Order Number 8820412

Depositional environments, basin evolution and tectonic significance of the Eocene Chumstick Formation, Cascade Range, Washington

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University of Washington, 1988

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Depositional Environments, Basin Evolution And Tectonic Significance Of The Eocene Chumstick Formation, Cascade Range, Washington

by

James Erwin Evans

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

University of Washington

1988

Approved by ______________________
Professor Joanne Bourgeois
Chairperson of Supervisory Committee
Department of Geological Sciences

Date 29 February 1988

Doctoral Dissertation

Signature James E. Evans

Date February 29, 1988

University of Washington

Abstract

DEPOSITIONAL ENVIRONMENTS, BASIN EVOLUTION, AND TECTONIC SIGNIFICANCE OF THE EOCENE CHUMSTICK FORMATION, CASCADE RANGE, WASHINGTON

by James Erwin Evans

Chairperson of the Supervisory Committee:
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The Chumstick Formation represents a Paleogene, humid-tropical, alluvial-fan system which filled a wrench-fault basin in Washington State. Chumstick deposition was characterized by stream-flow processes; low (<5 m/km) fan gradients; rapid (>1 m/k.y.) accumulation of sublithic feldspathic sediments; and extensive vegetation which imparted bank stability even in proximal facies. Coarse-grained fluvial facies near major fault zones consist of laterally stacked braid-bar deposits with an overall sheet geometry. The bulk of the basin fill consists of vertically stacked multistory-channel deposits, sandy overbank deposits, and lacustrine deposits.

Paleovegetation studies demonstrate the presence of broad-leaved, evergreen taxa typical of humid-tropical climatic conditions. The Chumstick flora can be grouped according to depositional sites as "upland" or "lowland" forest in either floodplain or channel-margin settings. Paleosols include entisols, inceptisols (incipient Cca or K horizon development) and histosols. Evidence for periodic (seasonal?) dryness includes xerophytic flora, pedogenic calcretes, and episodically reoccupied fluvial channels with mud-draped trough cross-bedding.

Three major phases of deposition can be discerned in the Chumstick Formation. Phase 1 (>51 Ma to about 42 Ma) consisted of westward-flowing streams in the western sub-basin, with no evidence for relief in the Leavenworth fault zone (LFZ). Phase 2 (about 42 Ma to 40 Ma) resulted from dextral faulting on all three fault zones. West-derived sediment sources resulted from uplift at two transpressive restraining bends in the LFZ. The eastern sub-basin opened as a transtensional step-over between the Eagle Creek (ECFZ) and Entiat (EFZ) fault zones. Tectonic disruption of drainage resulted in axial drainage systems which flowed SE, parallel to the LFZ and ECFZ, and a phase of internal drainage (lacustrine) in the eastern sub-basin. Phase 3 (about 40 Ma to 38 Ma) shows no relation to faults and may indicate tectonic quiescence. The basin was deformed in a zone of dextral transpression between about 38 Ma and 34 Ma. The stratigraphic thickness of the Chumstick Formation is about 12 km, however thermal maturity and geophysical data suggest an actual basin thickness of about 2 km. This discrepancy in thickness is explained by a conveyor-belt sedimentation model.

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ACKNOWLEDGMENTS

I would like to take the opportunity to thank some of the many people who have helped me in this study. First and foremost I would like to express my deepest appreciation to my advisor, Dr. Joanne Bourgeois, for her great enthusiasm, advice, and excellent editing skills during the course of this project. I appreciate the interest and involvement of my other committee members, Dr. Darrel Cowan, Dr. J. Dungan Smith, Dr. Joseph Vance, and Dr. Fiorenzo Ugolini.

This project benefitted from interactions and cooperative research with Dr. Scott Bogue (Occidental College), Mr. Timothy Walsh (Washington Division of Geology and Earth Resources), and Mr. Matt McClincey (Portland State University). I owe a great deal to the encouragement, enthusiasm, and advice of Dr. Samuel Johnson (U.S. Geological Survey). I wish to thank Dr. Jack Wolfe (U.S. Geological Survey), Dr. Karl Newman (Colorado School of Mines), and Dr. Estella Leopold (University of Washington) for their assistance with paleobotanical identifications and interpretations of data. I also express my thanks to Dr. Roland Tabor, Dr. Charles Naeser, and Dr. Roger Ashley (U.S. Geological Survey), to Mr. William Phillips and Mr. William Lingley (Washington Division of Geology and Earth Resources), to Ms. Sherri Goetsch, Mr. Neil Johnson, and Mr. Rick Lewis (Shell Onshore, Inc.), and to Ms. Becky Watson and Mr. Tom Fox (Atlantic Richfield Company) for their help with this project.

It is difficult to acknowledge properly all of the help I have received from fellow graduate students, but I wish to single out Robyn Burnham, Jacob Margolis, Tom Dube, David Mohrig, John Garver, Paul Umhoefer, and Mike McGroder. This study would not have been possible without the loving support of my wife, Penny.

This study received financial support from the Atlantic Richfield Company, Shell Onshore, Inc., the Geological Society of America, the Society of Sigma Xi, and the Corporation Fund of the University of Washington.

Chapter 1
INTRODUCTION

HISTORY OF THIS STUDY

I was first introduced to the Chumstick Formation during a University of Washington class field trip in the Fall of 1983. Situated in the foothills of the Cascade Range, on the drier east side, the excellent, large-scale exposures of Chumstick rocks were a favorable contrast to the scattered, vegetation-covered outcrops of the Olympic Mountains and western side of the Cascade Range.

My initial interest in this project centered on aspects of sedimentary tectonics and basin analysis. The Paleogene sedimentary history of the Pacific Northwest is recorded in a number of nonmarine to marginally marine basins with great sediment thicknesses (4 km to >9 km), and some of the most rapid sediment-accumulation rates known (Table 1.1). Some of these basins are characterized by deformation styles in accord with a system of dextral strike-slip faulting, and some are characterized by extension-generated volcanism. Earlier workers have proposed that these basins were strike-slip basins (Ewing, 1980; Johnson, 1982, 1984, 1985; Gresens, 1982; Tabor et al., 1984), after the style of the Miocene Ridge Basin of California (Crowell, 1974; Crowell and Link, 1982). In the Pacific Northwest, however, many of these basins do not demonstrate a clear-cut relationship to regional faults. The Chumstick Formation lies within a fault-bounded basin, yet a detailed basin analysis had not been attempted. This became one focus for this dissertation.

My other interest has evolved during this project. A number of inconsistencies that made it difficult to define the depositional environment only became resolved after a detailed paleobotanical analysis. The Chumstick Formation was deposited in a humid, tropical to subtropical climate. Humid-tropical fluvial systems are probably the least studied and understood of all terrestrial depositional environments (but see Kesel, 1985). The evolution of such a system in a tectonically active basin produces a distinctly different set of deposits, characterized by episodic sedimentation (induced by tectonic activity or heavy rainfall), rapid stabilization by vegetation, significant overbank deposition, and the accumulation of a thick wedge of compositionally immature sediments with shallow, weakly developed soils.

This dissertation is organized into three chapters, each intended to stand by itself, with a view toward publication. As a result, there is a certain overlap of material in each chapter.

CHUMSTICK FORMATION

Geologic Setting

The Chumstick Formation is located on the eastern side of the Cascade Range in Washington State, and is one of a series of Paleogene nonmarine basins associated with major regional faults (Figure 1.1). In Washington and southern British Columbia, about 80 to 90 km of right-lateral strike-slip displacement has been recognized along the north-trending Fraser River - Straight Creek fault system (Vance, 1957; Frizzell, 1979; Vance and Miller, 1981; Tabor et al., 1984), which truncates and offsets a system of major northwest-trending faults, including the Chewack-Pasayten, Ross Lake-Hozameen, Settler, Entiat, Leavenworth, and Cle Elum fault systems. At its southernmost exposure, the Straight Creek fault develops a series of splays which merge with the northwest-trending Olympic-Wallowa Lineament (Raisz, 1945), which may represent another major fault zone (Vine, 1969; Buckovic, 1979). Movement on the Straight Creek fault system was predominantly during Eocene time, based upon localized deformation of Eocene rocks and the presence of slices and small basins of Eocene rocks in the fault zone (Vance and Miller, 1981; Tabor et al.; 1984, Johnson, 1985). Sedimentary evidence for strike-slip movement along the Straight Creek fault system includes syndepositional folding and faulting, drainage disruptions and reversals, great sediment thickness, rapid sediment-accumulation rates, and contemporaneous extensional (?) magmatic activity; all of these are consistent with the formation of pull-apart basins (Johnson, 1982, 1984, 1985; Buckovic, 1979; Tabor et al., 1984; Turner et al., 1983; Taylor et al., in press). Movement on the Straight Creek fault system ceased prior to 25 to 30 Ma, when pluton emplacement sealed the fault zone (Tabor et al., 1984).

The nature and timing of movement along the northwest-trending system of faults is less clear. Davis et al. (1978) postulated movement on the Ross Lake fault system as early as Late Jurassic to Early Cretaceous. The Entiat fault system shows evidence for several episodes of movement, including a pre-Tertiary history resulting in the formation of mylonites that were later overlain by Eocene Chumstick Formation (Laravie, 1976; Gresens et al., 1981). It is likely that this system of northwest-trending faults developed as an expression of Late Mesozoic compressional tectonics, related to the accretion of allochthonous terranes, as described by Potter et al. (1986). Tertiary re-activation of some of these structures was apparently a response to subsequent extension coupled with oblique convergence (Potter et al., 1986; Monger and Price, 1979; Ewing, 1980; Price and

Carmichael, 1986; Tempelman-Kluit and Parkinson, 1986).

Stratigraphy and Age

The Chumstick Formation is situated in a fault-bounded basin in central Washington state (Figure 1.2), and has been studied by geologists since the early 1900's. Earlier workers focused on mapping and considered the Chumstick Formation to be part of the (adjacent) Swauk Formation on the basis of lithologic similarity and fossil leaf content (Russell, 1900; Willis, 1903; Smith, 1904; Waters, 1930, 1932; Chappell, 1936; Page, 1940). The basin was recognized as fault-bounded by Waters (1930). Willis (1950, 1953) labeled it the "Chiwaukum graben" and proposed a syntectonic origin for the faults and folds in the basin. Generally, attempts of earlier workers to define stratigraphic units and depositional history (e.g. Young, 1963; Rosenmeier, 1968; Lupe, 1971; Pongsapich, 1970) were hampered by poor stratigraphic control due to a lack of radiometric dating.

During the 1970's, fission-track dating from inter-bedded tuffs and palynological studies helped define the stratigraphic position of the Chumstick Formation. Newman (1981) found that pollen from the Chumstick Formation is coeval with the Middle to Late Eocene Roslyn Formation and Puget Group and not with the Lower to Middle Eocene Swauk Formation (Figure 1.3). Fission-track ages from the middle of the Chumstick Formation range from about 48 Ma to 41 Ma, and correlate this portion of the Chumstick to the Teanaway and Roslyn formations which unconformably overlie the Swauk Formation (Whetten, 1976; Gresens et al., 1981; Tabor et al., 1980, 1982, 1984). As a result of these studies, Gresens et al. (1981) formally defined the Chumstick Formation and an upper lacustrine unit called the Nahahum Canyon Member. A third unit in the "Chiwaukum graben," the Wenatchee Formation, has been dated as Oligocene and shown to overlie unconformably the Chumstick Formation (Gresens, 1976, 1980; Gresens et al., 1981). Detailed geologic mapping of the region was completed in the late 1970's and 1980's (Gresens, 1975, 1980, 1983; Whetten, 1980a,b,c; Whetten and Laravie, 1976; Whetten and Waitt, 1978; Tabor et al., 1980, 1982).

New results as part of this study have modified the stratigraphy and age relationships of the Chumstick Formation (Figure 1.4). New radiometric dates have shown that basal sediments extend back to >51 Ma (Ott et al., 1986; this study), while palynological studies have suggested that the upper Chumstick Formation approaches the Eocene-Oligocene boundary in age (Estella Leopold, verbal communication).

Gresens and other workers noted that the upper part of the Chumstick Formation is composed of finer-grained sandstones and shales. The Nahahum Canyon Member was defined by Gresens et al. (1981) as a dominantly lacustrine unit that conformably overlies the undivided lower part of the Chumstick Formation, and which interfingers with alluvial fan deposits near the basin margin. A detailed basin analysis undertaken as part of this study has uncovered major disagreements with the conclusions of Gresens et al. (1981). First, I have divided the Chumstick basin into two sub-basins which have had separate depositional and deformational histories. Second, I have identified three major phases of deposition: a dominantly fluvial phase in the western sub-basin (>51 Ma to about 42 Ma); a phase of fluvial deposition in the western sub-basin contemporaneous with mixed fluvial and lacustrine sedimentation in the eastern sub-basin (42 Ma to about 40 Ma); and a final fluvial phase of deposition throughout the basin (about 40 Ma to about 38 Ma).

In the strict sense, what Gresens et al. (1981) described as the Nahahum Canyon Member is only found in the eastern sub-basin, in the region from a few miles northwest of the town of Monitor, southeasterly to the city of Wenatchee, where it disappears under alluvium. This region includes one of the defined reference sections (the Easy Street or Sunnyslope Road section, T.23N., R.20E., Section 19 NE1/4) given by Gresens et al. (1981). It does not, however, include the type section along Eagle Creek (T.25N., R.18E., Sections 13 and 24; and T.25N., R.19E., Section 19), which are fluvial deposits of approximately the same age as the lacustrine deposits. It would be particularly inappropriate to refer to fluvial deposits in the northwest part of the basin (near Lake Wenatchee or the town of Plain) as part of the Nahahum Canyon Member, because these fluvial deposits are younger.

Gresens (1983) believed that there were as many as three stratigraphic units in the "Chiwaukum graben": the Swauk (?), Chumstick, and Wenatchee formations. Gresens (1980) distinguished the Swauk (?) Formation from the Chumstick Formation on the basis of lithologic differences, such as calcium carbonate content or the abundance of fresh biotite versus chloritized biotite. Recent studies, however, have shown that these exposures actually represent hydrothermally altered Chumstick Formation in the zone surrounding the syndepositional intrusives near the city of Wenatchee (Margolis, 1987). While the Chumstick Formation is mostly confined to the "Chiwaukum graben," the Wenatchee Formation is found over a larger region as a blanket deposit unaffected by regional faulting (Gresens, 1980, 1982a). Because the entire fill of the "Chiwaukum graben" is the Chumstick Formation, the simpler term "Chumstick basin" will be substituted in this dissertation.

RESULTS OF THIS STUDY

Depositional Environments

The Middle to Late Eocene Chumstick Formation represents a humid-tropical, alluvial-fan system that filled a tectonically active basin. Four facies associations have been recognized in the Chumstick Formation: gravel-bedload stream deposits, sand-bedload stream deposits, mixed-load stream deposits, and lacustrine deposits. Proximal regions of these humid-region fans are dominated by lateral stacking of gravel-bedload stream deposits, whereas distal portions are characterized by gravel-bedload and sand-bedload stream deposits with a sheet-like geometry. The basin-fill is dominated by vertical stacking of sand-bedload and mixed-load stream deposits and lacustrine deposits.

Gravel-bedload stream deposits consist of longitudinal-gravel bars and intervening channels which were filled by three-dimensional dune deposits and bar-margin deposits. Fine-grained deposits are preserved from bar-top and overbank settings. Bank stability is indicated by preserved cutbanks, cohesive bank failures and slumps (intraclasts up to 1 meter in longest dimension), and resedimented pedogenic nodules. Paleo-hydraulic reconstructions indicate that these streams had an average bankfull depth of 2 to 3 meters, an average bankfull width:depth ratio of 35:1, and average paleo-slopes of up to 5 m/km.

Sand-bedload stream deposits consist of multistory three-dimensional dune deposits with minor lateral-accretion sequences, gravel-bar deposits, and chute-channel deposits. Bank stability is indicated by preserved cutbanks, cohesive bank failures and slumps, and lateral-accretion surfaces. The dominance of vertically stacked, multistory-channel sequences suggests that aggradation was relatively rapid compared to the rate of lateral channel migration. Paleohydraulic reconstructions indicate that these streams had an average bankfull depth of 1 to 2 meters, an average bankfull width:depth ratio of about 20:1, and average paleoslopes of 1 to 3 m/km.

Mixed-load stream deposits consist of isolated, lenticular, channel-fill sequences and multistory channel-fill sequences, with adjacent overbank deposits. These channels are typically smaller than either of the bedload types. The small size of these channels, evidence for their abandonment and re-occupation, and extensive bioturbation suggest that they were floodbasin channels. In part of the basin, mixed-load stream deposits contain lateral-accretion surfaces and mud plugs and are interpreted to represent part of a lacustrine-deltaic distributary system.

Lacustrine deposits consist of turbidites, slumps, and channelized massive beds from a delta-front setting, and basin-plain laminated siltstone and shale. The lack of faunal remains, rarity of biogenic structures, high organic carbon content, corrosion of pollen, and abrasion of transported plant macrofossils suggest that rapid sedimentation rates and high turbidity may have restricted benthic fauna.

The combination of humid-tropical climatic conditions and rapid basin subsidence has resulted in a distinctive set of deposits. Rapid subsidence (>1 m/k.y.) was responsible for the accumulation of a thick sequence of compositionally immature nonmarine sediments with shallow and weakly developed soils. Rapid growth of vegetation on floodplains and channel-margins improved bank stability, resulting in cut-banks and cohesive bank failures even in coarse-grained proximal facies. Debris-flow deposits were only observed overlying tuffs, and probably represent local hillslope failure following the destruction of vegetation. Episodic events, such as heavy rainfall, rapid uplift, or volcanism, allowed transport of coarse-grained sediments on fan surfaces with slopes of 5 m/km or less. Basin subsidence and bank stability imparted by vegetation resulted in a basin fill dominated by vertically stacked, multistory-channel deposits and by sandy overbank deposits.

Paleobotany and Paleoclimatology

The Middle to Late Eocene Chumstick Formation comprises 12 km of fluvial and lacustrine strata deposited in a wrench-fault basin in Washington State. This study (1) uses the composition and floristic attributes of the paleoflora to interpret paleoclimate; (2) combines paleofloral and sedimentological data to reconstruct plant community structure; and (3) investigates the effect of paleo-vegetation on the fluvial architecture, bank stability, and preservation of the basin fill.

The Chumstick paleoflora comprises a diverse fossil suite of broad-leaved evergreen and broad-leaved deciduous vegetation. There are a number of tropical indicators present, including three tropical vine taxa, together with taxa from more temperate regions. The physiognomic characteristics of the Chumstick paleoflora are intermediate between paratropical- and subtropical-rainforest types. The Chumstick paleoflora may have occupied an intermediate paleogeographic position between lowland and montane rainforest, in a setting about 150 km inland from the coast at an elevation of 350 to 550 meters.

Paleosols in the Chumstick Formation are recognized on the basis of rootlets, mottling, destratification, rhizoconcretions, trace fossils, and calcretes that range from isolated nodules to laminated K horizons. Most of these soils were entisols, with poor horizonal development, probably due to rapid sediment accumulation rates (>1 m/k.y.). Other soil types include inceptisols (incipient Cca or K horizon development), and histosols (histic epipedons with up to 6% TOC).

Most plant macrofossils are found in proximal overbank sequences or on preserved tops of emergent mid-channel bars. Certain taxa are found to be typical of floodplain versus channel-margin sites. Key differences are also noted between "upland" (proximal to fault scarp) and "lowland" taxa, which may indicate differences in seasonality of rainfall or in soil drainage. The presence of certain taxa, of calcic soils, and of mud-draped trough cross-bedding supports an interpretation of seasonal rainfall patterns.

Paleovegetation had a significant effect on fluvial deposition in the Chumstick Formation. Even in coarse-grained, proximal facies there is evidence for bank stability, bank undercutting and failure, soil erosion, and overbank deposits. The dominance of vertical accretion over lateral channel migration in more distal deposits can be attributed to rapid subsidence coupled with bank stability imparted by the paleovegetation.

Basin Evolution and Tectonics

A complex wrench-fault setting was responsible for the deposition of over 12 km of fluvial and lacustrine rocks in the Chumstick Formation. Two sub-basins are recognized on the basis of facies relationships, provenance, and paleocurrent pattern. The western sub-basin opened prior to 51 Ma as a half-graben bounded on the east by the Eagle Creek fault zone. Gravel-bedload streams flowed west and southwest into an extensive, sandy braidplain. These deposits probably formed a continuous depositional system with the Swauk Formation, as there is no evidence for relief in the Leavenworth fault zone at this time. The Eagle Creek fault zone acted as a conduit for the emplacement of felsic intrusives, culminating with a dome complex at 43 Ma to 42 Ma. In the vicinity of this dome, older Chumstick deposits were hydrothermally altered and deformed.

A second phase of deposition was initiated at about 42 Ma as a result of dextral faulting on all three major fault systems. Local uplift along the Leavenworth fault zone was a response to transpression at two restraining bends. Gravel-bedload streams flowed east off the uplifted Leavenworth fault zone, into an axial-drainage system that flowed southeast, parallel to the trend of the Leavenworth fault zone. The eastern sub-basin opened as a transtensional step-over basin between two overlapping dextral faults, the Eagle Creek and Entiat fault zones. Gravel-bedload streams flowed west off the uplifted Entiat fault zone into an axial-drainage system that flowed southeast, down the axis of the basin, into a lacustrine-deltaic complex near the town of Wenatchee.

A third phase of deposition occurred between about 40 Ma and about 37 Ma, and consisted of sand-bedload and mixed-load streams in the northern and southeastern parts of the basin. These deposits show no relationship to the fault zones and overlie them in places. In the southern part of the basin, they unconformably overlie older Chumstick deposits. This phase of deposition is interpreted as an interval of tectonic quiescence.

The basin was deformed in an episode of dextral transpression between about 37 Ma and 34 Ma. The Chumstick Formation is unconformably overlain by the Wenatchee Formation, which extends out of the basin, and shows no relationship to the major fault zones. A possible fourth phase of Chumstick deposition consists of debris-flow deposits adjacent to basement blocks uplifted in the Eagle Creek fault zone during basin deformation. These deposits are unfossiliferous and are not directly overlain by the Wenatchee Formation, so their age is poorly constrained.

Thermal maturity indicators and geophysical data suggest that the actual basin thickness of the Chumstick strata was on the order of 2 km, while the stratigraphic thickness was on the order of 12 km. This discrepancy is explained as a result of conveyor-belt sedimentation, in which lateral offset of the sediment source region produces a shingling of depositional packages.

Evidence for tectonic control of sedimentation includes grain-size reduction away from major fault zones; major reorganizations of drainage types, drainage direction, and the location of sediment-source regions; two intervals of axial-drainage systems that paralleled major fault zones and one interval of internal drainage; syndepositional magmatism which included airfall and ash-flow tuffs and emplacement of a felsic dome into a major fault zone; and the development of at least one intraformational unconformity. Evidence that these faults were dominated by oblique-slip tectonics includes the orientation of secondary faults and folds; evidence for conveyor-belt sedimentation; uplift in regions that may represent dextral transpression, and opening of a step-over basin between two overlapping dextral faults. The Chumstick Formation provides significant evidence for a major interval of Eocene strike-slip faulting in this region of the Pacific Northwest.

Chapter Notes

Alexander, F., 1956, Stratigraphic and structural geology of the Blewett-Swauk area, Washington [M.S. Thesis]: Seattle, University of Washington, 62 p.

Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 147-163.

Chappell, W.M., 1936, Geology of the Wenatchee quadrangle [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 249 p.

Crowell, J.C., 1974, Origin of the Late Cenozoic basins in southern California, in Dickinson, W.R., editor, Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication no. 22, p. 190-204.

Crowell, J.C. and Link, M.H., editors, 1982, Geologic history of the Ridge Basin, southern California: Society of Economic Paleontologists abd Mineralogists, Pacific Section, 304 p.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Howell, D.G. and McDougall, K.A., editors, Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 2, p. 1-32.

Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619-638.

Frizzell, V.A., 1979, Petrology of Paleogene non-marine sandstone units in Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 113-118.

Gresens, R.L., 1980, Deformation of the Wenatchee Formation and its bearing on the tectonic history of the Chiwaukum graben, Washington, during Cenozoic time: Geological Society of America Bulletin, v. 91, p.4-7, 115-

Gresens, R.L., 1982, Early Cenozoic geology of central Washington State: part II, implications for plate tectonics and alternatives for the origin of the Chiwaukum graben: Northwest Science, v.56, p.259-264.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Geology and Earth Resources, Bulletin 75, 75 p.

Gresens, R.L., Naeser, C.W., and Whetten, J.T., 1981, Stratigraphy and age of the Chumstick and Wenatchee formations- Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 233-236, 841-876.

Johnson, S.Y., 1982, Stratigraphy, sedimentology, and tectonic setting of the Chuckanut Formation, North Cascades, Washington [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 221 p.

Johnson, S.Y., 1984, Evidence for a margin-truncating transcurrent fault (pre-late Eocene) in western Washington: Geology, v. 12, p. 538-541.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication no. 37, p. 283-302.

Kesel, R.H., 1985, Alluvial fan systems in a wet-tropical environment, Costa Rica: National Geographic Research, v. 1, p. 450-469.

Laravie, J.A., 1976, Geologic field studies along the eastern border of the Chiwaukum graben, central Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 55 p.

Lupe, R.D., 1971, Stratigraphy and petrology of the Swauk Formation in the Wenatchee Lake area [M.S. Thesis]: Seattle, Washington, University of Washington, 27 p.

Margolis, J., 1987, Hydrothermal alteration and structure associated with epithermal gold mineralization, Wenatchee Heights, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 120 p.

Monger, J.W.H. and Price, R.A., 1979, Geodynamic evolution of the Canadian Cordillera- progress and problems: Canadian Journal of Earth Sciences, v. 16, p. 770-791.

Newman, K.R., 1981, Palynologic biostratigraphy of some early Tertiary nonmarine formations in central and western Washington, in Armentrout, J.M., editor, Pacific Northwest Cenozoic Biostratigraphy: Geological Society of America Special Paper no. 184, p. 49-65.

Ott, L.E., Groody, D., Follis, E.L., and Siems, P.L., 1986, Stratigraphy, structural geology, ore mineralogy, and hydrothermal alteration at the Cannon Mine, Chelan County, Washington, in MacDonald, A.J., editor, Gold '86, An International Symposium on the Geology of Gold Deposits, Proceeding Volume, p. 425-435.

Page, B.M., 1939, Geology of a part of the Chiwaukum quadrangle [Ph.D. Dissertation]: Palo Alto, California, Stanford University, 203 p.

Pongsapich, W., 1970, A petrographic reconnaissance of the Swauk, Chuckanut, and Roslyn Formations, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 63 p.

Potter, C.J., Sanford, W.E., Yoos, T.R., Prussen, E.I., Keach, R.W., II, Oliver, J.E., Kaufman, S., and Brown, L.D., 1986, COCORP deep seismic reflection traverse of the interior of the North American Cordillera, Washington and Idaho: implications for orogenic evolution: Tectonics, v. 5, p. 1007-1025.

Price, R.A. and Carmichael, D.M., 1986, Geometric test for Late Cretaceous-Paleogene intracontinental transform faulting in the Canadian Cordillera: Geology, v. 14, p. 468-471.

Raisz, E., 1945, The Olympic-Wallowa Lineament: American Journal of Science, v. 243, p. 479-485.

Rosenmeier, F.J., 1968, Stratigraphy and structure of the Table Mountain - Mission Peak area in the Wenatchee Mountains, central Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 44 p.

Russell, I.C., 1900, A preliminary paper on the geology of the Cascade Mountains in northern Washington: U.S. Geological Survey, Annual Report, v. 20, p. 83-110.

Smith, G.O., 1904, Description of the Mount Stuart quadrangle, Washington: U.S. Geologic Atlas Folio 86, 10 p.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Waitt, R.B., Jr., 1980, Preliminary geologic map of the Chelan quadrangle, Washington: U.S. Geological Survey, Open-File Report no. 80-841.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee quadrangle: Washington: U.S. Geological Survey, Miscellaneous Geological Investigations I-1311.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26-44.

Taylor, S.B., Johnson, S.Y., Fraser, G.T., and Roberts, J.W., in press, Sedimentation and tectonics of the Swauk Formation, eastern Swauk basin- significance for hydrocarbon exploration in central Washington: American Association of Petroleum Geologists Bulletin.

Turner, D.L., Frizzell, V.A., Jr., Triplehorn, D.M., and Naeser, C.W., 1983, Radiometric dating of ash partings in coal of the Eocene Puget Group, Washington: implications for paleobotanical stages: Geology, v. 11, p. 527-531.

Tempelman-Kluit, D. and Parkinson, D., 1986, Extension across the Eocene Okanogan crustal shear in southern British Columbia: Geology, v. 14, p. 318-321.

Vance, J.A., 1957, The geology of the Sauk River area in the Northern Cascades of Washington [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 333 p.

Vance, J.A. and Miller, R.B., 1981, The movement history of the Straight Creek fault in Washington state, in Monger, J.W.H., editor, The Last 100 Million Years (Mid-Cretaceous to Holocene) of Geology and Mineral Deposits in the Canadian Cordillera: Geological Association of Canada, Program with Abstracts, p. 39-41.

Vine, J.D., 1969, Geology and coal resources of the Cumberland, Hobart, and Maple Valley quadrangles, King County, Washington: U.S. Geological Survey Professional Paper no. 624, 67 p.

Waters, A.C., 1930, Geology of the southern half of the Chelan quadrangle [Ph. D. Dissertation]: New Haven, Connecticut, Yale University, 265 p.

Waters, A.C., 1932, A petrographic and structural study of the Swakane Gneiss, Entiat Mountains, Washington: Journal of Geology, v. 40, p. 604-633.

Whetten, J.T., 1976, Tertiary sedimentary rocks in the central part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 8, p. 420-421.

Whetten, J.T., 1977, Sedimentology and structure of part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 9, p. 527.

Whetten, J.T., 1980a, Preliminary geologic map, Chiwaukum 4 NW quadrant: U.S. Geological Survey, Open-File Report no. 80-456.

Whetten, J.T., 1980b, Preliminary geologic map, Chiwaukum 4 Sw quadrant: U.S. Geological Survey, Open-File Report no. 80-616.

Whetten, J.T., 1980c, Preliminary geologic map of the east half of Chiwaukum 4 SE quadrant: U.S. Geological Survey, Open-File Report no. 80-723.

Whetten, J.T. and Laravie, J.A., 1976, Preliminary geologic map of the Chiwaukum 4 NE quadrangle, Chiwaukum graben, Washington: U.S. Geological Survey, Miscellaneous Field Studies, no. MF-794.

Whetten, J.T. and Waitt, R.B., Jr., 1978, Preliminary geologic map of the Cashmere quadrangle, Chiwaukum lowland, Washington: U.S. Geological Survey, Miscellaneous Field Studies, no. MF-908.

Willis, B., 1903, Physiography and deformation of the Wenatchee-Chelan district, Cascade Range: U.S. Geological Survey Professional Paper no. 19, p. 41-97.

Willis, C.L., 1950, Geology of the northeastern quarter of Chiwaukum quadrangle [Ph. D. Dissertation]: Seattle, Washington, University of Washington, 158 p.

Willis, C.L., 1953, The Chiwaukum graben, a major structure of central Washington: American Journal of Science, v. 251, p. 789-797.

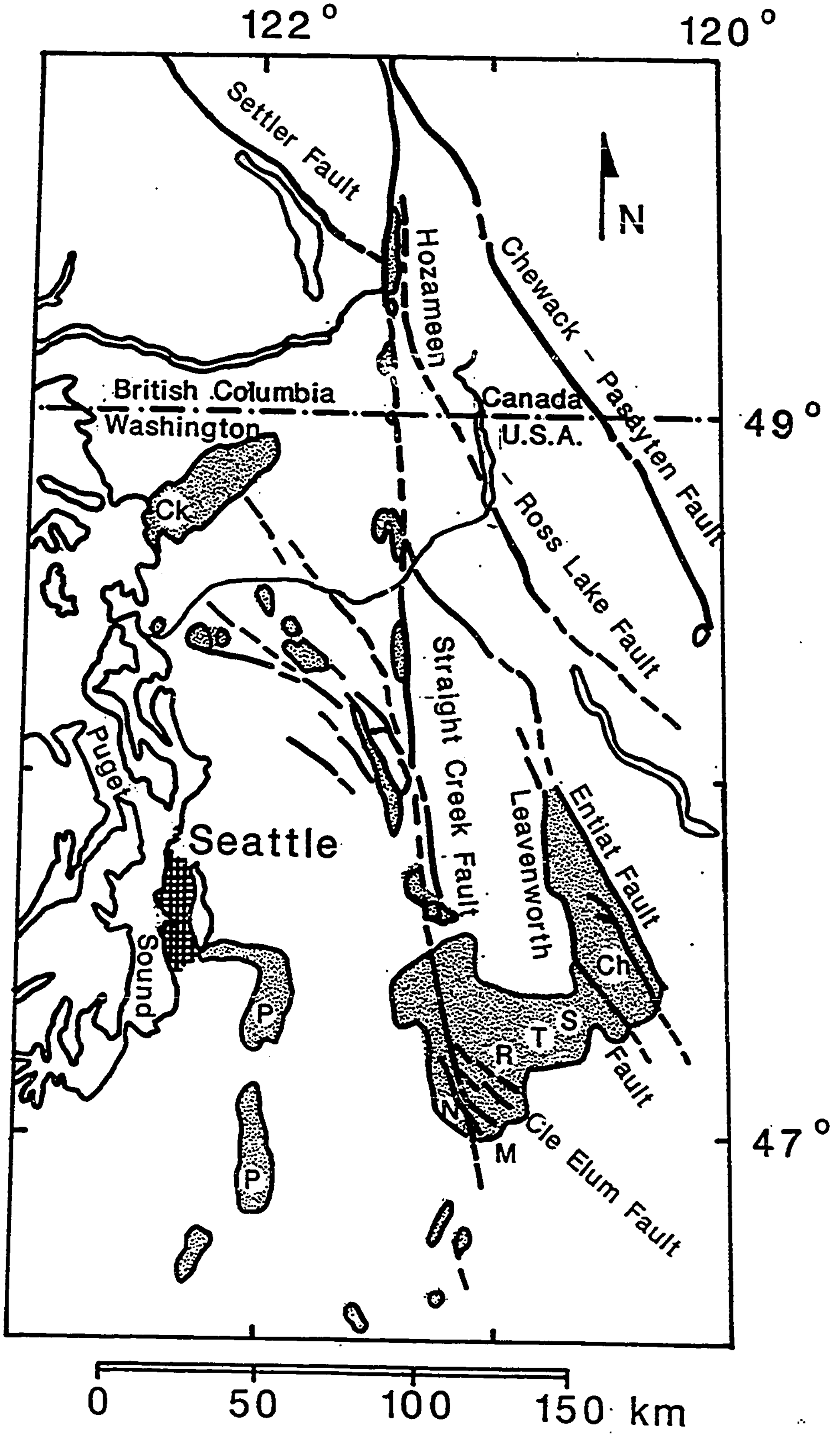
Young, R.E., 1963, Geology of the Swauk Formation in the Leavenworth, Washington area [B.S. Thesis]: Seattle, Washington, University of Washington, 49 p.

Table 1.1: Thickness and Sediment Accumulation Rates In Non-marine Basins

Rock Unit and Location	Stratigraphic Thickness (km)	Apparent Accumulation Rate (cm/ka.)
Old Red Sandstone (Spitsbergen)	2	10
Old Red Sandstone (Greenland)	2 - 5	30 - 50
Foreland Basins (Rocky Mountains)	2 - 6	10 - 20
Intermontane Basins (Rocky Mountains)	1 - 3	8 - 20
Rift Basins (New Jersy)	6	33 - 40
Andes Molasse (Columbia)	8	15
Alpine Molasse (Switzerland)	6	22 - 40
Alpine Molasse (Spain)	4	10 - 30
Himalayan Molasse (Pakistan)	7	16 - 64
Ridge Basin (California)	13	165 - 216
Hornelen Basin (Norway)	25	not avail.
Chuckanut Formation (Washington)	6.0	>50
Puget Group (Washington)	4.3	50 - 110
Swauk Formation (Washington)	7.7	>72
Chumstick Formation (Washington)	>2 to 12	14 - 109

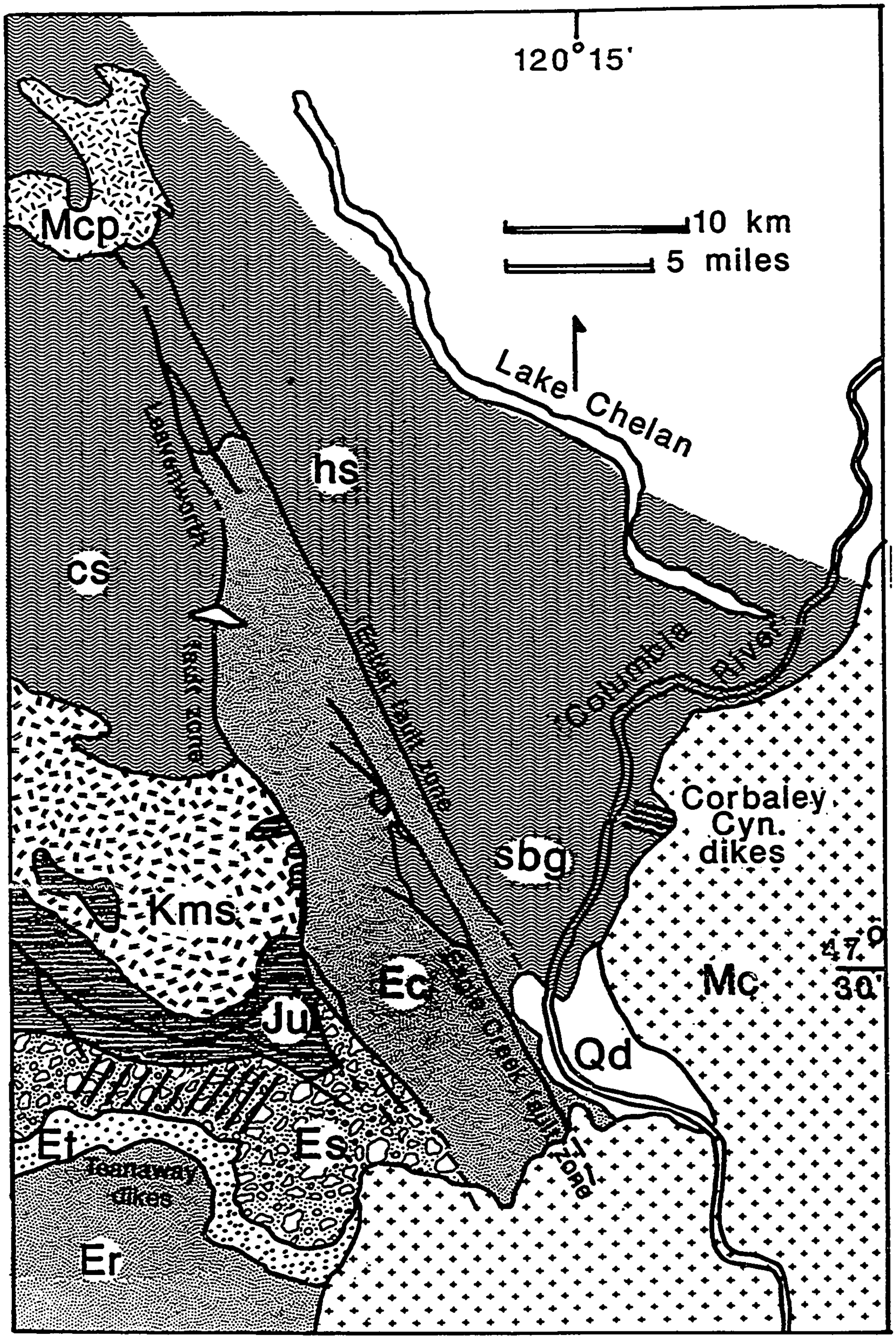
Chumstick data from this study
All other data compiled by Johnson (1985)

Figure 1.1--Generalized geologic map of northwestern Washington state and southwest British Columbia showing faults of known Mesozoic and Paleogene displacement, and Paleogene sedimentary units. Abbreviations used on map: Ch - Chumstick Formation, Ck - Chuckanut Formation, M - Manastash Formation, N - Naches Formation, P - Puget Group, R - Roslyn Formation, S - Swauk Formation, T - Teanaway Formation.



122°
120°
49°
47°
N
Settler Fault
Hozameen
Chewack - Pasayten Fault
British Columbia
Washington
Canada
U.S.A.
Ck
Ross Lake Fault
Straight Creek Fault
Puget
Sound
Seattle
Leavenworth
Entiat Fault
Ch
S
T
R
N
M
Fault
Cle Elum Fault
P
P
0
50
100
150 km

Figure 1.2--Generalized geologic map of the Chumstick basin ("Chiwaukum graben") and related rocks, based upon mapping by Tabor et al., 1980, 1982. Abbreviations used on map: cs - Chiwaukum Schist, Ec - Chumstick Formation, Er - Roslyn Formation, Es - Swauk Formation, Et - Teanaway Formation, hs - heterolithic schist, Ju - Ingalls Tectonic Complex, Kms - Mount Stuart Batholith, Mc - Columbia River Basalt, Mcp - Cloudy Pass Batholith, Qd - alluvium, sbg - Swakane Biotite Gneiss.



120°15'
10 km
5 miles
Lake Chelan
Mcp
hs
cs
Entiat fault zone
Columbia River
Corbaley Cyn. dikes
sbg
Kms
Ec
Eagle Creek fault zone
Mc
47° 30'
Ju
Qd
Et
Es
Teanaway dikes
Er

Figure 1.3--Regional stratigraphic relations of Paleogene sedimentary and volcanic units in central and western Washington, based upon data compiled by Johnson, 1985 and Tabor et al., 1984. Chumstick data from this study. Abbreviations used: Tb = Basalt of Frost Mountain, Th = Huntingdon Formation, Tm = Manastash Formation, Tt = Teanaway Formation, Tta = Taneum Formation, Tw = Wenatchee Formation.

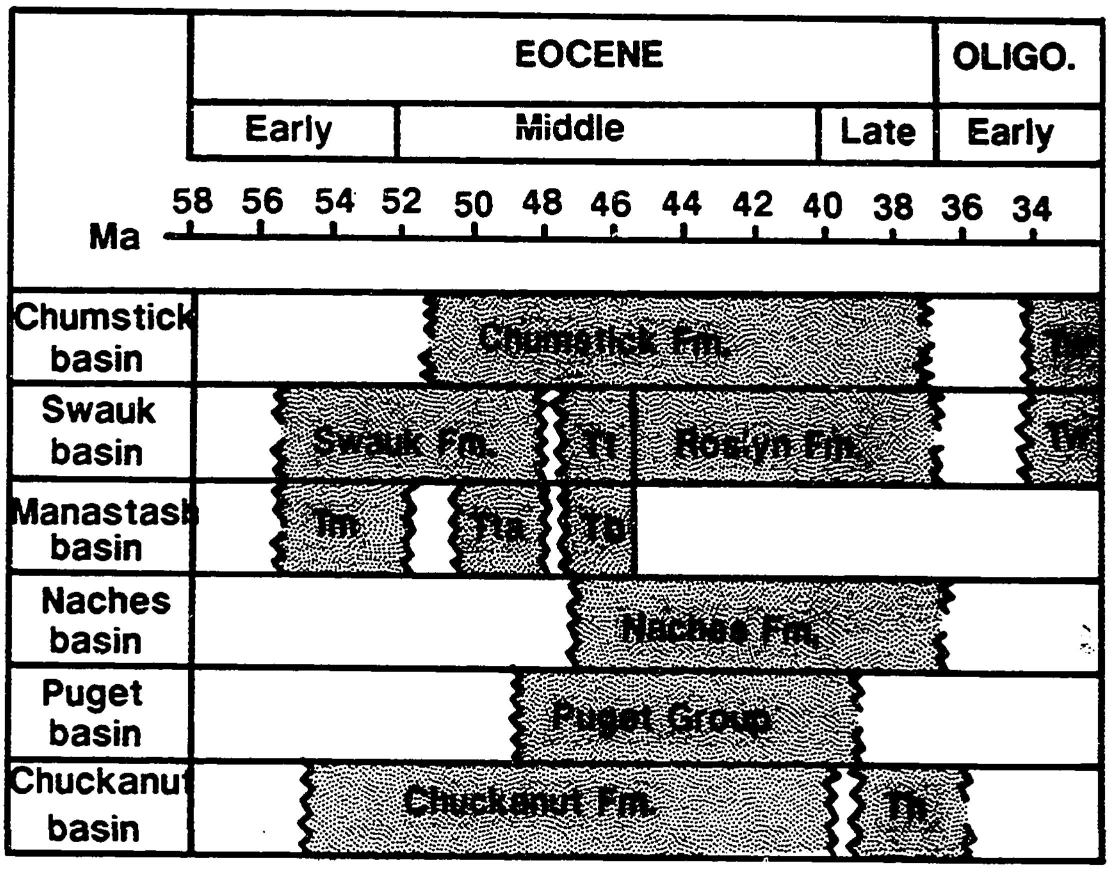
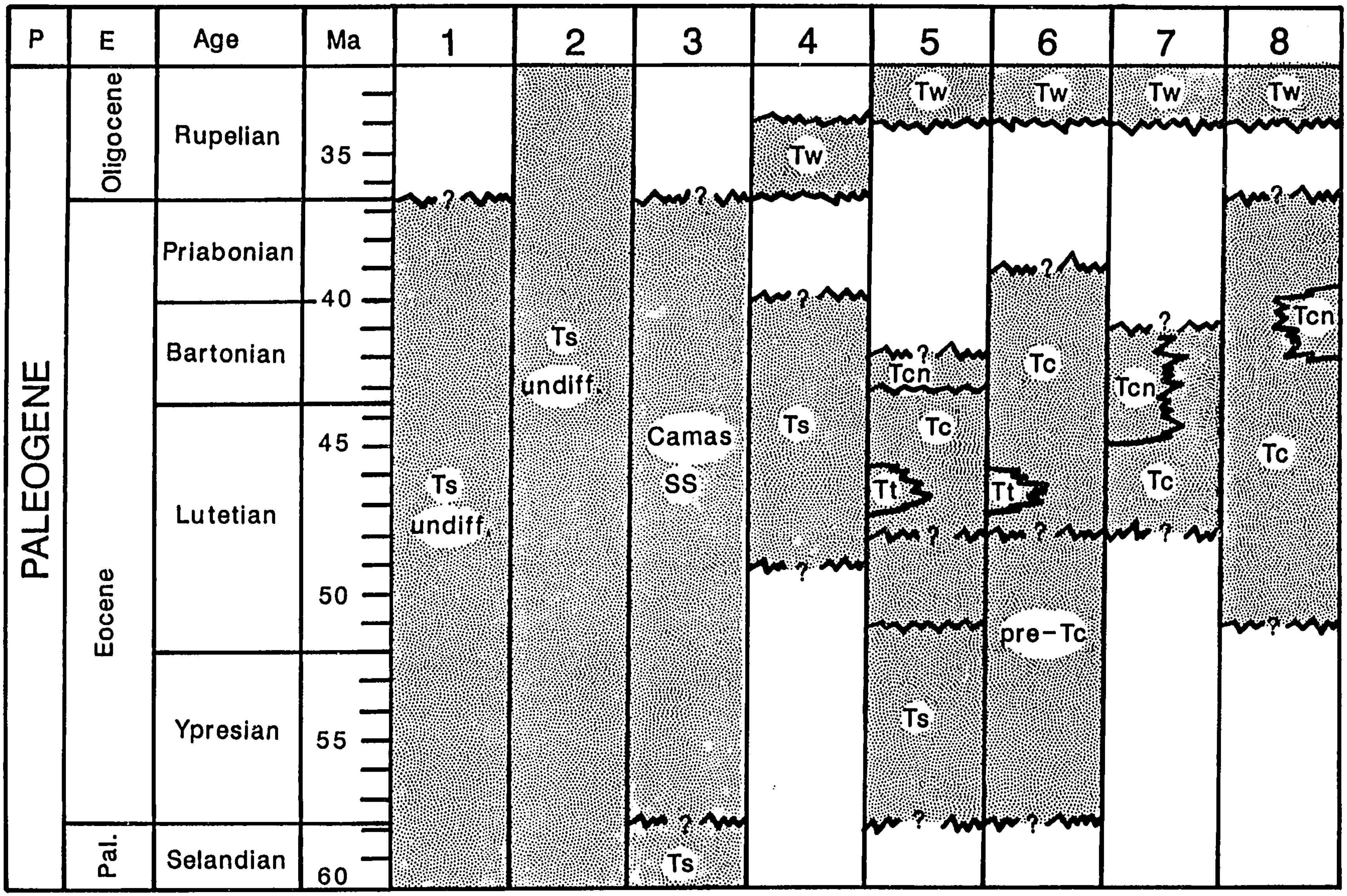

EOCENE
OLIGO.
Early
Middle
Late
Early
Ma
58 56 54 52 50 48 46 44 42 40 38 36 34
Chumstick basin
Swauk basin
Manastash basin
Naches basin
Puget basin
Chuckanut basin
Chumstick Fm.
Swauk Fm.
Tt
Roslyn Fm.
Tw
Tm
Tta
Tb
Naches Fm.
Puget Group
Chuckanut Fm.
Th

Figure 1.4--Stratigraphic nomenclature for the Chumstick Formation. References are given by numbers of columns:

1 - Smith, 1904; 2- Chappell, 1936; 3 - Alexander, 1956; 4 - Newman, 1981; 5 - Gresens _et al._, 1981; 6 - Tabor _et al._, 1984; 7 - Johnson, 1985; 8 - This study.

Abbreviations used: Ts = Swauk Formation, Tc = Chumstick Formation, Tcn = Nahahum Canyon Member, Tt = Teanaway Formation, Tw = Wenatchee Formation.



P
E
Age
Ma
1
2
3
4
5
6
7
8
PALEOGENE
Oligocene
Eocene
Pal.
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Selandian
35
40
45
50
55
60
Ts undiff.
Ts undiff.
Camas SS
Ts
Tw
Ts
Tw
Tcn
Tc
Tt
Ts
Tw
Tc
Tt
pre-Tc
Tw
Tcn
Tc
Tw
Tcn
Tc

Chapter 2

FACIES RELATIONSHIPS, ALLUVIAL ARCHITECTURE AND PALEOHYDROLOGY OF A PALEOGENE, HUMID-TROPICAL, ALLUVIAL-FAN SYSTEM: CHUMSTICK FORMATION, WASHINGTON STATE, U.S.A.

INTRODUCTION TO CHAPTER 2

Humid-tropical alluvial fans represent a class of depositional systems that deserve greater recognition and study. In the modern record, investigations of terrigenous depositional systems in the tropics have clearly lagged behind the application of integrated studies of sediment transport, fluvial geomorphology, soils, and vegetation to these systems in other climatic settings. As a result, workers on ancient humid-tropical alluvial fans have been overly reliant on the better-studied arid-region alluvial fans (e.g., Bull, 1964, 1977; Denny, 1965; Hooke, 1967), humid-glacial outwash fans (e.g., Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978), humid-temperate fans (e.g., Pierson, 1980; Kochel and Johnson, 1984; Wells, 1984; Wells and Harvey, 1987) and "terminal fans" of the Himalyans (e.g., Mukherji, 1976; Friend, 1978; Parkash et al., 1983; Wells and Dorr, 1987a,b).

Until recently, there have been few descriptions of modern examples of humid-tropical, fluvial systems in tectonically active settings. Ruxton (1970) described the features of alluvial fans in the orogenic mountain belt of northeast Papua, New Guinea. These fans are characterized by the accumulation of compositionally immature sediments, with shallow and weakly developed soils, on low angle (<5^0) fan slopes. Studies from the mountainous parts of Central America (e.g., Kuenzi et al., 1979; Davies et al., 1978; Vessell and Davies, 1981; Kesel, 1985) have emphasized the episodic nature of sediment supply and deposition on these humid-tropical fans, where active phases of fan growth are triggered by uplift or volcanic activity. During the active phase each fan is characterized by rapid aggradation and lateral shifting of braided rivers and rapid growth of vegetation. Runoff from relatively frequent, intense tropical storms is capable of transporting large volumes of coarse-grained sediment. During the inactive phase the fan is characterized by fan-head incision and by vertically accreting, sinuous, single channels (Kesel, 1985). In regions where volcanic activity governs sediment supply, the active phase may last from a few to 20 years following a major eruption, and the inactive phase may last for 10's to 100's of years (Vessell and Davies, 1981).

It seems reasonable at this time to conduct a detailed study of the facies relationships, alluvial architecture, and paleohydrology of an ancient, humid-tropical, alluvial-fan system, and to evaluate it in light of recent advances in understanding similar modern systems. This study will focus on some of the ways humid-tropical, alluvial-fan systems differ from other alluvial-fan systems and how these differences can be recognized in ancient deposits. It is hoped this study will stimulate further research in these interesting and, in some cases, economically valuable depositional systems. The example that will be used for this paper is the Eocene Chumstick Formation, a thick (>12 km), nonmarine sequence located in central Washington State. The Chumstick Formation has been shown to be deposited during tropical climatic conditions (Wolfe, 1968, 1971, 1977; Wolfe and Wehr, 1986; Evans, chapter 3) during an interval of regional strike-slip tectonics (Johnson, 1985; Evans, chapter 4).

CHUMSTICK FORMATION

The Chumstick Formation represents deposition in a tectonically active environment characterized by syn-depositional faulting, syndepositional volcanism, and a rapid basin subsidence rate that is indicated by a sediment accumulation rate between 0.2 and 1.2 m/k.y. (Evans, chapter 4). Paleobotanical analysis of the Chumstick Formation indicates the presence of tropical to subtropical plant communities, with evidence suggestive of strongly seasonal (monsoonal) rainfall (Evans, chapter 3). The paleogeography can be established by reference to regional paleobotanical and facies studies (Wolfe, 1968; Wolfe and Wehr, 1986; Buckovic, 1979) which suggest the Chumstick basin was located about 150 km inland from the coast, in a low mountain setting (350 to 550 meters elevation). This type of setting describes a humid-tropical, alluvial-fan depositional system.

Tectonic Setting

Regional Faults and Sedimentary Basins. Strike-slip faulting has played a significant role in the tectonic evolution of the Pacific Northwest during the Paleogene (Davis et al., 1978; Ewing, 1980; Gresens, 1982; Tabor et al., 1984; Johnson, 1982, 1984a, 1985). Major regional faults in the Pacific Northwest (Figure 2.1) are associated with localized Paleogene basins which were filled by unusually thick sequences of nonmarine sedimentary and volcanic rocks.

