Stratigraphy, Sedimentology, and Provenance of the Raging River Formation (Early? and Middle Eocene), King County, Washington

U.S. GEOLOGICAL SURVEY BULLETIN 2085–A

Cover. Steeply dipping beds (fluvial channel deposits) of the Eocene Puget Group in the upper part of the Green River Gorge near Kanaskat, southeastern King County, Washington. Photograph by Samuel Y. Johnson, July 1992.

Stratigraphy, Sedimentology, and Provenance of the Raging River Formation (Early? and Middle Eocene), King County, Washington

By Samuel Y. Johnson *and* Joseph T. O'Connor

EVOLUTION OF SEDIMENTARY BASINS—CENOZOIC SEDIMENTARY BASINS IN SOUTHWEST WASHINGTON AND NORTHWEST OREGON

Samuel Y. Johnson, Project Coordinator

U.S. GEOLOGICAL SURVEY BULLETIN 2085–A

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1994

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For sale by U.S. Geological Survey, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Johnson, Samuel Y.
Stratigraphy, sedimentology, and provenance of the Raging River Formation (Early? and Middle Eocene), King County, Washington/by Samuel Y. Johnson and Joseph T. O'Connor.
p. cm.—(U.S. Geological Survey bulletin; 2085)
(Evolution of sedimentary basins—Cenozoic sedimentary basins in southwest Washington and northwest Oregon; A)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:2085–A
1. Geology, Stratigraphic—Eocene. 2. Geology—Washington (State)—King County. 3. Raging River Formation (Wash.) I. O'Connor, Joseph T. (Joseph Tappan) II. Title. III. Series. IV. Series: Evolution of sedimentary basins—Cenozoic sedimentary basins in southwest Washington and northwest Oregon: A.
QE75.B9 no. 2085–A
[QE692.2]
553.7 s—dc20
[551.7'84'0979777] 94–25879
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CONTENTS

FIGURES

TABLES

Stratigraphy, Sedimentology, and Provenance of the Raging River Formation (Early? and Middle Eocene), King County, Washington

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ABSTRACT

The lower(?) and middle Eocene Raging River Formation is the oldest Tertiary stratigraphic unit exposed in the east-central Puget Lowland, Washington, and provides key information for reconstructing regional paleogeography. Three informal stratigraphic units in the Raging River Formation (designated units 1 to 3, from base to top) are recognized here on the basis of distinctive sedimentary facies and lithologies. A fourth unit (unit 0) might represent either the lowest exposed part of the Raging River Formation or semi-lithified Quaternary(?) colluvium. Unit 1, approximately 230 m thick, consists of interbedded sandstone, mudstone, and conglomerate of inferred nonmarine (lower part) and transgressive shallow-marine (upper part) origin. Unit 2, approximately 185 m thick, consists of interbedded conglomerate, sandstone, and mudstone and is inferred to be of mainly alluvial origin. A significant transgression resulting from rapid local subsidence is recorded by unit 3 (about 300 m thick). Unit 3 consists of gray silty mudstone and lesser sandstone and was deposited in a marine shelf (lower part) and bathyal slope (upper part) setting. The fine-grained marine rocks of unit 3 are commonly organic rich and, although now overmature, may have generated hydrocarbons in the past. The Raging River Formation is overlain by prodelta(?) marine shelf deposits of the lower part of the middle Eocene Tiger Mountain Formation. The Raging River Formation may provide a surface analog for conductive rocks that are in the subsurface beneath a large part of the southern Washington Cascade foothills.

Three sandstone petrofacies were identified in the Raging River Formation and the lower part of the Tiger Mountain Formation. These petrofacies reveal an upward evolution in sediment source from Mesozoic volcanic and sedimentary rocks of oceanic affinity (petrofacies 1), to lower Mesozoic and Tertiary volcanic rocks and minor(?) ultramafic rocks (petrofacies 2), to a mixed provenance including Mesozoic oceanic rocks, lower Tertiary volcanic rocks, and more distal plutonic or crystalline rocks (petrofacies 3). Contrasts between the petrology and sedimentology of the Raging River Formation and correlative rocks in western Washington argue for significant local tectonism and segregation of discrete sedimentary basins.

INTRODUCTION

The lower(?) and middle Eocene Raging River Formation is the oldest Tertiary stratigraphic unit exposed in the east-central Puget Lowland, Washington (figs. 1, 2), and provides key information for reconstructing regional paleogeography and tectonic history. The base of the Raging River Formation is not exposed. The unit is overlain by the sandstone and mudstone of the middle Eocene Tiger Mountain Formation, which is in turn overlain by, and interfingers with, volcanic and volcaniclastic rocks of the middle and late Eocene Tukwila Formation (fig. 3). The Raging River Formation was named by Vine (1962) for patchy outcrops that comprise a northwest-trending belt of about 8 km^2 on the forested east and north sides of Tiger Mountain and on the north flank of Taylor Mountain (fig. 2). Vine (1962, 1969) described the lithology, petrology, and clay mineralogy of the unit, measured two partial stratigraphic sections, and reported extensive invertebrate and foraminiferal fossil data. Vine interpreted the Raging River Formation as dominantly marine and suggested that a marine to nonmarine transition is at the base of the overlying Tiger Mountain Formation. Since Vine conducted his research, the distribution of exposures of the Raging River Formation has been significantly modified by the combined effects of logging, log-road construction, rapidly growing vegetation, and redeposition of unconsolidated Quaternary sediments. Some of the exposures Vine examined are now completely covered, and some new outcrops are present. Core from a 514-meter-deep (1,686 ft) borehole (fig. 2) that penetrates the upper Raging River and lower part of the Tiger Mountain Formations drilled in 1983 by AMOCO Production Company is now also

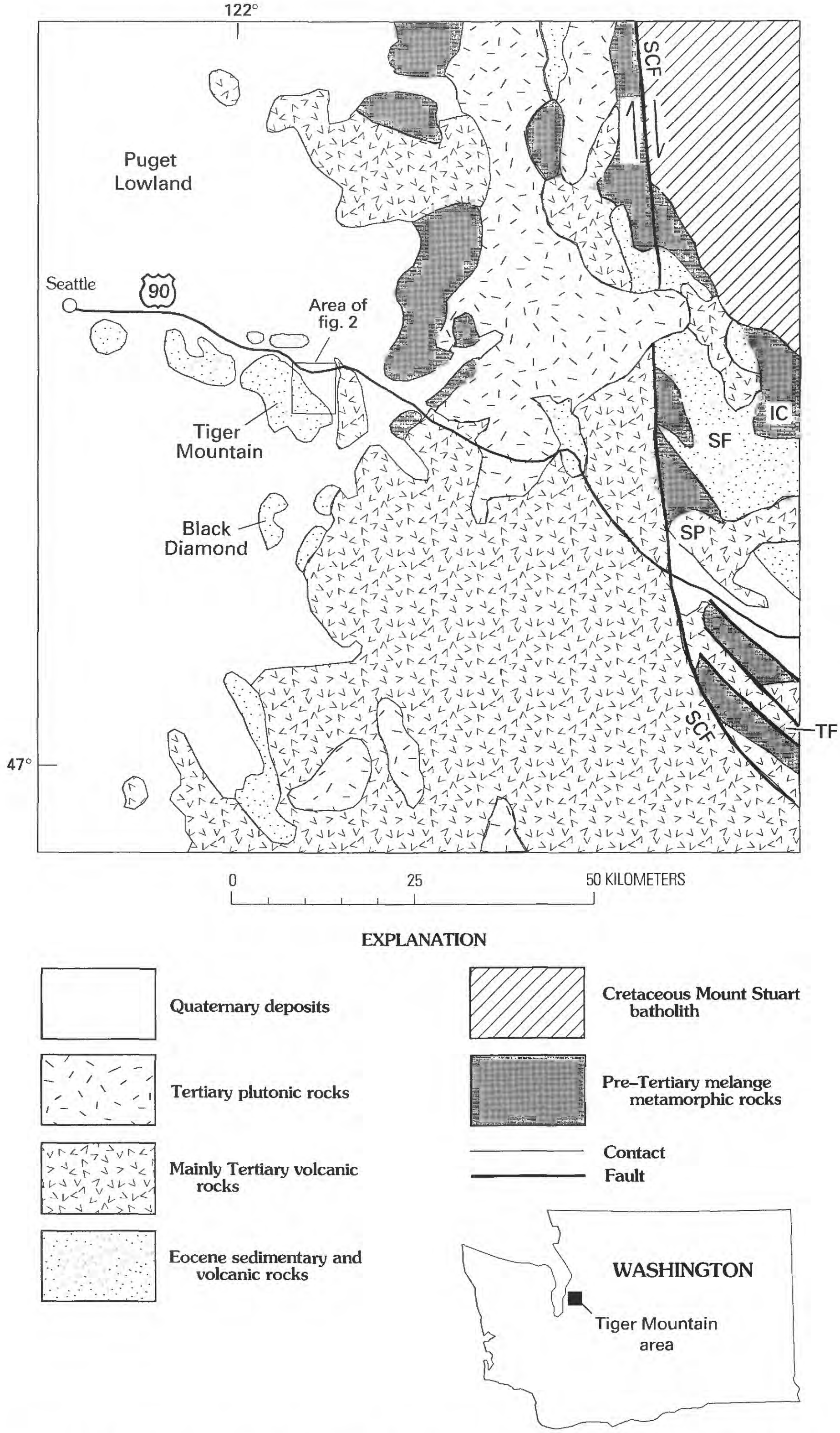


Figure 1. Schematic geologic map of the east-central Puget Lowland, Washington. IC, western part of outcrop of the Ingalls Tectonic Complex; SCF, Straight Creek fault (arrows indicate direction of movement); SP, outcrop area of the Silver Pass Volcanic Member of Swauk Formation; SF, western part of outcrop of the Swauk Formation; TF, area of outcrop of the Taneum Formation. Modified from Frizzell and others (1984), Tabor and others (1982, 1984), Walsh and others (1987), and Yount and Gower (1991).

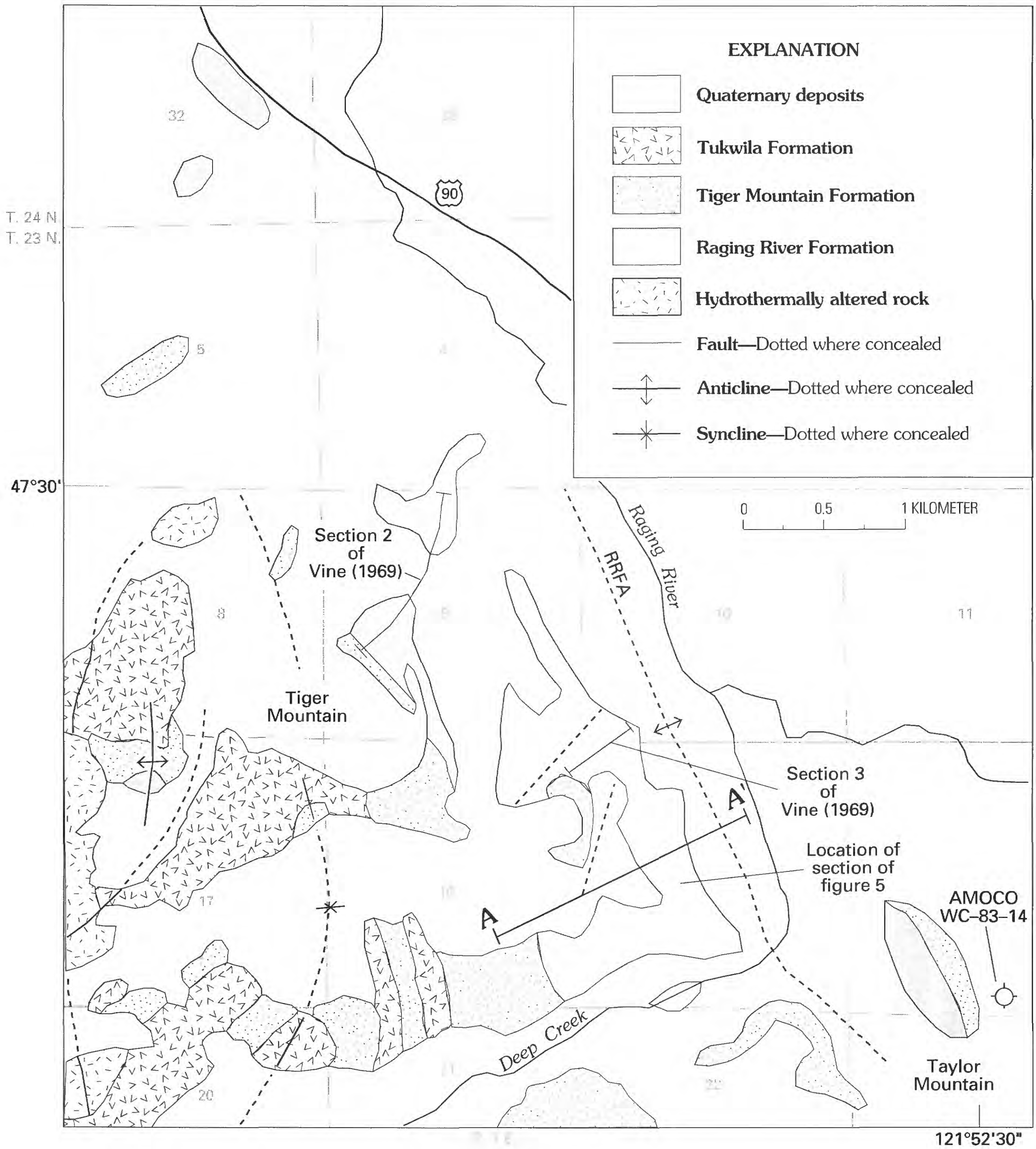


Figure 2. Schematic geologic map of the Tiger Mountain area, King County, Washington. Locations of outcrops, measured sections of Vine (1969) cited in this text, and the AMOCO WC–83–14 borehole are also shown. Line *A–A'* is line of section used by Vine (1969) to determine thickness of the Raging River Formation. RRFA indicates trace of Raging River fault and anticline. Sections in Tps. 23, 24 N., R. 7 E., are indicated by numbers. Location of map area is shown in figure 1. Modified from Vine (1969), Tabor and others (1982), Frizzell and others (1984), and Walsh (1984).

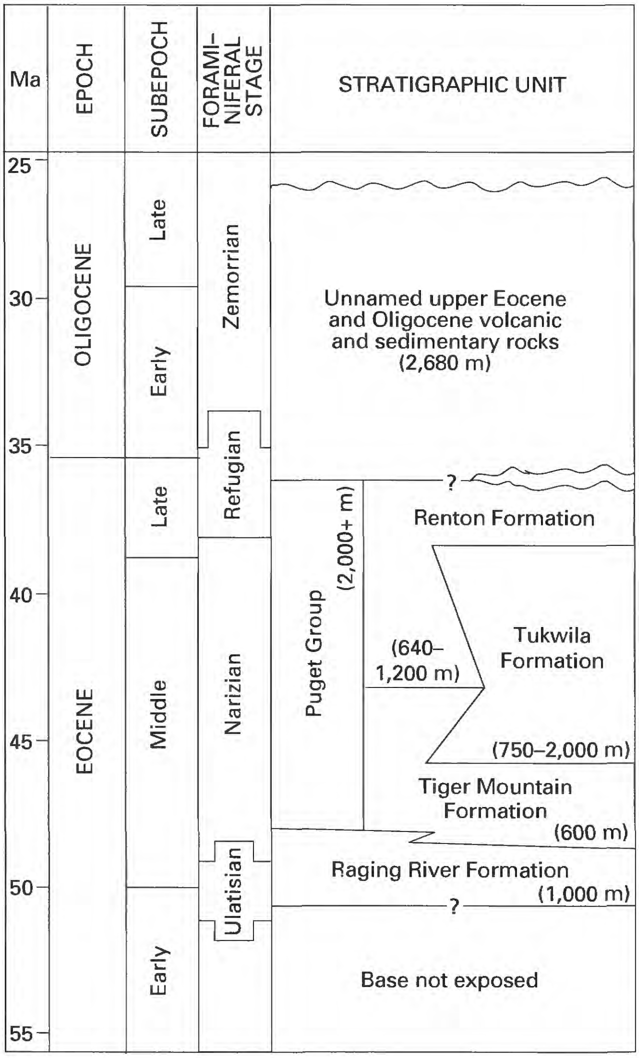


Figure 3. Generalized Eocene and Oligocene stratigraphy of the Tiger Mountain area. Modified after Vine (1969), Armentrout and others (1983), and Yount and Gower (1991); time scale from Harland and others (1990); correlation with foraminiferal stages based on Almgren and others (1988) and Niem and Niem (1992).

available for study. The purposes of this report are to present new information collected from outcrops, core, and petrographic studies and to supplement Vine's efforts with a new synthesis of the stratigraphy, sedimentology, and provenance of the Raging River Formation.

Acknowledgments.—We are grateful to the Weyerhaeuser Company, George Sharp, and Peter Hales for allowing us to examine and sample core from the important AMOCO WC–83–14 borehole and to Weldon Rau for identifying foraminifers in samples from this core. We thank Vito Nuccio for analysis of vitrinite reflectance. Tim Walsh and Ken Esposito provided very helpful reviews. We were helped and stimulated by discussions with John Armentrout, Don Anders, Peter Hales, William Lingley, Daniel McKeel, Chris Potter, Weldon Rau, Parke Snavely, Jr., William D. Stanley, Joe Vance, and Tim Walsh.

