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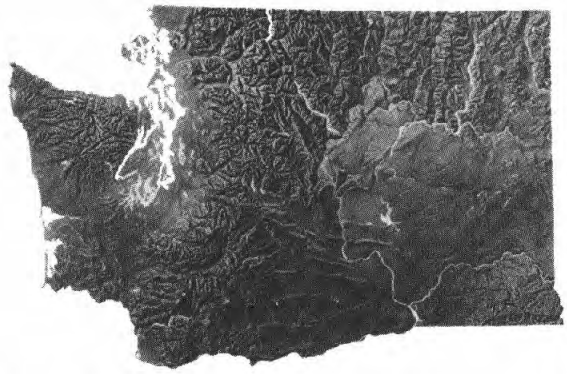

WASHINGTON GEOLOGY

VOL. 23, NO. 2
JUNE 1995

INSIDE THIS ISSUE

- Field sketches of late-1840s eruptions of Mount St. Helens, Washington, p. 3
- Preliminary observations on marine stratigraphic sequences, central and western Olympic Peninsula, Washington, p. 9
- Palm fossils from northwest Washington, p. 21
- Application of reflection seismology to the hydrogeology of the Spokane Aquifer, p. 27

WASHINGTON STATE DEPARTMENT OF
Natural Resources
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Cover Photo: Artist Paul Kane's studio painting of an eruption at Goat Rocks dome on Mount St. Helens' north-northwest flank on March 26, 1847. (Courtesy of the Royal Ontario Museum, Toronto, Canada, item 912.1.78). This is the best known early painting of Mount St. Helens. Kane may have used artistic license in adding the foreground, since we have not been able to find a similar viewpoint. The left side has been cropped to fit. (See article on p. 3.)

Goal-Based Management in the Department of Natural Resources

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During the regular 1993 Legislative session, Engrossed Substitute House Bill 1372 was passed into law. This bill established a state policy mandating that each state agency establish mission or goals statements. The bill further stated that each agency shall establish program objectives for each major program in its budget.

During 1994, under the leadership of Commissioner Jennifer Belcher, the Department of Natural Resources produced a document with four elements to guide the department toward the next century—the Commissioner's vision statement, the department's mission and guiding principles, a section for regulatory programs and service to the public, and a five-year goal statement.

The five-year goal is "to ensure that the Department of Natural Resources is recognized as the agency of choice:

- For leadership in natural resource issues
- As the model for exemplary stewardship in resource management
- As the acknowledged expert in our areas of responsibility
- As a partner with the public, other governments, other agencies, and interests
- For effective listening and communications
- As the model public agency."

As we enter the 1995–97 biennium, each unit of the department, including the Geology and Earth Resources Division, has been developing program goals and objectives that complement the department's published goals. Further, the biennium budgeting process will be linked to carrying out the goals. To facilitate this linkage, the division is fine-tuning individual tasks that will be undertaken to fulfill objectives currently under consideration.

These efforts will help us evaluate agency performance and improve our accountability. ■

Northwest Mining Association Convention Set for December 5–8, 1995

The 1995 Northwest Mining Association International Convention and Exposition is scheduled for December 5–8, 1995, at the Sheraton-Spokane Hotel, Convention & Agricultural Trade Center in Spokane, Washington. For more information, contact:

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10 N. Post Street, Suite 414
Spokane, WA 99201-0772
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Field Sketches of Late-1840s Eruptions of Mount St. Helens, Washington

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INTRODUCTION

On two occasions in September 1845, British spy Henry Warre saw and sketched watercolors of eruption columns forming over the north flank of Mount St. Helens, Washington. Yet Warre's drawings have not been widely known. No prior mention of them has been made in the scientific literature on the volcano's eruptive history. (See Pallister and others, 1992, and references cited by these authors.) This situation occurred largely because Warre's watercolors had not been published when Holmes (1955) wrote his classic paper on 19th-century accounts of Mount St. Helens activity (Holmes, 1980).

On two days in March 1847, artist Paul Kane observed eruptions from the same vent. Kane made watercolors in the field of each scene he witnessed; his second sketch includes an eruption column. Kane later used his sketches and associated journal entries as the basis for three oil paintings, one of which has been widely published and extensively studied by geologists and historians (see, for example, Hoblitt and others, 1980, and Harris, 1988). In the famous painting (see cover), the eruption has been transformed into an incandescent night eruption; other artistic embellishments include eight Native American spectators, streaming clouds of opaque smoke, and a reflection of the eruption on the surface of the water (painting previously reproduced in Holmes, 1955; Harper, 1971; Harris, 1988; and elsewhere). While the artistic nature of this painting has previously been recognized (Holmes, 1955, 1980; Majors, 1980), Kane's second field sketch and his remaining two paintings have largely been ignored. Yet, based on Kane's journal entries, these three artworks more accurately depict the scenes that he witnessed.

This article presents the field sketches of Warre, the forgotten sketch and paintings of Kane, the associated journal accounts, and related background information. We then consider the geological significance of the set as a whole.

THE FIELD SKETCHES, PAINTINGS, AND NARRATIVES

In 1845, Warre wrote in his journal (Warre, 1976):

> *Between Vancouver and the mouth of the Cowelitz River [sic] there is not much to attract the Eye or worthy of notice. The Views are certainly very pretty and the distance is always broken by the presence of one of the several snowy Mountains standing high above the surrounding Mountains....Mount Hood & Mt. St. Helens being the nearest & therefore the most conspicuous....* [Fig. 1]

> *The Morning was lovely and as we were descending one of the long reaches in the [Columbia] River my attention was attracted to Mount St. Helens standing as it were, at the head of the bend!...Suddenly a long black Column of Smoke & Ashes shot up into the Air, and hung as a Canopy over the dazzling Cap contrasting strongly with the Clear blue Sky behind it; this was an incipient Eruption, and my curiosity was excited the more from being the first Volcano I have ever seen in action....*

> *A few Miles above the Cowlitz, on the left bank of the Columbia River, is a...singular isolated Rock....Further down on the right [Washington] bank is another peculiar feature, called Mount Coffin....* [Figs. 2 and 3]

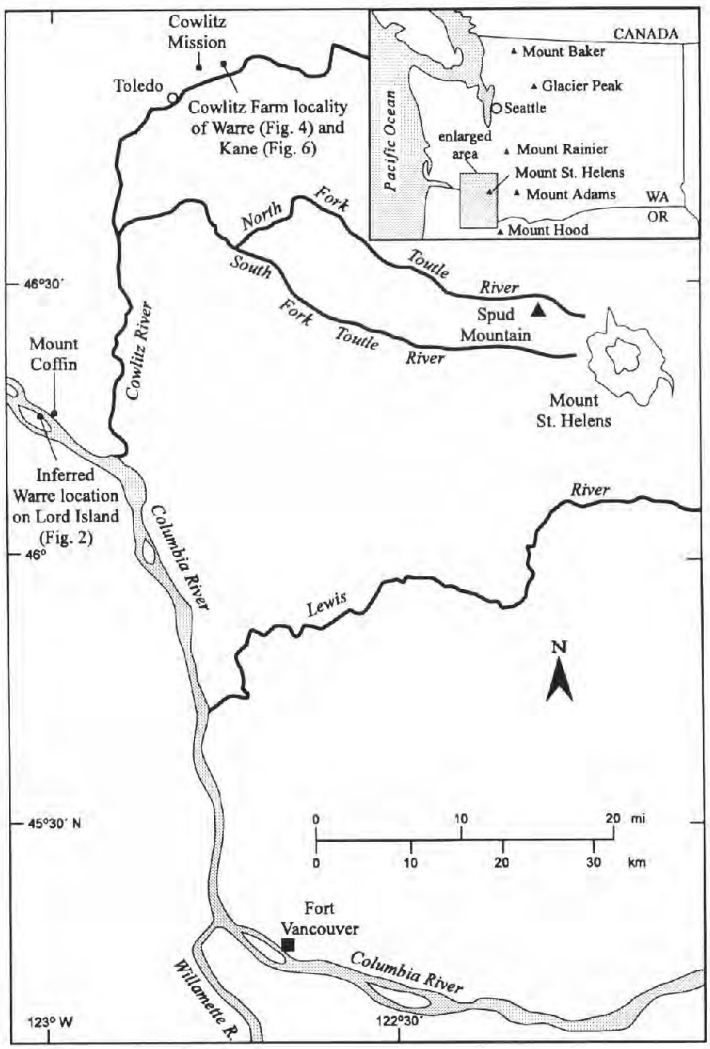

Figure 1. Maps showing vantage points for field sketches and other text localities. The Cowlitz Farm locality (46°28'28"N, 122°47'32"W) was determined from a description of the mission near the farm by another traveler (Harper, 1971, p. 98) and from George Herron (resident, Winlock, Washington), whose grandfather's farm occupied part of the Cowlitz Farm site. The mission site is shown on the U.S. Geological Survey 7.5-minute Toledo quadrangle (1993).

Figure 2. "Mount Coffin and Mount St. Helens (volcanic)", a watercolor by Henry James Warre, September 13(?), 1845 (courtesy of the American Antiquarian Society, Worcester, Massachusetts, Warre sketch no. 26). Previously published in Warre (1970) and Holmes (1980).

Figure 3. Comparative historical photograph of Mount Coffin taken between 1916 and 1929 (courtesy of the Cowlitz County Historical Museum, Kelso, Washington, item 61.2.13). The scene supports the veracity of Warre's watercolor by confirming that the foreground he sketched existed. It also places Warre's sketch vantage on the northeast shore of Lord Island in the Columbia River opposite the 'Mount Coffin' locality on U.S. Geological Survey 7.5-minute Kelso quadrangle (1970). Mount Coffin was almost completely mined for construction aggregate and riprap in the 1930s. (Photographs of the operations are on file at Cowlitz County Historical Museum.) The building behind the man, Weyerhaeuser Longview sawmill number 1, no longer exists.

Figure 2 is the first of two similar sketches Warre made from Mount Coffin (Majors, 1981). The Public Archives of Canada have assigned a date of September 13, 1845, to the second, more finished sketch, based on Warre's journal entries (Warre, 1976). The latter sketch is available in Warre (1976), as Majors' (1980) frontispiece, and in Holmes (1980).

Within a few days of his original sketches, Warre made a third sketch from Cowlitz Farm, a trading post along the Cowlitz River (Fig. 4). While Warre made no journal entries for this sketch, it was probably done between September 17 and September 20, 1845, based on his earlier and later notes.

Kane's 1847 journal reads:

> *March 25th.— I started from the Fort [Vancouver] for Vancouver's Island in a small wooden canoe, with a couple of Indians, and encamped at the mouth of the Walhamette [sic].*
>
> *March 26th.—When we arrived at the mouth of the Kattlepoutal [Lewis] River, twenty-six miles from Fort Vancou-*

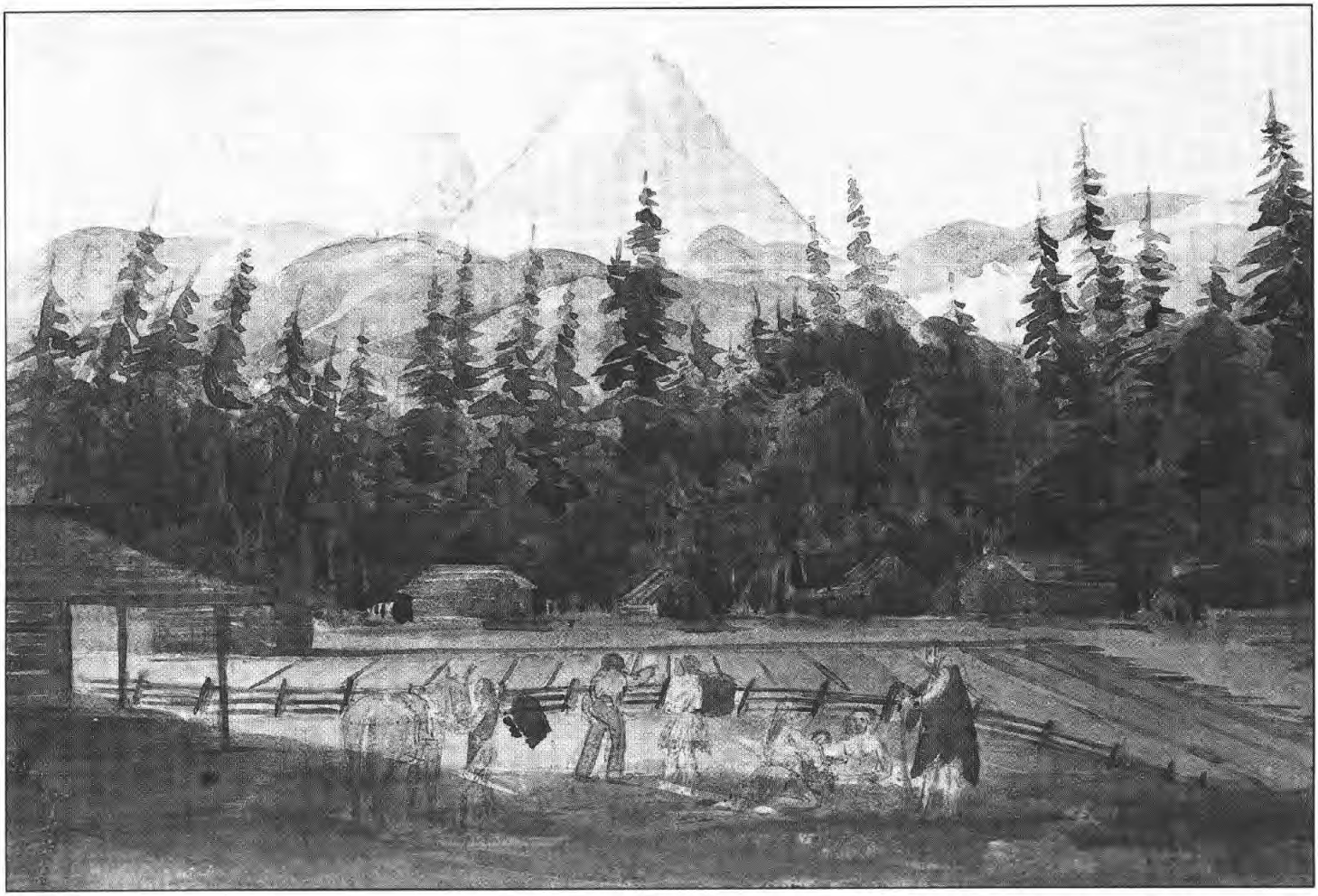

Figure 4. "Mount St. Helens from settlement on Cowalitz River [*sic*]" (Cowlitz Farm), a watercolor by Henry James Warre, September 17–20, 1845 (courtesy of the American Antiquarian Society, Warre sketch no. 24). Previously published in Warre (1970) and Holmes (1980).

Figure 5. "Mount St. Helens, with smoke cone", an oil painting by Paul Kane (courtesy of the Stark Foundation, Orange, Texas, item WOP 10, CRIV-461). Although Kane probably witnessed the steam plume he described, his "smoke cone" is actually an altocumulus standing lenticular cloud, formed when moist air is rapidly lifted orographically. Previously published in Harper (1971) and Holmes (1980).

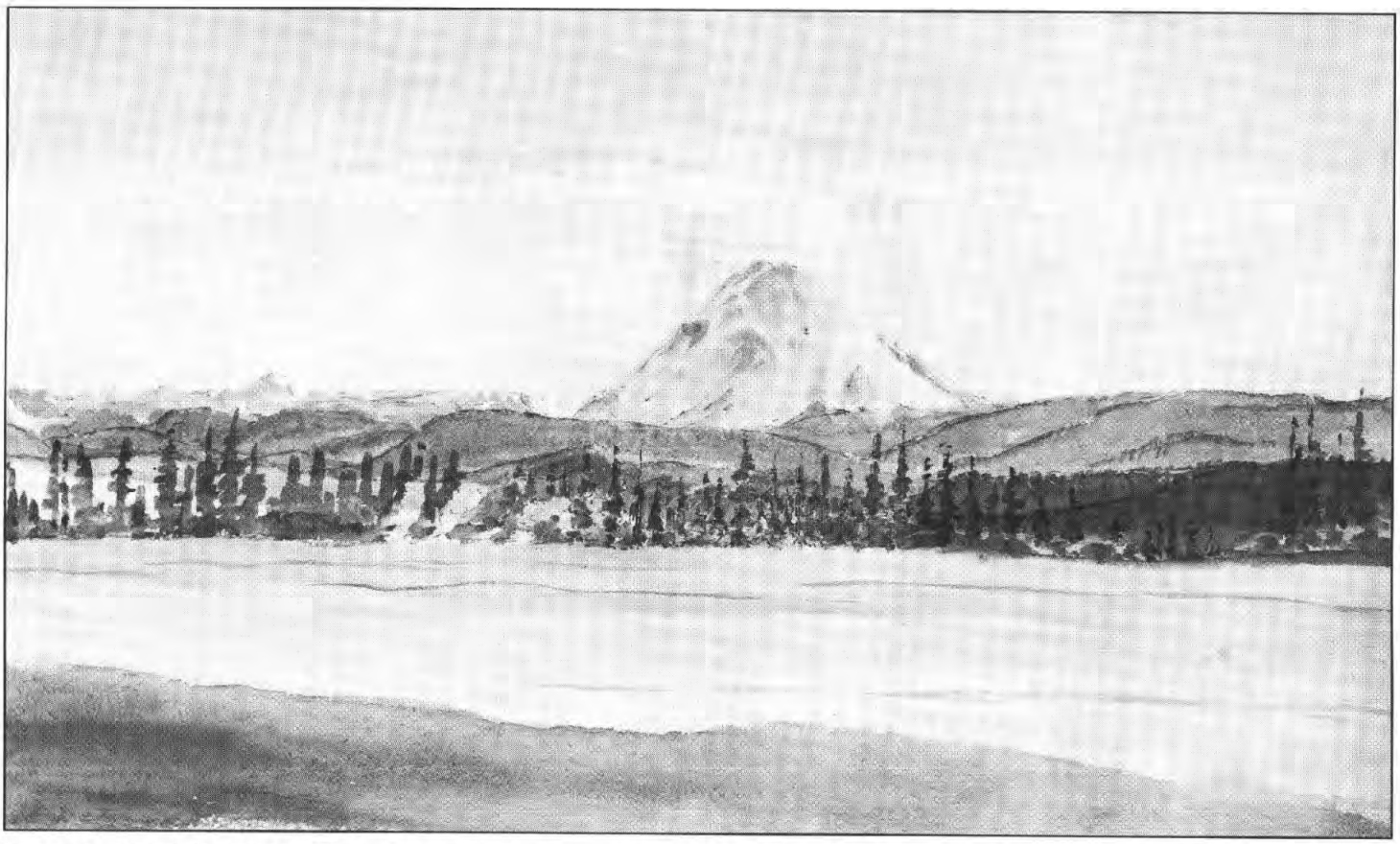

Figure 6. "Mount St. Helens seen from the Lewis River", a watercolor by Paul Kane (courtesy of the Royal Ontario Museum, Toronto, Canada, item 946.15.184). Note that the museum name of this sketch is in error. The sketch's Cowlitz Farm setting is evident from many features, including the presence of Mount Adams (on horizon at left) and of Spud Mountain (the tall mound-shaped peak at the base of the volcano). Here we assign a date of March 30, 1847, to this sketch, based on Kane's journal entry. Previously published in Majors and McCollum (1980).