Three of these basins have been studied in detail: the Chuckanut (Johnson, 1982, 1984b, 1984c), Swauk (Fraser, 1985; Roberts, 1985; Taylor, 1985; Taylor et al., in press) and Chumstick basins (Evans, chapter 4). Each of these displays many of the characteristics of strike-slip basins, including: great sediment thickness, rapid sediment-accumulation rates, abrupt vertical and lateral facies changes, changes in paleocurrent pattern and provenance, syndepositional magmatism, and a deformation style in accord with right-lateral shear (Johnson, 1985; Tabor et al., 1984; Taylor et al., in press; Evans, chapter 4).

Paleogene sedimentary basins in the Pacific Northwest indicate relatively coeval episodes of clastic and volcanic sedimentation (Figure 2.2). Efforts to reconstruct regional depositional systems have been hampered by lack of section between some basins, and Johnson (1985) has suggested that the formation, fill, and deformation of each basin was independent of others. There is evidence, however, that the Chumstick Formation formed part of a regional drainage system during two intervals. During earliest deposition, the Chumstick basin and part of the Swauk basin were interconnected (Evans, chapter 4; Taylor et al., in press). During latest deposition, paleocurrent and provenance data suggest that the Chumstick (coarse-grained fluvial deposits), Roslyn (fine-grained fluvial deposits and coal) and Puget (coal-bearing fluvial and deltaic deposits) basins formed a continuous depositional system (Frizzell, 1979; Byrnes, 1985; Evans, chapter 4).

Chumstick Basin Evolution. The stratigraphic position of the Chumstick Formation has been established by pollen (Newman, 1981), plant macrofossils (Evans, chapter 3), and radiometric dates (Gresens et al., 1981; Gresens, 1983; Tabor et al., 1980, 1982, 1984; Ott et al., 1986; Evans, chapter 4). There are 19 interbedded airfall and ash-flow tuffs, each with a distinctive trace-element chemistry (McClincy, 1986). Detailed correlation of these tuffs makes it possible to evaluate the geometry of individual depositional units.

Earlier workers (Gresens, 1983; Gresens et al., 1981) proposed that the Chumstick Formation could be divided into a lower, dominantly fluvial part, and an upper, dominantly lacustrine part named the Nahahum Canyon Member. This interpretation has been shown to be overly simplistic. The Chumstick basin represents two sub-basins that had separate depositional and deformational histories. Within this framework were at least three phases of deposition (Figure 2.3), each phase showing significant differences in facies pattern, paleocurrents, and provenance. There is strong evidence for tectonic control of sedimentation, including: grain-size reduction away from major fault zones; major reorganizations of drainage type, drainage direction, and the location of sediment-source regions; two intervals of axial-drainage systems that paralleled major fault zones; one interval of internal drainage; syndepositional magmatism which includes airfall and ash-flow deposits and the emplacement of a felsic dome into a major fault zone; and the development of at least one intraformational unconformity (Evans, chapter 4).

Climatic Setting

The paleoclimate of the Chumstick Formation has been interpreted from plant macrofossils, pollen, paleosols, and trace fossils (Evans, chapter 3). These data have been put into a regional context by comparison with other Paleogene paleofloras of the Pacific Northwest (e.g., Wolfe, 1968, 1971; Wolfe and Wehr, 1986). The Chumstick paleoflora contains a mixture of taxa with tropical rainforest and humid-temperate forest affinities. Physiognomic analysis (a type of study that emphasizes morphological characteristics of leaves, independent of their taxonomy) indicates that the Chumstick paleoflora had features intermediate between fully tropical and subtropical floras. In contrast, the coeval Puget and Steel's Crossing paleofloras, located southwest of the Chumstick basin and in a coastal paleogeographic setting, consisted of broad-leaved, evergreen forests that were fully tropical (Wolfe, 1968, 1971). To the northeast, the coeval Republic paleoflora represented an upland mixed conifer and broad-leaved deciduous forest that was subtropical (Wolfe and Wehr, 1986). The intermediate paleogeographic setting of the Chumstick basin suggests that the humid and tropical paleoclimate was modified either due to elevation effects (temperature and/or rainfall); or due to drainage (since deposition was dominated by sandy fluvial deposits).

Chumstick paleosols include entisols, inceptisols (incipient Cca or K horizon development), and thin histosols (Evans, chapter 3). These types of soils are shallow and weakly developed, and are typical of fluvial depositional systems that are aggrading (Duchaufour, 1977). Trace fossils are primarily vertical, unlined burrows (*Skolithos*) and rare surface traces (*Sinusites*). The dimensions of the burrows suggest that many were made by insects or oligochaetes.

FACIES ANALYSIS

Four major facies associations serve as the basis for interpreting the Chumstick Formation as an alluvial fan system: gravel-bedload stream deposits, sand-bedload stream deposits, mixed-load stream deposits, and lacustrine deposits. With regard to the three types of fluvial deposits, these terms are applied on the basis of textural content, and are not intended to have any implications about channel pattern or sinuosity.

Methodology

This section will focus on descriptions of the lithofacies composition, organization and geometry of depositional units, paleocurrents, and depositional sequences observed in each facies association. These characteristics establish the framework for paleohydraulic reconstructions in the following section.

At each field site (Figure 2.4), stratigraphic sections were described using a lithofacies descriptive code (Table 2.1) which formed the basis for later Markov Chain analyses using the computer program BMDP-4F (Brown, 1983). This form of analysis tests a model of the quasi-independence of lithofacies transitions and uses an iterative, proportional-fitting technique to obtain expected cell counts in a matrix of random expectations (Turk, 1979, 1982; Powers and Easterling, 1982). Facies transitions that are non-random are identified through analysis of residuals that have been converted to normalized variables and tested for significance (Powers and Easterling, 1982; Turk, 1979). The problem of masking of outliers (e.g., Harper, 1984) has been resolved using a multistep procedure that tests the matrix, identifies and removes the cell causing the greatest deviation from quasi-independence, then retests the matrix for other such cells (Carr, 1982).

Gravel-bedload Stream Deposits

Coarse-grained fluvial sediments interpreted as deposits of gravel-bedload streams were a significant part of the basin-fill during the first two phases of deposition. In general, gravel-rich deposits are found adjacent to the major fault zones that were active during deposition (Figure 2.3). Stacking of gravel-rich deposits along the margins of the sub-basins is probably a response to rapid subsidence (C. Paola, personal communication). In the Chumstick Formation, rapid basin subsidence can also be inferred from an average sediment-accumulation rate that ranged from 0.2 to 1.2 m/k.y.

Lithofacies Composition. These deposits comprise between 40% and 90% conglomerate (Table 2.2). The most significant component is massive to crudely stratified, pebble-cobble conglomerate (Gm); with subordinate massive, coarse-grained sandstone (Smc); parallel-bedded sandstone (Sh); and low-angle ($<10^0$), cross-laminated sandstone (Sl). Important minor elements include pebbly mudstone (Gms); trough cross-bedded sandstone (St); and laminated, very fine-grained sandstone to shale (Fl).

The conglomerate is composed primarily of rounded and sorted exoclasts of biotite gneiss, schist, granite, granodiorite, felsic to intermediate volcanics, and vein quartz, with minor amounts of amphibolite, marble, peridotite, pegmatitic granite, diabase, and basalt. Certain of these lithologies (e.g., granite, granodiorite, marble) have a low resistivity to abrasion (Abbott and Peterson, 1978; Bradley, 1970), but Chumstick gravels do not show proximal-to-distal trends in clast-type destruction, suggesting that transport distances were minimal. There are local sources for these lithologies, and the rounded nature of the clasts may be partly due to incipient weathering (e.g., spheroidal weathering) prior to erosion.

Two types of intraclasts have been observed: sandstone nodules cemented by carbonate that are present only in conglomerate, and siltstone-mudstone clasts that are present in both conglomerate and sandstone (lithofacies Se). The sandstone nodules are interpreted as parts of pedogenic calcretes that formed in the Cca or K horizon of Chumstick paleosols, slumped into channels due to bank undercutting, and were transported as single clasts. Some siltstone-mudstone intraclasts exceed 1 meter in longest dimension (Figure 2.5a) and are preserved either as isolated clasts or as rotated blocks which clearly demonstrate their former position on the channel floor or along channel banks. Rounding of the intraclasts indicates that they were cohesive, and some of them preserve primary lamination.

Depositional Units. Markov Chain analyses of two stratigraphic sections (Figure 2.6) have been helpful in identifying depositional sequences in these deposits. With reference to modern fluvial systems, these sequences are interpreted as:

(1) longitudinal-bar and bar-platform deposits
(sequence Ss --> Gm --> Sh
and Ss --> Gm --> St);

(2) bar-margin avalanche-face deposits
(sequence Ss --> Gp --> Sl);

(3) dune deposits
(sequence Ss --> ± Gt --> St
and Sp --> Sl);

(4) overbank deposits
(sequence Sr --> Fl/Fm --> P); and

(5) channel slumps

(sequence Ss --> Se).

One additional depositional unit that will be discussed is debris flows (lithofacies Gms).

Longitudinal-bar and bar-platform deposits are characterized by sharp basal contacts with broad, shallow scours (Figure 2.5b). The massive to crudely stratified conglomerate that represents the bar platform may be ungraded or show coarse-tail normal grading. Many conglomerates are inversely graded over the basal 5 to 10 clast layers. Basal inverse grading probably represents the down-stream migration of the coarse-grained bar-core region over the finer-grained bar-tail region (e.g., Bluck, 1979). Longitudinal-bar deposits commonly show *ab*-plane clast imbrication, with the clast *a* axis oriented transverse to flow. The geometry of longitudinal-bar deposits can be determined from lateral sections which were correlated using detailed tephrostratigraphy (Figure 2.7). Individual bar units average 2 to 3 meters in thickness and can be traced down paleocurrent direction for more than 0.5 km, giving an overall sheet-like geometry. These units are amalgamated in places, forming multistory units up to 15 meters thick.

Two types of bar-platform deposits are represented by parallel-bedded sandstone with primary current lineation (Sh) and by trough cross-bedded sandstone (St). Parallel-bedded sandstone is normally graded, contains leaves and plant debris, and may be rooted or show other signs of soil development (Figure 2.5c,d). This lithofacies is interpreted as vertical-accretion deposits above the bar platform during high-flow stage. Subsequent soil development occurred during low-stage emergence of the bar-top. Trough cross-bedded sandstone is present in small (up to 1 m deep and 5 m wide), lenticular channels cut into the bar platform. These deposits are interpreted as dunes that filled transverse or chute channels across the bar platform. Such secondary channels would be cut when the bar platform was exposed and dissected at low flow stage (e.g., Bluck, 1979).

Bar-margin avalanche-face deposits are represented by planar-tabular cross-bedded, granule-pebble conglomerate (Gp). These deposits are extremely rare in the Chumstick Formation, representing less than 1% of lithofacies. Rust (1984) has argued that bar-margin avalanche faces develop during high-flow stage, as minor gravel bedforms migrate across the bar-platform. The virtual absence of these deposits in the Chumstick Formation suggests that either (1) flow depth with respect to grain sizes in transport was not sufficient to generate bedforms on the bar platform, or (2) rapid stabilization of emergent bar surfaces by vegetation inhibited later movement of minor bedforms across the bar platform. Evidence for the latter is the common development of paleosols (rootlets and *in situ* stumps) and leaf-litter layers on paleo-bar surfaces.

Dunes are inferred from the presence of both trough cross-bedded and planar-tabular cross-bedded sandstone and pebbly sandstone. Set heights range to a maximum of 70 cm and are typically organized into multistory units several meters thick, which are not laterally continuous. In Figure 2.7, the left column shows the vertical stacking of several multistory, trough-cross-bedded sandstone bodies which appear to be transitional laterally into gravel bar-platform deposits (other sections). Individual gravel-bar deposits, soil horizons, and layers of intraclasts can be correlated laterally, and demonstrate a sheet-like geometry. The broadly lenticular units of trough cross-bedded sandstone units are interpreted to represent channels between the gravel braid-bars.

Detailed paleocurrent data (Figure 2.8) from these sections reveal different dispersion patterns for the various indicators. Clast imbrication, wood-cast orientation, primary current lineation, and some grooves were present in the longitudinal-bar or bar-platform deposits, and show a dominant W-NW orientation. These indicators formed when the bar-platforms were submerged and probably represent high-stage flow. In contrast, cross-bedding data come mostly from the trough-cross-bedded sandstone and show a higher dispersion to the west and north. This pattern suggests that the inter-bar channels represent low-stage flow, which "wandered" around the emergent gravel bars.

Overbank deposits, soils, and channel slumps represent a minor but significant portion of the deposits in the gravel-bedload stream facies. Virtually all fine-grained deposits show evidence for incipient soil formation, and the presence of cutbanks, intraclasts, and resedimented pedogenic nodules attests to bank cohesion and stability imparted by vegetation. Lateral continuity of soil horizons through a variety of deposits suggests there were periods of inactivity or abandonment of a portion of the fan. Similarly, the lateral correlation of intraclast horizons suggests regional episodes of incision and lateral channel migration, resulting in localized bank undercutting and failure.

Debris-flow deposits (Gms) represent a minor but significant component of this facies assemblage. There are two types of coarse-grained, poorly sorted deposits in the Chumstick Formation. Talus-cone deposits are found adjacent to the three major fault zones. They comprise boulder conglomerates and breccias set in a sandstone matrix, with individual clasts up to 2 m in maximum diameter. These deposits tend to be composed of a single lithology, either biotite gneiss, granodiorite, or peridotite, and the sandstone matrix consists of disaggregated clasts of these lithologies (see Cashman, 1974).

Rare volcaniclastic debris-flows are interbedded with fluvial deposits, closely associated with airfall and ash-flow tuffs. The debris flows contain pumice clasts, exoclasts, carbon fragments, leaves, and silicified wood (Figure 2.9). Each debris flow either directly overlies a tuff or is separated from one by a thin, tuffaceous sandstone or mudstone. These debris flows are probably the result of hillslope failure that followed the destruction of vegetation by volcanic activity.

Depositional Geometry. The alluvial architecture changes systematically down-fan. In the fan-head (proximal) regions, channel deposits comprise broadly lenticular (width:thickness ratios of 10:1 to 15:1), coarse-grained, longitudinal-bar and bar-platform deposits (lithofacies Gm, Smc, and Sh). A photomosaic and interpretive sketch (Figure 2.10) of a large cliff exposure of these deposits near the basin margin emphasizes the lateral stacking of successive channels. In these coarse-grained deposits, individual fining-upward sequences 1 to 5 meters thick are organized into megasequences, 15 to 40 meters thick, which coarsen- or fine-upward (Figure 2.11). The megasequences are probably tectonically controlled, representing progressive development and then abandonment of a portion of the fan (e.g., see Gloppen and Steel, 1981).

On distal portions of the fan, depositional units consist of gravel longitudinal-bar and bar-platform deposits, with smaller inter-bar channels. These deposits have an overall sheet-like geometry (width:thickness ratio >15:1), as shown in Figure 2.7. Vertical accretion occurs through a combination of lateral and vertical stacking of depositional units in this portion of the fan. Mega-sequences cannot be discerned in the more distal deposits of the fan (e.g., Figure 2.12). Distal-fan deposits are transitional basinward to the basin fill, which is dominated by vertically stacked channels with a ribbon-like geometry, and by overbank deposits with a sheet-like geometry.

Sand-bedload Stream Deposits

Dominantly sand-rich fluvial sediments interpreted as deposits of sand-bedload streams were a significant part of the basin fill during all three phases of Chumstick deposition. During Phase 1 (Figure 2.3b), proximal gravel-bedload streams flowed west into an extensive sandy braidplain. During Phase 2 (Figure 2.3c), gravel bedload-streams flowed west off the Entiat fault zone and east off the Leavenworth fault zone into axial-drainage systems composed of sand-bedload streams. During Phase 3 (Figure 2.3d), the major drainage systems were composed of sand-bedload streams.

<u>Lithofacies Composition</u>. These deposits comprise between 40% and 90% sandstone, with between 10% and 30% shale, and localized occurrences of up to 50% conglomerate (Table 2.2). Sand-bedload stream deposits are dominated by channel sequences consisting of trough cross-bedded sandstone (St) and pebbly sandstone (Gt), with subordinate

massive, coarse-grained sandstone (Smc) and parallel-bedded sandstone (Sh). A significant secondary component is proximal overbank sequences (Figure 2.13) dominated by ripple-laminated sandstone (Sr), laminated sandstone (Sl), and laminated, very fine-grained sandstone to shale (Fl). In many places these deposits have been destratified by bioturbation to form massive, fine-grained sandstone (Smf) and mudstone (Fm).

Mudstone and siltstone intraclasts (lithofacies Se) are a minor component of the sand-bedload stream deposits. There is evidence for vertical and undercut banks, rotational bank failures, and partly eroded portions of channel bottoms and banks. Small (<5 cm), rounded intraclasts are present on the lee-face cross-strata of dunes (lithofacies St). Given the overall sandiness of these deposits and the evidence for soil development, it is apparent that vegetation (roots and organic matter) had a significant influence on the development of bank stability.

Depositional Units. Markov Chain analyses of two stratigraphic sections (Figure 2.14) have been helpful in identifying depositional sequences in these deposits. With reference to modern fluvial systems, these units are interpreted as:

(1) point-bar deposits
(sequence Gm ± Smc --> St --> Sr --> Fm);

(2) gravel-bar deposits
(sequence Ss --> Gm --> Sh
and Ss --> Gm --> St);

(3) dune deposits
(sequence Ss --> ± Gt --> St); and

(4) overbank deposits and soils
(sequence Sr --> Fm
St --> Fl
and Smf --> Fm).

The bulk of this discussion shall focus on point-bar deposits. The gravel-bar deposits have a similar morphology and organization to the longitudinal-bar deposits that were discussed previously and are relatively rare in the sand-bedload stream facies. Due to poor exposure, it has not been possible to trace these deposits laterally, so it is unclear whether they formed mid-channel bars or were attached (i.e., lateral) bars.

Point-bar sequences typically exhibit a migrating series of lateral-accretion surfaces which grade laterally into a series of cutbanks and overbank deposits (Figure 2.15). In the Chumstick Formation, point-bar sequences show evidence that this lateral migration occurred while the entire system aggraded vertically. These channel sequences typically form vertically stacked, multistory sandstone bodies (Figure 2.16), each with a basal gravel lag, dune deposits, and finer-grained (upper point-bar, levee, and overbank) deposits.

In addition to larger channels associated with lateral-accretion surfaces, many smaller channels cut upper point-bar sequences and probably represent chute channels. Many of these chute-channel deposits show abrupt fining upward (Figure 2.17a), interpreted to represent abandonment of the chute channel and subsequent infilling by suspension-load deposits. Several chute channels were filled by mud-draped trough cross-bedding (Figure 2.17b). In contrast to other trough cross-sets with mud rip-ups on the lee face of dunes, these particular cross-sets exhibit continuous layers of suspension-load deposits which partly to completely drape the lee face of the dune. These structures probably formed in chute channels that were repeatedly abandoned (dune migration ceased, mud drape was deposited) and re-activated (new episode of dune migration). One mechanism that could explain this alternation would be periodic (i.e., seasonal) flooding that would re-activate the upper point bar chute channels.

Depositional Geometry. Sand-bedload stream deposits consist of vertically stacked, multistory-channel sequences 10 to 30 meters thick, and related proximal overbank sequences (Figure 2.18). In areas of good exposure, individual channel sequences can be traced laterally for up to 200 meters. In overall geometry, the channels form ribbons (width:thickness ratio of 10:1 to 15:1) and sheets (width:thickness ratio of >15:1).

Mixed-load Stream Deposits

Fluvial deposits that have characteristics intermediate between those of bedload and suspension-load streams are interpreted as mixed-load stream deposits. Mixed-load streams formed the more distal portions of the fan systems during Phase 1 (Figure 2.3b). During Phase 2, a lacustrine-deltaic complex formed in the eastern sub-basin (Figure 2.3c) and was dominantly composed of mixed-load fluvial deposits. During Phase 3, fluvial systems throughout the basin were dominated by mixed-load streams (Figure 2.3d).

Lithofacies Composition. These deposits comprise 50% to 70% sandstone and 30% to 50% mudstone, with virtually no conglomerate (Table 2.2). They can be subdivided into channel, proximal- and distal-overbank sequences. Channel deposits are dominated by multistory sequences of trough cross-bedded sandstone (St), with minor amounts of planar-bedded sandstone (Sh), planar-tabular cross-bedded sandstone (Sp), and ripple-laminated sandstone (Sr). The proximal-overbank deposits are dominated by laminated sandstone (Sl) and mudstone (Fl), and ripple-laminated sandstone (Sr). Thin (<30 cm) beds of carbonaceous mudstone (lithofacies C) containing up to 6% total organic carbon are present in some proximal-overbank settings. They are interpreted as organic soils (histosols) that formed in ephemeral swamps near the active channels. Distal-overbank deposits are dominated by laminated (Fl) and massive mudstone (Fm).

Virtually all of these deposits show evidence for biological activity. Channel deposits contain rare to abundant vertical, unlined burrows (*Skolithos*) and rare surface traces (*Sinusites*). Roots, rhizoliths, and pedogenic concretions are locally common. In overbank deposits, massive sandstone (Smf) and mudstone (Fm) probably have been destratified by root growth and organisms.

Depositional Units. Markov Chain analyses of two stratigraphic sections (Figure 2.19) have been helpful in identifying depositional sequences in these deposits. With reference to modern fluvial systems, these units are interpreted as:

(1) point-bar deposits
(sequence Ss --> St --> Sh --> Fm);

(2) dune deposits
(sequence Ss --> St
and Sp --> Sh);

(3) overbank deposits
(sequence Fl --> Fm,C --> P);

(4) channel slumps
(sequence Ss --> Se
and P --> Se); and

(5) massive channel-fill deposits
(sequence Ss --> Smc).

Most of these depositional units have already been discussed. In general, the channel deposits (point-bars, dunes, and massive channel-fills) are smaller in size and exhibit greater evidence for disturbance (dewatering and bioturbation) than those discussed previously. Most channel fills contain roots, burrows, rootcasts, and pedogenic concretions, indicating subaerial exposure of the channel deposits. Dewatering and related structures include convoluted bedding, deformed and overturned cross-bedding, clastic dikes, and frondescent marks. The prevalence of dewatering structures in these deposits probably resulted from rapid sedimentation of water-laden sediments and subsequent expulsion of water due to compaction or paleo-earthquake disturbance (see Evans, chapter 4). Massive channel fills are probably the result of some combination of destratification by organisms and by dewatering.

A typical stratigraphic section of these deposits (Figure 2.20) shows vertical stacking of meter-scale, lenticular channels which were filled by dune deposits. Proximal- and distal-overbank deposits constitute >60% of these sections, indicating a high proportion of suspended-load transport through these paleochannels. The channel deposits show evidence for channel abandonment and subsequent re-occupation (Figure 2.21), scour into cohesive substrates, and bank undercutting and failure (Figure

2.22). All of these features are consistent with a proximal floodplain setting, dissected by small floodbasin channels. Following each flood event, the channels deposits were dewatered, colonized by plants, and bioturbated.

Depositional Geometry. Mixed-load stream deposits are characterized by isolated, lenticular channels and vertically stacked, multistory channels that have an overall ribbon geometry (width:thickness ratio of 10:1 to 15:1). Channel deposits tend to form relatively thin, vertically isolated packages separated by great thicknesses of fine-grained deposits (Figure 2.23). Allen (1978) discussed how the degree of sand-body connection is determined by the rate of lateral channel migration relative to the rate of basin subsidence. The low degree of sand-body connection in the Chumstick basin-fill is probably a result of the large proportion of fine-grained sediments and relatively rapid basin subsidence.

Lacustrine Deposits

A portion of the eastern sub-basin of the Chumstick Formation was filled by a lacustrine-deltaic system during Phase 2 (Figure 2.3c). This system consisted of mixed-load stream deposits, delta-front turbidites, and basin-plain deposits. The eastern sub-basin formed an elongate linear basin, bounded on the northeast and southwest by major faults, which filled longitudinally (from northwest toward the southeast). The actual dimensions of the lacustrine system are difficult to estimate due to poor exposure. If isolated outcrops can be correlated, the maximum extent of the lake was about 4 km by 25 km.

Lithofacies Composition. The lacustrine deposits comprise 50% to 60% sandstone and 40% to 50% mudstone with virtually no conglomerate (Table 2.2). The most important lithofacies are planar-bedded sandstone (Sh), low angle (<10^0) cross-laminated sandstone (Sl), and laminated very fine-grained sandstone and shale (Fl). Important minor elements are trough cross-bedded sandstone (St), planar-tabular cross-bedded sandstone (Sp), ripples and ripple cross-lamination (Sr). Both symmetric and asymmetric ripplemarks are present and commonly show evidence for shallow-water origin, including truncated (planed-off) tops, crenulated or wrinkled surfaces, and mud-cracks.

Delta-front Deposits. Delta-front deposits are organized into isolated, lenticular channels separated by intervals of thin-bedded turbidites (Figures 2.24, 2.25). The morphology of most channels is convex-downward, with a scoured base. There are rare examples of sandstone bodies with planar bases and convex-upward upper surfaces (Figure 2.24), which are interpreted as channel cross-sections that have been modified by compaction. Analysis of syn-depositional slump folds indicates that paleoflow was perpendicular to paleoslope (Evans, chapter 4).

Channel-fill sequences typically include turbidites, massive sandstone beds, and channel-margin slumps, with rare examples of channel-fills dominated by dune deposits. All channel fills contain abundant plant fragments, mud rip-up clasts, and soft-sediment-deformation structures (flame structures, load structures, convoluted bedding, mud diapirs, and sandstone dikes). Typical turbidite channel-fills are Bouma sequences Tad/e and Tabd/e, with abundant sole marks, including flute and groove casts. Thin-bedded turbidite sequences in the delta-front deposits are dominantly composed of Bouma sequences Tde, Tcde, and Tbde. Bedding is tabular, with sharp, planar basal contacts. Slumps into channels consist of blocks of thin-bedded turbidites.

These deposits clearly represent rapid deposition of sediments in a deltaic system undergoing primarily vertical aggradation. The delta-front was characterized by the vertical stacking of isolated lenticular channels, a type of architecture predicted in models of rapidly aggrading systems (e.g., Allen, 1978). There is no evidence for southeastward delta progradation, down the axis of the lake basin. The vertical stacking of these channels at one locality, at the northwest margin of the lake basin, may be evidence for structural control of the lake margin. Evidence of a shoreline consists only of rare examples of mud-cracks, crenulated surfaces, and reworked (planed-off) tops of ripples. Structural control of the lake margin was probably responsible for development of narrow and vertically stacked shoreline facies, while rapid aggradation prevented development of certain diagnostic features, such as wave-sorted gravels.

Basin-plain Deposits. Lacustrine basin-plain deposits consist of laminated fine-grained sandstone, siltstone and shale. The individual depositional units consist of millimeter- to centimeter-scale, fining-upward Bouma Tde and Tcde sequences, interpreted as distal turbidites. Poor exposure makes it difficult to trace individual units laterally, but these basin-plain deposits appear to fill the eastern sub-basin from near the town of Monitor southeast beneath the city of Wenatchee, where they appear in drill core (Gresens et al., 1981; Margolis, 1987; locations on Figure 2.4).

Lacustrine Conditions. Evidence for high turbidity and rapid sedimentation in these lake deposits includes abraded organic debris, lack of faunal remains, and rarity of trace fossils. Compared to the excellent preservation of leaf fossils in fluvial overbank deposits, organic matter in the lake deposits consists of indistinct fragments of leaves and rounded pieces of stems, which indicates transport and abrasion. Pollen grains are similarly abraded and corroded in these deposits. Faunal remains have not been found, and trace fossils consist entirely of unlined, vertical burrows (*Skolithos*). These observations suggest that benthic organisms were restricted by high turbidity of the lake waters, due to repeated episodes of sedimentation.

The lake-water chemistry of this system is less well understood. Many humid-tropical lakes are characterized by annual or seasonal stratification, and some develop anoxic bottom conditions. Chumstick lacustrine deposits have a high organic-carbon content (up to 6% TOC), suggesting either rapid burial of organic-rich sediments or anoxic bottom conditions. Also, local hydrothermal activity, associated with syndepositional volcanism, may have included sub-aqueous hot-springs, vents, and eruption breccias (Margolis, 1987).

PALEOHYDROLOGY

Fluvial deposits in the Chumstick Formation have been interpreted as gravel-bedload, sand-bedload, and mixed-load stream deposits (Table 2.3). The intent of this section is to evaluate channel geometry at bankfull flow conditions, bed roughness, and paleoslope through these channel reaches.

Channel Geometry

Bankfull channel depth has been determined from a suite of indicators, including: cutbank height, scour depth, height of lateral-accretion surfaces, height of gravels bars from the basal scour to vertical-accretion deposits, dune height, and height of bar-margin avalanche faces (Table 2.4). Some of these indicators represent minimum estimates of bankfull depth, such as the height of cutbanks, or depth of scours and channels. Other indicators represent estimates of maximum flood-flow depth, such as the height of bar-platform deposits above the channel floor. The tabulation of hundreds of individual indicators, as shown in Table 2.4, gives a reasonable approximation of the bankfull depths of paleochannels.

Based on these observations, estimates for maximum bankfull depth are: 5.7 meters in gravel-bedload streams, 4.7 meters in sand-bedload streams, and 5 meters in mixed-load streams. Although these maximum values are reasonably close, they represent extremes of the data--the averages of hundreds of individual indicators for each facies converge on numbers much smaller. The data for gravel-bedload streams suggest that average flow depth may have been about 1 meter (heights of dunes and bar-margin foresets), and average bankfull depth may have been about 2.5 meters (from the thicknesses of vertical-accretion deposits on the bar platforms). The data for sand-bedload streams suggest an average flow depth of about 1 meter (heights of dunes), with the height of lateral accretion surfaces indicating an average bankfull depth of about 1.5 meters. For mixed-load streams, all of the indicators converge on a bankfull depth of about 1 meter.

Bankfull channel width was measured for 70 paleochannels in the Chumstick Formation. Each measurement presumably represents a minimum width, due to preservation effects (i.e., erosional loss of the top of each channel succession). A plot of the measured bankfull width-to-depth ratio (Figure 2.26) shows a wide range of scatter, and may not be statistically significant. Given the limitations of the data, it is still interesting that the bankfull width-to-depth ratios are about 35:1 for gravel bedload streams, 19:1 for sand bedload streams, and 17:1 for mixed-load streams. Given that the erosional loss of the top of a lenticular channel succession would have a greater effect on the observed width than the observed depth, these ratios are probably low.

Bank Cohesion and Bed Roughness

The percentage of silt- and clay-sized sediment in the channel bed and banks has important implications for bank cohesion and sediment transport. The uncommon preservation of cutbanks and the local abundance of siltstone-mudstone intraclasts in the Chumstick Formation attest to the significance of bank cohesion, at least in certain localities. It is difficult to quantify the overall significance of bank cohesion in Chumstick paleochannels, but a reasonable method is to use the relative percentage of lithofacies in representative stratigraphic sections. Over a large number of measurements, these percentages give an average value of the amount of silt and clay preserved in the channel bottom or channel banks and probably present an accurate picture of the importance of bank cohesion. The results (Table 2.5) show that the percentage silt and clay in the channel bottoms is relatively constant, but the percentage silt and clay in channel banks goes from 3.5% in gravel-bedload stream deposits to 35% in mixed-load stream deposits. A calculation of the percentage silt and clay in the channel perimeter (after Schumm, 1968) ranges from about 2% to 6% and is in accord with results from modern bedload and mixed-load streams (Ethridge and Schumm, 1978).

Bed roughness has been estimated by outcrop measurements of median grainsize, D_{50}, and of one of the largest available size classes, D_{95}. These particular size classes were chosen for convenience in the field--D_{50} can be visually estimated, while studies have shown that an average diameter of the 10 largest clasts in a bed approximates D_{95} (Maizels, 1983). Chumstick outcrops are predominantly two-dimensional, but studies by Kellerhals et al. (1975) have shown that with random, two-dimensional cuts through a triaxial ellipsoid, the largest apparent axis is approximately equivalent to the true intermediate (b) axis. The average median grain-size in Chumstick paleochannels ranges from granules to pebbles, with cobbles being the largest grain-size class in transport (Table 2.5).

Paleoslope Calculation

In order to calculate the paleoslope of channel reaches, the equations governing fluid flow are simplified by assuming the case of steady, horizontally uniform flow in a natural channel, where friction on the walls of the channel is negligible compared to that on the channel bottom. The lowest-order force balance between the gravitational force associated with the water-surface slope and the stress on the channel bottom is given by:

$$\tau_b = \rho ghS$$

where τ_b is the critical shear stress acting on the bed of the channel ("boundary shear stress"), ρ is the fluid density, g is the acceleration due to gravity, h is the depth of flow, and S is the slope of the water surface. The procedure used here for each case is to find an appropriate boundary shear stress from initial motion criteria, and then use this value in conjunction with measurements of paleo-bankfull depth and assumptions about the other variables, to calculate the paleoslopes. Initial motion of bed material in modern, coarse-grained rivers typically occurs at a transport stage ($(\tau_{cr})max$ / $(\tau_b)gen.motion$) of between 1 and 3 (Andrews, 1983, 1984). It is reasonable to assume that initial motion in coarse-grained, aggrading streams with broad floodplains will occur at a transport stage close to unity (Mohrig, 1987).

The critical shear stress (τ_{cr}) on a well-sorted bed can be obtained from the Shields relationship:

$$\tau_{cr} = (\tau^*)_{cr} \ (\rho_s - \rho)gD$$

where $(\tau^*)_{cr}$ is the non-dimensional critical shear stress, ρ_s is the particle density (assumed to be 2.65 g/cm^3), and D is the nominal grain diameter. For a well-sorted bed, the nominal grain diameter is the only length scale of importance in the Shields relationship. For nominal grain diameters greater than 0.60 cm, the non-dimensional critical shear stress is approximately constant at $(\tau^*)_{cr} = 0.06$.

While the critical shear stress for well-sorted sediments corresponds closely to the Shield's relationship, the critical shear stress for poorly sorted sediments depends on two additional factors, the relative protrusion of the grain into the flow and the particle angle of repose. Wiberg and Smith (1987) have proposed a model to calculate the critical shear stress for mixed grain-size beds that includes these factors. They have shown that the non-dimensional critical shear stress ($(\tau^*)_{cr}$) depends upon the ratio of the grain-size class of interest, D, and the local bed roughness, k_s. The median grain-size, D_{50}, is used to approximate the average bed roughness, k_s; and one of the largest available size classes, D_{95}, is used to approximate the largest diameter classes in motion (as in Mohrig, 1987). In the Chumstick Formation, gravel-bedload and sand-bedload streams typically had D/k_s ratios between 2 and 3 ($(\tau^*)cr$ of 0.02 - 0.03), while mixed-load streams had D/k_s ratios between 3 and 4 ($(\tau^*)cr$ of 0.015 - 0.02).

Calculated paleoslopes in the Chumstick Formation range from about 1.7 to 3.8 m/km in gravel-bedload streams, about 0.9 to 2.7 m/km in sand-bedload streams, and about 0.2 to 0.5 m/km in mixed-load streams (Table 2.6). These values are close to measured slopes of some modern, humid-tropical alluvial fans such as the Kosi Fan (e.g., 0.1 to 0.9 m/km from Wells and Dorr, 1987), although not as steep as humid-tropical alluvial fans on the flanks of active volcanoes (e.g., 19 to 101 m/km from Kesel, 1985).

Paleobotanical studies in the Chumstick Formation provide an independent method of confirming these paleoslope calculations. There is a well-established relationship between certain physiognomic characteristics of the flora (percentage of smooth-margin taxa) and mean annual temperature (Wolfe, 1978). Paleoflora data from the Chumstick Formation suggest a mean annual temperature of 14^0 to 15^0C (Evans, chapter 3), while similar data from the Puget Group, 150 km westward in a coastal setting, suggest a mean annual temperature of $17^{0}C$ (Wolfe, 1968; Wolfe and Wehr, 1986; Buckovic, 1978). Using a lapse rate of $0.55^{0}C/100$ meters elevation (Wolfe and Wehr, 1986), the elevation of the Chumstick basin was between 350 and 550 meters above sea level. The Chumstick paleoflora does not show any evidence for a rain-shadow effect, indicating it is reasonable to calculate a regional average paleoslope between the Chumstick and Puget basins as between 2.4 and 3.6 m/km. Given the uncertainties of the paleohydraulic and paleobotanical methods, both converge on paleoslopes in the range of 1 to 5 m/km.

DISCUSSION

Humid-tropical alluvial fans have a diagnostic set of characteristics that follow from the interaction of climate and tectonics. One example is the preservation of relatively unweathered sediments. The Chumstick basin accumulated between 2 km and 12 km of compositionally immature sediments (dominantly sublithic feldspathic arenites, see Frizzell, 1979). Fluvial overbank deposits and lacustrine deposits contain up to 6% total organic carbon and may show excellent preservation of leaf fossils. Chumstick paleosols demonstrate rudimentary development, and there is an absence of lateritic soils and other features characteristic of intensely weathered tropical climates. The accumulation of great thicknesses of compositionally immature sediments is usually considered to be an indication of semi-arid or cold climates, although Ruxton (1970) reported an example from modern humid-tropical alluvial fans in New Guinea. These data are interpreted to show the effect of tectonics (rapid uplift, high erosion rates, and rapid subsidence) at partly concealing the distinctive signature of intensive tropical weathering.

A second effect of tectonics was the development of characteristic facies distributions and fluvial architecture (Figure 2.27). Basin-margin faulting was responsible for stacking of coarse-grained facies along the basin margin. These coarse-grained deposits formed laterally stacked, sheet-like depositional units during intervals of tectonism. The basin-axis fill was dominated by finer-grained sediments which formed vertically stacked, ribbon-like depositional units. During intervals of tectonic quiescence, the basin fill onlapped the proximal regions. Thus stratigraphic sections in the proximal areas show well-developed coarsening-upward megasequences separated by finer-grained intervals of proximal onlaps.

The effects of climate and vegetation include the development of bank stability in sandy and silty sediments, the development of soils and leaf-litter layers, and introduction of woody debris to channels. Even coarse-grained, proximal fluvial deposits had a significant overbank component and show evidence for bank stability, cutbanks, and coherent bank failures. Debris-flow deposits are a minor component, probably because vegetation imparted hillslope stability to this system. The few volcaniclastic debris-flow deposits directly overlie airfall and ash-flow tuffs and may be a result of hillslopes failure following destruction of vegetation during a volcanic episode.

Kesel (1985) noted that sedimentation on humid-tropical alluvial fans in Central America was episodic, in response to tectonism, volcanic activity, and heavy rainfall. In the Chumstick Formation, evidence for episodic sedimentation can be observed in a number of outcrop-scale features. Laterally continuous soil horizons are interpreted as evidence of inactivity or abandonment of portions of the fan. Similarly, laterally continuous intraclast horizons are interpreted as evidence for episodes of incision or reactivation of portions of the fan. Channels that were cut and then infilled by fine-grained sediments may indicate avulsions, due to shifting and abandonment of channels. In some cases there is evidence for subsequent channel re-occupation, such as the partial removal of the fine-grained fill, and mud-draped trough cross-bedding. Shifting and abandonment of channels is a characteristic of modern humid-tropical alluvial fans, such as the Kosi Fan, and occurs in response to floodwater shifting from one unstable channel system to an adjacent low (Wells and Dorr, 1987a,b).

Despite the large volume of coarse-grained sediment transported during Chumstick deposition, there is evidence that paleoslopes were fairly low. Paleoslope calculations using paleohydraulics and paleobotanical data both converge on average fan slopes between 1 m/km and 5 m/km. Other evidence for fairly gentle slopes includes the relatively constant thickness of individual ashfall tuffs throughout the basin. These values are consistent with slopes on many modern humid-tropical alluvial fans (Gole and Chitale, 1966; Wells and Dorr, 1987a,b), but are much less that humid-tropical fans from the flanks of active volcanoes (Kesel, 1985).

SUMMARY

The Chumstick Formation represents deposition in a tectonically active environment characterized by active basin faulting, syndepositional volcanism, and rapid sediment accumulation rates. The Chumstick basin was located about 150 km inland from the coast, in a low mountain setting (350 to 550 meters elevation). The paleoclimate was humid and tropical, with evidence suggestive of strongly seasonal (monsoonal) rainfall. This type of setting describes a humid-tropical, alluvial-fan depositional system (Table 2.7).

Humid-tropical alluvial fans represent an important class of depositional system which deserves more study, in both the modern and ancient record. This study has focused on distinctive features that served to identify humid-tropical alluvial fans in the ancient record. These features include: large volumes of compositionally immature sediments, a wide range of grain sizes, dominance of fluvial processes over mass-wasting, lack of intensely weathered soil profiles, low paleoslopes, and evidence for bank cohesion. Coarse-grained deposits are relatively restricted to the basin margins, exhibit lateral stacking of depositional units, and may be organized into coarsening-upward or fining-upward megasequences. Distal portions of the fan consist of sheet-like depositional units, while the bulk of the basin fill is organized into vertically stacked depositional units. This study emphasizes the importance of integrated basin analysis studies that examine all aspects of a deposit: climate, tectonics, and sedimentology.

Chapter Notes

Abbott, P.L. and Peterson, G.L., 1978, Effects of abrasion durability on conglomerate clast populations: examples from Cretaceous and Eocene conglomerates of the San Diego area, California: Journal of Sedimentary Petrology, v. 48, p. 31-42.

Allen, J.R.L., 1978, Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion-controlled alluvial suites: Sedimentary Geology, v. 21, p. 129-147.

Andrews, E.D., 1983, Entrainment of gravel from naturally sorted riverbed material: Geological Society of America Bulletin, v. 94, p. 1225-1231.

Andrews, E.D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, p. 371-378.

Bluck, B.J., 1979, Structure of coarse-grained braided stream alluvium: Transactions of the Royal Society of Edinburg, v.70, p. 181-221.

Boothroyd, J.C. and Ashley, G.M., 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, in McDonald, B.C. and Jopling, A.V., editors, Glaciofluvial and Glaciolacustrine Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication no. 23, p. 193-222.

Boothroyd, J.C. and Nummedal, D., 1978, Proglacial braided outwash: a model for humid alluvial fan deposits, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 641-668.

Bradley, W.C., 1970, Effects of weathering on abrasion of granitic gravel, Colorado River, Texas: Geological Society of America Bulletin, v. 81, p. 61-80.

Bridge, J.S., 1985, Paleocurrent patterns inferred from alluvial deposits: a critical evaluation: Journal of Sedimentary Petrology, v. 55, p. 579-589.

Brown, M.B.,1983, Two-way tables, empty cells, and departures from independence, in Dixon, W.J. and Brown, M.B., editors, BMDP-83, Biomedical Computer Programs, P Series: Los Angeles, University of California Press, p. 278-296.

Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 147-163.

Bull, W.B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geological Survey Professional Paper no. 352-E, p. 89-129.

Bull, W.B., 1977, The alluvial fan environment: Progress in Physical Geography, v. 1, p. 222-270.

Byrnes, M.E., 1985, Provenance study of late Eocene arkosic sandstones in southwest and central Washington [M.S. Thesis]: Portland, Oregon, Portland State University, 65 p.

Carr, T.R., 1982, Log-linear models, Markov chains, and cyclic sedimentation: Journal of Sedimentary Petrology, v. 52, p. 905-912.

Cashman, S.M., 1974, Geology of the Peshastin Creek area, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 29 p.

Davies, D.K., Vessell, R.K., Miles, R.C., Foley, M.G., and Bonis, S.B., 1978, Fluvial transport and downstream sediment modifications in an active volcanic region: in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 61-84.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Howell, D.G. and McDougall, K.A., editors, Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 2, p. 1-32.

Denny, C.S., 1965, Alluvial fans in the Death Valley region, California and Nevada: U.S. Geological Survey Professional Paper no. 466, 62 p.

Ethridge, F.G. and Schumm, S.A., 1978, Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations, and assessment: in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 703-721.

Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619-638.

Fraser, G.T., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation in the Swauk Pass area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 219 p.

Friend, P.F., 1978, Distinctive features of some ancient river systems, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 531-542.

Friend, P.F., Slater, M.J., and Williams, R.C., 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of Geological Society London, v. 136, p. 39-46.

Frizzell, V.A., 1979, Petrology of Paleogene non-marine sandstone units in Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 113-118.

Gloppen, T.G. and Steel, R.J., 1981, The deposits, internal structure, and geometry in six alluvial fan-fan delta bodies (Devonian-Norway) - a study in the significance of bedding sequence in conglomerates, in Ethridge, R.G. and Flores, R.M., editors, Recent and Ancient Nonmarine Depositional Environments: Models for Exploration: Society of Economic Paleontologists and Mineralogists Special Publication no. 31, p. 49-69.

Gole, C.V. and Chitale, S.V., 1966, Inland delta building activity of Kosi River: Journal of Hydraulics Division, American Society of Civil Engineers, Proceedings, Paper 4722, v. HY 2, p. 111-126.

Gresens, R.L., 1982, Early Cenozoic geology of central Washington state: II. Implications for plate tectonics and alternatives for the origin of the Chiwaukum graben: Northwest Science, v. 56, p. 259-264.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Geology and Earth Resources, Bulletin 75, 75 p.

Gresens, R.L., Naeser, C.W., and Whetten, J.T., 1981, Stratigraphy and age of the Chumstick and Wenatchee formations- Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 233-236, 841-876.

Hooke, R. LeB., 1967, Processes on arid-region alluvial fans: Journal of Geology, v. 75, p. 438-460.

Johnson, S.Y., 1982, Stratigraphy, sedimentology, and tectonic setting of the Eocene Chuckanut Formation, northwestern Washington [Ph.D. dissertation]: Seattle, Washington, University of Washington, 221 p.

Johnson, S.Y., 1984a, Evidence for a margin-truncating transcurrent fault (pre-Late Eocene) in western Washington: Geology, v. 12, p. 538-541.

Johnson, S.Y., 1984b, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v.21, p. 92-106.

Johnson, S.Y., 1984c, Cyclic fluvial sedimentation in a rapidly subsiding basin, northwestern Washington: Sedimentary Geology, v. 38, p. 361-392.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 283-302.

Kellerhals, R., Shaw, J., and Arora, V., 1975, On grain size from thin sections: Journal of Geology, v. 83, p. 79-96.

Kesel, R.H., 1985, Alluvial fan systems in a wet-tropical environment, Costa Rica: National Geographic Research, v.1, p. 450-469.

Kochel, R.C. and Johnson, R.A., 1984, Geomorphology and sedimentology of humid-temperate alluvial fans, central Virginia: in Koster, E.H. and Steel, R.J., editors, Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists, Memoir 10, p. 109-122.

Kuenzi, W.D., Horst, O.H., and McGehee, R.V., 1979, Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala: Geological Society of America Bulletin, v. 90, p. 827-838.

MacGinitie, H.D., 1941, A Middle Eocene flora from the central Sierra Nevada: Carnegie Institute of Washington, Publication 534, 178 p.

MacGinitie, H.D., 1974, An early Middle Eocene flora from Yellowstone-Absaroka Volcanic Province, northwestern Wind River Basin, Wyoming: University of California, Publications in Geological Science, v. 108, p. 1-103.

Maizels, J.K., 1983, Paleovelocity and paleodischarge determination for coarse gravel deposits, in Gregory, K.J., editor, Background to Paleohydrology, John Wiley and Sons, Ltd., p. 101-139.

Margolis, J., 1987, Hydrothermal alteration and structure associated with epithermal gold mineralization, Wenatchee Heights, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 120 p.

McClincy, M., 1986, Tephrostratigraphy of the Chumstick Formation [M.S. Thesis]: Portland, Oregon, Portland State University, 127 p.

Miall, A.D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v.13, p. 1-62.

Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 597-604.

Mohrig, D., 1987, Facies and paleohydrology of a floodplain-dominated btaided fluvial system: Cretaceous Ventura redbeds, Washington, U.S.A. [M.S. Thesis]: Seattle, Washington, University of Washington, p.

Mukherji, A.B., 1976, Terminal fans of inland streams in Sutlej-Yamuna plain, India: Zeitschrift fur Geomorphologie, v. 20, p. 190-204.

Ott, L.E., Groody, D., Follis, E.L., and Siems, P.L., 1986, Stratigraphy, structural geology, ore mineralogy, and hydrothermal alteration at the Cannon Mine, Chelan County, Washington, in MacDonald, A.J., editor, Gold '86, An International Symposium on the Geology of Gold Deposits, Proceedings Volume, p. 425-435.

Parkash, B., Awasthi, A.K., and Gohain, K., 1983, Lithofacies of the Markanda terminal fan, Kurukshetra District, Haryana, India, in Collinson, J.D. and Lewin, J., editors, Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication no. 6, p. 337-344.

Pierson, T.C., 1980, Erosion and deposition by debris flows at Mt. Thomas, New Zealand: Earth Surface Processes, v. 5, p. 227-247.

Powers, D.W. and Easterling, R.G., 1982, Improved methodology for using embedded Markov chains to describe cyclical sediments: Journal of Sedimentary Petrology, v. 52, p. 913-923.

Roberts, J.W., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation along Tronsen Ridge, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 188 p.

Rust, B.R., 1978, Depositional models for braided alluvium, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 605-625.

Rust, B.R., 1984, Proximal braidplain deposits in the Middle Devonian Malbaie Formation of Eastern Gaspe, Quebec, Canada: Sedimentology, v. 31, p. 675-695.

Ruxton, B.P., 1970, Labile quartz-poor sediments from young mountain ranges in northeast Papua: Journal of Sedimentary Petrology, v. 40, p. 1262-1270.

Schumm, S.A.,1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Waitt, R.B., Jr., 1980, Preliminary geologic map of the Chelan quadrangle: U.S. Geological Survey, Open-File Report no. 80-841.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Nyerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee quadrangle, Washington: U.S. Geological Survey, Miscellaneous Geological Investigations I-1311.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26-44.

Taylor, S.B., 1985, Stratigraphy, sedimentology, and paleogeography of the Swauk Formation in the Liberty area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 199 p.

Taylor, S.B., Johnson, S.Y., Fraser, G.T., and Roberts, J.W., in press, Sedimentation and tectonics of the Swauk Formation, eastern Swauk basin- significance for hydrocarbon exploration in central Washington: American Association of Petroleum Geologists Bulletin.

Turk, G., 1979, Transition analysis of structural sequences: discussion and reply: Geological Society of America Bulletin, v. 90, p. 989-991.

Vessell, R.K. and Davies, D.K., 1981, Nonmarine sedimentation in an active arc basin, in Ethridge, F.G. and Flores, R.M., editors, Recent and Ancient Nonmarine Depositional Environments: Models for Exploration: Society of Economic Paleontologists and Mineralogists, Special Publication no. 31, p. 31-45.

Wells, N.A., 1984, Sheet debris flow and sheetflood conglomerates in Cretaceous cool-maritime alluvial fans, South Orkney Islands, Antarctica, in Koster, E.H. and

Steel, R.J., editors, Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists, Memoir 10, p. 133-145.

Wells, N.A. and Dorr, J.A., Jr., 1987a, Shifting of the Kosi River, northern India: Geology, v.15, p. 204-207.

Wells, N.A. and Dorr, J.A., Jr., 1987b, A reconnaissance of sedimentation on the Kosi alluvial fan of India, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., editors, Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists, Special Publication no. 39, p. 51-61.

Wells, S.G. and Harvey, A.M., 1987, Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England: Geological Society of America Bulletin, v. 98, p. 182-198.

Wiberg, P.L. and Smith, J.D., 1987, Calculations of the critical shear stress for motion of uniform and heterogeneous sediments: Water Resources Research, v.

Wolfe, J.A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: U.S. Geological Survey Professional Paper no. 571, 33p.

Wolfe, J.A., 1971, Tertiary climatic fluctuations and methods of analysis of Tertiary floras: Paleogeography, Paleoclimatology, Paleoecology, v. 9, p. 27-57.

Wolfe, J.A., 1977, Paleogene floras from the Gulf of Alaska region: U.S. Geological Survey Professional Paper no. 997, 108 p.

Wolfe, J.A. and Wehr, W., 1986, Middle Eocene dicotyledonous plants from Republic, northeastern Washington: U.S. Geological Survey Professional Paper no. 1597, 74 p.

Table 2.1: Fluvial Lithofacies Description

Facies Code	Description	Interpretation
Gms	massive, matrix supported gravel	debris-flow deposits
Gm	massive or crudely stratified gravel	longitudinal bars
Gt	trough cross-stratified gravel	channel fills
Gp	planar cross-stratified gravel	transverse bar or bar-margin foresets
Smc	massive, coarse-grained sand	rapid deposition or destratification
Sh	horizontally stratified sand, current lineation	upper plane bed flow
Sl	low angle (<10^0) cross-bedded sand	scour fills, crevasse splays, antidunes
St	trough cross-bedded sand	three-dimensional dunes
Sp	planar cross-bedded sand	two-dimensional dunes
Sr	ripple cross-laminated sand	ripples
Smf	massive, fine-grained sand	destratified by roots, organisms, etc.
Se	erosional scour fills with intraclasts	scour fills & cohesive bank failures
Ss	erosional scours	scour pits
Fl	laminated and ripple cross-laminated sand, silt, mud	overbank or waning flood deposits
Fm	massive sand, silt, mud	overbank or drape deposits
Fr	silt, mud with rootlets	paleosol
C	carbonaceous muds with rootlets	swamp deposits or peat
P	carbonate concretions to laminated horizons	paleosol (Cca or K horizon)

Modified from Miall, 1977, 1978; Rust, 1978

Table 2.2: Lithofacies Composition* of Depositional Units

GRAVEL-BEDLOAD STREAM DEPOSITS

Section	Gms	Gm	Gt	Gp	Se	Smc	Sh	Sl	Smf	St	Sp	Sr	Fl
	% Lithofacies												
Eagle Ck. Cyn.	10	81	3	0	0	6	0	0	0	0	0	0	0
Tumwater Mtn.	2	67	3	0	0	19	9	<1	0	0	0	<1	0
Camasland	0	40	0	<1	1	18	16	3	5	4	<1	<1	12
Cashmere	1	65	2	0	0	26	4	3	0	0	0	0	0
Clark Cyn.	1	23	31	0	2	0	18	10	0	6	0	3	7
Chumstick Creek	1	40	4	0	0	5	36	8	0	0	0	0	6
Bjork Cyn.	0	43	0	0	12	8	25	5	0	2	4	0	1
Sunitsch Cyn.	0	31	6	0	0	21	11	22	0	6	0	1	4

SAND-BEDLOAD STREAM DEPOSITS

Section	Gm	Gt	Se	Smc	Sh	Sl	Smf	St	Sp	Sr	Fl/Fm
	% Lithofacies										
Eagle Ck. Road	9	40	3	0	4	2	0	28	0	1	12
Malaga	4	33	3	3	5	<1	3	10	<1	18	22
Nahahum Cyn.	9	20	<1	0	0	0	4	16	0	19	34
Camas Ck.	1	5	2	19	16	3	4	39	0	3	8
Fish Lake	4	0	1	9	11	18	11	20	0	6	20
North Tumwater Canyon	14	0	3	13	8	11	3	5	0	8	37

Table 2.2 (con't.)