STRATIGRAPHY AND SEDIMENTOLOGY

The Raging River Formation forms patchy outcrops in a northwest-trending outcrop belt of about 8 km^2 on the east and north flanks of Tiger Mountain and the north flank of Taylor Mountain in the east-central Puget Lowland (figs. 1, 2). This area is heavily forested and covered by a significant amount of Quaternary glacial drift. Outcrops are generally of poor quality and are mainly in the beds of small creeks and along former logging roads. Vine (1969) measured two partial stratigraphic sections of the Raging River Formation (fig. 2) including (1) a 560-meter-thick (1,836 ft) section between 357 m (1,170 ft) and ~564 m (~1,850 ft) elevation in the bed of a small tributary in W 1/2 sec. 9, T. 23 N., R. 7 E. (section 2 of Vine) and (2) a 410-meter-thick (1,345 ft) section exposed in the bed of a small tributary in secs. 10, 15, and 16, T. 23 N., R. 7 E. (section 3 of Vine). Vine (1969) estimated that each tributary section included about 48 percent cover. The proportion of cover at each tributary locality is now much greater, and, although they still provide important sedimentologic, structural, and stratigraphic data, these sites are no longer suitable for measured sections. There, however, is now a short section exposed on a logging road that is suitable for detailed analysis, and the quality of many other exposures may have improved since Vine conducted his research.

Vine (1969) suggested that the cumulative thickness of the Raging River Formation is as much as 915 m (3,000 ft) on the basis of projection of outcrop attitudes onto a generalized cross section (line *A–A′* of fig. 2). This projection extends from the contact with the overlying Tiger Mountain Formation (figs. 2, 3) to the axis of the faulted, south-plunging part of the doubly plunging Raging River anticline (Vine, 1969, p. 38), which is covered by glacial drift (fig. 2). Because the base of the Raging River Formation is not exposed (fig. 3) and Vine's section extends only to the anticline axis (at the surface, fig. 2), the actual thickness of the unit may be greater than Vine's estimate.

As a result of field work and core description conducted in the summer of 1991, Johnson (1992) recognized three informal stratigraphic units within the Raging River Formation (fig. 4). A fourth unit (designated unit 0) could either represent the lowest part of the Raging River Formation or (more likely) semilithified Quaternary(?) colluvium. Vine's (1969) sections were also used in developing this framework, but it is re-emphasized that much of the rock in the sections that Vine measured is no longer exposed. The four units were recognized on the basis of distinctive sedimentary facies and lithologies and are described below. Because of

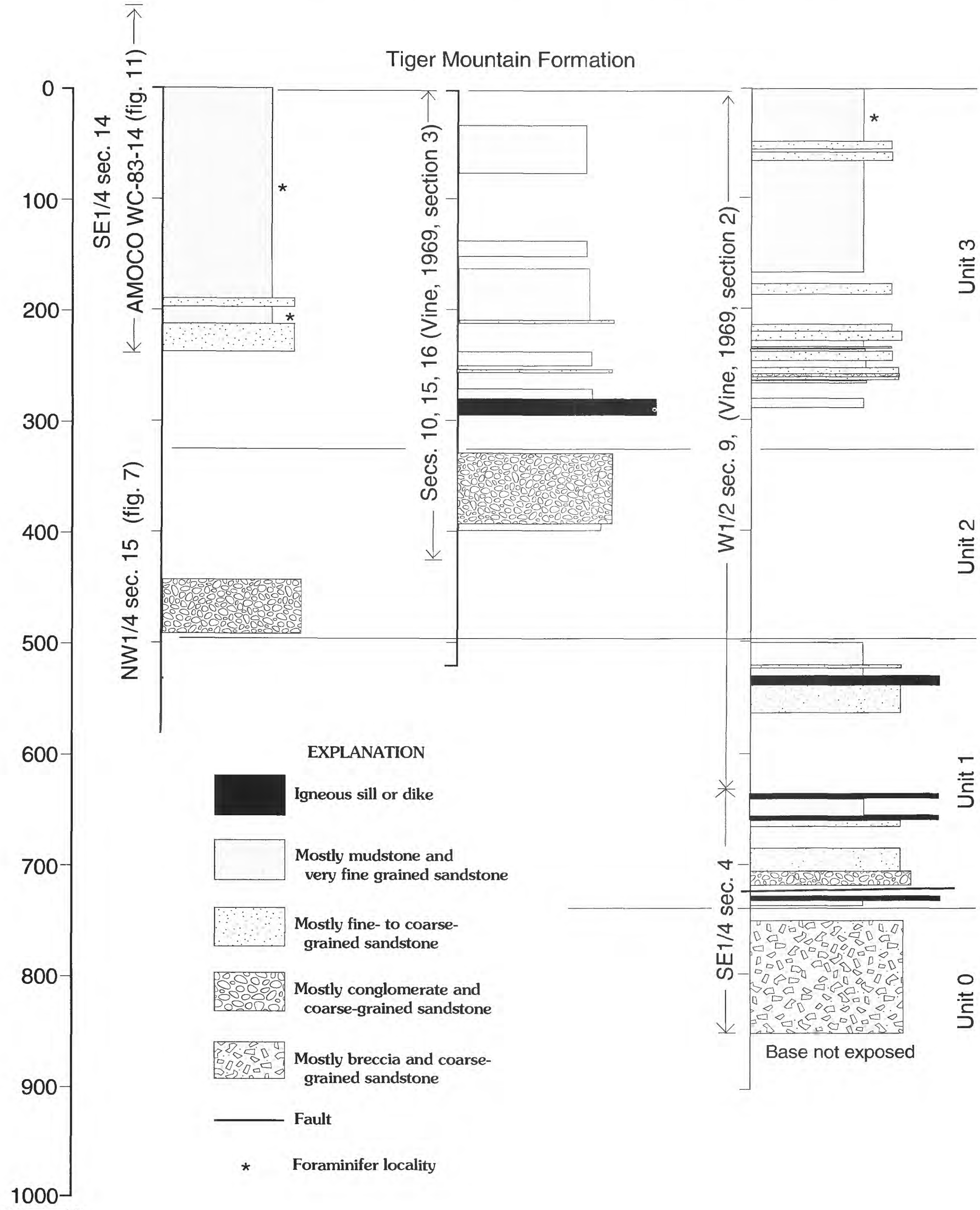


Figure 4. Schematic diagram showing composite section of the Raging River Formation. All locations are in T. 23 N., R. 7 E., King County, Washington. Unit 0 could represent either the lowest exposed part of the Raging River Formation or semilithified Quaternary(?) colluvium (see text for discussion).

limited exposure, the thickness of the different units is based mostly on map projections of bedding-plane attitudes.

W.W. Rau (*in* Vine, 1969, p. 16) identified benthic foraminifers from the upper part of the Raging River Formation (unit 3 of this report, fig. 4) and referred them to the upper Ulatisian or possibly lower Narizian stage of the middle Eocene (fig. 3) (Armentrout and others, 1983). Rau (written commun., 1991) subsequently restricted these foraminifers to the lower Narizian and identified a comparable fauna in core of the upper part of the Raging River Formation (see discussion of unit 3 below) from the AMOCO WC–83–14 borehole. Strata underlying the foraminifers localities are undated and are probably early(?) to early middle Eocene in age. The overlying Tiger Mountain Formation (fig. 3) has not been dated. Turner and others (1093) reported late middle Eocene fission-track and K-Ar dates (41.3±2.3 Ma and 42.0±2.4 Ma, respectively) from the upper part of the volcanic Tukwila Formation, which overlies and interfingers with the Tiger Mountain Formation (fig. 3). For the reasons discussed above, we consider the overall age range of the Raging River Formation to be early(?) and middle Eocene.

UNIT 0 OF THE RAGING RIVER FORMATION

Unit 0, which is questionably part of the Raging River Formation, consists of a massive breccia-conglomerate. This unit is exposed only in discontinuous outcrops at elevations between 238 m (780 ft) and 251 m (840 ft) in the bed of a tributary to the Raging River in SE1/4 sec. 4, T. 23 N., R. 7 E. (figs. 2, 4). Strata in this tributary were also examined by Vine (fig. 4) (his section 2); however, he chose not to measure or describe strata lower in the tributary (units 0 and 1 of this study) because of the effects of faulting and intrusions (see following). Bedding-plane attitudes in the unit 0 breccia-conglomerate could not be determined because of the unit's massive character. If unit 0 is part of the Raging River Formation and has the same attitude as the lowest exposures of overlying unit 1 that are unaffected by faulting or slumping, then unit 0 is about 95 m thick. Unit 0 outcrops are resistant and underlie a 3-meter-high waterfall. Boulders of unit 0 breccia-conglomerate are present near unit 0 stream outcrops but are not present at higher elevations in the streambed.

No textural variations, fabric, or other features suggestive of primary bedding are discernible in outcrops of unit 0 that are as large as 3 m in mean dimension. Clasts are poorly sorted, angular to subrounded, and dispersed in a matrix of mud and coarse-grained to granular sand. Clasts are as large as 80 cm in maximum dimension; the mean size of the 10 largest clasts in an outcrop is generally 20–30 cm. Clasts are dominantly gray lithic sandstone, grayish-black mudstone, and minor chert and greenstone. All of these lithologies are present within the Raging River Formation, either as stratified rocks or as clasts in conglomerate (mainly unit 2, see below). The massive, coarse-grained, texturally immature character of this poorly exposed breccia-conglomerate indicates deposition proximal to source as colluvium or coarse-grained alluvium.

Unit 0 could represent either the lowest part of the Raging River Formation or semilithified Quaternary(?) colluvium. The resistant character of the unit (it underlies waterfalls and forms large subrounded boulders in the creekbed) is the strongest argument for inclusion in the Raging River Formation. Quaternary deposits (including texturally identical colluvium) are widespread on Tiger Mountain (Vine, 1969), but they are typically unconsolidated and highly weathered. The resistant, semilithified character of unit 0 and its local occurrence could, however, reflect early cementation by spring waters and (or) an anomalously high mud content in the rock matrix. Origin as locally derived Quaternary(?) colluvium is consistent with the clast lithologies, all of which could have been derived from local outcrops of the Raging River Formation. Alternatively, these lithologies also are in and could have been derived from the Mesozoic melange belts (Frizzell and others, 1987) that presently crop out less than 10 km east of Tiger Mountain (fig. 1; see section on "Provenance," following). If derived from this Mesozoic source, a nearby Eocene uplift (fault-bounded?) of considerable relief would be required to account for the coarse texture of unit 0.

Although there is no conclusive evidence to distinguish between the hypotheses just discussed, we consider a Quaternary(?) colluvial origin more likely. Because of the uncertainty, we do not include unit 0 in discussions about the Eocene paleogeography of the Tiger Mountain area and the Puget Lowland.

UNIT 1 OF THE RAGING RIVER FORMATION

Unit 1 (fig. 4) also crops out in the bed of the tributary to the Raging River that passes through secs. 4 and 9, T. 23 N., R. 7 E. (fig. 2). There is approximately 5 m (change in elevation) of cover between the highest outcrops of unit 0 and the lowest outcrops of well-stratified unit 1. The lower part of unit 1 (from about 560 to 740 m in the column of fig. 4) is from elevations of 256 m (840 ft) to 326 m (1,070 ft) and is also below the base of the 560-meter-thick section measured by Vine (1969, section 2) in this tributary. This lower interval is poorly and discontinuously exposed, intruded by dikes and (or) sills, and cut by faults that disrupt bedding-plane attitudes. As a result, the lithologies and thicknesses shown in the stratigraphic column in figure 4 are at best approximations. The upper part of unit 1 (fig. 4) was plotted from Vine's (1969) section 2 descriptions of rocks cropping out between elevations of 357 m (1,170 ft) and 396

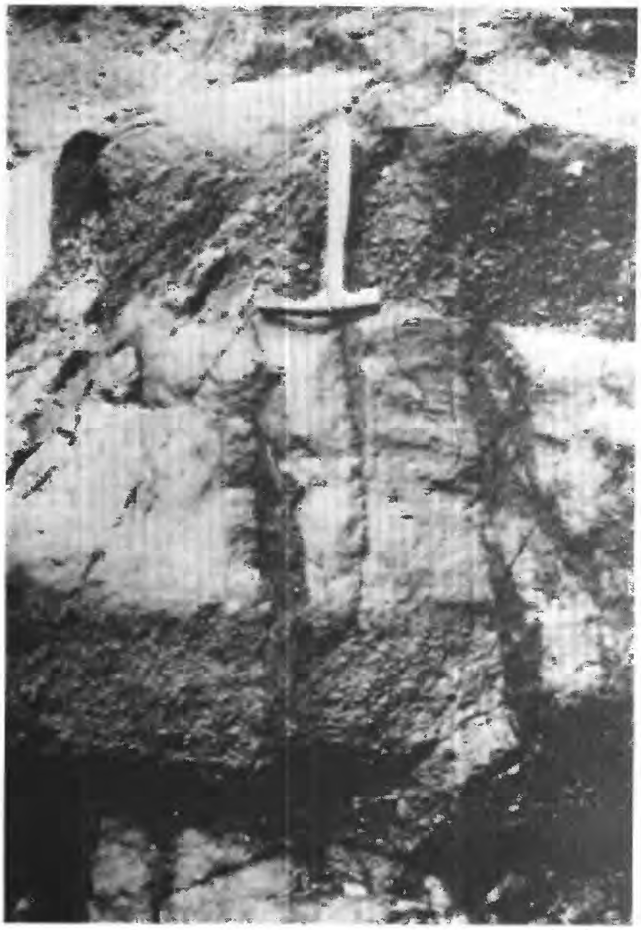


Figure 5. Graded conglomerate sandstone couplet of unit 1 of the Raging River Formation. Hammer head rests at base of overlying couplet.

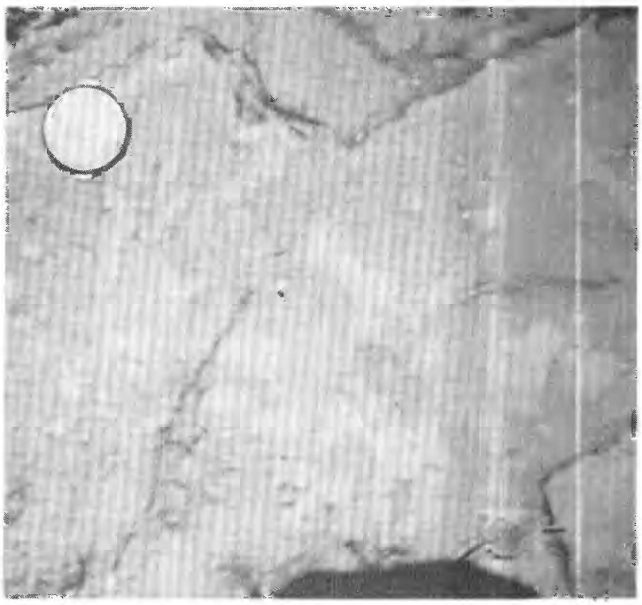


Figure 6. Bedding-plane view of oval and branching sand-filled burrows in unit 1 of the Raging River Formation. Lens cap (5.5 cm in diameter) is shown for scale.

m (1,300 ft) in this creekbed. The only bedrock exposed in the creekbed in this interval (in the summer of 1991) is an igneous sill (elevation 343 m) and a few small, poor outcrops of silty sandstone. Strata in the upper part of unit 1 also crop out in a few roadcuts and one borrow pit along a logging road in SE 1/4 sec. 9 and NW 1/4 sec. 15, T. 23 N., R. 7 E. On the basis of map patterns, unit 1 is about 230 m thick.

Strata of unit 1 consist of interbedded sandstone, mudstone, and conglomerate. Outcrops in the creekbed at an elevation of 256 m (840 ft) consist of grayish-black, massive to flatbedded mudstone and minor very fine grained sandstone. Bed thickness is about 10–20 cm. At approximately 264 m (865 ft) elevation in the creekbed, there are fair exposures of pebble and granule conglomerate and fine-grained to very coarse grained sandstone. Beds (fig. 5) form 20–100-centimeter-thick fining-upward sequences separated by scour surfaces that have as much as 20 cm of erosional relief within 100 cm of lateral exposure. The fining-upward sequences are internally massive or are characterized by crude horizontal stratification. Conglomerate pebbles are typically subrounded, moderately well sorted, and less than 5 cm in diameter and consist mainly of lithic sandstone, mudstone, and chert.

Outcrops of unit 1 in the creek bed at elevations of 274 m (900 ft), 287 m (940 ft), 293 m (960 ft), 297 m (975 ft), and 305–326 m (1,000–1,070) consist of gray, interbedded and interlaminated, very fine to medium grained sandstone and mudstone. Beds are typically structureless or are characterized by diffuse and disrupted plane lamination, less commonly hummocky bedding and wavy bedding, and possibly wave-ripple lamination. Small (<1 cm) mudstone rip-up clasts are dispersed in a few sandstone beds. Locally strata are intensely bioturbated (fig. 6). Burrow forms resemble *Thalassanoides* and are typically straight to branching (at angles of 90° or 120°), horizontal to subhorizontal, 1–2 cm in diameter, and as long as 10 cm and have no obvious internal structure. Burrowed horizons are commonly tightly cemented by calcite. This interval also includes a few thin (<10 cm) concretionary layers that contain dispersed, broken gastropod and pelecypod shell fragments.

Medium- to dark-gray, generally aphanitic, igneous sills or dikes intrude the unit 1 section at elevations of about 259 m (850 ft), 287 m (940 ft), and 308 m (1,010 ft) in the creekbed. These igneous bodies disrupt stratification on outcrop scale and have planar to irregular margins.

Roadcut exposures are typically massive and badly weathered. The best exposures (upper part of unit 1) are in a borrow pit in NW 1/4 sec. 15 (fig. 2). Strata are structureless or, less commonly, have poorly preserved parallel stratification highlighted by thin laminations of plant debris. Isolated plant fragments are present on many bedding planes and coalified logs as large as 13 cm in length and 5 cm in diameter are also present. Strata are extensively bioturbated. The most common trace fossils are vertical *Skolithos* burrows that are as long as 18 cm and have typical diameters of 1–2 cm. Gastropod (mainly *Turritella*) and pelecypod shells and shell fragments are dispersed in many beds.

The more fine grained, extensively burrowed, fossiliferous strata of the upper part of unit 1 are inferred to be of shallow marine origin on the basis of stratification styles, extensive bioturbation, and fossil content. The limited exposures of the graded conglomerate-sandstone facies in the lower part of unit 1 are not sufficient for reliable interpretation. On the basis of their stratigraphic association with overlying shallow-marine rocks, they might represent gravity-flow deposits of a shallow-marine fan delta (Nemec and Steel, 1988). Alternatively, the lack of evidence of marine reworking and the scale of erosion surfaces between units is consistent with a fluvial origin, as inferred for conglomerate of unit 2.

