since I last reported on state geologic map progress in December 1992 (Schuster, 1992), there have been several developments.

First, we have nearly completed the 1:100,000-scale geologic maps for the southeast quadrant of Washington. Priest Rapids, Connell, and the east half of Yakima will be completed shortly. Figure 1 shows these reports, previous 1:100,000 maps issued by the Division in the southwest and northeast quadrants, and U.S. Geological Survey 1:100,000 maps in the Cascades. Modern 1:100,000-scale geologic maps are now available for about 85 percent of Washington.

Second, Division staff have finished preliminary compilations for all of the northwest quadrant 1:100,000 quadrangles, except for quadrangles for which recent U.S. Geological Survey maps exist. Field and office work is continuing this summer in an effort to complete the northwest-quadrant maps by the summer of 1995. We hope to have the full-color 1:250,000 northwest quadrant geologic map printed by mid-1996. Compilation assignments for the northwest quadrant are shown in Table 1.

Third, I completed a 1:250,000-scale draft geologic map of the southeast quadrant last year. I will bring it up to date in the coming months so we can begin cartographic preparation of the map for printing. Our intent is to have the southeast quadrant map ready for distribution in about a year. We still do not have the funds to print this map, but we are proceeding in faith that the resources will be found.

Table 1. Compilation assignments for the northwest quadrant of the state geologic map. References (in parentheses) are to published 1:100,000-scale quadrangles; these will be 'translated' into the Division's system for representing the geologic units and updated with more recent geologic data. Tabor and Cady (1978) is an important source of geologic map data for all or parts of the Cape Flattery, Forks, Mount Olympus, Port Angeles, Port Townsend, and Shelton 1:100,000-scale quadrangles.

1:100,000-scale quadrangle	Compiler
Bellingham	Pat Pringle
Cape Flattery	Hank Schasse
Chelan (west half)(Tabor and others, 1987)	Joe Dragovich
Forks	Wendy Gerstel
Mount Baker (Tabor and others, 1994)	Dave Norman
Mount Olympus	Wendy Gerstel
Port Angeles	Hank Schasse
Port Townsend (Pessl and others, 1989; Whetten and others, 1988)	Hank Schasse
Robinson Mountain (west half)(Stoffel and McGroder, 1990)	Joe Dragovich
Roche Harbor	Josh Logan
Sauk River (Tabor and others, 1988)	Hank Schasse
Seattle (Yount and others, 1991, 1993)	Tim Walsh
Shelton (north half)	Josh Logan
Skykomish River (Tabor and others, 1993)	Joe Dragovich
Snoqualmie Pass (north half)(Frizzell and others, 1984)	Joe Dragovich
Tacoma (north half)	Tim Walsh
Twisp (west half)	Joe Dragovich
Wenatchee (northwest quarter) (Tabor and others, 1982)	Tim Walsh

Fourth, Division geologists are working on the first two contracts from the U.S. Geological Survey in their STATEMAP program, which is going forward under the National Geologic Mapping Act of 1992. These contracts are allowing Josh Logan and Pat Pringle to acquire age and chemical data for poorly constrained geologic units in the Roche Harbor and Bellingham quadrangles and Joe Dragovich to do field mapping and analytical work in the west half of the Twisp quadrangle.

Finally, the Division is making progress toward converting the 1:100,000-scale geologic maps into a statewide geographic information system coverage in ARC-INFO. So far, the Richland and Priest Rapids quadrangles have been almost completed under a contract from the Washington State Department of Ecology, and we have completed digitizing the Chehalis River, Centralia, Westport, Ilwaco, and Astoria quadrangles. We are now searching for the resources to get all of the maps converted to digital form within two or three years.

Geologic Maps of Washington at 1:100,000 and 1:250,000 scales

Quadrant maps at 1:250,000

Stoffel, K. L.; Joseph, N. L.; Waggoner, S. Z.; Gulick, C. W.; Bunning, B. B., 1991, Geologic map of Washington—Northeast quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-39, 36 p., 1 plate, and two accompanying explanatory sheets, including a bedrock geologic and tectonic map at 1:625,000 scale. (GM-39)

Walsh, T. J.; Korosec, M. A., Phillips, W. M.; Logan, R. L.; Schasse, H. W., 1987, Geologic map of Washington—Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, with 28 p. text. (GM-34)