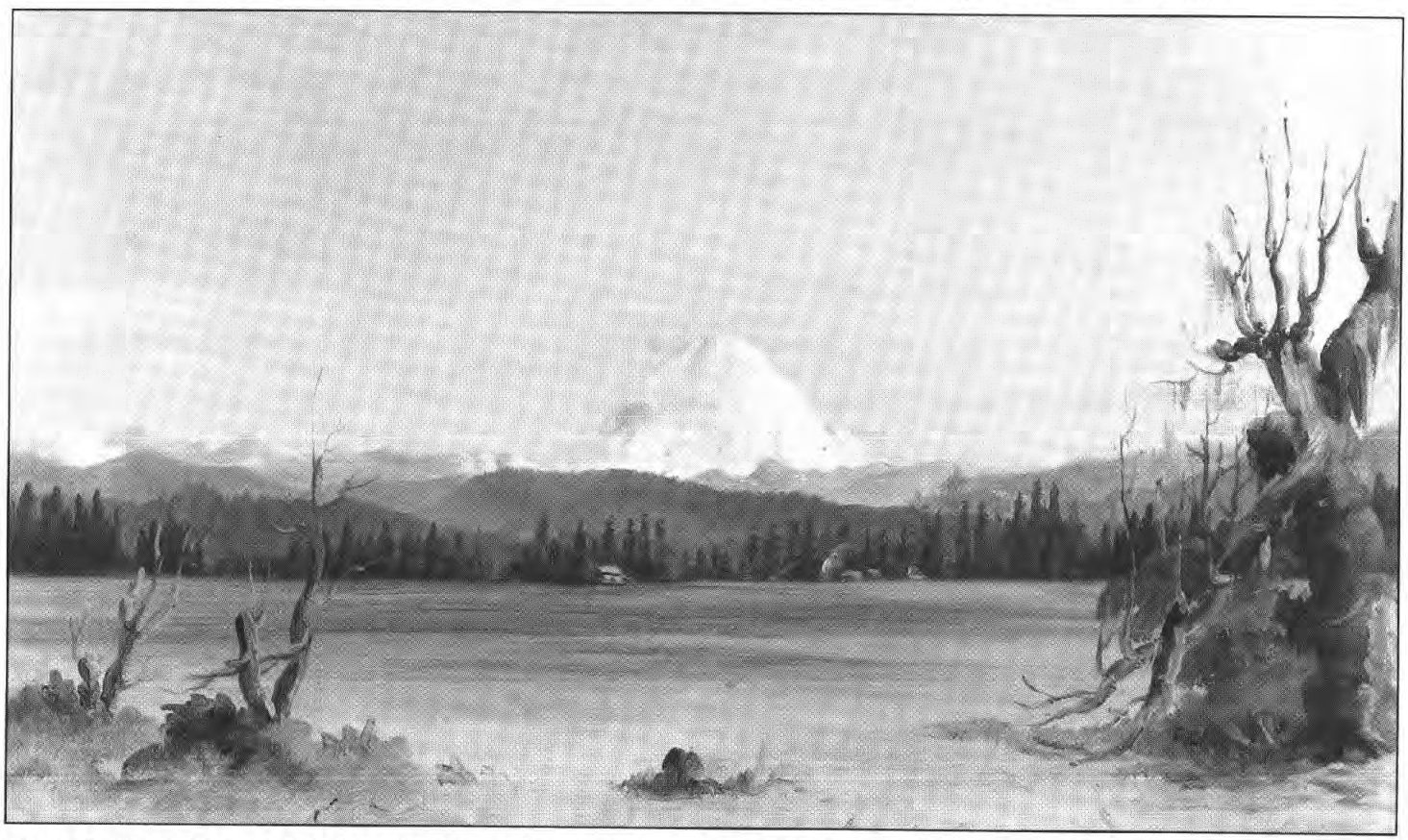

Figure 7. "Mount St. Helens", an oil painting by Paul Kane based on the Fig. 6 field sketch (courtesy of the Stark Foundation, WOP 21, CRIV-464). Previously published in Harper (1971) and Holmes (1980).

ver, I stopped to make a sketch of the volcano, Mount St. Helen's, distant, I suppose, about thirty or forty miles....It is of very great height, and being eternally covered with snow, is seen at a great distance. There was not a cloud visible in the sky at the time I commenced my sketch, and not a breath of air was perceptible: suddenly a stream of white smoke shot up from the crater of the mountain, and hovered a short time over its summit; it then settled down like a cap. This shape it retained for about an hour and a-half; and then gradually disappeared.... [Fig. 5]

March 30th.—We landed at the Cowlitz farm, which belongs to the Hudson's Bay Company. Large quantities of wheat are raised at this place. I had a fine view of Mount St. Helen's throwing up a long column of dark smoke into the clear blue sky [Figs. 6 and 7]. *Here I remained until the 5th of April....* (Harper, 1971)

Warre's eruption columns appear to originate from a small dome on Mount St. Helens' lower north flank. Kane's sketch and Cowlitz Farm painting clearly show an eruption column issuing from a north flank vent.

SIGNIFICANCE

Warre's and Kane's drawings and narratives strengthen historical evidence for continuing volcanic activity at Goat Rocks dome, a subsidiary dacite cone on Mount St. Helens' north-northwest flank, during the late 1840s. The existence of the dome was first documented in the early 1840s; it may have appeared in the early 1830s, or possibly even earlier (Table 1). It was probably the most active between November 22, 1842, and September 20, 1845, when it was observed to be in eruption on at least 13 different occasions. Goat Rocks dome was destroyed by Mount St. Helens' May 18, 1980 eruption (Lipman and Mullineaux, 1981).

Warre's billowing ash clouds suggest an emission generated by dome collapse. Kane's eruption columns confirm that the dome was still hot in March 1847. They might represent steam clouds generated by a phreatic explosion (Fig. 5) or a plume generated by ash-and-gas emissions or a rock avalanche at the dome (Figs. 6 and 7).

A possible problem with these interpretations is that the north-flank dome in Warre's sketches might be too low on the horizon to be Goat Rocks dome. To evaluate this possibility, a colleague photographed the view for us from a site 3 km upstream of Warre's vantage (Fig. 8; Warre's Lord Island viewpoint is relatively inaccessible).

The photograph shows Northwest dome, actually a thick section of andesite lava flows on the northwest flank, near the horizon. (The dome name was applied hastily and incorrectly in 1980 but has unfortunately stuck). Yet Goat Rocks dome (2,316 m) was only 158 m higher than Northwest dome (2,158 m). Thus, Goat Rocks dome would also have appeared low on the horizon, behind Northwest dome, to Warre. Lipman and Mullineaux (1981, their figs. 33 and 89) and Crandell

Table 1. Examples of historical accounts of Mount St. Helens eruptions probably related to Goat Rocks dome growth*. (F), first person account

Date	Account	Recorder	Ref.**
Summer 1831	Ashfall-induced darkness	Meredith Gairdner	Ho, M
August 1831	Ash fall and related darkness at Ft. Vancouver; white snowy flanks of volcano darkened (same event as above)	Samuel Parker	Ho, M
Dec. 1842–Feb. 1844	"Cinders and scoria" and dead fish in Toutle River	Modeste Demers (Cowlitz Mission)	Ho, Ha
June 1844	Smoke column above volcano (F)	J. T. Heath	M
Feb. 15, 1845	Eruption column (F)	S. B. Crockett	Ha
Feb. 15–16, 1845	Night rumbling distinct from thunder; thought to originate from volcano (F)	J. T. Heath	M
Sept. 17–20, 1845	Eruption column from north base of peak (F)	H. J. Warre	TR (Fig. 4)
Late Feb. 1854	Smoke columns above volcano (F)	W. H. H. Halls, Charles Stevens	Ho, M

*Table supplements 21 similar observations from 1835–1857 summarized by Yamaguchi and Lawrence (1993; their table 2).

**Ho, Holmes (1980); M, Majors (1981); Ha, Harris (1988); TR, this report.

Figure 8. Mount St. Helens from 3 km upstream of Warre's Lord Island vantage, March 8, 1993. Dark area on left flank is "Northwest dome". (Photograph taken with 300-mm lens by David Wieprecht.)

(1987, his fig. 54) illustrate the similar heights and former proximity of Goat Rocks dome and Northwest dome.

Warre's and Kane's artwork and journal entries contribute to a scenario of a hot dome that intermittently grew, crumbled, and steamed from at least late 1842 into the 1850s (Yamaguchi and Lawrence, 1993). In March 1847, dome extrusion was evidently still ongoing or only recently completed.

More generally, the two accounts increase our understanding of Mount St. Helens' past eruptive behavior. Such understanding is central to anticipating its possible future behavior.

ACKNOWLEDGMENTS

We thank the staffs of the American Antiquarian Society, the Cowlitz County Historical Museum, the Royal Ontario Museum, and the Stark Museum for the cover photo and Figures 2–7, publication permission, and insightful discussions. Cynthia Gardner found Figure 3 when she and David Wieprecht stopped at the Cowlitz County Museum on their way home from shooting Figure 8. Weyerhaeuser Company, Longview, Washington, identified the building in Figure 3. Shirley Lewis lent us photos she took of Mount St. Helens in April 1980 from Winlock (northwest of Toledo) that were useful in evaluating the sketches done at Cowlitz Farm. Partial funding was provided by a Science and Technology Agency of Japan fellowship to Yamaguchi and by a grant from the University of Colorado Program Enrichment Fund. Comments from Donald Swanson, Richard Waitt, William Scott, John Lockwood, Richard Hoblitt, Dennis Geist, and Cynthia Gardner improved earlier versions of the manuscript.

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New Volcanic Hazards Videotape Released

A new videotape, "Understanding Volcanic Hazards", is now available from the Northwest Interpretive Association (NWIA). The videotape features stunning images of seven types of volcanic hazards: ash falls, hot ash flows, mudflows, landslides, volcanic tsunamis, lava flows, and volcanic gases.

The video was produced by the late Maurice Krafft, who was killed, along with his wife Katia and Washington geologist Harry Glicken, by a hot ash flow while filming at Unzen Volcano in Japan in 1991. Sponsored by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and the United Nations Educational, Scientific and Cultural Organization (UNESCO), this program is intended to help prevent future deaths from volcanic eruptions by showing compelling images of destructive volcanic activity.

The Northwest Interpretive Association (NWIA), a nonprofit organization that sells products related to the natural history of the Pacific Northwest's National Forests and Parks, is distributing the video for IAVCEI. Orders can be placed by mail with an enclosed check or by phone with a VISA card number.

Cost of the tape is $19.95 plus postage. Add $5.00 for postage in the United States, Canada, and Mexico. For all other destinations, add $13.05 for airmail postage or $5.55 for surface postage. Make checks payable to NWIA.

The video comes in English and Spanish versions in either NTSC (U.S. and Japanese standard) or PAL (European standard) video format. Be sure to specify English or Spanish and NTSC or PAL. Allow 2–4 weeks for delivery.

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Preliminary Observations on Marine Stratigraphic Sequences, Central and Western Olympic Peninsula, Washington

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INTRODUCTION

This article describes preliminary results from field investigations of Tertiary rocks that crop out between the easternmost Olympic Mountains and the Pacific Ocean. These rocks form the "Core Complex" of Tabor and Cady (1978a,b) and lie outboard of the Crescent terrane (Babcock and others, 1994). For the most part, they comprise hemipelagic sediments that were deposited directly on the Juan de Fuca plate. Thin- to medium-bedded units and thick multistory sandstones or conglomerates, together with volcaniclastic rocks and basic to intermediate(?) fine-grained crystalline igneous rocks, make up most of the Core Complex.

These ongoing investigations have been performed since 1989 as part of the Washington Department of Natural Resources, Division of Geology and Earth Resources' state geologic map program (Schuster, 1994). We made our observations during four multiweek traverses on foot in the Olympic Mountains and during reconnaissance traverses along a large proportion of the remaining logging roads in the western Olympic Peninsula (Fig. 1).

This work was undertaken in order to:

- Clarify the relations among undifferentiated units, identify unmapped structures, and eliminate 'scratch' boundaries on existing maps (e.g., Tabor and Cady, 1978a);
- Provide data for forest practices applications, petroleum assessments, and seismic risk studies;
- Determine whether the Core Complex is composed of (1) two or more discrete terranes or (2) a single terrane or accretionary depositional sequence, which reflects several provenances and has been dissected by multiple thrusting events (Boyer and Lingley, 1991, 1994).

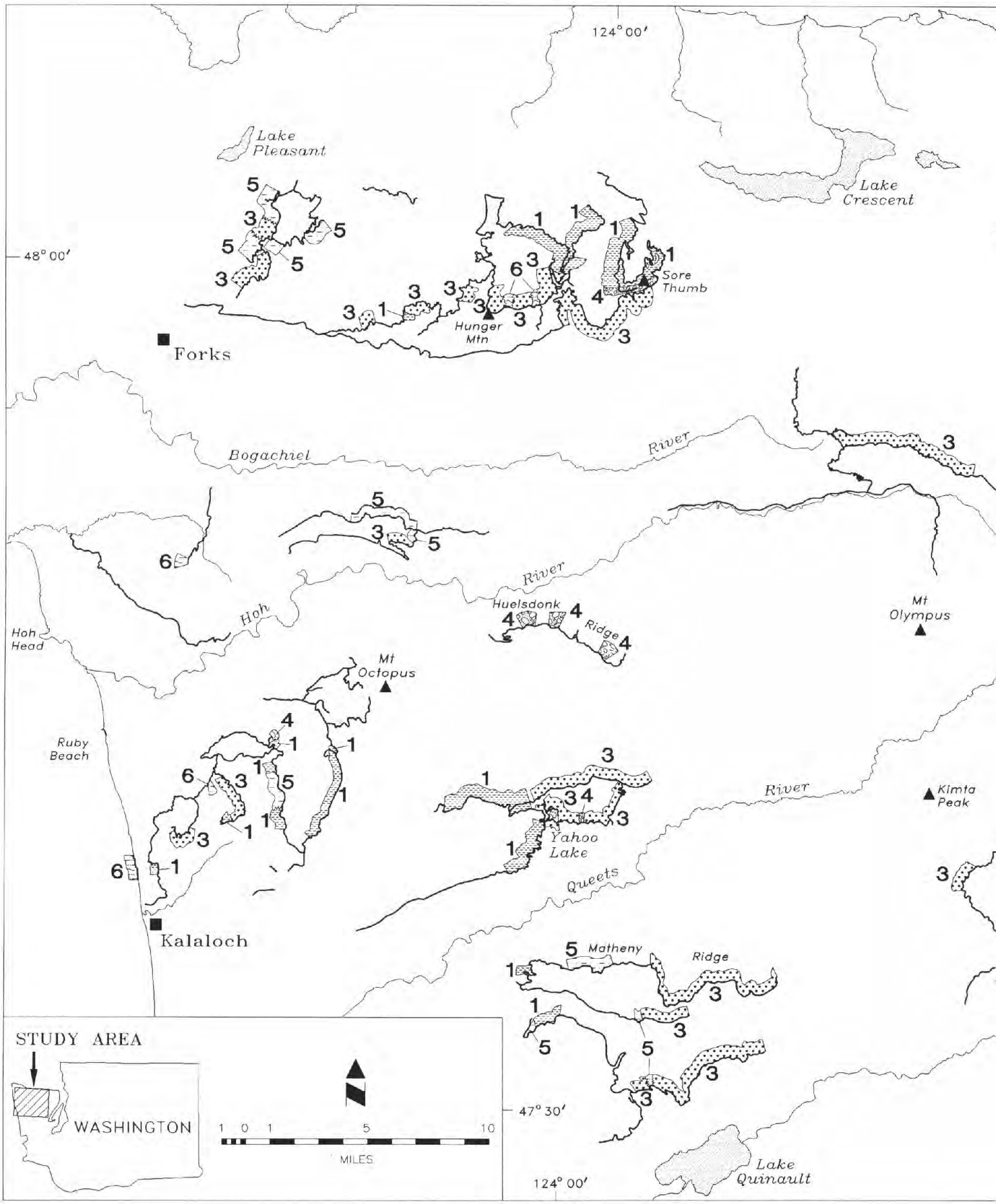
The following interpretation is subject to considerable uncertainty owing to dense vegetative cover, overlying glacial deposits, steep terrain, poor induration in coastal areas, sheared and distorted outcrops, and wretched weather. Many logging roadcuts that were useful for previous field studies are now overgrown or are being intentionally obliterated by land-management agencies.