UNIT 2 OF THE RAGING RIVER FORMATION

Unit 2 (fig. 4) consists of interbedded conglomerate, sandstone, and mudstone. At the base of his section 3 (secs. 10, 15, and 16, T. 23 N., R. 7 E.) (fig. 2), Vine (1969) described about 60 m of mainly medium-grained to conglomeratic sandstone in the bed of a tributary to the Raging River that is here considered the upper part of unit 2. Unit 2 strata also form fair outcrops along the logging road in NW 1/4 sec. 15, about 750 m south of Vine's section 3 (fig. 2). A 49-meter-thick section of these roadcut outcrops (fig. 7) projects onto the line of generalized cross section used by Vine (1969) at a slightly lower stratigraphic level than the tributary exposures. Using the base of these roadcuts as the base of unit 2 and the top of the conglomeratic interval in the tributary section as its top, unit 2 is approximately 185 m thick. The isolated northern exposures of the Raging River Formation (E 1/2 sec. 32, T. 24 N., R. 7 E.) (fig. 2) are included in unit 2 on the basis of similarly distinct lithologies and sedimentary structures; however, because of poor exposures and local faulting, stratigraphic continuity between the two outcrop areas cannot be positively demonstrated. Strata at the same stratigraphic level as unit 2 (measuring down from the contact with the overlying Tiger Mountain Formation) are covered in Vine's (1969) section 2 (figs. 2, 4).

The streambed outcrops of unit 2 measured by Vine (1969, section 3) are now poorly exposed. They include gray to yellowish-brown, poorly sorted, massive to crudely stratified conglomerate and low-angle bedded sandstone. Conglomerate beds are as thick as several meters. Clasts include abundant chert and aphanitic volcanic rock. Plant fragments are common. The maximum clast size in beds is typically about 6 cm. Low-angle bedded sandstone crops out at an elevation of 325 m (1,065 ft) in the creekbed and is inferred to represent the uppermost part of unit 2. These outcrops contain scattered organic debris, mudstone rip-up clasts, and locally abundant vertical *Skolithos (?)* burrows.

The 49-meter-thick measured section of unit 2 (fig. 7) includes approximately 42 percent silty mudstone, 38 percent conglomerate, and 20 percent sandstone. Conglomerate beds are 60–545 cm thick, have low-angle erosional bases, and generally fine upward. Internally beds are poorly to moderately sorted and structureless and exhibit crude low-angle stratification that has common scour surfaces (fig. 8). Pebbles are typically subrounded, commonly imbricate, and are clast supported or dispersed in granular sandstone. The maximum size of pebbles in conglomerate beds ranges from 5 to 8 cm. Plant fragments are common. Several conglomerate beds include lenses of massive to crossbedded coarse-grained sandstone that are as thick as 30 cm and more than 100 cm wide (fig. 7). Restored paleocurrent directions determined from pebble imbrications, channel axes, and cross-beds indicate sediment transport to the west (fig. 9).

Sandstone and silty mudstone beds in the measured section are typically poorly exposed and structureless, contain dispersed plant fragments, and weather gray to olive green. These beds have common fracture planes lined with clay skins, a characteristic typical of paleosols (Retallack, 1988). A 20-centimeter-thick bed of fine-grained, grayish-orange, lithic tuff is in the lowest mudstone (fig. 7). The tuff bed contains scattered plant fragments and small (<1 cm long, <1 mm wide) root structures.

The isolated northern outcrops of unit 2 along Interstate Highway 90 are intruded by a sill (T. Walsh, Washington Department of Geology and Earth Resources, written commun., 1993) and dikes and are relatively indurated. These strata consist of gray pebble conglomerate and interbedded sandstone. Conglomerate beds are as thick as a few meters and are bounded by low-angle (<10°) erosional surfaces. Beds are internally structureless or crudely stratified and uncommonly graded. Conglomerate clasts are subrounded to rounded, poorly to moderately sorted, generally dispersed in a granular matrix, and uncommonly imbricate. The mean size of the largest clasts in a bed is typically about 12 cm. Several large blocks of conglomerate were collected and slabbed for pebble counting. A count of 1,180 clasts (fig. 10) indicates that lithic sandstone, chert, and aphanitic green or black volcanic rocks are the most common clast types.

Unit 2 strata are interpreted as mainly alluvial deposits. Poorly to moderately sorted, imbricate conglomerate and conglomeratic sandstone were deposited as coarse bedload in fluvial channels. Abundant internal scours and low-angle stratification suggest that deposition occurred mainly on low-relief gravel bars characteristic of braided rivers. Uncommon crossbedded sandstone formed by migration of

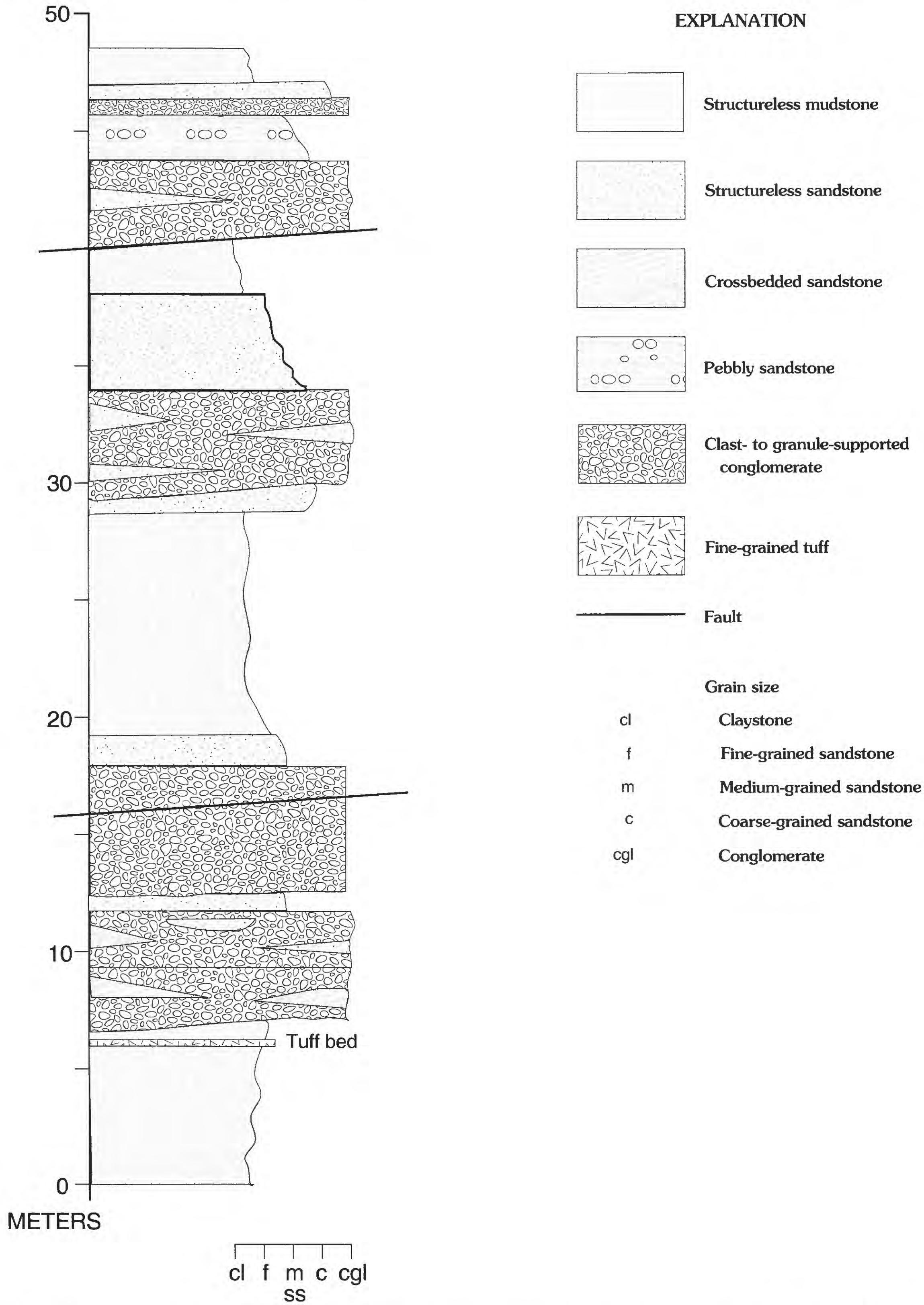


Figure 7. Measured section of the lower part of unit 2 of the Raging River Formation, described in outcrops along logging road in NW 1/4 sec. 15, T. 23 N., R. 7 E. Stratigraphic location of section is shown in figure 4.

Figure 8. Crudely stratified conglomerate and conglomeratic sandstone of unit 2 of the Raging River Formation. Hammer is shown for scale.

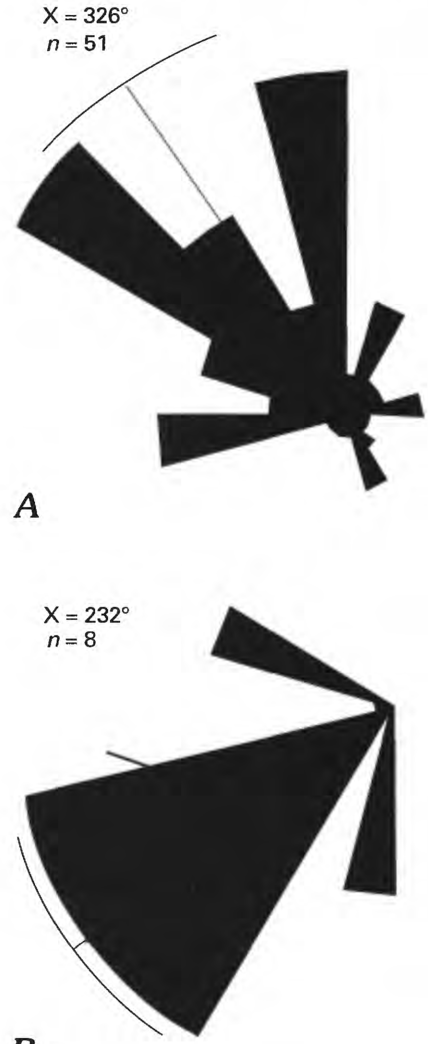


Figure 9. Rose diagrams showing restored paleocurrent data including vector mean and confidence angle for unit 2 of the Raging River Formation based on (*A*) pebble imbrications (51 measurements), and (*B*) crossbeds (4 measurements) and channel axes (4 measurements). All data were collected from the measured section of figure 7 except three pebble imbrications which were collected from isolated northern exposures in SE¼ sec. 32, T. 23 N., R. 7 E. (fig. 1). Variation between and within diagrams is inferred to represent variable orientations of channels and bars within alluvial system.

dunes or sand waves. Massive greenish-gray mudstone containing scattered plant fragments and evidence of paleosol formation is characteristic of floodplain deposits in Eocene alluvial sequences elsewhere in western Washington (for example, Johnson, 1984a) and is notably different from the medium- to dark-gray, commonly bioturbated mudstone of clearly marine origin in overlying unit 3. The bioturbated sandstone that is at the top of unit 2 (see above) is probably shallow marine in origin and represents a transition to the marine rocks of unit 3.

UNIT 3 OF THE RAGING RIVER FORMATION

Unit 3 consists of gray silty mudstone and lesser sandstone. Vine (1969) measured two partial stratigraphic sections through unit 3 (figs. 2, 4). The quality of exposure is now so poor along each creekbed traverse that only a few small outcrops could be described. Along the traverse for Vine's (1969) section 2 (fig. 2), small outcrops between the elevations of 494 m (1,620 ft) and 537 m (1,760 ft) consist of gray, massive to parallel-stratified silty mudstone and very fine to fine grained sandstone Along the traverse for Vine's (1969) section 3 (fig. 2), a sill that crops out at an elevation of 323 m (1,090 ft) represents the lowest exposure of unit 3 (measured as 50 ft (15.2 m) thick by Vine). There are poor discontinuous outcrops above this sill in the creekbed to an elevation of

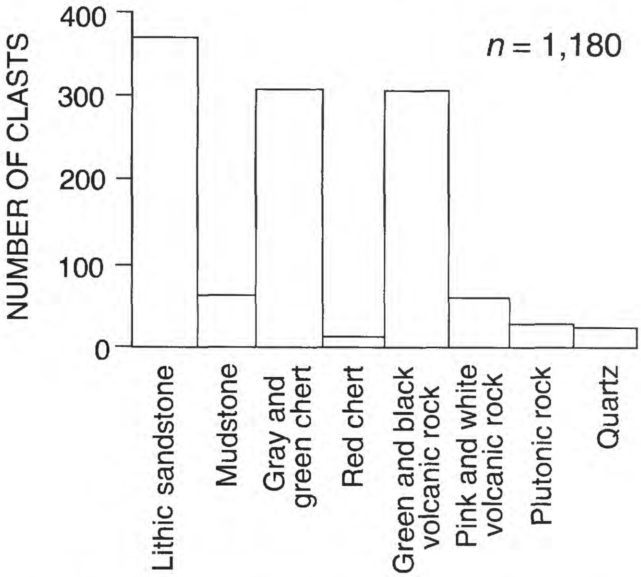


Figure 10. Histogram showing lithology of conglomerate clasts from the inferred unit 2 conglomerate of the Raging River Formation in SE 1/4 sec. 32, T. 24 N., R 7 E.

about 360 m (1,180 ft), above which outcrops mostly disappear. The discontinuous outcrops consist of parallel, wavy, and hummocky bedded, very fine to fine grained sandstone. Hummocks are about 3 cm high and have wavelengths of 20–25 cm. Beds are locally bioturbated.

The best outcrops of unit 3 are in a large borrow pit at the end of a spur off the Kerriston-Echo Lake Road on the north flank of Taylor Mountain (SE 1/4SW 1/4 sec. 14., T. 23 N., R. 7 E.). About 10 m of section is exposed in this pit, consisting of medium- to dark-gray, very fine to medium grained sandstone and brownish-gray to dark-gray silty mudstone. Sandstone is parallel bedded and less commonly ripple laminated and bioturbated and contains common pelecypod and gastropod (*Turritella*) shell fragments. Burrows are most commonly horizontal to subhorizontal and include circular tubes (~1 cm diameter and ≤5 cm long) and 2–3-centimeter-long meandering forms. Vertical and inclined burrows are much less common. Mudstone is typically massive and is best exposed adjacent to a dike on the east side of the borrow pit.

The best opportunity to study the sedimentology of unit 3 is in the core collected from the AMOCO WC–83–14 borehole. The borehole was drilled to a depth of 534 m (1,752 ft) and was cored almost continuously from 46 m to total depth (fig. 11). The mean dip of beds encountered by the borehole was about 50°; thus, the amount of section represented by the core is only about 310 m. Of this section, the lower 234 m is assigned to the upper part of unit 3 of the Raging River Formation and the upper 76 m to the overlying Tiger Mountain Formation. The contact between the Tiger Mountain Formation and the underlying Raging River Formation is characterized by an upward change from dominantly light to medium gray, bioturbated, poorly stratified mudstone and minor lithic sandstone to yellowish-gray, well-stratified, micaceous sandstone.

Unit 3 strata in the WC–83–14 core consist mainly of medium- to dark-gray silty or sandy mudstone and light- to medium-gray, very fine to medium grained sandstone (fig. 12*A*). The sandstone to mudstone ratio is approximately 1:4. Mudstone is typically massive, but markedly fissile horizons are also present. Primary parallel lamination is rare. The massive character probably reflects at least partial deposition by suspension and extensive bioturbation. Trace fossils are abundant in many horizons of silty and sandy mudstone. *Helminthoida* sp. traces (fig. 12*B*) are between depths of about 338 and 213 m (1,109 and 700 ft), and *Teichichnus*, *Chondrites*, *Ophiomorpha*, and other trace fossils are present at several horizons (fig. 12*C*). Thick intervals of mudstone uncommonly include thin (<10 cm) interbeds of very fine to medium grained sandstone. Where not extensively bioturbated, these beds are typically parallel laminated and have sharp bases marked by load casts and rare rip-up clasts. Rare gastropod (*Turritella*) and pelecypod shells and shell fragments are present in the mudstone at depths of 431, 419, 288, and 250 m (1,415, 1,374, 944, and 819 ft), and shell fragments are present at several intervals. Shells and shell fragments have variable orientations and clearly were redeposited.

Sandstone-rich strata in the WC–83–14 core are most abundant at depths of 534–502, 468–459, 283–279, and 276–254 m (1,752–1,648, 1,535–1,504, 927–916, and 906–835 ft). Strata are typically fine to medium grained and well sorted. Beds in the lower two sandstone-rich horizons are structureless, parallel laminated, or extensively burrowed and exhibit relict parallel lamination. Sandstone beds with inclined laminations (recognized by intersections and truncations at angles as large as 30°) are at depths of about 511 m (1,676 ft), 504 m (1,654 ft), and 465 m (1,525 ft). Rare wave (?)-ripple-lamination (ripple height < 2 cm) is present at 507 m (1663 ft). Chert-pebble conglomerate (maximum clast diameter <2 cm) forms a 14-centimeter-thick interbed at a depth of 465 m (1,524 ft). In the upper two sandstone-rich horizons, beds are similarly massive to parallel laminated. Massive beds are characterized by subtle vertical grain-size changes suggesting amalgamation on internal erosion surfaces. Parallel-laminated beds are commonly bounded by or include low-relief (<1 cm) erosion surfaces overlain by mudstone rip-up clasts. Grading is rare, but a few thin (<20 cm) beds fine upward. Convolute lamination is present in a few beds.