Southwest quadrant 1:100,000 maps

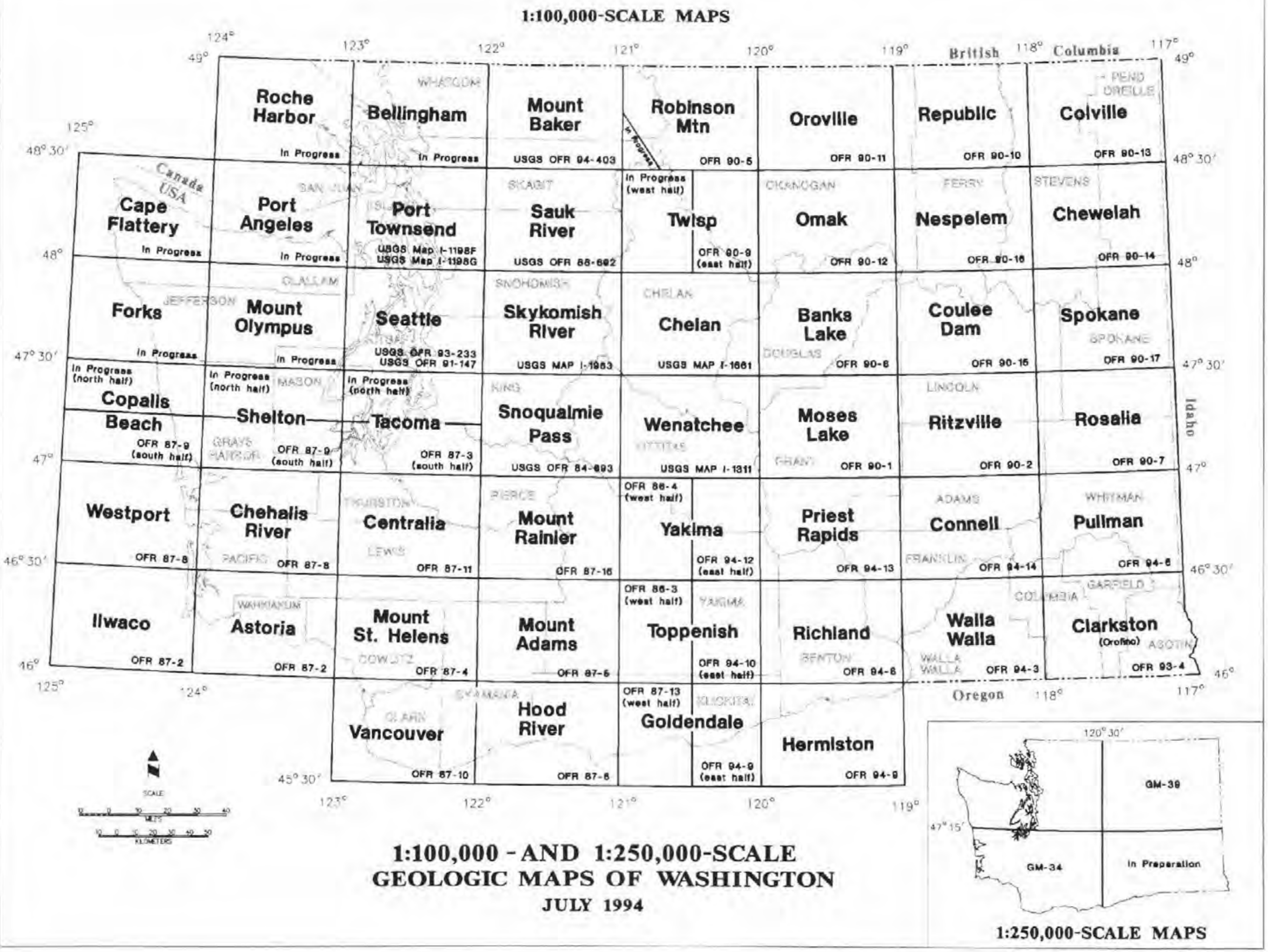
Frizzell, V. A., Jr.; Tabor, R. W.; Booth, D. B.; Ort, K. M.; Waitt, R. B., 1984, Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 84-693, 43 p., 1 plate. (USGS OFR 84-693)

Korosec, M. A., compiler, 1987, Geologic map of the Hood River quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-6, 40 p., 1 plate. (OFR 87-6)

Korosec, M. A., compiler, 1987, Geologic map of the Mount Adams quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-5, 39 p., 1 plate. (OFR 87-5)

Logan, R. L., compiler, 1987, Geologic map of the Chehalis River and Westport quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-8, 16 p., 1 plate. (OFR 87-8)

Logan, R. L., compiler, 1987, Geologic map of the south half of the Shelton and south half of the Copalis Beach quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-9, 15 p., 1 plate. (OFR 87-9)



1:100,000 - AND 1:250,000-SCALE GEOLOGIC MAPS OF WASHINGTON

JULY 1994

Phillips, W. M., compiler, 1987, Geologic map of the Mount St. Helens quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-4, 48 p., 1 plate. (OFR 87-4)

Phillips, W. M., 1987, Geologic map of the Vancouver quadrangle, Washington [and Oregon]: Washington Division of Geology and Earth Resources Open File Report 87-10, 27 p., 1 plate. (OFR 87-10)

Phillips, W. M.; Walsh, T. J., compilers, 1987, Geologic map of the northwest part of the Goldendale quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-13, 7 p., 1 plate. (OFR 87-13)

Schasse, H. W., compiler, 1987, Geologic map of the Centralia quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-11, 27 p., 1 plate. (OFR 87-11)

Schasse, H. W., compiler, 1987, Geologic map of the Mount Rainier quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-16, 43 p., 1 plate. (OFR 87-16)

Tabor, R. W.; Waitt, R. B.; Frizzell, V. A.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 26 p., 1 plate. (USGS Map I-1311)

Walsh, T. J., compiler, 1987, Geologic map of the Astoria and Ilwaco quadrangles, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-2, 28 p., 1 plate. (OFR 87-2)

Walsh, T. J., compiler, 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-3, 10 p., 1 plate. (OFR 87-3)

Walsh, T. J., compiler, 1986, Geologic map of the west half of the Toppenish quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 86-3, 7 p., 1 plate. (OFR 86-3)

Walsh, T. J., compiler, 1986, Geologic map of the west half of the Yakima quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 86-4, 9 p., 1 plate. (OFR 86-4)

Northeast Quadrant 1:100,000 maps

Bunning, B. B., compiler, 1990, Geologic map of the east half of the Twisp 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-9, 52 p., 1 plate. (OFR 90-9)

Gulick, C. W., compiler, 1990, Geologic map of the Moses Lake 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-1, 9 p., 1 plate. (OFR 90-1)

Gulick, C. W., compiler, 1990, Geologic map of the Ritzville 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-2, 7 p., 1 plate. (OFR 90-2)