Cursory examination of the Tertiary stratigraphic section exposed in the western foothills of the Olympic Mountains suggests very high sand/shale ratios. However, good exposures in this area are found mainly on sub-summits of ridges created by rivers that flow southwest down the regional slope of the accretionary prism. Many of the sub-summits result from second-order streams that 'hook' around resistant sandstone units and a few volcanogenic bodies, both of which have limited extent along strike. In coastal areas, drill data (Palmer and Lingley, 1989) indicate a higher sand/shale ratio than is observed in outcrop because the shales (claystones) are more resistant than the coarse-grained sandstones.

In general, exposures are progressively better to the northeast, so mapping is more detailed in that region. For example, bundles of two or three sandstone beds, each less than 3 m thick, are depicted in the Mount Angeles quadrangle (Tabor and Cady, 1972, 1978a), whereas far thicker sandstone units located 5 km southeast of Kimta Peak and on Matheny Ridge have not been mapped.

Rocks in much of the Olympic Peninsula are metamorphosed; grade increases eastward from the foothills to the central part of the Olympic Mountains (Tabor and Cady, 1978a; Brandon and Calderwood, 1990). However, mapped units are generally defined by sedimentary protolith rather than on the basis of metamorphic grade (Tabor and Cady, 1978a; Rau, 1975, 1979). For the purposes of this report, all rocks composed of clay minerals are referred to as shale even though these are claystones in many coastal areas and slates in the central portion of the peninsula. All sandstones are reported as such, although some have a schistose appearance ("semischists" of Tabor and Cady, 1978a). The coarse-grained siliciclastic rocks are chiefly feldspathic litharenites with lesser amounts of lithofeldspathic arenite (Stewart, 1970; Grady, 1985; Koch, 1968; this study).

Foraminifera identified by W. W. Rau (in samples collected as part of this study and various U.S. Geological Survey investigations; see Rau, 1975, 1979, 1981) include faunas that apparently range from late middle Eocene (Narizian stage) to middle Miocene (Relizian stage). A few diagnostic benthic forams indicate bathyal conditions, but most forms are planktonic. Rau (Dept. of Natural Resources, retired, oral commun., 1991) has observed that "most of the turbidites are barren". Except for a few lowermost and uppermost Oligocene forms, confirmed Oligocene (Zemorrian stage) faunas are absent. Fission-track dates (Brandon and Vance, 1992) corroborate the biostratigraphic ages and suggest an 8-m.y.-long hiatus or a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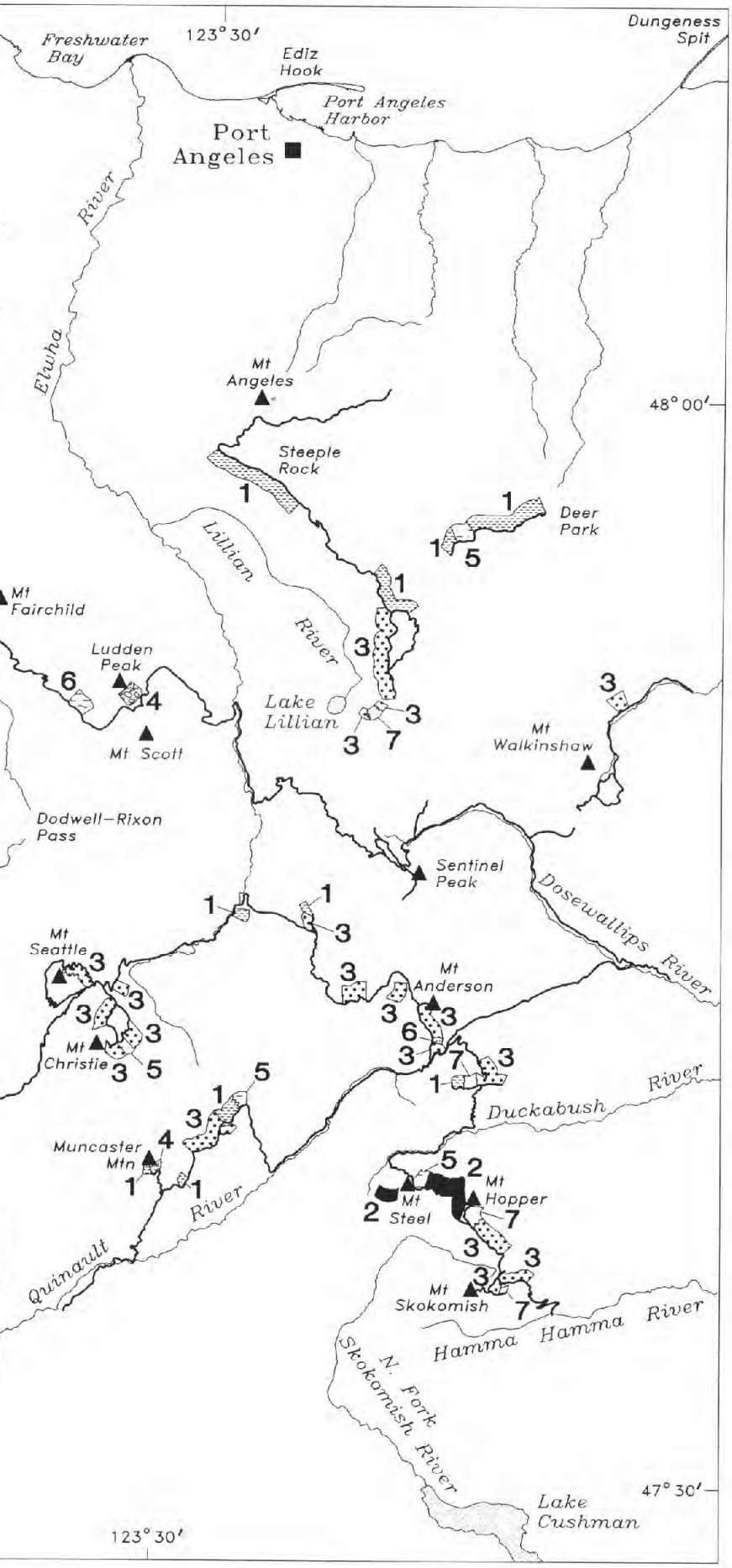


EXPLANATION

1 Lithofacies I: Primarily monotonous thin–bedded shales and laminated siltstones (D_3 and G facies). The unit also includes a few isolated sandstone beds that are generally less than 1 m thick.

2 Lithofacies I: Mainly monotonous shale with minor siltstone (G facies) of the Elwha Lithic Assemblage.

3 Lithofacies II: Mostly 0.5– to 25–m–thick nongraded sandstones and conglomerates that are laterally discontinuous and vertically separated by 0 to >100 m of thin–bedded shales and laminated siltstones (B with D_3 and G facies) or by medium–bedded sandstones and finer grained siliciclastic rocks (B, D, and E facies).

4 Lithofacies III: Chert–pebble conglomerates that are laterally discontinuous and vertically separated by 0 to >100 m of thin–bedded shales and laminated siltstones (A with D_3 and G facies) or by medium–bedded sandstones and finer grained siliciclastic rocks (B, D, and E facies).

5 Lithofacies IV: Mostly 0.5– to 1–m–thick nongraded sandstones vertically separated by 0 to >25 m of shales (B with D_3 and E (?) facies).

6 Complete Bouma sequences: Sandstones, siltstones, and shales with T_a–T_e divisions (Bouma and Brouwer, 1964) (C facies).

7 Strata with indicators of possible shallow–water deposition such as flaser bedding and trough cross–bedding.

Figure 1. Traverse routes (heavy lines) and dominant lithofacies (sedimentary protoliths) observed during this reconnaissance study.

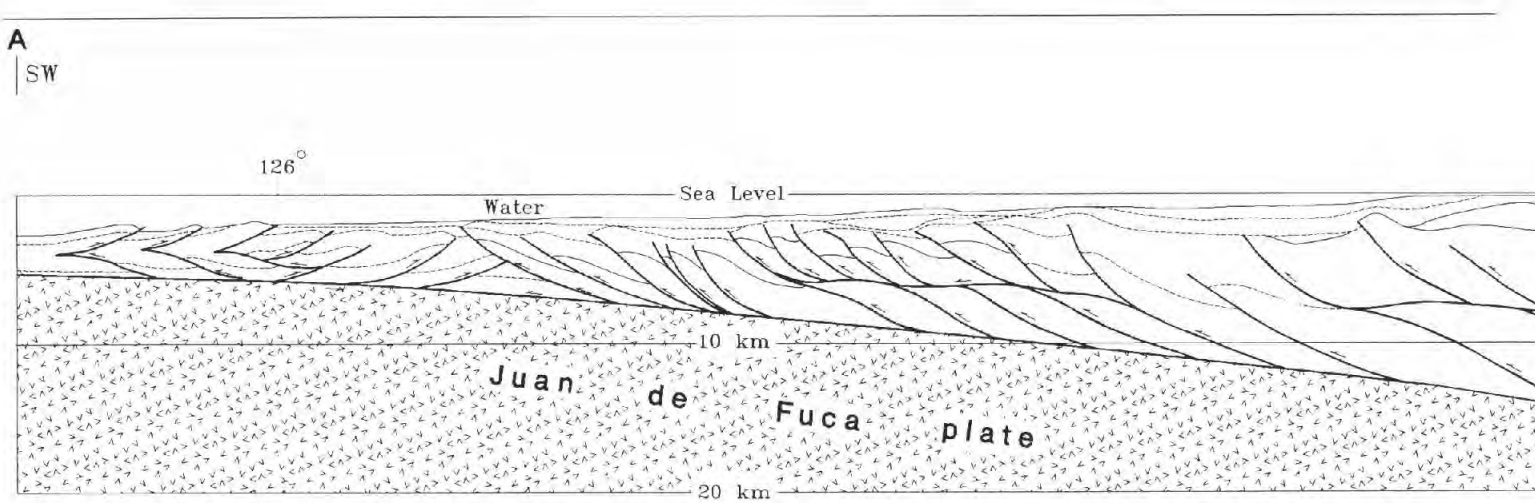


Figure 2. A hypothetical southwest-to-northeast balanced (geometrically correct) cross section showing possible configurations of thrust faults within the Juan de Fuca accretionary prism and adjacent regions (section by S. E. Boyer, Univ. of Washington, and the author). Unlabeled polygons southwest of the Hurricane Ridge fault represent the Core Complex of Tabor and Cady (1978a) and its offshore depositional continuation on the Washington continental margin. Unlabeled polygons between the Hurricane Ridge and Leech River faults reflect rocks of the Fuca–Tofino basin. The unlabeled polygon northeast of the Leech River fault represents Mesozoic metamorphic rocks. The northwestern part of the study area (Fig. 1) is shown.

period of slow deposition in a starved basin during much of the Oligocene.

MAJOR LITHIC ASSEMBLAGES

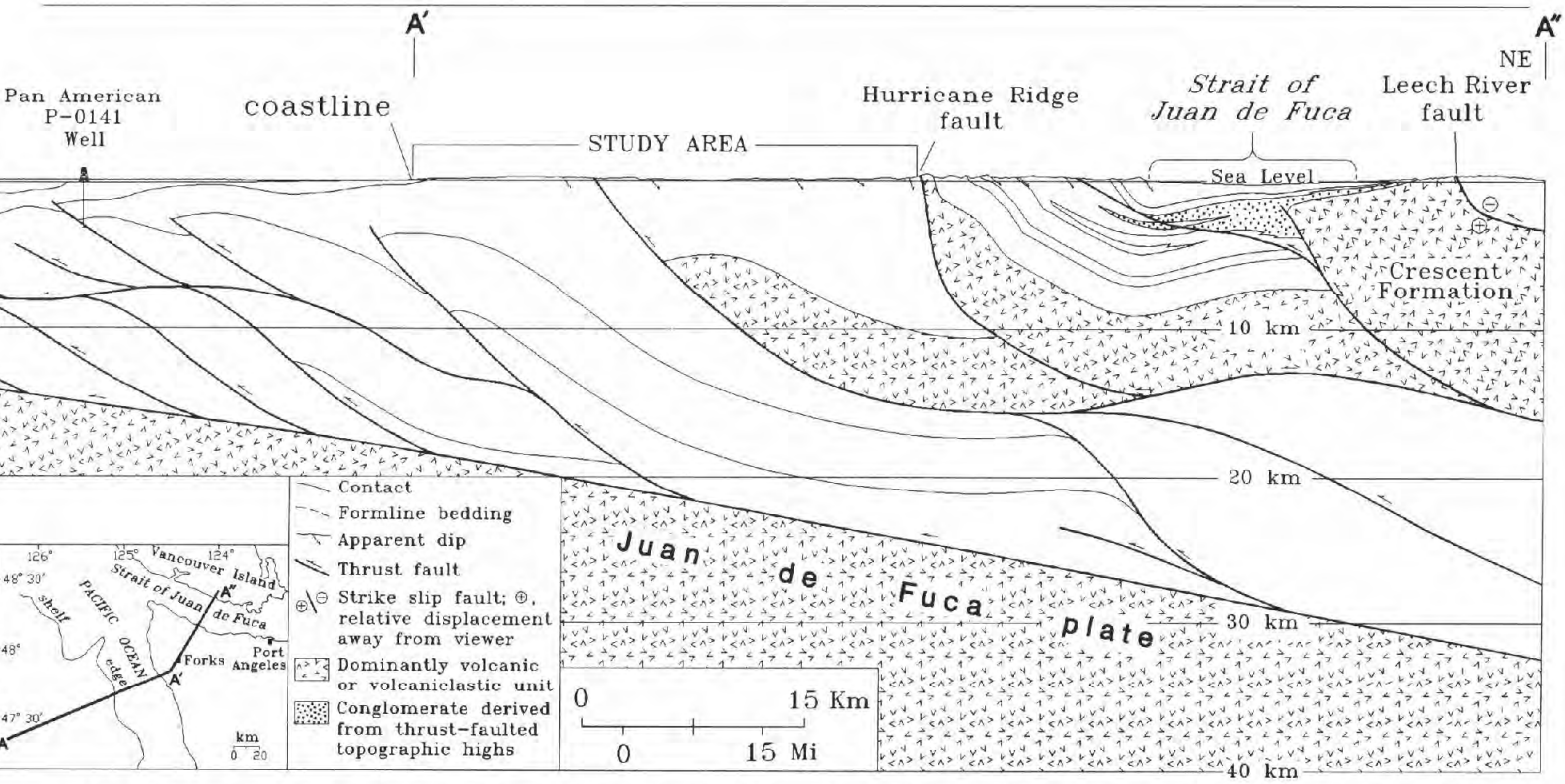
Tabor and Cady (1978a) subdivided rocks of the Core Complex into major lithic assemblages, mainly on the basis of subtle differences among large packets of remarkably monotonous lithologies. The Elwha Lithic Assemblage, for example, is largely composed of homogeneous, thin-bedded, fine-grained siliciclastic rocks, whereas the Needles–Gray Wolf Lithic Assemblage is composed of homogeneous, thin-bedded, fine-grained siliciclastic rocks with a few areally restricted, massive sandstone units, some of which contain minor basaltic detritus. The Western Olympic Lithic and the Grand Valley Lithic Assemblages are composed mostly of homogeneous, fine-grained siliciclastic rocks with many areally restricted, massive sandstone units. These subtle differences among the major lithic assemblages apparently led to some scratch boundaries and undifferentiated units (for example, unit "Tur" and the "Tsc"/"Tgs" contact on Tabor and Cady, 1978a).

The mapping and facies analysis described below support the positions of contacts and choices of lithic assemblages as shown on Tabor and Cady (1978a). Although the effects of tectonic telescoping cannot be quantified, geometric relations suggested by Tabor and Cady (1978b) and unpublished work by S. E. Boyer and the author indicate considerable thrust duplication (Fig. 2). Most existing mapping lacks sufficient detail to determine whether individual contacts are normal lithologic boundaries, accreted terrane boundaries, thrusts (whether seaward- or arc-dipping), or normal faults. However, the juxtaposition of rocks laid down in dissimilar depositional environments suggests that some of the boundaries between the lithic assemblages are tectonic.

Heller and others (1992) found that a few white micas from the Western Olympic Lithic Assemblage are isotopically similar to those from the Omineca crystalline belt of British Columbia. Micas from sandstones in lithic assemblages located farther east in the Core Complex resemble those in coeval sandstones from the Fuca–Tofino basin and Puget trough, which are located north and east of the Core Complex (Fig. 2).

Except in the central part of the Olympic Mountains, many primary sedimentary structures are recognizable, even in the metamorphosed rocks. Areas of greatest deformation include disharmonically folded semischists in a mylonite developed within a few tens of meters of the Southern Fault Zone at

Figure 3. Monotonous lithofacies I beds consisting of very fine grained sandstone, siltstone, and shale, which are generally laminated but not graded. This section is located east of Kalaloch.



Mount Skokomish and rocks near Dodwell Rixon Pass (M. T. Brandon, Yale Univ., oral commun., 1991; Brandon and others, 1991).

LITHOFACIES

To date, four volumetrically significant lithofacies and several minor lithofacies have been observed in the study area (Fig. 1). The thick-bedded lithofacies (II and III as defined herein) include sequences of rocks similar to the thinner bedded lithofacies (I and IV).