Weldon Rau (Washington Department of Geology and Earth Resources, written commun., 1991) identified sparse foraminiferal faunas from two intervals in the well and suggested that, although small, they are reasonably diagnostic of an early Narizian age. In a composite sample between 516.2 and 518.3 m (1,700–1,693 ft), Rau reported

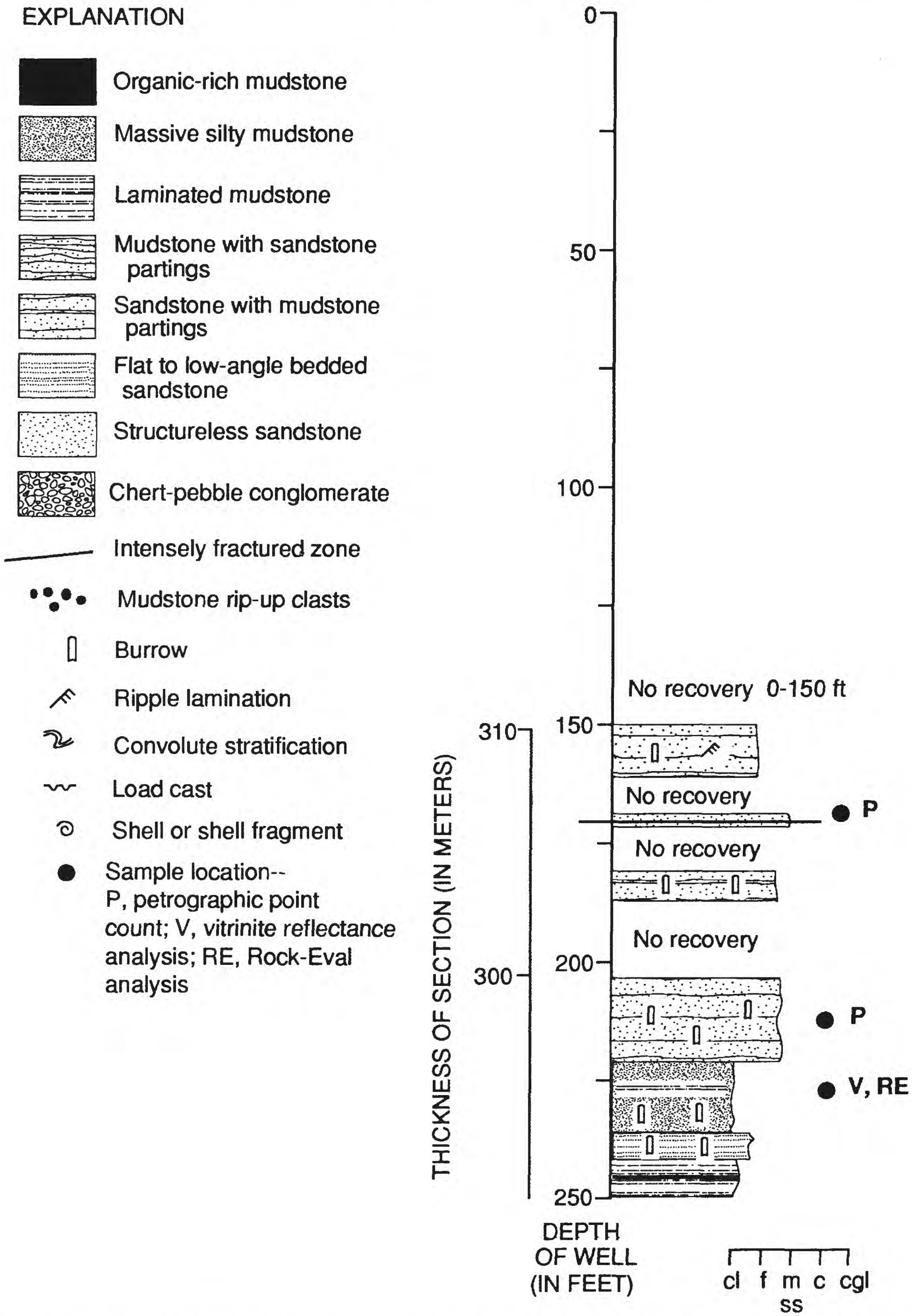
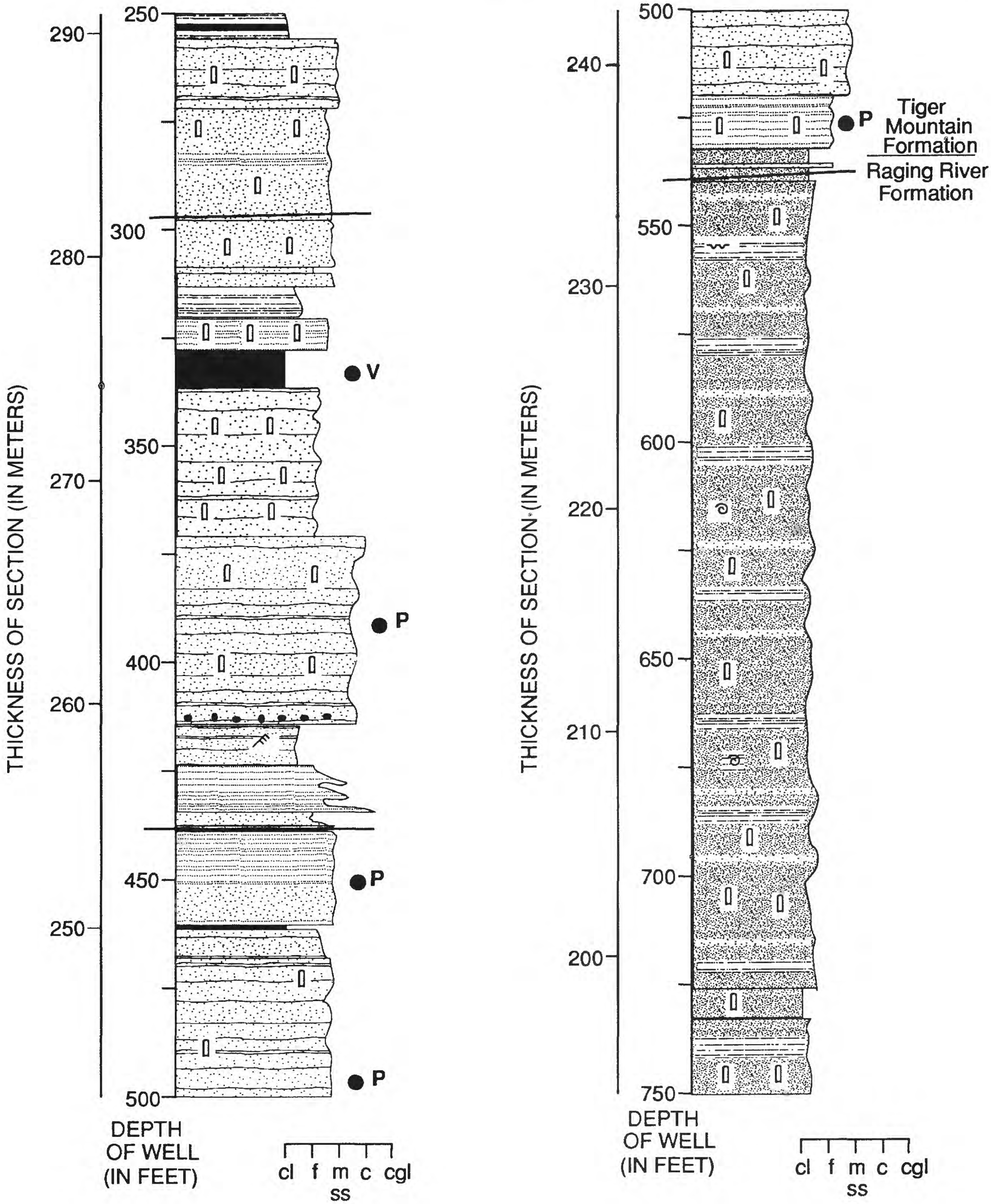
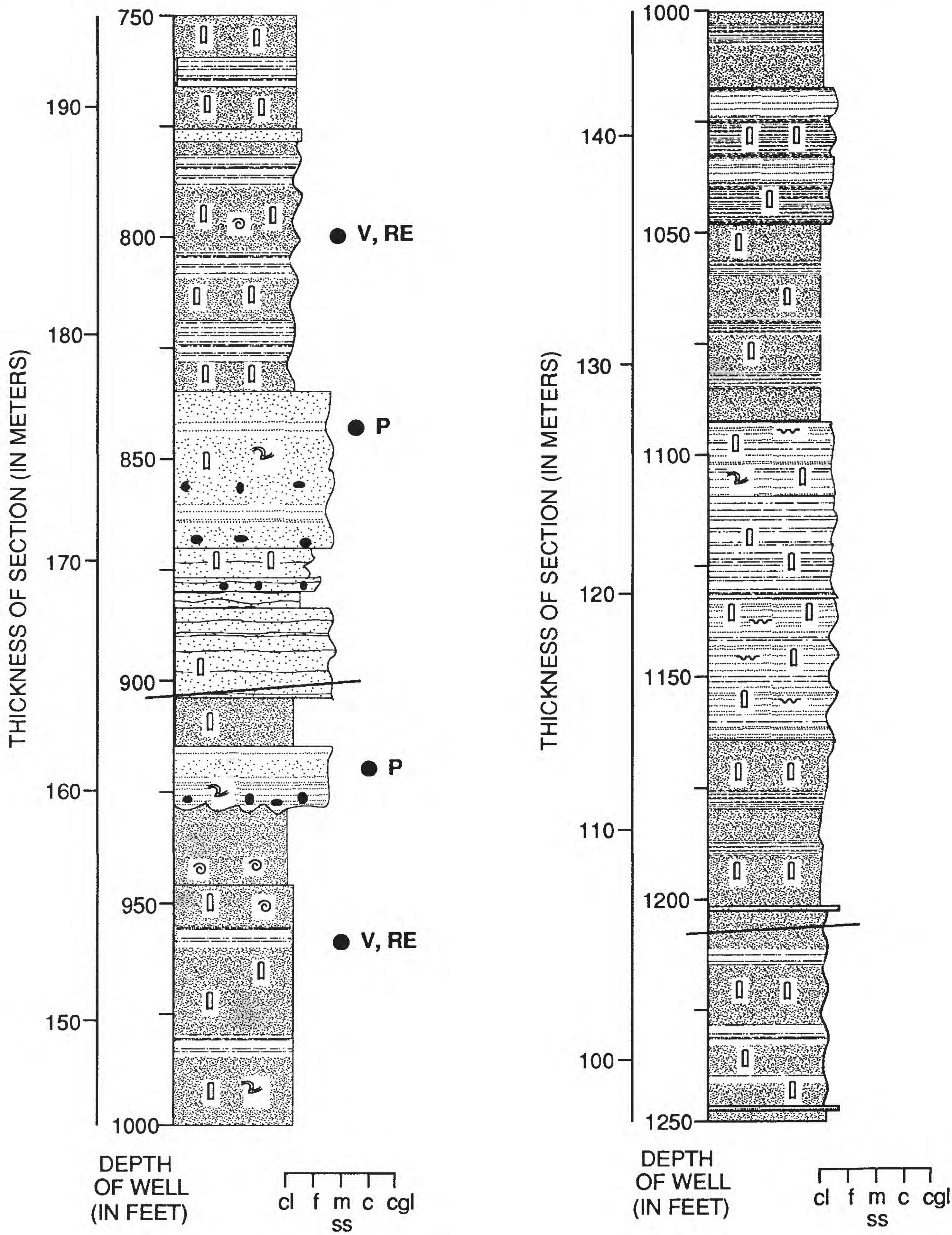
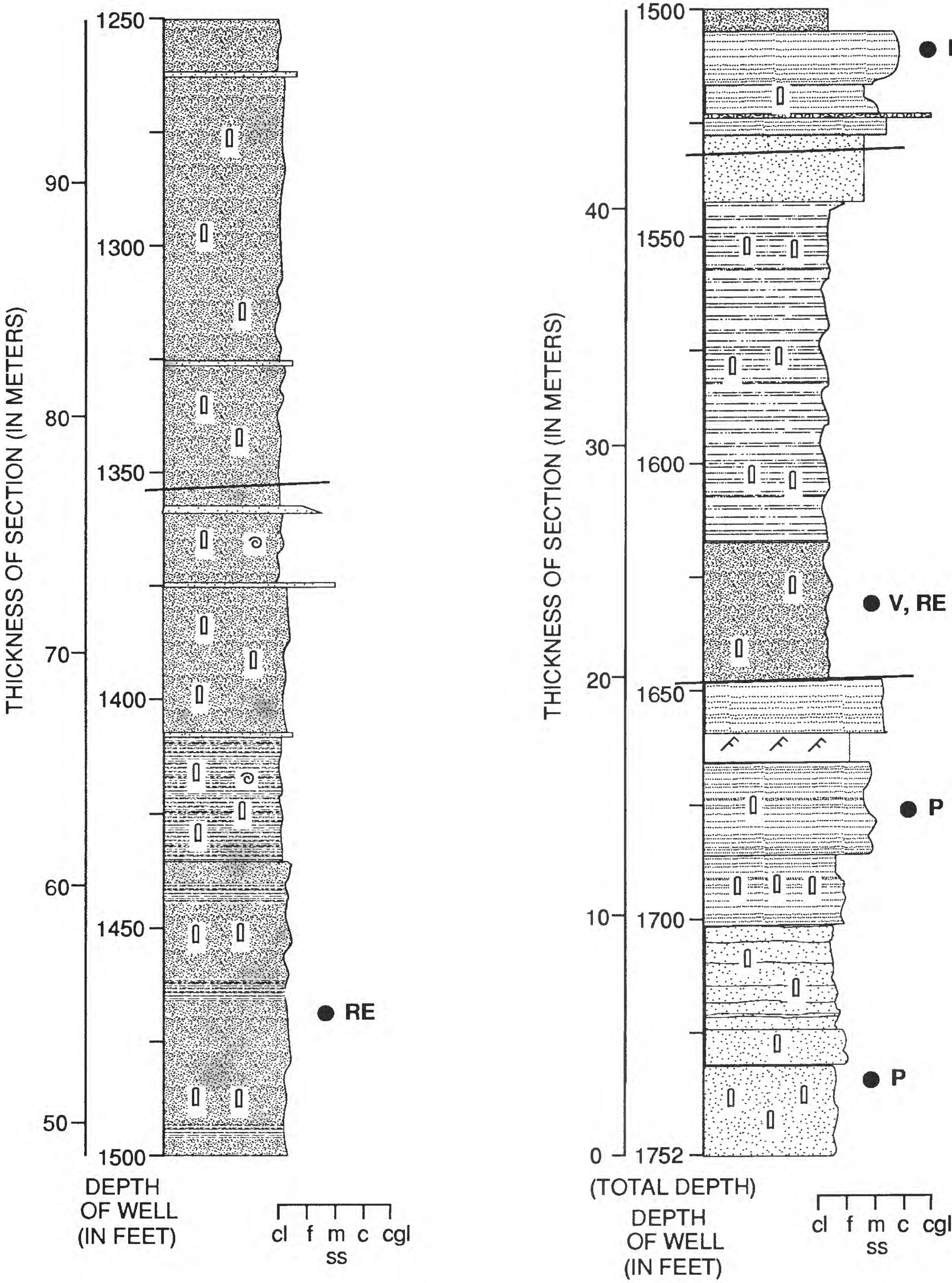


Figure 11 (above and following pages). Sedimentologic log of core from the AMOCO WC–83–14 borehole, SE 1/4 sec. 14, T. 23 N., R. 7 E., King County, Washington. The mean dip of bedding planes encountered by the borehole was about 50°; thus, the thickness of the section penetrated is significantly less than total depth. Vitrinite reflectance, Rock-Eval, and petrographic analyses from core samples are given in tables 1 and 2 and appendix 1. Location of borehole is shown in figure 2.


THICKNESS OF SECTION (IN METERS)
290
280
270
260
250
250
300
350
400
450
500
V
P
P
P
DEPTH OF WELL (IN FEET)
cl f m c cgl
ss
THICKNESS OF SECTION (IN METERS)
240
230
220
210
200
500
550
600
650
700
750
P
Tiger Mountain Formation
Raging River Formation
DEPTH OF WELL (IN FEET)
cl f m c cgl
ss


750
190
800
V, RE
180
P
850
170
900
P
160
950
V, RE
150
1000
THICKNESS OF SECTION (IN METERS)
DEPTH OF WELL (IN FEET)
cl f m c cgl
ss
1000
140
1050
130
1100
120
1150
110
1200
100
1250
THICKNESS OF SECTION (IN METERS)
DEPTH OF WELL (IN FEET)
cl f m c cgl
ss



THICKNESS OF SECTION (IN METERS)
90
80
70
60
50
1250
1300
1350
1400
1450
1500
DEPTH OF WELL (IN FEET)
RE
cl f m c cgl
ss
THICKNESS OF SECTION (IN METERS)
40
30
20
10
0
1500
1550
1600
1650
1700
1752
(TOTAL DEPTH)
DEPTH OF WELL (IN FEET)
P
V, RE
P
P
cl f m c cgl
ss

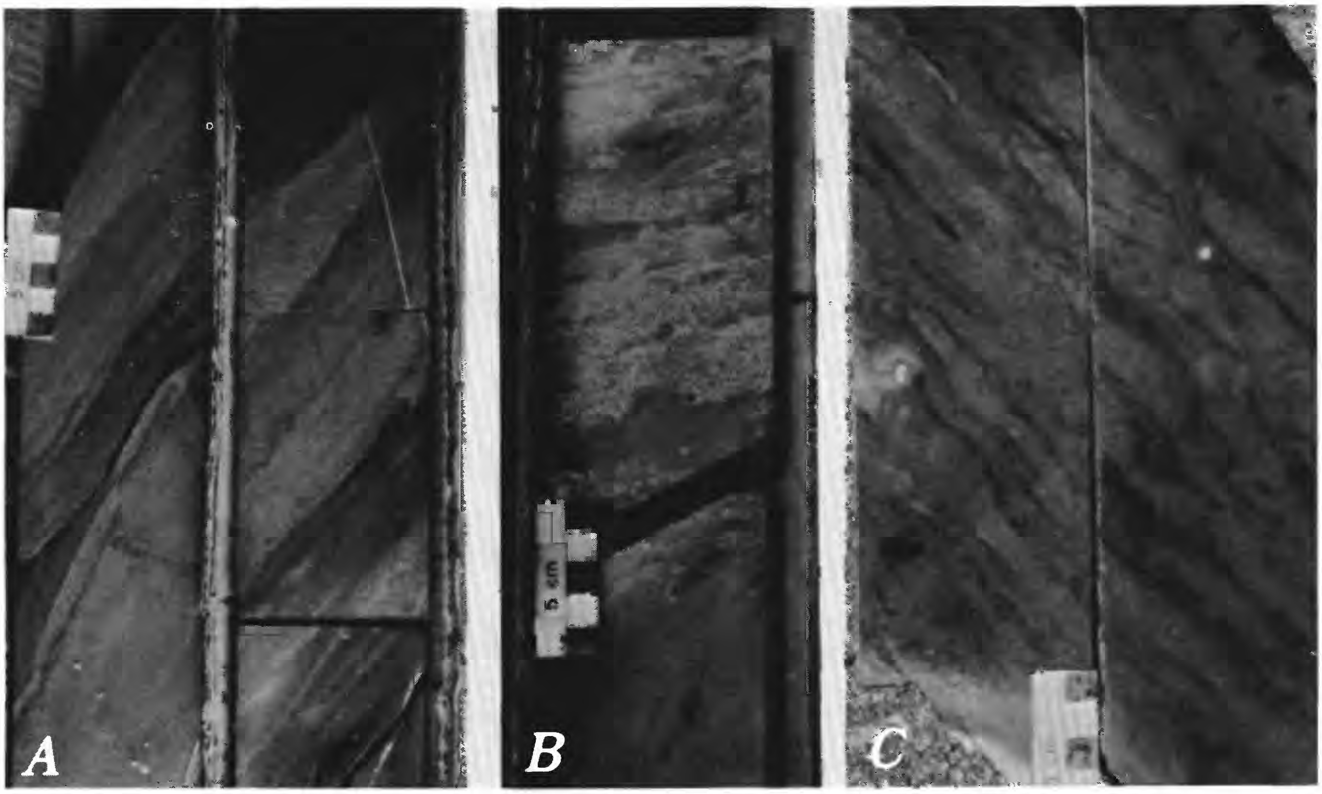


Figure 12. Photographs of core of the Raging River Formation from the AMOCO WC–83–14 borehole. Location of borehole shown in figure 2; log of corehole is shown in figure 11. Centimeter scale is shown for each. *A*, Parallel stratified, very fine to fine grained sandstone and mudstone, unit 3. Core is from interval between 336 and 338 m (1,102–1,109 ft). *B*, *Helminthoida* sp. trace fossils in mudstone, unit 3. Core is from depth of 333 m (1,092 ft). *C*, Burrowed, very fine grained sandstone and interlaminated mudstone, unit 3. Core is from interval between 514 and 518 m (1,686–1,699 ft).