Gulick, C. W.; Korosec, M. A., compilers, 1990, Geologic map of the Banks Lake 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-6, 20 p., 1 plate. (OFR 90-6)

Gulick, C. W.; Korosec, M. A., compilers, 1990, Geologic map of the Omak 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-12, 52 p., 1 plate. (OFR 90-12)

Joseph, N. L., compiler, 1990, Geologic map of the Colville 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-13, 78 p., 1 plate. (OFR 90-13)

Joseph, N. L., compiler, 1990, Geologic map of the Nespelem 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-16, 47 p., 1 plate. (OFR 90-16)

Joseph, N. L., compiler, 1990, Geologic map of the Spokane 1:100,000 quadrangle, Washington–Idaho: Washington Division of Geology and Earth Resources Open File Report 90-17, 29 p., 1 plate. (OFR 90-17)

Stoffel, K. L., compiler, 1990, Geologic map of the Oroville 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-11, 58 p., 1 plate. (OFR 90-11)

Stoffel, K. L., compiler, 1990, Geologic map of the Republic 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-10, 62 p., 1 plate. (OFR 90-10)

Stoffel, K. L.; McGroder, M. F., compilers, 1990, Geologic map of the Robinson Mtn. 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-5, 39 p., 1 plate. (OFR 90-5)

Tabor, R. W.; Frizzell, V. A., Jr.; Whetten, J. T.; Waitt, R. B.; Swanson, D. A.; Byerly, G. R.; Booth, D. B.; Hetherington, M. J.; Zartman, R. E., 1987, Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1661, 1 sheet, scale 1:100,000, with 29 p. text. (USGS Map I-1661)

Tabor, R. W.; Waitt, R. B.; Frizzell, V. A.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 26 p., 1 plate. (USGS Map I-1311)

Waggoner, S. Z., compiler, 1990, Geologic map of the Chewelah 1:100,000 quadrangle, Washington–Idaho: Washington Division of Geology and Earth Resources Open File Report 90-14, 63 p., 1 plate. (OFR 90-14)

Waggoner, S. Z., compiler, 1990, Geologic map of the Coulee Dam 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-15, 40 p., 1 plate. (OFR 90-15)

Waggoner, S. Z., compiler, 1990, Geologic map of the Rosalia 1:100,000 quadrangle, Washington–Idaho: Washington Division of Geology and Earth Resources Open File Report 90-7, 20 p., 1 plate. (OFR 90-7)

Figure 1. *(facing page)* 1:100,000- and 1:250,000-scale geologic maps of Washington, as of July 1994. 1:100,000-scale maps are shown on the larger map and the 1:250,000-scale quadrant maps are shown on the inset. If no 1:100,000 map is yet available, the quadrangle is shown as 'In Progress'. Each 1:100,000 quadrangle map and 1:250,000 quadrant map is identified by its report number. All U.S. Geological Survey reports shown on this map have the prefix USGS. USGS maps (for example, USGS Map I-1198F) can be purchased from: USGS, 904 W. Riverside, Rm. 135, Spokane, WA 99201. USGS open-file reports (for example, USGS OFR 84-693) can be purchased from: USGS ESIC, Open-File Report Section, Box 25286, MS 517, Denver Federal Center, Denver, CO 80225. Information about prices of these USGS products can be obtained from those addresses. All OFRs without the USGS prefix and the two 1:125,000-scale quadrant maps (GMs) are products of the Washington Division of Geology and Earth Resources and can be purchased from the Division at the address given on p. 2. Contact the Division for information about prices.

Southeast quadrant 1:100,000 maps

Gulick, C. W., compiler, 1990, Geologic map of the Moses Lake 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-1, 9 p., 1 plate. (OFR 90-1)

Gulick, C. W., compiler, 1990, Geologic map of the Ritzville 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-2, 7 p., 1 plate. (OFR 90-2)

Gulick, C. W., compiler, 1994, Geologic map of the Connell 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-14, 18 p., 1 plate. (OFR 94-14)

Gulick, C. W., compiler, 1994, Geologic map of the Pullman 1:100,000 quadrangle, Washington–Idaho: Washington Division of Geology and Earth Resources Open File Report 94-6, 23 p., 1 plate. (OFR 94-6)

Reidel, S. P.; Fecht, K. R., compilers, 1994, Geologic map of the Priest Rapids 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-13, 22 p., 1 plate. (OFR 94-13)

Reidel, S. P.; Fecht, K. R., compilers, 1994, Geologic map of the Richland 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-8, 21 p., 1 plate. (OFR 94-8)

Schuster, J. E., compiler, 1993, Geologic map of the Clarkston 1:100,000 quadrangle, Washington–Idaho, and the Washington portion of the Orofino 1:100,000 quadrangle: Washington Division of Geology and Earth Resources Open File Report 93-4, 43 p., 1 plate. (OFR 93-4)

Schuster, J. E., compiler, 1994, Geologic map of the east half of the Toppenish 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-10, 15 p., 1 plate. (OFR 94-10)

Schuster, J. E., compiler, 1994, Geologic map of the east half of the Yakima 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-12, 22 p., 1 plate. (OFR 94-12)

Schuster, J. E., compiler, 1994, Geologic map of the Walla Walla 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 94-3, 18 p., 1 plate. (OFR 94-3)

Schuster, J. E., compiler, 1994, Geologic maps of the east half of the Washington portion of the Goldendale 1:100,000 quadrangle and the Washington portion of the Hermiston 1:100,000 quadrangle: Washington Division of Geology and Earth Resources Open File Report 94-9, 17 p., 1 plate. (OFR 94-9)

Tabor, R. W.; Waitt, R. B.; Frizzell, V. A.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 26 p., 1 plate. (USGS Map I-1311)