Lithofacies I

This sequence is composed of monotonous interbedded siltstones, very fine grained sandstones, and shales that vary in thickness from millimeters to a few centimeters (Figs. 3, 4, 5). Few ripples, traces of bioturbation, macrofossils, or skeletal remnants have been observed to date. Foraminifera are mostly open-water planktonic forms, but some bathyal assemblages have been recognized. These are flysch sequences composed of D_3 and (or) G facies (alphabetic terminology used herein from Mutti and Ricci Lucchi, 1978). Many of these beds are parallel laminated. Graded bedding is uncommon, but a few units are composed of a basal sandstone bed that grades upward into siltstone and (or) shale in turn. A majority of bedding sequences observed during this study show no obvious coarsening or fining-upward trends. Most lithofacies I sandstone and siltstone beds have rectangular weathering profiles and form a colluvium with 3-cm blocks. Weathering colors are generally dark gray, medium reddish brown, or, in coastal areas, a distinctive orange-brown.

Folds, faults, and multiple cleavages are common throughout many exposures of lithofacies I, so unit thicknesses cannot be measured or estimated. However, this lithofacies makes up at least half of all exposures we have observed within the Core Complex.

The Needles–Gray Wolf, northeastern Grand Valley, and much of the Elwha Lithic Assemblages are composed chiefly of lithofacies I. Lithofacies I beds are also common in coastal areas mapped by Rau (1975, 1979) and in unmapped areas northwest of Lake Quinault. Unit "Thrs" on Tabor and Cady (1978a) is representative of this lithofacies.

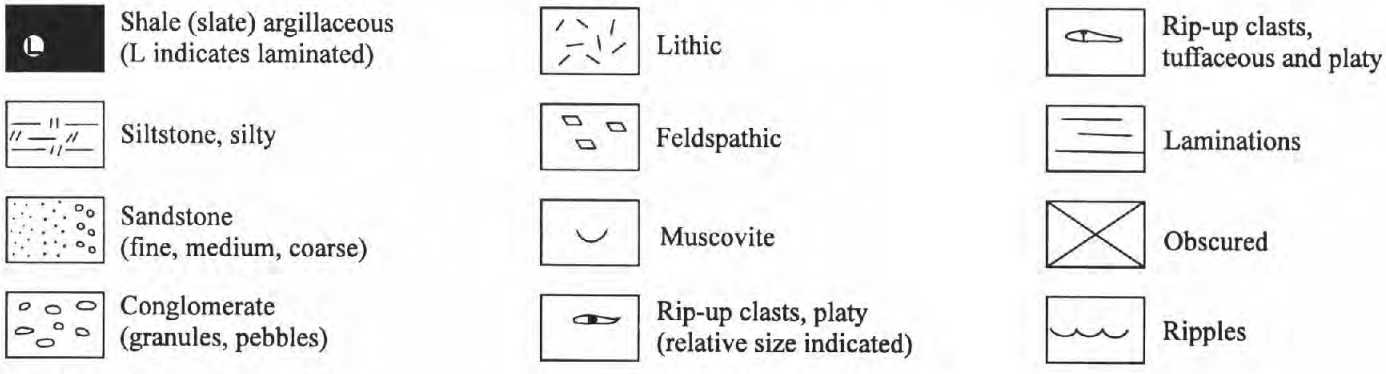


Figure 4. Key to Figures 5, 7, and 13.

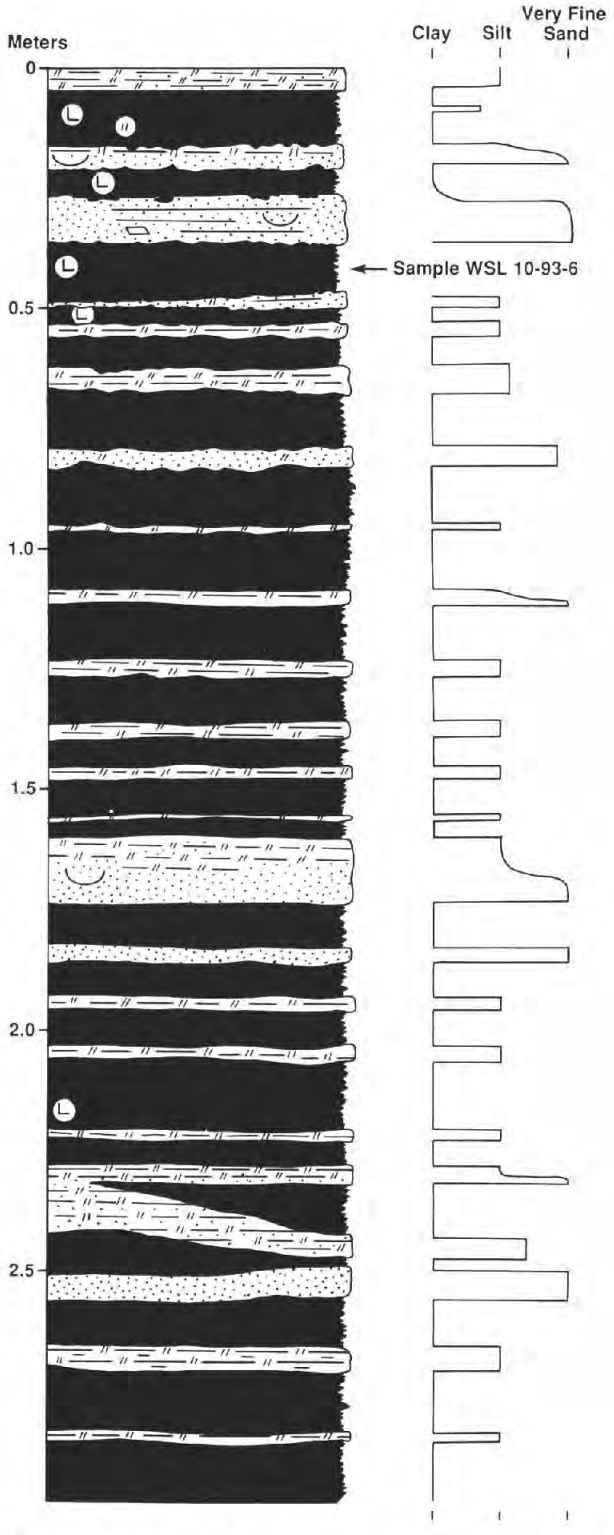


Figure 5. Columnar stratigraphic section showing bed forms and other structures typical of lithofacies I. This section is located 4.7 km west of Yahoo Lake, at elevation 332 m on Road 3100 (SE¼ sec. 11, T25N, R11W). Analysis by W. W. Rau (Dept. of Natural Resources, written commun., 1994) of a small assemblage of foraminifera in Sample WSL 10-93-6 suggests rocks in this outcrop were deposited in a bathyal environment during the late Eocene (Narizian stage).

The dearth of graded units and lack of midfan sandy lobes (see Minor Lithofacies, below) suggest that much of lithofacies I was deposited as overbank sequences adjacent to proximal channels rather than from the distal margins of turbidity flows on the basin plain. However, the uniformity and paucity of coarse clastic rocks in much of the Elwha Lithic Assemblage implies that these monotonous shales may have been deposited in a basin-plain setting.

Lithofacies II

This lithofacies is composed mainly of 3- to 42-m-thick multistory massive sandstone units. It also includes sandstones of similar thicknesses that have massive bases and widely spaced, parallel laminations and (or) parallel banding developed within a meter of the top of individual beds (B facies). Lithofacies II sandstones are commonly conglomeratic; the granules or pebbles (less common) have roughly the same composition and weathering color as the finer matrix. All of the conglomerates are matrix supported.

These sandstones are separated by 'thin-bedded turbidites' or by thin- to medium-bedded sandstones with fine clastic interbeds, which resemble lithofacies I and IV, respectively. Sandstone to shale ratios of lithofacies II are varied, depending on the vertical separation between multistory sandstone units. This vertical separation can exceed 100 m. Both the massive sandstone units and sandstone units with laminated/banded tops are generally lenticular, although map patterns suggest that some larger units are tabular. These sandstone outcrops typically range from 200 m to 4 km along apparent depositional strike (perpendicular to rare paleocurrent indicators). Observed lateral separation between the sandstone units can exceed 2 km.

Most lithofacies II exposures include 10 or more vertically stacked beds, each ranging from 0.5 to 8 m thick (Figs. 6–9). In the few units where such relations are unambiguously exposed, most individual beds maintain fairly constant thickness, but some beds are scoured into underlying units (Figs. 6,8,9). Typically, scours have amplitudes less than 1 m and wave lengths of several meters. Sand-on-sand concave-up scours are typical, but clay-draped scours are also present. It is interesting to note that differential compaction in the metamorphosed rocks does not appear to invert the original morphology of channels and scours. Most sandstone beds show no grading. However, a few poorly developed, normally graded beds (C_1) are present, but no coarsening-upward beds have been observed. We have not (yet) seen large-scale patterns of fining or coarsening upwards in the Core Complex in this lithofacies.

Beds with widely spaced (0.5 to 3 cm) parallel laminae and banding are common in this lithofacies. Generally, these laminae are developed at the top of each bed. Banding consists of light yellowish-brown-weathering layers, 1 to 2 cm in width and parallel with bedding (Fig. 8). Low-angle cross laminations (wedge shaped) are scarce. A few flaps (underlying strata that are partially torn up and partially surrounded by overlying sand) have been observed in this facies. Dish structures are present in some outcrops, and loading features are noted on some bedding planes. Rare tool marks and current lineations together with the structural interpretation shown on Figure 2 suggest mostly southwest-directed paleocurrents.

Many massive or laminated/banded sandstone beds contain rip-up clasts or intraclasts of shale, very dark gray siltstone, and (or) tuffaceous siltstone. These are generally tabular and range from 0.3 mm to more than 30 cm in length. Most rip-up

clasts parallel bedding. In a few outcrops, however, localized groups of rip-up clasts are aligned nearly perpendicular to bedding (suggesting liquefaction?). Many of the tabular rip-up clasts taper to very thin, fragile edges. North of Kalaloch, some of the intraclasts are prismatic, indicating that these were selectively plucked from the intersections of bedding and nearly orthogonal cleavage surfaces. These clasts are eroded "pencils" (see Tabor and Cady, 1978b). Within the Core Complex, cleavages are developed in areas that have been exhumed from deeper parts of the subduction complex and have higher metamorphic grade (Tabor and Cady, 1978a; Brandon and Calderwood, 1990).

Northeast of Kalaloch, one unit composed of massive sandstone beds grades into a Bouma sequence.

The massive sandstones and sandstones with laminated and (or) banded tops are abundant in all of Tabor and Cady's lithic assemblages, especially in parts of the Western Olympic Lithic Assemblage, the Grand Valley Lithic Assemblage, and in the eastern portion of the undifferentiated unit "Tur" (between Lake Quinault and Matheny Ridge).

Lithofacies II sandstones and conglomerates are interpreted as channel-fill sequences deposited from high-density turbidity currents or sandy debris flows.

Figure 6. View south to a typical section of lithofacies II sandstone, here conglomeratic. This section is located about 300 m east of Lake Lillian near the headwaters of the Lillian River in unit "Tgst" of Tabor and Cady (1978a). The stratigraphic top is to the left, and the sandstone unit is 42 m thick.

Lithofacies III

Lithofacies III is also composed of conglomerates and finer clastic rocks. It is distinguished from lithofacies II by composition, larger mean clast diameter, and clast support. Lithofacies III conglomerates (A_2) are separated by 0 to 100 m of 'thin-bedded turbidites' (D_3 and G facies) or by thin- to medium-bedded rocks similar to lithofacies IV. Like lithofacies II conglomerates, these are also discontinuous along strike. This lithofacies is made up of pebble and lesser amounts of cobble conglomerates composed in part of very dark gray chert clasts not observed in the other lithofacies.

Many of these beds have a very small proportion of matrix. Most lithofacies III conglomerates are disorganized (lacking internal flow structure) but well bedded; thicknesses range from 0.5 to 4 m. A few beds near Yahoo Lake show poorly developed imbrication of elongate clasts. Conglomerate units we have mapped consist of 10 or more beds.

Clasts are composed of sedimentary and metasedimentary rocks that may have been derived from the Core Complex and cherts and other rock types that probably had an extrabasinal origin (Fig. 10). The pebbles are typically subspherical to oblate and measure 2 to 8 cm along the long axis and 1 to 3 cm in section. A few cobbles are present. In some outcrops, clast induration is varied (Fig. 10). The more indurated lithologies are rounded to subrounded, but some of the weaker sedimentary pebbles and cobbles are subangular. Conglomerates at Ludden Peak, Huelsdonk Ridge, Mount Octopus, and 11 km west-northwest of Lake Quinault are typical of lithofacies III.

The variety of clast lithologies, varying clast induration, unit morphology, and limited lateral extent suggests that lithofacies III rocks are submarine channel deposits.

Lithofacies IV

This lithofacies consists of fine- to coarse-grained sandstone beds mostly ranging from 15 cm to 1.0 m thick, together with very thin bedded sandstones, siltstones and lesser amounts of shale in units ranging from 0.5 to 50 cm thick (Fig. 11). The sand/shale ratio in lithofacies IV commonly exceeds 0.75. For the most part, the sandstones are not graded. The very thin bedded sandstones are separated by thin shale beds or less commonly by parallel shale laminae that are typically 2 mm wide and 5 cm long. Lithofacies IV includes B, D, E, and G facies. It is distinguished from lithofacies II by finer grain size, thinner mean bed thickness, a high sandstone/shale ratio, and less vertical separation between sandstone beds.

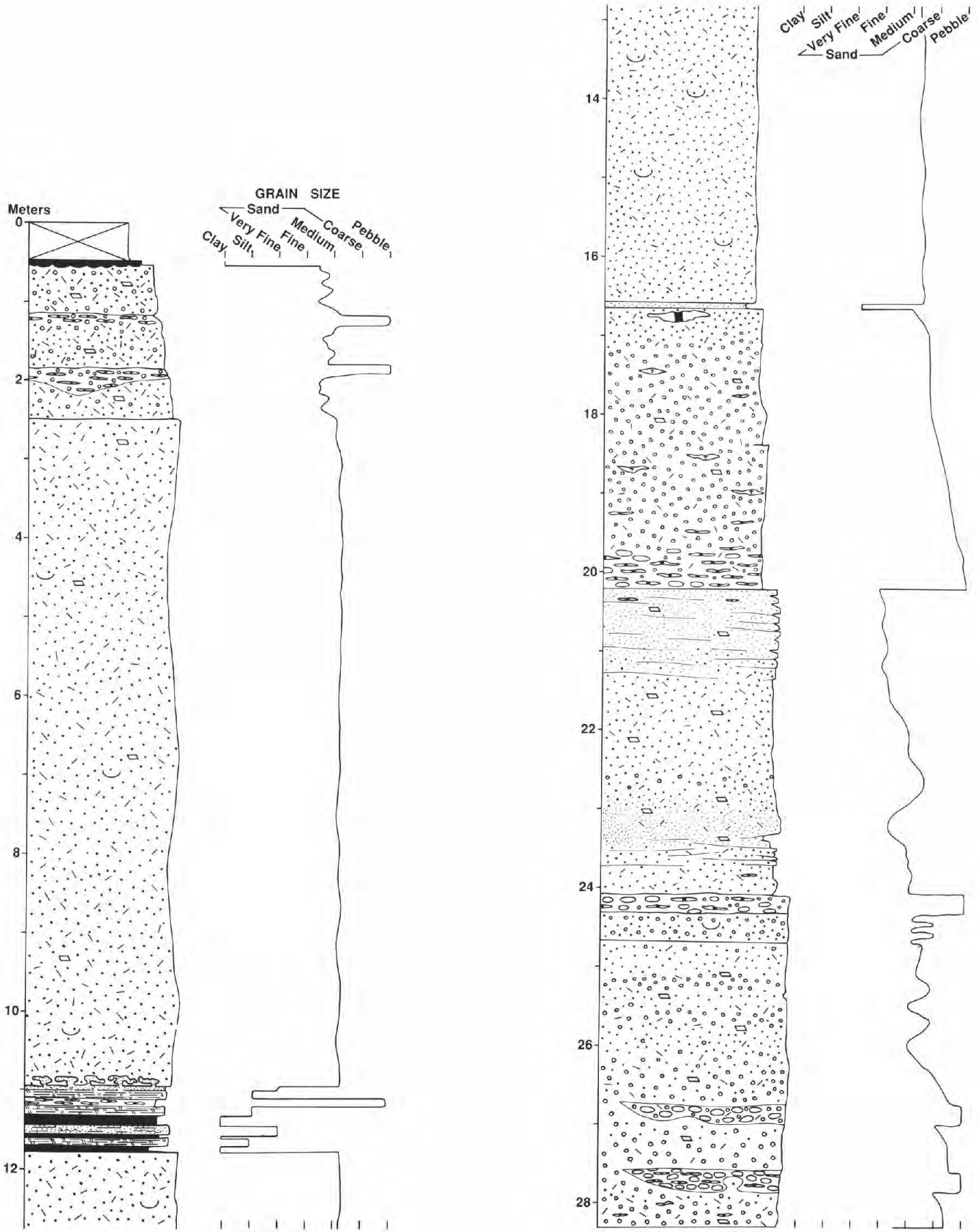


Figure 7. Columnar stratigraphic section showing bed forms and other structures typical of lithofacies II. The location is given in Figure 6. Note scour between meters 37 and 38, channeling, and the distribution and orientation of claystone and siltstone intraclasts. While uniform grading patterns are not apparent, most sandstone beds show widely spaced laminations and (or) banding near the stratigraphic tops.