Plectofrondicularia packardi packardi Cushman and Schenck, *Pseudoglandulina* cf. *P. pyrula* d'Orbigny, and *Dentalina* sp. On the basis primarily of the presence of *Plectofrondicularia* and comparison to the biofacies outlined by Ingle (1980) for California Cenozoic paleobathymetry, Rau suggested a probable middle bathyal depositional environment for this assemblage. D.R. McKeel (paleontology consultant, oral commun., 1992), however, suggested that *Plectofrondicularia* is more characteristic of an outer shelf environment, an interpretation more consistent with sedimentologic observations (see below) for the lower part of unit 3. In a composite sample for the interval between 382.6 and 385.1 m (1,255–1,263 ft), Rau reported *Dentalina* sp., *Gyroidina* sp., *Quinqueloculira* cf. *Q. triangularis* d'Orbigny, *Amphimorphina* cf. *A. californica* Cushman and McMasters, and ?*Pseudoglandulina* sp. Rau (*in* Vine, 1969, p. 16) reported a more extensive foraminifers species list for the upper part of unit 3 from a locality in Vine's section 2 (fig. 2), about 49 m below the base of the Tiger Mountain Formation (equivalent to a drilling depth of about 236 m in the WC–83–14 borehole; fig. 11). Rau (written commun., 1992) suggested a middle bathyal depositional environment for this assemblage, which is consistent with the sedimentologic interpretations described following.

Unit 3 represents a transition from shelf to slope deposition. Hummocky bedded sandstone in creekbed outcrops of the lower part of unit 3 indicates deposition above wave base in a shallow-marine or shelf setting. The lower two sandstone-rich horizons in the WC–83–14 core include low-angle laminated and ripple-laminated sandstone that probably also reflects wave reworking. The dominance in overlying rocks of structureless silty mudstone suggests a slope depositional environment (for example, Mutti and Ricci Lucchi, 1972), consistent with the middle-bathyal paleobathymetry (500–2,000 m; Ingle, 1980) inferred from the foraminifera. The upper two sandstone-rich horizons in the WC–83–14 core were probably deposited by turbidity currents in channels cut into the slope. Massive and parallel-laminated facies represent the Bouma A and B turbidite divisions, respectively.

LOWER PART OF THE TIGER MOUNTAIN FORMATION

Strata of the lower part of the Tiger Mountain Formation were examined mainly in core from the AMOCO WC–83–14 borehole (fig. 11). Approximately 118 m (386 ft) of the Tiger Mountain was cored, representing (correcting for structural dip) about 75 m of section. The contact (criteria for placement defined above in section on unit 3) is in a gouge zone between 164.3 and 163.9 m (539.0 and 537.5 ft) in the core. Although this gouge zone does not appear to be a significant fault, structural displacement resulting in stratigraphic offset on this feature provides an explanation for the very abrupt facies transition at the contact (see below) and is considered possible.

The lower part of the Tiger Mountain Formation consists of interbedded yellowish-gray sandstone and medium-gray to grayish-black silty mudstone. The sandstone to mudstone ratio is about 5–6:1. Sandstone is typically moderately sorted and fine to medium grained and forms beds several meters thick. Primary stratification is mainly parallel lamination; low-angle lamination and wave-ripple lamination are uncommon. Many sandstone beds overlie erosion surfaces lined with small mudstone rip-up clasts. Upper bed contacts are both graded and abrupt. An anomalous interval from 132.5 to 129.2 m (434.5–423.7 ft) consists of 10 thin graded beds that fine upward from massive coarse-grained or granular sandstone to commonly parallel laminated, fine-grained sandstone. More subtle vertical grain-size variations and inversions are common within many thicker sandstone beds and similarly indicate episodic deposition. Trace fossils, mainly vertical to horizontal lined burrows (*Skolithos* and *Scoyenia*), are present in most sandstone beds and range from rare to abundant. Where abundant, primary stratification is poorly preserved. Silty mudstone and carbonaceous mudstone laminae commonly form thin (<1 cm) layers within thick sandstone beds. Fossil plant fragments are common in carbonaceous mudstone partings.

Silty mudstone in the lower part of the Tiger Mountain Formation ranges from parallel laminated and fissile to massive. Parallel-laminated beds commonly include very thin (<1 cm) lenticular layers of very fine grained sandstone. These sandstone layers were probably also present in massive beds but have been mixed with bounding fine-grained sediment by bioturbation. A bed of medium- to dark-gray organic-rich mudstone, about 1.5 m thick, is between 102.4 and 100.2 m (336 and 328.5 ft).

The fine- to medium-grained sandstone of the lower part of the Tiger Mountain Formation represents deposition in a marine shelf environment, possibly in a prodelta setting. Parallel and less common low-angle and wave-ripple laminated beds must in part reflect deposition by storm processes. Some sandstone beds might be hummocky bedded, but the limited lateral perspective provided by the core and the extensive sediment mixing by bioturbation make this determination difficult. The more coarse grained, graded beds formed as turbidites (Bouma A and in some cases B divisions) that were probably transported by density underflows at a delta front. Deposition of these turbidites below storm-wave base by storm-generated currents (as in Hamblin and Walker, 1979) is unlikely given their coarse grain size relative to adjacent strata. Preservation of turbidite features probably reflects rapid removal from the zone of bioturbation by burial. Given the evidence for some deposition by turbidity currents, it is likely that many other massive bioturbated sandstone beds also had a turbidite origin. The variable amount of bioturbation in sandstone beds indicates variable sediment accumulation rates. Thick intervals of bioturbated sand indicate slow sediment accumulation, whereas the presence of graded sandstone beds, sandstone beds with only moderate sorting, and abundant mudstone partings indicates minimal winnowing and relatively rapid accumulation. This inferred variation in sediment supply is consistent with a position in front of a laterally migrating delta.

A prodelta shelf setting for the lower part of the Tiger Mountain Formation is consistent with its stratigraphic position. As discussed above, underlying rocks near the top of the Raging River Formation (unit 3) were deposited at bathyal depths. Strata higher in the Tiger Mountain Formation described by Vine (1969) contain large-scale crossbedded sandstone and pebble conglomerate, siltstone with abundant plant fragments, and coal, clearly indicating nonmarine deposition.

PETROLEUM SOURCE ROCK?

Fine-grained marine rocks of inferred early and early middle Eocene age (such as the Raging River Formation) are apparently widespread in the subsurface in the southern Washington Cascade foothills. Stanley and others (1987, 1992, 1994) described a major conductivity anomaly that underlies upper middle Eocene to Oligocene rocks in the southern Washington Cascade foothills. They inferred that a section consisting mainly of fine grained marine strata is the source of the anomaly. The Tiger Mountain–Taylor Mountain exposures of the Raging River Formation (figs.1, 2) and the AMOCO WC–83–14 (fig. 11) core provide the only known window or analog for rocks fitting the inference of Stanley and others (1987, 1992, 1994).

Stanley and others (1992) further suggested that the rocks representing the conductivity anomaly could be a significant petroleum source rock. Rock-Eval pyrolysis data (table 1) suggest that unit 3 bathyal mudstone from the AMOCO WC–83–14 core (three samples) and outcrop (two samples) is now overmature with respect to hydrocarbon generation (T_{max} 509°C–542°C) and thus cannot be reliably evaluated as petroleum source rocks (Peters, 1986). In slight contrast, vitrinite reflectance measurements in five samples from the AMOCO core (table 1; range of 1.96± 0.33 percent at 498 m depth to 1.65±08 percent at 69 m depth) suggest that rocks are highly mature but still capable of generating lean to dry gas. Peters (1986) reported that anomalously high T_{max} values can result from the presence of oxidized, highly mature, or type IV (inert), kerogen. Given the inferred marine shelf and slope environment of unit 3, primary

Table 1. Vitrinite reflectance and Rock-Eval analyses for samples of the Raging River Formation and the lower part of the Tiger Mountain Formation, King County Washington.

[Units: RRF1, Raging River Formation unit 1; RRF3, Raging River Formation unit 3; TM, lower part of the Tiger Mountain Formation. Locations: 1, AMOCO Production WC–83–14 borehole, footage is given in parentheses; 2, SE¼ sec. 4, T. 23 N., R.7 E.; 3, SE¼ sec. 9, T. 23 N., R.7 E.; 4, SW¼ sec. 14, T. 23 N., R. 7 E. R_o is vitrinite reflectance (in percent); T_{max} is temperature (in °C) at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter; S_1 is integral of first peak (existing hydrocarbons volatilized at 250°C for 5 minutes (in milligrams per gram); S_2 is integral of second peak (hydrocarbons produced by pyrolysis of solid organic matter (kerogen between 250°C and 550°C) (in milligrams per gram); S_3 is integral of third peak (CO_2 produced by pyrolysis of kerogen between 250°C and 390°C) (in milligrams per gram); TOC is total organic carbon (in percent); HI is hydrogen index (S_2/TOC); OI is oxygen index (S_3/TOC); PI is production index ($S_1/(S_1+S_2)$. Leader (—) indicates no data available]

Sample No.	Unit	Location	R_o	T_{max}	HI	OI	TOC	S_1	S_2	S_3	PI
SJ–91–11	RRF1	2	1.18±0.04	—	—	—	—	—	—	—	—
SJ–91–18	RRF3	3	—	511	17	81	1.12	0	0.20	0.91	0
SJ–91–43	RRF3	1(1,633)	1.96±0.33	—	—	—	—	—	—	—	—
SJ–91–45	RRF3	1(1,470)	—	533	21	10	0.80	0.01	0.17	0.08	0.06
SJ–91–47	RRF3	1(959)	1.48±0.26	542	47	9	0.65	0.01	0.31	0.06	0.03
SJ–91–49	RRF3	1(798)	1.65±0.14	535	37	2	0.86	0.02	0.32	0.02	0.06
SJ–92–120	RRF3	4	—	509	12	92	0.83	0.02	0.10	0.77	0.17
SJ–92–124	RRF3	4	4.01±0.40	—	—	—	—	—	—	—	—
SJ–91–55	TM	1(332)	1.74±0.10	—	—	—	—	—	—	—	—
SJ–91–57	TM	1(226)	1.65±0.08	484	60	14	2.84	0.11	1.73	0.42	0.06

kerogen in unit 3 was probably type III (gas prone) or even type II (oil prone), not type IV; thus, the noted discrepancy between the pyrolysis and vitrinite maturity indicators reflects oxidation and (or) high levels of maturity. There is good correlation in the level of maturity suggested by pyrolysis and vitrinite reflectance values of the Tiger Mountain Formation sampled in the AMOCO well (table 1); the data suggest that rocks are highly mature but still capable of generating lean to dry gas.

One outcrop sample from unit 1 yielded a vitrinite reflectance value of 1.18±04 percent, and an outcrop sample from unit 3 yielded a value of 4.01±0.40 percent (table 1). The latter high value may reflect proximity to a concealed intrusion. The range of vitrinite reflectance values for the Raging River Formation indicates that there were significant lateral as well as vertical thermal gradients during the Tertiary in the Tiger Mountain–Taylor Mountain area, a point also noted by Walsh and Phillips (1982) and Walsh and Lingley (1991) on the basis of coal-rank data.

Despite the indicators of high thermal maturity, there is still as much as 0.8–1.1 percent total organic carbon in fine-grained marine rocks of the Raging River Formation (table 1). Assuming primary type III or type II organic matter, the rocks were once more organic rich (Daly and Edman, 1987) and capable of generating significant hydrocarbons. The Raging River Formation provides a viable source for the oil and gas shows in the nearby Black Diamond area (Anderson, 1959; McFarland, 1983) (fig. 1) and may have similar viability in untested areas of the eastern Puget Lowland.

SANDSTONE PETROGRAPHY

Vine (1962, 1969) provided a brief description of the sandstone petrology of the Raging River Formation. He stated that the sandstone is unsorted and that it is commonly difficult to distinguish clast and chloritic matrix. He also suggested that plagioclase is typically abundant, that quartz and potassium feldspar are rare or absent in some samples, and that proportions of quartz, chert, mafic minerals, and opaque minerals are variable. For this study, 20 sandstone samples from units 1, 2, and 3 of the Raging River Formation and 7 samples from the overlying lower part of the Tiger Mountain Formation were examined and point counted (table 2, appendix 1). Sandstone compositions were then plotted on ternary provenance diagrams (fig. 13) after Dickinson (1985).

UNIT 1

Seven moderately sorted, medium- to coarse-grained sandstone samples of unit 1 were examined petrographically. Grains are typically moderately sorted and subrounded. These sandstones are classified as lithic arenite (Dott, 1964). Monocrystalline quartz and volcanic lithic fragments are the most common grain types, but plagioclase feldspar (albite based on optical determination), sedimentary lithic fragments, polycrystalline quartz, and chert grains are also present in significant amounts (table 2, appendix 1). At least some of the albite in this unit and in overlying units may result from alteration of calcic plagioclase. Potassium feldspar is very rare. Volcanic lithic fragments have lathwork to microlitic textures and less common felsitic textures and commonly include chlorite, epidote, and other low-grade metamorphic minerals. Sedimentary lithic fragments range from microgranular quartzite grains to matrix-rich siltstone. Polycrystalline quartz grains are typically equigranular and nonfoliated. Nonframework grains include epidote, chlorite, hornblende, pyroxene, and opaque mafic minerals. Bent

Table 2. Composition of sandstone of the Raging River Formation and the lower part of the Tiger Mountain Formation, King County, Washington.

[Percentage of grain type (not normalized) is presented as a mean (X) and standard deviation (SD). Statistical parameters calculated after Dickinson (1985). Percentages based on point counts of more than 300 framework grains (quartz, feldspar, lithic fragments) per thin section or grain mount using the "Gazzi-Dickinson" method (Ingersoll and others, 1984). Raw petrographic data used in constructing this table is given in appendix 1]

	Raging River Formation						Lower part of Tiger Mountain Formation	
	Unit1 (*n*=7)		Unit 2 (*n*=3)		Unit 3 (*n*=10)		(*n*=7)	
	X	SD	X	SD	X	SD	X	SD
Monocrystalline quartz	28.0	10.5	11.8	1.0	12.6	10.8	28.1	2.4
Polycrystalline quartz	8.1	3.2	5.1	3.4	2.5	1.8	3.1	1.2
Chert	3.6	2.3	3.0	2.8	0.2	0.4	2.5	1.6
Plagioclase feldspar	11.8	5.8	24.8	5.6	33.3	12.3	29.1	4.6
Potassium feldspar	0	0.1	0	0	0	0	0.1	0.2
Sedimentary lithic	9.7	2.4	12.1	9.6	2.9	3.7	7.9	1.7
Volcanic lithic	28.4	5.0	34.3	12.6	40.3	14.3	20.7	5.9
Metamorphic lithic	0.8	0.8	0.3	0.3	0.7	1.0	1.2	1.0
Mica	0.8	0.5	0.9	0.5	1.7	1.7	2.9	1.8
Accessories	2.3	1.8	1.3	1.4	1.7	1.4	0.5	0.5
Matrix and cement	6.6	2.3	5.2	6.6	4.8	4.5	3.8	1.4
Plagioclase/total feldspar	1.00	0.01	1.0	0	1.0	0	1.0	0.01
QFL	44,13,43		22,27,51		17,36,47		37,31,32	
QmFLt	31,12,56		13,27,60		14,36,50		31,31,38	
QmPK	70,30,0		33,67,0		27,73,0		51,49,0	
QpLvLs	23,58,19		4,64,22		7,85,8		15,61,26	

lithic fragments, calcite cement, and clay pseudomatrix (Dickinson, 1970) have resulted in the loss of all primary porosity.