Waggoner, S. Z., compiler, 1990, Geologic map of the Rosalia 1:100,000 quadrangle, Washington–Idaho: Washington Division of Geology and Earth Resources Open File Report 90-7, 20 p., 1 plate. (OFR 90-7)

Northwest Quadrant 1:100,000 maps

Frizzell, V. A., Jr.; Tabor, R. W.; Booth, D. B.; Ort, K. M.; Waitt, R. B., Jr., 1984, Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 84-693, 43 p., 1 plate. (USGS OFR 84-693)

Pessl, Fred, Jr.; Dethier, D. P.; Booth, D. B.; Minard, J. P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-F, 1 sheet, scale 1:100,000, with 13 p. text. (USGS Map I-1198-F)

Stoffel, K. L.; McGroder, M. F., compilers, 1990, Geologic map of the Robinson Mtn. 1:100,000 quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-5, 39 p., 1 plate. (OFR 90-5)

Tabor, R. W.; Booth, D. B.; Vance, J. A.; Ford, A. B.; Ort, M. H., 1988, Preliminary geologic map of the Sauk River 30 by 60 minute quadrangle, Washington: U. S. Geological Survey Open-File Report 88-692, 50 p., 2 plates. (USGS OFR 88-692)

Tabor, R. W.; Frizzell, V. A., Jr.; Booth, D. B.; Waitt, R. B.; Whetten, J. T.; Zartman, R. E., 1993, Geologic map of the Skykomish River 30- by 60-minute quadrangle, Washington: U. S. Geological Survey Miscellaneous Investigations Series Map I-1963, 1 sheet, scale 1:100,000, with 42 p. text. (USGS Map I-1963)

Tabor, R. W.; Frizzell, V. A., Jr.; Whetten, J. T.; Waitt, R. B.; Swanson, D. A.; Byerly, G. R.; Booth, D. B.; Hetherington, M. J.; Zartman, R. E., 1987, Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1661, 1 sheet, scale 1:100,000, with 29 p. text. (USGS Map I-1661)

Tabor, R. W.; Haugerud, R. A.; Booth, D. B.; Brown, E. H., 1994, Preliminary geologic map of the Mount Baker 30- by 60-minute quadrangle, Washington: U. S. Geological Survey Open File Report 94-403, 1 sheet, with 54 p. text. (USGS OFR 94-403)

Tabor, R. W.; Waitt, R. B.; Frizzell, V. A.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1311, 26 p., 1 plate. (USGS Map I-1311)

Whetten, J. T.; Carroll, P. I.; Gower, H. D.; Brown, E. H.; Pessl, Fred, Jr., 1988, Bedrock geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1198-G, 1 sheet, scale 1:100,000. (USGS Map I-1198-G)

Yount, J. C.; Gower, H. D., 1991, Bedrock geologic map of the Seattle 30′ by 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, 37 p., 4 plates, scale 1:100,000. (USGS OFR 91-147)

Yount, J. E.; Minard, J. P.; Dembroff, G. R., 1993, Geologic map of surficial deposits in the Seattle 30′ by 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 93-233, 2 sheets, scale 1:100,000. (USGS OFR 93-233)

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Tabor, R. W.; Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000. ■

BLM Moves Spokane Office

The Spokane Office of the U.S. Bureau of Land Management has moved to:

U.S. Bureau of Land Management
Spokane District Office
1103 N. Fancher
Spokane, WA 99212-1275
(509) 536-1200

Low-Temperature Geothermal Resources of Washington

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About 2 years ago, the U.S. Department of Energy (USDOE) received funding from Congress to update databases for low-temperature geothermal resources of the western states. USDOE awarded a contract, by way of the University of Utah Research Institute and the Oregon Institute of Technology Geo-Heat Center, to the Division of Geology and Earth Resources (DGER) to update the geothermal database for Washington. DGER, in turn, awarded a small contract to the Washington State Energy Office (WSEO), and this enabled our two organizations to continue their long joint interest in assessing and encouraging the use of Washington's geothermal resources.

The only previous assessment of Washington's geothermal resources was published in 1981, as DGER Geologic Map GM-25 (Korosec and others, 1981), a 1:500,000-scale map showing the distribution of thermal (at or above 20°C or 68°F) springs and wells in the state and a tabulation of basic information about them. Publication of this map was also funded by USDOE. GM-25 reported on 31 thermal springs, 29 mineral springs, and 338 thermal wells. The thermal and mineral springs are, for the most part, located in the Cascade Mountains, and many are associated with stratovolcanoes. Most of the thermal wells are located in the Columbia Basin.

The new geothermal assessment, which has just been released as Washington Division of Geology and Earth Resources Open File Report 94-11 (Schuster and Bloomquist, 1994), reports on 34 thermal springs and 941 thermal wells (Fig. 1). The springs and wells are located in the same geographic areas as reported in GM-25. The numbers indicate that we have not found many new springs since 1981, but we now have data on almost three times as many thermal wells. The increase is due to two factors: first, we consulted an important source of data that had not been consulted for the 1981 report, and second, there have been many wells drilled since 1981. The new source of data is the unpublished water well reports held in the Yakima and Spokane regional offices of the Washington State Department of Ecology.

In 1981, the focus was on high-temperature geothermal resources that could be used to generate electricity. Since then it has become clear that the high-temperature geothermal resources of the Cascade Range are difficult to evaluate and would be very difficult to develop. Now the focus is on low-temperature geothermal resources, particularly those that could be used with water-source heat pumps to heat buildings. These lower temperature geothermal resources are overwhelmingly (97 percent) located in the Columbia Basin. Further, within the Columbia Basin, just six counties contain 83.5 percent of Washington's thermal wells. They are Adams (113 wells), Benton (123), Franklin (60), Grant (118), Walla Walla (113), and Yakima (259).