MIXED-LOAD STREAM DEPOSITS

Section	% Lithofacies Gm	Gt	Se	Smc	Sh	Sl	Smf	St	Sp	Sr	Fl/Fm
South Plain	1	0	2	5	20	8	0	14	0	4	46
Deadhorse Cyn.	0	0	3	14	4	7	14	16	<1	9	34
Cole's Corner	0	0	3	0	0	1	3	40	2	19	32
North Plain	0	0	2	0	10	20	9	27	0	5	28
Monitor	0	0	2	2	0	2	18	40	0	5	32
Pole Ridge	0	0	3	3	5	13	3	19	0	8	46

LACUSTRINE DEPOSITS

Section	% Lithofacies Gm	Se	Sh	Sl	St	Sp	Sr	Fl
Sunnyslope Road	1	1	33	13	<1	<1	1	51
Railroad Canyon	0	4	16	43	0	1	<1	36

* Lithofacies abbreviations from Table 2.1

Table 2.3: Characteristics of Fluvial Facies
Chumstick Formation

	Gravel-Bedload Stream Deposits	Sand-Bedload Stream Deposits	Mixed-load Stream Deposits
Lithology (%cgl:ss:sh)	50:40:10	10:70:20	0:60:40
Lithofacies Composition: > 20%	Gm	Gt,St	St,Fl,Fm
10% - 20%	Smc,Sh	Smc,Sh,Fl,Fm	Smf,Sl
5% - 10%	Gt,St,Sl	Gm,Sl,Sr,Smf	Sh,Sr
< 5%	Gms,Gp,Se, Sp,Sr,Smf, Fl,Fm,C	Gp,Sp,Se,C	Gm,Smc,Se, Sp,C
Depositional Geometry	sheet	ribbon and sheet	ribbon and isolated channel
Stacking	lateral stacking of braid bars	vertical stacking multistory channels	vertical stacking multistory channels

Table 2.1 provides key to lithofacies abbreviations

Table 2.4: Estimates of Bankfull Depth In Fluvial Depositional Units

	Gravel-Bedload Stream Deposits (m)	Sand-Bedload Stream Deposits (m)	Mixed-load Stream Deposits (m)
Cutbank Height			
average	0.40	0.77	1.05
maximum	0.40	1.80	2.10
(observations)	(1)	(14)	(12)
Scour Depth			
average	1.46	1.25	0.96
maximum	5.00	4.50	3.60
(observations)	(70)	(21)	(35)
Height of Lateral Accretion Surfaces			
average	no	1.37	0.89
maximum	data	4.50	1.00
(observations)	(0)	(9)	(4)
Height of Gravel Bar Surfaces			
average	2.42	3.20	1.18
maximum	5.70	4.70	2.20
(observations)	(340)	(6)	(5)
Flow Depth From Heights of Dunes*			
average	0.97	0.92	0.96
maximum	3.50	3.25	5.00
(observations)	(48)	(172)	(168)
Height of Bar-margin Avalanche-faces			
average	1.13	1.22	no
maximum	1.40	1.40	data
(observations)	(4)	(3)	(0)

* Estimated as Dune Ht. = 0.20 Flow Depth

Table 2.5: Bank Cohesion and Bed Roughness of Channels

	Gravel-Bedload Stream Deposits	Sand-Bedload Stream Deposits	Mixed-load Stream Deposits
% Silt-Clay in Channel Bed	1.9 %	2.2 %	2.5 %
% Silt-Clay in Channel Bank	3.5 %	15.0 %	35.0 %
% Silt-Clay in Channel Perimeter*	1.9 %	2.8 %	4.3 %
Average Bed Roughness:			
D_{50} (cm)	5.7	2.1	0.4
D_{95} (cm)	15.3	5.5	1.6
number of measurements	350	31	42

* Parameter M of Schumm (1968), Ethridge and Schumm (1978).

Table 2.6: Paleohydraulic Calculations
--Chumstick Formation--

	Gravel-Bedload Stream Deposits	Sand-Bedload Stream Deposits	Mixed-load Stream Deposits
Estimated Average Bankfull Depth (meters)	2 to 3	1 to 2	1 to 2
Estimated Average Bankfull Width (meters)	70 to 105	19 to 38	17 to 34
Bed Roughness (k_s) (cm)	5.74	2.13	0.44
Average Maximum Clast Size (D_{95}) (cm)	15.25	5.50	1.60
Critical Boundary Shear Stress (dynes/cm^2)	493 to 740	178 to 267	39 to 52
Slope of Channel Reach	1.7 to 3.8 $\times 10^{-3}$	0.9 to 2.7 $\times 10^{-3}$	0.2 to 0.5 $\times 10^{-3}$
Average Velocity (m/sec)	3.9 to 5.0	2.4 to 3.2	1.4 to 1.7
Average Discharge (m^3/sec)	5.4 to 15.8 $\times 10^2$	0.5 to 2.5 $\times 10^2$	0.2 to 1.2 $\times 10^2$

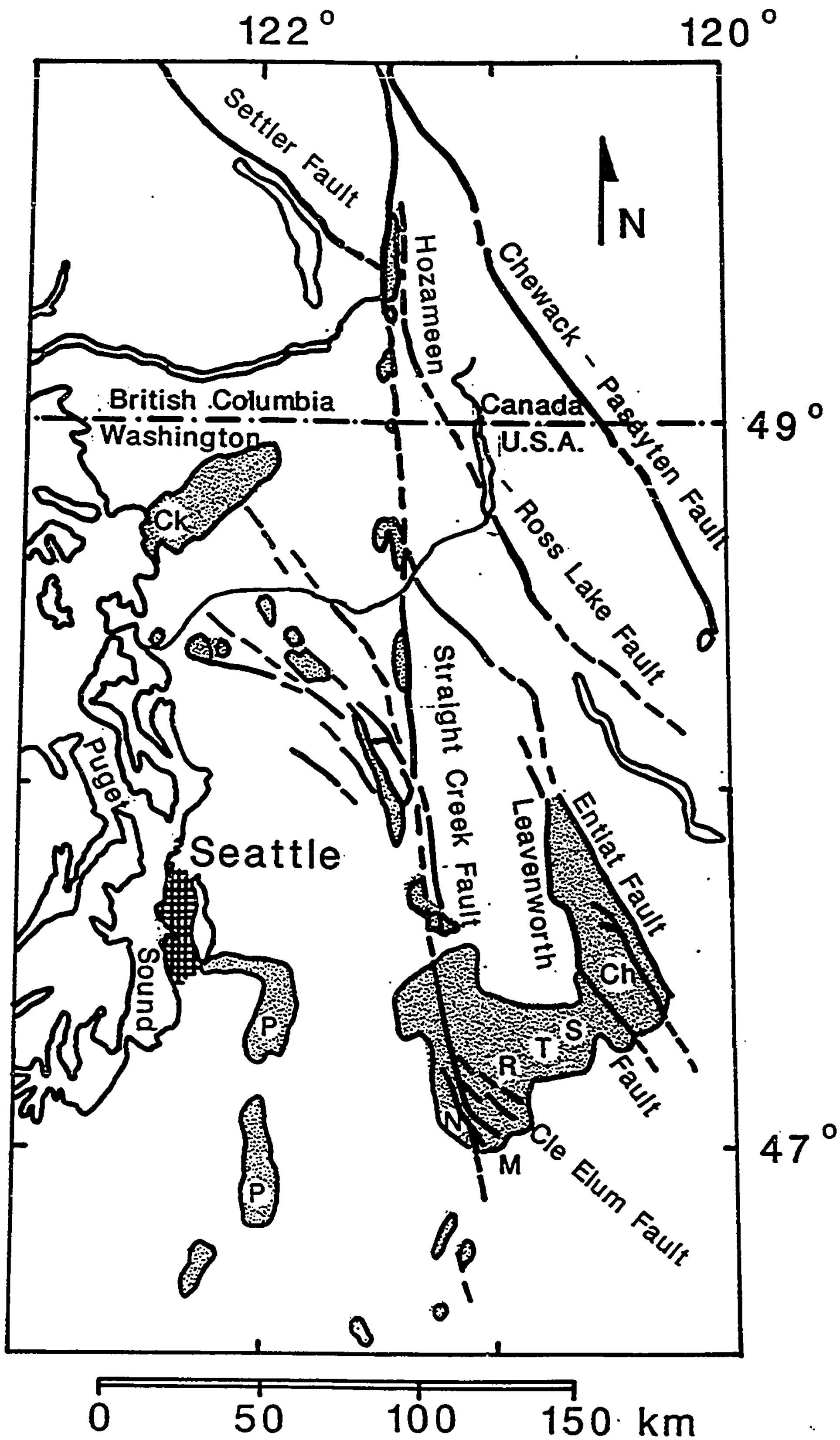
see text for discussion of range of values

Table 2.7: Characteristics of Alluvial Fans

	General Types of Alluvial Fans			
Feature	Arid Region	Humid-Glacial	Humid-Tropical	Chumstick Formation
Regional Slope:	20-100 (m/km)	1-20 (m/km)	1-10* (m/km)	1-5 (m/km)
Depositional Processes:				
stream flow	common	common	common	common
debris flow	common	minor	minor	minor
sheetflood	common	rare	rare	rare
Return Interval:	discrete (floods)	seasonal (melt-off)	seasonal (monsoon)	seasonal(?) (periodic dryness)
Soils:	entisols calcretes	entisols histosols	latosols oxisols entisols	entisols calcretes histosols
Eolian:	active	active	none	none

Modified from Kochel and Johnson, 1984
*excludes slopes from flanks of volcanoes (e.g. Kesel, 1985)

Figure 2.1--Generalized geologic map of northwestern Washington State and southwest British Columbia showing faults of known Mesozoic and Paleogene displacement and Paleogene sedimentary units. Abbreviations used on map: Ch - Chumstick Formation, Ck - Chuckanut Formation, M - Manastash Formation, N - Naches Formation, P - Puget Group, R - Roslyn Formation, S - Swauk Formation, T - Teanaway Formation.



122°
120°
Settler Fault
Hozameen
Chewack - Pasayten Fault
N
British Columbia
Washington
Canada
U.S.A.
49°
Ck
Ross Lake Fault
Straight Creek Fault
Puget
Sound
Seattle
Leavenworth
Entiat Fault
Ch
S
T
R
P
P
Fault
47°
M
Cle Elum Fault
0
50
100
150 km

Figure 2.2--Regional stratigraphic relations of Paleogene sedimentary and volcanic units in central and western Washington, based upon data compiled from Johnson, 1985 and Tabor _et al_., 1984. Chumstick Formation data modified from Evans (chapter 3 and chapter 4). Abbreviations used-- Tb = Basalt of Frost Mountain, Th = Huntingdon Formation, Tm = Manastash Formation, Tt = Teanaway Formation, Tta = Taneum Formation, Tw = Wenatchee Formation.

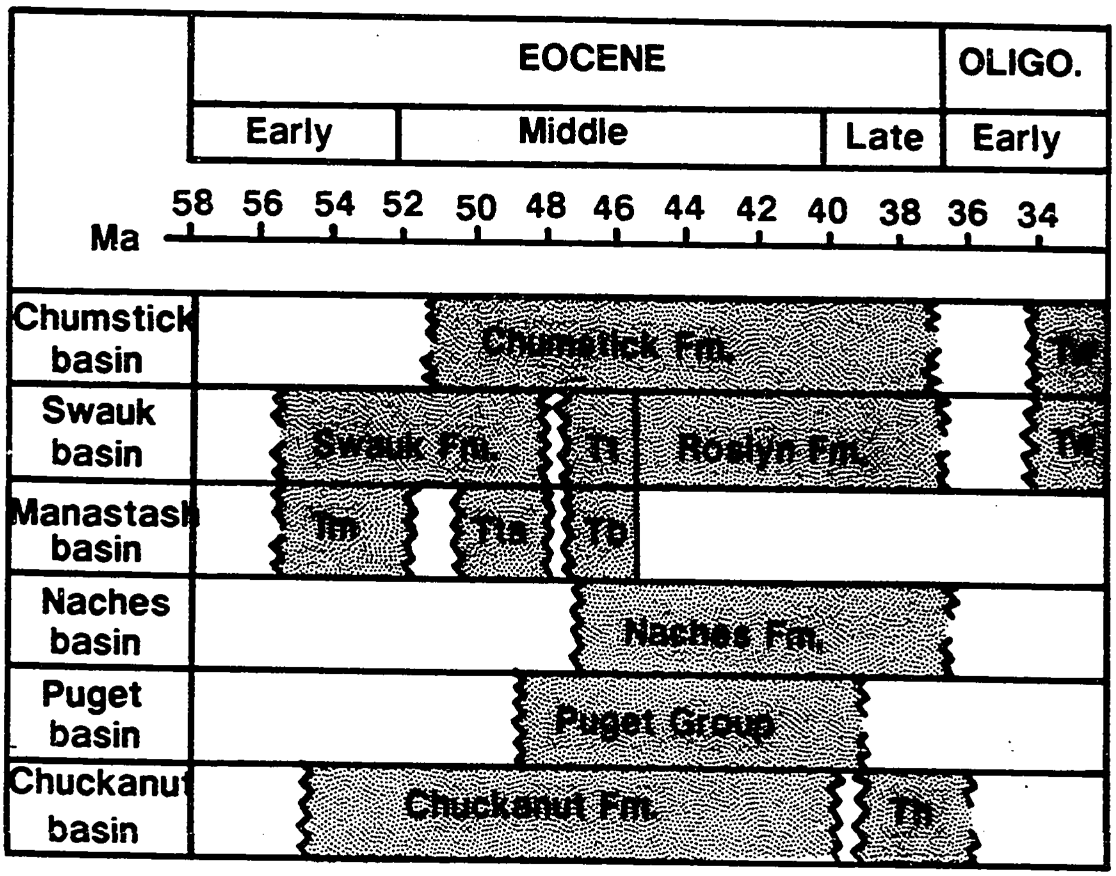

EOCENE
OLIGO.
Early
Middle
Late
Early
Ma
58 56 54 52 50 48 46 44 42 40 38 36 34
Chumstick basin
Chumstick Fm.
Tw
Swauk basin
Swauk Fm.
Tt
Roslyn Fm.
Tw
Manastash basin
Tm
Tta
Tb
Naches basin
Naches Fm.
Puget basin
Puget Group
Chuckanut basin
Chuckanut Fm.
Th

Figure 2.3--Basin evolution of the Chumstick Formation. A: map showing the distribution of interstratified tuffs in the Chumstick Formation. B: Phase 1 of Chumstick deposition, restricted to the region west of the Eagle Creek fault zone. C: Phase 2 of Chumstick deposition, showing the development of sediment source regions in the Leavenworth fault zone and opening of the eastern sub-basin. D: Phase 3 of Chumstick deposition, showing no evidence for tectonic control of facies. In B, C, and D individual circles represent average maximum clast size measurements; small arrows represent vector means of paleocurrent distributions; and the large rose diagram summarizes all paleocurrent data from one of the shaded regions (details in Evans, chapter 4).

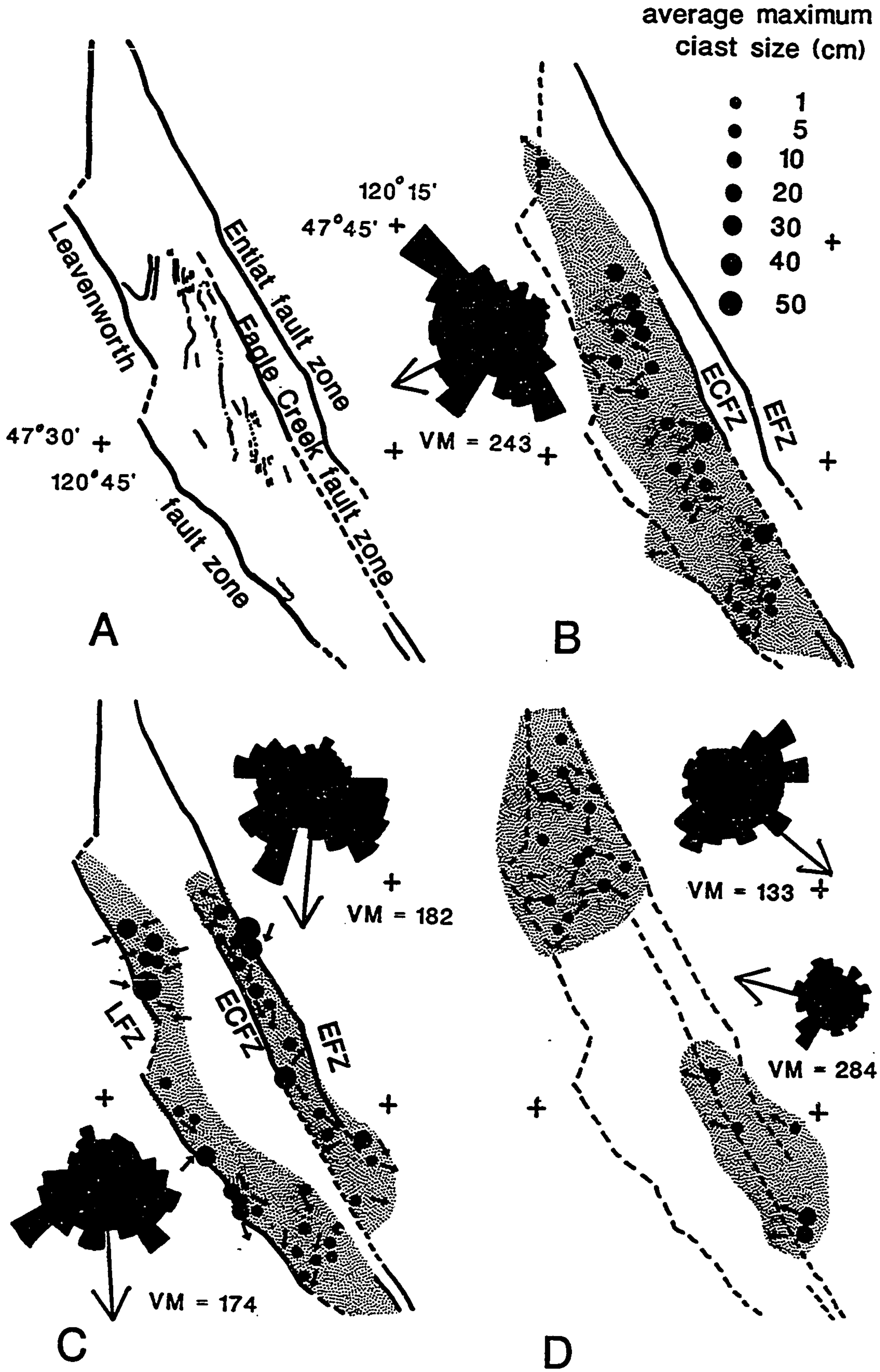

average maximum
ciast size (cm)
1
5
10
20
30
40
50
120°15'
47°45'
Leavenworth
fault zone
Entiat fault zone
Eagle Creek fault zone
47°30'
120°45'
VM = 243
ECFZ
EFZ
A
B
VM = 182
LFZ
ECFZ
EFZ
VM = 174
VM = 133
VM = 284
C
D

Figure 2.4--Location map showing major regional faults, towns, and the locations of stratigraphic sections referred to in the text. Abbreviations used: c - Camasland, ca - Cashmere, cc - Cole's Corner, cl - Clark Canyon, cm - Camas Creek, d - Derby Canyon, dc - Deadhorse Canyon, ec - Eagle Creek, f - Fish Lake, ic - Ingall's Creek, ma - Malaga, mo - Monitor, n - Number Two Canyon, nc - Nahahum Canyon, np - North Plain, pr - Pole Ridge, rh - Red Hill, s - Sunitsch Canyon, sp - South Plain, tm - Tumwater Mountain, v - Van Canyon, and w - Wright Canyon.

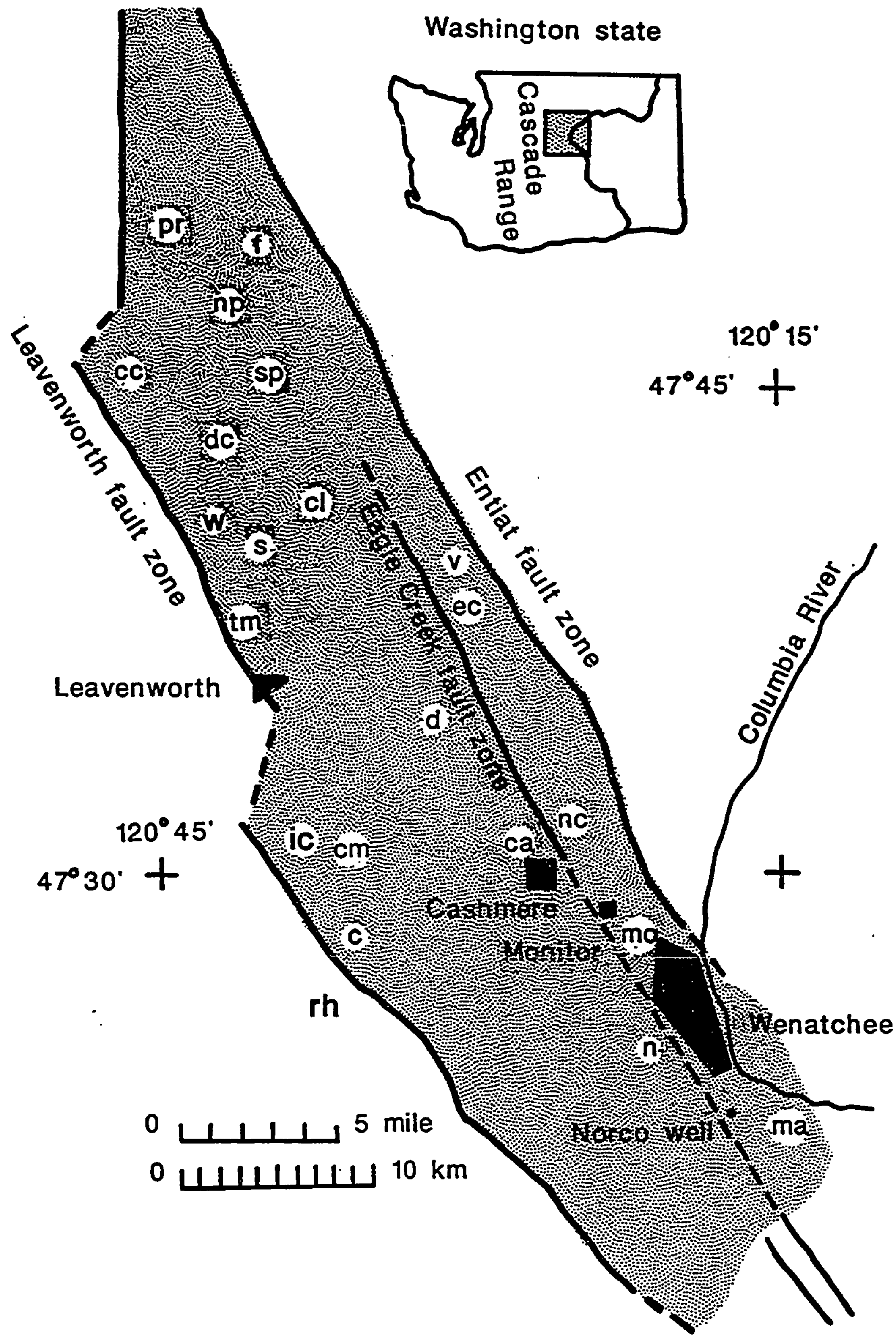

Washington state
Cascade Range
120° 15'
47°45'
Leavenworth fault zone
Entiat fault zone
Eagle Creek fault zone
Columbia River
Leavenworth
120° 45'
47°30'
Cashmere
Monitor
Wenatchee
Norco well
pr
f
np
cc
sp
dc
cl
w
s
v
ec
tm
d
nc
ic
cm
ca
c
mo
rh
n
ma
0 5 mile
0 10 km

Figure 2.5--Photographs of gravel bedload stream deposits. Top: basal mudstone rip-up clasts (lithofacies Se), rule is 15 cm in length. Bottom: shallow scours at the base of horizontally stratified conglomerate (lithofacies Gm), rule is 15 cm in length.

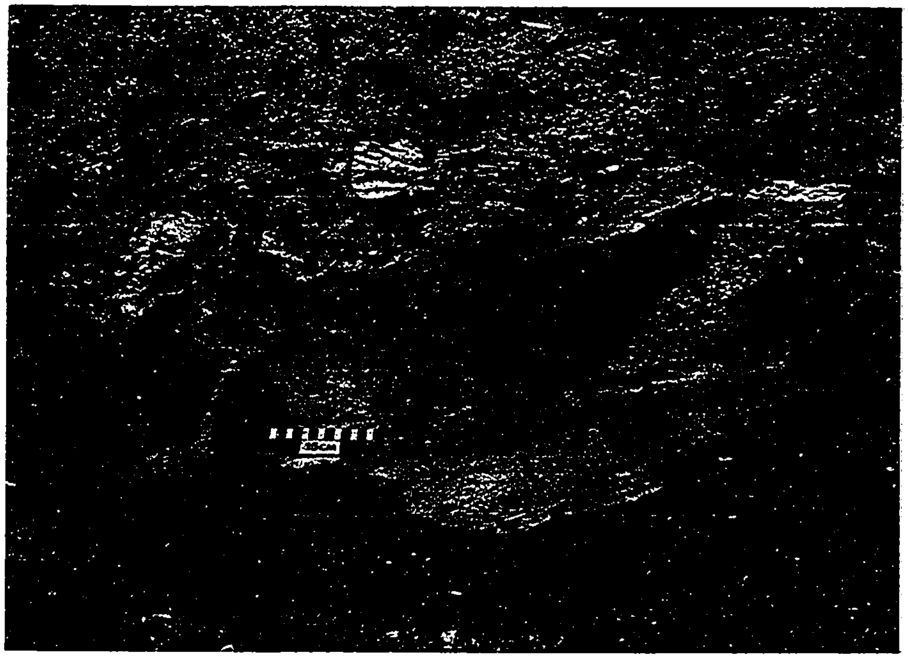
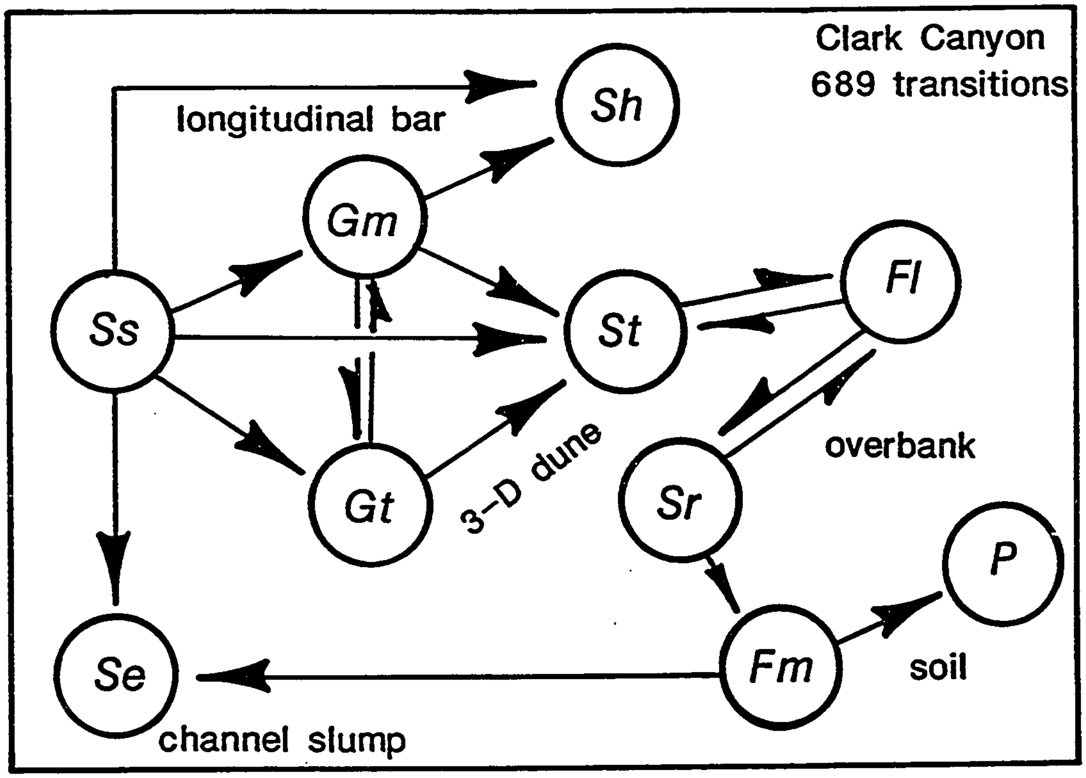


Figure 2.5 (con't.)-- Top: bar platform deposits, horizontally stratified sandstone (lithofacies Sh), hammer is 30 cm in length. Bottom: bar platform deposits, low angle (<10^0) cross-laminated sandstone (lithofacies Sl) and shale (Lithofacies Fl), rule is 15 cm in length.

Figure 2.6--Markov Chain analyses from gravel bedload stream deposits. Top: Clark Canyon section (689 lithofacies transitions). Bottom: Camasland section (505 lithofacies transitions). Lithofacies code from Table 2.1.



Camasland
505 transitions

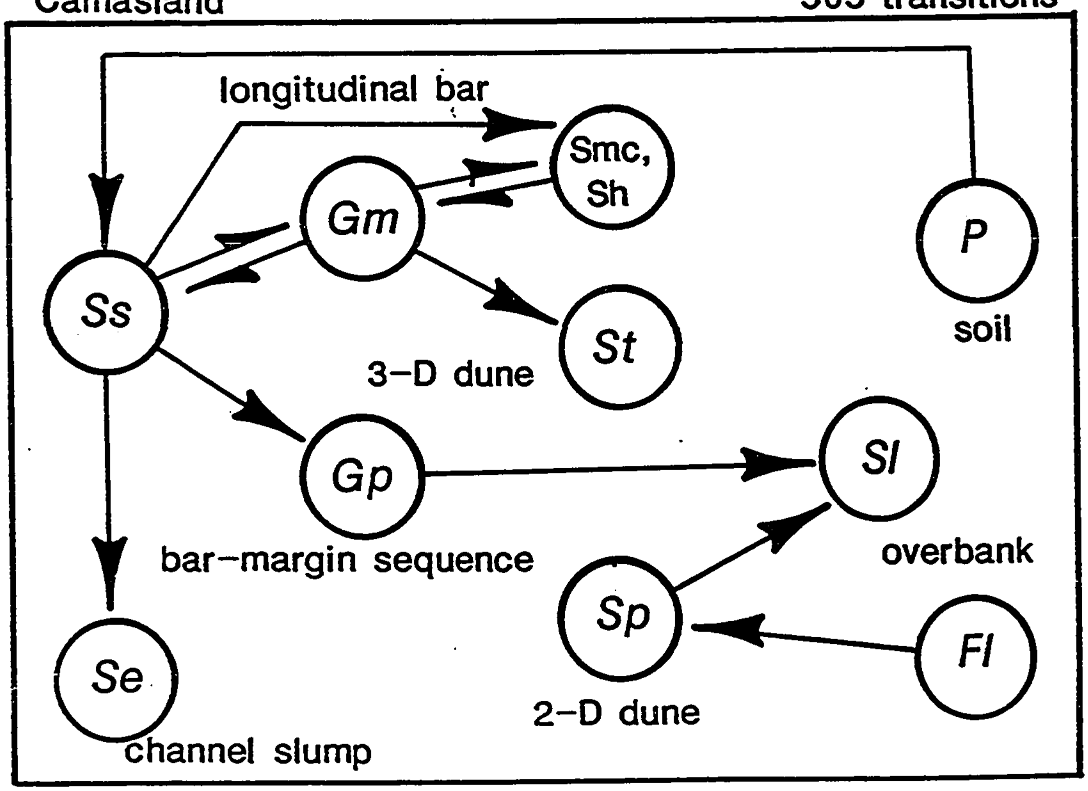
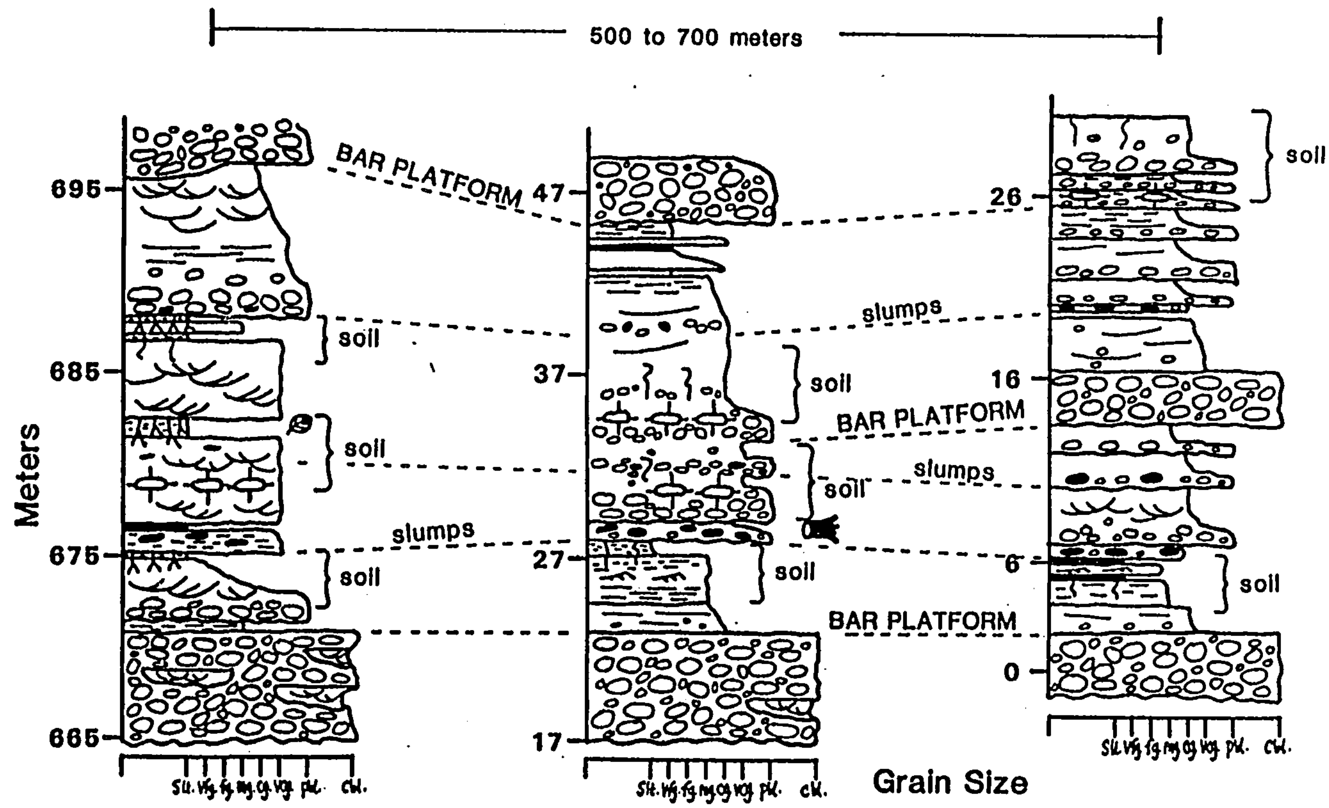


Figure 2.7--Lateral relationships of depositional units in gravel-bedload stream deposits, Clark Canyon section (see Figure 2.4 for location). Gravel longitudinal-bar and bar-platform deposits have a sheet-like geometry, while intervening channels have a broadly lenticular geometry. Soil horizons and intraclast layers can be traced laterally.

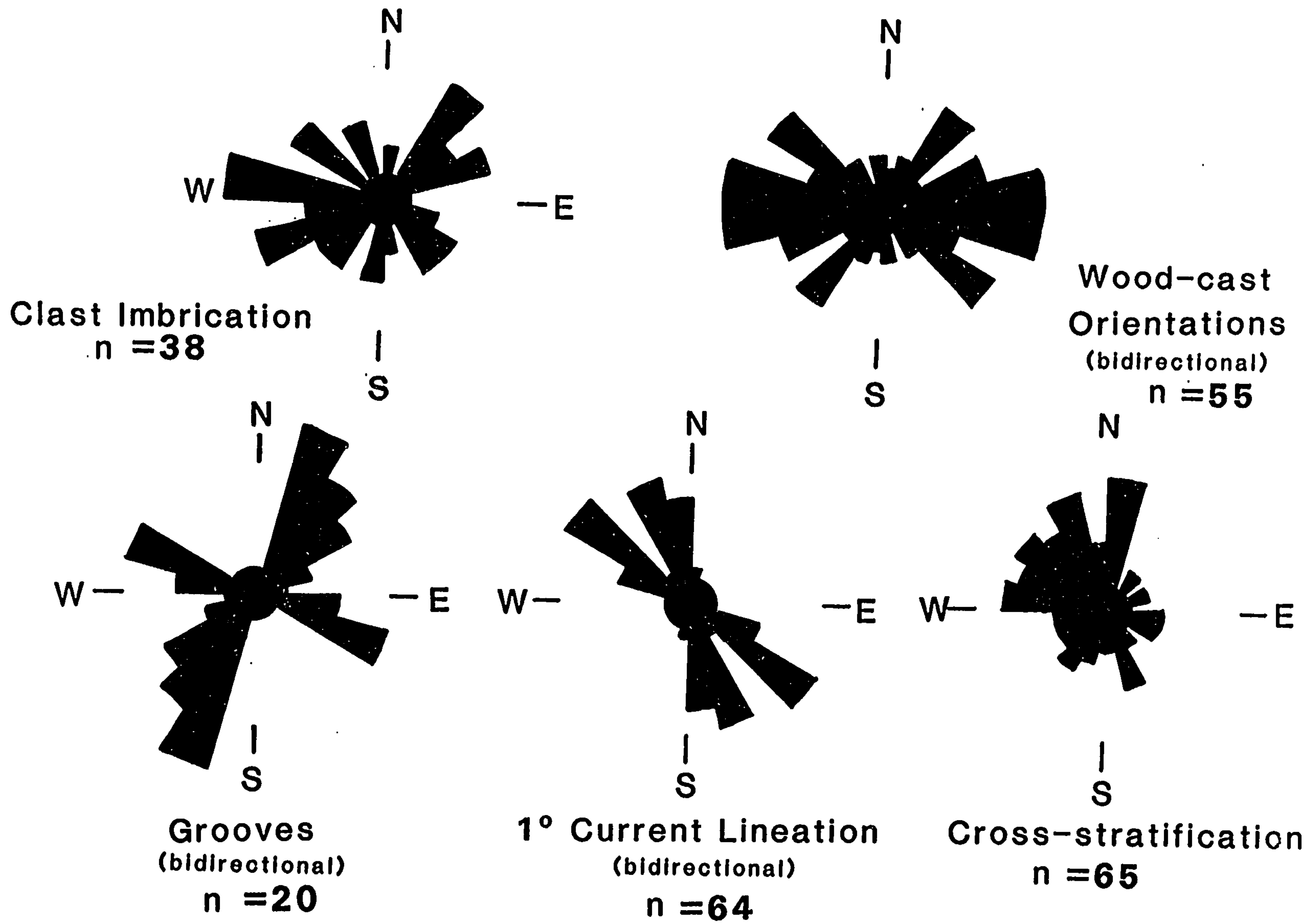
Key to symbols:

- exoclasts
- intraclasts
- planar bedding
- planar lamination
- trough x-bedding
- planar x-bedding
- ripple x-lamination
- convoluted bedding
- climbing ripple x-lamination
- plant macrofossils
- rootlets
- stumps and logs
- infaunal bioturbation
- bedding surface bioturbation
- clastic dike
- concretion horizon
- coarsening-upward sequence



500 to 700 meters
Meters
695
685
675
665
47
37
27
17
26
16
6
0
BAR PLATFORM
soil
slumps
Grain Size

Figure 2.8--Rose diagrams for paleocurrent indicators in gravel-bedload stream deposits from the Clark Canyon section. Paleocurrent measurement type and numbers of measurements as indicated.

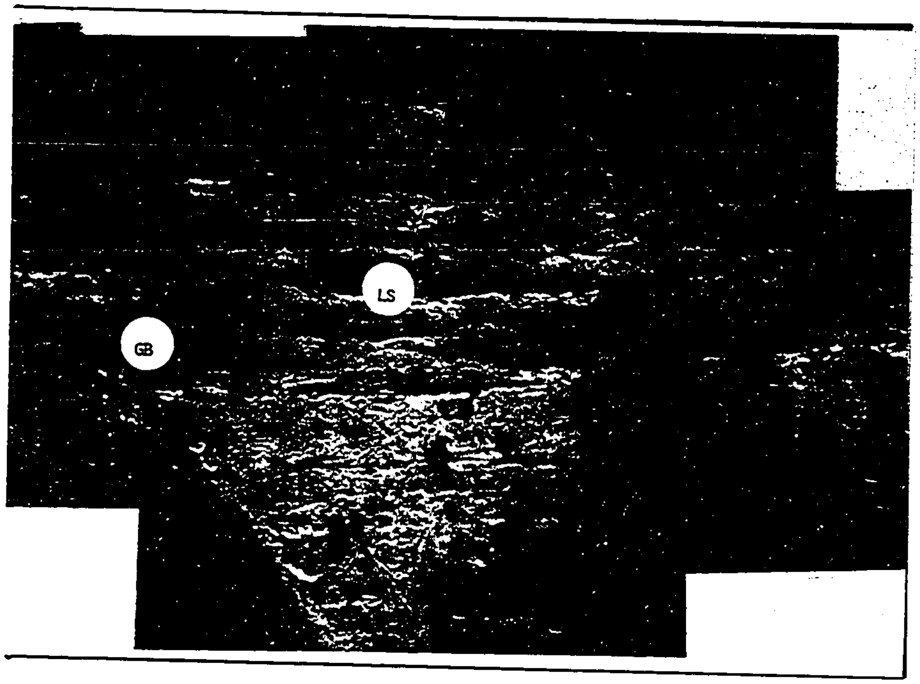


N
W
E
S
Clast Imbrication
n =38
N
S
Wood-cast
Orientations
(bidirectional)
n =55
N
W
E
S
Grooves
(bidirectional)
n =20
N
W
E
S
1° Current Lineation
(bidirectional)
n =64
N
W
E
S
Cross-stratification
n =65

Figure 2.9--Photographs of volcaniclastic debris flows in the Chumstick Formation. Top: debris flow 1.5 meters thick containing exoclasts, pumice, leaves, and branches. Hammer (30 cm) for scale. Bottom: detail of base of debris flow showing nonerosive basal contact.


in.
cm.

Figure 2.10--Photomosaic and interpretive drawing of fan-head channels in gravel-bedload stream facies, Tumwater Mountain section (see Fig. 2.4 for location). Paleoflow is directed into the outcrop. Note the lateral stacking of broadly lenticular channel forms (one outlined by arrows).


LS
GB

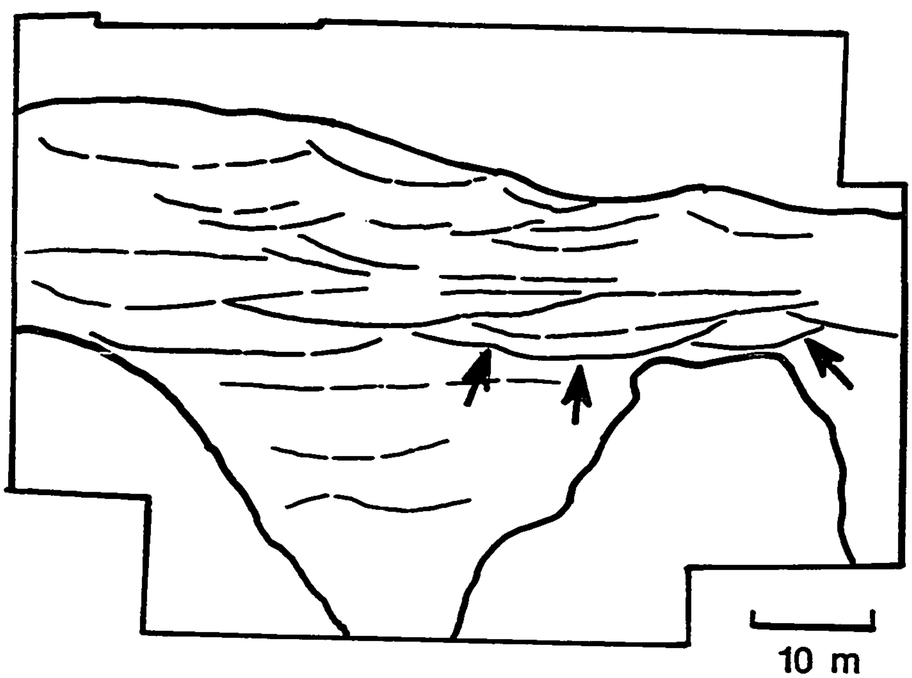
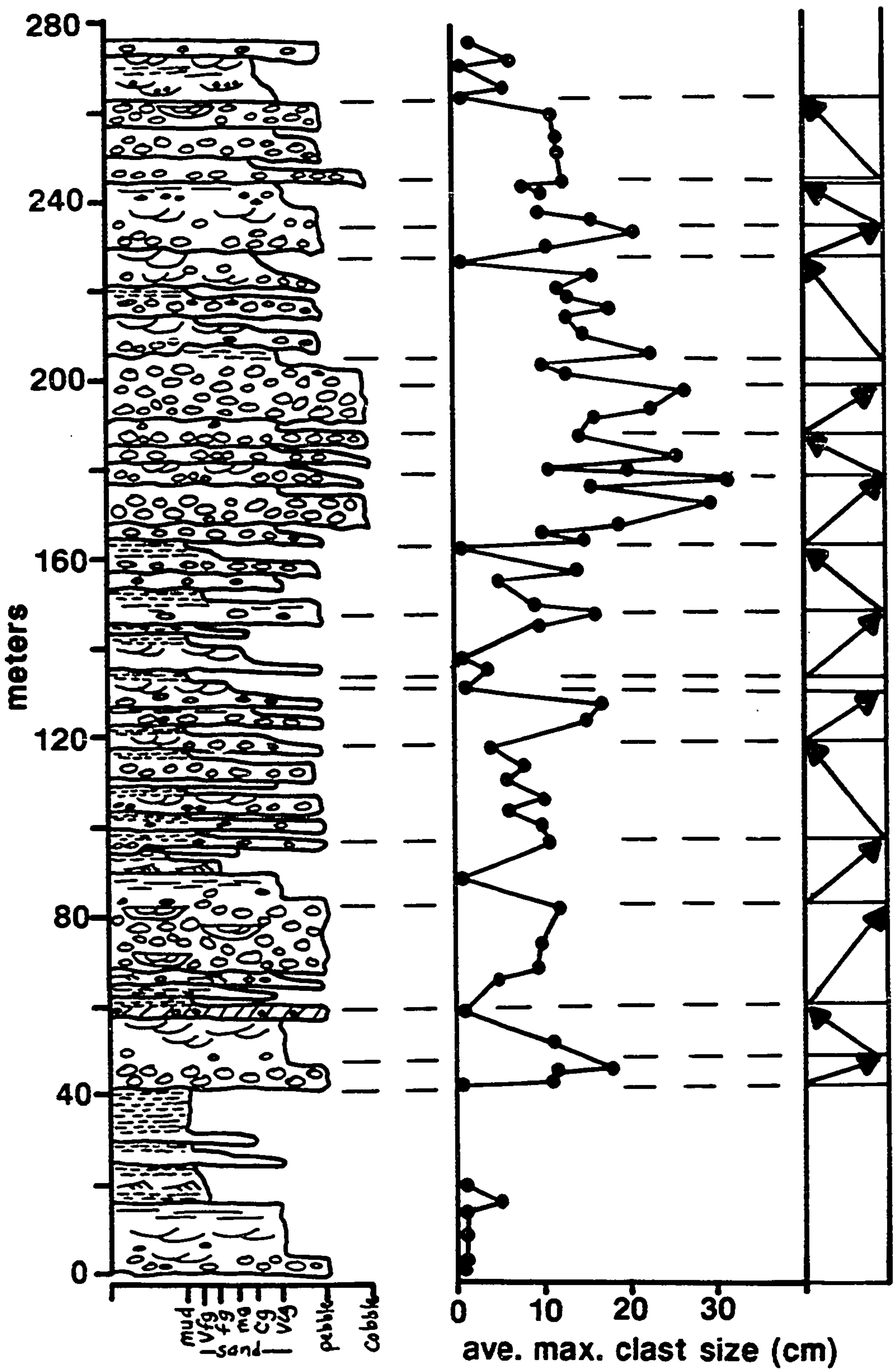
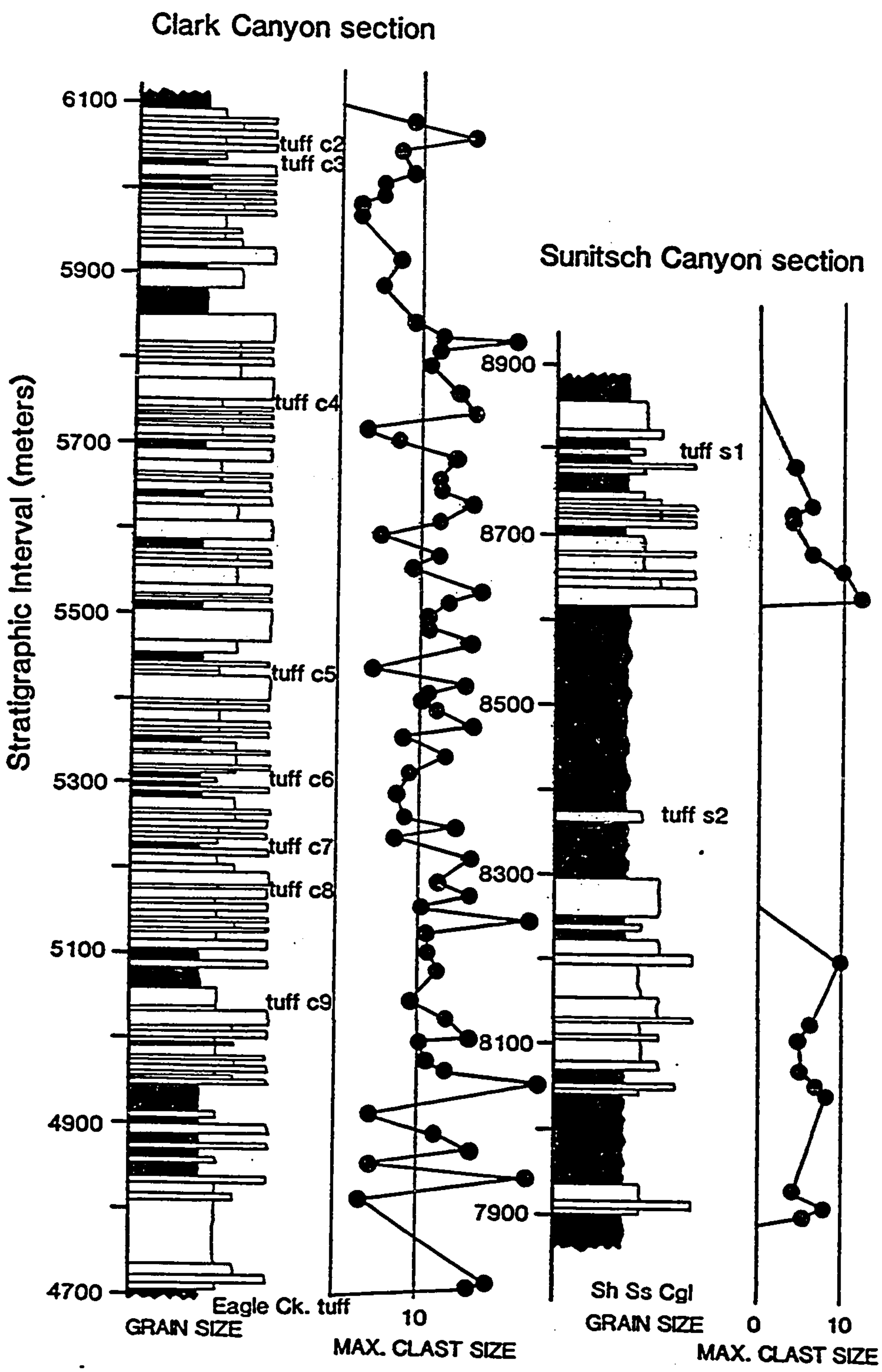

10 m

Figure 2.11--Stratigraphic section of gravel bedload stream deposits, Camasland section, showing coarsening-upward or fining-upward megasequences 10 to 40 meters in thickness (middle column indicates average maximum clast size, and right column summarizes fining-upward or coarsening-upward trend). Refer to Fig. 2.4 for the location of this section. Symbols are the same as in Fig. 2.7.



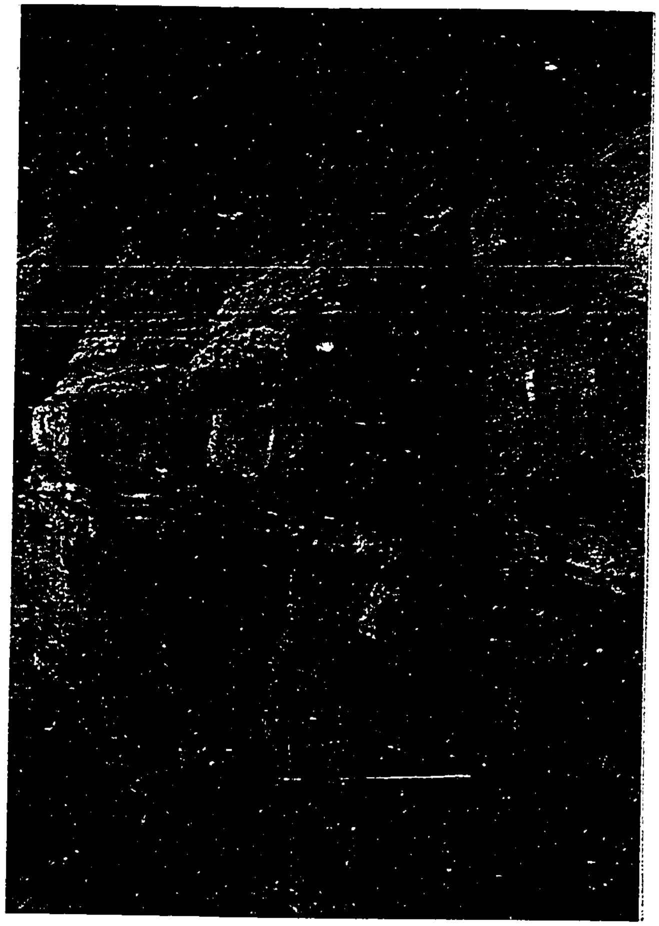
280
240
200
160
120
80
40
0
meters
mud
vfg
fg
mg
cg
vcg
sand
pebble
cobble
0
10
20
30
ave. max. clast size (cm)

Figure 2.12--Stratigraphic sections of distal gravel-bedload stream deposits, Clark Canyon section, and sand-bedload stream deposits, Sunitsch Canyon section. See Fig. 2.4 for location of sections. Symbols symplified to show thickness and texture only. Maximum clast size is the average of the largest diameter of the 10 largest clasts per bed. See text for discussion.