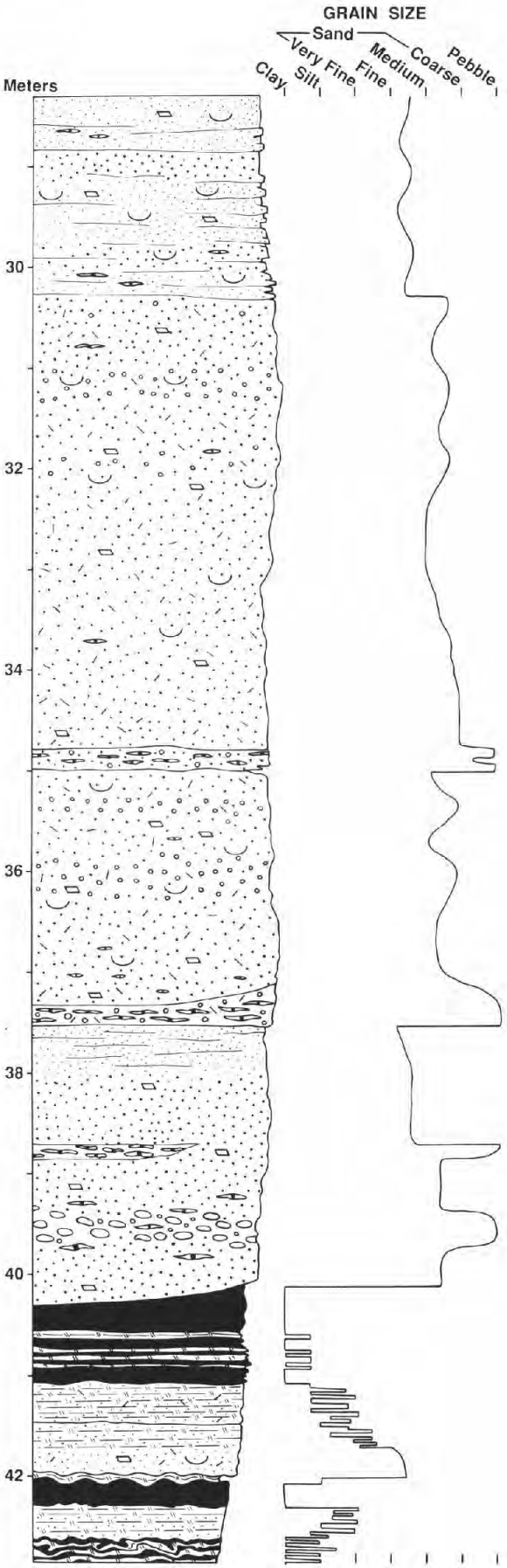


Figure 8. Detail of meters 36–38 of the lithofacies II columnar stratigraphic column (Fig. 7). The stratigraphic top is to the left. Note banding and laminations near the top of the lower sandstone bed (darker gray, fine-grained sandstone) and the scouring (at hammerhead) at the base of the upper bed (light gray, coarse-grained sandstone).

Lithofacies IV sandstones in the Matheny Ridge area appear to have lateral continuity on the order of several hundred meters. These sequences are mostly observed adjacent to, or grading into, lithofacies II sandstones. Some scouring is present, but many units maintain constant thicknesses over tens of meters (Fig. 11).

Lithofacies IV sandstones and finer clastic rocks are interpreted as submarine levee and overbank deposits.

Minor Lithofacies

Complete Bouma sequences have been observed in only a few outcrops in the western and central parts of the Olympic Peninsula. Bouma sequences are best exposed near Browns Point north of Kalaloch (Grady, 1985; Rau, 1979). It seems unlikely that more extensive Bouma sequences are present but not exposed because ubiquitous thrusting (Fig. 2) would have revealed parts of any extensive midfan sandy lobe sequence.

Igneous rocks in the Core Complex consist of basic to intermediate(?) lavas and heterogeneous volcaniclastic rocks. Sedimentary structures and heterogeneous lithologies at Sore Thumb, and possibly at Steeple Rock, suggest that some of the

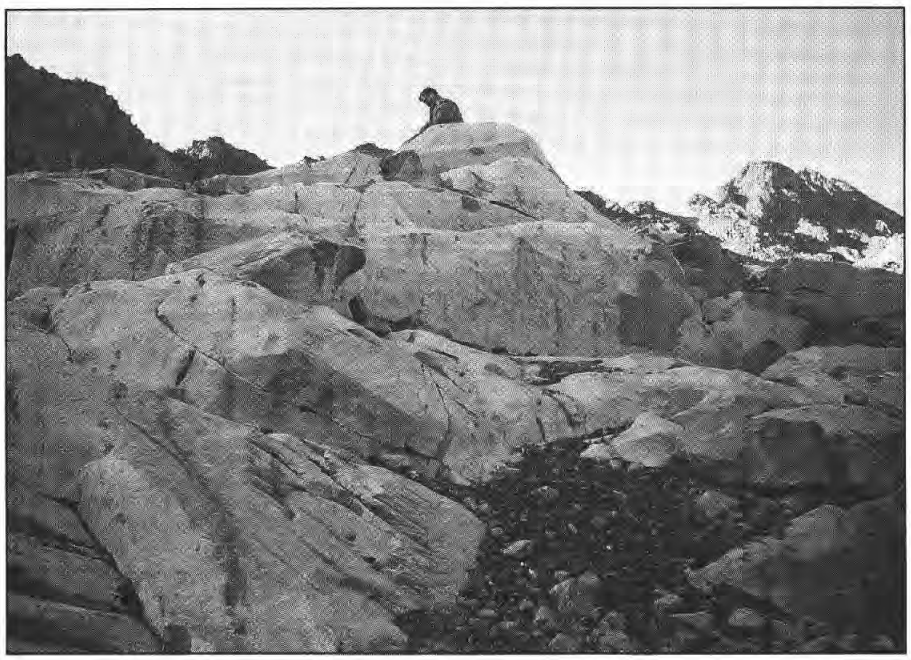


Figure 9. Detail of meters 30–40 of the lithofacies II columnar stratigraphic column (Fig. 7). The stratigraphic top is to the left. Note the size and distribution of shale and siltstone rip-up clasts.

volcaniclastic units may be channel-fill sequences similar to those of lithofacies III.

If the accretionary prism developed in a normal sequence, progressive westward shoaling through time could be expected. However, the incomplete faunal record indicates mainly deep marine biofacies. The few shelfal forms observed are mixed with deeper water assemblages, suggesting redeposition. Heller and others (1992) noted flaser bedding and cross-bedding in the Grand Valley Lithic Assemblage, suggesting shallow-water deposition. We have observed small-scale trough cross-beds near Mount Hopper and Sentinel Peak and cross laminations in many other parts of the Core Complex. Thin coal stringers and traces of bioturbation are present in a few outcrops. However, none of these features are necessarily indicative of shoaling. (See Mutti and others, 1992.)

Most 'melanges' described in the Core Complex are broken formations typical of rocks in thrust belts worldwide. Melanges appear to be limited to muds injected along thrusts, diapirs, and late Miocene strike-slip faults (Palmer and Lingley, 1989; Orange, 1990). The Clearwater River Shear Zone of Stewart (1970), which cuts across regional structure, and the equant Duck Creek diapir (Rau and Grocock, 1974) are well-documented examples. A 5-km-wide band of intense shearing and phacoid development that parallels regional structure and extends for about 10 km northwest from Lake Quinault may be the result of thrust faulting. In this area, shear sets are oriented subparallel to or at about 60 degrees to the lithologic layering. A scaly cleavage and crudely aligned phacoids are also subparallel to bedding (Fig. 12). Many similar features are mapped by Rau (1975, 1979). Except for minor slumps, we have not observed turbidite landslide deposits (F facies) in the Core Complex. The lateral continuity of the bands of shearing and phacoids suggests that these are not relict submarine debris flows.

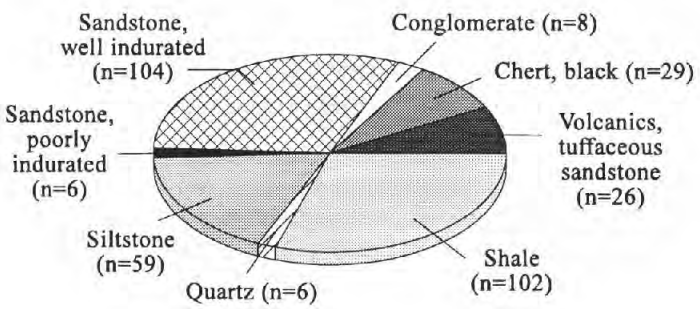


Figure 10. Relative abundances of some lithofacies III clasts observed east of Yahoo Lake, south of Mount Octopus, on Huelsdonk Ridge, and southwest of Matheny Ridge.

DISCUSSION

Lithofacies II and III are interpreted here as submarine channel-fill sequences. Lithofacies IV beds are probably levee and overbank deposits associated with these channels. The 'thin-bedded turbidites' of lithofacies I are thought to be mainly interchannel/overbank deposits. Shales in the Elwha Lithic Assemblage are the only rocks that may be the distal equivalent of these channel deposits. These relations are shown in Figure 13. Faunal paleobathymetry and a lack of bioturbation suggest these rocks were mostly deposited on the outer shelf or slope.

The Olympic Core Complex contains abundant marginal wedge sequences (lithofacies I) that are commonly associated with major rivers elsewhere (Mutti and others, 1992). These deposits, together with the large apparent width of some channel deposits, suggest that a single large river could have fed the entire depositional system.

By middle Eocene time, Crescent Formation basalts formed a fairly continuous highland that may have isolated the Core Complex from adjacent terranes (Palmer and Lingley, 1989). However, the 'Sequim gap', located between two probable eruptive centers in the northeastern Olympic mountains (Babcock and others, 1994), may have allowed a paleo-Fraser or paleo-Columbia river to issue out onto the Eocene shelf and carve an extensive submarine channel system. During the Oligocene, adjacent basins in the Puget trough foundered (Lingley and others, 1993; Johnson and others, 1994). These deep basins may have pirated rivers that supplied detritus to the Juan de Fuca plate, thus starving the Core Complex between 34 and 27 Ma. Following early Miocene filling of the adjacent subbasins, rapid sedimentation continued in the Core Complex, possibly in thrust-bounded piggyback basins (Boyer and Lingley, 1994).

Initial uplift of the Olympic mountains may have begun as early as 17 Ma, as evidenced by abundant Crescent-like detritus in cores from coastal wells that penetrated the Hoh Lithic Assemblage (Palmer and Lingley, 1989; Rau, 1973) and a lack of basaltic detritus in many sections of the younger Montesano Formation, which unconformably overlies rocks of the Core Complex (Bigelow, 1987; Palmer and Lingley, 1989). This incipient uplift of the Olympic mountains may have exhumed and eroded foliated Elwha Lithic Assemblage slates. Pencils plucked from these slates may have been redeposited from a

smaller channel system(s) in areally restricted midfan sandy lobes on a localized fan(s) now located near the coastline.

Boundaries between lithic assemblages mapped by Tabor and Cady and by Rau are explicable in terms of facies associations and thrust tectonics. It is not necessary to invoke terrane boundaries to explain contacts. A possible exception is in the northwesternmost Olympic Peninsula where Jurassic and Cretaceous rocks mapped by Snavely and others (1993) may be a hanging-wall imbricate of a buried Mesozoic terrane. However, lithologic monotony of Paleogene strata suggests that most of the Core Complex is a single terrane.

Acknowledgments

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Figure 11. Typical exposes of lithofacies IV sandstones and fine siliciclastic rocks located southwest of Matheny Ridge.

Figure 12. Penetratively sheared sandstones, shales, and siltstones on Matheny Ridge. Note the sandstone phacoid on the left, which is subparallel with the dominant shear set (weathered nonresistant layers rising to the left) and large rotated phacoid ('map of Africa' on the right).

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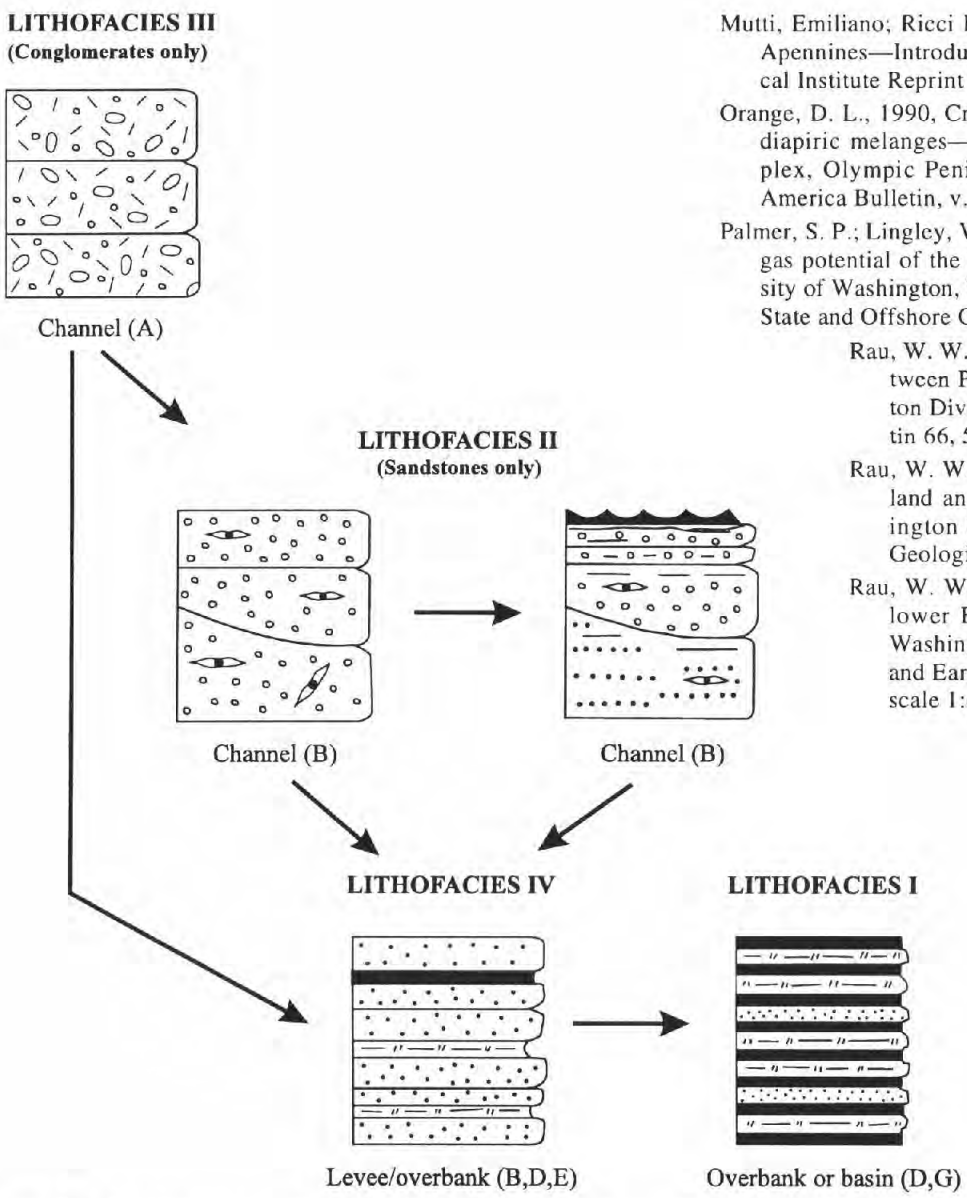

Figure 13. A tentative interpretation of important lithofacies observed within the Olympic Core Complex. Arrows indicate transitional relations observed in the field.

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Palm Fossils from Northwest Washington

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INTRODUCTION

'Ancient forests', 'global climate change', 'destruction of the rain forest'— these phrases appear almost daily in the pages of our newspapers, describing phenomena that are interpreted as important barometers of environmental change. We can also look at these 'barometric' concepts in a very different way, using fossils to study evolutionary progressions that occurred eons before humans arrived on the scene. Plant remains are particularly important for understanding our region's history because they provide an accurate indication of ancient climate and topography, and they are much more abundant than animal fossils.

Cretaceous leaf impressions provide the earliest evidence of Washington plant communities, but our first comprehensive knowledge of ancient flora comes from the Early Tertiary, when the landscape was dominated by lowland environments conducive to both luxuriant plant growth and preservation of leaf imprints. Fossils from these deposits indicate that semi-tropical rain forests flourished on an extensive plain that existed prior to the rise of the Cascades. The abundance of palm fossils in the Eocene Chuckanut Formation provides prominent evidence that these plant communities were much different from the temperate forests that exist today. These fossils include large leaf imprints, wood casts, and pollen grains (Figs. 1–4). Palm fronds are on display at the Burke Museum (Univ. of Washington) in Seattle and at the Western Washington University Geology Department in Bellingham.

Figure 1. Palm frond imprints exposed on a bedding plane in the Mount Baker foothills near Canyon Lake, Whatcom County, Washington.

GEOLOGIC SETTING

The Chuckanut Formation consists of nearly 6,000 m of strata exposed in a 20 km by 60 km outcrop belt that extends from Puget Sound to the foothills of the North Cascades in western Whatcom and Skagit Counties (Fig. 5). Johnson (1984) subdivided the Chuckanut Formation into seven stratigraphic members that represent different depositional environments within an ancient fluvial system. Leaf impressions are particularly abundant in siltstones of the Bellingham Bay and Slide Mountain Members. These strata represent wetlands that bordered the ancient river, where the abundance of vegetation and conditions of sedimentation combined to offer an ideal environment for the preservation of fossils. In contrast, the arkosic sandstones and conglomerates that make up much of the Chuckanut Formation were deposited along beaches and river bars; they contain many driftwood impressions but few fossil leaves.

Fission-track dating of detrital zircon grains and volcanic interlayers suggests that Chuckanut sediments were deposited during the Eocene epoch and are younger than the Late Cretaceous–Paleocene age estimate previously deduced from plant fossils (Pabst, 1968). Johnson (1984) estimates that the base of the formation is no older than 55 Ma and the the youngest strata were deposited about 40 Ma. He reported a tuff layer, 2,700 m above the base of the formation, that has a fission-track age of 49 ± 1.2 Ma. An interbedded rhyolite flow of uncertain stratigraphic position has been dated at 52.7 ± 2.5 Ma (Whetten and others, 1988).