On ternary provenance diagrams (Dickinson, 1985) (fig. 13), the mean of sandstones of unit 1 plots in the more "oceanic" part of the recycled orogen field on a QFL diagram, in the more chert rich part of the recycled orogen field on a QmFLt diagram, and in the arc orogen field on a QpLvLs diagram.

UNIT 2

Three sandstones were examined from conglomerate-rich unit 2. These samples are also lithic arenite (Dott, 1964) and consist of poorly to moderately sorted, medium-grained sandstone (table 2, appendix 1). Two of the samples were collected on the east flank of Tiger Mountain, and the third sample was collected about 5 km to the northwest on the north flank of Tiger Mountain (fig. 2).

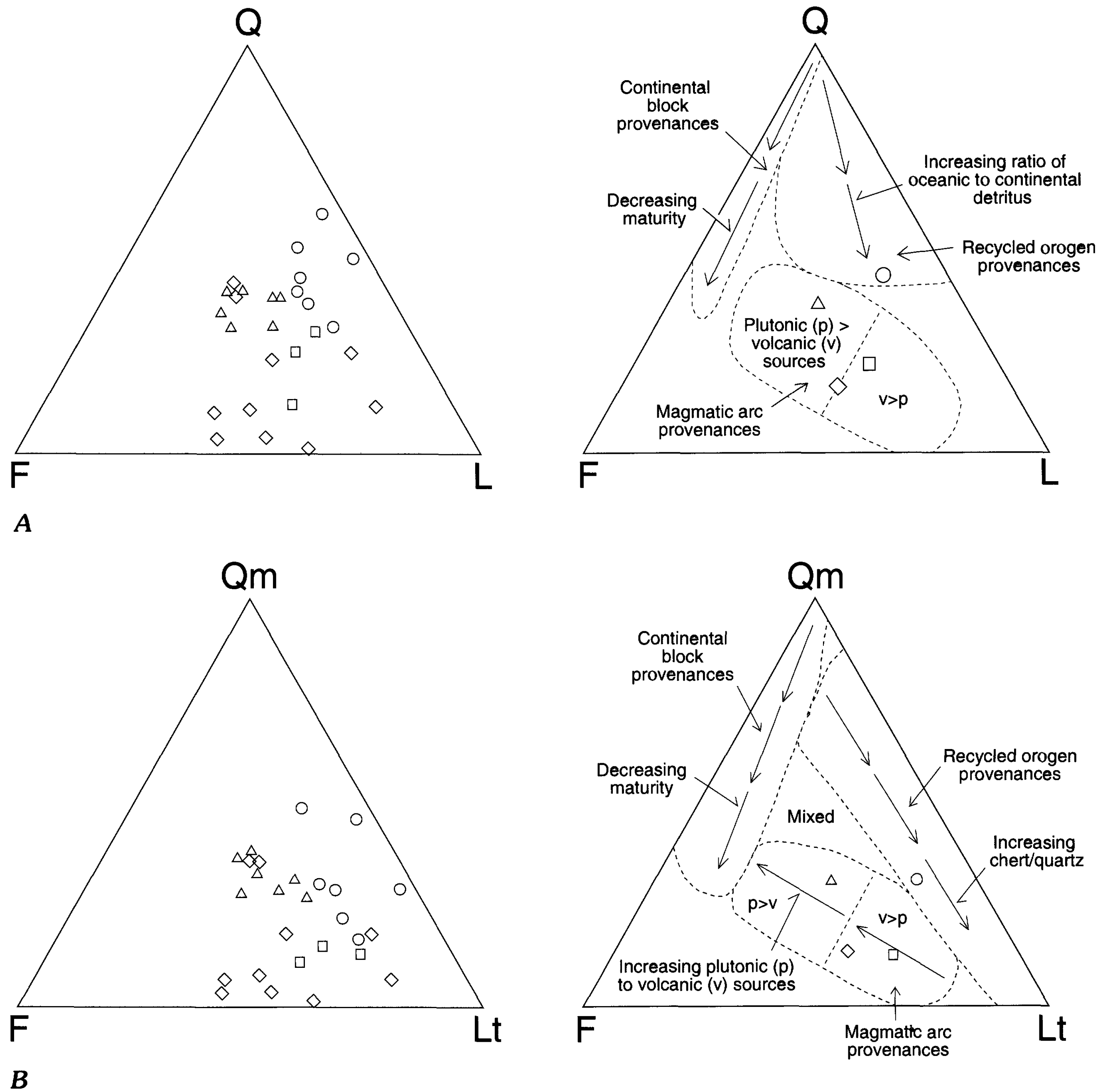
The most common component of the two samples from the east flank of Tiger Mountain (SJ–91–32 and SJ–92–131) is volcanic lithic fragments, which have mainly lathwork and microlitic textures. Plagioclase (albite based on optical determinations) is also abundant and ranges from fresh to highly altered. Potassium feldspar is absent. Monocrystalline quartz makes up about 10 percent of each sample; polycrystalline quartz and chert are less common.

Sample SJ–91–200 from the north flank of Tiger Mountain contains about 25 percent volcanic lithic fragments and 23 percent sedimentary lithic fragments. Volcanic lithic fragments have lathwork, microlitic, and felsitic textures. Sedimentary lithic fragments range from quartzite to matrix-rich siltstone. Polycrystalline quartz (including chert) and monocrystalline quartz make up about 13 and 16 percent of the rock, respectively. Plagioclase feldspar (about 20 percent) is albite (based on optical determination) and variably altered to clays; potassium feldspar is absent. Primary porosity in all samples of unit 2 has been completely filled by bent lithic fragments, clay pseudomatrix (Dickinson, 1970), and (or) calcite cement.

All three samples of unit 2 plot in the magmatic arc field on both QFL and QmFLt ternary provenance diagrams (Dickinson, 1985) (figs. 13*A*, *B*), and in the arc orogen field on a QpLvLs diagram (fig. 13*D*). The compositional variation between the samples from the two outcrop areas could reflect (1) different local source terranes for sediments deposited 5 km apart at about the same stratigraphic level, (2) sampling from different stratigraphic levels within unit 2, or (3) incorrect correlation of the two different outcrop areas (see preceding discussion).

UNIT 3

Ten samples of poorly to moderately sorted, fine- to coarse-grained sandstone from unit 3 were examined



EXPLANATION

△ **Lower part of the Tiger Mountain Formation**

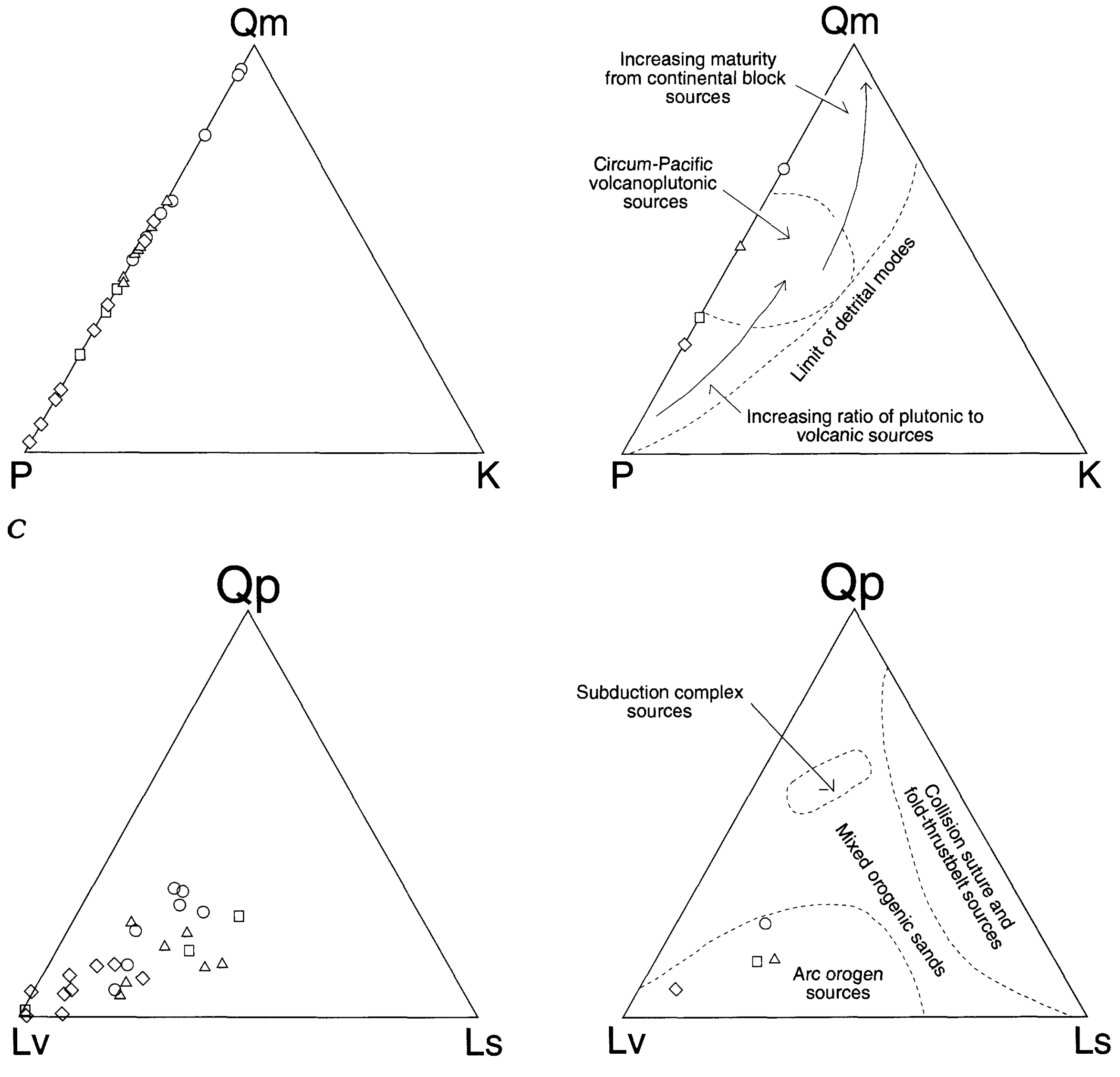
Raging River Formation

◇ **Unit 3**

□ **Unit 2**

○ **Unit 1**

Figure 13 (above and facing page). Ternary provenance diagrams showing range and mean of (*A*) QFL, (*B*) QmFLt, (*C*) QmPK, and (*D*) QpLvLs parameters for units 1, 2, and 3 of the Raging River Formation and the lower part of the Tiger Mountain Formation. Sandstone compositional data are summarized in table 2, and raw petrographic data and field definitions are given in appendix 1. Provenance fields from Dickinson (1985).



petrographically (table 2, appendix 1). Six of the samples are lithic arenite, and four samples (including the two stratigraphically highest samples from the AMOCO WC–83–14 well) are arkosic arenite (Dott, 1964). Volcanic lithic fragments (20–67 percent) and plagioclase feldspar (15–52 percent) are the most abundant two components in samples of unit 3. Volcanic lithic fragments have lathwork, microlitic and felsitic textures. Other types of lithic grains (including polycrystalline quartz and chert) make up less than 10 percent of most samples. Plagioclase feldspar is albite (based on optical determination). Potassium feldspar is absent. Monocrystalline quartz ranges from 1 to 18 percent in all but the upper two samples from the AMOCO WC–83–14 core. Chlorite, epidote, and opaque minerals are common accessory minerals. Biotite, which is rare in underlying units and in most of unit 3, makes up more than 3 percent of the stratigraphically highest sample. Primary porosity has been eliminated (to varying degree in different samples) by bent lithic fragments, pseudomatrix (Dickinson, 1970), calcite cement, and fibrous phyllosilicate cement. Samples of unit 3 plot in or closest to the magmatic arc provenance fields on QFL and QmFLt ternary provenance diagrams, and in the arc orogen field on a QpLvLs diagram (Dickinson, 1985) (figs. 13*A*, *B*, *D*).

Table 3. Normalized proportions of detrital heavy minerals in the Raging River Formation and the lower part of the Tiger Mountain Formation, King County, Washington.

[Sample locality information and point-count data are given in appendix 2. Unit numbers refer to units 1, 2, and 3 of the Raging River Formation; TM indicates Tiger Mountain Formation. Sample SJ–91–25 is a composite sample from units 2 and 3. Petrofacies A, B, and C are described in text. Detrital indicates percentage of grains in heavy-mineral suite that are of inferred detrital origin. ZTGA includes zircon, monazite, tourmaline, garnet, apatite, and allanite; EPZ includes epidote and zoisite; UM includes chromite, chromium-rich chlorite, and olivine; pyroxene includes orthopyroxene and diopside; amphibole includes hornblende and tremolite; mica includes biotite, muscovite, chlorite, and margarite]

	SJ–92–114	SJ–91–25	SJ–92–117	SJ–92–129	SJ–92–127
Unit	1	2, 3	3	3	TM
Petrofacies	A	B	B	B	C
Detrital	1.0	44.8	86.6	32.6	59.56
ZTGA	66.67	12.70	3.56	13.19	8.67
EPZ	0	0	0	0	56.26
UM	0	36.54	0	3.31	0.96
Pyroxene	0	0.44	0	0	0
Amphibole	0	0.51	0	1.10	0
Mica	0	37.80	96.44	82.45	14.42
Magnetite	0	11.47	0	0	0
Rutile	33.33	0	0	0	0
Sphene	0	0.51	0	0	18.75
Calcium-rich plagioclase ($>An_{60}$)	0	0	0	0	0.94

LOWER PART OF THE TIGER MOUNTAIN FORMATION

Seven samples of moderately sorted, medium-grained sandstone from the lower part of the Tiger Mountain Formation were examined (table 2, appendix 1). These samples are classified as lithic arenite (four samples) and arkosic arenite (three samples) and have fairly uniform compositions (fig. 13). Plagioclase feldspar (albite based on optical determinations) is the most abundant framework component (23–35 percent), followed by monocrystalline quartz (26–31 percent). Volcanic lithic fragments (13–29 percent) have lathwork, microlitic, and felsitic textures. Sedimentary lithic fragments (6–11 percent), polycrystalline quartz (2–4 percent), and chert (1–6 percent) are present in lesser amounts. Biotite (1–5 percent) is the most common accessory mineral. Primary porosity was eliminated (to varying degree in different samples) by bent lithic fragments, pseudomatrix (Dickinson, 1970), and calcite cement. Samples plot in the magmatic arc provenance fields on QFL and QmFLt ternary provenance diagrams, and in the arc orogen field on a QpLvLs diagram (Dickinson, 1985) (figs. 13*A*, *B*, *D*).

HEAVY-MINERAL STUDIES

Heavy-mineral studies were carried out on four samples of the Raging River Formation and one sample from the lower part of the Tiger Mountain Formation in order to supplement petrographic studies. Grain counts of the heavy-mineral suites are listed in appendix 2. Samples included a mix of heavy minerals of inferred detrital and authigenic origin. Detrital heavy minerals, which make up from 1 to 87 percent of the grains counted for each sample, are grouped and listed in table 3. Three of the mineral groups listed in table 3 are based on inferred common genetic association. Zircon, monazite, tourmaline, garnet, apatite, and allanite (ZTGA group) are most commonly associated with granitoid igneous or metamorphic rocks, epidote and zoisite (EPZ group) are most commonly present in metabasic rocks, and chromite, chromium-rich-chlorite, and olivine (UM group) are most commonly present in ultramafic rocks. Chlorite is the most common phyllosilicate. Although some chlorite in the Raging River Formation is present as an authigenic clay mineral, the grains that were counted for the heavy-mineral analysis are larger and mainly formed by alteration of biotite that could have occurred either prior to erosion of the sediment source or during burial of the Raging River Formation.

Samples contained a high proportion (14–99 percent) of minerals that are of inferred authigenic origin, including calcite and other carbonate minerals, anatase, barite, hematite, and sulfide minerals. The large proportion of these minerals and abundant replacement textures within grains (carbonate by carbonate, carbonate by sulfide, silicate by carbonate) indicate a chemically dynamic diagenetic environment. The range of sulfide phases (abundant pyrite and minor sphalerite, galena, chalcopyrite, chalcocite, tetrahedrite, and molybdenite) also implies that metal-bearing fluids may have circulated through the rocks, an interpretation consistent with the numerous dikes that intrude the rocks (fig. 4) and their geographic proximity to the Tukwila volcanic center (Vine, 1969).