Clark Canyon section
Sunitsch Canyon section
Stratigraphic Interval (meters)
6100
5900
5700
5500
5300
5100
4900
4700
tuff c2
tuff c3
tuff c4
tuff c5
tuff c6
tuff c7
tuff c8
tuff c9
Eagle Ck. tuff
GRAIN SIZE
10
MAX. CLAST SIZE
8900
8700
8500
8300
8100
7900
tuff s1
tuff s2
Sh Ss Cgl
GRAIN SIZE
0
10
MAX. CLAST SIZE

Figure 2.13--Photographs of proximal overbank deposits in sand-bedload stream deposits. Top: coarsening- and thickening-upward sequence from lithofacies Fm through Fl and Sr, followed by abrupt change back to Fm (refer to Table 2.1 for lithofacies code). This sequence is interpreted to result from lateral migration of a channel toward this location, which caused deposition of successively thicker and coarser-grained flood deposits, followed by probable channel abandonment (hammer is 30 cm in length). Bottom: photograph of sand stringers in a mudstone matrix, interpreted as proximal overbank deposits (Scale is 15 cm in length).



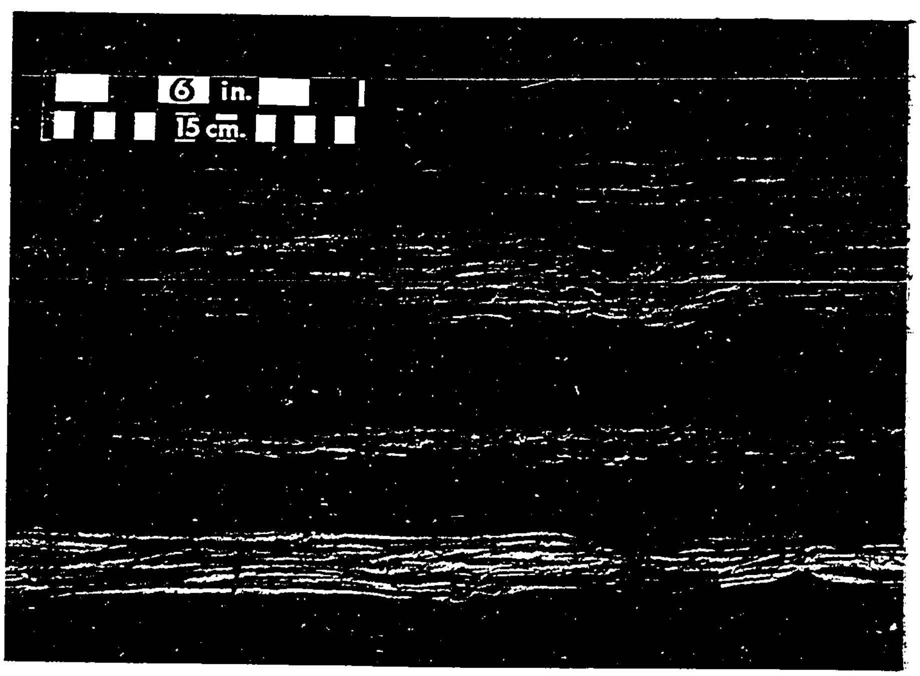
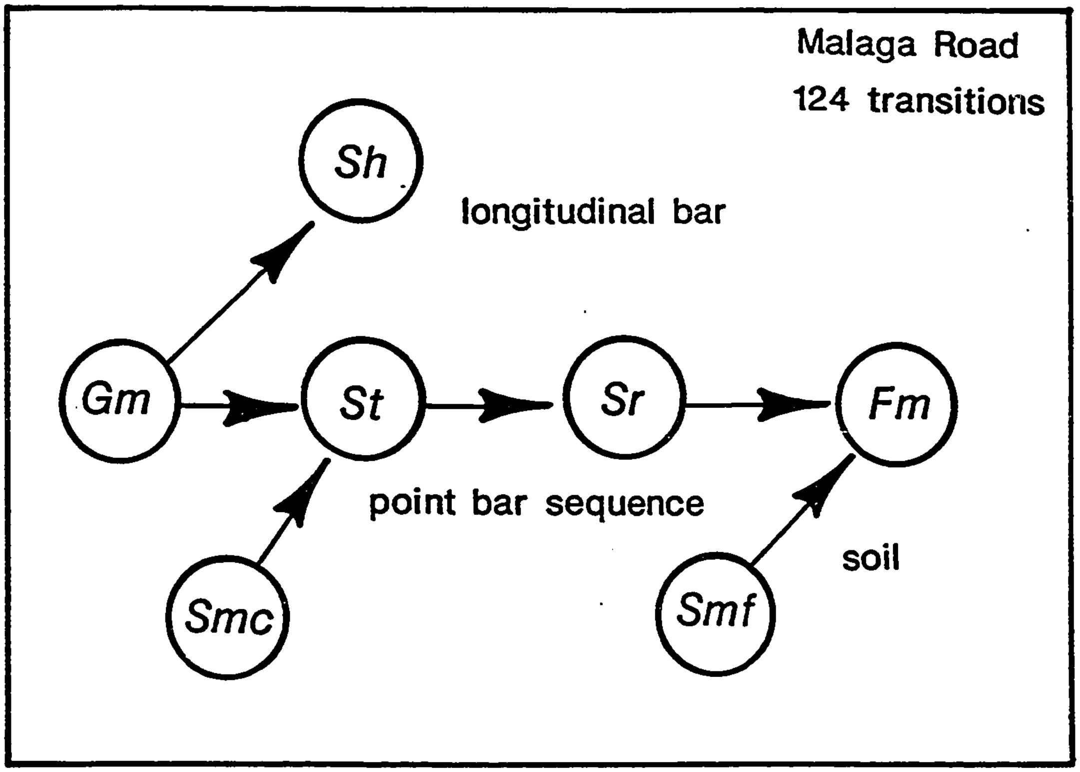

6 in.
15 cm.

Figure 2.14--Markov Chain analyses of sand-bedload stream deposits. Top: Malaga Road section (124 lithofacies transitions). Bottom: South Plain section (224 lithofacies transitions). See Table 2.1 for explanation of lithofacies codes. Locations of sections given in Fig. 2.4.


Malaga Road
124 transitions
Sh
longitudinal bar
Gm
St
Sr
Fm
point bar sequence
Smc
Smf
soil

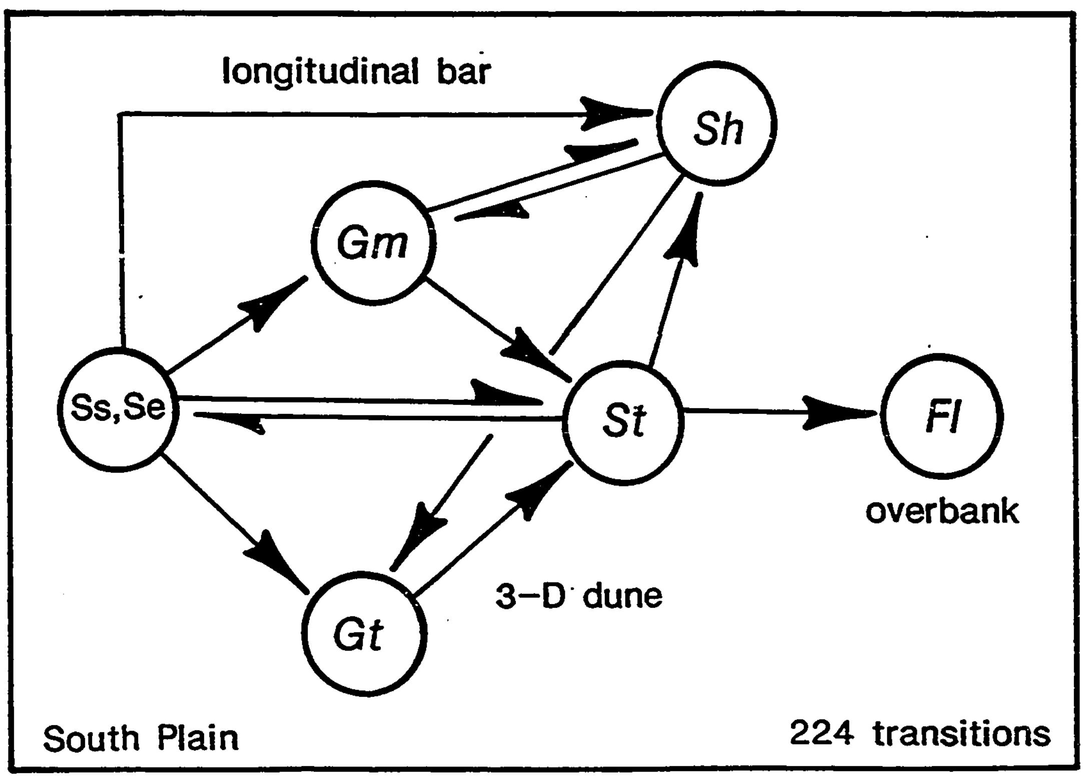
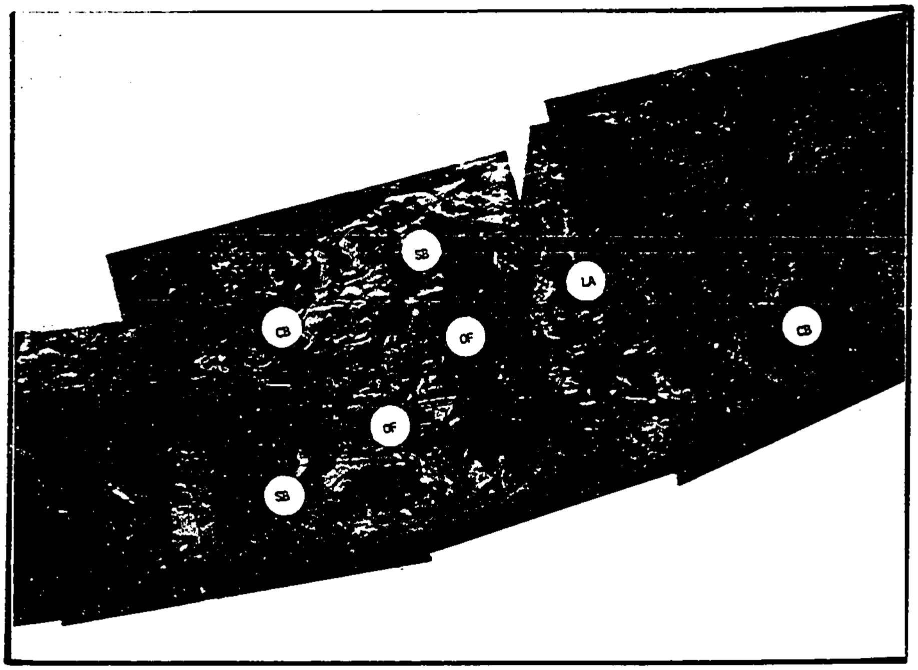

longitudinal bar
Sh
Gm
Ss,Se
St
Fl
overbank
3-D dune
Gt
South Plain
224 transitions

Figure 2.15--Photomosaic of sand-bedload stream facies with interpretative sketch at the Malaga Road section (see Fig. 2.4 for location). As this system vertically aggraded, a set of lateral-accretion sets (LA) with about 2 meters relief indicate migration of one channel to the left, forming a series of cutbanks (CB) into older overbank deposits (OF). A second channel migrates from left to right, and the two channels appear to join near the top. Paleoflow is into the outcrop, and the maximum channel width is about 35 meters. The apparent steepness of the road is a distortion.


SB
LA
CB
OF
CB
OF
SB

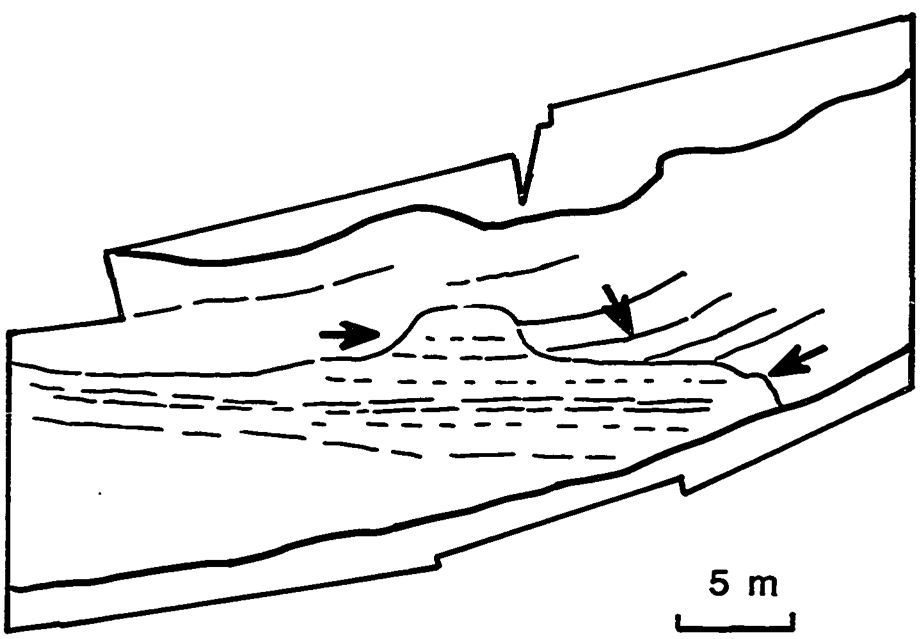
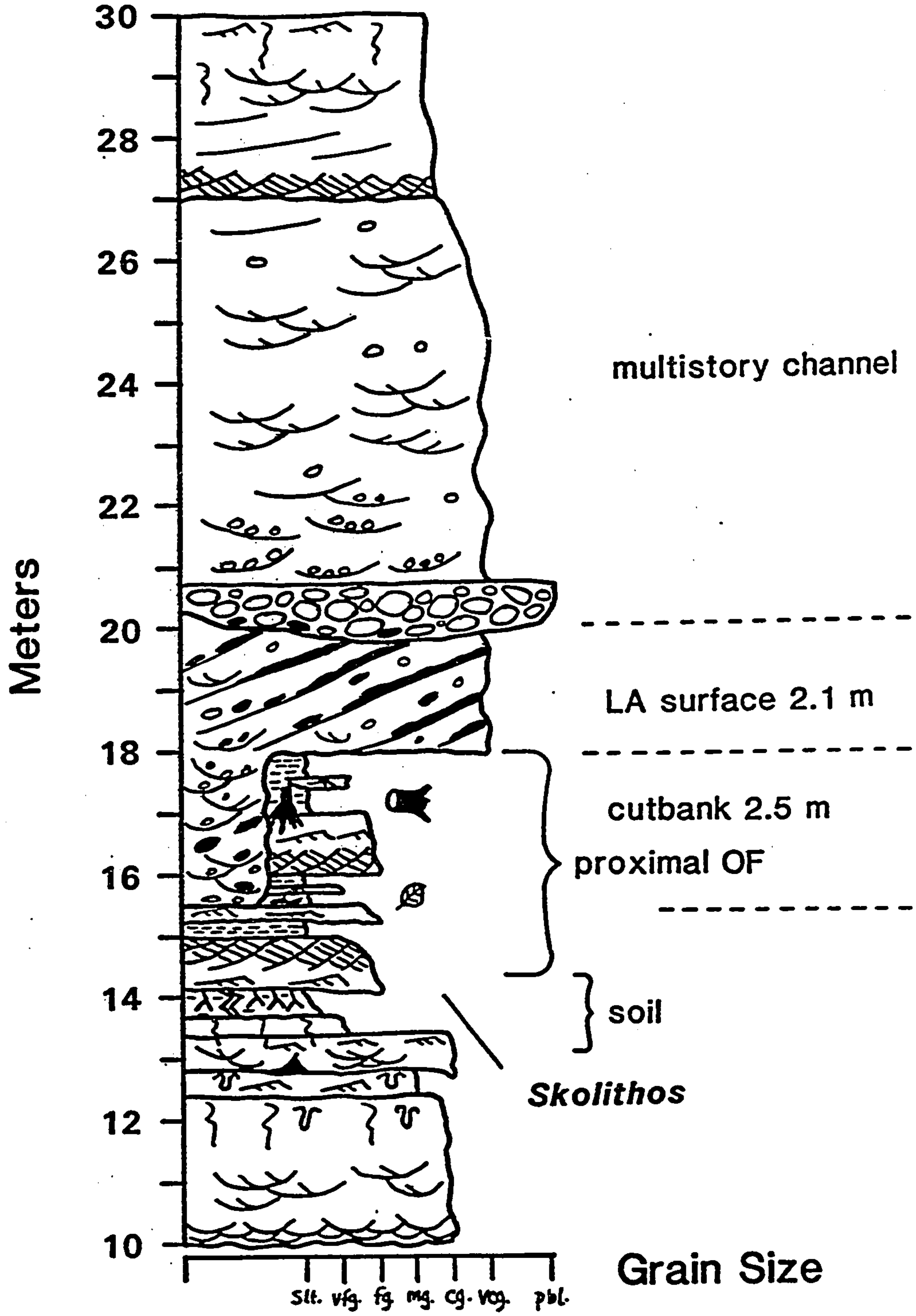
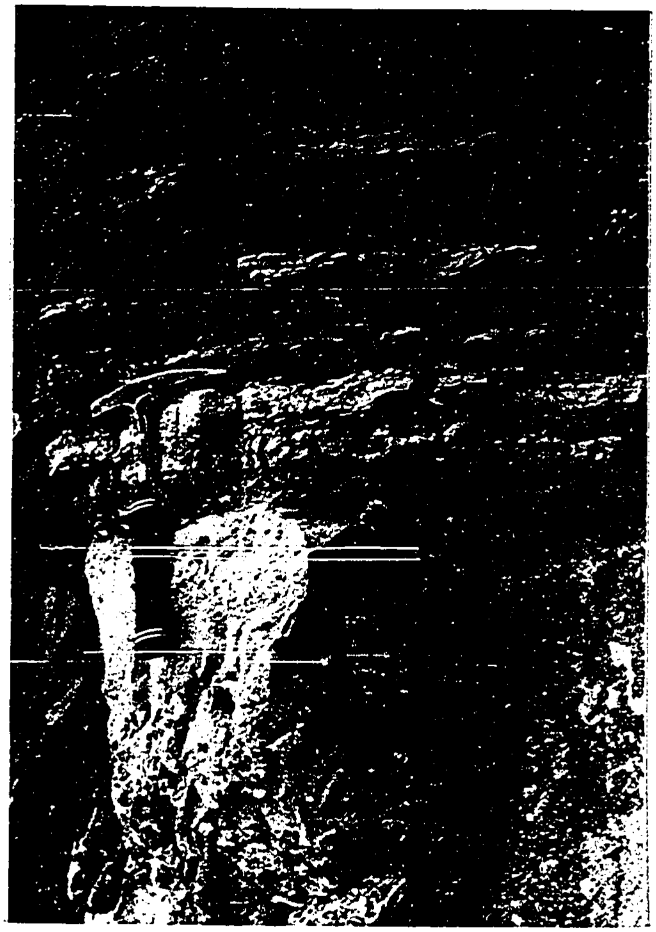

5 m

Figure 2.16--Stratigraphic section of the exposure shown in Figure 2.15, taken along the right side of the outcrop. Symbols are the same as in Fig. 2.7, LA = lateral-accretion surface, OF = overbank fines.



30
28
26
24
22
20
18
16
14
12
10
Meters
multistory channel
LA surface 2.1 m
cutbank 2.5 m
proximal OF
soil
Skolithos
Grain Size
slt. vfg. fg. mg. cg. vcg. pbl.

Figure 2.17--Photographs of sand-bedload stream deposits. Top: abrupt grain size change at the top of a channel sequence. These features are interpreted as the result of channel abandonment and infilling by suspension load deposits. See discussion in text. Bottom: mud-draped trough cross-bedding, interpreted as a chute channel sequence that had episodes of abandonment and re-activation. Hammer for scale (30 cm). Lithofacies codes are defined in Table 2.1.



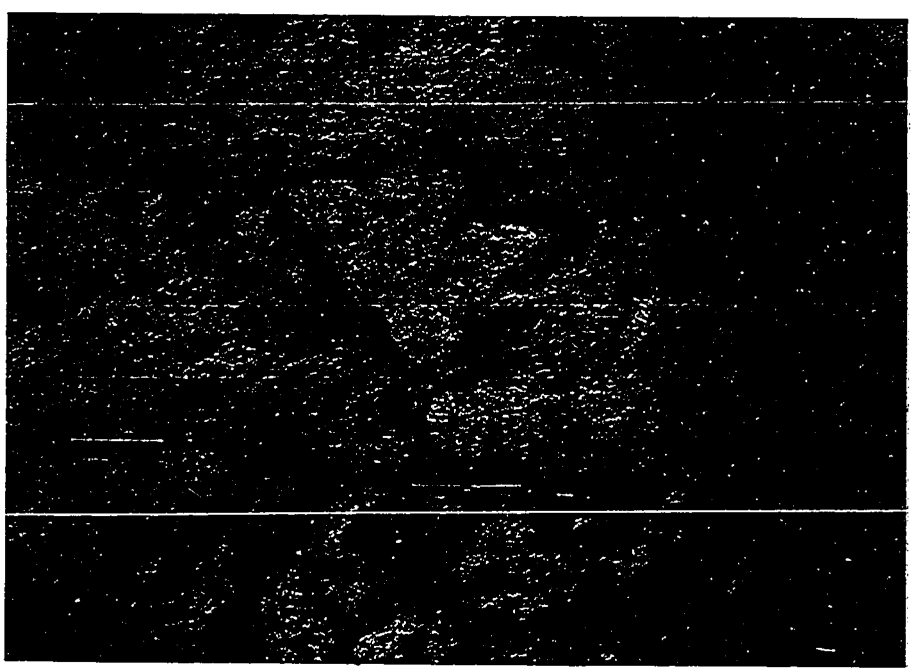
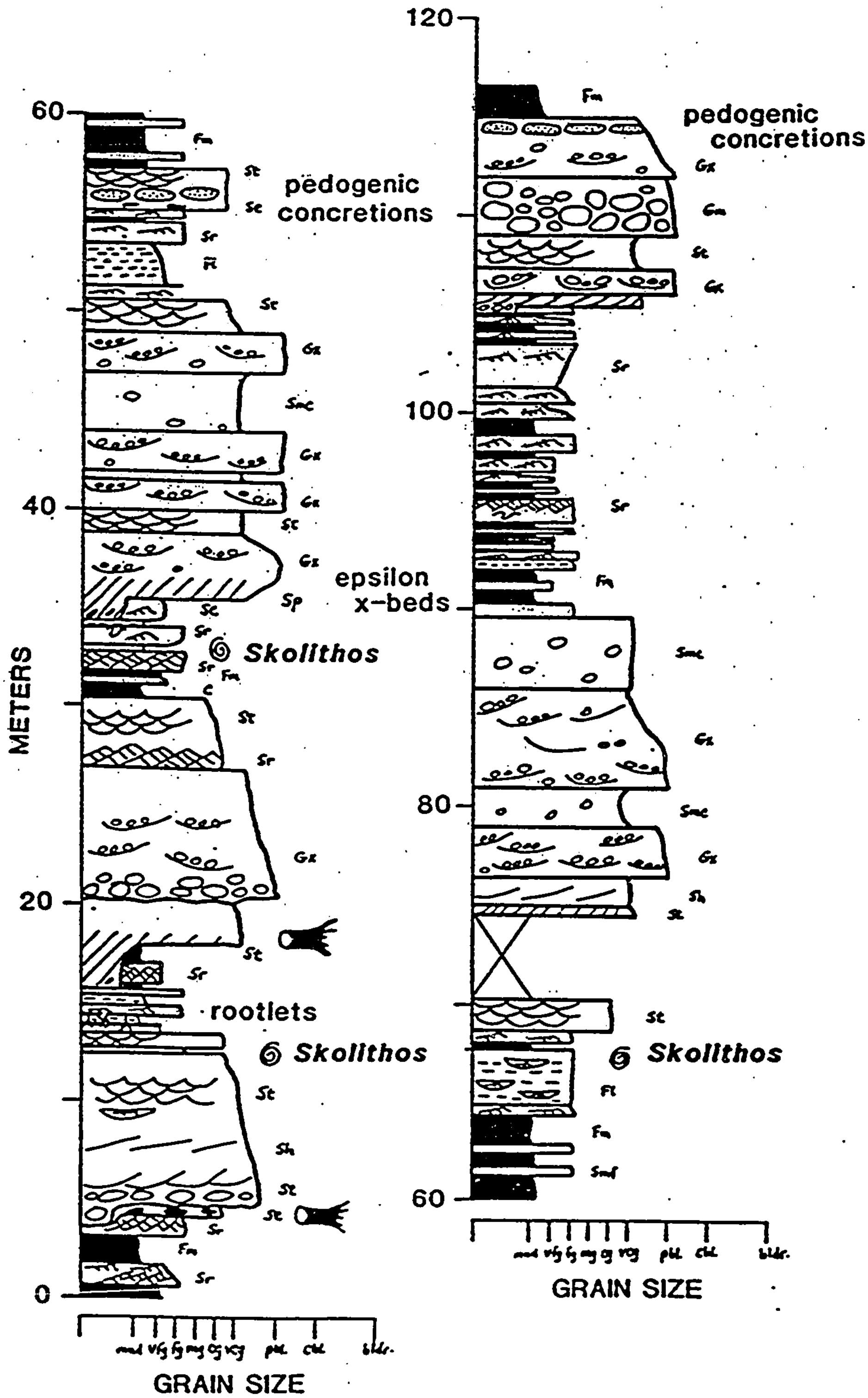
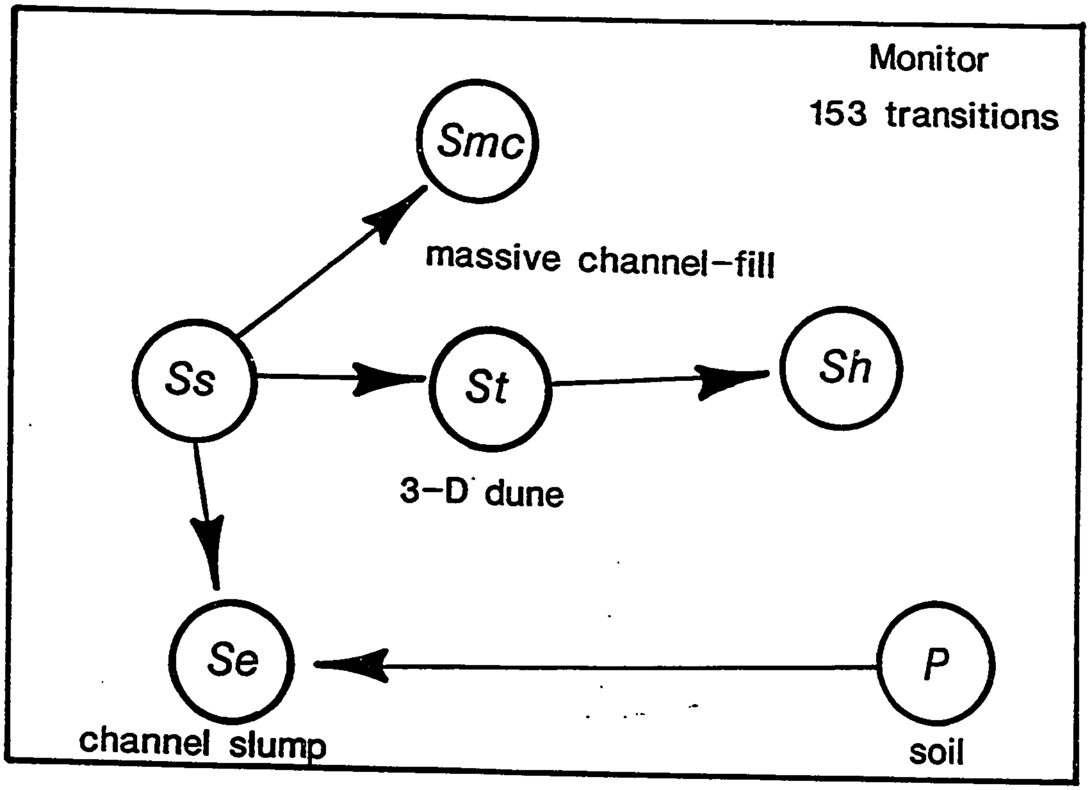


Figure 2.18--Stratigraphic section of sand-bedload stream deposits showing vertical stacking of multistory channels and associated, sandy, proximal overbank sequences. Section is from Malaga Road location (see Figure 2.4). Symbols are the same as Fig. 2.7.



120
100
80
60
40
20
0
METERS
pedogenic concretions
epsilon x-beds
Skolithos
rootlets
Skolithos
Skolithos
pedogenic concretions
GRAIN SIZE
GRAIN SIZE

Figure 2.19--Markov Chain analyses of mixed-load stream deposits. Top: Monitor section (153 lithofacies transitions). Bottom: Deadhorse Canyon section (434 lithofacies transitions). Lithofacies code from Table 2.1. See text for details.



Deadhorse Canyon 434 transitions

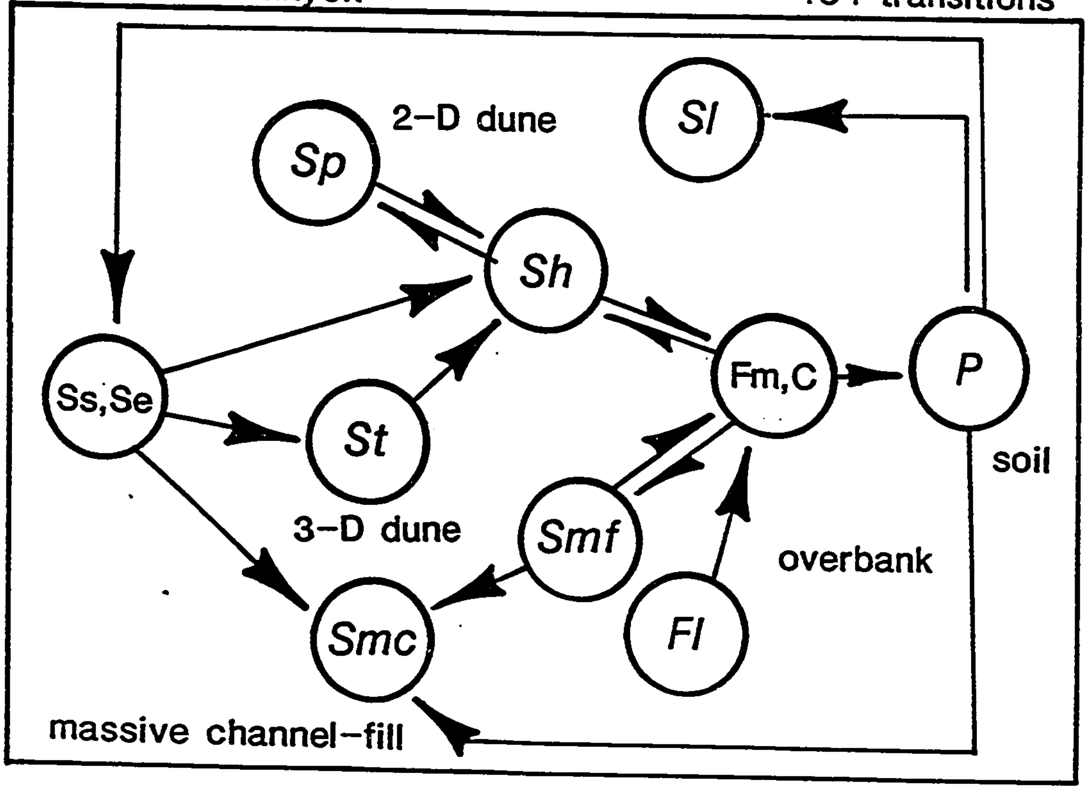


Figure 2.20--Stratigraphic section of mixed-load stream deposits, North Plain section (see Figure 2.4 for location). This section is interpreted as showing meter-scale, lenticular channels from a flood-basin setting. Symbols are the same as Figure 2.7.

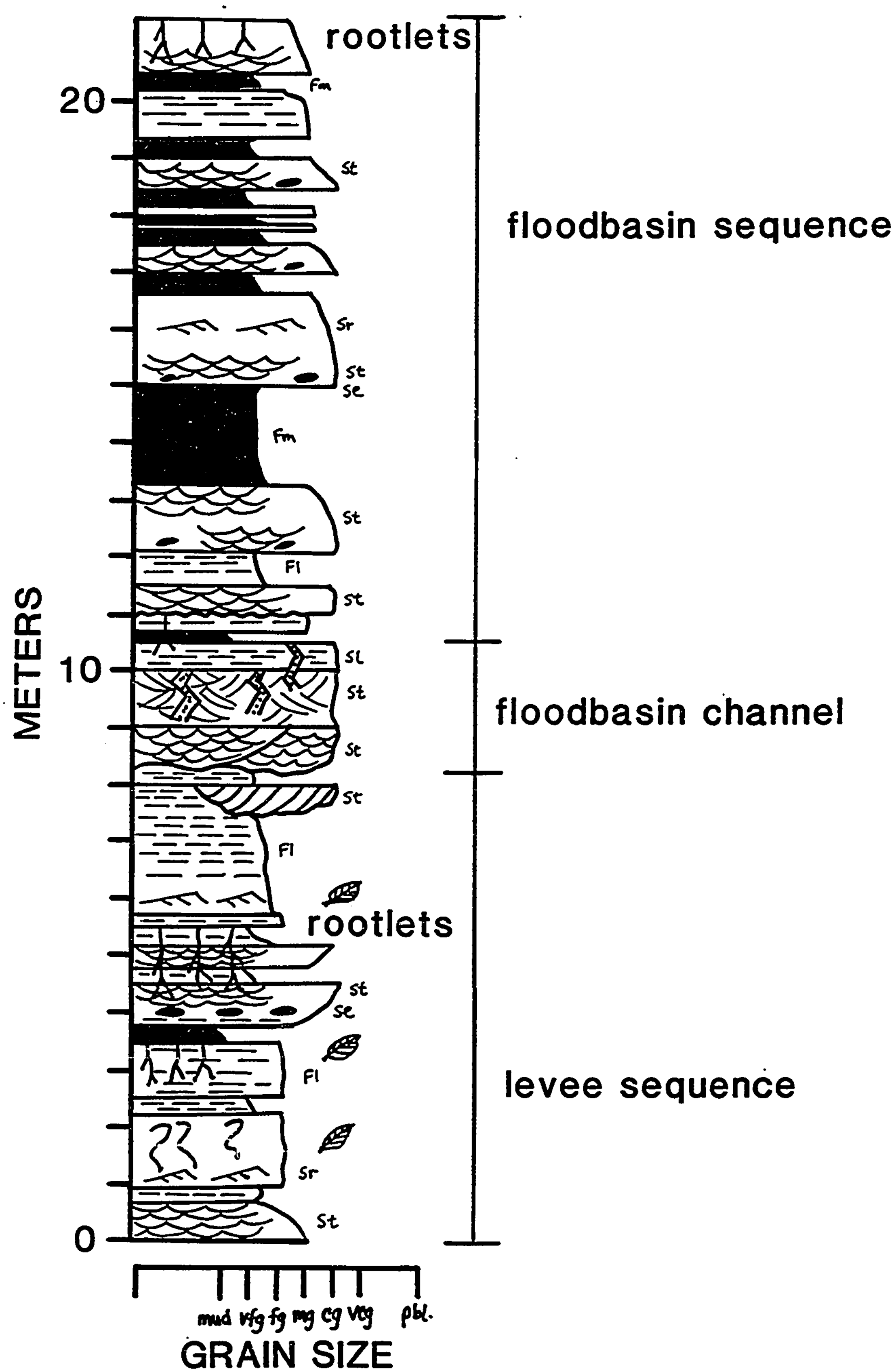
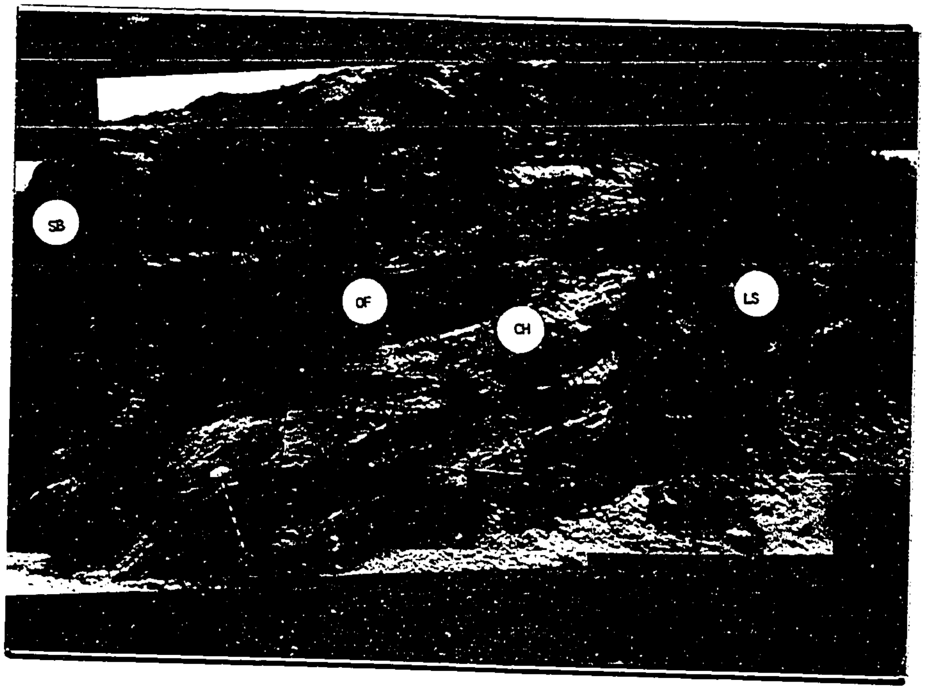

rootlets
Fm
20
St
floodbasin sequence
Sr
St
Se
Fm
St
Fl
St
10
METERS
SL
St
floodbasin channel
St
St
Fl
rootlets
St
Se
Fl
levee sequence
Sr
St
0
mud vfg fg mg cg vcg pbl.
GRAIN SIZE

Figure 2.21--Photomosaic and interpretative sketch of mixed-load stream deposits, Monitor section (see Figure 2.4 for location). Channel in center was cut, abandoned and filled by suspension deposits, re-activated, and filled by dunes, see text for discussion. Scale is 1.5 meter jacob staff. Symbols are the same as Figure 2.7, SB = sandy bedforms, OF = overbank fines, LS = laminated sand sheets, CH = channel. Arrows outline bottom of channel.


SB
OF
CH
LS

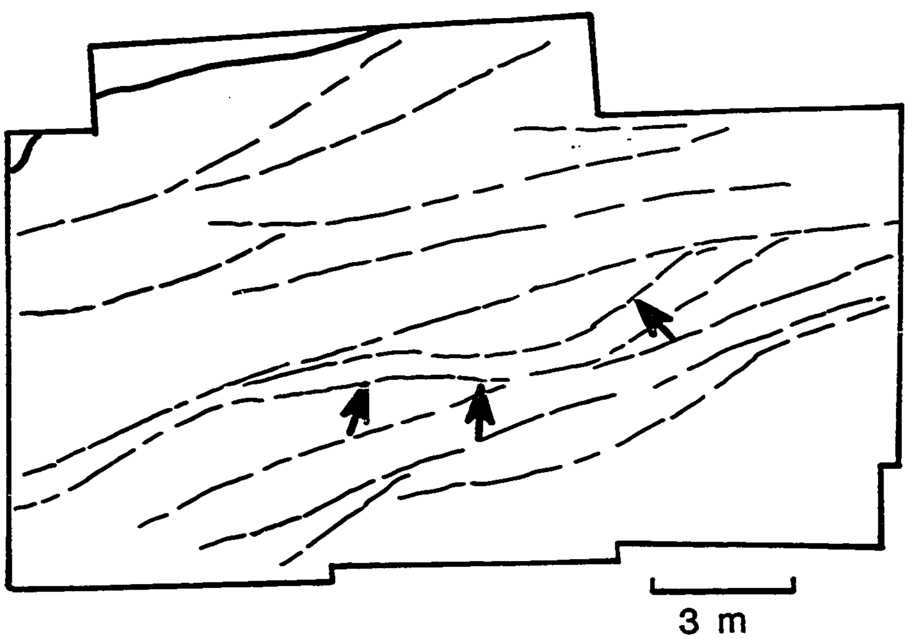
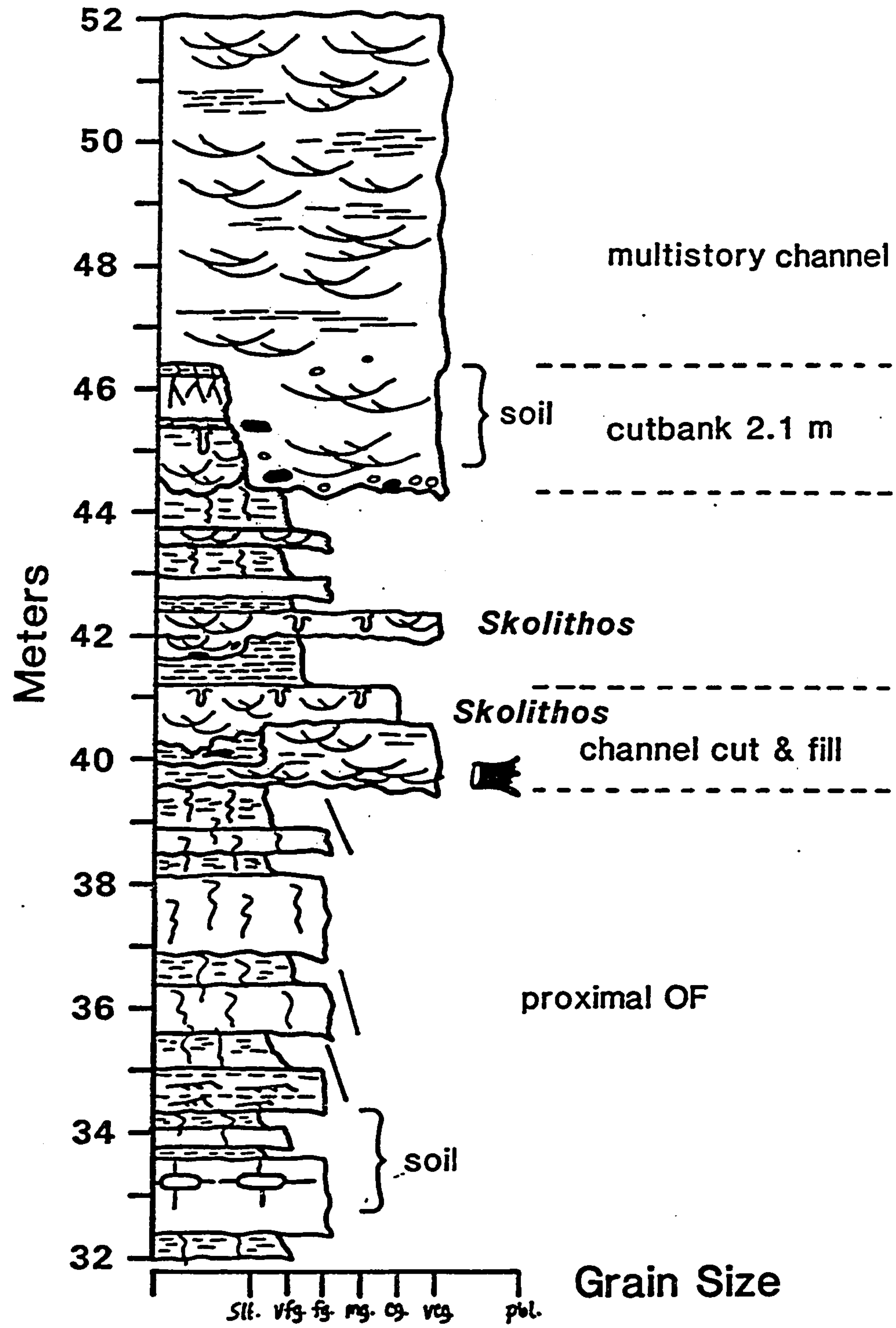
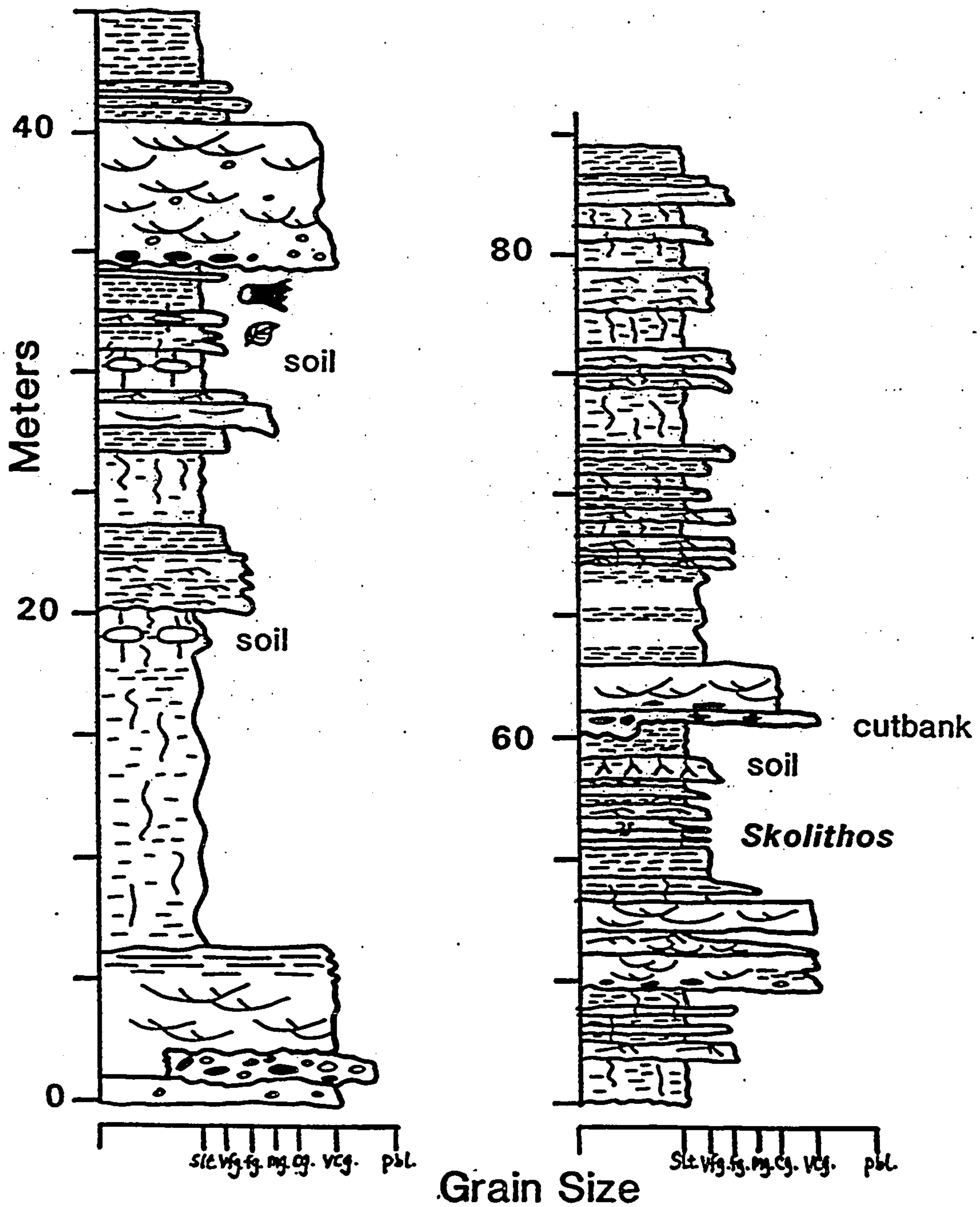

3 m

Figure 2.22--Stratigraphic section of highly bioturbated, mixed-load stream deposits, Monitor section, as shown in Figure 2.21. The Monitor section is interpreted to represent part of a lacustrine-deltaic distributary system in the eastern sub-basin. Location given in Fig. 2.4, symbols are the same as shown in Fig. 2.7.



52
50
48
46
44
42
40
38
36
34
32
Meters
multistory channel
soil
cutbank 2.1 m
Skolithos
Skolithos
channel cut & fill
proximal OF
soil
Grain Size
Slt.
vfg.
fg.
mg.
cg.
vcg.
pbl.

Figure 2.23--Stratigraphic section of mixed-load stream deposits, Pole Ridge section, showing vertically stacked, multistory channel sequences and thick intervals of overbank fines. Location given in Fig. 2.4, symbols the same as in Fig. 2.7.



40
20
0
Meters
soil
soil
80
60
cutbank
soil
Skolithos
slt. vfg. fg. mg. cg. vcg. pbl.
Slt. vfg. fg. mg. cg. vcg. pbl.
Grain Size

Figure 2.24--Photomosaic and interpretative sketch of isolated, lenticular channels in the delta-front setting, Sunnyslope Road section (location from Fig. 2.4, symbols the same as Fig. 2.7). Convex-upward lenticular channels interpreted as the result of differential compaction. Channel-fills include turbidites, channelized massive beds, and slumps from channel margins. Intervening fine-grained deposits are thin-bedded turbidites.

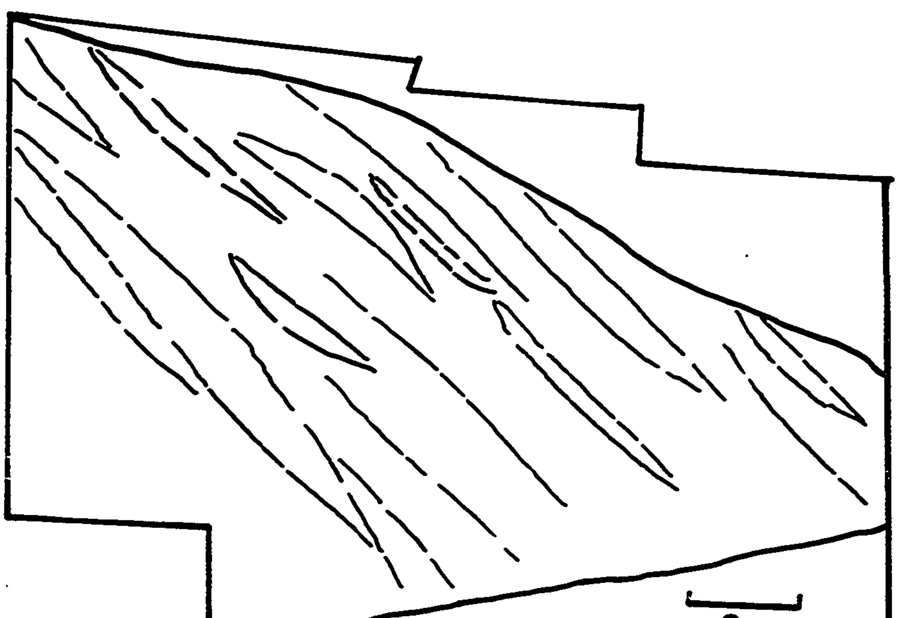
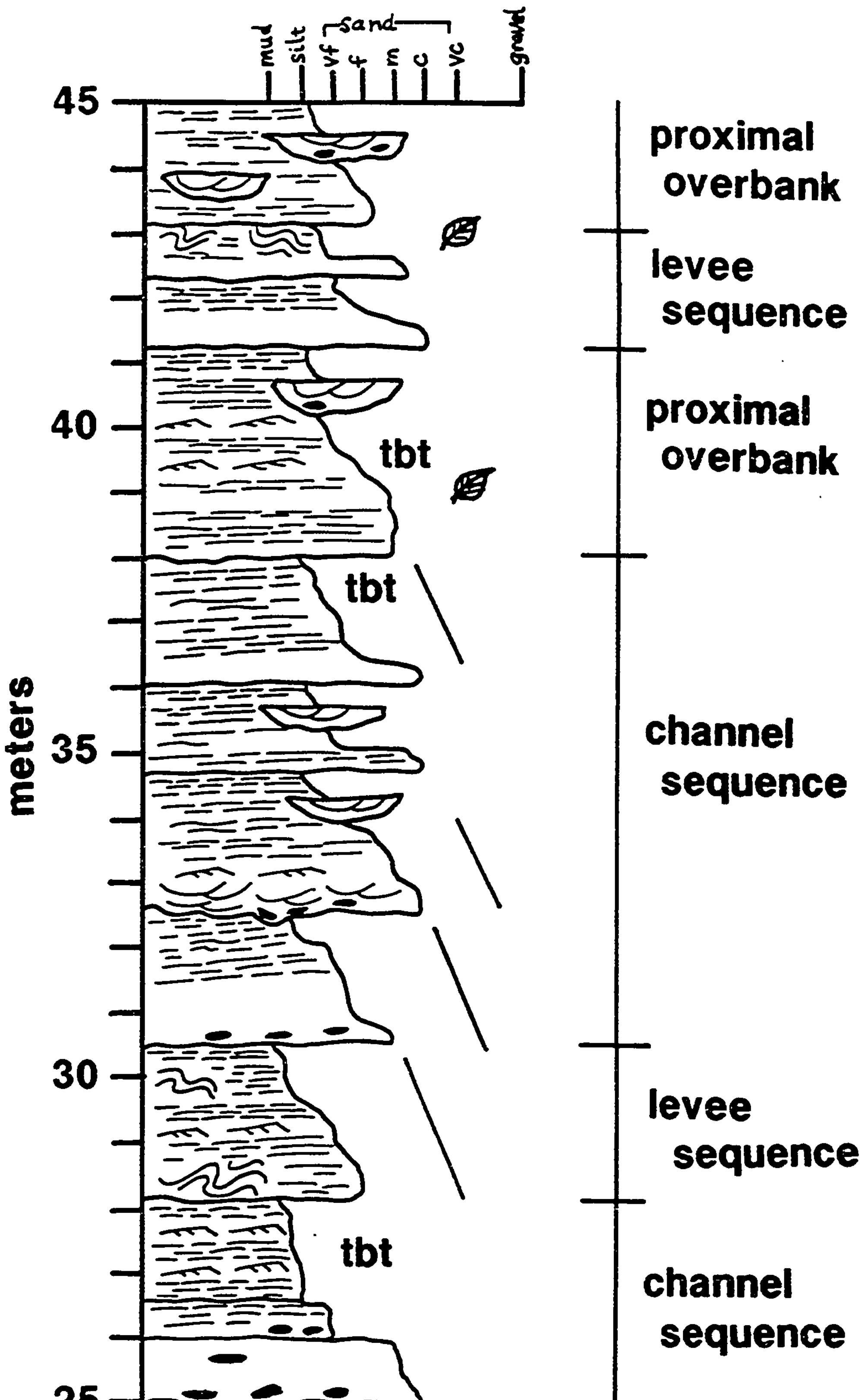

3 m

Figure 2.25--Stratigraphic section of delta-front deposits at Sunnyslope Road, see text for discussion. Symbols are the same as Fig. 2.7.



mud
silt
sand
vf
f
m
c
vc
gravel
45
40
35
30
25
meters
tbt
tbt
tbt
proximal overbank
levee sequence
proximal overbank
channel sequence
levee sequence
channel sequence

Figure 2.26--Hydraulic geometry of channels in the Chumstick Formation. The plots show the measured dimensions of paleochannels for the three facies associations: the bankfull width/depth ratio is about 35:1 in gravel-bedload streams, 19:1 in sand-bedload streams, and 17:1 in mixed-load streams. These ratios are probably minimal values, since the effect of erosional loss of the top of a channel sequence would reduce width more than depth.