PALEONTOLOGY

Descriptions of Chuckanut Formation fossils include brief reports by Lesquereux (1859), Newberry (1863, 1898), Knowlton (1902), LaMotte (1938), Chaney (1951), and Butala and Cridland (1973). Pabst (1968) studied fossil ferns, conifers, and horsetails, and her unpublished manuscripts contain de-

Figure 2. Cast of palm trunk preserved in growth position, discovered near the summit of Bacon Peak, North Cascades. Photo by R. A. Haugerud, USGS.

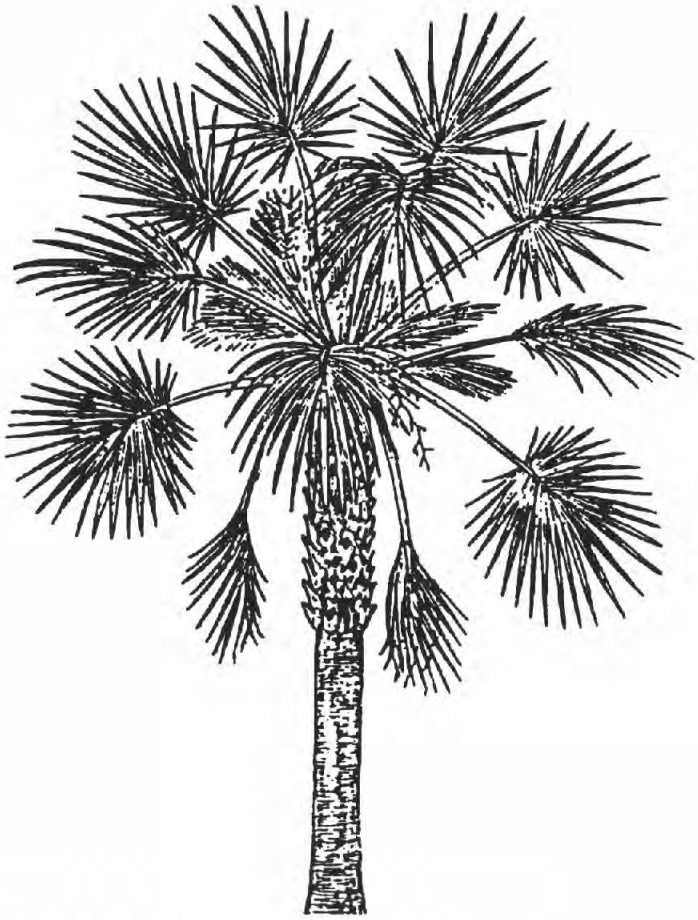


Figure 3. Reconstruction of *Sabalites* (Berry, 1930).

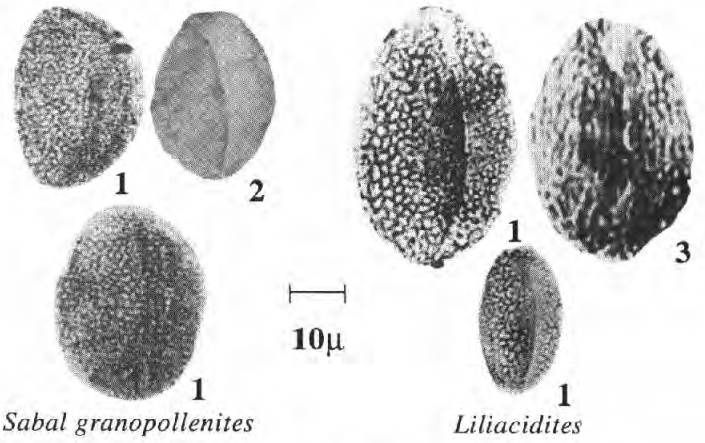


Figure 4. Fossil pollen from the Chuckanut Formation. (Sources: 1, Hopkins, 1966; 2, Griggs, 1970; 3, Reiswig, 1982.)

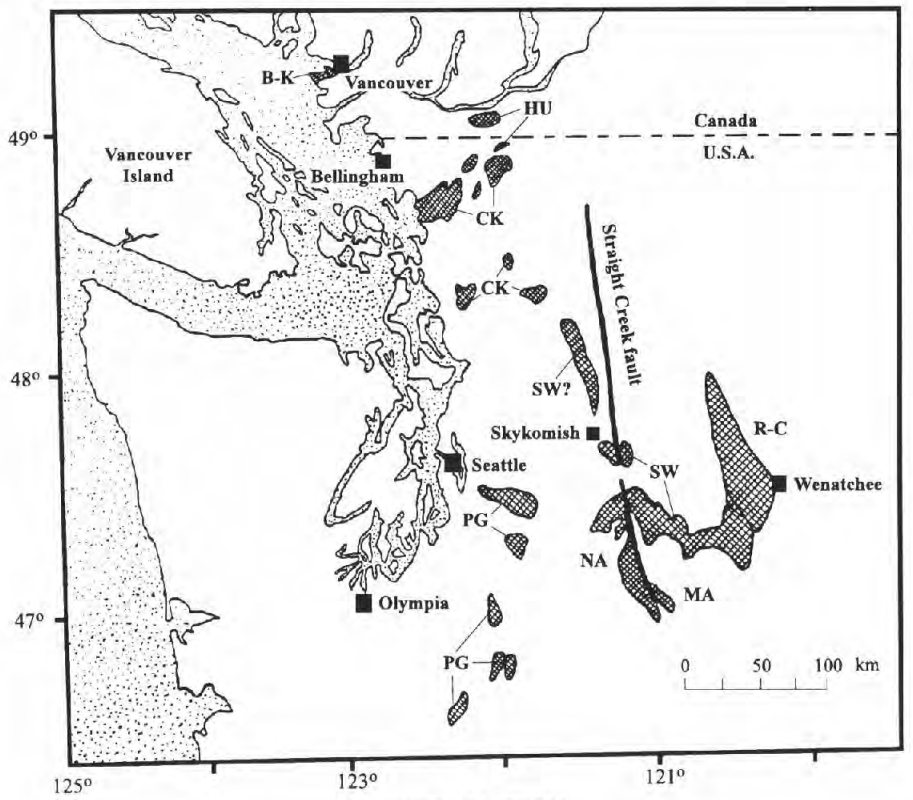
scriptions of many flowering plants (Pabst, 1952). Pollen has been examined by Crickmay and Pocock (1963), Hopkins (1966), Griggs (1970), and Reiswig (1982). Other fossils include a turtle, fresh-water mollusks, and tracks of a heron-like bird (Mustoe and Pevear, 1981; Mustoe, 1993).

The Chuckanut flora probably represents a paratropical rain forest, as defined by Wolfe (1977). These forests have more open canopies than true tropical rain forests and have a greater abundance of large single trees. Paratropical rain forests occur in humid climates that have a mean annual temperature of 20–25°C. The lowland forests of southern China provide a modern example.

Dicotyledonous leaves are common fossils in the Chuckanut Formation, but few have so far been identified. However, their vegetational characteristics (such as the abundance of large, simple leaves having smooth margins, and the relative scarcity of lobed or serrate margins) are typical of plants that inhabited a humid frost-free climate. Distinctive semitropical taxa include a tree fern, *Cyathea pinnata* (MacGinitie) La Motte, and a variety of climbing plants (such as the climbing fern *Lygodium kaulfussi* Heer, and two flowering vines, *Tetracera* and *Goweria*). However, the flora is diverse and includes *Platanus* (sycamore), *Alnus* (alder), *Corylus* (hazel), *Sassafras*, and other genera that now inhabit temperate forests. Conifers consisted of lowland-dwelling members of the Taxodiaceae (yew family) and Cupressaceae (cypress family) such as *Taxodium*, *Mesocyparis*, and *Glyptostrobus*.

PALM FOSSILS

Early paleobotanists commonly attempted to classify ancient frond imprints using genus names previously established for living palms, an approach that proved to be unreliable. Instead, Read and Hickey (1972) proposed a classification scheme that divides ancient palms into 'form genera' based on leaf shape, without regard to actual genetic relationships. Palmate (fan-shaped) fronds are identified as *Sabalites* or *Palmacites*, depending on the geometry of the leaf base; pinnate (feather-shaped) fronds are placed in the form genus *Phoenicites*. A



EXPLANATION

Middle to late Eocene (46–36 Ma)

HU, Huntingdon Formation
R-C, Roslyn and Chumstick Formations
PG, Puget Group*
NA, Naches Formation*

Early to middle Eocene (55–40 Ma)

B-K, Burrard* and Kitsilano Formations
SW, Swauk Formation*
MA, Manastash Formation
CK, Chuckanut Formation*

Figure 5. Early Tertiary nonmarine sedimentary rocks in western Washington and adjacent British Columbia. *, contains fossil palms. References: Heller and others (1987), Griggs (1970), and Gresens (1982).

similar form genus system has long been used to describe other types of plant tissue; fossil palm wood is identified as *Palmoxylon*, while seeds similar to to those of living palms are named *Palmocarpon*. Fossilized roots, flowers, and pollen are identified using other generic names. Although this system results in the organs of a single plant being given a variety of scientific names, it provides a workable solution to a difficult taxonomic situation.

Palm leaf fossils collected from Bellingham Bay by the 1841 Wilkes Exploring Expedition were named *Sabal campbelli* (Newberry, 1863, 1898), amended to *Sabalites campbelli* by Lesquereux (1878). These identifications were later questioned by other paleobotanists. Duror (1916) identified imprints from the Swauk Formation near Skykomish, Washington, as *Sabal powelli*, a species first reported from the Eocene Green River Formation of Wyoming (Newberry, 1883). If outcrop map patterns are corrected for an estimated 190 km of north-south relative motion along the Straight Creek fault during the subsequent rise of the North Cascades range, the Swauk and Chuckanut Formations appear to have been deposited as part of a single depositional basin (Frizzell, 1979).

Brown (1962) claimed that palms from the Chuckanut Formation were actually *Sabalites grayanus*, a species name first used to describe Eocene fronds from the southeastern U.S. (Lesquereux, 1878). Knowlton (1919) stated that Newberry's specimens of *S. campbelli* included a second species of palm, *Sabal (?) ungeri*, an allegation repeated by Knowlton (1930) and LaMotte (1952). Thorne (1976) independently observed that the Chuckanut flora contains at least two types of palms.

Leaves of *Sabalites campbelli* (Newberry) Lesquereux are the most common palm fossil in the Chuckanut flora (Fig. 6). Brown (1962) claims that these frond imprints should be identified as *Sabalites grayanus*. Lesquereux is doubtful for several reasons. The name *S. grayanus* was originally assigned to Eocene palm fossils from Lafayette County, Mississippi, by Lesquereux (1869), but his published description is vague, and the original specimens have been lost for nearly a century. The best available definition of the species is that of Berry (1916), who studied specimens from Lesquereux's type locality and about 40 other sites in Mississippi, Arkansas, Louisiana, Texas, and Tennessee. Examination of leaf cuticle indicates that these fronds actually represent several coryphoid palms that have similar leaf shapes (Dilcher, 1968; Daghlian, 1978). *S. grayanus* has also been used as a catchall term to describe a wide variety of palmate leaf impressions from the western U.S. For example, Brown (1962) uses this name to include eleven forms that he considered to be synonymous.

Fronds of *S. campbelli* and *S. grayanus* both have petioles that extend into to the underside of the leaf as an acutely terminated triangle (acumen) having concave margins. On the upper leaf surface, the acumen is very short with a rounded or broadly triangular margin. Despite these structural similarities, fronds from the Chuckanut Formation are much larger in diameter than specimens of *S. grayanus* from type locations in the southeastern states. *S. grayanus* fronds typically have diameters of about 1 m, approximately half the size of typical Chuckanut *S. campbelli* imprints. Although the size of a particular palm leaf may be related to stage of growth, environmental factors, or conditions of fossilization that selectively favor intact preservation of small fronds, the consistently observed differences in leaf diameter indicate that *S. campbelli* and *S. grayanus* are not synonymous. In addition, paleogeographic barriers that separated the Pacific Northwest from the southeastern region probably would have hindered the transcontinental dispersal of either species.

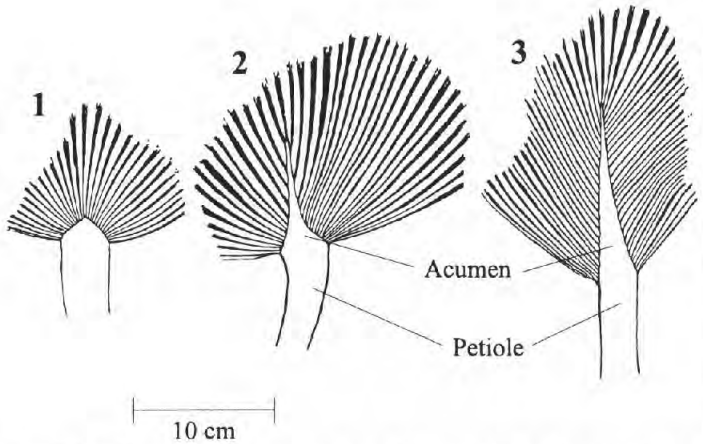


Figure 6. Sketches showing leaf base architecture of Chuckanut Formation palm imprints. 1, *Sabalites campbelli* (upper leaf surface); 2, *S. campbelli* (lower leaf surface); 3, *Sabalites* cf. *S. ungeri* (lower leaf surface). Specimens showing the upper surface of the latter species have yet to be found.

Sabalites campbelli occurs abundantly in fossiliferous strata of the Chuckanut Formation, regardless of geographic location and stratigraphic position. Less commonly, outcrops contain fronds of a second type, recognizable by the extension of the petiole into the lower surface of the leaf for a distance of 15 cm or more. This acumen is in the form of a narrow, straight-sided triangle, in contrast to the curved acumen margins characteristic of *S. campbelli*. These leaves closely resemble descriptions of *Sabal (?) ungeri* (Lesquereux) Knowlton from the Paleocene Raton Formation of New Mexico (Knowlton, 1917), later renamed *Sabalites ungeri* (Dorf, 1939).

The presence of two types of fronds is consistent with palynologic evidence. Griggs (1970) identified *Sabal granopollenites* Rouse from outcrops along Chuckanut Drive near Bellingham, a palynomorph that is similar to pollen of the modern *Sabal palmetto*. Griggs also recognized abundant occurrences of *Liliacidites*, a form genus of uncertain botanical affinity that he believed to be from a palm because of its presence in strata that also contain frond imprints. Although *S. campbelli* and *S. ungeri* fronds have not yet been found together, the mutual occurrence of *Sabal granopollenites* and *Liliacidites* pollen at sites spanning approximately 2,700 m of stratigraphic section exposed along Chuckanut Drive suggests that the two taxa were contemporaneous and broadly distributed in time. *S. granopollenites* and *Liliacidites* have also been identified from other sites in the Chuckanut Formation (Hopkins, 1966; Reiswig, 1982).

PALEOECOLOGY

Sabalites and *Palmicites* leaf imprints occur in other Tertiary formations in the Pacific Northwest, extending from Alaska to California (Table 1), and their distribution provides important indications of paleogeography and paleoclimate. Although early palms show great latitudinal range, their distribution was restricted to regions of low elevation and frost-free climate. Prior to the onset of the Cascade Range orogeny at the close of the Eocene, a broad coastal plain extended well into central Oregon and Washington, providing suitable habitat for palms and other subtropical vegetation. These plants are not present in sediments of the same age that were deposited at paleoaltitudes exceeding approximately 300 m (Axelrod, 1968). Examples of Early Tertiary upland floras where palms are absent include Republic (Wolfe and Wehr, 1987) and Pipestone Canyon, Washington (Royse, 1965), and Thunder Mountain, Idaho (Axelrod, 1990).

Table 1. Occurrence of Tertiary palms in western North America. Data from La Motte, 1952; Lakhanpal, 1958; Tuta, 1967; Wolfe, 1968; Gregory, 1969

Location	Formation
PALEOCENE:	
Colorado Springs, Colorado	Dawson Arkose
Pagosa, Colorado	Animas Formation
Golden, Colorado	Denver Formation
Fishers Peak, Colorado	Raton Formation
Raton Mountains, New Mexico	Raton Formation
Yellowstone River, Montana	Fort Union Formation
EOCENE:	
Plumas County, California	La Porte flora
Nevada County, California	Chalk Bluffs flora
Clarno, Oregon	Clarno Formation
Green River, Wyoming	Green River Formation
Tipperary, Wyoming	Bridger Formation
Bellingham, Washington	Chuckanut Formation
Skykomish, Washington	Swauk Formation
King County, Washington	Puget Group
Gulf of Alaska	various
Vancouver, British Columbia	Burrard Formation, Kitsilano Formation
OLIGOCENE:	
Cottage Grove, Oregon	Rujada flora
Multnomah County, Oregon	Eagle Creek Formation
Skamania County, Washington	Eagle Creek Formation
MIOCENE:	
Tehachapi, California	not listed
Barstow, California	not listed
PLIOCENE:	
Last Chance Canyon, California	Ricardo beds
Rosamond, Mohave area, California	not listed

Evidence from the middle Eocene Allenby Formation near Princeton, British Columbia, is more complicated. Although silicified palm stem and leaf fragments are abundant in a thick sequence of chert beds, palms are absent in the nearby clastic sediments. Fossils in these shales indicate a mixed deciduous inland forest. In contrast, the chert unit was deposited within a marshy environment rich in monocotyledons (Erwin and Stockey, 1991). This botanical variation within a single geologic formation is significant because our knowledge of ancient plants mostly comes from fossils collected from shales and siltstones, which do not necessarily represent the only favorable palm habitat.