Most of Washington's thermal wells are 100 to 500 m (328–1,640 ft) deep; water temperatures range between 20°C and 32°C (68–90°F). The wells are quite dilute chemically, with an average total concentration of only 260 parts per million for Na, K, Ca, Mg, HCO_3, CO_3, Cl, and SO_4.

A few wells have been developed as heat sources for heat pumps. The most notable uses are, perhaps, heating the Grant County Courthouse in Ephrata and the Yakima County Detention Center in Yakima.

The water used to heat the Grant County Courthouse passes from the Courthouse heat exchanger into the Ephrata city water system and is consumed by humans. This usage was approved over a decade ago, but there still seems to be some confusion on the part of regulatory agencies over whether such a practice constitutes a threat to public health. There has been no public health problem with the Ephrata system. In addition, a water right is required in order to appropriate water for a source of heat, and the Washington State Department of Ecology is currently 3-4 years behind in adjudicating water rights. In some areas of Washington further development of shallow ground water is not being allowed because the shallow waters are deemed to have been fully allocated. These seem to be the major legal and institutional barriers to significant development of low-temperature geothermal resources in Washington.

We think Washington's low-temperature geothermal resources are located in the Columbia Basin, and especially in the six counties noted above, for several reasons.

- There are more deep wells in the six-county area than in many other parts of the State, and this provides more opportunity for penetration of thermal aquifers.
- At 41°C/km (2.3°F/100 ft), the regional geothermal gradient is higher than for any other part of Washington except for the high heat-flow areas of the Cascade Range.
- The hydrologic setting is favorable. Laterally extensive aquifers of the Columbia River Basalt Group and associated inter-flow sedimentary deposits, low vertical permeability, complex basinal structural shape, and recharge areas to the west and far to the east provide for the depth of circulation and residence time necessary to produce thermal ground water.

The geologic setting does not suggest that there are local sources of heat, such as cooling magma chambers, to account for the thermal wells in the Columbia Basin.

We recommend the following to encourage use of Washington's low-temperature geothermal resources:

- Match existing thermal wells, especially publicly owned wells that produce large quantities of water year-round under existing water rights, with closely collocated proposed new construction or remodeling of public buildings, such as

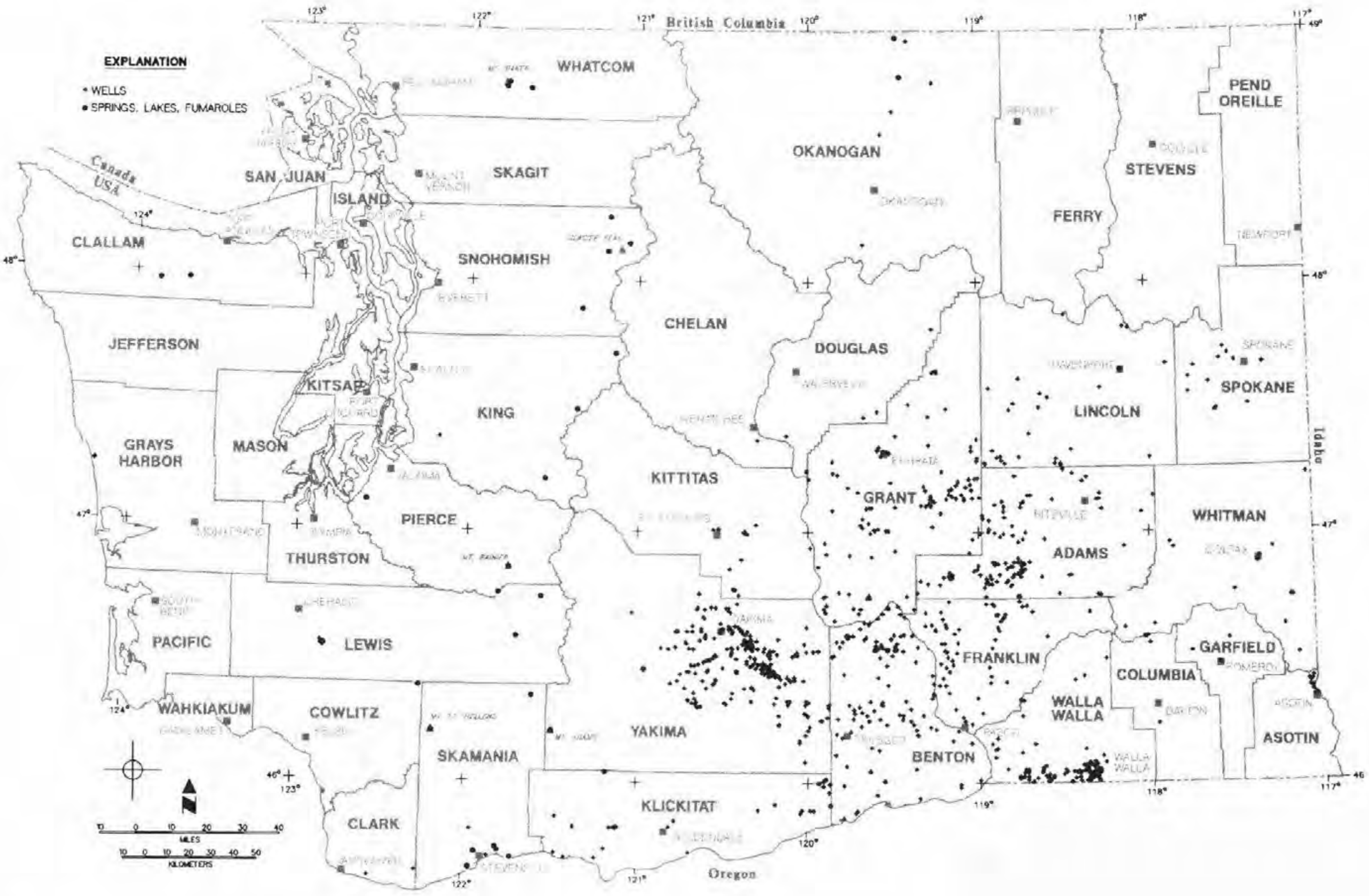

Figure 1. Low-temperature geothermal resources of Washington.