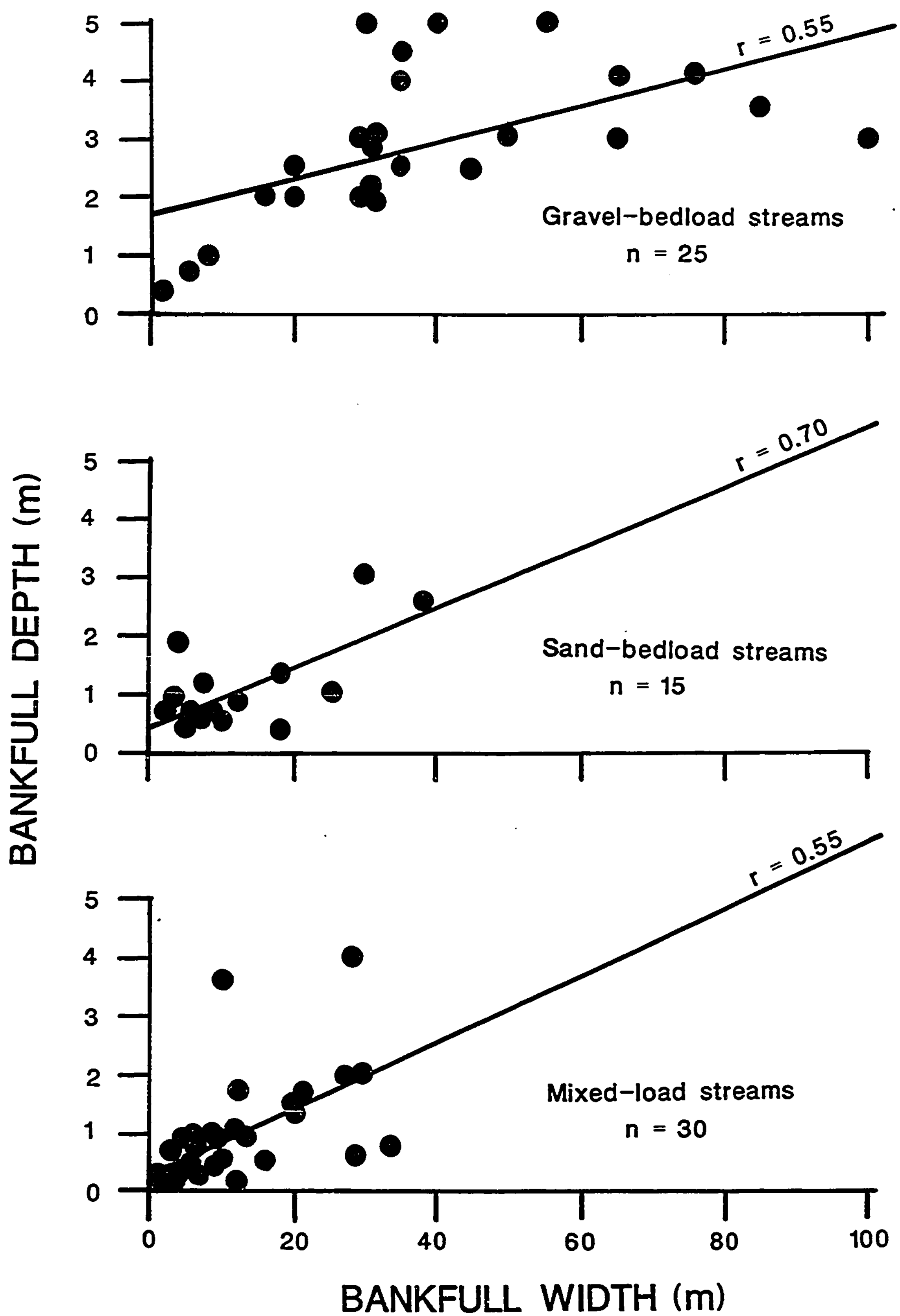
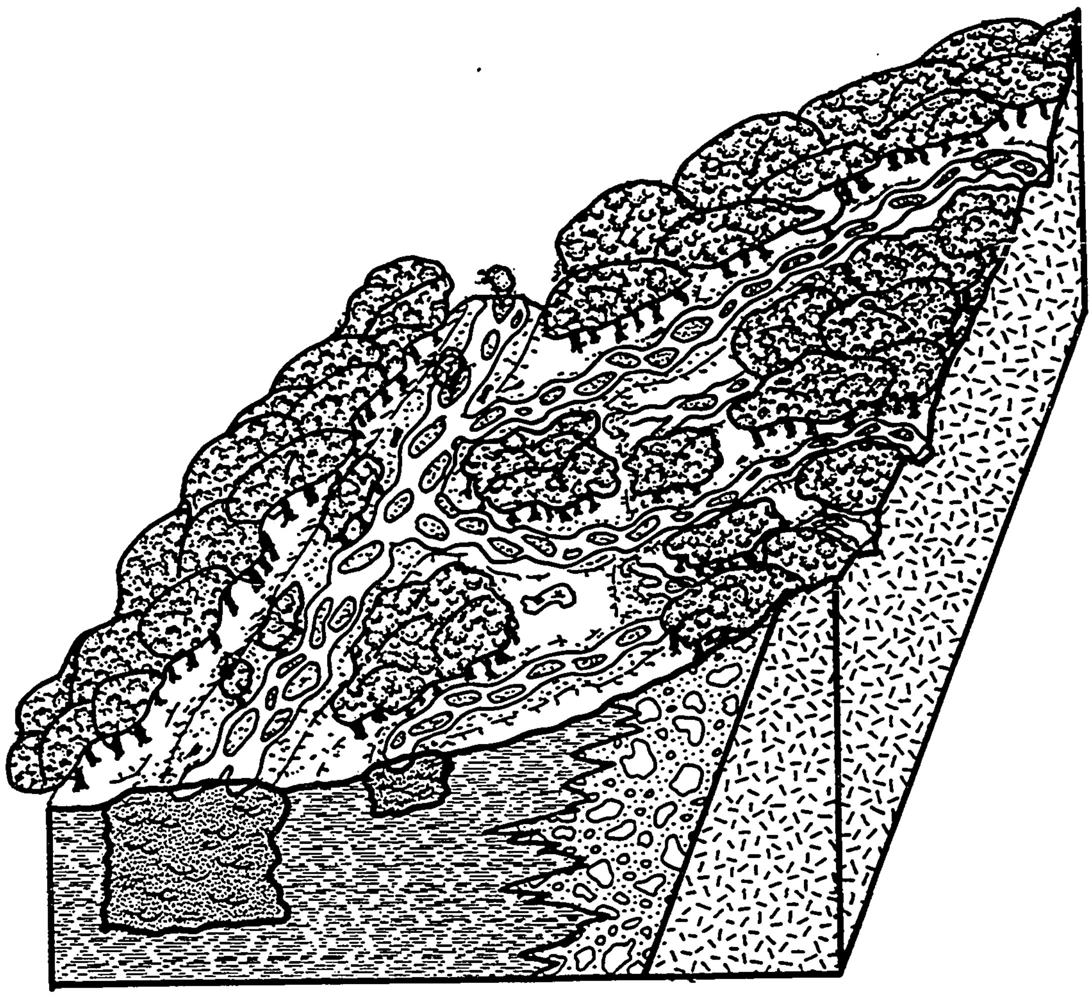

BANKFULL DEPTH (m)
r = 0.55
Gravel-bedload streams
n = 25
r = 0.70
Sand-bedload streams
n = 15
r = 0.55
Mixed-load streams
n = 30
0
1
2
3
4
5
0
20
40
60
80
100
BANKFULL WIDTH (m)

Figure 2.27--Model for Chumstick humid-tropical, alluvial-fan system. Proximal areas are vegetated fault scarps with low relief. Coarse-grained deposits are localized as laterally stacked depositional units on the proximal part of the fan. The distal fan is dominated by gravel-bedload and sand-bedload fluvial deposits with a sheet-like geometry. The basin fill is dominated by vertically stacked sand-bedload streams, with extensive sandy overbank deposits.



Chapter 3

PALEOCLIMATOLOGY AND PALEOBOTANY OF THE EOCENE CHUMSTICK FORMATION, CASCADE RANGE, WASHINGTON (U.S.A.): A RAPIDLY SUBSIDING ALLUVIAL BASIN

INTRODUCTION TO CHAPTER 3

The morphology and evolution of a nonmarine depositional system is strongly influenced by the climatic and tectonic factors acting on the basin. The influence of tectonism on basin architecture and depositional style has been long recognized (e.g., Steel and Aasheim, 1978; Alexander and Leeder, 1987). Paleoclimatic effects may be more subtle or difficult to assess, and they have traditionally been treated as invariant, with all changes ascribed to tectonic effects on the basin.

The signature of paleoclimate on nonmarine sediments might include paleovegetation types and communities; paleosol types, development, and lateral extent; erosional processes and rate of sediment production; sediment textures; mineralogy; bank stability; and characteristic sedimentary structures. The importance of paleoclimate has been reevaluated recently, with studies showing that changes in paleoclimate, as expressed in paleovegetation (Wing, 1984) or paleosols (Retallack, 1986), can have significant effects on the resulting architecture and vertical successions of fluvial deposits.

This study will focus on the paleoclimatic record preserved in a tectonically active nonmarine basin, the Eocene Chumstick Formation, in Washington State. Chumstick fluvial deposits exhibit excellent preservation of plant macrofossils (Burnham, 1985; this study) and pollen (Newman, 1981; this study). Paleosol horizons are present in many localities and can be traced laterally for hundreds of meters. The goals of this study are to use the composition and floristic attributes of the paleoflora to interpret paleoclimate; to combine paleofloral and sedimentological data to reconstruct plant community structure; and to investigate the influence of vegetation on deposition.

CHUMSTICK FORMATION

Geologic Setting

The Paleogene setting of the Pacific Northwest features a number of nonmarine basins associated with regional strike-slip faults (Figure 3.1). Each of these basins displays many of the characteristics of strike-slip basins, including: great sediment thickness, rapid sediment-accumulation rates, rapid vertical and lateral facies changes, changes in paleocurrent pattern and provenance, syndepositional magmatism, and a deformation style in accord with right-lateral shear (Johnson, 1985; Tabor et al., 1984; Evans, chapter 4).

The Middle to Late Eocene Chumstick Formation comprises over 12,000 meters of fluvial and lacustrine strata in a fault-bounded basin in central Washington (Figure 3.2). Three major fault zones divide the Chumstick basin into two sub-basins which had different depositional and deformational histories. The thickest section is found in the western sub-basin, west of the Eagle Creek fault zone, which contains fluvial sediments with a number of tuffaceous units, some of which are dated (Figure 3.3). The eastern sub-basin, between the Eagle Creek and Entiat fault zones, contains fluvial sediments with a thick lacustrine sequence.

Stratigraphy and Age

The Chumstick Formation was defined by Gresens et al. (1981), and it has been correlated to other units in the

Pacific Northwest by radiometric dating and by plant-macrofossil and pollen biostratigraphy (Figure 3.4). Because the Chumstick Formation is lithologically similar to the Lower to Middle Eocene Swauk Formation, it was mapped as part of that formation until the late 1970's. Newman (1981) demonstrated that pollen from Chumstick strata is Middle to Late Eocene in age, coeval with the Roslyn Formation and Puget Group (see Figure 3.2).

Further age control for the Chumstick Formation is provided by a suite of radiometric dates. There are 19 inter-stratified airfall and ash-flow tuffs that are mappable units (Figure 3.5a), each with a distinctive trace-element chemistry (McClincy, 1986). These tuffs yield fission-track ages of about 45 Ma to 41 Ma in the middle part of the Chumstick Formation (Gresens, 1983; Gresens et al., 1981; Tabor et al., 1980, 1982, 1984; Evans, chapter 4). The base of the Chumstick Formation has been harder to date, but fission-track analyses of detrital-zircon suites from basal sandstones indicate a depositional age of 46 Ma to 44 Ma (Evans, chapter 4). In addition, fission-track and potassium-argon radiometric dates from intrusives in the Chumstick Formation indicate a maximum age of >51 Ma (Ott et al., 1986; Gresens, 1983; Tabor et al., 1980, 1982, 1984). The Chumstick Formation is unconformably overlain by the Early Oligocene Wenatchee Formation, which contains interstratified tuffs yielding fission-track ages of 33 Ma to 34 Ma (Gresens et al., 1981).

Earlier workers (Gresens, 1983; Gresens et al., 1981) proposed that the Chumstick Formation could be divided into a lower, dominantly fluvial part, and an upper, dominantly lacustrine part named the Nahahum Canyon Member. This interpretation has been shown to be overly simplistic. There were at least three phases of deposition (Figure 3.5), each phase showing significant differences in facies pattern, paleocurrents, and provenance. There is strong evidence for tectonic control of sedimentation, including: grain-size reduction away from major fault zones; major reorganizations of drainage type, drainage direction, and the location of sediment-source regions; two intervals of axial-drainage systems that paralleled major fault zones and one interval of internal drainage; syndepositional magmatism which included airfall and ash-flow deposits and the emplacement of a felsic dome into a major fault zone; and the development of at least one intraformational unconformity.

This study will refer to fossil collections from the three phases of Chumstick deposition shown in Figure 3.5. Phase 1 deposits are approximately early middle Eocene; being constrained by radiometric dates to between >51 Ma and about 42 Ma. Phase 2 deposits are approximately late middle Eocene; they overlie tuffs dated at 42 Ma, and are constrained by radiometric dates from coeval hydrothermal activity at about 40 Ma. Phase 3 deposits are approximately late Eocene; they overlie earlier dated units, and contain pollen that is probably latest Eocene in age (Estella Leopold, verbal communication). The resultant age ranges of taxa collected in this study (Figure 3.6) correspond with known age ranges from other regional studies (e.g., Wolfe, 1968, 1977; Wolfe and Wehr, 1986).

Depositional Environments

The Chumstick Formation is entirely nonmarine and comprises a variety of fluvial and lacustrine depositional environments within a humid-tropical, alluvial-fan system

(Evans, chapter 2). Three fluvial facies associations have been described and interpreted as gravel-bedload stream deposits, sand-bedload stream deposits, and mixed-load stream deposits. Chumstick lacustrine sediments are not discussed in this paper due to poor preservation of organic debris in these deposits. The locations of key stratigraphic sections is given in Figure 3.7.

Gravel-Bedload Stream Deposits. Gravel-bedload stream deposits consist of gravel longitudinal-bar deposits, bar-platform deposits, channel-fill deposits, and overbank deposits (Figure 3.8). Gravel longitudinal-bars formed sheet-like deposits 2 to 3 meters thick which can be traced laterally up to several hundred meters (Figure 3.9). These depositional units consist of massive to crudely stratified, pebble-cobble conglomerate, with rare bar-margin avalanche-face deposits. Bar-platform deposits include planar-bedded sandstone, which may contain organic partings or laminae of preserved leaf-litter laminae. Soil profiles developed on many of the emergent bar-tops (see later section). Adjacent channel-fill sequences consist of trough cross-bedded sandstone and pebbly sandstone which probably represent three-dimensional dune deposits. Some channel-fill sequences are dominated by massive, coarse-grained sandstone overlain by finer-grained sandstone and mudstone. The lack of stratification in these units may have resulted from rapid deposition of sediment with a high water content, or else from destratification by organisms.

Proximal overbank deposits include ripple cross-laminated sandstone, laminated sandstone, siltstone, and mudstone which grade laterally and vertically into finer-grained distal overbank deposits. Many of these deposits have been destratified by growth of roots or by burrowing organisms (see later section). Overbank deposition is significant even in the most proximal regions of this humid-region, alluvial-fan system, representing up to 20% of lithofacies in some gravel-bedload stream deposits. Evidence for bank cohesion and stability in these deposits includes preserved cutbanks, cohesive bank failures and slumps, and resedimented pedogenic calcrete nodules.

Sand-Bedload Stream Deposits. Sand-bedload stream deposits consist of vertically stacked, multistory-channel sequences and related proximal and distal overbank deposits (Figure 3.10). Channel sequences are dominated by amalgamated trough cross-bedded sandstone and pebbly sandstone, which represent three-dimensional dune deposits (Figure 3.11). Subordinate massive to crudely stratified conglomerate and coarse-grained sandstone are interpreted as longitudinal-bar deposits. Lateral-accretion surfaces and related deposits are present in many of these deposits, indicating that lateral channel migration did occur in this depositional system. Overall, however, the abundance of multistory channel bodies suggests that vertical accretion dominated over lateral channel migration in this rapidly subsiding basin.

Proximal overbank sequences are dominated by ripple cross-laminated and laminated fine-grained sandstone and siltstone (Figure 3.12). Distal overbank sequences consist of laminated and massive siltstone and mudstone. Many of the overbank units show evidence for incipient soil development and bioturbation. Preserved cutbanks, cohesive bank failures and slumps, and resedimented pedogenic calcrete nodules attest to bank stability.

Mixed-load Stream Deposits. Mixed-load stream deposits consist of isolated channel deposits, vertically stacked, multistory-channel deposits, and thick sequences of proximal and distal overbank deposits (Figure 3.13). Channel-fill sequences include trough cross-bedded sandstone which represent three-dimensional dunes; ripple cross-laminated and laminated sandstone and shale which represent proximal overbank deposits; and massive sandstone and mudstone which represent destratified units. Mud plugs are present in several localities. Some channel sequences are extensively bioturbated, particularly in the portion of the basin dominated by a lacustrine-deltaic depositional environment (Figure 3.14).

Overbank deposits are similar to those previously described and comprise over 60% of these sections. Most of these deposits show evidence for incipient soil development and may also include laminae of leaf litter. These deposits also contain carbonaceous mudstones, which are interpreted as histosols (organic soils). Preserved cutbanks, cohesive bank failures and slumps, and lateral-accretion surfaces indicate bank cohesion and stability.

PALEOSOLS

Several hundred individual paleosols are present in the Chumstick Formation. Most are relatively thin (<1 meter depth), rudimentary, and have only a local areal extent.

Evidence for Paleosols

Fossil soils are ubiquitous in the fluvial facies of the Chumstick Formation and may be recognized by some of the following features: presence of roots, burrows, and surface traces; destratification and development of massive soil structure; concentration of organic matter in some green and gray mudstones; accumulation of rhizoliths (root penetration features), including root casts and rhizoconcretions; ped structures; development of calcic soil horizons; and lateral persistence of individual paleosols across lithologic boundaries.

Roots in the Chumstick Formation range from very rare to locally abundant (Table 3.1) and vary in size from about 0.1 cm in diameter (rootlets) to the roots and stumps of trees in growth position (Figure 3.15). One stump consisted of roots >90 cm in length and 5 to 6 cm in diameter, derived from a rootball 50 cm in width. A second stump consisted of roots >110 cm in length and 12 cm in width. Even relatively thin (<1 cm diameter) roots can commonly be traced vertically downward for tens of centimeters. Bracken and Picard (1984), finding similar root dimensions and shapes, suggested that the great length of individual roots might indicate a deep or fluctuating water table.

Units of massive, very fine-grained sandstone, siltstone, and mudstone are abundant in the Chumstick Formation and may be associated with roots, burrows, and leaf debris. Intact leaf fossils are rare in the massive units, but are locally abundant in laminated sandstone and siltstone, where they form laminae of leaf litter. This association strongly suggests that the massive units were destratified by the burrowing activity of roots and organisms. Other features in the massive mudstones that are suggestive of soil structures include blocky or hackly fractures with iron-stained surfaces, which are similar to ped structures described by others (Retallack, 1981; Bown and Kraus, 1981). The mudstones range in color from grayish-green (10 GY 5/2) to light olive gray (5 Y 5/2), and are mottled in places.

The organic carbon content of fine-grained deposits in the Chumstick Formation ranges from 0.1% to 5.2% total organic carbon (Table 3.2). The organic content of soils appears to be related to depositional setting, with the highest values in mixed-load stream deposits (0.2-5.2% TOC), followed by sand-bedload stream deposits (0.2-3.6% TOC), then gravel-bedload stream deposits (0.1-1.4 % TOC). This trend may reflect higher rates of vertical accretion in the distal facies (basin fill), resulting in greater preservation of organic matter. Alternatively, there may have been less oxidation of organic matter due to higher water tables in the finer-grained sediments.

Rhizoliths are calcareous fabrics that accumulate in a host sediment as a direct or indirect result of the activity of roots. The development of rhizolith fabrics is an indication of capillary draw of soil water due to the presence of roots. Types of rhizoliths include root molds and casts, rhizosheaths, and rhizoconcretions. In the Chumstick Formation, cylindrical molds 1 to 2 cm in diameter have an outer portion composed of calcium carbonate, typically infilled with sand (Figure 3.16a). Vertical sections of rhizosheaths show a similar morphology (Figure 3.16b).

Calcic horizons in the Chumstick Formation range from discontinuous pebble coatings and micronodules to laminated, continuous horizons (stage I through stage V, according to Gile et al., 1965, 1966; as modified by Machette, 1985). The individual nodules are pale red (5 R 6/2) to grayish red purple (5 RP 4/2) in color. In morphology, they range from spherical and ellipsoidal shapes to irregular masses. They are often found in distinctive horizons (Figure 3.17a), which may consist of isolated nodules to coalesced nodules (Figure 3.17b) to coherent layers (Figure 3.17c).

The timing of formation of calcareous nodules is constrained by the uncommon occurrence of individual nodules in the basal parts of channel sequences (Figure 3.17d). These nodules are composed of calcite-cemented sand, so their presence among pebble-cobble conglomerate in basal channel deposits indicates a syndiagenetic origin. It is likely that soil erosion and bank failure due to the lateral migration of channels caused some of these nodules to be introduced into the channels, where they behaved as individual clasts.

Soil Classification

In the American soil classification system (Soil Survey Staff, 1975; Flach, 1978), Chumstick paleosols are entisols, inceptisols, and histosols. All three represent relatively thin soils with rudimentary soil-horizon development, typical of soils from aggrading alluvial systems (Duchaufour, 1977). Petrographic studies show there has been insignificant alteration of primary mineral assemblages in these paleosols. These observations are consistent with other evidence that there was rapid sedimentation in the Chumstick basin. All three soil types may occur together in the same stratigraphic section. Individual soils may be from <1 to 3 meters thick, and rarely show evidence for being superimposed (Figure 3.18). Some individual soils can be traced laterally for hundreds of meters (Figure 3.9), but none of the observed paleosols has a regional extent.

<u>Entisols</u>. Entisols are an order of soils that are very slightly developed and lack diagnostic soil horizons.

Over 150 soil profiles fitting that description are present in the Chumstick Formation. About one-third of these soils have preserved roots, while the rest are characterized as massive, organic-rich, and commonly mottled. Entisols in the Chumstick Formation range from about 0.5 to 2.5 meters thick, averaging about 1.5 meters thick. They are observed in three types of depositional sites. About 77% occur in proximal overbank deposits, typically as massive mudstones overlying ripple cross-laminated, laminated, or massive fine-grained sandstone. About 14% occur in distal overbank deposits, typically as massive mudstones overlying laminated mudstones, carbonaceous mudstones, and ash-layers. The remaining 9% are within channel-fill sequences. Most of these entisols would be classified as xerofluvents and tropofluvents, with a smaller quantity being psamments (Soil Survey Staff, 1975; Flach, 1978).

Inceptisols. Inceptisols are an order of slightly developed soils in which diagnostic horizons have formed rapidly. In the Chumstick Formation, inceptisols are characterized by rudimentary ochric epipedons (surface horizons that are not strongly colored and are relatively low in organic content), cambic B horizons (characterized by incomplete weathering of primary minerals) and a calcic (Cca or K) horizon at depth. They range from 0.8 to 2.4 meters thick, averaging about 1.5 meters thick. Chumstick inceptisols probably represent ustropepts or xerochrepts (Soil Survey Staff, 1975; Flach, 1978).

Gile et al. (1965, 1966) created a classification for the development of calcic horizons in Quaternary deposits based upon the increasing size and coalescence of nodules, and Machette (1985) modified this classification by adding categories. In the Chumstick Formation, stage I of Gile et al., calcite coatings on grains, was so pervasive it was not measured. A total of 87 paleosols with calcic horizons greater than stage I were observed in measured sections; of these 31% were stage II (few to common nodules in horizons), 62% were stage III (abundant nodules with internodule filling), 6% were stage IV (continuous horizons and coalesced nodules), and 1% were stage V (laminated horizons).

The development of calcic horizons in these deposits apparently depended on a thick, well-drained, sandy substrate. Only 5% of the inceptisols are present in distal overbank settings, where massive mudstones directly overlie the calcic horizon, and only 21% are found in proximal overbank settings, where massive mudstone and thin-bedded massive fine-grained sandstone and ripple cross-laminated sandstone overlie the calcic horizon. The remaining 74% of the inceptisols are present in channel deposits (17% on bar-tops and 57% in channel-fill sequences).

Inceptisols provide some indication of the rate of soil development in the Chumstick Formation. Radiocarbon studies on Quaternary soils in southwestern U.S. have shown that about 10^4 years are required to develop stage II to stage IV calcic horizons (Williams and Polach, 1971; Williams, 1973). Other workers have made similar calculations in modern and ancient soils and obtained comparable values (e.g., Allen, 1974; Leeder, 1975; McPherson, 1979; Bown and Kraus, 1981). The development of each paleosol represents a period of time when the rate of deposition was less than the rate of soil formation in at least part of the depositional system. The development of calcic soil horizons in Chumstick sediments suggests that portions of the alluvial-fan system were inactive (i.e., not receiving much sediment) for intervals of 10^4 years. These paleosols also have important paleoclimatic implications which will be addressed in a later section.

Histosols. Histosols are an order of soils that include an organic-rich surface layer (histic epipedon). In the Chumstick Formation, 15 carbonaceous mudstones are present and consist of olive gray (5 Y 3/2) and dark gray (N 3), massive, organic-rich horizons. These units range from 0.1 to 0.7 meters in thickness and were typically found in proximal overbank sequences. They probably originated as thin, peaty layers which developed in topographic lows adjacent to the channels.

TRACE FOSSILS

Nonmarine lebensspuren in the Chumstick Formation consist predominantly of vertical, unlined burrows (Skolithos) and rare traces on bedding plane surfaces (Sinusites). No faunal remains were found.

Vertical Burrows. Vertical burrows are endostratal, unbranched, cylindrical shafts lacking ornamentation or a terminal cell (Figure 3.19a). Approximately 84% of these are oriented downward and the remainder are oriented upward (Figure 3.19b). The two kinds are similar in size, with a mean length of about 3 cm and a mean diameter of about 0.5 cm. Burrow-fills are typically finer than the surrounding material, with about 43% mud-filled or 28% finer-grained sand-filled in sandstone, versus only 5% sand-filled in mudstone or 24% coarser-grained sand-filled in sandstone. Upwards-oriented burrows were 75% mud-filled in sandstone and only 25% coarser-grained sand-filled in sandstone. These observations suggest that the burrows were dwelling or shelter structures, used by organisms to burrow down below the finer-grained, organic-rich surface layers.

Since both types of burrows occur in the same horizons and have the same dimensions, it is likely they were produced by the same organism(s). Ratcliffe and Fagerstrom (1980) have observed that a majority of Holocene floodplain lebensspuren are produced by insects, some of which produce vertical burrows for shelter purposes. Burrows in Chumstick deposits may have been made by insects, but the specialized structures that insects can produce (e.g., Ratcliffe and Fagerstrom, 1980; Retallack, 1984) were not apparent.

Surface Traces. Rare biogenic structures on bedding plane surfaces include surficial (exogenic), unbranched trails. These trails are typically 0.2 to 0.3 cm in width and up to 5 cm in length, having a surface relief of about 0.1 cm. The trails vary in plan from straight, to intersecting straight sections, to gently curved segments. The morphology and size of the structures suggests that they are Sinusites, and they were probably produced by insects.

PALEOBOTANICAL DATA

Plant macrofossils were collected where observed at surface outcrops, and the stratigraphic positions of the fossiliferous layers were carefully described and recorded as part of measured sections. Plant macrofossils are primarily impressions and compressions, with a minor amount of silica petrifications. In the laboratory, fossiliferous rock slabs were cleaned, identified using published descriptions, and photographed. All samples were added to the permanent collection of the Burke Memorial Washington State Museum at the University of Washington. Macerations from four samples of carbonaceous mudstone were studied for palynology by Shell Onshore, Inc.

Chumstick Paleoflora

The paleobotanical composition of the Chumstick Formation was determined from leaf fossil, pollen, and spore data (Table 3.3). Published data from palynology studies by Newman (1981) on these same rocks is included for completeness. Because pollen and leaf data may indicate the same taxa, possible equivalents are shown in Table 3.4.

The Chumstick paleoflora contains taxa that have affinities to the modern paratropical and subtropical rainforest (Table 3.5). Three of the taxa are tropical vines or lianes: Cocculus, Calkinsia, and Phytocrene (Wolfe, 1977); while Gleicheniidites is a tropical fern (Hopkins, 1966). Other taxa typical of tropical to subtropical rainforests include Myristica, Litsea, Artocarpus, Hamamelis, Mimosites, Parashorea, and Eugenia. In addition to these, Chumstick sediments contain pollen from tropical and subtropical families such as the Bombacaceae and Taxodiaceae (Newman, 1981), and genera such as Sciadopitys (Shell Onshore, Inc., written communication, 1986). There is also a large component typical of humid temperate forests, including Salix, Populus, Tetracentron, Pterocarya, Platycarya, Carya, Alnus, Dryophyllum, Chaetoptelea, Celtis, Fothergilla, Platanus, Rhus, Aesculus, Ilex, Tilia, and Viburnum, as well as pollen from Buxaceae (Newman, 1981) and from

Pinus, Picea, and Tsuga (Shell Onshore, Inc., written communication, 1986).

Mixtures of tropical and temperate taxa have been observed in many of the other Paleogene floras in western North America (e.g., MacGinitie, 1941, 1971; Wolfe, 1968, 1977; Wolfe and Wehr, 1986; Axelrod, 1966). MacGinitie (1974) proposed two hypotheses to explain such mixtures: (1) that the paleoclimate was similar to modern tropical highlands, where mean annual temperatures are lower than tropical rainforests, but where many tropical species are supported due to the high temperature minima; or (2) that the paleoclimate was fully tropical, but many species have subsequently adapted to cooler climates, and are found in temperate forests today. It is not the intent of this study to address these issues, but merely to show that the Chumstick paleoclimate supported a diverse mixture of tropical and temperate forest types, and that the Chumstick paleoflora shares this characteristic with many of the other Paleogene floras.

PALEOCLIMATIC ANALYSIS

Physiognomic Analysis of Climate

One method for paleoclimatic analysis uses aspects of the physiognomic characteristics of leaves, such as the presence or absence, size, and shape of certain leaf structures. An advantage of physiognomic analysis is that the measurements are independent of taxonomy, such that it emphasizes the similarities in leaf morphology between widely separated regions that have a similar climate (Wolfe, 1971). The method also has the advantage of being quantitative, with the variables expressed as percentages, and it has obtained highly reproducible results among various workers (Wolfe, 1971). This type of analysis has been widely applied to the study of Tertiary paleofloras (e.g. MacGinitie, 1941, 1971; Chaney and Sanborn, 1933; Wolfe and Hopkins, 1967; Wolfe, 1977, 1978; Hickey and Wolfe, 1975; Wolfe and Wehr, 1986).

The most useful characteristics to measure are the type of leaf margin; leaf size; leaf texture; type of apex; and type of leaf base and petiole. There is a strong correlation between mean annual temperature and the percentage of entire leaf margins (Wolfe, 1978). Leaves with entire margins are overwhelmingly prevalent in tropical or tundra regions, and leaves that have non-entire margins are characteristic of humid temperate regions (Bailey and Sinnott, 1915, 1916). Leaf size is another important climatic indicator. Larger leaves tend to be found in warmer and wetter climates (Wolfe, 1978). This study will refer to leaf-size classes using the classification of Raunkiaer (1934) as modified by Webb (1959). Although these size classes refer to leaf surface area, according to MacGinitie (1974) these can be approximated by leaf length as follows: microphyllous (<7.5 cm), notophyllous (7.5 to 12.5 cm), and mesophyllous (>12.5 cm).

Thick leaves with a leathery (coriaceous) texture are typical of evergreen plants and are common in two climatic settings: mesophyllous tropical vegetation and microphyllous desert or tundra vegetation. In contrast, thin leaves are typical of humid temperate regions (Wolfe, 1978). The shapes of the tip and the base of the leaves also have climatic implications. The presence of an attenuated apex or "drip-tip" has been correlated to tropical regions (Richards, 1952; Wolfe, 1978). The presence of cordate (heart-shaped) bases is typical of tropical vegetation, especially of types of climbing vines

(Richards, 1952; Wolfe, 1977, 1978).

The Chumstick paleoflora has the following physiognomic characteristics: 41% have entire leaf margins, 27% have drip tips, and 68% have coriaceous textures (Table 3.6). The leaf-size data show that 10% are microphyllous, 31% are notophyllous, and 59% are mesophyllous (Table 3.6). These data can be compared with known characteristics of modern paratropical, subtropical, and humid temperate forests (see Table 3.7). In vegetation types and percentage of entire leaf margins, the Chumstick paleo-flora most closely resembles the flora of a modern subtropical rainforest. In leaf size, the Chumstick paleoflora compares more closely with the modern paratropical rainforest. This discrepancy is difficult to resolve because aspects of transport and preservation can affect the size and types of vegetation ultimately preserved. Wolfe (1977) found that riparian vegetation tends to have a lower percentage of entire margin taxa than the surrounding flora; thus depositional environments dominated by riparian settings could result in an anomalously low percentage of entire leaf margins. This situation could easily apply to the Chumstick Formation because most samples come from channel-margin, proximal-overbank, and bar-top depositional sites.

A comparison of the Chumstick paleoflora to other later Eocene paleofloras of the Western U.S. reveals a basic similarity (Table 3.8). The Susanville, Puget, Steel's Crossing, and Kushtaka paleofloras represent lowland tropical or paratropical rainforest (Wolfe, 1971, 1977), while the Middle Clarno paleoflora represents microphyllous montane rainforest (Wolfe, 1971). The Chumstick paleoflora shows intermediate characteristics between these two groups, which is in accord with the known paleogeography of the Chumstick basin, being about 150 km inland from the coast in a region of moderate relief. The Chumstick paleoflora does not resemble the Republic paleoflora, located about 180 km northeast, which was an upland mixed conifer and broad-leaved deciduous forest (Wolfe and Wehr, 1986).

Chumstick Basin Topography and Relief

It is possible to obtain an estimate of the paleo-elevation and relief of the Chumstick basin by using the paleovegetation data. There is a well established relationship between mean annual temperature and the percentage of entire-margin leaves in a flora (Wolfe, 1978). This relationship can be used for the Chumstick paleoflora (Figure 3.20) to obtain a mean annual temperature of $14^{0}C$ to $15^{0}C$ (a range of values is used to account for the probable under-representation of entire-margin leaves in a riparian setting). The Puget Group represents a fluvial-deltaic system which formed near sea level about 150 km due west of the Chumstick basin (Buckovic, 1979). The mean annual temperature of of the Puget Group paleoflora has been calculated to be $17^{0}C$ (Wolfe and Wehr, 1986). If we use a lapse rate of $0.55^{0}C/100$ m elevation (Axelrod, 1968; Wolfe and Wehr, 1986), the elevation of the Chumstick basin would have been between 350 and 550 m above sea level.

The Chumstick paleoflora does not show any evidence for a rain-shadow effect, so it is reasonable to calculate a regional paleoslope between the Chumstick and Puget basins, which would be between about 2.4 and 3.6 m/km. These calculations are in agreement with an independent paleoslope calculation based upon paleohydraulics, which shows that the paleoslopes necessary to transport the observed grain sizes through Chumstick paleochannels ranged from about 1 to 5 m/km (Evans, chapter 2).

Evidence for Seasonality

Chumstick paleosols provide important evidence for variation in rainfall. Calcic soil horizons typically develop in arid or semi-arid environments (Gile et al., 1965, 1966; Machette, 1985), and in ancient rocks they are usually cited as evidence for arid or semi-arid paleoclimates (e.g., Steel, 1973; Allen, 1974). There is evidence, however, that calcic soil horizons can develop in wetter climates given higher temperatures, rapid infiltration rates, and presence of adequate sources for calcium (Reeves, 1970). Sandy, arkosic sediments have high carbonate solubility and promote rapid translocation of carbonate by infiltrating water (McFadden and Tinsley, 1985). The development of calcic soil horizons in subtropical climates requires at least periodic intervals of drying of the soil. The presence of calcic horizons thus could indicate seasonal rainfall variations and the resulting fluctuation of the water table (Duchaufour, 1977; Bown and Kraus, 1981), rather than overall aridity. Members of the Chumstick paleoflora have representatives in today's monsoonal forests of India and Burma, including Eugenia, Ilex, and some members of the Bombacaceae (MacGinitie, 1974). Wolfe (written communication, 1987) observed that none of the Chumstick taxa is an indicator of strong seasonality, but also none negates the possibility of some moderate seasonal variations in rainfall.

There is additional evidence that water levels in Chumstick paleochannels fluctuated on a relatively frequent time scale, i.e., mud-draped trough cross-bed sets (Figure 3.21), interpreted as deposits in chute channels along the margins of main channels. The development of mud drapes on the avalanche faces of these three-dimensional dunes indicates abandonment of the channel and subsequent re-occupation, resulting in reactivation of the dune. The repeated development of mud-draped avalanche faces indicates that repeated re-occupation of these channels took place, presumably during higher flow levels (floods).

The evidence suggests that the water levels in channels and the water table in soils fluctuated. Although there is no direct evidence, the simplest explanation is to attribute both to changes in rainfall, and it is speculated that these changes could be seasonal or monsoonal in nature.

Paleoclimate Summary

The Chumstick paleoflora contains a diverse suite of broad-leaved evergreen and broad-leaved deciduous vegetation, with a minor conifer component. A number of tropical indicators are present, including three tropical vine taxa, together with a number of taxa from more temperate regions. Physiognomic characteristics place the Chumstick flora as intermediate between paratropical and subtropical rainforest types. The Chumstick paleoflora may have occupied a paleogeographic position intermediate between lowland rainforest and montane rainforest, in a setting 150 km inland from the coast at an elevation of 350 to 550 m. There is some evidence that precipitation may have been seasonal.

PLANT COMMUNITY - DEPOSITIONAL SITE RELATIONSHIPS

Plant Community Structure

Interpretation of the plant community structure of the Chumstick paleoflora is complicated by two factors. First, the fossil assemblages are death assemblages and represent leaves that were probably transported to a depositional site by floods. Thus differences between communities will be blurred, especially by over-representation of robust types of leaves. Second, the composition of the floras changed over the period of time that deposition in the basin took place. Other workers (e.g. Wolfe, 1968, 1977; Wolfe and Wehr, 1986) have demonstrated that climatic changes during the Eocene were responsible for changes in the taxonomic composition of the floras. To address these concerns, the Chumstick paleoflora is examined on the generic level, and only broadest distinctions are used to characterize depositional sites.

The Chumstick paleoflora can be classified by depositional sites into floodplain (distal overbank) and channel (channel margin, bar-top, and proximal overbank) communities. Table 3.9 shows that channel communities are dominated by typical riparian trees such as Salix, Populus, Alnus, Platanus, and Macginitiea, vines such as Calkinsia and Phytocrene, and shrubs such as Viburnum and Rhododendron. Floodplain communities are dominated by trees such as Pterocarya, Carya, Vinea, Dryophyllum, Chaetoptelea, Fothergilla, Aesculus, and Eugenia, with the vines Cocculus, Calkinsia, and Phytocrene, and shrubs Viburnum and Rhus. These data suggest that floodplain sites were well-drained, and that they supported taxa with less coriaceous leaves that are adapted to mesic conditions (e.g., MacGinitie, 1969). Well-drained, oxidized floodplains in the Chumstick paleoenvironment would help to explain the lack of thick coal sequences, in comparison to those found in the coeval Roslyn Formation and Puget Group.

Topographic Effects on Plant Distributions

The Chumstick paleoflora can also be classified according to topography within the basin. Fluvial deposits in the Chumstick Formation formed part of a humid-region, alluvial-fan system. Gravel-bedload stream deposits and sand-bedload stream deposits are found adjacent to the basin-bounding faults; distally these deposits change to sandy braidplain deposits (sand-bedload stream deposits and mixed-load stream deposits) and a lacustrine-deltaic distributary system (mixed-load stream deposits and lacustrine deposits). It seems likely that the fault-proximal regions represent dissected fault scarps ("uplands"), which change distally into low-lying braidplains and floodbasins ("lowlands").

Plant-fossil assemblages collected in the Chumstick Formation can be divided into "upland" or "lowland" communities based upon characteristics of the depositional site. Table 3.10 lists of the composition of these two plant communities. A number of taxa overlap, including some of the important indicators of subtropical or paratropical climate, such as Myristica, Parashorea, Litseaphyllum, and Tetracentron. Some of the key differences, however, are instructive. "Lowland" plant communities contain an adundance of stenophylls (narrow-leaved forms), including Salix, Eugenia, Rhus, and Mimosites, which are typical of streamside vegetation and suggest that the "lowlands" had a more riparian character overall. In contrast, the "uplands" contained all three vine taxa, which suggests that the "uplands" had a high-statured forest (Wolfe, written communication, 1987).

The distribution of certain taxa appears to be related to differences in rainfall or soil drainage between "upland" and "lowland" sites. For example, Macginitiea in not found in the Puget Group flora (near sea level), but is found in the volcanic terrain at Steel's Crossing and is found at an elevation of about 700 to 900 meters in the Republic flora (Wolfe and Wehr, 1986). In the Chumstick flora, Macginitiea is found in "upland" sites but not "lowland" sites. Wolfe (written communication, 1987) suggests that Macginitiea requires well-drained soils. Alternatively, there may be differences in total rainfall or in seasonality of rainfall between these sites.

SUMMARY AND CONCLUSIONS

The Chumstick Formation represents rapid deposition in a humid-tropical, alluvial-fan system situated in a tectonically active basin. Paleobotanical analysis of the Chumstick Formation reveals a mixture of broad-leaved evergreen and broad-leaved deciduous taxa which probably represent subtropical or paratropical climate. The paleogeographic setting of the Chumstick basin was at about 350 to 550 m above sea level, and about 150 km inland from the coast. Within the basin, plant assemblages can be divided into floodplain and channel communities, and into "upland" and "lowland" communities. The presence or absence of individual taxa from these communities may be due to differences in soil drainage or due to periodic (seasonal?) variations in rainfall that permit soils to dry, and water table levels to fluctuate.

Paleovegetation had a significant effect on deposition in the Chumstick Formation. Even coarse-grained, proximal streams show evidence for bank stability, the preservation of overbank deposits, and the development of soils on overbank, channel margin, and bar-top deposits. Distal sandy deposits are predominantly vertically stacked, multistory-channel sequences and related overbank deposits, which resemble descriptions by other workers of modern and ancient deposits of anastomosed streams (Smith and Putnam, 1980; Smith and Smith, 1980). The dominance of vertical accretion over lateral channel migration in these types of deposits may be due to rapid basin subsidence, or to bank cohesion and stability imparted by vegetation, or to both. In the Chumstick Formation, it is clear that both factors were important. Sediment accumulation rates exceeded 1 m/k.y., and evidence for bank cohesion includes cutbanks, mudstone intraclasts, resedimented pedogenic nodules, lateral-accretion surfaces, and mud-plugs.

The Chumstick Formation differs from most published descriptions of tropical alluvial systems. There are no examples of "mature" tropical soils, such as laterites or vertisols (Duchaufour, 1977). For a humid region, there is surprisingly little evidence for thick accumulations of coal or peat. There are only minor examples of hydromorphic soils, or of ephemeral floodbasin lacustrine deposits. On the other hand, there are no examples of arid-tropical features, such as evaporites or eolian deposits. The combination of humid-tropical climate and an active tectonic setting has produced a distinctively different set of deposits, and there is reason to suspect that these types of deposits are not rare in the geological record.

Chapter Notes

Alexander, J. and Leeder, M.R., 1987, Active tectonic control on alluvial architecture, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., editors, Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication no. 39, p. 243-252.

Allen, J.R.L., 1974, Studies in fluviatile sedimentation: implications of pedogenic carbonate units: Lower Old Red Sandstone, Anglo-Welsh outcrop: Geological Journal, v. 9, p. 181-208.

Axelrod, D.I., 1966, The Eocene Copper Basin flora of northeastern Nevada: University of California Publications in Geological Science, v. 59, 125 p.

Bailey, I.W. and Sinnott, E.W., 1915, A botanical index of Cretaceous and Tertiary climates: Science, v. 41, p. 831-834.

Bailey, I.W. and Sinnott, E.W., 1916, The climatic distribution of certain types of Angiosperm leaves: American Journal of Botany, v. 3, p. 24-39.

Bown, T.M., and Kraus, M.J., 1981, Lower Eocene alluvial paleosols (Willwood Formation, northwest Wyoming, U.S.A.) and their significance for paleoecology, paleoclimatology, and basin analysis: Paleogeography, Paleoclimatology, Paleoecology, v. 34, p. 1-30.

Bracken, B. and Picard, M.D., 1984, Trace fossils from Cretaceous/Tertiary North Horn Formation in central Utah: Journal of Paleontology, v. 58, p. 477-487.

Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 147-163.

Burnham, R.J., 1986, Foliar morphological analysis of the Ulmoidae (Ulmaceae) from the early Teriary of western North America: Palaeontographica, v. 201, p. 135-167.

Chaney, R.W. and Sanborn, E.I., 1933, The Goshen flora of west-central Oregon: Carnegie Institute of Washington Publication, v. 439, 103 p.

Duchaufour, P., 1977, Pedology: Pedogenesis and Classification. London: George Allen and Unwin, 448 p.

Flach, K.W., 1978, Soil Taxonomy: approved amendments and clarification of definitions: Soil Conservation Service, Washington, D.C.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1965, The K horizon: a master soil horizon of carbonate accumulation: Soil Science, v. 99, p. 74-82.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences in carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Geology and Earth Resources, Bulletin 75, 75 p.

Gresens, R.L., Naeser, C.W., and Whetten, J.T., 1981, Stratigraphy and age of the Chumstick and Wenatchee formations- Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 233-236, 841-876.

Hickey, L.J. and Wolfe, J.A., 1975, The basis of Angiosperm phylogeny: vegetative morphology: Annals of the Missouri Botanical Garden Society, v. 62, p. 538-589.

Hopkins, W.S., Jr., 1966, Palynology of Tertiary rocks of the Whatcom Basin, southwestern British Columbia and northwestern Washington [Ph.D. Dissertation]: Vancouver, British Columbia, University of British Columbia, 184 p.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington: in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 283-302.

Knight, K.L., 1987, Rhizolite/calcrete: nonpedogenic plant root diagenesis (Middle Pennsylvanian) from Kansas [abstract]: American Association of Petroleum Geologists Bulletin, v.71, p. 578.

Leeder, M.R., 1975, Pedogenic carbonates and flood sediment accretion rates: a quantitative model for alluvial arid-zone lithofacies: Geological Magazine, v. 112, p. 257-270.

Machette, M.N., 1985, Calcic soils of the American Southwest, in Weide, D.L. and Faber, M.L., editors, Soils and Quaternary Geology of the Southwestern United States, Geological Society of America, Special Publication no. 203, p. 1-21.

MacGinitie, H.D., 1941, A middle Eocene flora from the central Sierra Nevada: Carnegie Institute of Washington, Publication 534, 178 p.

MacGinitie, H.D., 1969, The fossil flora of the Green River beds in northwestern Colorado and northeastern Utah: University of California, Publications in Geological Science, v. 83, 140 p.

MacGinitie, H.D., 1974, An early middle Eocene flora from Yellowstone-Absaroka Volcanic Province, northwestern Wind River Basin, Wyoming: University of California, Publications in Geological Science, v. 108, p. 1-103.

McClincy, M., 1986, Tephrostratigraphy of the Chumstick Formation [M.S. Thesis]: Portland, Oregon, Portland State University, 127 p.

McFadden, L.D. and Tinsley, J.C., 1985, Rates and depth of pedogenic-carbonate accumulation in soils: formulation and testing of a compartment model, in Weide, D.L. and Faber, M.L., editors, Soils and Quaternary Geology of the Southwestern United States, Geological Society of America, Special Publication no. 203, p. 23-41.

McPherson, J.G., 1979, Calcrete (caliche) paleosols in fluvial redbeds of the Aztec Siltstone (Upper Devonian) southern Victoria Land, Antarctica: Sedimentary Geology, v. 22, p. 267-285.

Newman, K.R., 1981, Palynologic biostratigraphy of some early Tertiary nonmarine formations in central and western Washington, in Armentrout, J.M., editor, Pacific Northwest

Cenozoic Biostratigraphy, Geological Society of America Special Paper no. 184, p. 49-65.

Ott, L.E., Groody, D., Follis, E.L., and Siems, P.L., 1986, Stratigraphy, structural geology, ore mineralogy, and hydrothermal alteration at the Cannon Mine, Chelan County, Washington, in MacDonald, A.J., editor, Gold '86, An International Symposium on the Geology of Gold Deposits, Proceedings Volume, p. 425-435.

Ratcliffe, B.C. and Fagerstrom, J.A., 1980, Invertebrate lebensspuren of Holocene floodplains: their morphology, origin, and paleoecological significance: Journal of Paleontology, v. 54, p. 614-630.

Raunkiaer, C., 1934, The Life Forms of Plants and Statistical Plant Geography. Oxford: Clarendon Press, 632 p.

Reeves, C.C., Jr., 1970, Origin, classification, and geologic history of caliche in southern high plains, Texas and eastern New Mexico: Journal of Geology, v. 78, p. 352-362.

Retallack, G.J., 1981, Fossil soils: indicators of ancient terrestrial environments, in Niklas, K.J., editor, Paleobotany, Paleoecology, and Evolution, v. 1, p. 55-102.

Retallack, G.J., 1984, Trace fossils of burrowing beetles and bees in an Oligocene paleosol, Badlands National Park, South Dakota: Journal of Paleontology, v. 58, p. 571-592.

Retallack, G.J., 1986, Fossil soils as grounds for interpreting long-term controls on ancient rivers: Journal of Sedimentary Petrology, v. 56, p. 1-18.

Richards, P.W., 1952, The Tropical Rain Forest. Cambridge: Cambridge University Press, 450 p.

Smith, D.G. and Putnam, P.E., 1980, Anastomosed river deposits: modern and ancient examples in Alberta, Canada: Canadian Journal of Earth Sciences, v. 17, p. 1396-1406.

Smith, D.G. and Smith, N.D., 1980, Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta: Journal of Sedimentary Petrology, v. 50, p. 157-164.

Soil Survey Staff, 1975, Soil Taxonomy: Agricultural Handbook 436, Soil Conservation Service, Washington, D.C.

Stanley, K.O. and Fagerstrom, J.A., 1974, Miocene invertebrate trace fossils from a braided river environment, western Nebraska, U.S.A.: Paleogeography, Paleoclimatology, Paleoecology, v. 15, p. 63-82.

Steel, R.J., 1974, Cornstone (fossil caliche)- its origin, stratigraphic and sedimentological importance in the New Red Sandstone, western Scotland: Journal of Geology, v. 82, p. 351-369.

Steel, R.J. and Aasheim, S.M., 1978, Alluvial sand deposition in a rapidly subsiding basin (Devonian, Norway), in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 385-412.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Waitt, R.B., Jr., 1980, Preliminary geologic map of the Chelan quadrangle, Washington: U.S. Geological Survey, Open-File Report no. 80-841.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee quadrangle, Washington: U.S. Geological Survey, Miscellaneous Geological Investigations I-1311.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26-44.

Webb, L.J., 1959, Physiognomic classification of Australian rain forests: Journal of Ecology, v. 47, p. 551-570.

Williams, G.E., 1973, Late Quaternary piedmont sedimentation, soil formation, and paleoclimate in arid South Australia: Zeitschrift fur Geomorphologie, v. 17, p. 102-125.

Williams, G.E. and Polach, H.A., 1971, Radiocarbon dating of arid-zone calcareous paleosols: Geological Society of America Bulletin, v. 82, p. 3069-3085.

Wing, S.L., 1984, Relation of paleovegetation to geometry and cyclicity of some fluvial carbonaceous deposits: Journal of Sedimentary Petrology, v. 54, p. 52-66.

Wolfe, J.A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: U.S. Geological Survey Professional Paper no. 571, 33p.

Wolfe, J.A., 1971, Tertiary climatic fluctuations and methods of analysis of Tertiary floras: Paleogeography, Paleoclimatology, Paleoecology, v. 9, p. 27-57.

Wolfe, J.A., 1977, Paleogene floras from the Gulf of Alaska region: U.S. Geological Survey Professional Paper no. 997, 108 p.

Wolfe, J.A., 1978, A paleobotanical interpretation of Tertiary climates in the northern hemisphere: American Scientist, v. 66, p. 694-703.

Wolfe, J.A. and Hopkins, D.M., 1967, Climatic changes recorded by Tertiary land flora in northwestern North America, in Kotora, H., editor, Tertiary correlations and climatic changes in the Pacific, Pacific Science Congress, Symposium no. 25, p. 67-76.

Wolfe, J.A. and Wehr, W., 1986, Middle Eocene dicotyledonous plants from Republic, northeastern Washington: U.S. Geological Survey Professional Paper no. 1597, 74 p.