Palms began to disappear from the Pacific Northwest near the close of the Eocene Epoch in response to climatic cooling (Wolfe, 1978) and geographic changes associated with uplift of the Cascade and Coast Ranges. This orogeny destroyed the

extensive coastal plain, altered the pattern of rainfall, and reduced the influence of warm ocean currents on inland climate. Of these multiple factors, the decline in global temperatures seems to have been the most important factor in causing the extinction of palms. This observation is based on the presence of *Sabalites* imprints in the middle to late Eocene Swauk Formation of central Washington and their absence in the slightly younger Roslyn and Chumstick Formations. The petrologic similarity of these arkosic formations suggests that they were all deposited in similar fluvial settings and that paleobotanical differences are largely due to climatic variation rather than geographic change.

Sabalites occurs in the Rujada flora near Cottage Grove, Oregon (Lakhanpal, 1958), and in the Eagle Creek flora of the Columbia Gorge (Chaney, 1920). These sites are believed to be of Oligocene age, although neither has been dated with certainty. If these age estimates are correct, these fossils are the youngest known occurrence of palms in the Pacific Northwest. By the middle Tertiary, palms had retreated to the frost-free regions of southern California, as indicated by various Miocene and Pliocene fossils (Tuta, 1967). At present, the only remaining native palms of western North America are three species of *Washingtonia* that inhabit the dry interior regions of southern California and Mexico.

What ecologic lessons can be learned from the extinction of the palms that once inhabited the Pacific Northwest? For one thing, the phenomenon points out our poor understanding of global climatic trends, as we have little explanation for the Eocene–Oligocene temperature shift. The fossils also provide a reminder that major biologic transitions are not reversible. If we were able to change our region's climate back to the temperature and rainfall conditions of the Eocene Epoch, our forests would again take on a semitropical character, but they would not revert to the original floral composition. This is partly because many Early Tertiary plants became extinct, leaving no close modern relatives. In addition, we would see a proliferation of introduced species as the decorative plants of our greenhouses and living rooms escaped to the freedom of the great outdoors. If palms returned to a new Washington climate, they would likely be relatives of courtyard palms of hotels and shopping malls, rather than descendants of *Sabalites campbelli*.

It's also important to realize that the global-cooling episode that so greatly affected the ancient Pacific Northwest forests probably occurred at a rate that would have been undetectable by climatologists. Indeed, if the survival time of *Homo sapiens* as a species proves to be similar to that of other specialized mammals, our entire existence could have been played out during the Early Tertiary without our ever noticing a change in the weather.

Finally, modern plants and animals face environmental influences unlike those that existed 50 million years ago. Fossil palms are evidence of a major botanical shift that resulted from gradual natural processes, but the patterns of biologic change we observe today are different. Compared to the dominant organisms of the Early Tertiary, humans have an astonishing ability to alter the environment. We have become important agents of geologic and biologic change, and our activities influence the survival and extinction of many of the organisms with whom we share the planet. Rather than being caused by the uplift of new mountain ranges or changing positions of the continents, future climate change may possibly be due to the effects of air pollution. Extinction of species is commonly a result of habitat destruction, and unexpected patterns of succession may result when pests, predators, and disease-producing microbes are transported to distant regions on ships or planes. For these reasons, modern forests may be experiencing transition rates quite unlike their Cenozoic counterparts.

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A free 1995 Pocket Guide to Oregon Museums has just been published by the Oregon Museum Association, the Oregon Historical Society, and museums throughout the state. It lists locations, hours, general contents, and admission charges, if any, of over 130 museums.

The guide tells you where you can find out about Oregon's history, art, geology, wildlife, plants, natural resources, and industries and which museums have hands-on displays and activities where you can learn by doing.

The guide is available at most Oregon museums. Single copies may be obtained by sending a self-addressed, stamped, legal-size envelope to the Nature of the Northwest Information Center, 800 NE Oregon Street #5, Portland, OR 97232.

Application of Reflection Seismology to the Hydrogeology of the Spokane Aquifer

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INTRODUCTION

The Spokane Aquifer is part of a regional ground-water system termed the Spokane Valley–Rathdrum Prairie Aquifer, which encompasses portions of the north Idaho panhandle and eastern Washington near Spokane (Fig. 1). The aquifer is known to be one of the most transmissive alluvial-type aquifers in the United States and is the designated sole-source aquifer for more than 350,000 people living in the Spokane Valley area.

The Spokane Aquifer consists predominantly of sand- to boulder-size sediments deposited by catastrophic outburst floods from episodic draining of Pleistocene glacial Lake Missoula. These unconsolidated deposits consist of coarse main-channel sediments in the Spokane Valley and finer eddy deposits in tributary valleys. The deposits overlie relatively impermeable Precambrian to Cretaceous crystalline bedrock and Miocene sedimentary rocks of the Latah Formation and Columbia River basalts. The flood deposits are typically 400 to 600 ft thick in the main valley east of Spokane and more than 700 ft thick north of Spokane in the Hillyard trough. The aquifer is unconfined throughout most of the valley and typically exhibits a strong degree of hydraulic interconnection with the Spokane River. However, previous water balance estimates for the Spokane Aquifer have relied upon little direct data on aquifer thickness.

The bedrock topography beneath the valley floor is the primary control on aquifer thickness and, in turn, affects the direction, rate, and quantity of ground-water flow. Shallow seis-

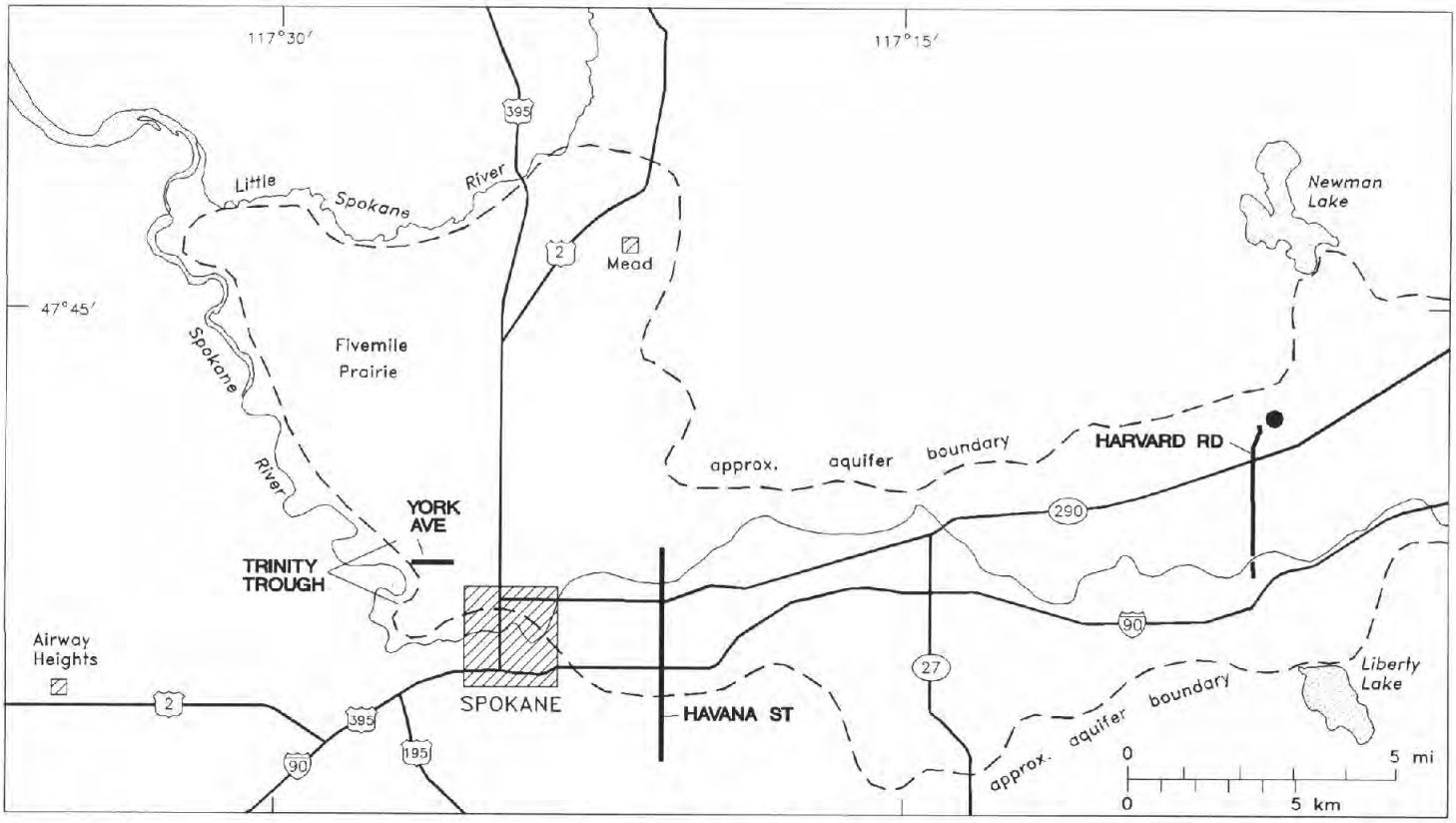

Figure 1. Location map of the greater Spokane Valley and vicinity. The Spokane Valley–Rathdrum Prairie Aquifer is outlined. The location of the Harvard Road, Havana Street, and York Avenue seismic profiles is shown.

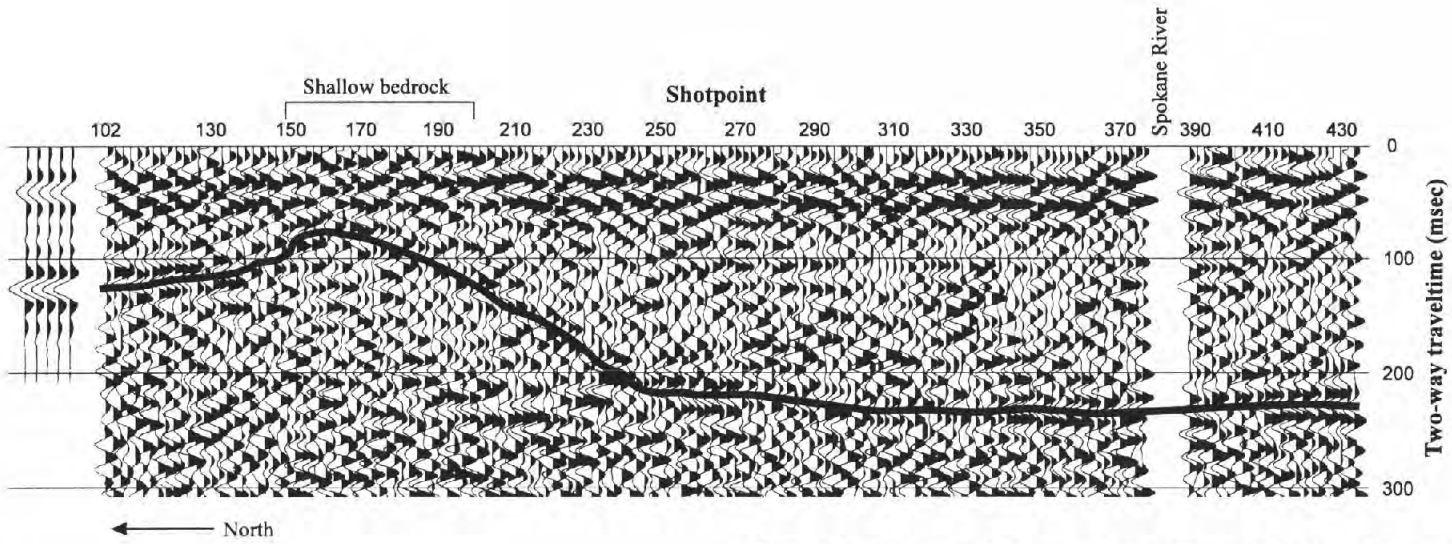

Figure 2. Seismic profile acquired along Harvard Road; we interpret the highlighted reflector as originating at the aquifer–bedrock contact. Shotpoint numbers are shown along the top edge of the profile; north is to the left. The five identical traces at the very left of the profile are synthetic seismograms developed from the Harvard Road check-shot survey.

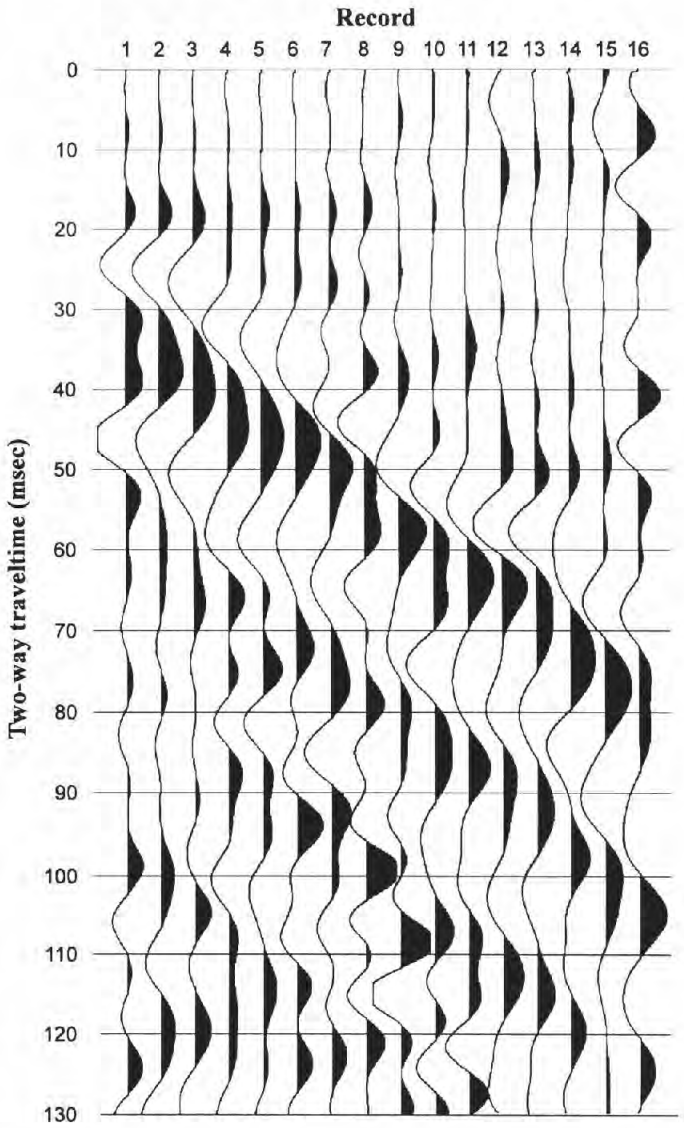

Figure 3. Waveform data from the Harvard Road check-shot survey. The direct seismic wave traveling from source to downhole geophone is the high amplitude event arriving between 20 and 80 msec.

mic reflection profiling was conducted to provide better definition of the aquifer thickness and bedrock topography. This information will be used in aquifer-management investigations conducted by Spokane County and in wellhead protection studies performed by the City of Spokane and other water purveyors. Seismic profiles acquired in the eastern Spokane Valley (Fig. 1) will provide constraints on aquifer thickness and geometry, which are critical parameters in any future estimate of water balance and supply. Seismic reflection data obtained in an area between Spokane Falls and Five Mile Prairie (Fig. 1) will be used to refine boundary conditions for a wellhead protection ground-water flow model and may influence future location of municipal water supply wells.

METHODOLOGY

The seismic reflection data were acquired using a new impulsive seismic source that inhibits ground roll (large amplitude seismic waves that travel on the ground surface from source to receiver). The lack of ground-roll interference from the source enables the implementation of a near-offset method of reflection seismic surveying in which a short source-receiver offset, as close as 5 ft, is employed using a limited number of geophones (usually 2 or 3). The short offset and limited number of geophones permits rapid collection of vertically summed reflection data. This near-vertical ray path eliminates the need for long cable layouts used in the acquisition of Common Depth Point reflection data, and reduces the data processing to a few basic steps: appropriate temporal filtering, static correction, and amplitude scaling. Preliminary processed sections can be available on a next-day basis, which allows the flexibility to locate "today's" profiles on the basis of "yesterday's" data. Additionally, the near-offset method's flexibility and minimal source noise impacts allow it to be used in a wide variety of hydrogeologic settings, including noise-sensitive urban environments.

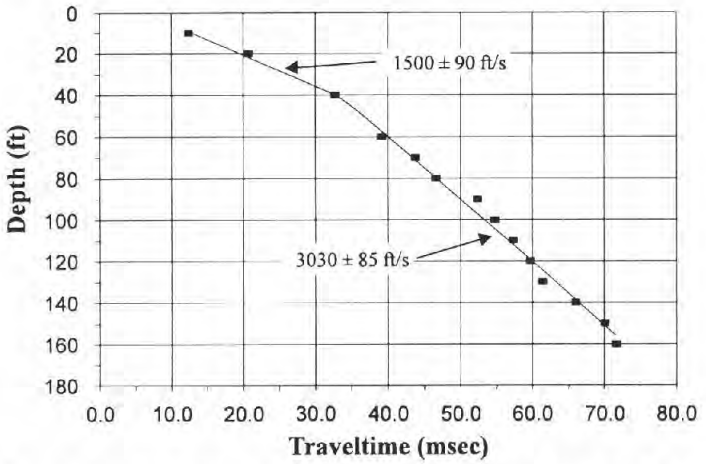

Figure 4. Traveltime–depth curve developed from the Harvard Road check-shot data shown in Figure 3.