schools. Determine which projects could make advantageous use of the geothermal resource to heat and (or) cool the building, and encourage and facilitate such applications. These actions would lead to significant development of geothermal resources with little drilling or exploration and minimal conflict with the current legal and institutional setting.

- Station one or two investigators in the Columbia Basin to measure downhole temperature gradients, obtain well-test data, obtain drill cuttings for measurement of thermal conductivity and geochemistry, and collect water samples for chemical analysis. This work would better define the regional and local distribution of heat flow and temperature gradients, better define the chemistry and stratigraphy of the deeper aquifers, build accurate statistics about the volumes and temperatures of water available from wells, and assist formulation of exploration strategies that would minimize unproductive drilling.
- Institute a long-term effort to inform the people of the state about uses of low-temperature geothermal resources, work with public policy makers to make certain that the legal and institutional framework encourages wise use of low-temperature geothermal resources, and advocate for use of geothermal resources in place of fossil fuels.

DGER Open File Report 94-11 is available in paper form or on disk from the Division of Geology and Earth Resources at the main DGER office address listed above for author Schuster. The database is available as geographic information system ARC-INFO files from the Washington State Energy Office. Contact WSEO at the address given for author Bloomquist above.

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Schuster, J. E.; Bloomquist, R. G., 1994, Low-temperature geothermal resources of Washington: Washington Division of Geology and Earth Resources Open File Report 94-11, 53 p. 2 plates, scales 1:1,000,000, and 1:500,000. ■

The 1st Symposium on the Hydrogeology of Washington State

August 28–30, 1995
The Evergreen State College
Olympia, Washington

The Washington State Department of Ecology is hosting a three-day symposium on the Hydrogeology of Washington State. The symposium will include formal oral and poster presentations covering a wide variety of subdisciplines, including hydrogeochemistry, hydrology, physical hydrogeology, and applied science and technology.

The national and worldwide ground-water and hydrologic science community is invited to participate, including businesses, engineering/environmental consulting firms, universities, government agencies, tribes, and other groups. Students will be provided travel/lodging scholarships on request on a first-come, first-served basis. Dormitory lodging will be available for all attendees.

Abstracts for oral and poster presentations must be double-spaced and 450 words or less. Abstract deadline is Feb. 30, 1995. Authors of accepted papers will be notified by April 30, 1995. An abstract and proceedings volume will be published for the symposium.

For information, contact: Nadine Romero, Symposium Chair, Dept. of Ecology, PO Box 47600, Olympia, WA 98504-7600. Phone: 206-407-6116; Fax: 206-407-6102.

Gold Mining Companies Pledge $120,000 to National Park Foundation

When five Americans won six gold medals at the Lillehammer Olympic games, they earned more than respect. They also earned $120,000 for our national parks, a contribution by six gold mining companies in their honor.

"We pledge this gift to the National Park Foundation on behalf of our hard-working athletes and as a way to express our appreciation for the important educational and environmental role that our national parks play," said Richard C. Kraus, president of Echo Bay Mines. "The gold mining industry feels a responsibility to enhance public lands, and this is one way in which to demonstrate our commitment."

The 367 national parks have urgent needs ranging from deteriorating trails to limited staffing to campsites in need of repair. While federal funding has been reduced, the parks have seen more use.

"The contribution is a fine example of the type of entrepreneurial response that is needed to meet the national parks' mounting needs," said Alan A. Rubin, president of the National Park Foundation.

In addition to Echo Bay Mines, the other contributing gold mining companies are Amax Gold Inc., American Barrick Resources Corporation, Independence Mining Co. Inc., Newmont Mining Corporation, and Santa Fe Pacific Gold Corporation. These companies produce about one-half the gold mined in the United States.

The National Park Foundation is the official nonprofit partner of the National Park Service. The foundation was chartered by Congress in 1967 to channel private resources into the parks. The Foundation awards $2 million in grants each year to support education, visitor services, and volunteer activities to preserve and enhance the parks.

From a March 4 news release from Echo Bay Mines, operator of mines and a mill in Republic, WA.

Selected Additions to the Library of the Division of Geology and Earth Resources

July 1994

THESIS

Gridley, J. M., 1993, Crustal structure of western Washington State: University of Texas at El Paso Doctor of Philosophy thesis, 232 p.

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Fuhrer, G. J.; McKenzie, S. W.; Rinella, J. F.; Sanzolone, R. F.; Skach, K. A., 1994, Surface-water-quality assessment of the Yakima River basin in Washington—Analysis of major and minor elements in fine-grained streambed sediment, 1987: U.S. Geological Survey Open-File Report 93-30, 131 p., 3 pl.

Includes:

Gannett, M. W., 1994, Assessment approach—Geologic classification of lower order stream-sampling sites, p. 28-31.

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Smith, Charles; Furukawa, Cindy, 1994, Introduction to earthquake retrofitting—Tools and techniques: Building Education Center [Berkeley, Calif.], 77 p. ■

Staff Notes

David K. Norman has been promoted from Geologist 3 to Geologist 4, Chief Reclamationist.