Table 3.1: Occurrence of Rootlets in Paleosols

	absent	rare	common	abundant
Entisols				
n	108	18	23	2
%	72	12	15	1
Histosols				
n	15	0	0	0
%	100	0	0	0
Inceptisols				
n	79	2	6	0
%	91	2	7	0

absent = 0 per meter
rare = 1 to 3 per meter
common = 3 to 10 per meter
abundant = > 10 per meter

Table 3.2: Organic Carbon Content of Paleosols

Locality	Sample No.	Munsell Color		% TOC
__Gravel-bedload stream deposits__				
No.2 Canyon	85JE136	5GY3/2	grayish olive green	0.49
Cashmere	85JE116	5Y4/2	light olive gray	1.39
Eagle Ck. Rd.	85JE147	5Y5/2	light olive gray	0.73
Eagle Ck. Rd.	85JE142	5Y5/2	light olive gray	0.22
Clark Canyon	85JE163	10GY5/2	grayish green	0.28
Clark Canyon	84CC40	5GY5/2	dusky yellow green	0.06
Clark Canyon	84CC79	5GY5/2	dusky yellow green	0.09
Peshastin	85JE110	5GY5/2	dusky yellow green	0.51
Mission Ridge	85JE127	5GY5/2	dusky yellow green	1.04
__Sand-bedload stream deposits__				
Locality	Sample No.	Munsell Color		% TOC
Beehive Res.Rd.	85JE130	5Y5/2	light olive gray	1.60
Camas Ck. Rd.	86JE31	5GY3/2	grayish olive green	3.58
South Plain	84JE19	5GY4/2	dusky yellow green	1.04
South Plain	85JE151	10Y4/2	grayish olive	0.34
Tumwater Cyn.	85JE108	N3	dark gray	3.71
Cole's Corner	85JE87	5GY3/2	grayish olive green	0.21
Cole's Corner	86JE1	5GY3/2	grayish olive green	1.51
Fish Lake	85JE91	5G5/2	grayish green	0.21
Malaga	85JE100	5BG5/2	grayish blue-green	1.46
__Mixed-load stream deposits__				
Locality	Sample No.	Munsell Color		% TOC
Monitor	86JE60	5GY5/2	dusky yellow green	3.30
Monitor	86JE76	5G3/2	dusky green	5.18
Wenatchee	86JE67	5Y3/2	olive gray	3.43
Natapoc Ridge	86JE19	5Y3/2	olive gray	4.26
North Plain	85JE75	10GY5/2	grayish green	1.86
__Lacustrine deposits__				
Locality	Sample No.	Munsell Color		% TOC
Sunnyslope	85JE119	5GY3/2	grayish olive green	3.22
Sunnyslope	85JE122	N3	dark gray	5.04

Total Organic Carbon (TOC) determined on the Leco Carbon Analyzer.

Table 3.3: Chumstick Formation Paleobotanical Summary

	Phase 1	Phase 2	Phase 3
FICALES			
Osmundaceae			
Osmunda sp.*	S		S
Schizaeaceae			
Cicatricosisporites sp.*	S	S	S
Anemia elongata(?)			L
Polypodiaceae			
Polypodiidites sp.*	S	S	S
Cyatheaceae			
Cyathea pinnata			L
Aspidiaceae			
Dryopteris gibbsi		L	L
Laevigatosporites sp.*	S	S	S
Gleicheniaceae			
Gleicheniidites sp.*	S		
LYCOPDIALES			
Lycopodiaceae			
cf. Lycopodiumsporites sp.*	S		
Selaginellaceae			
Selaginella sp.*			S
PTERIDOPHYTA incertae sedis			
form genera			
Trilites solidus*	S	S	S
Deltoidospora sp.*	S	S	S
Cingulatisporites sp.*		S	
CONIFERALES			
Pinaceae			
Pinus sp.			P
Picea sp.			P
Tsuga sp.			P
form genera			
bisaccate sp.*	P		P
Pityosporites sp.			P
pine needles			N
Taxodiaceae			
Taxodiaceaepollenites sp.*	P		P
Sciadopityspollenites sp.			P
PRINCIPES			
Palmae			
cf. Liliacidites sp.*	P		

	Phase 1	Phase 2	Phase 3
SALICALES			
Salicaceae			
Salix sp.		L	L
Populus sp.			L
RANALES			
Menispermaceae			
Cocculus sp.		L	
Calkinsia franklinensis	L		
Tetracentraceae			
Tetracentron piperoides	L	L	L
Myristicaceae			
Myristica sp.	L	L	L
Lauraceae			
Litseaphyllum sp.	L		L
JUGLANDALES			
Juglandaceae			
Pterocarya pugetensis	L	L	
*Pterocarya sp.**	P	P	
Pterocaryapollenites sp.			P
*Platycarya sp.**	P		P
Carya sp.			L
Caryapollenites inelagans	P		
Caryapollenites veriptes	P		
*Caryapollenites sp.**	P	P	P
Vinea pugetensis		L	
FAGALES			
Betulaceae			
Alnus sp.		L	L
*Alnus sp.**	P	P	P
Alnus sp.	P		P
Alnipollenites verus	P		
Carpinus sp.	L		
Fagaceae			
Dryophyllum pugetensis	L		
Cupuliferoipollenites sp.	P		
URTICALES			
Ulmaceae			
Chaetoptelea sp.			L
cf. *Ulmus sp.**		P	
Ulmus sp.			P
cf. *Ulmoideipites sp.**	P		
Celtis tschudyi	P		
Moraceae			
Artocarpus lessigiana (?)		L	

	Phase 1	Phase 2	Phase 3
ROSALES			
Hamamelidaceae			
Hamamelis inequalis (?)			L
Fothergilla durhamensis			L
Platanaceae			
Platanus macginitei (?)		L	
Platanus appendiculata	L		L
Platanus sp.	L		
Macginitiea whitneyi		L	
Macginitiea angustiloba		L	
Leguminosae			
Mimosites (?) sp.		L	L
Cladrastis pugetensis		L	
EUPHORBIALES			
Buxaceae			
Erdtmanipollis sp.*	P		
SAPINDALES			
Anacardaceae			
Rhus mixta		L	
Rhus sp.		L	
Icacinaceae			
Phytocrene sordida		L	
Hippocastanaceae			
Aesculus sp.	L		
Sapindaceae			
Thouinopsis sp.		L	
Aquifoliaceae			
Ilex sp.*	P (?)	P	P
MALVALES			
Tiliaceae			
cf. _Tilia sp.*_	P	P	P
Tilia sp.	P		P
Bombacaceae			
cf. _Bombacacidites sp.*_	P		
GENTIANALES			
Gentianaceae			
Pistillipollenites mcgregorii*	P		
PARIETALES			
Dipterocarpaceae			
Parashorea pseudogoldiana	L		L

	Phase 1	Phase 2	Phase 3
MYRTALES			
Myrtaceae			
<u>Eugenia americana</u>		L	
ERICALES			
Ericaceae			
<u>Rhododendron (?) sp.</u>		L	
RUBIALES			
Caprifoliaceae			
<u>Viburnum pugetensis</u>			L
<u>Viburnum sp.</u>		L	
Incertae sedis			
Dicotyledonae			
<u>Macclintockia pugetensis</u>			L
<u>Pesavis tagluensis</u>	P		P
<u>Proteacidites sp.</u>*	P	P	P
<u>Verrucatosporites sp.</u>			P
form genera			
<u>Retitricolpites sp.</u>			P
<u>Retitricolporites sp.</u>			P
<u>Tricolpites sp.</u>*	P		
<u>Tricolpate sp.</u>*	P		
<u>Tricolporate sp.</u>*	P		
bisaccate sp.*	P		P
<u>Pityosporites sp.</u>			P
cf. <u>Plicatopollis sp.</u>*			P
<u>Monosulcites sp.</u>*			P

SYMBOLS: * = data from Newman, 1981.
L = leaf fossil
P = pollen
S = spore

SITE LOCALITY DATA:

Phase 1: Leaf fossils: Derby Canyon, Clark Canyon
Pollen: Cannon Mine, Cashmere, Derby Canyon*, North Derby Canyon*

Phase 2: Leaf fossils: Tumwater Mountain, Camas Creek, Van Canyon, Nahahum Canyon, Sunnyslope
Pollen: Sunnyslope Road*

Phase 3: Leaf fossils: Deadhorse Canyon, South Plain, North Plain, Fish Lake, Natapoc Ridge
Pollen: North Plain*, Malaga

Table 3.4: Plant Macrofossil - Pollen Equivalents In Chumstick Paleoflora

family	macrofossil	pollen
Schizaeaceae	Anemia elongata	*Cicatricosisporites sp.
Aspidiaceae	Dryopteris gibbsi	*Laevigatosporites sp.
Pinaceae	Pinus sp.	Pinus sp.
Juglandaceae	Pterocarya pugetensis	*Pterocarya sp.
	Carya sp.	*Caryapollenites sp.
	" "	C. inelagans
	" "	C. veriptes
Betulaceae	Alnus sp.	Alnus sp.
	" "	Alnipollenites verus
Fagaceae	Dryophyllum pugetensis	Cupuliferoipollenites sp.
Ulmaceae	Chaetoptelea sp.	Ulmus sp.
	"	*Ulmoideipites sp.

* = data from Newman, 1981

Table 3.5: Chumstick Paleoflora Indicator Taxa

tropical forest types	temperate forest types	seasonal rainfall
Calkinsia	Salix	Eugenia
Cocculus	Populus	Bombacaceae
Tetracentron	Tetracentron	Ilex
Myristica	Pterocarya	
Litseaphyllum	Platycarya	
Artocarpus	Carya	
Phytocrene	Alnus	
Bombacaceae	Dryophyllum	
Parashorea	Chaetoptelea	
Eugenia	Hamamelis	
	Fothergilla	
	Platanus	
	Rhus	
	Aesculus	
	Ilex	
	Tilia	

Table 3.6: Summary of Characteristics of Chumstick Paleoflora

	n	%
Leaf Margins		
entire	17	41.4
non-entire	24	58.6
Drip-Tips		
present	11	26.8
absent	30	73.2
Coriaceous Texture		
coriaceous	28	68.3
not coriaceous	13	31.7
Organization		
simple	29	70.7
compound	12	29.3
Venation		
pinnate	32	78.0
palmate	9	22.0
Leaf Size Data		
microphyllous	4	9.8
notophyllous	13	31.7
mesophyllous	24	58.5

Table 3.7: Comparison of Chumstick Paleoflora To Modern Plant Communities

	Paratropical rainforest	Subtropical rainforest	Temperate forest	Chumstick flora
Vegetation:				
dominant	broad-leaved evergreen	broad-leaved evergreen	broad-leaved deciduous	broad-leaved evergreen
subordinate		conifers broad-leaved deciduous	conifers	broad-leaved deciduous conifers
% Entire Leaf Margins	57-75%	39-55%	<39%	41%
Leaf Size				
% Meso-phyllous	50-70%	15-30%	n.a.	58%
% Noto-phyllous	30-40%	50-70%	n.a.	32%
% Micro-phyllous	0-5%	10-20%	n.a.	10%

Chumstick data from this study, all other data from Wolfe, 1977

Table 3.8: Comparison of Later Eocene Paleofloras of the Western U.S.

Paleoflora	no. taxa	% entire margin	% micro-phyllous	% noto-phyllous	% meso-phyllous
Susanville (Calif.)	22	68	14	36	50
Middle Clarno Fm. (Ore.)	33	40	60	28	12
Puget Group (Wash.)	41	62	10	56	34
Steel's Crossing (Wash.)	36	75	11	39	50
Chumstick Fm. (Wash.)	41	41	10	32	58
Kushtaka (Alaska)	62	65	16	50	34

Chumstick data from this study
all other data from Wolfe (1971)

Table 3.9: Chumstick Paleoflora Community Structure

Taxa	Floodplain Community	Channel-Margin Community
Ficales	Dryopteris, Cyathea	Dryopteris
Salicaceae	Salix	Salix, Populus
Menispermaceae	Cocculus, Calkinsia	Calkinsia
Tetracentraceae	Tetracentron	Tetracentron
Myristicaceae	Myristica	Myristica
Lauraceae	Litseaphyllum	Litseaphyllum
Juglandaceae	Pterocarya,Vinea,Carya	
Betulaceae	Carpinus	Alnus
Fagaceae	Dryophyllum	
Ulmaceae	Chaetoptelea	
Moraceae	Artocarpus	
Hamamelidaceae	Fothergilla	
Platanaceae	Platanus, Macginitiea	Platanus, Macginitiea
Leguminosae		Mimosites (?), Cladrastis
Anacardaceae	Rhus	
Icacinaceae	Phytocrene	Phytocrene
Hippocastanaceae	Aesculus	
Sapindaceae	Thouinopsis	
Dipterocarpaceae	Parashorea	Parashorea
Myrtaceae	Eugenia	
Ericaceae		Rhododendron
Caprifoliaceae	Viburnum	Viburnum
Incertae sedis	Macclintockia	

Table 3.10: Chumstick Paleoflora Forest Composition

Taxa	"Lowland" Forest	"Upland" Forest
Ficales	Dryopteris, Cyathea	Dryopteris
Salicaceae	Salix, Populus	
Menispermaceae		Cocculus, Calkinsia
Tetracentraceae	Tetracentron	Tetracentron
Myristicaceae	Myristica	Myristica
Lauraceae	Litseaphyllum	Litseaphyllum
Juglandaceae	Pterocarya, Carya	Pterocarya, Vinea
Betulaceae	Alnus	Alnus, Carpinus
Fagaceae		Dryophyllum
Ulmaceae	Chaetoptelea	Celtis
Moraceae	Artocarpus	
Hamamelidaceae	Hamamelis, Fothergilla	
Platanaceae	Platanus	Platanus, Macginitiea
Leguminosae	Mimosites	Mimosites, Cladrastis
Anacardaceae	Rhus	
Icacinaceae		Phytocrene
Hippocastanaceae		Aesculus
Sapindaceae	Thouinopsis	
Tiliaceae	Tilia	Tilia
Dipterocarpaceae	Parashorea	Parashorea
Myrtaceae	Eugenia	
Ericaceae		Rhododendron
Caprifoliaceae	Viburnum	Viburnum
Incertae sedis	Macclintockia	

Figure 3.1--Generalized geologic map of northwestern Washington State and southwestern British Columbia showing faults of known Mesozoic and Paleogene displacement, and Paleogene sedimentary units. Abbreviations used on map: Ch - Chumstick Formation, Ck -Chuckanut Formation, M - Manastash Formation, N - Naches Formation, R - Roslyn Formation, S - Swauk Formation, T -Teanaway Formation.

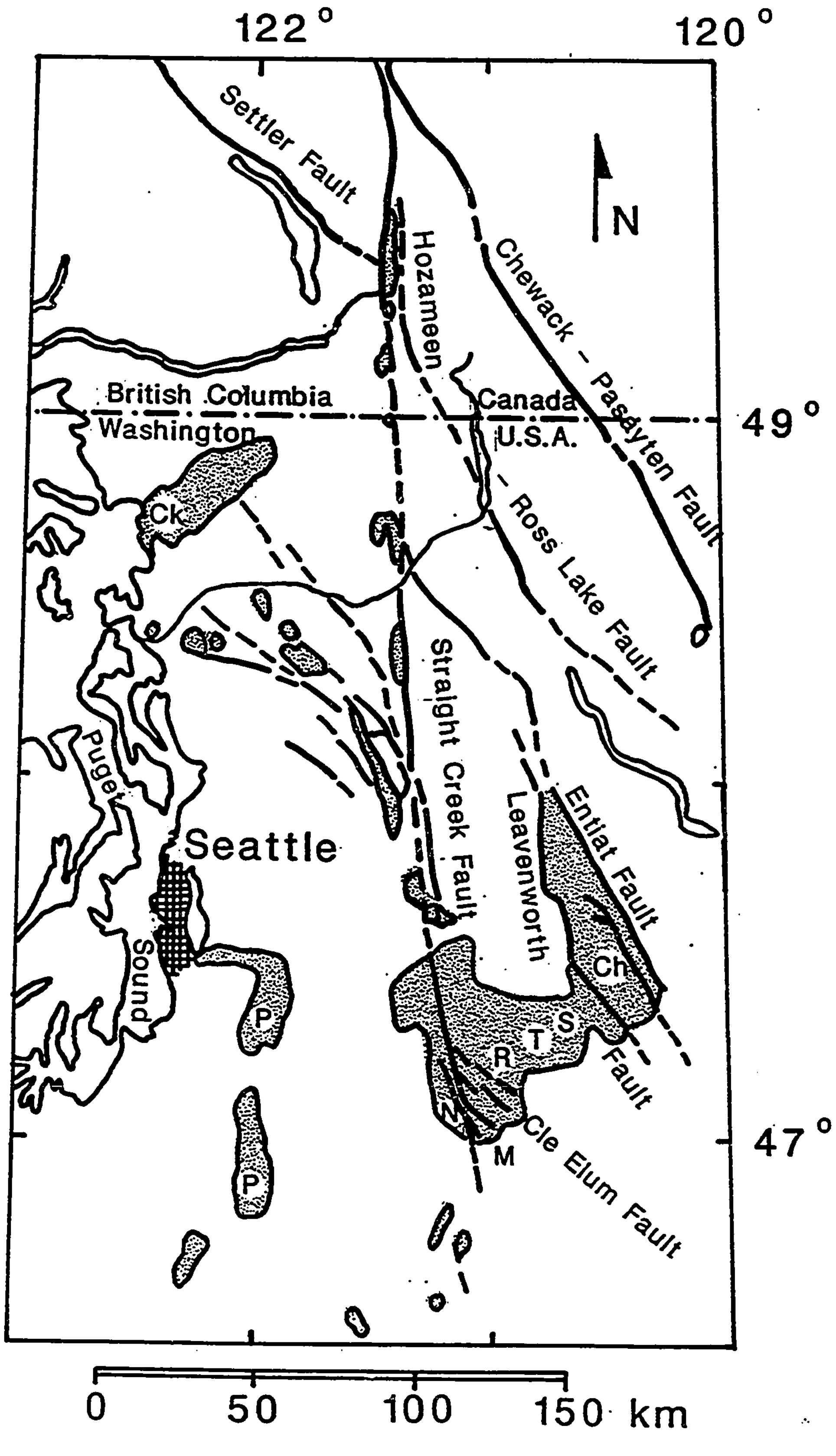
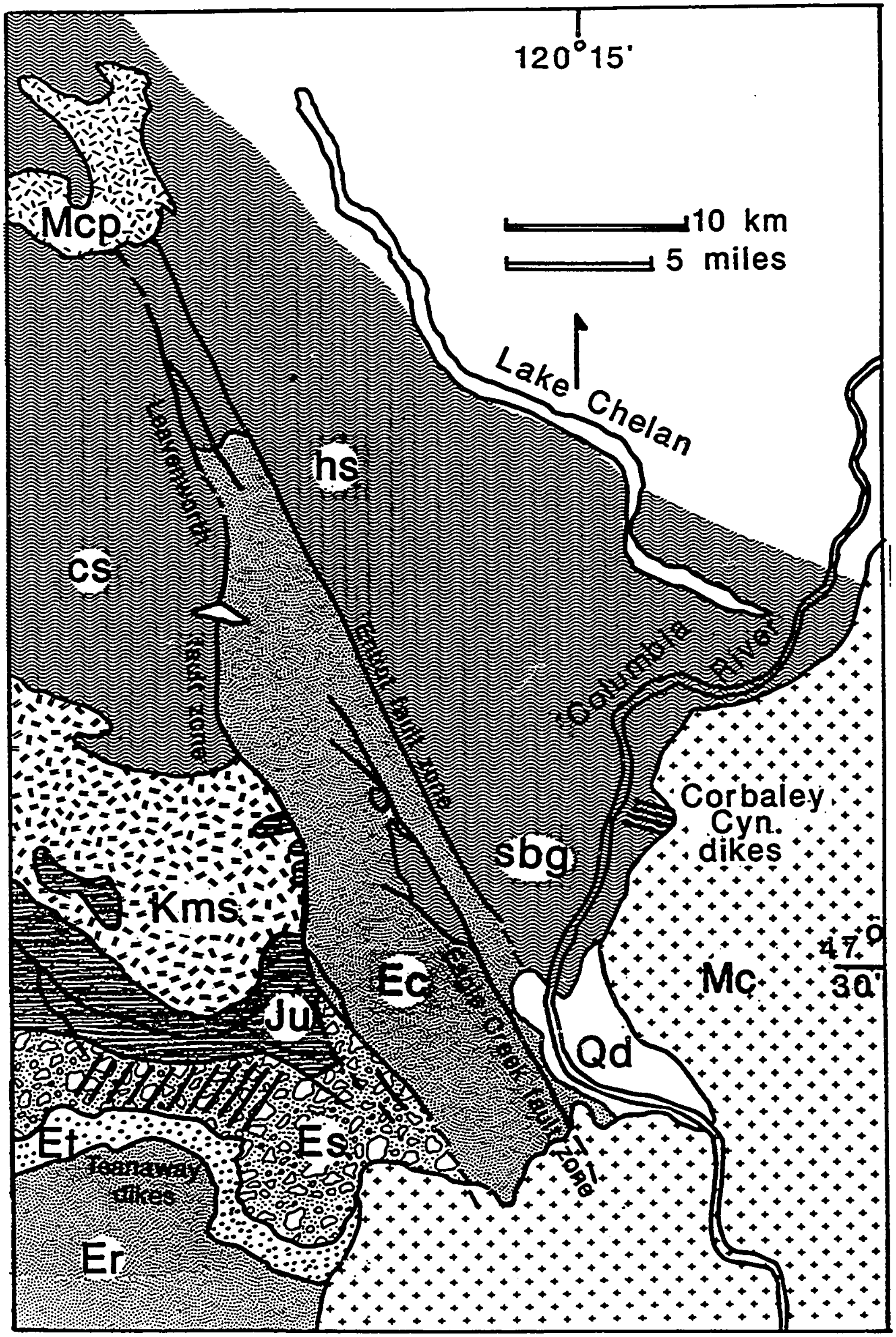

122°
120°
N
Settler Fault
Hozameen
Chewack - Pasayten Fault
British Columbia
Washington
Canada
U.S.A.
49°
Ck
Ross Lake Fault
Straight Creek Fault
Leavenworth
Entiat Fault
Puget
Seattle
Sound
P
Ch
S
T
R
Fault
N
M
Cle Elum Fault
47°
P
0
50
100
150 km

Figure 3.2--Generalized geologic map of the Chumstick basin ("Chiwaukum graben") and related rocks, based on mapping by Tabor et al., 1980, 1982. Abbreviations used on map: cs - Chiwaukum Schist, Ec - Chumstick Formation, Er - Roslyn Formation, Es - Swauk Formation, Et - Teanaway Formation, hs - heterolithic schist, Ju - Ingalls Tectonic Complex, kms - Mount Stuart Batholith, Mc - Columbia River Basalt, Mcp - Cloudy Pass Batholith, Qd - alluvium, sbg - Swakane Biotite Gneiss.



120°15'
10 km
5 miles
Lake Chelan
Mcp
hs
cs
Leavenworth fault zone
Entiat fault zone
Columbia River
Corbaley Cyn. dikes
sbg
Kms
Ec
Eagle Creek fault zone
Ju
Mc
47°30'
Qd
Et
Es
Teanaway dikes
Er

Figure 3.3--Stratigraphic relationships of depositional phases in the Chumstick Formation. Tephrostratigraphy based upon McClincy, 1986. Zircon fission-track ages of tuffs from Gresens et al., 1981; Gresens, 1983; Tabor et al., 1980, 1982; Evans, chapter 4.

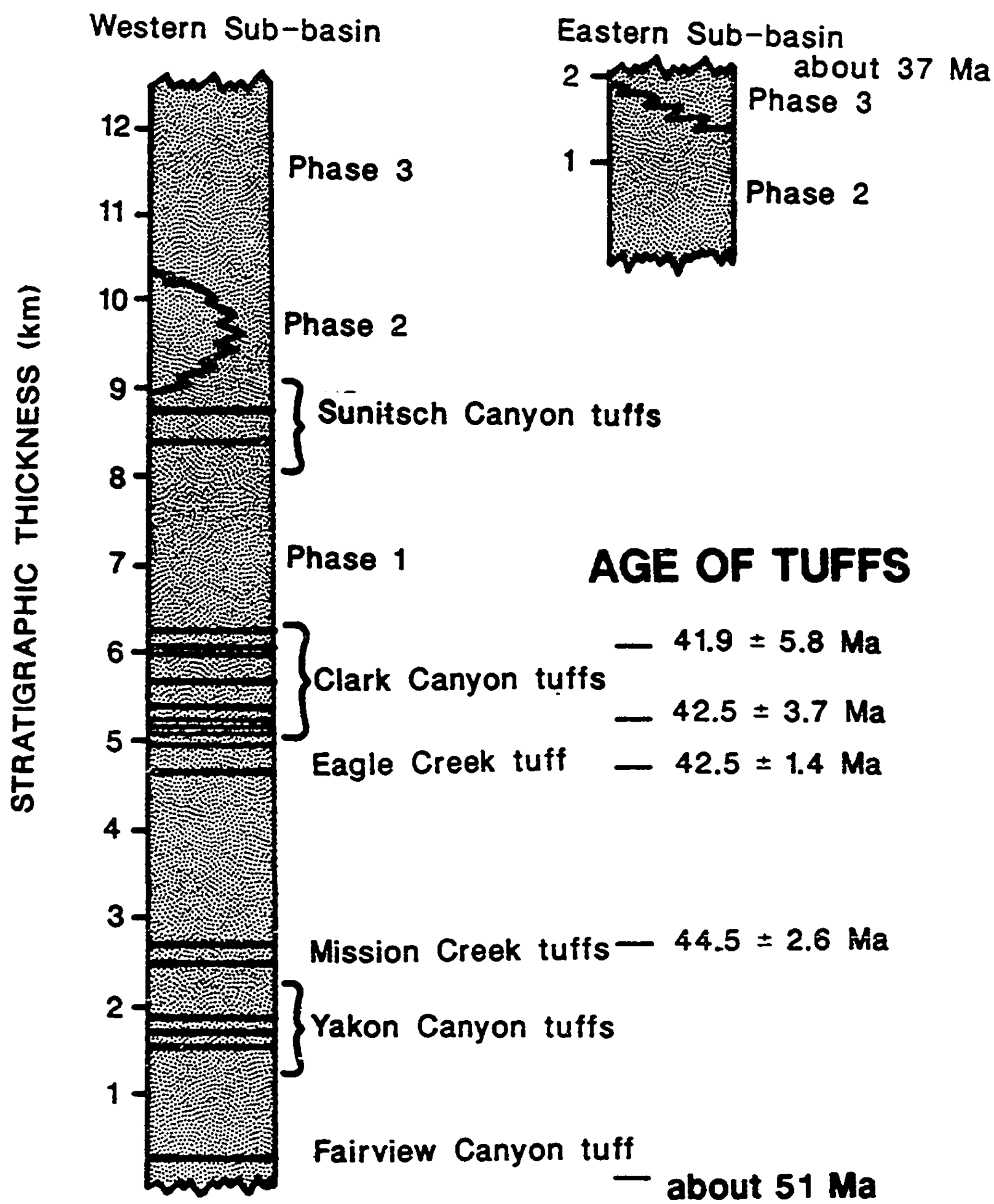
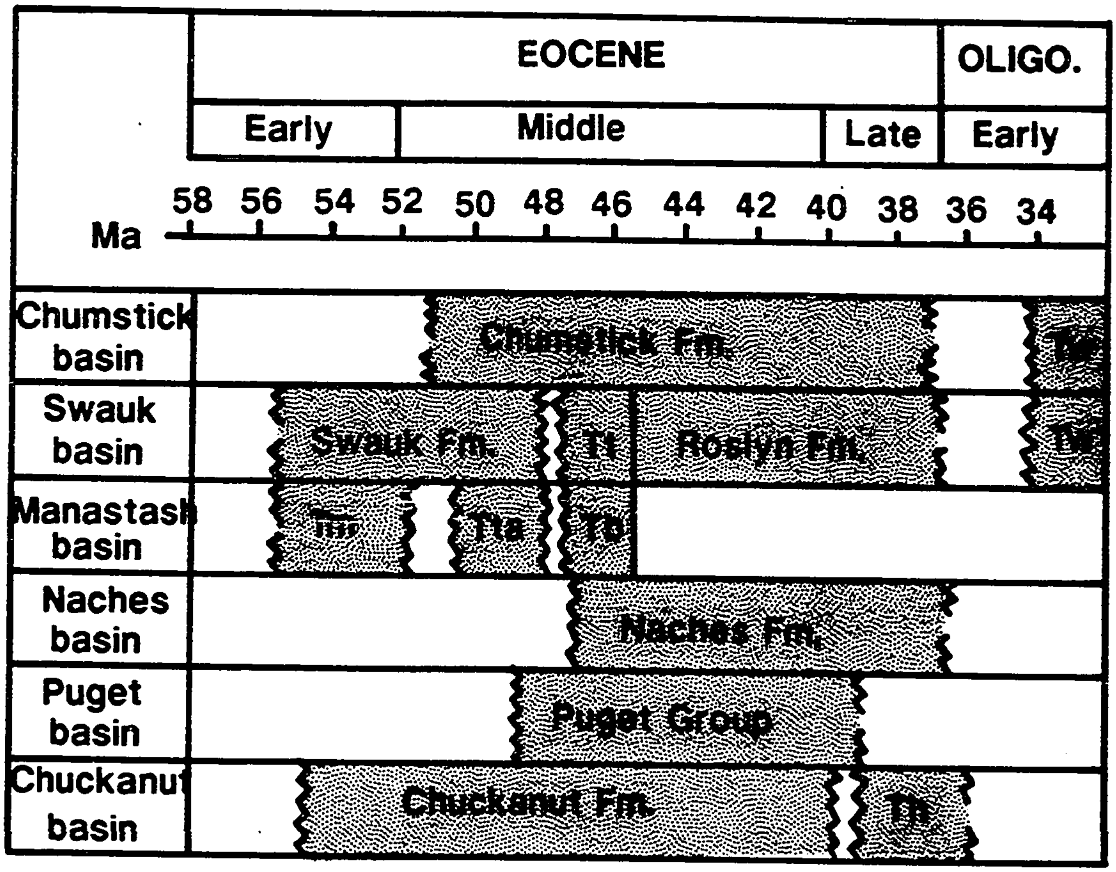
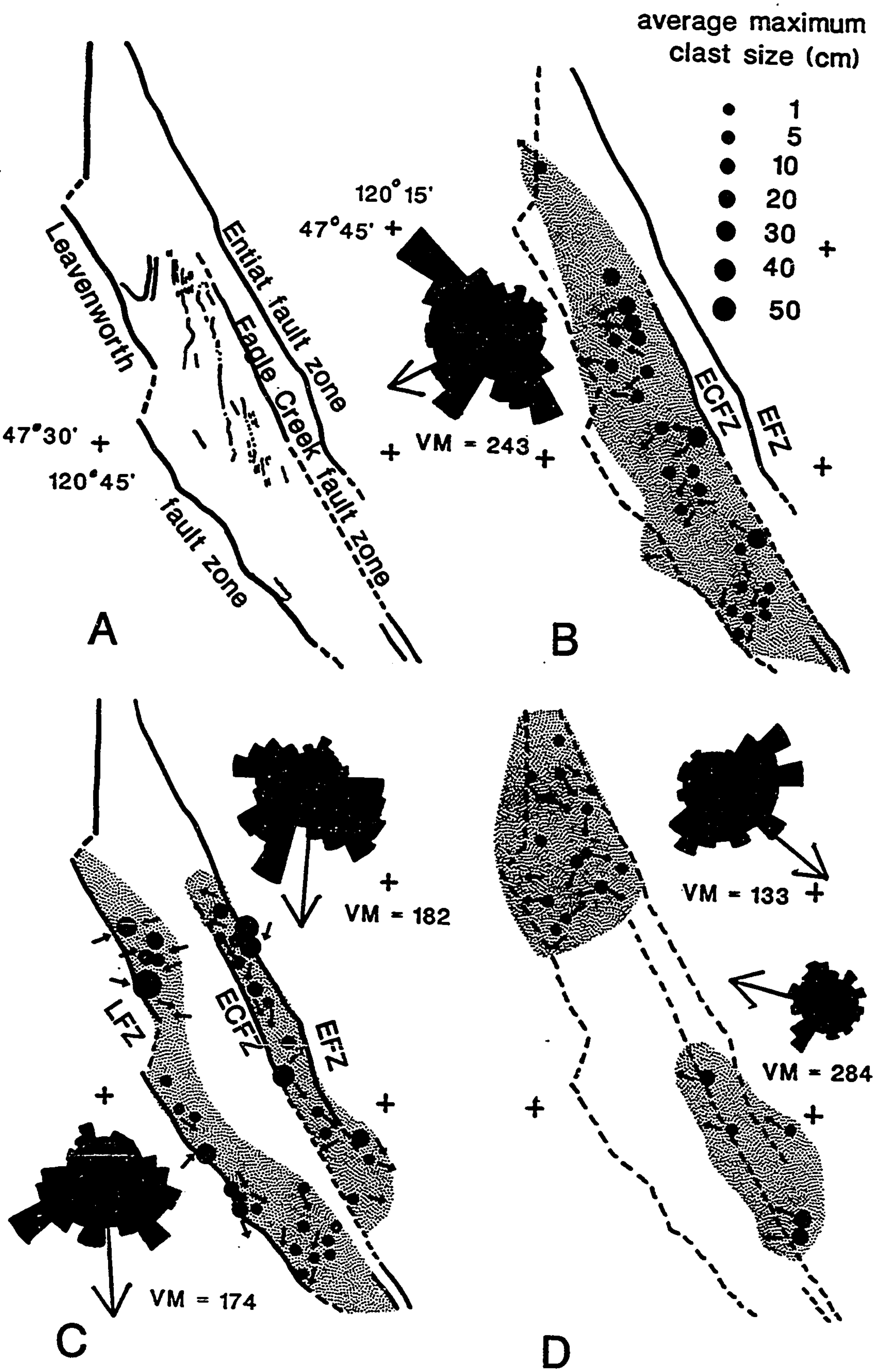

Western Sub-basin
Eastern Sub-basin
about 37 Ma
2
1
Phase 3
Phase 2
STRATIGRAPHIC THICKNESS (km)
12
11
10
9
8
7
6
5
4
3
2
1
Phase 3
Phase 2
Sunitsch Canyon tuffs
Phase 1
AGE OF TUFFS
Clark Canyon tuffs
— 41.9 ± 5.8 Ma
— 42.5 ± 3.7 Ma
Eagle Creek tuff — 42.5 ± 1.4 Ma
Mission Creek tuffs — 44.5 ± 2.6 Ma
Yakon Canyon tuffs
Fairview Canyon tuff
— about 51 Ma

Figure 3.4--Regional stratigraphic relations of Paleogene sedimentary and volcanic units in central and western Washington, based upon data compiled by Johnson, 1985 and Tabor et al., 1984. Chumstick Formation data modified from Evans (chapter 4, this study). Abbreviations used--Tb = Basalt of Frost Mountain, Th = Huntingdon Formation, Tm = Manastash Formation, Tt = Teanaway Formation, Tta = Taneum Formation, Tw = Wenatchee Formation.



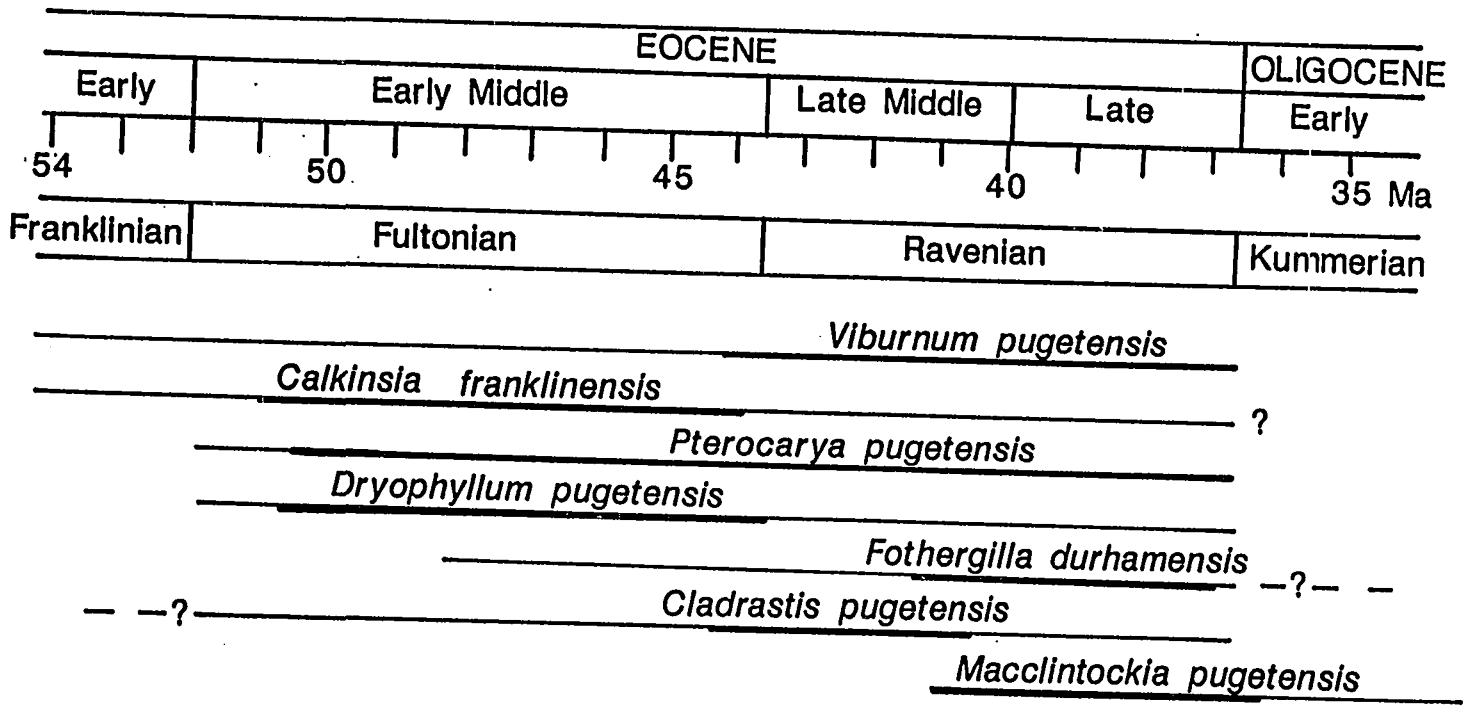
EOCENE
OLIGO.
Early
Middle
Late
Early
Ma
58 56 54 52 50 48 46 44 42 40 38 36 34
Chumstick basin
Chumstick Fm.
Swauk basin
Swauk Fm.
Tt
Roslyn Fm.
Manastash basin
Tta
Naches basin
Naches Fm.
Puget basin
Puget Group
Chuckanut basin
Chuckanut Fm.

Figure 3.5--Basin evolution of the Chumstick Formation. A: Map showing the distribution of interstratified tuffs in the Chumstick Formation (based on mapping by McClincy, 1986). Tuffs are restricted to Phase 1 deposits in the western sub-basin, and young to the northwest. B: Phase 1 deposition (>51 Ma to about 42 Ma). C: Phase 2 deposition (about 42 Ma to about 40 Ma). D: Phase 3 deposition (about 40 to about 37 Ma). Symbols used: small arrows are vector means of paleocurrent distributions; paleocurrent rose shows total paleocurrent data at that time; circles indicate the maximum average clast size at outcrops (key in Figure 3.5b).



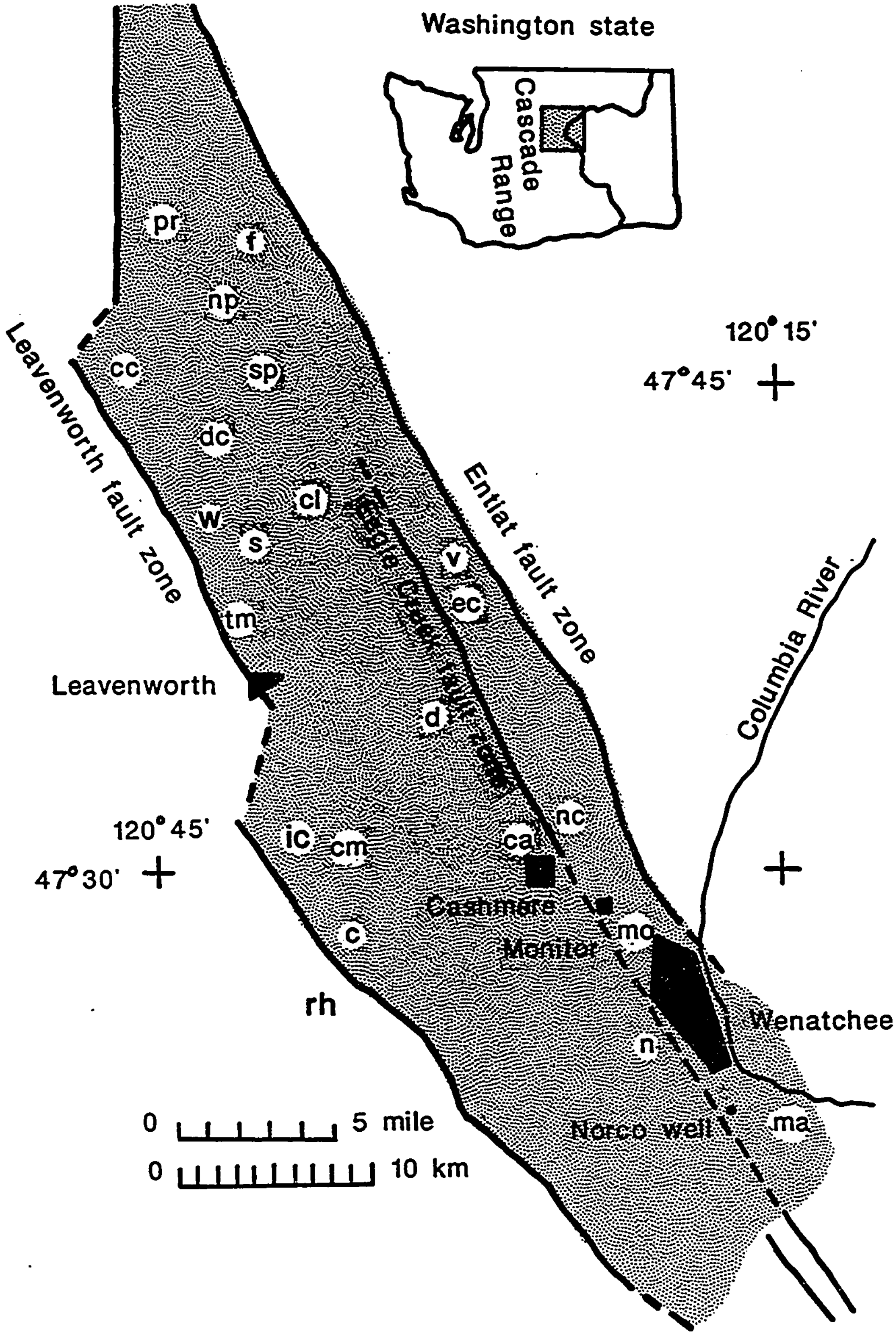
average maximum
clast size (cm)
1
5
10
20
30
40
50
Leavenworth
fault zone
Entiat fault zone
Eagle Creek fault zone
47°30'
120°45'
120°15'
47°45'
VM = 243
ECFZ
EFZ
A
B
LFZ
ECFZ
EFZ
VM = 182
VM = 174
VM = 133
VM = 284
C
D

Figure 3.6--Age relationships of some taxa from the Chumstick paleoflora. The thinner and dashed lines indicate the known or postulated age ranges of taxa (from Wolfe, 1968, 1977). The thicker lines indicate the ages of samples from the Chumstick Formation, these sample ages are constrained by radiometric dates (see text for discussion). Floral Stages from Wolfe (1968).



EOCENE
OLIGOCENE
Early
Early Middle
Late Middle
Late
Early
54
50
45
40
35 Ma
Franklinian
Fultonian
Ravenian
Kummerian
Viburnum pugetensis
Calkinsia franklinensis
?
Pterocarya pugetensis
Dryophyllum pugetensis
Fothergilla durhamensis
?
?
Cladrastis pugetensis
Macclintockia pugetensis

Figure 3.7--Map showing the location of major fault zones, towns (Leavenworth, Cashmere, Monitor, and Wenatchee) and stratigraphic sections discussed in this paper. Abbreviations for stratigraphic sections-- c = Camasland, ca = Cashmere, cc = Cole's Corner, cl = Clark Canyon, cm = Camas Creek, d = Derby Canyon, dc = Deadhorse Canyon, ec = Eagle Creek, f = Fish Lake, ic = Ingalls Creek, ma = Malaga Road, mo = Monitor, n = Number 2 Canyon, nc = Nahahum Canyon, np = North Plain, pr = Pole Ridge, rh = Red Hill, s = Sunitsch Canyon, sp = South Plain, tm = Tumwater Mountain, v = Van Canyon, w = Wright Canyon.



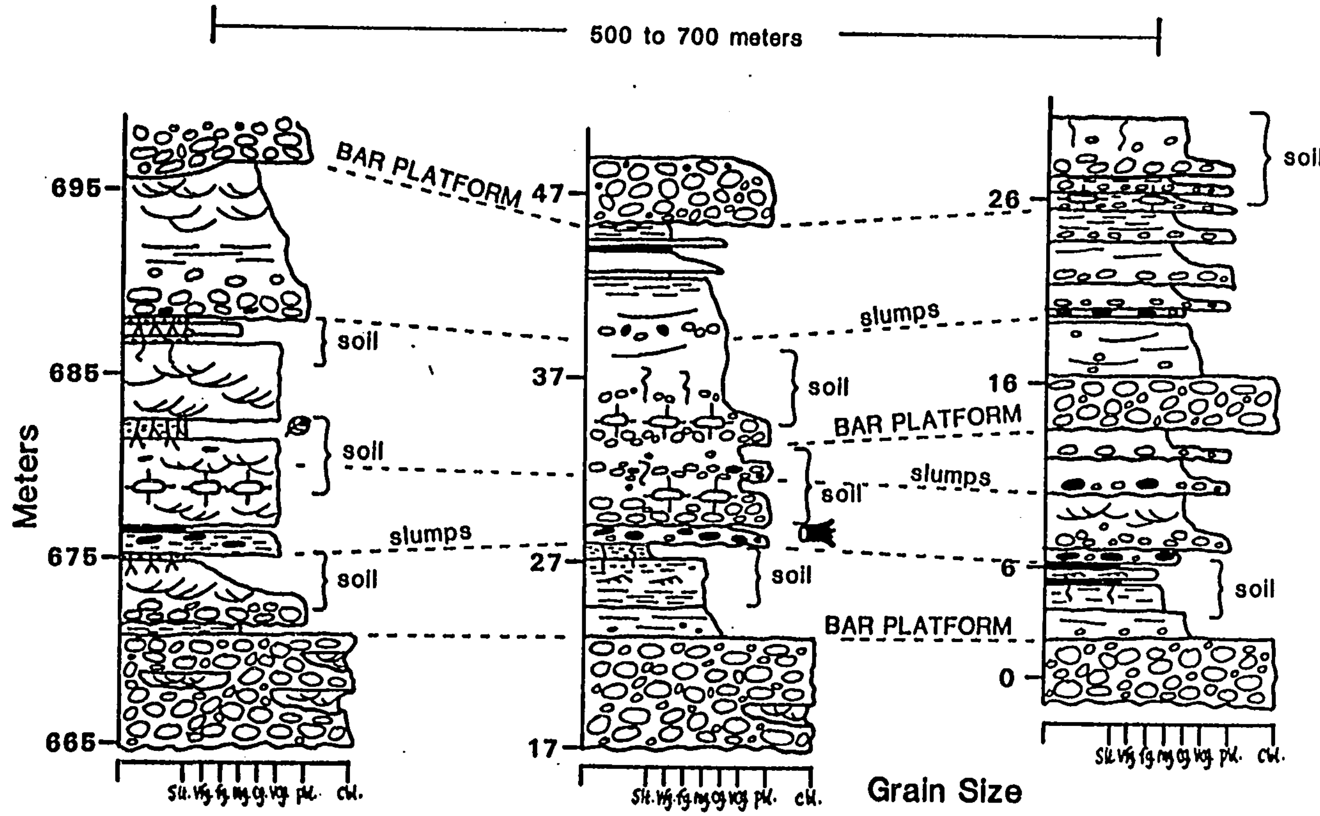
Washington state
Cascade Range
120° 15'
47°45'
Leavenworth fault zone
Entiat fault zone
Columbia River
Leavenworth
120° 45'
47°30'
pr
f
np
cc
sp
dc
cl
w
s
v
ec
tm
d
nc
ic
cm
ca
Cashmere
Monitor
mo
c
rh
Wenatchee
n
Norco well
ma
0 5 mile
0 10 km

Figure 3.8--Photographs of gravel-bedload stream deposits, Clark Canyon section (see Figure 3.7 for location). Top: photograph of typical longitudinal-bar unit, composed of massive to crudely stratified conglomerate overlain by laminated sandstone. Hammer for scale (30 cm). Bottom: photograph of bar-platform deposits, laminated and low angle (< 10^{o}) cross-laminated sandstone with organic partings overlain by laminated siltstone and mudstone. Scale is 15 cm.

Figure 3.9--Lateral relationships of depositional units in gravel-bedload stream deposits, Clark Canyon section (see Figure 3.7 for location). Gravel longitudinal-bar and bar-platform deposits have a sheet-like geometry, while intervening channels have a broadly lenticular geometry. Soil horizons and intraclast layers can be traced laterally.

Key to symbols:

exoclasts	plant macrofossils
intraclasts	rootlets
planar bedding	stumps/logs
planar lamination	infaunal bioturbation
trough x-bedding	bedding surface bioturbation
planar x-bedding	clastic dike
ripple x-lamination	concretion horizon
climbing ripple x-lamination	coarsening-upward sequence
convoluted bedding	



500 to 700 meters
Meters
695
685
675
665
47
37
27
17
26
16
6
0
BAR PLATFORM
BAR PLATFORM
BAR PLATFORM
soil
soil
soil
soil
soil
soil
soil
soil
slumps
slumps
slumps
Slt. vfg. fg. mg. cg. vcg. pbl. cbl.
Grain Size

Figure 3.10--Stratigraphic section of some sand-bedload stream deposits, Malaga Road section (see Figure 3.7 for location). This section comprises vertically stacked, multistory-channel sequences, lateral-accretion surfaces, proximal and distal overbank sequences, and paleosols. Symbols are the same as Figure 3.9. Abbreviations used: LA = lateral-accretion surface, OF = overbank fines.

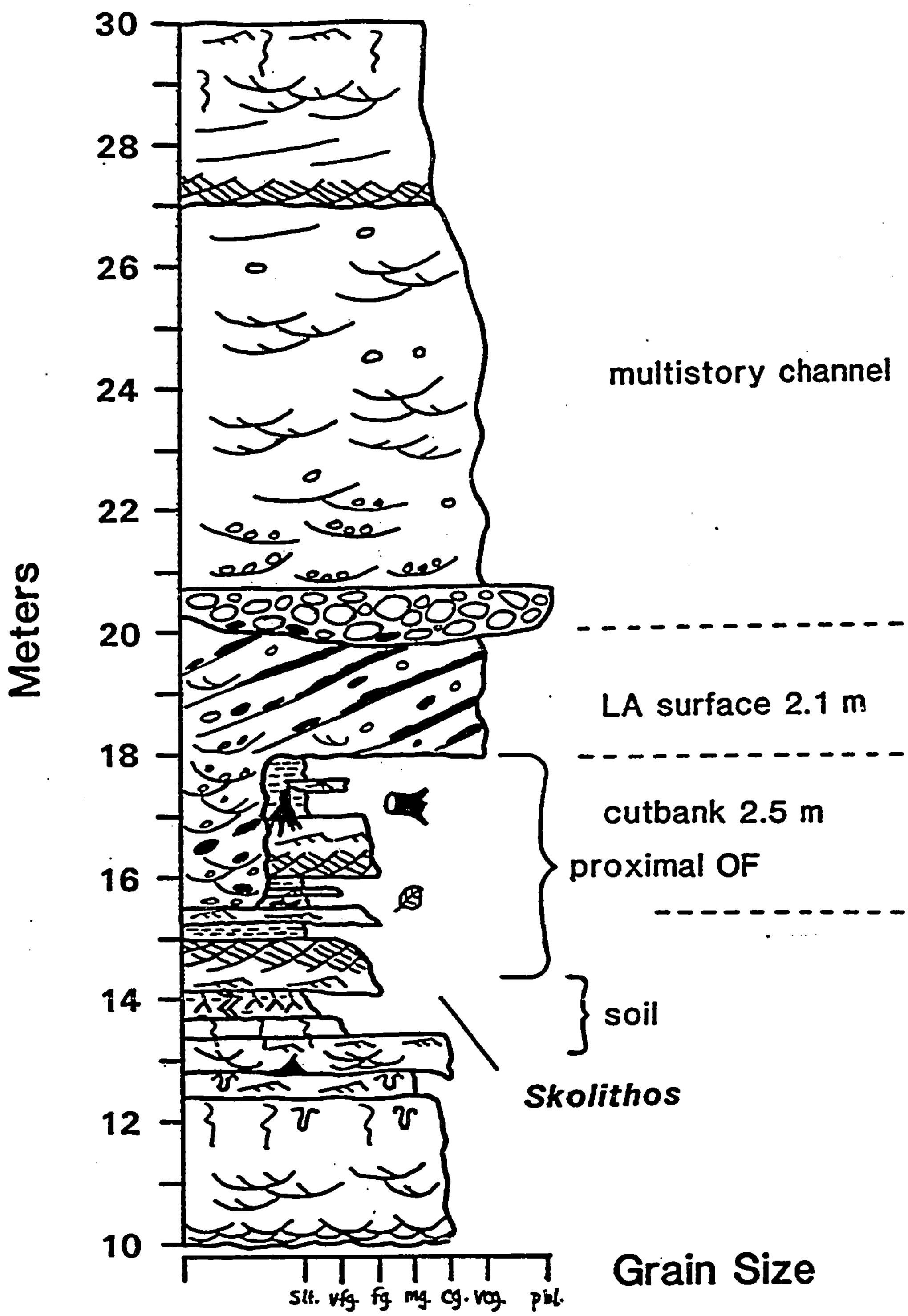
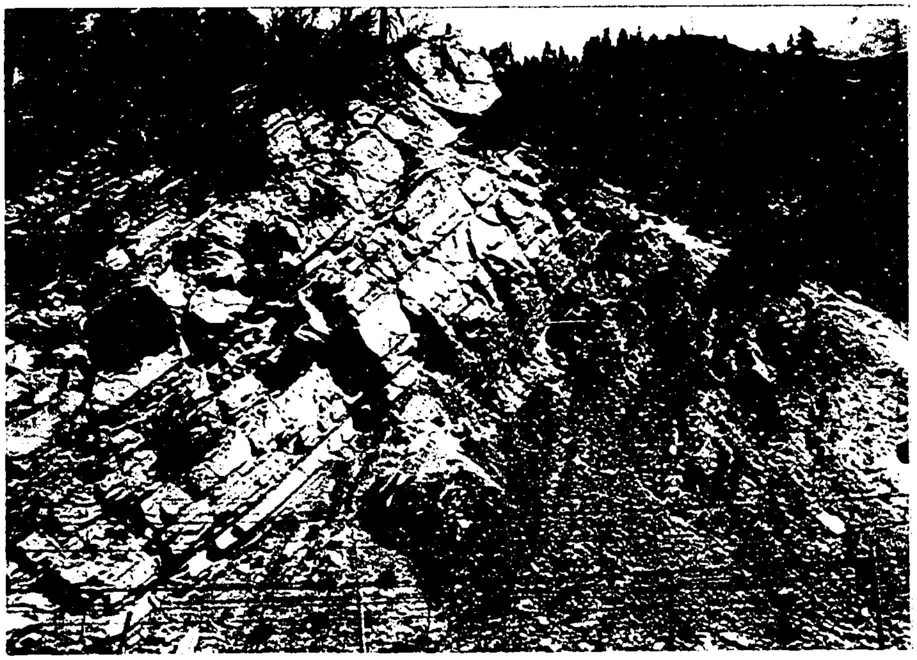

Meters
30
28
26
24
22
20
18
16
14
12
10
multistory channel
LA surface 2.1 m
cutbank 2.5 m
proximal OF
soil
Skolithos
Grain Size
slt.
vfg.
fg.
mg.
cg.
vcg.
pbl.