Although the heavy-mineral grain counts provide important information on the petrology of Raging River

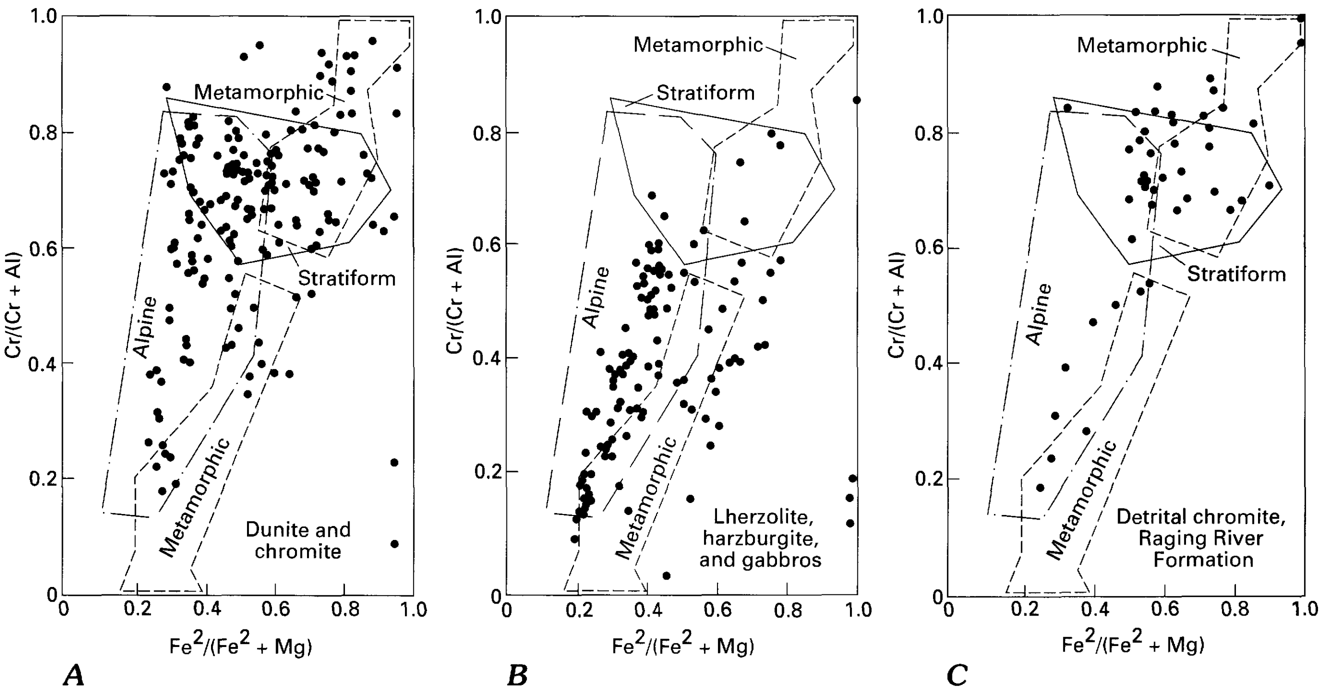


Figure 14. Comparison of chemical analyses of chromite from Cordilleran ultramafic rocks. Fields are modified slightly from Loferski (1986). Chromites having compositions that plot in the upper right corner of diagrams are probably from serpentinite (Evans and Frost, 1974). Data from Himmelberg and Coleman (1968), Thayer (1969), Loney and others (1971), Himmelberg and Loney (1973, 1980, 1981), Onyeagocha (1974), Evans and Frost (1974), Irvine (1974), Dick (1977), Quick (1981), Snoke and others (1981), Loferski and Lipin (1983), Dick and Bullen (1984), Harper (1984), Himmelberg and others (1985), Miller and Mogk (1987), Loferski (1986), and Loney and Himmelberg (1983, 1989). *A*, Cumulate ultramafic rocks (dunite and chromitite). *B*, Alpine-type or metamorphic peridotite (lherzolite and harzburgite). *C*, Detrital chromite from units 2 and 3 of the Raging River Formation.

sandstone, their utility for distinguishing provenance is limited by the number of samples analyzed and the flooding effects of authigenic minerals (see preceding). To provide additional information, the chemistry of detrital chromite was also analyzed (fig. 14). Chromite (including ferritchromit, chromium-rich magnetite, and chrome-spinel), present in three of the five analyzed samples, is a good provenance indicator because it has a restricted origin (primarily ultramafic rocks). Figure 14 shows the compositions of Raging River Formation chromites plotted beside those from cumulate ultramafic rocks (dunite and chromitite) and those from alpine-type or metamorphic peridotite (lherzolite and harzburgite). These plots indicate that the chromite in the Raging River Formation had a likely source in cumulate ultramafic bodies. Analyses of six other detrital mineral grains are provided in appendix 3.

PROVENANCE

Sandstone petrography and scanning electron microscope–energy-dispersal spectral heavy-mineral data indicate variable sources for the Raging River Formation and the lower part of the Tiger Mountain Formation. These sources are difficult to identify precisely because of the abundant cover of younger rocks and because of probable large-scale, Eocene displacement on the Straight Creek fault (fig. 1). The Straight Creek fault experienced approximately 85–190 km of right-lateral slip, probably mainly of Eocene age (Misch, 1977; Vance and Miller, 1981, 1992; Tabor and others, 1984; Johnson, 1985; Ague and Brandon, 1990; Coleman and Parrish, 1991); thus, sediment source terranes east of the Straight Creek fault were displaced at least several tens of kilometers following deposition of the Raging River Formation.

On the basis of sandstone petrography, three stratigraphically controlled sandstone petrofacies were identified in the Raging River Formation and the lower part of the Tiger Mountain Formation (fig. 15). Petrofacies A represents sandstone of unit 1 and is distinguished on the basis of relatively equal amounts of monocrystalline quartz and volcanic lithic fragments and significant amounts of plagioclase, sedimentary lithic fragments, polycrystalline quartz, and chert. On ternary provenance diagrams (figs. 13, 15), the mean composition plots in either the oceanic or chert-rich parts of the recycled orogen field or in the mixed-source field. The heavy-mineral suite identified in the single sample of petrofacies A is dominated by authigenic minerals and therefore yields little provenance information. The inferred probable source for petrofacies A was nearby uplifts of Mesozoic rock of oceanic affinity, probably the western and eastern melange belts mapped by Frizzell and others (1987) less than 10 km east of Tiger Mountain (fig. 1). These oceanic basement rocks are present regionally (for example, Frizzell and others, 1987; Miller, 1989) and contain abundant chert, graywacke, and greenstone. The variable sedimentology and texture of rocks of petrofacies A must reflect a combination of variable relief in the source, sediment supply, and relative sea level.

Petrofacies B includes sandstone from unit 2 and from the stratigraphically lower part of unit 3 (all samples except the upper two from the AMOCO WC–83–14 core) (table 2, appendix 1). This petrofacies is distinguished on the basis of the large proportion of volcanic lithic fragments and plagioclase. The mean composition plots in the more volcanic part of the magmatic arc field on provenance diagrams (fig. 15), indicating a volcanic source terrane. The increased proportion of volcanic lithic fragments in petrofacies B most likely indicates derivation from a different, more volcanic rich, erosional level within Mesozoic melange belts that are inferred to be the source for petrofacies A. Petrofacies B was, however, at least partly deposited at bathyal depths, making a more distal source of volcanic sediment also possible (because proximal sources might have also been submerged). Suitable volcanic rocks east of the Mesozoic melange belts and on the east side of the Straight Creek fault include the volcanic part of the Late Jurassic or Early Cretaceous ophiolitic Ingalls Tectonic Complex (Tabor and others, 1982; Miller, 1985), the lower Tertiary Taneum Formation, and the Silver Pass Volcanic Member of the Swauk Formation (Tabor and others, 1984).

The presence of detrital chromite in rocks of petrofacies B (fig. 14, table 3, appendix 2) indicates that some ultramafic rock was also exposed in the source terrane for petrofacies B. Frizzell and others (1984) mapped minor ultramafic rock (serpentinite) in the western melange belt, and Walsh (1984) mapped Quaternary terrace deposits along the Cedar River (about 10 km south of the Raging River Formation outcrop belt shown in fig. 2) that contain ultramafic boulders. These boulders range in diameter from about 1.8 to 6.1 m (6–20 ft) and consist of peridotite and pyroxenite, commonly with cumulate textures. The size of these boulders indicates that they must have been locally derived from a part of the western melange belt that is now concealed or, alternatively and less likely, was completely eroded in the Eocene. Similar ultramafic bodies in the western melange belt of dunite or chromitite composition are the most likely source of detrital chromite in the Raging River Formation. Correlative Jurassic ophiolitic rocks (Vance and others, 1980) in western Washington include significant cumulate ultramafic bodies such as the Twin Sisters Dunite (Ragan, 1963).

The ophiolitic Ingalls Tectonic Complex (Miller, 1985; Miller and Mogk, 1987), which is present within about 50 km of the Tiger Mountain area (fig. 1) and contains a significant proportion of ultramafic rocks, is a more distant candidate for the source of the detrital chromite. Most of the ultramafic rocks (≥90 percent) in the Ingalls Tectonic Complex, however, are lherzolite and harzburgite (Miller, 1985, oral commun., 1993), not the dunite or chromitite that the chemical data of figure 14 suggest are the probable source for the detrital chromite.

Petrofacies C includes the upper part of the Raging River Formation (upper two samples of unit 3) and sandstone of the lower part of the Tiger Mountain Formation (table 2, appendix 1). This petrofacies is distinguished on the basis of relatively equal amounts of quartz (including polycrystalline quartz and chert), plagioclase feldspar, and lithic fragments (mainly volcanic and sedimentary). The mean composition for petrofacies C plots in the more plutonic part of the magmatic arc field on provenance diagrams (fig. 15) and is easily distinguished from petrofacies B on the basis of a smaller proportion of volcanic lithic fragments. The sample of petrofacies C analyzed for heavy minerals contains a large proportion of epidote (table 3, appendix 2). Petrofacies C was probably derived from a variety of sources, including the Mesozoic oceanic rocks (the most likely source of detrital epidote) and lower Tertiary volcanic rocks inferred for petrofacies A and B, and plutonic or crystalline rocks. Plutonic and crystalline rocks are the main sources for Eocene sandstone in the Puget Lowland and Cascade Range (for example, Frizzell, 1979; Johnson, 1984b, 1985; Taylor and others, 1988), including those of the Puget Group, which overlies the Raging River Formation. Possible plutonic or crystalline sources include the Mount Stuart batholith (fig. 1) and high-grade metamorphic rocks now exposed in northeastern Washington, and the Idaho batholith (Johnson, 1984b). Petrofacies C was thus deposited in a transitional period of drainage reorganization, during which more eastern sources could be tapped.

In summary, the petrofacies reveal an evolution in source terrane for lower(?) and middle Eocene sediments deposited in the Puget Basin (Johnson, 1985) of the central Puget Lowland. The oldest strata represented by petrofacies A were derived primarily from Mesozoic basement rocks of oceanic affinity. Stratigraphically higher petrofacies B was derived from Mesozoic oceanic rocks and also possibly from lower Tertiary volcanic rocks. The stratigraphically highest rocks examined in this study, represented by petrofacies C, were probably derived from a variety of sources that includes Mesozoic oceanic rocks,

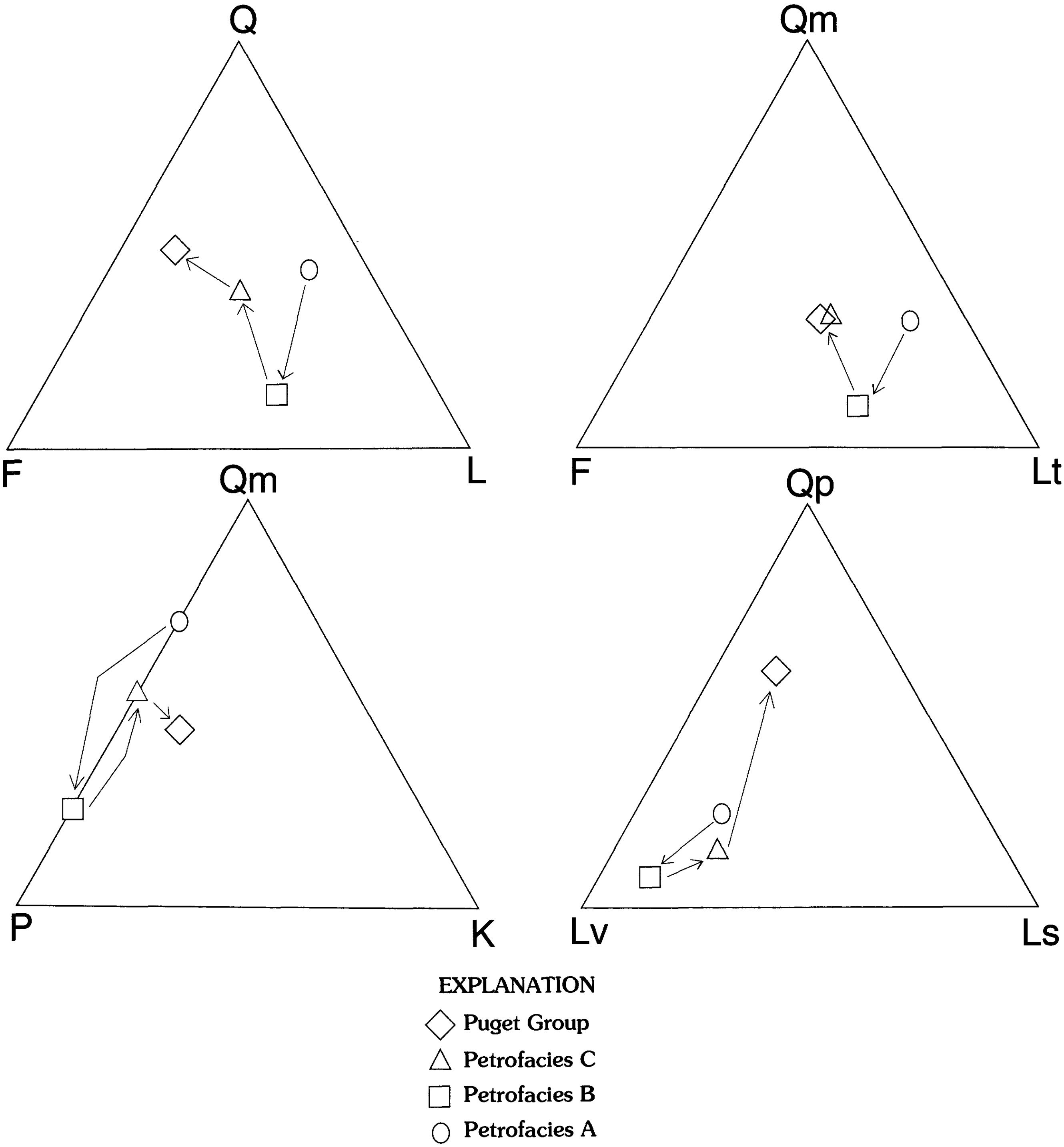


Figure 15. Ternary provenance diagrams showing the mean of QFL, QmFLt, QmPK, and QpLvLs parameters for the three petrofacies (A, B, and C) recognized in the Raging River Formation and the lower part of the Tiger Mountain Formation (raw data in appendix 1) and for the younger Puget Group (data from Frizzell, 1979). Field definitions are given in appendix 1.

lower Tertiary volcanic rocks, and regional plutonic or crystalline rocks. Petrofacies C represents a transition from oceanic and volcanic sediment sources to more plutonic and crystalline sources represented by the overlying Puget Group (fig. 15) (Frizzell, 1979).

DISCUSSION

Sedimentologic and petrologic data for the Raging River Formation and the lower part of the Tiger Mountain Formation provide important data for regional paleogeographic reconstruction. Paleocurrent data (fig. 9) were collected from only a small area but suggest a west-dipping paleoslope, consistent with other studies in the Cascade foothills and with petrologic data (for example, Buckovic, 1979; Johnson, 1984a, b, 1985, unpublished data). The rapid transition in the Raging River Formation from nonmarine deposits of unit 2 to middle bathyal (depths of 500–2,000 m) deposits of unit 3 provides evidence for abrupt subsidence and submergence of this paleoslope in the early middle Eocene (early Narizian, about 48 Ma; Johnson, 1993). This dramatic pulse of basin subsidence is not seen in the correlative Chuckanut Formation farther to the north in the Puget Lowland and Cascade foothills (Johnson, 1984b) or in the Swauk Formation to the east (Taylor and others, 1988) and thus probably is related to local tectonism and not to regional transgression. Furthermore, global sea-level curves (Haq and others, 1988) do not show a major rise in sea level at this time. Following this pulse of rapid subsidence, an uplift event is recorded by the abrupt transition from the middle bathyal deposits of unit 3 of the Raging River Formation to the inferred shelf deposits of the lower part of the Tiger Mountain Formation (Johnson, 1993). This transition (provided there is minimal or no section cut out at the contact) requires at least several hundred meters of shoaling but occurs within a few tens of meters of section (fig. 11). Thus, the basin floor must have been rising during deposition of the lower Tiger Mountain Formation. Comparisons of the subsidence history of the Tiger Mountain area and other sites in the Puget Lowland will provide important data for reconstructing the tectonic and sedimentary history of the region (Johnson, 1993).

Recognition of eastern Mesozoic basement terranes as early(?) and early middle Eocene sediment sources is important for understanding the paleogeography of correlative rocks deposited farther to the west on the eastern Olympic Peninsula. On the basis mostly of a significant component of sedimentary, metasedimentary, chert, and volcanic lithic fragments, Melim (1984) suggested that the lower middle Eocene sandstone of Scow Bay (Armentrout and Berta, 1977) must have been derived from rocks in the San Juan Islands to the north (Brandon and others, 1988), an area mostly underlain by terranes similar to those in the melange belts mapped by Frizzell and others (1987). Einarsen (1987) similarly suggested a source in the San Juan Islands for a chert-rich petrofacies in the lower Eocene Blue Mountain unit (sedimentary interbeds in the Crescent Formation); however, there is no independent evidence that the main part of the San Juan Islands were uplifted during the early to early middle Eocene. For example, the western part of the main outcrop belt of the Chuckanut Formation, less than 10 km east of the eastern San Juan Islands, is relatively fine grained and dominantly arkosic and was derived from sources to the east and north, not the west (Johnson, 1984b). In contrast, there is now compelling evidence (this study) that lithologically similar source rocks were exposed and eroding in the western Cascade foothills in the early(?) and early middle Eocene.

The inferred uplifts of Mesozoic rocks may have been associated with activity along the Straight Creek fault. The Raging River Formation is probably correlative with the upper part of the Swauk Formation, which mainly crops out east of Tiger Mountain on the east side of the Straight Creek fault (fig. 1) (Tabor and others, 1984; Taylor and others, 1988). These upper Swauk strata consist of fluvial and lacustrine deposits; sandstones are arkosic arenite (Taylor and others, 1988), in marked contrast to the dominantly marine lithic arenite of the Raging River Formation (Taylor and others, 1988). These contrasts suggest that the two units were not part of one contiguous sedimentary basin. On the basis of facies and paleocurrent analysis in the Swauk, Taylor and others (1988) inferred that tectonic uplift occurred in the Straight Creek fault zone during early middle Eocene time. The lithologic contrasts between the Swauk and Raging River Formations provide supporting evidence for this tectonic partition. Contrasts between the inferred paleogeography of the Swauk basin and Puget basin (Johnson, 1985) no doubt also reflect significant juxtaposition of disparate paleogeographic elements by dextral strike-slip offset on the Straight Creek fault.