Lorraine Powell is the new Geologist 2 for the Southeast Region, working out of Ellensburg. Lorraine has a B.S. in geology and a B.S. in education from Central Washington University and an M.S. in mineral exploration geology from the University of Idaho College of Mines. She has worked in the western states and Alaska in copper, molybdenum, lead, zinc, and gas exploration. Prior to joining the Division, she taught math and science for 3 years at Naches Middle School, evidence of her continuing concern for good science teaching in the public schools.

Carl F. T. Harris has been promoted from Cartographer 2 to Computer Information Consultant.

Jaretta M. (Jari) Roloff has been promoted from Editorial Assistant to Geologist 2/Editor.

Penny Dow has come on board as temporary Clerk Typist 2. Her previous assignment was temporary Clerk Typist 3 with DSHS Developmental Disabilities office.

Smithsonian Fellowships and Internships Available

The Smithsonian Institution has announced its 1995 research fellowships in the earth sciences. Smithsonian fellowships are awarded to support independent research in residence at the Smithsonian in association with the research staff and using the Institution's resources.

Under this program, senior, postdoctoral, predoctoral, and graduate student fellowships are awarded on the basis of merit. The fellowships are open to all qualified individuals without reference to race, color, religion, sex, national origin, age, or condition of handicap of any applicant. Proposals for research may be made in meteoritics, mineralogy, paleobiology, petrology, planetary geology, sedimentology, and volcanology. The application deadline is Jan. 15, 1995.

Fellowships

Postdoctoral fellowships are open to scholars who have held the degree or equivalent for less than 7 years, and senior fellowships to those who have had the degree or equivalent for 7 years or more. The term is 3 to 12 months. Both fellowships offer a stipend of $25,000/yr plus allowances. Predoctoral fellowships are open to doctoral candidates who have completed preliminary course work and examinations. The term is 3 to 12 months; the stipend is $14,000/yr plus allowances. These stipends are prorated for periods of less than 12 months.

Graduate student fellowships are offered to students to conduct research in association with research staff members of the Smithsonian. Students must be formally enrolled in a graduate program, have completed at least one semester, and have not yet been advanced to candidacy in a Ph.D. program. The term is 10 weeks; the stipend is $3,000.

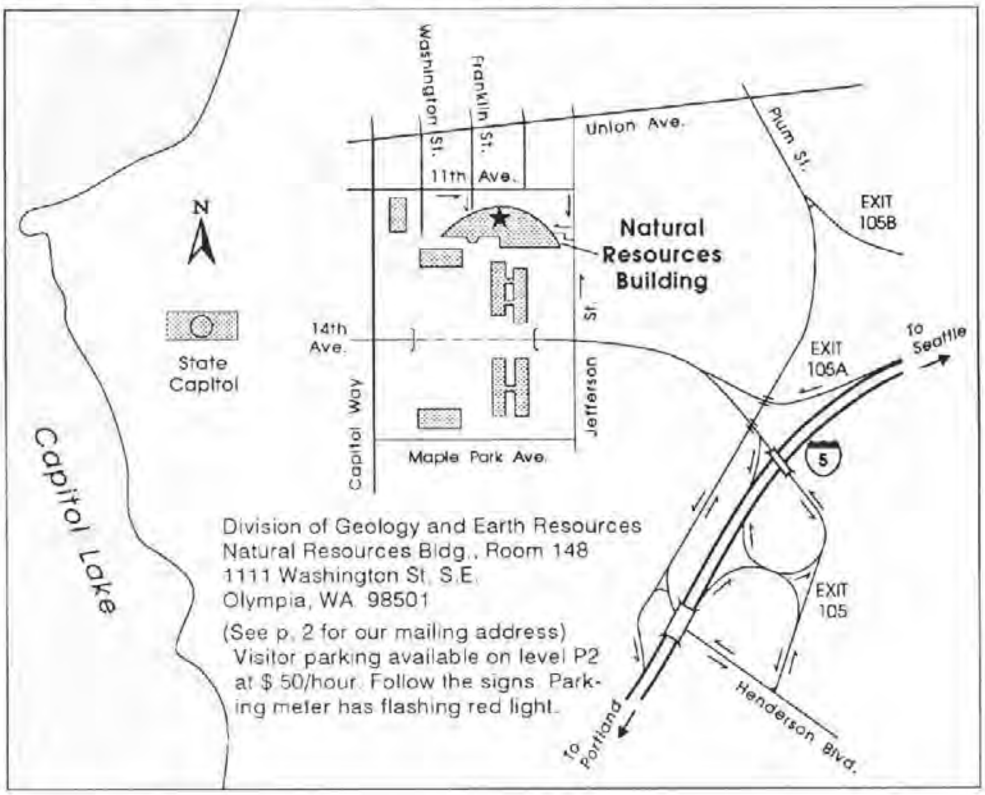
Internships

Internships are available for minority students to participate in research and museum-related activities for 9–12 weeks during the summer, fall, or spring. The appointment carries a stipend of $250/wk for undergraduates and $300/wk for graduate students and may provide a travel allowance. Deadlines: Oct. 15 for spring (to begin after Jan. 1), Feb. 15 for summer (to begin after June 1), and June 15 for fall (to begin after Sept. 1).

Application Information

For more information and application forms, write: Smithsonian Institution, Office of Fellowships and Grants, 955 L'Enfant Plaza, Suite 7000, Washington, DC 20560, or e-mail: sifg@sivm.si.edu. Indicate the area in which you propose to conduct research and give the dates of degrees received or expected.