Figure 3.11--Photographs of some sand-bedload stream deposits. Top: photograph of vertically stacked, multistory-channel deposits, Deadhorse Canyon section (see Figure 3.7 for location). Scale is given by 1.4 meter jacob staff. Bottom: photograph of amalgamated, trough cross-bedded sandstone, Clark Canyon section (see Figure 3.7 for location). Hammer (30 cm) for scale.



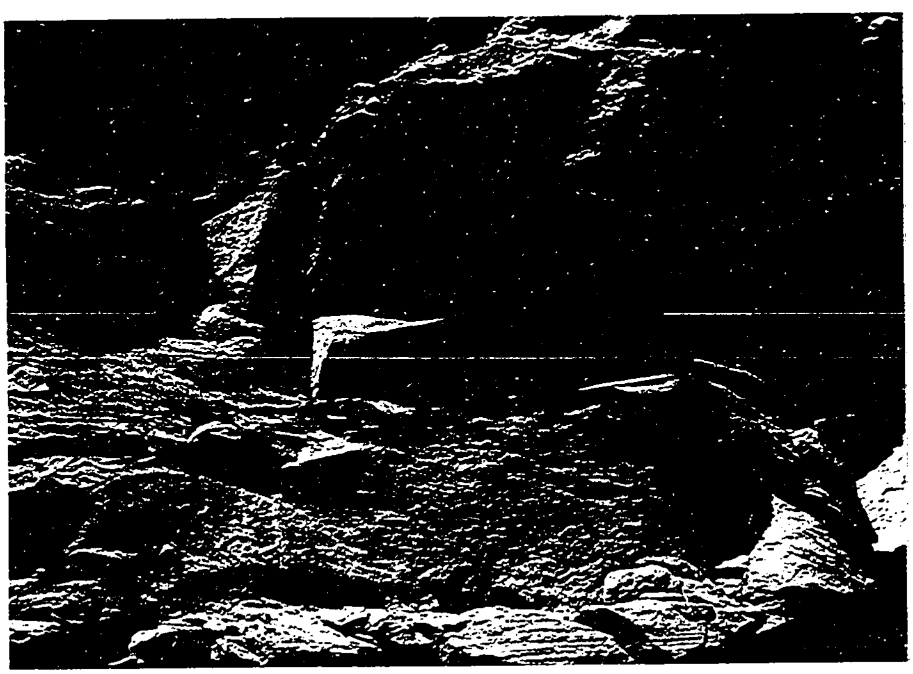
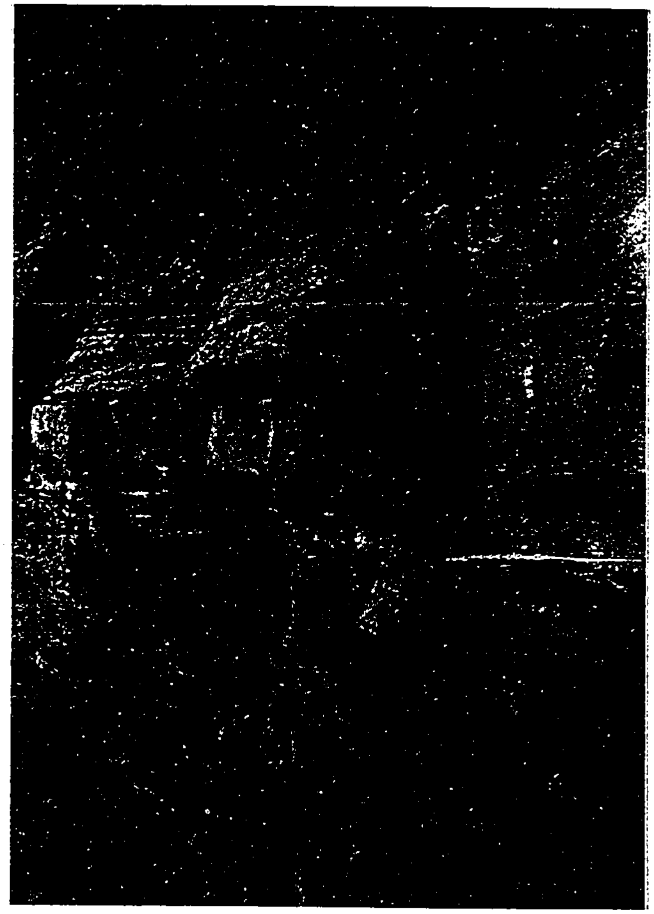


Figure 3.12--Photographs of proximal overbank deposits. Top: profile that thickens- and coarsens-upward from massive mudstone (Fm) to laminated mudstone and siltstone (Fl) to amalgamated ripple cross-laminated sandstone (Sr), then thins- and fines-upward. This sequences probably represents a levee deposit (from Malaga Road section, see Figure 3.7 for location, hammer is 30 cm). Bottom: photograph of sand stringers in siltstone and mudstone, Clark Canyon section. Scale is 15 cm.



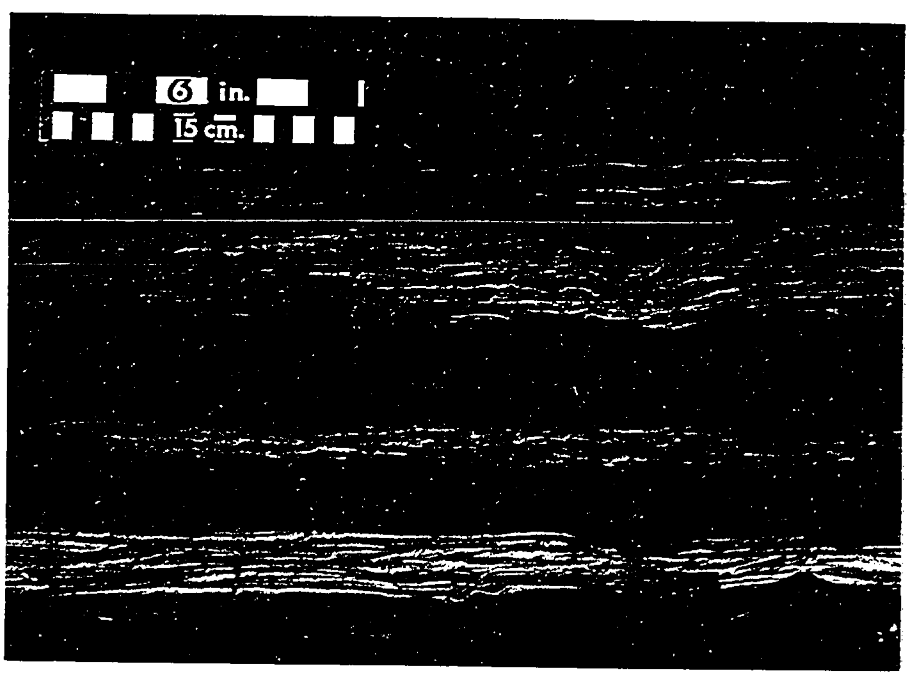
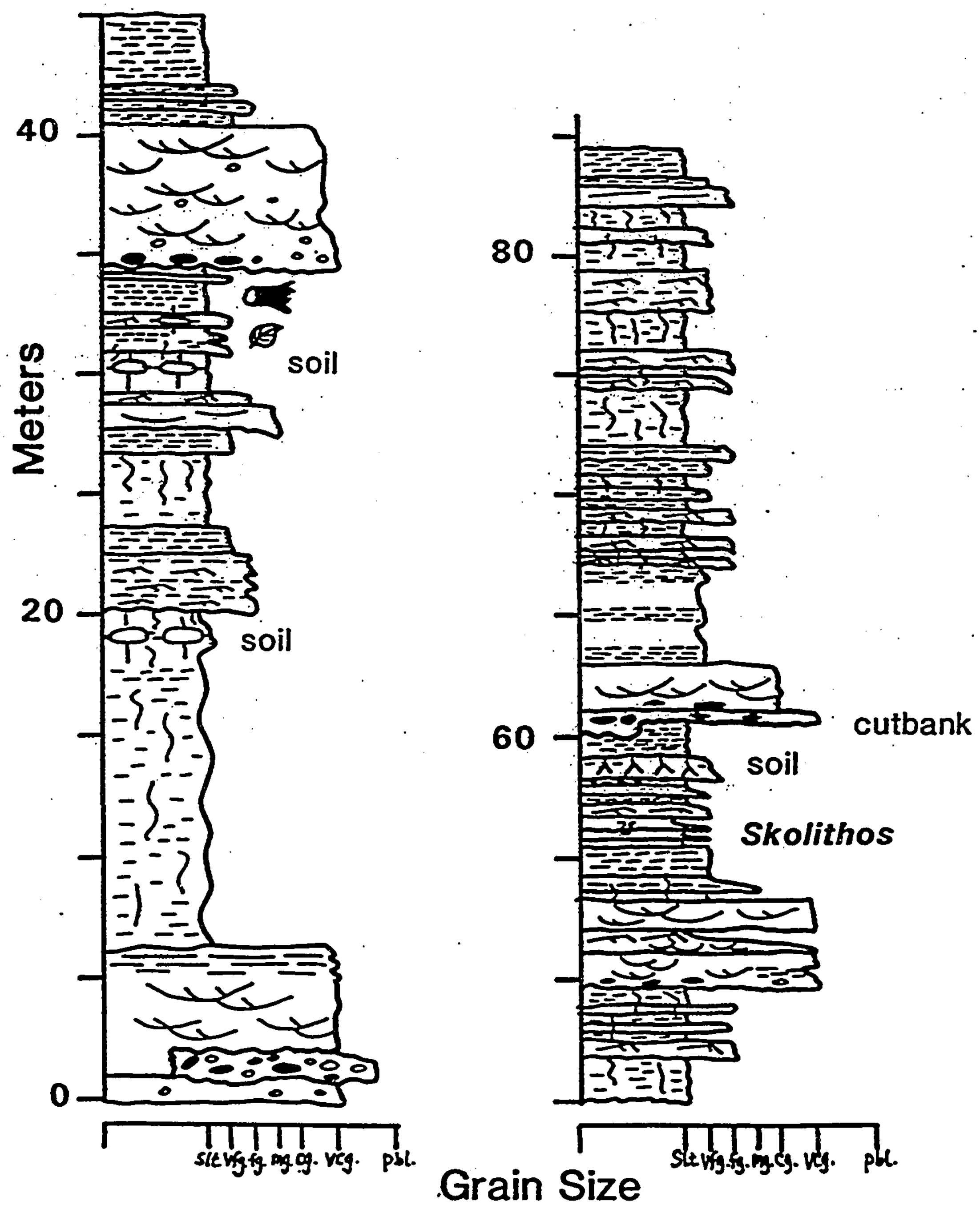

6 in.
15 cm.

Figure 3.13--Stratigraphic section of some mixed-load stream deposits, Pole Ridge section (see Figure 3.7 for location). These deposits comprise isolated channel-fill deposits; vertically stacked, multistory-channel deposits; proximal and distal overbank sequences, and soils. Symbols are the same as Figure 3.9.



40
20
0
Meters
soil
soil
80
60
cutbank
soil
Skolithos
Slt. Vfg. fg. mg. cg. vcg. pbl.
Grain Size

Figure 3.14--Stratigraphic section of mixed-load stream deposits from part of the lacustrine-deltaic system that filled the eastern sub-basin. The Monitor section (see Figure 3.7 for location) comprises extensively bioturbated channel and overbank sequences, with mud-plugs, massive channel-fills, and paleosols. Symbols are the same as Figure 3.9.

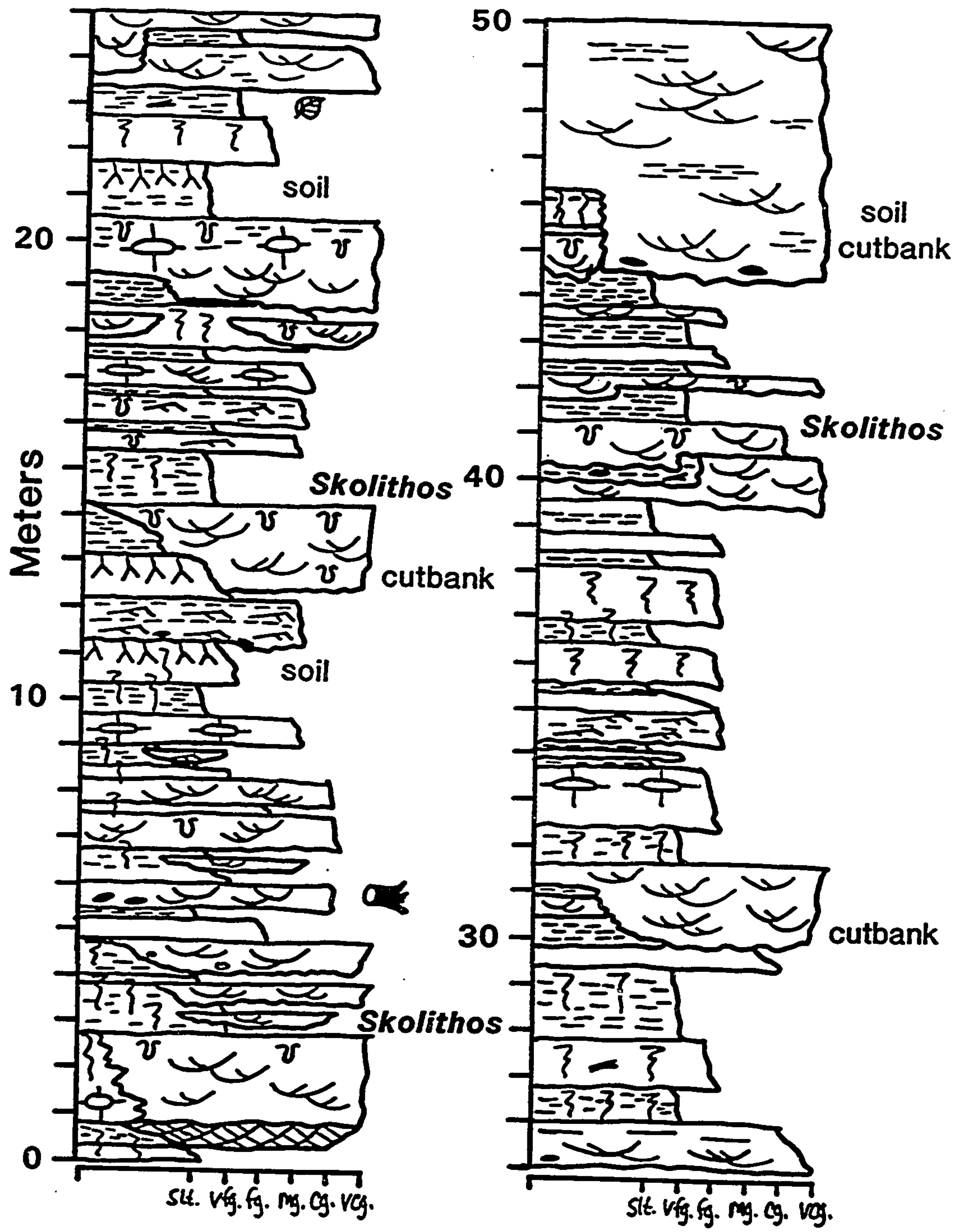
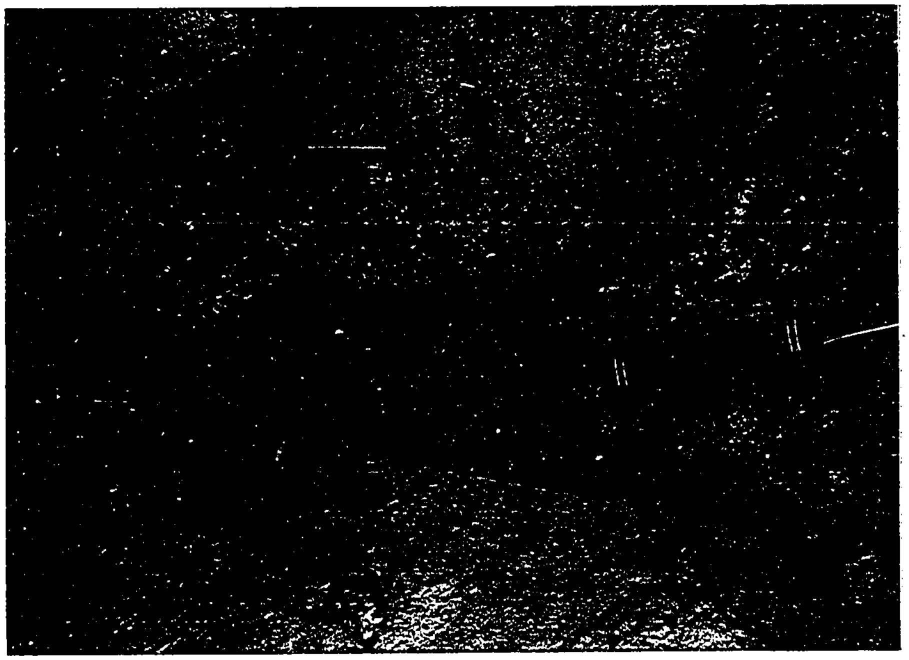

Meters
0
10
20
30
40
50
soil
cutbank
Skolithos
soil
cutbank
Skolithos
cutbank
Skolithos
soil
cutbank
slt. vfg. fg. mg. cg. vcg.
slt. vfg. fg. mg. cg. vcg.

Figure 3.15--Photographs of in-place rootlets in the Chumstick Formation. Left: rootlets branching downward in mudstone and siltstone (below knife), rootlet length about 25 cm (scale: knife = 8 cm). Right: rootlets branching downward from in-place stump, rootlet length >110 cm (scale: hammer = 30 cm).



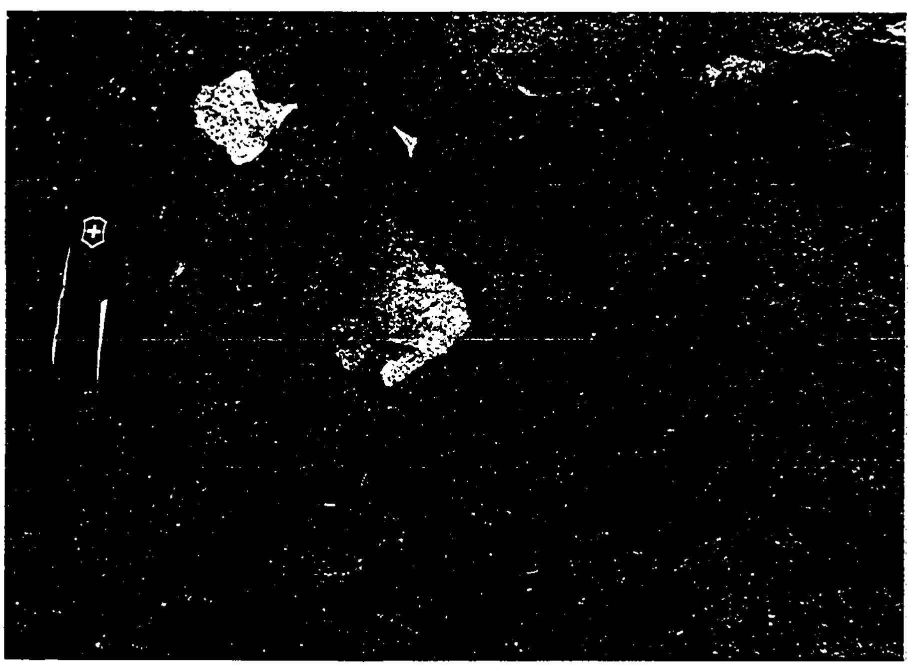
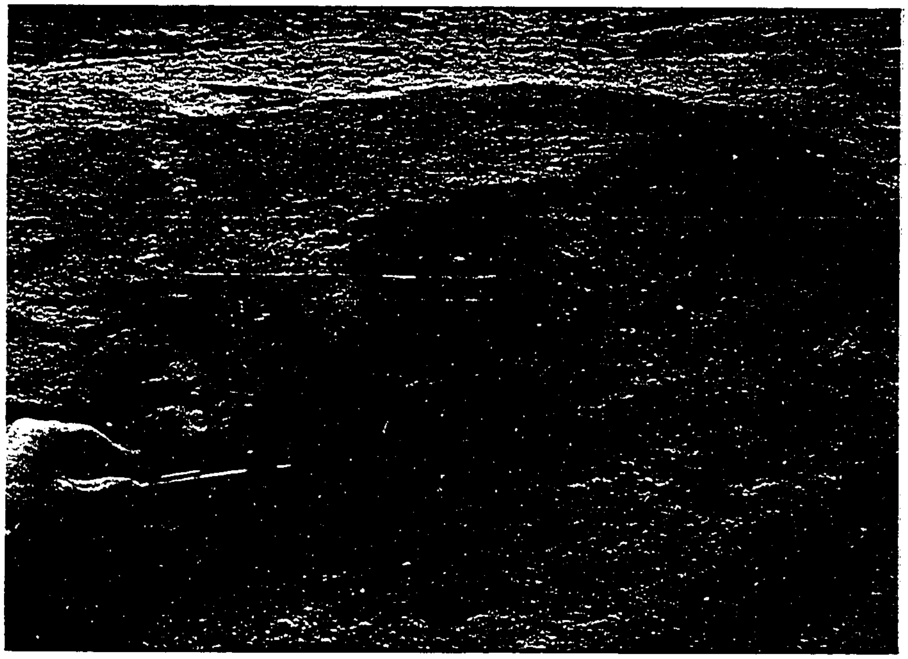
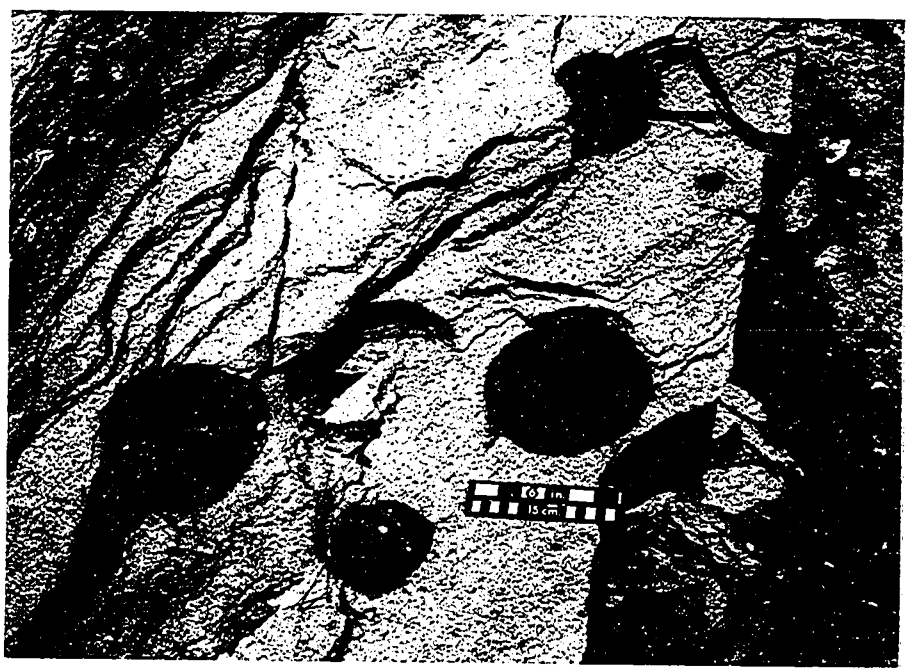


Figure 3.16--Rhizoliths in the Chumstick Formation. Top: photograph of a bedding plane surface showing concentric root molds that are carbonate cemented and infilled with sand, photo also shows surface traces (scale: knife = 8 cm). Bottom: photograph of of a vertical section showing an example of rhizosheaths, rootlets surrounded by an accumulation of calcium carbonate (scale: hammer = 30 cm).

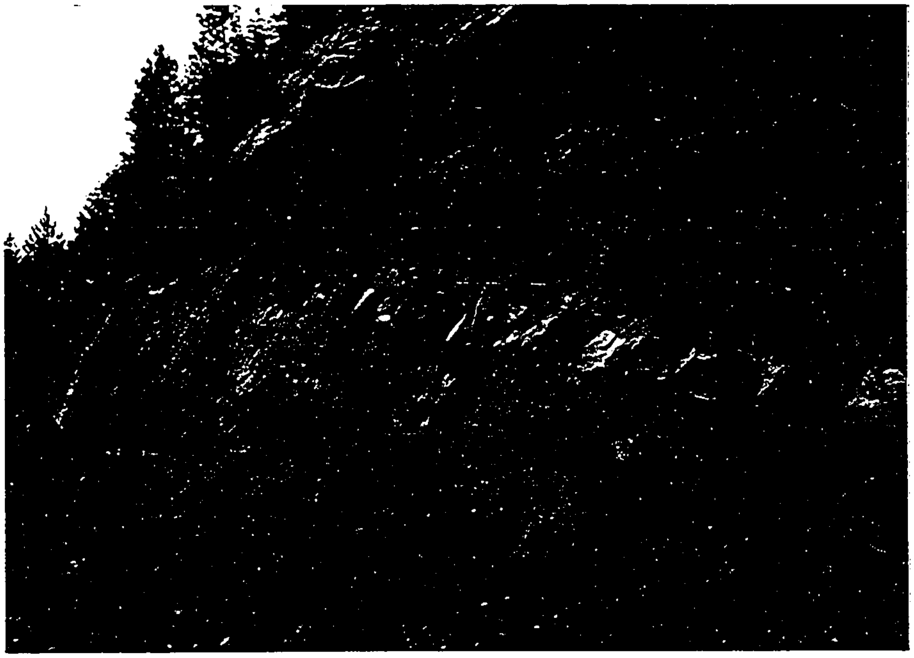
Figure 3.17--Photographs of calcic horizons (Cca or K horizons) in Chumstick paleosols. Top: horizon of isolated and coalesced calcrete nodules in coarse-grained sandstone (scale: pencil = 15 cm). Abbreviation: P = pedogenic layer. Bottom: bedding-plane view of isolated and coalesced nodules (scale = 15 cm).





6 in.
15 cm

Figure 3.17 (con't.)--Top: photograph of the Cole's Corner section, showing paleosol about 2.5 meters thick. Paleosol consists of massive mudstone (Fm), rooted mudstone to fine-grained sandstone (Fr), and continuous (stage IV) calcic horizon (P) overlying trough cross-bedded and planar-bedded sandstone (St and Sh, respectively). Hammer for scale (40 cm). Bottom: resedimented calcrete nodule at the base of channel sequence, (scale = 15 cm).



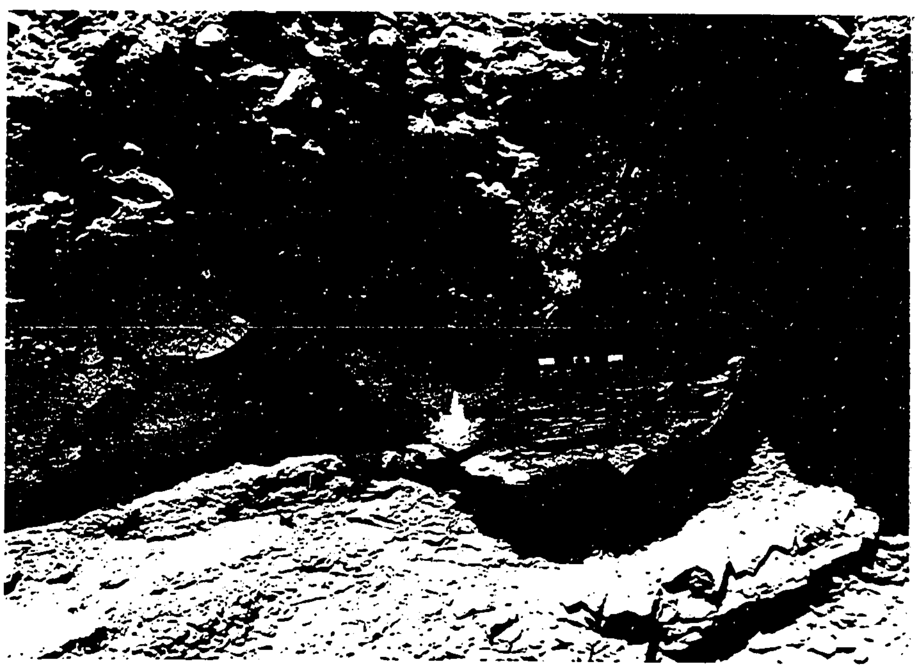
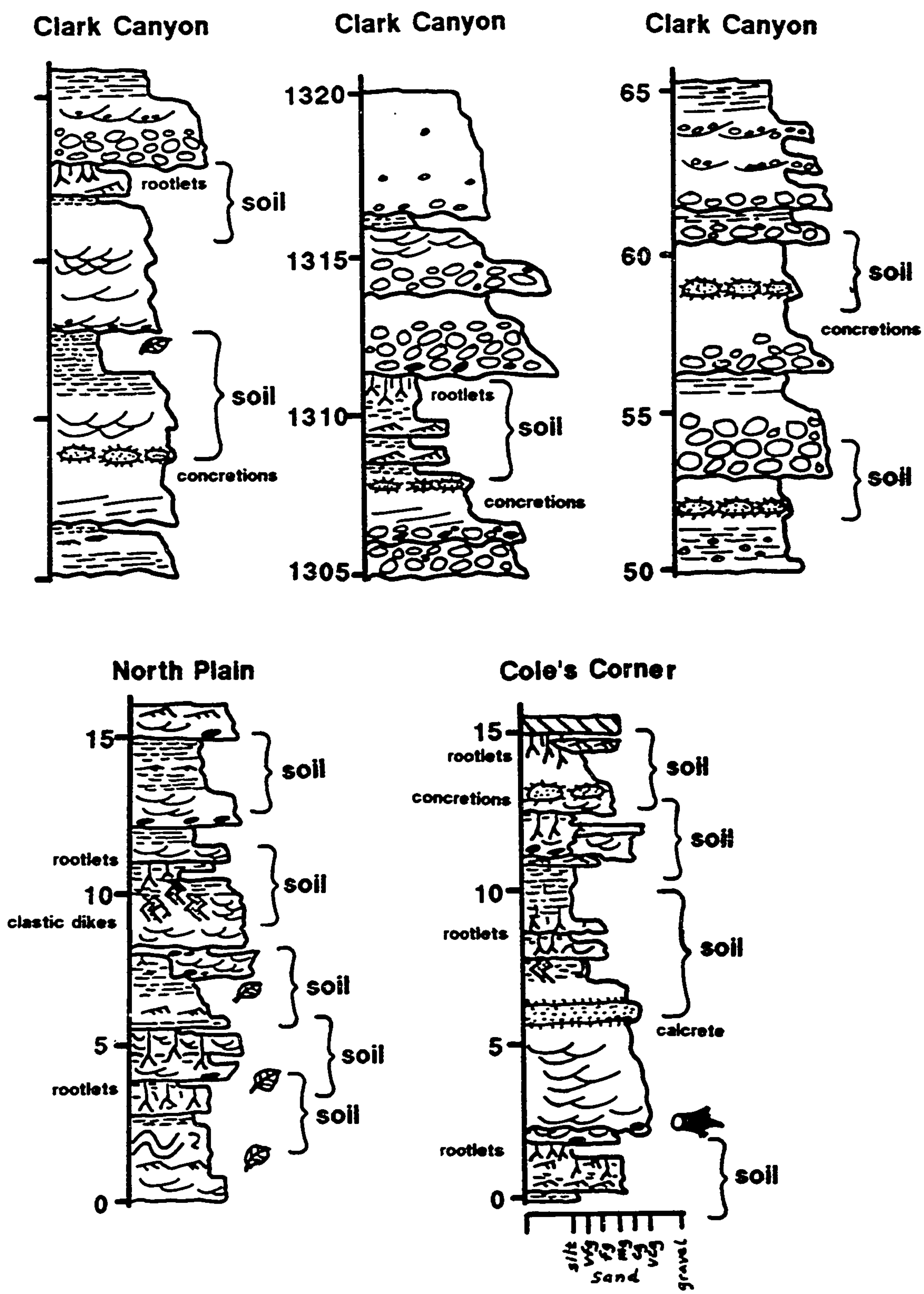
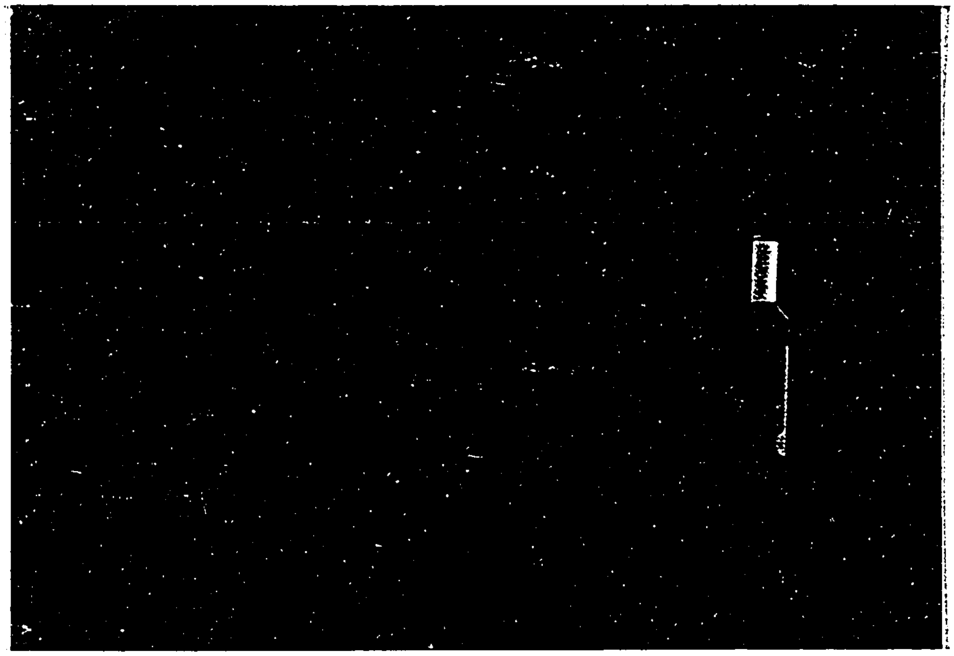


Figure 3.18--Stratigraphic sections of some typical paleosols in the Chumstick Formation, see Figure 3.7 for locations. The thickness of each soil has been estimated as the depth from the massive or rooted fine-grained deposit to the pedogenic concretion horizon. Symbols are the same as Figure 3.9.



Clark Canyon
rootlets
soil
soil
concretions
Clark Canyon
1320
1315
1310
1305
rootlets
soil
concretions
Clark Canyon
65
60
55
50
soil
concretions
soil
North Plain
15
10
5
0
soil
rootlets
soil
clastic dikes
soil
soil
rootlets
soil
Cole's Corner
15
rootlets
concretions
soil
soil
10
rootlets
soil
calcrete
5
rootlets
0
soil
silt
Sand
gravel

Figure 3.19--Photographs of vertical burrows in the Chumstick Formation. Top: vertical, unbranched, unlined burrows filled with coarse-grained sandstone, length up to about 2 cm (scale: upper part of pencil = 8 cm). Bottom: photograph of upward burrows, fine-grained sandstone and siltstone fill into overlying coarse-grained sandstone, length about 3 cm (scale: upper part of pencil = 8 cm).



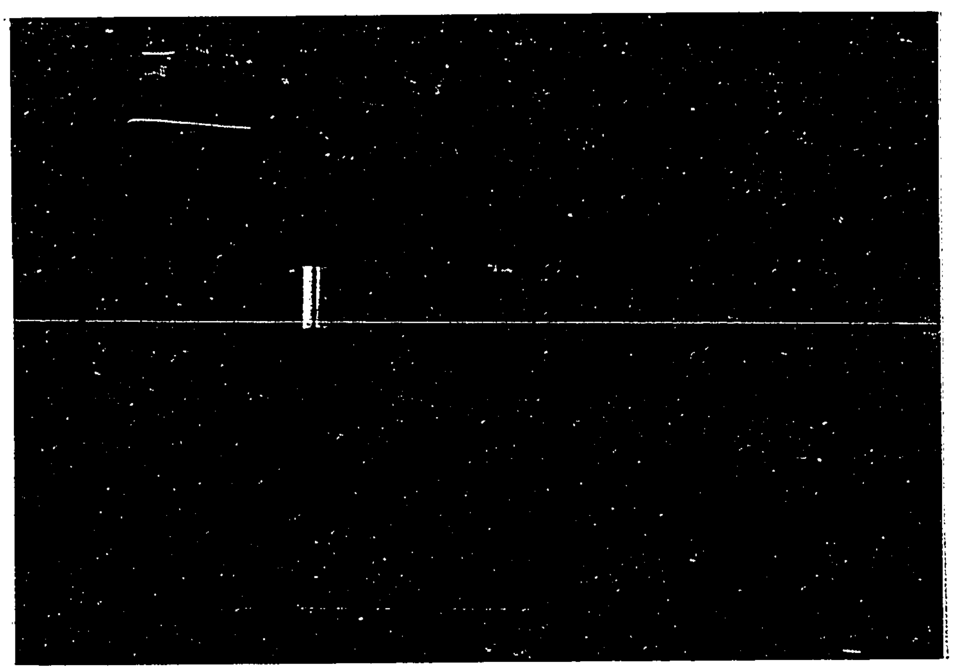


Figure 3.20--Correlation between mean annual temperature and the percentage of taxa with smooth (entire) leaf margins in a plant community. Data compiled by Wolfe (1978), with Chumstick paleoflora data indicated by diamond.

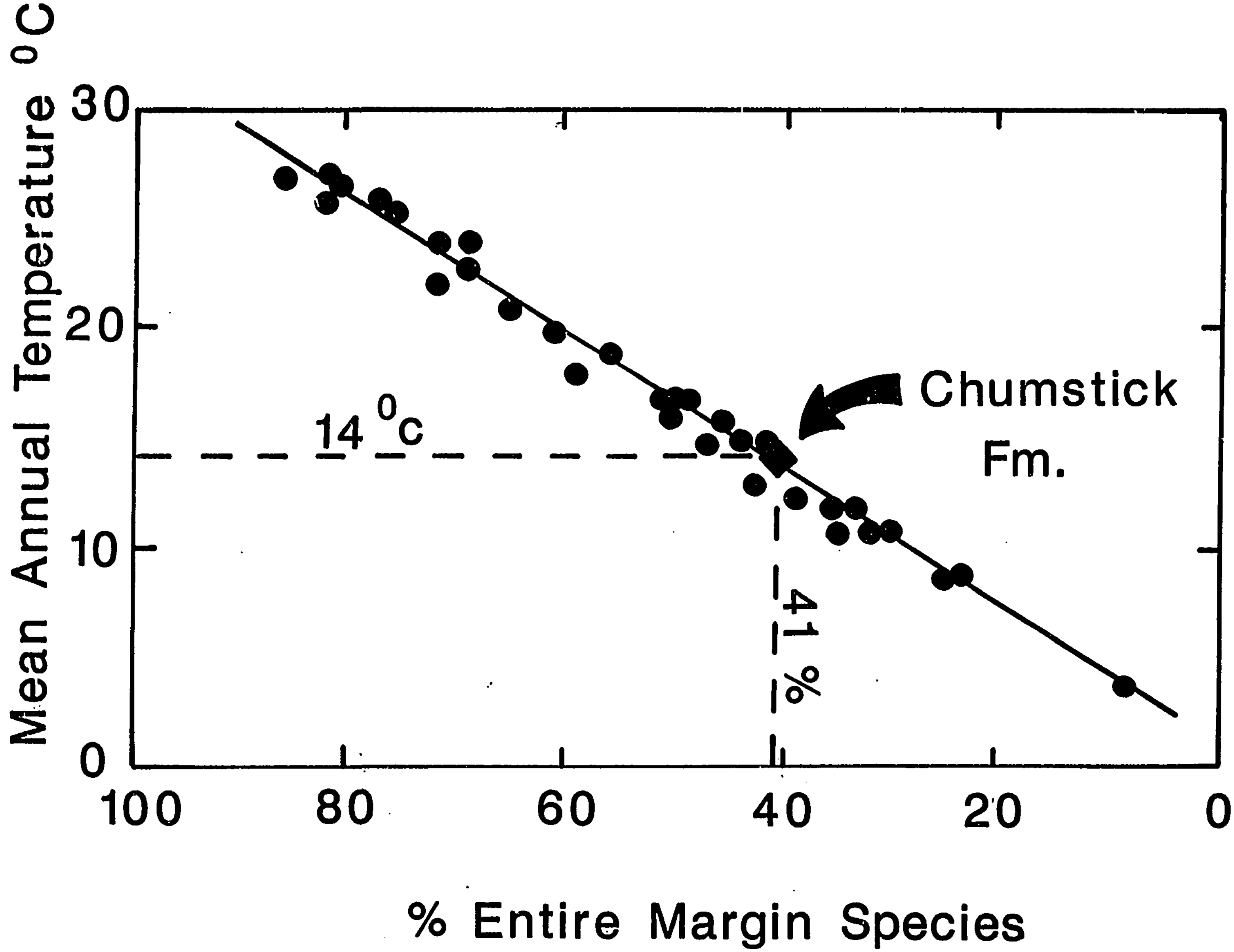
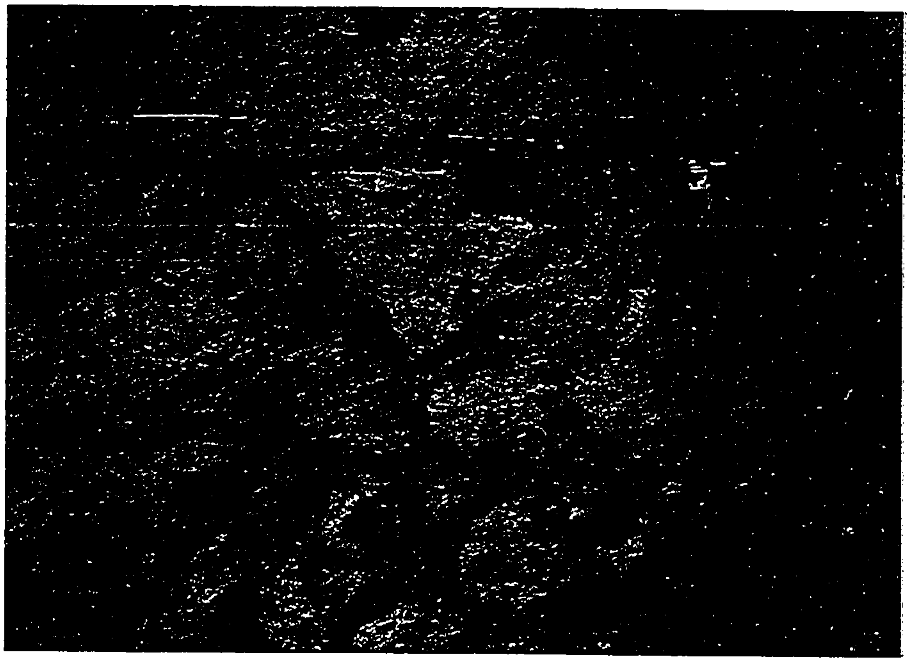
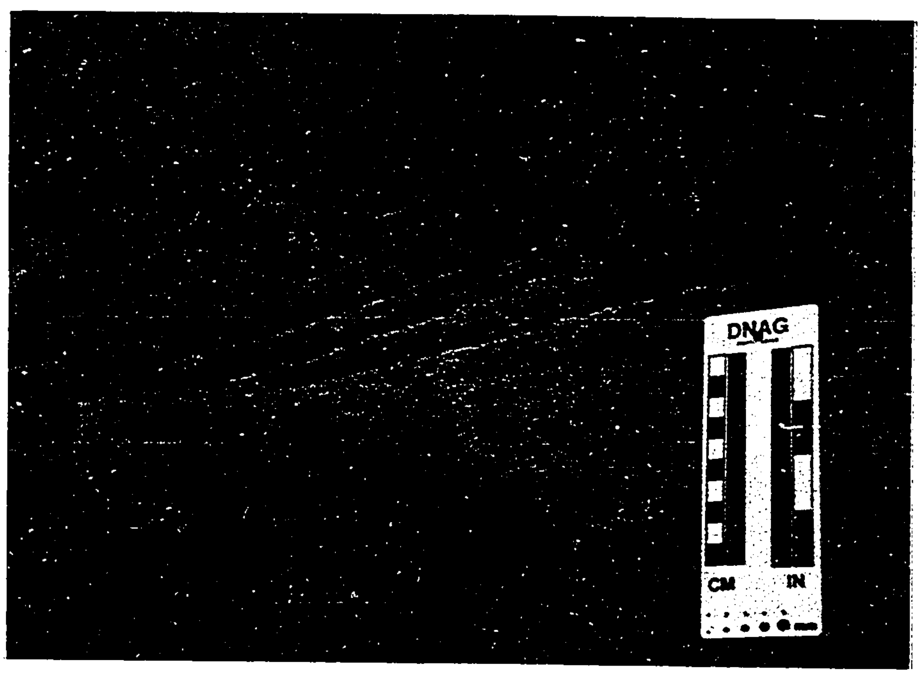

Mean Annual Temperature °C
30
20
10
0
100
80
60
40
20
0
% Entire Margin Species
14 °c
41 %
Chumstick
Fm.

Figure 3.21--Photographs of mud drapes on the avalanche faces of trough cross-bedded sandstone (St), from Clark Canyon (A) and Deadhorse Canyon (B) sections. These features are interpreted as a chute channel sequence that had intervals of abandonment and reactivation. Scale: hammer = 40 cm.




DNAG
CM
IN

Chapter 4

TECTONICS AND BASIN EVOLUTION OF A PALEOGENE WRENCH-FAULT BASIN: CHUMSTICK FORMATION, WASHINGTON (U.S.A.)

INTRODUCTION TO CHAPTER 4

Strike-slip faulting played a significant role in the tectonic evolution of the Pacific Northwest during the Tertiary (Davis et al., 1978; Ewing, 1980; Gresens, 1982a,b; Tabor et al., 1984; S.Y. Johnson, 1982, 1984a, 1985). Major regional faults in the Pacific Northwest include the north-trending Straight Creek fault and northwest-trending Chewack-Pasayten, Ross Lake-Hozameen, Settler, Entiat, Leavenworth, and Cle Elum faults (Figure 4.1). Localized Paleogene sedimentary basins associated with these faults were filled by unusually thick (up to 12 km, this study), nonmarine sequences (S.Y. Johnson, 1985). It is now widely recognized that the sedimentary and deformational histories preserved in strike-slip basins provide important constraints on interpretations of regional tectonic history (e.g., Crowell, 1974a,b; Ballance and Reading, 1980; Biddle and Christie-Blick, 1985).

Only two of the Paleogene sedimentary basins in the Pacific Northwest have been subjects of detailed basin analysis, prior to this study. S.Y. Johnson (1982, 1984b,c, 1985) has shown that the Lower to Middle Eocene Chuckanut basin displays many of the characteristics of strike-slip basins, including great sediment thickness, rapid subsidence rates, rapid vertical and lateral changes in sedimentation style, syndepositional magmatism, and a deformation style in accord with a system of right-lateral shear. Similar characteristics have been observed in the Lower to Middle Eocene Swauk Formation, in the region between the Straight Creek and Leavenworth faults, where changes in provenance and reversals in paleocurrent directions indicate tectonic control of drainage. In addition, deformation and syndepositional magmatism is in accord with a system of right-lateral shear (Taylor, 1985; Roberts, 1985; Fraser, 1985; Johnson, 1985; Taylor et al., in press). Similar characteristics have been observed in the Chumstick Formation (Gresens, 1982a,b), Naches Formation (Tabor et al., 1984), Manastash Formation (Tabor et al., 1984), and Puget Group (Vine, 1969; Buckovic, 1979; Turner et al., 1983); and Johnson (1985) has proposed that all of these are strike-slip basins.

Although there is strong evidence to suggest a strike-slip basin origin for some of these basins, several problems remain. In certain cases (e.g., the Puget Group) there is no direct relationship between facies and major faults. Even in the well-studied cases, the timing and style of faulting associated with these basins is not sufficiently well constrained, for example, none of the evidence precludes a tectonic history of syndepositional extensional faulting followed by a post-depositional episode of transpression. A related question is whether regional faulting was relatively continuous or episodic.

A second concern is the degree to which these sedimentary basins were connected. Studies of sandstone petrology (Frizzell, 1979; S.Y. Johnson, 1984a) and the trace element composition of sandstones (Byrnes, 1985) indicate that the basins had similar sediment sources. On the other hand, local variability in deformation history might suggest each behaved as a separate basin. Did these basins form continuous, regional depositional systems at times? This question has important implications for regional hydrocarbon exploration (Gresens and Stewart, 1981; Lingley and Walsh, 1986; Taylor et al., in press). A detailed basin analysis of the Chumstick Formation was conducted to gain insight into these questions.

CHUMSTICK FORMATION

Stratigraphy and Age

The Chumstick Formation comprises over 12,000 meters of fluvial and lacustrine rocks, mostly deposited in the region between the Entiat and Leavenworth fault zones (Figure 4.2). The stratigraphic position of the Chumstick Formation (Figure 4.3) has been established from palynology (Newman, 1981; Evans, chapter 3), plant macrofossils (Evans, chapter 3), and from radiometric dates from interstratified tuffs and intrusives (Tabor et al., 1980, 1982, 1984; Gresens, 1983; Gresens et al., 1981; Ott et al, 1986; this study). Tuffs in the lower to middle part of the Chumstick Formation provide excellent stratigraphic control in the western part of the basin (Figure 4.4). Chumstick tuffs are between 30 cm and 20 meters thick, have distinctive trace-element chemistries (McClincy, 1986), and form mappable units that have been traced up to 41 km.

The region between the Entiat and Leavenworth faults has been referred to as the "Chiwaukum graben" (Willis, 1953), and Gresens (1983) believed that as many as three stratigraphic units were found there: the Swauk(?), Chumstick, and Wenatchee formations. Gresens (1980) distinguished the Swauk(?) Formation from the Chumstick Formation on the basis of lithologic differences, such as calcium carbonate content or the abundance of fresh biotite versus chloritized biotite. Recent studies, however, have shown that these exposures actually represent hydrothermally altered Chumstick Formation in the zone surrounding the syndepositional intrusives near the city of Wenatchee (Margolis, 1987). Whereas the Chumstick Formation is mostly confined to the "Chiwaukum graben," the Wenatchee Formation is found over a larger region as a blanket deposit unaffected by regional faulting (Gresens, 1980, 1982a). Because the entire fill of the "Chiwaukum graben" is the Chumstick Formation, the simpler term "Chumstick basin" will be substituted in this dissertation. The locations of key stratigraphic sections and other features are given in Figure 4.5.

Paleoclimate and Depositional Environments

The Chumstick Formation demonstrates excellent preservation of plant macrofossils, pollen, spores, and paleosols. The Chumstick paleoflora has characteristics somewhat intermediate between tropical and subtropical floras, and shows evidence for seasonal (i.e., monsoonal) rainfall patterns (Evans, chapter 3). By comparison with other regional paleobotanical studies (Wolfe, 1968; Wolfe and Wehr, 1986), the paleogeographic setting of the Chumstick basin was about 150 km inland from the coast at an elevation of about 350 to 550 meters, and the vegetation is interpreted as a type of montane rainforest (Evans, chapter 3).

Depositional environments include gravel-bedload streams, sand-bedload streams, mixed-load streams, and lacustrine environments. The depositional system is interpreted as a humid-tropical, alluvial-fan system, consisting of moderate-sized rivers dissecting vegetated fault scarps of moderate to low relief (Evans, chapter 2).

Proximal fan regions are dominated by gravel-bedload stream deposits. These fluvial systems are composed of massive coarse-grained channel-fills, gravel longitudinal-bar units, and overbank deposits. Large cliff exposures of these deposits reveal there was a lateral stacking of broadly lenticular channels, which probably indicates that channel switching (avulsion) of fan-head channels occurred in the proximal regions of these fans. Measured sections in the fan-head regions show that meter-scale fining-upward depositional units are organized into megasequences 15 to 40 meters thick which fine-upward or coarsen-upward (Figure 4.6). The megasequences are interpreted to show successive construction and abandonment of individual fan lobes, probably as a response to tectonic activity (e.g., Steel and Gloppen, 1980).

Distal portions of these fans are dominated by gravel-bedload stream deposits and sand-bedload stream deposits. These deposits include gravel longitudinal-bar units, massive channel-fills, three-dimensional dune deposits, bar-platform deposits, and over-bank deposits. Detailed tephrostratigraphy has shown that distal fan deposits formed sheet-like depositional units (Figure 4.7). Intervals of non-deposition and incision on the distal fan are indicated by the local correlation of individual paleosol units and of siltstone intraclast horizons, respectively, the latter representing cohesive channel-bank failures.

The bulk of the basin fill consists of sand-bedload streams, mixed-load streams, and lacustrine deposits. The fluvial deposits are organized into vertically stacked, multistory-channel sequences which have an overall ribbon-like geometry, and related sandy overbank deposits with a sheet-like geometry (Figure 4.8). There are some lateral-accretion deposits, but the prevalence of vertically stacked depositional units suggests that the rate of vertical aggradation greatly exceeded the rate of lateral channel migration. Part of the basin was filled by a lacustrine-deltaic depositional system that comprises mixed-load stream deposits, delta-front turbidites (Figure 4.9) and lacustrine basin-plain deposits.