CONCLUSIONS

Three informal stratigraphic units are recognized in the lower(?) and middle Eocene Raging River Formation based on distinctive sedimentary facies and lithologies. A fourth unit (unit 0) consisting of breccia-conglomerate could represent either the lowest part of the Raging River Formation or, more likely, lithified Quaternary(?) colluvium. Unit 1, approximately 230 m thick, consists of interbedded sandstone, mudstone, and conglomerate of inferred nonmarine (lower part) and shallow-marine (upper part) origin. Unit 2, approximately 185 m thick, consists of interbedded conglomerate, sandstone, and mudstone and is interpreted as mainly alluvial deposits. A major transgression resulting from rapid local subsidence is recorded by unit 3 (about 300 m thick), which consists of gray silty mudstone and lesser sandstone and was deposited in a marine shelf (lower part) and bathyal slope (upper part) setting. The Raging River Formation is overlain by prodelta(?) marine shelf deposits in the lower part of the Tiger Mountain Formation. Marine rocks correlative with the Raging River Formation probably underlie a significant part of the eastern Puget Lowland and represent a possible source for hydrocarbons.

Three sandstone petrofacies were identified in the Raging River Formation and lower part of the Tiger Mountain Formation. These petrofacies reveal an upward evolution in sediment source from Mesozoic volcanic and sedimentary rocks of oceanic affinity (petrofacies A), to lower Tertiary and Mesozoic volcanic rocks and minor(?) ultramafic rocks (petrofacies B), to a mixed provenance including Mesozoic oceanic rocks, lower Tertiary volcanic rocks, and more distal plutonic or crystalline rocks (petrofacies C). Contrasts between the petrology and sedimentology of the Raging River Formation and correlative rocks in western Washington argue for significant local tectonism and segregation of discrete sedimentary basins.

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Published in the Central Region, Denver, Colorado
Manuscript approved for publication April 29, 1994
Edited by Judith Stoeser
Graphics prepared by Samuel Y. Johnson and Gayle Dumonceaux
Photocomposition by Norma J. Maes

Appendix 1. Raw petrographic data for sandstone from the Raging River Formation and the lower part of the Tiger Mountain Formation, King County, Washington.

[Point counts were made using the Gazzi-Dickinson method (Ingersoll and others, 1984). All thin sections were stained for potassium feldspar. Petrographic data are plotted in figures 13 and 15 and summarized in table 2. Sample localities are shown in figure 2]

CODES FOR PETROGRAPHIC DATA

1. Stratigraphic unit: R1, unit 1 of the Raging River Formation; R2, unit 2 of the Raging River Formation; R3, unit 3 of the Raging River Formation; TM, lower part of the Tiger Mountain Formation
2. Locality: 1, Amoco Production WC–83–14 borehole; footage given in parentheses following locality number; 2, outcrops in drainage in S½ sec. 4, N½ sec. 9, T. 23 N., R. 7 E.; 3, roadcut outcrops in W½, sec. 15, T. 23 N., R. 7 E.; 4, roadcut outcrops in SW¼ sec. 32, T. 24 N., R. 7 E.; 5, outcrops in drainage in SW¼ sec. 10, T. 23 N., R. 7 E.; 6, outcrops in SW¼ sec. 14, T. 23 N., R. 7 E.; 7, outcrops in N½, sec. 21, T. 23 N., R. 7 E.
3. Grain size of sample: F, fine-grained sandstone; M, medium-grained sandstone; C, coarse-grained sandstone
4. Number of points counted
5. Number of framework grains counted

6–22. Modal percent of composition (not normalized to 100 percent)

6. Monocrystalline quartz
7. Foliated polycrystalline quartz
8. Undifferentiated polycrystalline quartz
9. Chert
10. Plagioclase feldspar
11. Potassium feldspar
12. Sedimentary rock fragments
13. Volcanic rock fragments
14. Quartz-mica tectonite rock fragments
15. Low-grade metamorphic rock fragments
16. Biotite, muscovite, and chlorite
17. Epidote, amphibole, and pyroxene
18. Opaque minerals, garnet, sphene, and other heavy minerals
19. Matrix and hematite cement
20. Calcite cement
21. Porosity
22. Plagioclase/total feldspar
23. QFL (total quartz, feldspar, lithic fragments)
24. QmFLt (monocrystalline quartz, feldspar, lithic fragments)
25. QmPK (monocrystalline quartz, plagioclase feldspar, potassium feldspar, lithic fragments)
26. QpLvLs (polycrystalline quartz, volcanic lithic fragments, sedimentary lithic fragments)

For calculating ternary ratios QFL, QmFLt, QmPK, and QpLvL: Q=6+7+8+9; Qm=6; F=10+11; L=12+13+14+15; Lt=7+8+9+12+13+14+15; Qp=2=3=4; Lv=8; Ls=7.

	SJ–91–10A	SJ–91–12	SJ–91–13B	SJ–91–15	SJ–91–16	SJ–91–200	SJ–91–32
1	R1	R1	R1	R1	R1	R2	R2
2	2	2	2	2	2	4	3
3	C	M–C	M	M	M	M	M
4	407	358	380	384	390	380	384
5	347	333	334	355	348	371	370
6	14.5	20.1	25.3	43.0	26.2	12.9	10.4
7	0.5	0.6	0.8	0	0.3	1.8	0
8	9.8	10.6	8.2	6.0	11.6	7.6	0.8
9	6.4	5.9	3.2	3.9	5.1	6.8	0
10	15.7	17.9	14.7	3.4	2.6	19.7	32.6
11	0	0	0.3	0	0	0	0
12	9.6	10.6	12.6	6.3	12.8	22.6	0.5
13	26.5	26.5	22.1	27.9	30.8	25.3	52.1
14	0.5	0.3	0.8	0	0	0.8	0
15	1.7	0.6	0	0	0	0	0
16	1.5	0.8	0.6	0	0.8	1.6	0.3
17	5.1	1.1	0	0	0.5	0	0.3
18	1.2	1.4	2.4	0.8	1.0	0	0.3
19	0	0	6.8	0	0.5	0	2.9
20	6.9	3.6	2.4	8.9	7.9	0.8	0.3
21	0	0	0	0	0	0	0
22	1.0	1.0	0.98	1.0	1.0	1.0	1.0
23	37,18,45	40,19,41	43,17,40	59,4,37	48,3,49	30,20,50	12,34,54
24	17,18,65	22,19,59	29,17,54	46,4,50	29,3,68	13,20,67	11,34,55
25	48,52,0	53,47,0	62,37,1	93,7,0	94,6,0	40,60,0	24,76,0
26	32,50,18	31,49,20	26,47,27	22,63,14	28,51,21	25,39,35	1,98,1

Appendix 1. Raw petrographic data for sandstone from the Raging River Formation and the lower part of the Tiger Mountain Formation, King County, Washington—Continued.

	SJ–91–22	SJ–91–27	SJ–91–41	SJ–91–42	SJ–91–44	SJ–91–48	SJ–91–48A
1	R3	R3	R3	R3	R3	R3	R3
2	3	3	1(1,733)	1(1,676)	1(1,509)	1(918)	1(839.5)
3	M	M–C	F–M	M–C	M–C	M	M
4	392	387	389	383	376	417	383
5	370	368	370	357	353	345	356
6	3.3	0.8	17.5	7.0	6.7	29.5	33.7
7	0	0	0.3	0	0	0.2	0.3
8	0	0.3	4.1	1.8	4.0	3.1	3.1
9	0	0	0	1.3	0.3	0	0
10	41.3	34.1	31.4	38.4	15.4	26.6	29.2
11	0	0	0	0	0	0	0
12	1.0	0.5	0	3.4	0.3	0.2	3.9
13	48.7	59.4	37.3	38.4	67.0	20.1	19.8
14	0	0	0.5	0	0.3	0.5	2.9
15	0	0	1.5	0	0	0	0
16	0.5	0	0.5	0.6	0.3	3.1	4.0
17	0	0	3.1	0	1.1	0	0.5
18	0.5	2.6	1.0	0.8	0.3	1.2	0.5
19	2.6	2.1	1.0	5.0	1.9	0.2	1.3
20	2.0	0.3	1.8	0.5	2.7	15.1	0.8
21	0	0	0	0	0	0	0
22	1.0	1.0	1.0	1.0	1.0	1.0	1.0
23	4,44,53	1,36,63	23,33,44	11,44,45	12,16,72	40,32,28	40,31,29
24	4,44,53	1,36,63	18,33,49	8,44,48	7,16,77	36,32,32	36,31,33
25	7,93,0	2,98,0	36,64,0	15,85,0	30,70,0	53,47,0	54,46,0
26	0,98,2	1,99,1	10,84,6	7,85,8	6,94,0	13,77,10	13,73,14

	SJ–91–51	SJ–91–52	SJ–91–53	SJ–91–54	SJ–91–58	SJ–91–58A	SJ–92–112
1	TM	TM	TM	TM	TM	TM	R1
2	1(526)	1(497)	1(450)	1(389)	1(213)	1(168)	2
3	M	M	M	M–C	F–M	M	M
4	383	382	372	363	422	383	349
5	350	357	349	353	383	353	334
6	26.4	26.2	31.2	26.7	25.6	28.7	22.6
7	0	0.3	0	0.6	0	0.5	0.3
8	1.6	3.4	4.0	4.4	1.4	3.1	6.0
9	0.8	2.9	2.7	5.8	1.2	3.1	0.6
10	28.7	35.3	29.6	23.1	34.6	22.7	15.8
11	0	0.5	0	0	0	0	0
12	7.0	10.7	8.3	5.8	5.7	8.9	9.7
13	28.7	14.1	17.2	28.9	20.9	22.2	39.2
14	0.3	0	0.8	1.9	1.4	2.9	1.2
15	0	0	0	0	0	0	0.3
16	3.7	0.5	2.4	1.1	4.2	2.1	0.6
17	0.3	0	0	0	0	0	0
18	0	0	0.5	0.3	0.9	0	0.9
19	0.3	0	0.5	1.4	1.4	0.3	0
20	4.4	5.0	2.7	0	2.6	5.5	2.9
21	0	0	0	0	0	0	0
22	1.0	0.99	1.0	1.0	1.0	1.0	1.0
23	31,29,40	35,38,27	40,32,28	39,24,38	31,38,31	39,25,37	31,16,53
24	29,29,42	28,38,34	33,32,35	27,24,49	28,38,34	31,25,44	24,16,60
25	50,50,0	42,57,1	51,49,0	62,38,0	43,57,0	56,44,0	59,41,0
26	6,75,19	14,49,37	21,53,26	24,64,13	9,72,29	18,59,23	13,70,17

Appendix 1. Raw petrographic data for sandstone from the Raging River Formation and the lower part of the Tiger Mountain Formation, King County, Washington—Continued.

	SJ–92–113	SJ–92–131	SJ–92–116	SJ–92–121	SJ–92–123	SJ–92–128
1	R1	R2	R3	R3	R3	TM
2	2	5	6	6	6	7
3	F–M	M	F–M	F–M	M–C	M
4	383	429	335	345	366	393
5	350	347	326	335	335	344
6	44.4	12.1	3.9	7.2	16.4	32.1
7	0	0.7	0	0	0.5	0.5
8	2.3	4.7	0.3	2.0	5.2	1.8
9	0	2.3	0	0.3	0.5	1.0
10	12.8	22.1	52.5	50.4	13.9	29.5
11	0	0	0	0	0	0
12	6.3	13.3	3.9	2.9	13.1	8.7
13	25.6	25.4	36.7	34.2	41.0	13.2
14	0	0.2	0	0	0.5	0.5
15	0	0	0	0	0.3	0
16	1.6	0.7	0	3.6	4.4	6.3
17	1.0	0	1.2	0	3.2	0.8
18	0	0.7	0	0	0.9	0.8
19	0	0	1.5	0	0	2.3
20	6.0	14.5	8.9	0	0	0
21	0	13.3	0	0	0	0
22	1.0	1.0	1.0	1.0	1.0	0.99
23	51,14,36	25,27,48	4,54,42	10,52,38	25,15,60	40,34,26
24	49,14,37	15,27,58	4,54,42	7,52,41	18,15,67	37,34,29
25	78,22,0	35,65,0	7,93,0	13,87,0	54,46,0	52,48,0
26	7,75,18	17,55,29	1,90,9	6,87,7	10,68,22	13,53,34

Appendix 2. Point-count data for the heavy-mineral suites of four sandstone samples from the Raging River Formation and one sample from the lower part of the Tiger Mountain Formation, King County, Washington.

[Sandstone samples were crushed, sieved, and washed to fine sand size and separated using a $Na(WO_4)_n$ liquid of density +2.85. Several thousand grains from the heavy fraction of each separation were mounted in epoxy on a glass petrographic slide and ground to slightly thicker than a standard thin section. The slides were polished with alumina. Grain mounts were studied with an optical petrographic microscope, a scanning electron microscope (SEM), and an electron microprobe. Heavy-mineral modes were counted using the energy-dispersive spectral (EDS) capability of the SEM. SEM-EDS analysis (as opposed to traditional analysis by petrographic microscope) allowed opaque mineral phases including provenance-specific chromite and sulfide minerals to be clearly distinguished and made it possible to document compositional breaks among many silicate families (for example, garnet, tourmaline, and amphibole). Where SEM-EDS data were not sufficient to clearly distinguish between some mineral phases (for example, calcium-rich garnet and zoisite), supplemental analysis by optical microscope was undertaken]

CODES FOR HEAVY-MINERAL DATA

1. Stratigraphic unit: R1, unit 1 of the Raging River Formation; R2, unit 2 of the Raging River Formation; R3, unit 3 of the Raging River Formation; TM, lower part of the Tiger Mountain Formation
2. Locality: 2, outcrops in drainage in S½ sec. 4, N½ sec. 9, T. 23 N., R. 7 E.; 3, roadcut outcrops in W½, sec. 15, T. 23 N., R. 7 E.; 4, roadcut outcrops in SW¼ sec. 32, T. 24 N., R. 7 E.; 5, outcrops in drainage in SW¼ sec. 10, T. 23 N., R. 7 E.; 6, outcrops in SW¼ sec. 14, T. 23 N., R. 7 E.; 7, outcrops in N½, sec. 21, T. 23 N., R. 7 E.
3. Number of points counted

4–41. Modal percent of composition (not normalized to 100 percent)

4. Magnetite
5. Titanium-rich magnetite
6. Hematite
7. Chromite[1]
8. Rutile
9. Anatase
10. Sphene
11. Zircon
12. Monazite
13. Tourmaline, undifferentiated
14. Garnet, undifferentiated
15. Apatite
16. Epidote
17. Zoisite
18. Allanite
19. Calcium-rich plagioclase (>An_{60})
20. Muscovite
21. Biotite
22. Margarite
23. Chlorite
24. Chromium-rich chlorite
25. Orthopyroxene
26. Diopside
27. Olivine
28. Hornblende
29. Tremolite
30. Pyrite
31. Chalcopyrite
32. Sphalerite
33. Chalcocite
34. Tetrahedrite
35. Molybdite
36. Calcite
37. Siderite
38. Ankerite
39. Rhodochrosite
40. Barite
41. Rock fragments

[1]Includes chromium-rich magnetite and ferritchromit (Lipin, 1984).

Appendix 2. Point-count data for the heavy-mineral suites of four sandstone samples from the Raging River Formation and one sample from the lower part of the Tiger Mountain Formation, King County, Washington—Continued.

	SJ–92–114	SJ–91–25	SJ–92–117	SJ–92–129	SJ–92–127
1	R1	R2–3	R3	R3	TM
2	2	3,4	6	3	6
3	304	419	360	350	557
4	0	5.14	0	0	0
5	0	0	0	0	0
6	15.18	0	3.63	3.94	0.57
7	0	15.57	0	1.08	0.57
8	0.33	0	0	0	0
9	4.62	27.04	3.35	20.25	5.73
10	0	0.23	0	0	11.17
11	0.33	1.4	0.28	0.54	0
12	0.33	1.16	0.28	0	0
13	0	0.1	0	0	0
14	0	0.23	0.56	0	0
15	0	2.10	1.96	3.76	5.16
16	0	0	0	0	32.08
17	0	0	0	0	1.43
18	0	0.70	0	0	0
19	0	0	0	0	0.56
20	0	0	1.96	0	0
21	0	1.78	4.75	0.18	1.72
22	0	0	0	0	0
23	0	15.16	76.81	26.70	6.87
24	0	0.70	0	0	0
25	0	0.10	0	0	0
26	0	0.10	0	0	0
27	0	0.10	0	0	0
28	0	0.23	0	0.18	0
29	0	0	0	0.18	0
30	42.90	13.33	0.28	31.54	30.65
31	0	0.47	0	0	03
32	0	0	0.28	1.43	0.29
33	0.33	0	0	0	0
34	1.42	0	0	0	0
35	0.33	0	0	0	0
36	18.15	4.73	0.28	9.14	1.43
37	10.89	0	0	0	0.29
38	0	0	0	0	0
39	0	0.20	0	0	0
40	1.95	0	1.68	0.72	0.57
41	3.30	9.54	4.75	0.18	1.65

Appendix 3. Electron microprobe analyses of selected detrital mineral grains from sample SJ–91–25, Raging River Formation, King County, Washington.

[Sample SJ–91–125 is a composite sample of unit 2 and 3 of the Raging River Formation. Sample locality data and point-count data for the heavy-mineral suite are given in appendix 2. Data are not normalized. Total iron is reported as FeO]

	Hypersthene	Pyroxene	Hyspersthene	Tourmaline	Garnet	Garnet
SiO_2	50.65	51.30	57.42	34.57	36.92	37.26
Al_2O_3	0.54	1.33	0.58	25.00	20.96	20.66
TiO_2	0.01	0.09	0.02	1.80	0.20	0.42
FeO	28.77	9.14	7.47	12.06	34.79	33.09
MgO	17.38	13.87	26.19	8.06	1.45	1.06
MnO	1.22	0.62	0.14	0	1.66	1.96
CaO	0.77	21.52	4.32	2.97	3.68	5.64
Na_2O	0	0.42	0	1.09	0	0
K_2O	0	0	0	0	0	0
Cr_2O_3	0	0	1.08	0	0	0

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