HOW TO FIND OUR MAIN OFFICE



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(See p. 2 for our mailing address)
Visitor parking available on level P2 at $.50/hour. Follow the signs. Parking meter has flashing red light.

Wildlife Education for Teachers and Students

Washington state is losing fish and wildlife habitat, wetlands, hunting grounds, working landscape, wild space, streamside and river banks at the rate of 80 acres/day.

Washington Wild is an environmental education program designed to develop stewardship for wildlife among youth and adults. Sponsored by the Washington Department of Fish and Wildlife, the program is designed to develop awareness, knowledge, skills, and commitment that will result in informed decisions, responsible behavior, and constructive actions for wildlife and the environment.

Washington Wild programs include teacher workshops, volunteer monitoring of wildlife and habitat, environmental learning labs for schools, and $1,000 grants to enhance local stream or upland habitats. The workshops are open to K–6 and secondary teachers, as well as Campfire and Scout leaders and homeschoolers. Other education-related programs are district-sponsored in-service training, subject-area-related courses, and nature center staff training.

You may request a workshop for your area or join scheduled workshops. *Washington Wild* workshops are available through local school district curriculum directors and educational service districts.

For more information, write or call:

Washington Department of Wildlife
Washington Wild
600 Capitol Way N.
Olympia, WA 98501-1091
(206) 753-1702

The Division's Role in Environmental Regulation

Continued from p. 2

stood and must be interpreted in terms of case law and customary mining practices. (See Lingley and Norman, 1991.) For these reasons, the Division has made an aggressive effort to attend various public forums and explain the statutes to the public. Division personnel frequently speak before community action groups and at public hearings on mine-related issues.

- The Department took the lead by convening a balanced task force of experts in mine regulation including representatives from environmental groups, community action groups, industry, and other State agencies. In five meetings, this group hammered out a comprehensive rewrite of Chapter 78.44 Revised Code of Washington (RCW) that was adopted with few modifications by overwhelming votes in the Washington State House and Senate. During 1993, the Department also participated in the Metals Mining Advisory Committee to the Washington State Legislature.

On August 2, 1994, we adopted new procedural rules (Washington Administrative Code 332-18) to implement the revised surface mining statute (RCW 78.44). The rules were developed through a process of scoping meetings and public involvement, satisfying both the spirit and letter of the Regulatory Reform Act.

This year we have stepped up our efforts. Under the guidance of Commissioner of Public Lands Jennifer Belcher, the Division has reorganized to give environmental regulation greater emphasis.

A new Assistant Division Manager position was created for all regulatory programs of the Division. Bill Lingley successfully competed for this post. To meet the requirements of the Legislature, a metals mining and milling specialist position was also established to enforce the provisions of the Metals Mining and Milling Act of 1994. Dave Norman will carry out the duties of that position.

Washington State is taking a leadership role in its regulation of the extractive industries.

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Norman, D. K., 1992, Reclamation of quarries: Washington Geology, v. 20, no 4, p. 3-9.

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Division Publications

Earthquake Hypocenters in Washington and Northern Oregon, 1987–1989, and Operation of the Washington Regional Seismograph Network, Information Circular 89, by R. S. Ludwin, A. I. Qamar, S. D. Malone, C. Jonientz-Trisler, R. S. Crosson, R. Benson and S. C. Moran. This 40-page report provides a chronological compilation of earthquake locations and other information for 1987 to 1989, with a separate section containing a detailed description of how the University of Washington network operates. 13 figs., 11 tables. $1.84 + .16 tax (WA residents only) = $2.00.

Low-Temperature Geothermal Resources of Washington, Open File Report 94-11, by J. Eric Schuster and R. Gordon Bloomquist. This 53-page report has three appendices and two plates, scale 1:500,000. $4.16 + .34 tax (WA residents only) = $4.50.

Geologic Map of the East Half of the Yakima 1:100,000 Quadrangle, Washington, Open File Report 94-12, compiled by J. Eric Schuster. A 22-page text accompanies this map. $1.84 + .16 tax (WA residents only) = $2.00.

Geologic Map of the Priest Rapids 1:100,000 Quadrangle, Washington, Open File Report 94-13, compiled by Stephen P. Reidel and Karl R. Fecht. A 22-page text accompanies this map. $1.84 + .16 tax (WA residents only) = $2.00.

Geologic Map of the Connell 1:100,000 Quadrangle, Washington, Open File Report 94-14, compiled by C. W. Gulick. An 18-page text accompanies this map. $1.84 + .16 tax (WA residents only) = $2.00.

Bibliography and Index of the Geology and Mineral Resources of Washington, 1993, Open File Report 94-15, compiled by Connie J. Manson. This preliminary 102-page bibliography is $3.94 + .31 tax (WA residents only) = $4.25.

Metal Mining and the Environment—A Bibliography, Open File Report 94-16, compiled by Rebecca A. Christie. This 109-page bibliography is a compilation of materials relating to the reclamation of open-pit mines. Also available as WordPerfect 5.1 or ASCII file on MSDOS diskette (1MB); send a formatted 3.5-in. or 5.25-in diskette, which will be returned with data. Free.

Publications of the Washington Division of Geology and Earth Resources has been revised as of July. This catalog contains a complete list of Division publications, both in and out of print, and indexes by author and subject. Free.

Reprint available

A limited supply of **Geology of Seattle, Washington, United States of America** (Bulletin of the Association of Engineering Geologists, v. 28, no. 3, p. 235-302) has again been made available to the Division through the generosity of the authors, R. W. Galster and W. T. Laprade. Requests for copies will be filled on a first-come, first-served basis. These copies are free.

Please include $1.00 to cover postage and handling on each order.

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