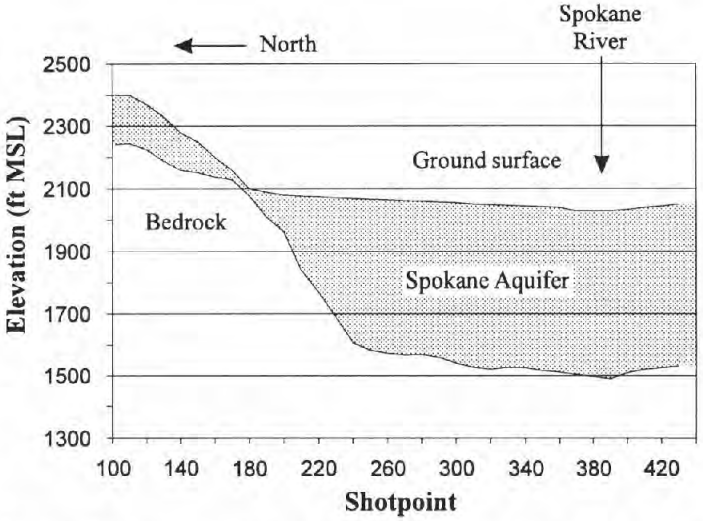

Figure 5. Cross section showing the depth to the bedrock surface along Harvard Road developed from the seismic profile and velocity data. The aquifer thickness exceeds 500 ft in the center of the main valley.

REGIONAL SEISMIC PROFILING

Seismic reflection profiles acquired in the eastern Spokane Valley provide data about the depth and configuration of the aquifer–bedrock contact that will be used for future water balance analyses. A north–south profile shot along Harvard Road (Fig. 1) provides an excellent example of our approach to mapping the aquifer–bedrock contact.

Figure 2 presents the Harvard Road seismic reflection profile; the spacing between individual traces (shotpoints) is 100 ft. We interpret the strong, flat-lying reflection observed between shotpoints 250 and 430 at approximately 220 to 240 millliseconds (msec) two-way traveltime as originating from the aquifer–bedrock contact. Starting at shotpoint 240 this reflector begins to climb, and between shotpoints 150 and 190 the bedrock contact is very near the ground surface. Water wells drilled near shotpoint 170 penetrated crystalline bedrock at depths ranging from 20 to 50 ft; bedrock outcrops can also be observed adjacent to this portion of the profile. North of shotpoint 150, a prominent reflector can be observed between 100 and 125 msec two-way traveltime, which is interpreted as the bedrock–aquifer contact. Water wells located near this segment of the profile encountered crystalline bedrock at depths of 150 to 200 ft.

Well-velocity, or check-shot, surveys are performed in order to (1) estimate seismic velocities for the rock or soil units penetrated in a well and (2) obtain the two-way traveltime to stratigraphic interfaces that give rise to strong reflections (for example, the aquifer–bedrock contact). A check-shot survey involves lowering a geophone to known depths in a well and then measuring the seismic wave traveltime from a source located near the wellhead to the downhole geophone.

Figure 3 presents the check-shot data for a water well near the north end of the Harvard Road seismic profile. The data were recorded in 10-ft depth intervals from a depth of 10 ft (record 1) to 160 ft (record 16). The check-shot well penetrates 180 ft of unsaturated aquifer sand and gravel lying over crystalline bedrock. Water is produced from fractured bedrock just below this contact. A traveltime–depth curve (Figure 4) was constructed from the check-shot data, and seismic velocities were estimated. We find that unsaturated sand and gravel in the upper 40 ft has a velocity of 1,500 ft/s; below this depth the velocity increases to 3,030 ft/s. Check-shot surveys performed in other water wells in the Spokane Valley indicate that the seismic velocity of saturated sand and gravel is approximately 5,500-6,000 ft/s. Crystalline bedrock can have seismic velocities ranging from 10,000 to 15,000 ft/s.

A synthetic reflection trace was generated from the velocity data obtained in the Harvard Road well for comparison to the reflection data acquired near the well. The five identical traces displayed on the left in Figure 2 are the synthetic seismograms developed from the check-shot data. The aquifer–bedrock interface appears on both the synthetic seismogram and the seismic profile as a strong reflector at 100 to 125 msec two-way traveltime. The flat-lying reflection at about 40 msec two-way traveltime results from a velocity increase of 1,500 to 3,030 ft/s occurring at a depth of 30 ft. The check-shot survey confirms our interpretation of the bedrock reflector, as well as explaining the origin of the flat-lying, shallow reflector observed along the Harvard Road profile.

Two-way traveltimes of the aquifer–bedrock contact were converted to depth-below-ground-surface using the seismic velocities estimated from the check-shot surveys. The elevation of the bedrock surface was then calculated using these depths and topographic profiles. Figure 5 presents the depth profile developed from the Harvard Road seismic reflection data.

SITE EVALUATIONS FOR THE CITY OF SPOKANE

A seismic reflection profile was shot along Havana Street to determine the thickness and configuration of the aquifer near a major well field operated by the City of Spokane (profile location shown in Fig. 1). The 2.5-mile-long seismic traverse across the entire width of the valley was made in an area where the aquifer was locally constricted. The seismic reflection data along Havana Street reveal a hummocky, irregular basement topography and an aquifer thickness that locally exceeds 450 feet. The seismic survey data from this transect will be used to refine the aquifer thickness estimates essential for estimating

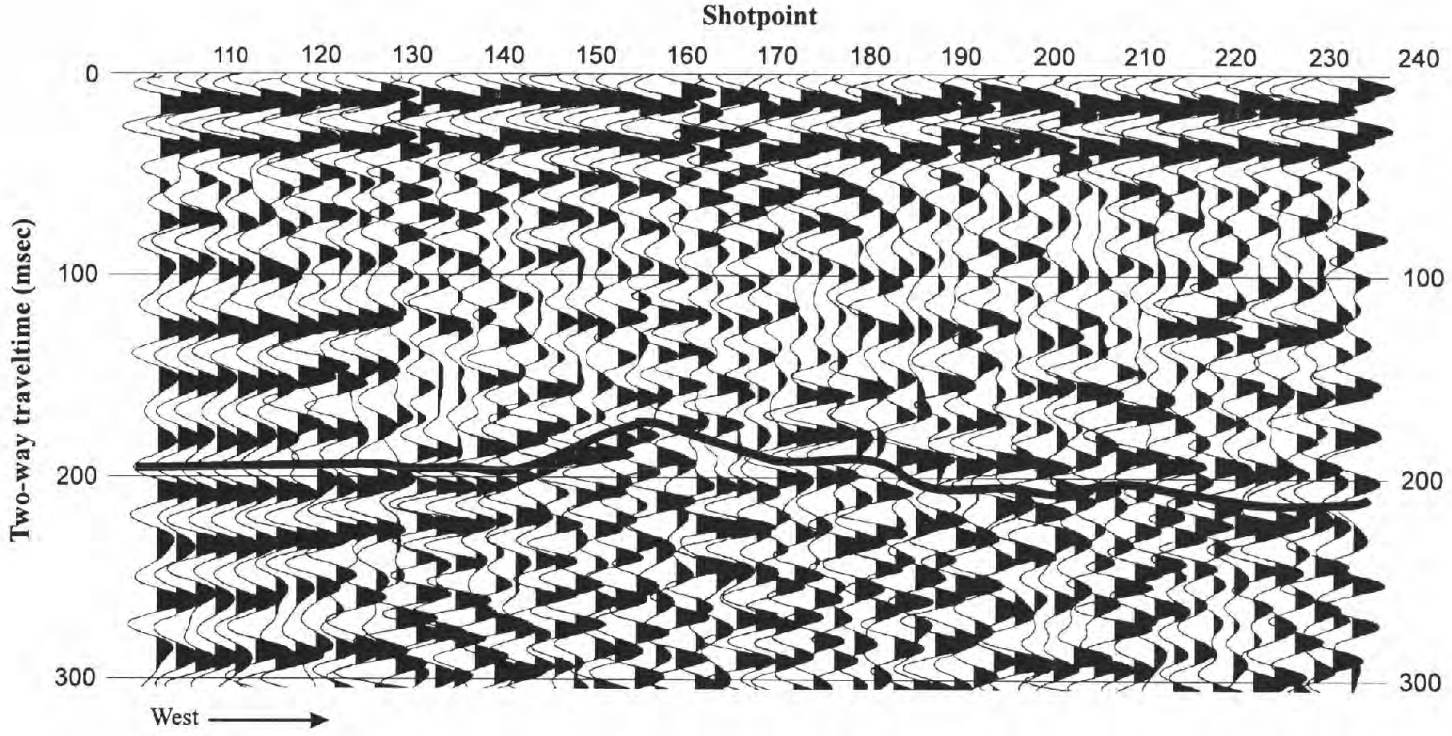

Figure 6. York Avenue seismic profile showing the Trinity Trough and a central ridge that acts as a 'weir' for ground-water movement. Bedrock outcrops both north and south of this east–west profile.

ground-water through-flow and understanding the overall aquifer water balance.

Seismic reflection profiling in northwest Spokane, used in conjunction with a limited borehole exploration program, allowed accurate delineation of a previously unknown buried bedrock channel of the ancestral Spokane River. This channel feature, termed the Trinity Trough, is approximately 1 mi wide and ¾ mi long and is filled with more than 300 ft of flood deposit materials. The channel was cut through a north-trending bedrock basalt ridge that extends from downtown Spokane to Five Mile Prairie, a prominent basalt-capped mesa northwest of the city (see Fig. 1). The bedrock ridge acts as a hydraulic barrier to ground-water flow and, along with Five Mile Prairie, separates the aquifer into two distinct segments. The Trinity Trough channel is believed to act as a subsurface 'weir', controlling ground-water flow between two portions of the aquifer that previously were believed to have little direct hydraulic connection. Figure 6 is an east–west seismic profile along York Avenue (see Fig. 1) showing a cross-sectional view of the Trinity Trough and its 'weir'. Knowledge of the channel's existence and its overall geometry will be important in developing a representative ground-water flow model of the aquifer and is expected to influence decisions regarding siting of future municipal water supply wells.

CONCLUSIONS

The near-offset method of reflection seismic surveying implemented in this investigation has been successfully used to determine bedrock topography beneath the Spokane Aquifer. Bedrock topography strongly affects the direction, rate, and quantity of ground-water flow as it determines both the aquifer thickness and overall aquifer flow geometry. Better definition of these aquifer characteristics is vitally important for comprehensive aquifer management and wellhead protection delineation. Many other ground-water sources in Washington consist of unconfined gravel and sand aquifers overlying impermeable bedrock and are analogous in this way to the Spokane Aquifer. Consequently, the near-offset seismic reflection method should be applicable to both regional and site-specific evaluation of the bedrock depth and geometry of these other aquifers. ■

Nature of the Northwest Info Center Receives Hammer Award

The Oregon Department of Geology and Mineral Industries (DOGAMI) and the U.S. Department of Agriculture Forest Service received the Hammer Award on May 30 in Portland. The award was presented by Doug Farbrother of Vice President Al Gore's National Performance Review Team.

The award was given to DOGAMI and the Forest Service for their partnership in running the Nature of the Northwest Information Center, one-stop shopping for information about outdoor recreation and natural resources in the Pacific Northwest. The center is located on the first floor of the State Office Building at 800 NE Oregon St. in Portland. It carries brochures, publications, and maps from a variety of state (Washington included), federal, and local governments, as well as commercial publications related to outdoor recreation.

The Hammer Award gives special recognition to governmental teams that have made a significant contribution in support of National Performance Review principles—putting customers first, cutting red tape, empowering employees, and slashing government spending. The award, named for the infamous $600 hammer, consists of a hammer (not the same one) framed with a signed citation from Vice President Gore.

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Additional Listings of Current Faculty and Student Geological Research at Washington Universities and Colleges

CENTRAL WASHINGTON UNIVERSITY

Faculty Research

Mesozoic deformation of the Little Maria Mountains, southeastern California—*R. D. Bentley*

Structural geology of the Yakima fold belt—*R. D. Bentley*

Petrologic evolution of the Columbia River Basalts—*R. D. Bentley*

The OWL is not a strike-slip fault—*R. D. Bentley*

Graduate Student Research

Tectono-geomorphic development of the Valle de San Filipe fault, northern Baja California, Mexico—*Tracy Morgan Grover*

Quaternary history of the Cleman Mountains area, Yakima and Kittitas Counties—*Steve Jensvold*

Hydrogeology of Kittitas Valley, Kittitas County, Washington—*Ron Owens*

UNIVERSITY OF WASHINGTON SCHOOL OF OCEANOGRAPHY

Faculty Research

Integrated geological interpretation of deep tow sonar, submersible, and petrological observations of the upper and lower oceanic crust—*John R. Delany*

Arc upflow zones boundaries between adjacent hydrothermal systems? Geological and geochemical tests—*John R. Delaney, Russell E. McDuff, Marvin D. Lilley*

Crustal evolution processes on the Mendocino and Costa Rica Rift corridors—*H. Paul Johnson*

Development of the capability to measure 'bare rock heat flow'on the sea floor—*H. Paul Johnson*

Time-dependent changes in very young oceanic crust—*H. Paul Johnson*

Sediment properties in shelf and slope environments—*Arthur R. M. Nowell, Richard W. Sternberg*

Sediment transport measurements in a regional seasonal ice cover—*Arthur R. M. Nowell, Richard W. Sternberg*

Carbon-bearing fluids in the oceanic crust—*Russell E. McDuff, Deborah Kelley*

Geophysical investigation of the Mid-Atlantic Ridge off axis using Hydrosweep—*Jean-Christophe Sempere*

Southeast Indian Ridge between 90°E and 120°E: From a hot spot to a cold spot—*Jean-Christophe Sempere*

Field measurements of sediment transport processes in strataform: Component 1, extended duration observations—*Richard W. Sternberg*

Investigations of sediment dynamics in the nearshore environment—*Richard W. Sternberg*

Analysis of absolute amplitudes observed in a marine seismic refraction experiment—*William S. D. Wilcock*

Compiled by Rebecca A. Christie, Division of Geology and Earth Resources; Meghan Miller, Central Washington University; and Laurie K. Bryan, University of Washington.

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BULLETINS

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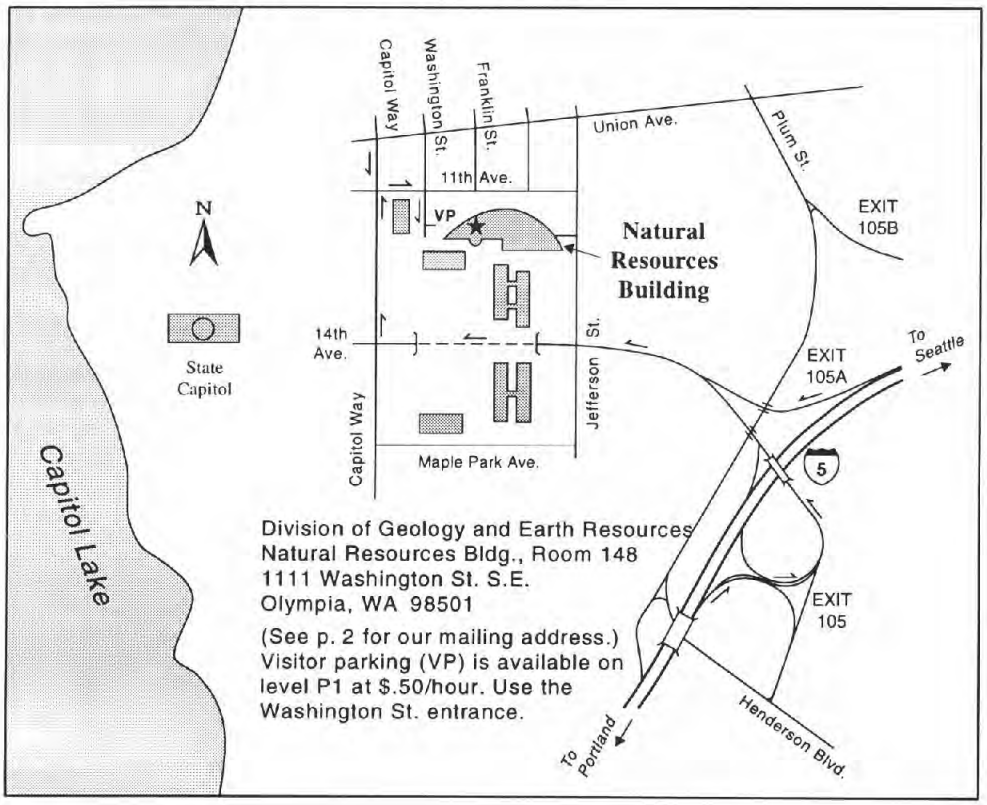

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Staff Notes

Heidi Thomsen, Clerk Typist 2, is at the front desk replacing **Steve Luceno**, who was promoted to auditor at the Department of Labor and Industries. Heidi was formerly with the Business Computer Training Institute in Lacey.

Judy Henderson, Clerk Typist 3, replaces **Karin Lang** on accounts payable, travel, training, and payroll. Karin moved up to Electronic Parts Specialist for the Radio Shop at the DNR Compound in Lacey. Judy was previously a Word Processing Specialist with the Wildlife Division of the Department of Fish and Wildlife.

Rebecca Christie has been promoted from Librarian 1 to Library Information Specialist.

Nancy Eberle, Cartographer 2, has returned to DGER after a one-year developmental assignment with the Forest Practices Division. She is acting as temporary geologist/public information officer, assuming a portion of the geologists' Rock Week duties fielding questions from the public. Nancy is also working on a departmental committee preparing for National Geography Awareness Week, Nov. 12–18.

Chuck Gulick, Geologist 2, has transferred from the Spokane office to Colville as the new Northeast Regional Geologist.

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The following CD-ROM databases are available for use in the Division Library:

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GEOINDEX
A compilation of references to geologic maps of the United States.

Water Resources Abstracts
Bibliographic database of water resources literature since 1967.

Hydrodata
U.S. Geological Survey peak values—United States
U.S. Geological Survey daily values—West 2

Climatedata
Hourly precipitation—Western region
Summary of the day—West 2

NOAA & MMS Marine Minerals CD-ROM Data Set

Geophysics of North America

Erratum for GM-41

In the text accompanying Geologic Map 41, *Liquefaction Susceptibility for the Des Moines and Renton 7.5-minute Quadrangles, Washington*, Figure 4 has been printed upside down.

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