Chumstick deposits include a wide variety of soft-sediment deformation structures, including clastic dikes, large flame structures, mud diapirs, convoluted bedding, load structures, and deformed cross-bedding (Figure 4.10). All of these features represent the effects of disturbance and dewatering, and the prevalence of these near basin-margin faults may indicate paleo-earthquake activity (e.g., see Plint, 1985).

Structural Geology

Three major fault zones (Figure 4.11) divide the Chumstick basin into two sub-basins, which are informally named the "eastern sub-basin" (between the Entiat and Eagle Creek fault zones) and the "western sub-basin" (between the Eagle Creek and Leavenworth fault zones). The Entiat fault zone is a linear zone over 40 km in length and between 0.3 to 0.8 km wide, with at least three episodes of movement (Laravie, 1976). A pre-Middle Eocene episode of predominantly dip-slip movement resulted in extensive mylonite formation in the western part of the fault zone. It was followed by an episode of probable oblique-slip that coincided with deposition of the Chumstick Formation. A third episode of predominantly dip-slip movement occurred in the eastern part of the fault zone and cut a Late Miocene erosional surface (Laravie, 1976). Gresens (1982b) noted features that suggest the Entiat fault was a significant strike-slip fault for part of its history, including the linearity of the fault; the difference in pre-Tertiary rocks on opposite sides of the fault; and a difference in Tertiary structural style, expressed in the divergent orientation of coeval Teanaway and Corbaley Canyon tensional dike swarms (Figure 4.2), on opposite sides of the fault.

The Leavenworth fault zone, on the west, contains a number of major bends and en-echelon fault-segments and slices (Cashman, 1974). Kinematic indicators in the Leavenworth fault zone show both strike-slip and dip-slip movement (P. Johnson, 1983). S.Y. Johnson (written communication to R.W. Tabor, 1984) has suggested that the Leavenworth fault zone shows a reversal of movement sense, being west side down during deposition of the Swauk Formation (Taylor et al., in press), and east side down during deposition of the Chumstick Formation. He pointed out that this type of "porpoising" is observed in strike-slip fault zones. Other evidence for strike-slip motion on the Leavenworth fault includes the orientation of Teanaway Basalt feeder dikes (Tabor et al., 1984) and the occurrence of granodiorite fanglomerate deposits near Mission Ridge (Frizzell and Tabor, 1977), approximately 34 km southeast of the nearest known source rocks of the Mount Stuart Batholith.

A third set of faults is located in the central portion of the Chumstick basin, and is herein referred to as the Eagle Creek fault zone (Figure 4.12). Previous workers described this structure as a fold ("Eagle Creek anticline" of Willis, 1953) and as a horst block (Whetten, 1976, 1977; Buza, 1979; Gresens et al., 1981). In the north-central part of the basin, where it is best exposed, the structure consists of a number of fault-bounded basement blocks of Swakane Biotite Gneiss which are, in some cases, partly to completely surrounded by poorly sorted, monolithological, fanglomerate deposits. In the south-central part of the basin, the structure consists of folded Chumstick rocks (Gresens, 1980). Paleocurrent studies in the vicinity of this structure indicates that it was a syndepositional feature that redirected drainage (Buza, 1979; this study). Along its trace are syn-depositional intrusives near the town of Wenatchee (Gresens, 1983). A recent study of hydrothermal mineralization associated with these intrusives strongly suggests that the structure acted as a conduit for the emplacement of intrusives and movement of hydrothermal fluids (Margolis, 1987). Drill-core evidence in the mineralized zone also suggests that one or more small grabens formed in the trace of the structure (Margolis, 1987).

I propose that the Eagle Creek fault zone is a through-going, north to northwest-trending, fault or set of faults which parallels and partly overlaps the Entiat fault zone (Figure 4.12). In the north, the Eagle Creek fault zone appears to terminate in a set of northwest-trending fault splays in the region southeast of the town of Plain. The Eagle Creek fault continues southeast along the eastern side of the uplifted basement blocks, through the trend of the felsic intrusives near the town of Wenatchee, and along the eastern side of Wenatchee Heights. The trace of the Eagle Creek fault zone coincides with the Colockum Creek and Laurel Hill monocline structures in the Miocene Columbia River Basalt (mapped by Tabor et al., 1982). These monoclines have been interpreted as fault-propagation folds generated by sub-basalt structures (Plescia and Golombek, 1986; Price, 1982; Reidel, 1984).

There is strong evidence that the Eagle Creek fault zone has had a history of strike-slip or oblique-slip movement. First, the geometric orientation of faults and fold axes in the northern part of the basin are consistent with the types of horsetail splays and other structures observed at the terminus of a strike-slip fault (e.g., Aydin and Nur, 1982; Aydin and Page, 1984; Christie-Blick and Biddle, 1985). Second, some of the uplifted basement blocks are bordered on the west by overturned bedding in the Chumstick Formation (particularly near the town of Cashmere). The orientation of these compressional features is not consistent with an extensional (i.e., horst-and-graben) setting, but is consistent with transpression in a system of dextral shear (e.g., Harding, 1974). All of these contractional faults and related fold axes diverge northwestward from the main fault by 15^0 to 30^0 (Figure 4.12). Third, this study determined that the Entiat and Eagle Creek fault zones acted to form a transtensional step-over basin, similar to those described by Aydin and Page (1984). Fourth, it will also be shown here that the Eagle Creek fault zone was apparently a region of low relief during Chumstick deposition. This type of setting-- low relief with a number of small uplifts and basins in the fault zone-- is more consistent with the strike-slip fault hypothesis than either of the anticline or horst block explanations advanced previously.

BASIN EVOLUTION

Introduction

The Chumstick basin can be split into eastern and western sub-basins, on the basis of facies distributions, paleocurrent data, provenance data, and thermal maturity indicators. Three major phases of sedimentation and deformation can be discerned (Figure 4.13), with a subsequent episode of basin-wide deformation and localized deposits of possible Chumstick affinity. Phase 1 deposition resulted from the opening of the western sub-basin and related magmatic activity along the Eagle Creek fault zone. Phase 2 deposition resulted from dextral faulting on all three major fault zones. In the western sub-basin, uplift occurred in the Leavenworth fault zone at two restraining bends. The eastern sub-basin opened at this time as a transtensional step-over basin. Phase 3 deposition did not show any relationship to the major fault zones, and probably indicates tectonic quiescence.

Phase 1 (>51 Ma to about 42 Ma)

Stratigraphy and Age. The bulk of the Chumstick Formation was deposited during Phase 1 time. Phase 1 deposits comprise about 9,000 m of fluvial and volcanic rocks found only in the western sub-basin (Figure 4.4). Stratigraphic control is provided by 19 interstratified tuffs in the western sub-basin that form mappable units (Figure 4.13a). The lowest part of the section, near the town of Wenatchee, has been intruded by andesite which has a K-Ar date of 50.9 ± 3.9 Ma (Ott et al., 1986). Detrital zircon suites from a sandstone at the base of the section yields a depositional age of 46 Ma to 44 Ma (Figure 4.14). Zircon fission-track ages from the tuffs (Figure 4.4) yield ages of about 45 Ma to 42 Ma (Gresens, 1983; Gresens et al., 1981; Tabor et al., 1980, 1982, 1984; this study).

Depositional Environments. Phase 1 deposits represent part of a humid-tropical, alluvial-fan system. Proximal fluvial deposits (adjacent to the Eagle Creek fault zone) consist of gravel-bedload and sand bedload-stream deposits, with minor overbank deposits and rare debris-flow deposits. Depositional units are composed of massive to crudely stratified conglomerate overlain by laminated sandstone and mudstone, representing gravel longitudinal-bars. The tops of emergent longitudinal-bars supported vegetation and developed soil horizons. Inter-bar channels were filled by dune deposits (trough cross-bedded pebbly sandstone and sandstone) or by massive channel-fills. Proximal overbank sequences consist of ripple cross-laminated sandstone, laminated sandstone and mudstone, and massive (destratified) sandstone and mudstone; many of these show evidence for soil development. Rare volcaniclastic debris-flow deposits are found in proximal fan settings. These contain tuffaceous clasts, pumice, silicified wood, carbonized leaf fossils, and lithic clasts. Because these debris flows directly overlie air-fall and ash-flow tuffs, they probably resulted from hillslope failure following the destruction of vegetation by volcanic activity.

Distal deposits consist of sand-bedload and mixed-load stream deposits and related overbank deposits. Channel-fill sequences include dune deposits, point-bar deposits, and massive channel-fills. Evidence from paleohydraulic reconstructions and from paleovegetation analysis suggest that these distal deposits formed an extensive sandy braidplain divided into active channel belts (composed of numerous, shallow channels) and extensive regions of proximal overbank deposits.

Paleocurrents and Provenance. Paleocurrent data were obtained by analysis of sedimentary structures (Table 4.1) and by examining trends in the average maximum clast size of fluvial deposits. In general, paleoflow was directed west and southwest across the basin (Figure 4.13b). There is no evidence for relief in the Leavenworth fault zone at this time. This trend is mirrored by textural data; grain size decreases from pebble-cobble conglomerate adjacent to the Eagle Creek fault zone to fine-grained sandstone and shale near the trace of the Leavenworth fault zone.

Conglomerate clast compositions include felsic volcanics, biotite gneiss, vein quartz, felsic to intermediate plutonic rocks, and minor amphibolite, hornblende schist, and marble. These lithologies are consistent with an eastern source terrane (mapping by Tabor et al., 1980). Conspicuously lacking from Phase 1 deposits are clasts from the Leavenworth fault region, including peridotite, metavolcanic and metasedimentary rocks of the Ingalls Tectonic Complex (Tabor et al., 1980), garnet- and staurolite-bearing graphite-biotite-quartz schist of the Chiwaukum Schist (Page, 1939; Tabor et al., 1980), and granodiorite of the Mt. Stuart batholith (Tabor et al., 1980).

Magmatic activity within and adjacent to the Chumstick basin was coeval with Phase 1 deposition and is reflected in the composition of Phase 1 deposits (Figure 4.15). Northeast of the basin are several felsic to intermediate plutonic complexes: the Duncan Hill Pluton, with K-Ar dates ranging from 47 Ma to 40 Ma (Cater and Crowder, 1967; Engels et al., 1976; Tabor et al., 1980); the Cooper Mountain Pluton, with a K-Ar date of 48 $\pm$ 1.7 Ma (Tabor et al., 1980); the Railroad Creek Pluton, with K-Ar dates ranging from 54 Ma to 43 Ma (Engels et al., 1976), and several smaller and undated intrusives (Tabor et al., 1980). Intermediate to mafic dike rocks east of the basin (Corbaley Canyon dike swarm) and within the basin (Number One Canyon dike) have K-Ar dates ranging from 49 Ma to 47 Ma (Tabor et al., 1982; Gresens, 1983).

Within the Chumstick basin, a major intrusive complex was emplaced near the town of Wenatchee. This complex includes a felsic dome and associated dikes, flows, ash-flows, and eruption breccias (Margolis, 1987; Gresens, 1983; Gresens et al., 1981). Hydrothermally altered Chumstick Formation (Margolis, 1987) is unconformably overlain by younger and unaltered Chumstick Formation in this region (Gresens, 1983). Radiometric dating of the intrusive complex indicates episodic magmatic activity from about 51 Ma to about 40 Ma (Gresens, 1983; Tabor et al., 1982; Ott et al., 1986; Margolis, 1987).

Two of the tuffs interstratified with the Chumstick Formation are ash flows (Gresens et al., 1981; McClincy, 1986). McClincy used thickness trends and lithology of detrital clasts in the ash flows to show that one of these had a northern source (possibly one of the northeastern intrusives) and one had a southern source (possibly the Wenatchee intrusives).

Pebble counts from fluvial conglomerates in the Chumstick Formation provide important provenance data. Figure 4.16 shows the increase up-section in the percentage composition of flow-banded rhyolite clasts, green cherty tuff clasts, and porphyritic rhyodacite clasts, suggesting a correlative magmatic source. The trend in flow-banded rhyolite clasts is particularly interesting, because it is prevalent in the margins of the Wenatchee Dome. The Wenatchee Dome had an emplacement age of about 43 Ma (Gresens et al., 1981), so the appearance of flow-banded rhyolite clasts in Chumstick sediments by about 42 Ma suggests rapid unroofing of these intrusives. Taken together, these data suggest (1) that basin formation, faulting, emplacement of intrusives, and sedimentation were coeval; and (2) that unroofing of at least one of the magmatic complexes was extremely rapid, probably due to its emplacement in a major fault zone.

Tectonics. Grain-size trends, facies relations, and provenance data from Phase 1 deposits demonstrate that relief was greatest on the eastern side of the western sub-basin (in the Eagle Creek fault zone), and there was negligible relief in the Leavenworth fault zone. Paleocurrent data demonstrates a consistent west-southwest direction to drainage, even immediately adjacent to the trace of the Leavenworth fault zone. Collectively, these data suggest that the western sub-basin formed a half-graben structure during Phase 1 time (Figure 4.17).

Low relief in the Leavenworth fault zone is also suggested by deposits west of the Leavenworth fault zone that show affinities to the Chumstick Formation. The "arkosic facies of Red Hill" (Tabor et al., 1982) consists of vertically stacked, multistory-channel deposits with thick overbank sequences, and paleocurrent data indicates flow to the southwest (Roberts, 1985; this study). Although direct dating control is not available, the Red Hill facies probably represents the distal equivalent of Phase 1 deposition in the Chumstick Formation. These deposits were folded prior to 47 Ma, when the Teanaway Formation was deposited unconformably over the Swauk Formation (Tabor et al., 1982; Gresens, 1982a,b). Taken together, these data imply that the oldest part of the Chumstick Formation and youngest part of the Swauk Formation formed a continuous depositional system.

Phase 2 (about 42 Ma to about 40 Ma)

Stratigraphy and Age. Phase 2 was characterized by deposition of about 1,000 meters of fluvial sediments in the western sub-basin, and by about 1,500 meters of fluvial and lacustrine sediments in the eastern sub-basin (Figure 4.13). Radiometric dating of Phase 2 has not been possible, but pollen and plant-macrofossil data are consistent with a Middle to Late Eocene age. In the western sub-basin, Phase 2 deposits overlie Phase 1 deposits with a zircon-fission track age of about 42 Ma (Gresens et al., 1981). Phase 2 deposits contain basalt clasts of Teanaway Formation (K-Ar dates range from 47 Ma to 46 Ma) and an individual granodiorite clast of the Mount Stuart Batholith that has a K-Ar date of 46.3 ± 0.3 Ma (Tabor et al., 1982, 1984). The upper age limit of 40 Ma is tentative and is based on the youngest known age of hydrothermal activity in the Eagle Creek fault zone, which was characterized by coeval faulting and hydrothermal activity. The Eagle Creek fault was active during Phase 2 sedimentation, but was inactive during subsequent Phase 3 sedimentation.

Depositional Environments. During Phase 2 time, two separate depositional systems operated in the eastern and western sub-basins, respectively. The western sub-basin was characterized by gravel-bedload streams proximal to the Leavenworth fault zone, and distal sand-bedload and mixed-load streams to the east. These deposits show many similarities to the deposits of Phase 1, and are interpreted as part of a humid-tropical, alluvial-fan system.

Proximal parts of the eastern sub-basin were dominated by gravel-bedload streams deposits. The trough between the Entiat and Eagle Creek fault zones was filled by sand-bedload and mixed-load stream deposits in the northwest, and by a lacustrine-deltaic complex to the southeast. The lacustrine-deltaic complex consisted of mixed-load streams with highly bioturbated overbank deposits; lacustrine delta-front turbidites; and lacustrine basin-plain deposits which are poorly exposed, but appear continuous from a region northeast of Cashmere to beneath the city of Wenatchee, where they are present in drill core (Margolis, 1987).

Paleocurrents and Provenance. Paleoflow in the western sub-basin was generally east and southeast, and paralleled the trend of the Leavenworth fault zone along at least part of its length (Figure 4.13c). This pattern is matched by trends in average maximum clast size. Lithologies of the proximal fluvial deposits include basalt clasts from the Teanaway Formation; peridotite, metasedimentary, and metavolcanic clasts from the Ingalls Tectonic Complex; granodiorite from the Mount Stuart Batholith; and metamorphic clasts from the Chiwaukum Schist-- all local sediment sources from immediately west of the Leavenworth fault zone.

Paleoflow of the distal fluvial deposits in the western sub-basin shows two different patterns. On the northern flank of Tumwater Mountain, above the highest tuff unit (Tcts1 of McClincy, 1986), gravel-bedload streams with east-directed paleocurrents are inter-stratified with sand-bedload streams with northwest-directed paleocurrents (Figure 4.18). These opposing paleocurrents are interpreted to indicate onlaps of basin fill into the Leavenworth fault zone. The stratigraphic position of these deposits, the ages of included lithologies, and vitrinite-reflectance data (see later section) are keys to interpreting Phase 2 deposits as younger than Phase 1 deposits.

Farther south along the Leavenworth fault zone, in the vicinity of Camasland, sand-bedload stream deposits have paleocurrent patterns that parallel the Leavenworth fault zone (Figure 4.13c). The development of an axial-drainage system that flowed southeast represents a major change in drainage patterns, and probably indicates tectonic disruption of drainage due to uplift in the Leavenworth fault zone.

In the eastern sub-basin, deposition was mostly restricted to a linear trough between the partly overlapping Eagle Creek and Entiat fault zones. The pattern of average maximum clast size (Figure 4.7c) suggests a more complex pattern than in previous cases. The concentration of largest clasts proximal to the Entiat fault zone, in the region of Van Canyon and Eagle Creek Canyon, indicates this region acted as a major sediment source. Grain size decreases westward from the Entiat fault zone, but also decreases southeastward, down the trough of the sub-basin. There is at least one secondary sediment source at the southern exposed margin of the Eagle Creek fault zone, in the Nahahum Canyon area. Paleocurrent data (Table 4.1) indicate that westward-directed flow off the Entiat uplands merged into a southeast-directed axial drainage system that paralleled both the Eagle Creek and Entiat fault zones. These drainage systems flowed southeast into a lacustrine-deltaic system north of Wenatchee. Delta-front deposits form vertically stacked units that are localized near Sunnyslope. Paleoslope data from slump folds indicates that paleoflow was approximately perpendicular to paleoslope (Figure 4.19).

The lacustrine deposits represent a phase of internal drainage resulting from tectonic disruption of drainage (i.e. relief in the Eagle Creek fault zone). The deltaic deposits are vertically stacked at the northwestern margin of the lacustrine system, and do not show evidence of southeastward delta progradation, down the axis of the lake basin. The localization of delta-front deposits in one area may be evidence for structural control of the lake margin. In addition, shoreline facies are poorly developed, consisting only of rare examples of mud-cracks, crenulated surfaces, and reworked (planed-off) tops of ripples. Structural control of the lake margin was probably responsible for development of narrow, vertically stacked shoreline deposits, while rapid aggradation prevented development of distinctive features, such as wave-sorted gravels.

Age relations between Phase 1 deposits in the western sub-basin and Phase 2 deposits in the eastern sub-basin can be established by provenance and paleocurrent data. Clast lithology and paleocurrents indicate Phase 1 sediments were derived from the region east of the Chumstick basin. The formation of the eastern sub-basin (Phase 2), which also had eastern sediment sources, beheaded the Phase 1 drainage system. Drainage was redirected south as a result of the formation of this new basin. Thus, the formation of the eastern sub-basin had to have been subsequent to Phase 1 deposition (about 42 Ma).

It is significant that Phase 2 paleocurrents in both the eastern and western sub-basins have southeast-directed components of flow. It has been speculated that the Chumstick Formation extends beneath the Columbia River Basalt (e.g., Gresens and Stewart, 1981) and may represent a potential natural gas reservoir which has been observed in exploration wells (Lingley and Walsh, 1986; Campbell, 1987). The paleocurrent data given here support this interpretation and suggest that the exploration targets may consist of relatively narrow, fault-controlled valleys with a thick (> 1,000 meters) basin fills (Evans and Walsh, in preparation).

Tectonics. The structure of the eastern sub-basin is suggestive of a transtensional step-over basin between two overlapping dextral faults (e.g., Aydin and Nur, 1984). The orientation of faults and folds in both the Eagle Creek and Entiat fault zones is compatible with right-lateral shear (Figure 4.12). In addition, vitrinite-reflectance data (see below) suggest that the eastern sub-basin contains a number of northeast-trending extensional faults, also compatible with dextral shear. The discontinuous nature of topographic relief in the fault zones is fairly common in strike-slip fault zones, which may contain a discontinuous array of uplifts or pop-ups (Christie-Blick and Biddle, 1985). Finally, sedimentation in the eastern basin appears to have "curled" around the northern terminus of the Eagle Creek fault and the southern terminus of the Entiat fault (Figure 4.20), a pattern predicted for step-over basins by Aydin and Page (1984).

The pattern of sedimentation in the western sub-basin also suggests dextral faulting. The Leavenworth fault zone has two right-stepping bends. Dextral movement on the Leavenworth fault would have caused transpression in these regions, resulting in deformation and uplift. These two regions, near Tumwater Mountain and the Ingalls Creek-Camasland areas, were the source areas for the coarsest-grained, west-derived sediment during Phase 2 deposition in the western sub-basin.

In summary, the evidence is consistent with an episode of dextral faulting on all three major fault zones during Phase 2 time (Figure 4.20). This dextral faulting resulted in transpressive uplifts in the right-stepping Leavenworth fault zone and in the formation of a trans-tensional step-over basin between the partly overlapping Entiat and Eagle Creek fault zones. Tectonic disruption of drainage resulted in the formation of two axial-drainage systems that flowed parallel to major fault zones, and in an episode of internal drainage.

Phase 3 (about 40 Ma to about 37 Ma)

Stratigraphy and Age. Phase 3 was characterized by deposition of about 2,000 meters of dominantly fluvial sediments, which are preserved in the northern and southeastern parts of the basin (Figure 4.13d). The stratigraphy of Phase 3 deposits is difficult to establish in many areas due to poor exposure, lack of marker horizons, and lack of radiometric ages. The stratigraphic relationship of Phase 3 deposits to Phase 1 and 2 deposits is based on pollen, vitrinite reflectance, and provenance data. Pollen from Phase 3 deposits shows an increase in conifer pollen and disappearance of certain Eocene indicator species, suggesting the deposits are Latest Eocene in age (Estella Leopold, verbal communication, 1987; Shell Onshore Inc., written communication, 1987).

These deposits have the lowest vitrinite-reflectance values in the Chumstick Formation (see below), indicating that they were buried the least. Finally, in the southern area, Phase 3 deposits unconformably overlie deformed and hydrothermally altered older Chumstick rocks (the "Swauk(?) Formation" of Gresens, 1983). Some Phase 3 deposits contain mineralized clasts eroded from this intraformational unconformity.

<u>Depositional Environments</u>. Phase 3 deposition consisted of sand-bedload stream deposits and mixed-load stream deposits. Channel-fill sequences are dominated by dune deposits, massive channel-fills, and point-bar deposits. Typical depositional sequences consist of vertically stacked, multistory-channel sequences which are interbedded with proximal- and distal-overbank fines.

<u>Paleocurrents and Provenance</u>. Phase 3 deposits do not show any relationship, in terms of grain size, facies, paleocurrents, or provenance, to the major fault zones. The average maximum clast size of Phase 3 deposits is less than observed in Phases 1 and 2, and there are no obvious proximal-to-distal trends in grain size. Paleocurrent data (Table 4.1) in the northern region indicates that paleoflow was generally southeasterly, with a high dispersion (s = 70.4) while in the southern region paleoflow was to the northeast, also with a high dispersion (s = 70.2). The presence of lateral-accretion surfaces and the relatively high paleocurrent dispersion suggests that the basin was filled by the deposits of high sinuosity (meandering) streams.

<u>Tectonics</u>. Phase 3 deposits show nc evidence for tectonic control of facies. In the northern part of the basin, paleoflow was directed toward the Leavenworth fault zone, and may indicate that the fault zone was over-topped by these deposits (Figure 4.17). In the southern part of the basin, Phase 3 deposits appear to unconformably overlie the intrusives of the Wenatchee Dome and older, hydrothermally altered and deformed, Chumstick deposits (Figure 4.17). Together, the data imply that Phase 3

deposition took place during an episode of tectonic quiescence.

Basin Deformation (Prior to 34 Ma)

Chumstick strata were folded prior to the deposition of the Early Oligocene Wenatchee Formation, which unconformably overlies the Chumstick Formation and contains tuffs with zircon-fission track ages of 34 Ma to 33 Ma (Gresens et al., 1981; Gresens, 1983). The style of folding is slightly different along the Leavenworth fault zone versus the Eagle Creek and Entiat fault zones.

Along the Leavenworth fault zone, the orientation of folds follows two general trends (Figure 4.11). In the region north of Coles Corner and between Leavenworth and Ingalls Creek, fold axes are en echelon and diverge northwesterly from the trend of the Leavenworth fault by 15^0 to 40^0. The orientation of these fold axes is consistent with a system of dextral shear. In the region of the two, right-stepping, transpressive bends (from Coles Corner to Leavenworth, Ingalls Creek to Mission Ridge), fold axes are generally parallel to the trend of the Leavenworth fault zone.

The orientation of these fold axes at restraining bends resembles the forced-parallel folds observed in other wrench-fault basins (e.g., Harding et al., 1985). The origin of forced-parallel folds is probably related to vertical components of movement in the principal displacement zone. As in the case of forced folds related to extensional faults, anticlines or monoclinal knees form adjacent and parallel to the relatively higher side of the principal displacement zone, and synclines or monoclinal ankles form adjacent and parallel to the edge of the relatively down-thrown block (Harding et al., 1985). In the Leavenworth fault zone, forced-parallel folds only develop in the Chumstick and Swauk formations, and not in the pre-Tertiary crystalline rocks.

In the Eagle Creek and Entiat fault zones, folds are en echelon and diverge northwesterly from the trend of the faults by 15^0 to 30^0 (see Figure 4.22). Folding affects Chumstick strata, and folds with similar orientation are also present in the pre-Tertiary Swakane Biotite Gneiss. The orientation of these structures is in accord with right-lateral shear.

In the Eagle Creek fault zone, uplifted basement blocks are bounded on the west by probable reverse faults. Faulting in this area was responsible for overturned bedding in the Chumstick Formation, particularly near Hay, Ollala, and Williams canyons. The orientation of these contractional faults and related folds is suggestive of a positive flower structure (Figure 4.21), as described by Harding et al. (1983).

In summary, dextral transpression folded Chumstick deposits after Phase 3 deposition (minimum age of 37 Ma) and prior to Wenatchee Formation deposition (about 34 Ma). The expression of dextral transpression was the development of en echelon folds and forced-parallel folds adjacent to the principal displacement zones, and uplift of basement blocks in a zone of reverse separation, which may be analagous to a positive flower structure.

Phase 4(?)

Phase 4(?) deposits are red-weathering, angular to subrounded, matrix-supported conglomerates containing clasts of biotite gneiss and minor vein quartz with a matrix consisting of disaggregated gneiss. These deposits lack stratification and other sedimentary structures, and probably represent debris-flow deposits. The stratigraphic position of these deposits is difficult to establish, since they are poorly exposed, unfossiliferous and not susceptible to radiometric dating.

These deposits have been mapped along the margins of the uplifted basement blocks in the Eagle Creek fault zone (Tabor et al., 1980; Gresens et al., 1981). Gresens et al. (1981) suggested that they represent the basal unit of the Chumstick Formation, but there are several problems with this interpretation. The deposits are dissimilar to any of the known coarse-grained deposits in the Chumstick Formation. The oldest Phase 1 deposits contain felsic and intermediate plutonic rocks, amphibolite, hornblende schist, and marble, in addition to biotite gneiss and vein quartz. Successively younger Chumstick rocks contain felsic and intermediate volcanic clasts, even from areas proximal to the Eagle Creek and Entiat fault zones. The fact that Phase 4 deposits contain only biotite gneiss and related vein quartz suggests a limited source area. Also, debris flows are rare in Phase 1 and 2 deposits and are totally absent in Phase 3 deposits; whereas Phase 4 deposits are entirely debris flows. I propose that these "redbed fanglomerates" are not basal Chumstick Formation, but instead represent colluvium that surrounded basement blocks uplifted and exposed as part of basin deformation. The actual age of these deposits is unknown, because they can not be dated and are not known to overlie or underlie other sedimentary units.

BASIN STRUCTURE

Introduction

The information from thermal maturity indicators, geophysical data, and stratigraphic data make it possible to interpret the structure of the Chumstick basin. This discussion will focus on two questions. First, given both the great stratigraphic thickness of the Chumstick Formation and its setting in a strike-slip basin, is there evidence for shingling or imbrication of depositional packages ("conveyor-belt" sedimentation style of Crowell, 1982)? Second, what were the kinematics of the newly proposed Eagle Creek fault zone during Phase 1 time?

Thermal Maturity Indicators

The reflectance of vitrinite provides a scale that has been correlated to basin burial temperatures (Castano and Sparks, 1974). As part of this study, 64 vitrinite outcrop samples were collected from log compressions and thin coal seams, and an additional 14 samples were collected from core cuttings in the NORCO #1 Well from Wenatchee Heights. The samples were analyzed by Shell Onshore, Inc., and by the Washington Division of Geology and Earth Resources (Evans and Walsh, in preparation).

Vitrinite reflectance values in the Chumstick Formation range from about 0.3% to 2.1% reflectance (Ro), as shown in Figure 4.22. The values higher than about 0.90% Ro are localized near intrusives or represent pre-altered samples (e.g., wood that burned prior to burial), and these higher values are not considered in the following discussion.

The distribution of vitrinite reflectance values throughout the basin shows a different pattern for thermal maturity for the eastern and western sub-basins. In the western sub-basin, a "half bull's-eye" pattern shows that maximum burial thickness (basin depocenter) was in the region just west of the Eagle Creek fault zone. Using the interbedded tuffs for stratigraphic control, it can be shown that Phase 1 deposits of equivalent age have received less burial distally (to the southwest) than proximally (to the northeast). This type of burial history strongly suggests a half-graben structure to the western sub-basin during Phase 1 deposition. Vitrinite reflectance values decrease toward the northwest, moving upward through the stratigraphy, as expected. Phase 3 deposits in the northern area have the lowest vitrinite reflectance values for the western sub-basin. Two inliers of lower vitrinite values can be observed along the Leavenworth fault zone and correspond to the location of younger and less deeply-buried Phase 2 deposits in the western sub-basin.

The pattern of vitrinite reflectance values in the eastern sub-basin suggests a different set of structures. The maximum vitrinite values (basin depocenter) are found in the lacustrine deltaic sequence near Monitor and Sunnyslope. Lower values to the northwest and southeast suggest a set of down-to-basin steps. The stress regime of a transtensional step-over basin between two overlapping dextral faults could produce tensional features with an orientation similar to the trend of these thermal maturity indicators.

Basin Burial Temperatures

Basin burial temperatures can be calculated from a number of sources, including discordant apatite and zircon fission-track ages, zeolite mineral assemblages, and vitrinite-reflectance data (Table 4.2). One of the Mission Creek tuffs (Tctm2 of McClincy, 1986) has a zircon fission-track age of 44.4 ± 2.6 Ma and an apatite fission-track age of 15.1 ± 3.0 Ma (Gresens et al., 1981). These data suggest that the basin was heated to above the blocking temperature for apatite, (105 $\pm$ 10^{0}C according to Parrish, 1983) and below the blocking temperature for zircon (175 $\pm$ 10^{0}C according to Naser, 1979).

Zeolite minerals in the Chumstick Formation include laumontite and clinoptilolite in sandstones and tuffs (Gresens et al., 1981). Peridotite clasts in the Leavenworth fault zone contain lizardite overgrowths (Cashman, 1974). This suite of zeolite minerals is in accord with maximum burial temperatures of about 100^{0}C to 130^{0}C (Castano and Sparks, 1974; Cashman, 1974; Cashman and Whetten, 1976).

The basinwide vitrinite-reflectance values range from about 0.3% to 0.9% Ro. Burial temperatures can be calculated from vitrinite reflectance using either the time-independent model (Barker and Pawlewicz, 1986) or time-dependent model (Hood et al., 1975). In the time-independent model, paleotemperatures in the Chumstick Formation ranged from 90^{0}C to 170^{0}C. For the time-dependent model, a burial-exposure time of 10 to 20 m.y. was chosen, because the Chumstick basin was characterized by rapid subsidence between about 51 Ma and 37 Ma, followed by uplift and erosion prior to 34 Ma. The time-independent model yields a range of burial temperatures from 90^{0}C to 150^{0}C.

Basin-fill Thickness

Basin burial temperature from discordant zircon and apatite fission-track dates, zeolite mineral assemblages, and vitrinite reflectance are reasonably consistent with maximum basin burial temperatures in the range of 90^{0}C to 175^{0}C (Table 4.2). The vitrinite reflectance values from the NORCO #1 Well have been used to reconstruct a geothermal gradient curve for the Chumstick Formation.

The paleo-geothermal gradient in this region was 85^{0}C/km to 110^{0}C/km (see Appendix E; Evans and Walsh, in preparation). This paleo-geothermal gradient is relatively high, probably because the well is located in the Eagle Creek fault zone near the intrusives in the Wenatchee Dome, thus using this paleo-geothermal gradient will generate minimum basin-fill thickness values. Considering the maximum and minimum values, the thermal-maturity indicators suggest that the western sub-basin subsided between 1 and 2.3 km, and the eastern sub-basin subsided between 1 and 1.6 km (Table 4.3).

Silling (1979) conducted three gravity transects across the northern part of the Chumstick basin. Following a terrain correction and employing estimates of rock densities, Silling predicted the thickness of the Chumstick Formation to be about 2 km. Figure 4.23 shows one transect line that has been modified to account for previous discussion. The significance of the gravity transect is that it provides an independent confirmation of the calculation using thermal maturity indicators, despite the use of a high paleo-geothermal gradient.

Analysis of thermal maturity and gravity data agree that the thickness of the basin fill was $\geq$2 km in the western sub-basin, and $\geq$1 km in the eastern sub-basin (Table 4.3). These values contrast strongly with the stratigraphic data, which demonstrate a stratigraphic thickness of $\geq$12 km in the western sub-basin (based on tephrostratigraphy), and $\geq$2 km in the eastern sub-basin (Table 4.3).

The great contrast between stratigraphic thickness and actual basin-fill thickness has been observed in other strike-slip basins, particularly the Ridge Basin, where Crowell (1974a,b, 1982; Crowell and Link, 1982) called it "conveyor-belt sedimentation." The basic idea of conveyor-belt sedimentation is that lateral offset of sediment source regions during deposition will produce a shingling of depositional units (Figure 4.24). In the Chumstick Formation, conveyor-belt sedimentation may explain the prevalence of lateral stacking of depositional units in the fault-proximal regions, versus predominantly vertical stacking of the basin-fill in distal regions.

Kinematics of Phase 1 Faulting

One remaining problem is the sense of movement on the Eagle Creek fault zone during Phase 1 sedimentation. The Phase 1 deposits young to the northwest; thus, if conveyor-belt sedimentation occurred, either the Eagle Creek fault was left-lateral (see Figure 4.25a) or a combination of right-lateral movement and tilting in the fault zone occurred (Figure 4.25b). Left-lateral movement seems incompatible with the strong evidence for right-lateral movement on both the Eagle Creek and Entiat faults during Phase 2 sedimentation and during later basin deformation. However, left-lateral movement during Phase 1 deposition would explain the orientation of the coeval Corbaley Canyon tensional dike swarm east of the basin. The orthogonal orientation of two major, coeval tensional dike swarms, the Teanaway Formation basalt feeder dikes (general orientation N35E; Tabor et al., 1982, 1984) and the Corbaley Canyon dikes (general orientation N65W; Tabor et al., 1982; Gresens, 1982a,b) has been a regional tectonic controversy (e.g., Gresens, 1982b). These dikes would, however, be in accord with the stress regime imposed by right-lateral movement on the Leavenworth fault and left-lateral movement on the Eagle Creek fault.

It is more likely, however, that the Eagle Creek fault zone was right-lateral and experienced tilting during Phase 1 deposition. The trend of the Corbaley Canyon dikes may be discounted by the fact they were emplaced in the Swakane Biotite Gneiss, which has a strong northwest foliation (Gresens, 1983). Some additional evidence for right-lateral movement on the Eagle Creek fault comes from a preliminary paleomagnetic study (Bogue and Evans, 1985; Appendix G). The history of the magnetization is not well constrained, but paleomagnetic samples from Phase 1 sediments in the Clark Canyon area indicate counter-clockwise rotation and tilting. Counter-clockwise rotation would be expected on the west side of a dextral fault.

SUMMARY AND CONCLUSIONS

The tectonic evolution of the Chumstick Formation illustrates the structural and depositional complexity of stike-slip basins (Figure 4.26). The first phase represented deposition in a half-graben bounded on the east by the Eagle Creek fault zone. The evidence for conveyor-belt sedimentation during this phase indicates that the Eagle Creek fault zone was an oblique-slip fault between 51 Ma and 42 Ma (Figure 4.26a). The second phase represented an interval of dextral faulting on three major fault systems between 42 Ma and about 40 Ma. The eastern sub-basin formed as a transtensional step-over basin between two parallel, partly overlapping, dextral faults, (the Eagle Creek and Entiat fault zones). Right-stepping bends on the Leavenworth fault zone resulted in transpressional uplifts west of the Chumstick basin (Figure 4.26b). The third phase represented an interval of tectonic quiescence between about 40 Ma and about 37 Ma (Figure 2.26c). Finally, the basin was deformed in an interval of dextral transpression between about 37 Ma and about 34 Ma (Figure 4.26d).

The Chumstick Formation displays convincing evidence for coeval strike-slip faulting, magmatic activity, basin formation and sedimentation, and deformation during the Middle to Late Eocene in central Washington State. This study has shown that several episodes of strike-slip faulting occurred during the depositional history of the Chumstick Formation. Faulting was responsible for several major episodes of drainage disruption, which truncated an early Chumstick-Swauk depositional system. Finally, the delineation of a phase of southeast-flowing depositional systems (Phase 2) suggests that Chumstick sediments can be found beneath the Columbia River Basalt in central Washington State. Paleocurrent, provenance, and facies data are suggestive that the Chumstick and Roslyn formations formed a single depositional system during Phase 2 (42 Ma to 40 Ma) time.

Chapter Notes

Aydin, A. and Nur, A., 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v.1, p. 91-105.

Aydin, A. and Page, B.M., 1984, Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California: Geological Society of America Bulletin, v. 95, p. 1303-1317.

Ballance, P.F. and Reading, H.G., editors, 1980, Sedimentation in Oblique-slip Mobile Zones: International Association of Sedimentologists, Special Publication no. 4, 265 p.

Barker, C.E. and Pawlewicz, M.J., 1986, The correlation of vitrinite reflectance with maximum paleotemperature in humic organic matter, in Buntebarth, G. and Stegena, L., editors, Paleogeothermics. New York: Springer-Verlag, p.79-93.

Biddle, K.T. and Christie-Blick, N., editors, 1985, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, 386 p.

Bogue, S.W. and Evans, J.E., 1986, Discordant paleo-magnetic component from the Eocene Chumstick Formation, central Washington state [abstract]: Geological Society of America, Abstracts with Programs, v. 18, p. 88.

Buza, J.W., 1979, Dispersal patterns and paleogeographic implications of lower to middle Tertiary fluviatile sandstones in the Chiwaukum graben, east-central Cascades, Washington in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 63-74.

Byrnes, M.E., 1985, Provenance study of Late Eocene arkosic sandstones in southwest and central Washington [M.S. Thesis]: Portland, Oregon, Portland State University, 65 p.

Campbell, N.P., 1987, Structural and stratigraphic relationships between the northwestern Columbia River Basalt margin and recent sub-basalt gas wells [abstract]:

Geological Society of America, Abstracts with Programs, v. 19, p. 364.

Cashman, S.M., 1974, Geology of the Peshastin Creek area, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 29 p.

Cashman, S.M. and Whetten, J.T., 1976, Low-temperature serpentinization of peridotite fanglomerate on the west margin of the Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 87, p. 1773-1776.

Castano, J.R. and Sparks, D.M., 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals, in Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.A., editors, Carbonaceous Materials as Indicators of Metamorphism: Geological Society of America Special Paper no. 153, p. 31-52.

Cater, F.W. and Crowder, D.F., 1967, Geologic map of the Holden quadrangle, Washington: U.S. Geological Survey, Geological Quadrangle Map 646.

Christie-Blick, N. and Biddle, K.T., 1985, Deformation and basin formation along strike-slip faults, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 1-34.

Crowell, J.C., 1974a, Sedimentation along the San Andreas fault, California, in Dott, R.H., Jr. and Shaver, R.H., editors, Modern and Ancient Geosynclinal Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication no. 19, p. 292-303.

Crowell, J.C., 1974b, Origin of the Cenozoic basins in southern California, in Dickinson, W.R., editor, Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication no. 22, p. 190-204.

Crowell, J.C., 1982, The tectonics of Ridge Basin, southern California, in Crowell, J.C. and Link, M.H., editors, Geological History of Ridge Basin, Southern California, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 25-42.

Crowell, J.C. and Link, M.H., editors, 1982, Geologic History of the Ridge Basin, Southern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, 304 p.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Howell, D.G. and McDougall, K.A., editors, Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 2, p. 1-32.

Engels, J.C., Tabor, R.W., Miller, F.K., and Obradovich, J.D., 1976, Summary of K-Ar, Rb-Sr, U-Pb, and fission track ages of rocks from Washington state prior to 1975 (exclusive of Columbia Plateau Basalts): U.S. Geological Survey, Miscellaneous Field Studies, no. 710.

Evans, J.E. and Walsh, T., in preparation, Thermal evolution, maturity, and petroleum potential of the Eocene Chumstick Formation, a wrench-fault basin in the Cascade Range, Washington.

Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619-638.

Fraser, G.T., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation in the Swauk Pass area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 219 p.

Frizzell, V.A., 1979, Petrology of Paleogene non-marine sandstone units in Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 113-118.

Frizzell, V.A., Jr. and Tabor, R.W., 1977, Stratigraphy of Tertiary arkoses and their included monolithological fanglomerates and breccias in the Leavenworth fault zone, central Cascades, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 9, p. 421.

Gresens, R.L., 1980, Deformation of the Wenatchee Formation and its bearing on the tectonic history of the Chiwaukum graben, Washington, during Cenozoic time: Geological Society of America Bulletin, v. 91, p.115-155.

Gresens, R.L., 1982a, Early Cenozoic geology of central Washington state: I. Summary of sedimentary, igneous, and tectonic events: Northwest Science, v. 56, p. 218-229.

Gresens, R.L., 1982b, Early Cenozoic geology of central Washington state: II. Implications for plate tectonics and alternatives for the origin of the Chiwaukum graben: Northwest Science, v. 56, p. 259-264.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Geology and Earth Resources, Bulletin 75, 75 p.

Gresens, R.L. and Stewart, R.J., 1981, What lies beneath the Columbia Plateau? Oil and Gas Journal, v. 79, p. 157-164.

Gresens, R.L., Naeser, C.W., and Whetten, J.T., 1981, Stratigraphy and age of the Chumstick and Wenatchee Formations- Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 233-236, 841-876.

Harding, T.P., Gregory, R.F., and Stephens, L.H., 1983, Convergent wrench fault and positive flower structure, Ardmore Basin, Oklahoma, in Bally, A.W., editor, Seismic Expression of Structural Styles: American Association of Petroleum Geologists, Studies in Geology, Series 15, v. 3, p. 4.2-13 to 4.2-17.

Harding, T.P., Vierbuchen, R.C., and Christie-Blick, N., 1985, Structural styles, plate-tectonic settings, and hydrocarbon traps of divergent (transtensional) wrench faults, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 51-77.

Harland, W.B., 1971, Tectonic transpression in Caledonian Spitsbergen: Geological Magazine, v. 108, p. 27-42.

Hauptman, J.L., 1983, The sedimentology of the Wenatchee Formation: Late Paleogene fluvial and lacustrine strata of the east-central Cascade Range, Washington state [M.S. Thesis]: Seattle, Washington, University of Washington, 164 p.

Hood, A., Gutjahr, C.C.M., and Heacock, R.L., 1975, Organic metamorphism and the generation of petroleum: American Association of Petroleum Geologists Bulletin, v.59, p. 986-996.

Johnson, P.E., 1983, The origin of the Chiwaukum graben, Chelan County, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 96 p.

Johnson, S.Y., 1982, Stratigraphy, sedimentology, and tectonic setting of the Eocene Chuckanut Formation, northwest Washington [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 221 p.

Johnson, S.Y., 1984a, Evidence for a margin-truncating transcurrent fault (pre-Late Eocene) in western Washington: Geology, v. 12, p. 538-541.

Johnson, S.Y., 1984b, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, p. 92-106.

Johnson, S.Y., 1984c, Cyclic fluvial sedimentation in a rapidly subsiding basin, northwest Washington: Sedimentary Geology, v. 38, p. 361-392.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 283-302.

Kesel, R.H., 1985, Alluvial fan systems in a wet-tropical environment, Costa Rica: National Geographic Research, v. 1, p. 450-469.

Laravie, J.A., 1976, Geologic field studies along the eastern border of the Chiwaukum graben, central Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 55 p.

Lingley, W.S., Jr. and Walsh, T.J., 1986, Issues relating to petroleum drilling near the proposed high-level nuclear waste repository at Hanford: Washington Division of Geology and Earth Resources, Geologic Newsletter, v.14, p. 10-19.

Margolis, J., 1987, Hydrothermal alteration and structure associated with epithermal gold mineralization, Wenatchee Heights, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 120 p.

McClincey, M., 1986, Tephrostratigraphy of the Chumstick Formation [M.S. Thesis]: Portland, Oregon, Portland State University, 127 p.

Naeser, C.W., 1979, Fission-track dating and geologic annealing of fission tracks, in Jager, E. and Hunziker, J.C., editors, Lectures in Isotope Geology. New York: Springer-Verlag, p. 154-169.

Newman, K.R., 1981, Palynologic biostratigraphy of some early Tertiary nonmarine formations in central and western Washington, in Armentrout, J.M., editor, Pacific Northwest Cenozoic Biostratigraphy: Geological Society of America Special Paper no. 184, p. 49-65.

Ott, L.E., Groody, D., Follis, E.L., and Siems, P.L., 1986, Stratigraphy, structural geology, ore mineralogy, and hydrothermal alteration at the Cannon Mine, Chelan County, Washington, in MacDonald, A.J., editor, Gold '86, An International Symposium on the Geology of Gold Deposits, Proceedings Volume, p. 425-435.

Parrish, R.R., 1983, Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia, 1. Fission-track dating, apparent uplift rates, and patterns of uplift: Tectonics, v.2, p. 601-631.

Plescia, J.B. and Golombek, M.P., 1986, Origin of planetary wrinkle ridges based on the study of terrestrial analogs: Geological Society of America Bulletin, v. 97, p. 1289-1299.

Plint, A.G., 1985, Possible earthquake-induced soft-sediment faulting and remobilization in Pennsylvanian alluvial strata, southern New Brunswick, Canada: Canadian Journal of Earth Sciences, v. 22, p. 907-912.

Riedel, S.P., 1984, The Saddle Mountains: the evolution of an anticline in the Yakima fold belt: American Journal of Science, v.284, p. 942-978.

Roberts, J.W., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation along Tronsen Ridge, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 188 p.

Silling, R.M., 1979, A gravity study of the Chiwaukum graben, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 100 p.

Steel, R.J. and Gloppen, T.G., 1980, Late Caledonian (Devonian) basin formation, western Norway: signs of strike-slip tectonics during infilling, in Ballance, P.F. and Reading, H.E., editors, Sedimentation in Oblique-slip Mobile Zones: International Association of Sedimentologists, Special Publication no. 4, p. 79-103.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Waitt, R.B., Jr., 1980, Preliminary geologic map of the Chelan quadrangle, Washington: U.S. Geological Survey, Open-File Report no. 80-841.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee quadrangle, Washington: U.S. Geological Survey, Miscellaneous Geological Investigations I-1311.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26-44.

Taylor, S.B., 1985, Stratigraphy, sedimentology, and paleogeography of the Swauk Formation in the Liberty area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 199 p.

Taylor, S.B., Johnson, S.Y., Fraser, G.T., and Roberts, J.W., in press, Sedimentation and tectonics of the Swauk Formation, eastern Swauk basin- significance for hydrocarbon exploration in central Washington: American Association of Petroleum Geologists Bulletin.

Whetten, J.T., 1976, Tertiary sedimentary rocks in the central part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 8, p. 420-421.

Whetten, J.T., 1977, Sedimentology and structure of part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 9, p. 527.

Willis, C.L., 1953, The Chiwaukum graben, a major structure of central Washington: American Journal of Science, v.251, p. 789-797.

Wolfe, J.A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: U.S. Geological Survey Professional Paper no. 571, 33p.

Wolfe, J.A. and Wehr, W., 1986, Middle Eocene dicotyledonous plants from Republic, northeastern Washington: U.S. Geological Survey Professional Paper no. 1597, 74 p.

Table 4.1: Chumstick Formation Paleocurrent Data

PC Type	Phase 1 Western	Phase 2 Western	Phase 2 Eastern	Phase 3 North	Phase 3 South
1	280 (88)	102 (45)	159 (75)	131 (6)	278 (9)
2	265 (13)	180 (154)	152 (67)	162 (119)	284 (80)
3	308 (3)	n/a (0)	143 (7)	n/a (0)	n/a (0)
4	264 (112)	167 (44)	163 (40)	094 (86)	n/a (0)
5	270 (91)	128 (5)	n/a (0)	075 (40)	n/a (0)
6	315 (73)	048 (56)	128 (63)	089 (5)	n/a (0)
7	253 (20)	n/a (0)	248 (24)	143 (3)	n/a (0)
8	225 (6)	n/a (0)	206 (19)	n/a (0)	n/a (0)
n	(528)	(304)	(295)	(259)	(89)
$\bar{0}$	243	174	182	133	284
r	.257	.243	.257	.242	.246
s	69.7	70.4	69.7	70.4	70.2

Explanations:
280 (88) represents vector mean and number of measurements (in parentheses)
1 = clast imbrication
2 = cross-bedding
3 = flute casts
4 = clast long axis orientation
5 = log cast orientation
6 = primary current lineation
7 = groove cast orientation
8 = orientation of symmetric ripple crests

n = total number of measurements

$\bar{0}$ = vector mean for all measurements

r = vector strength

s = circular standard deviation

Table 4.2: Thermal Maturity Indicators In The Chumstick Formation

1. Discordant Apatite and Zircon Fission Track Ages from Interbedded Tuffs: Between 105^0 - 175^0C.

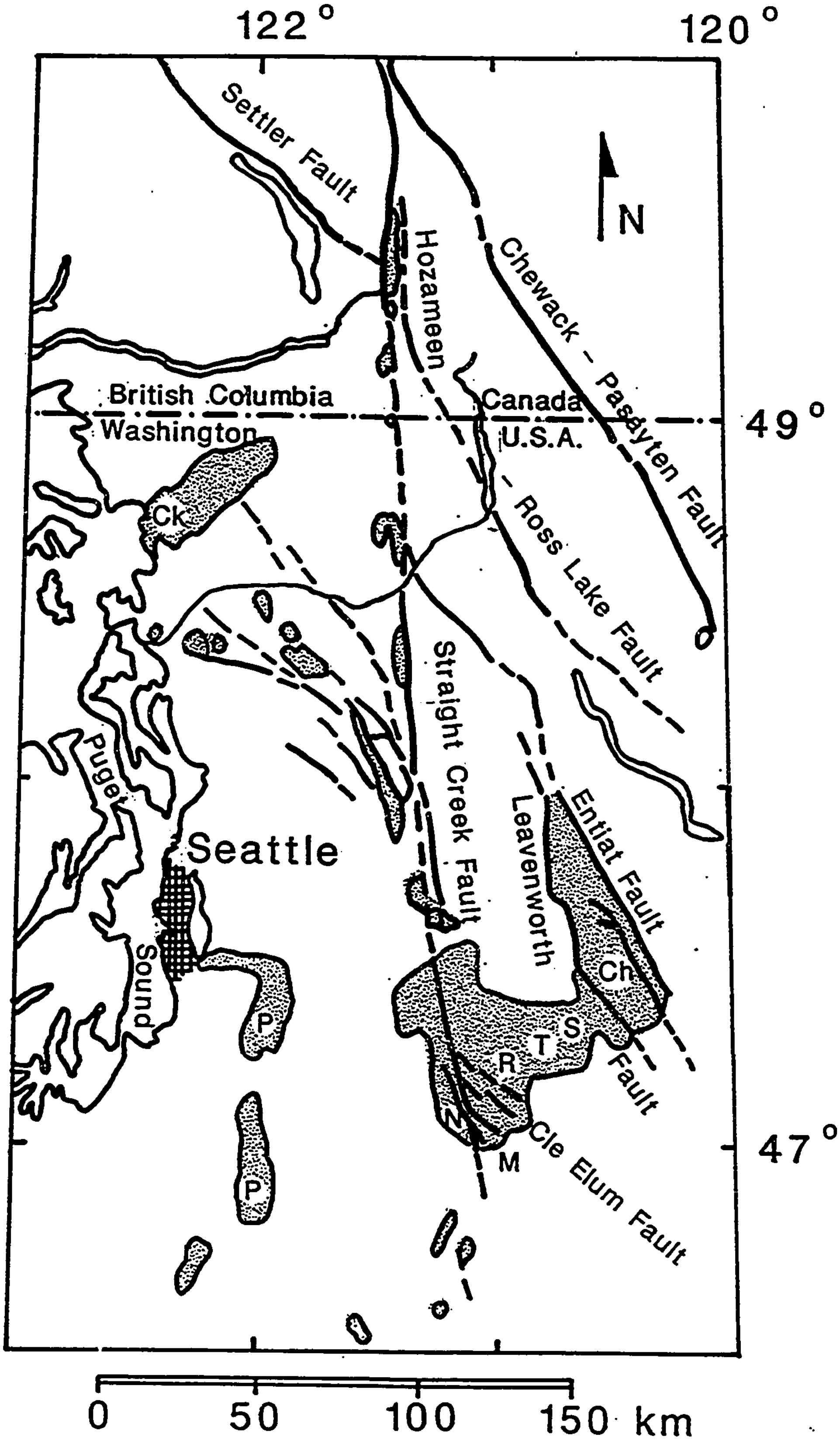
2. Zeolite Mineral Assemblage: Laumontite, Lizardite, Clinoptilolite: 100 - 130^0C.

3. Vitrinite Reflectance Data: Ro = 0.3 to 0.9;
   Time Independent Model: 90^0 - 170^0C
   Time Dependent Model (10 - 20 m.y.): 90^0 - 150^0C

Table 4.3: Summary of Basin Depth Indicators

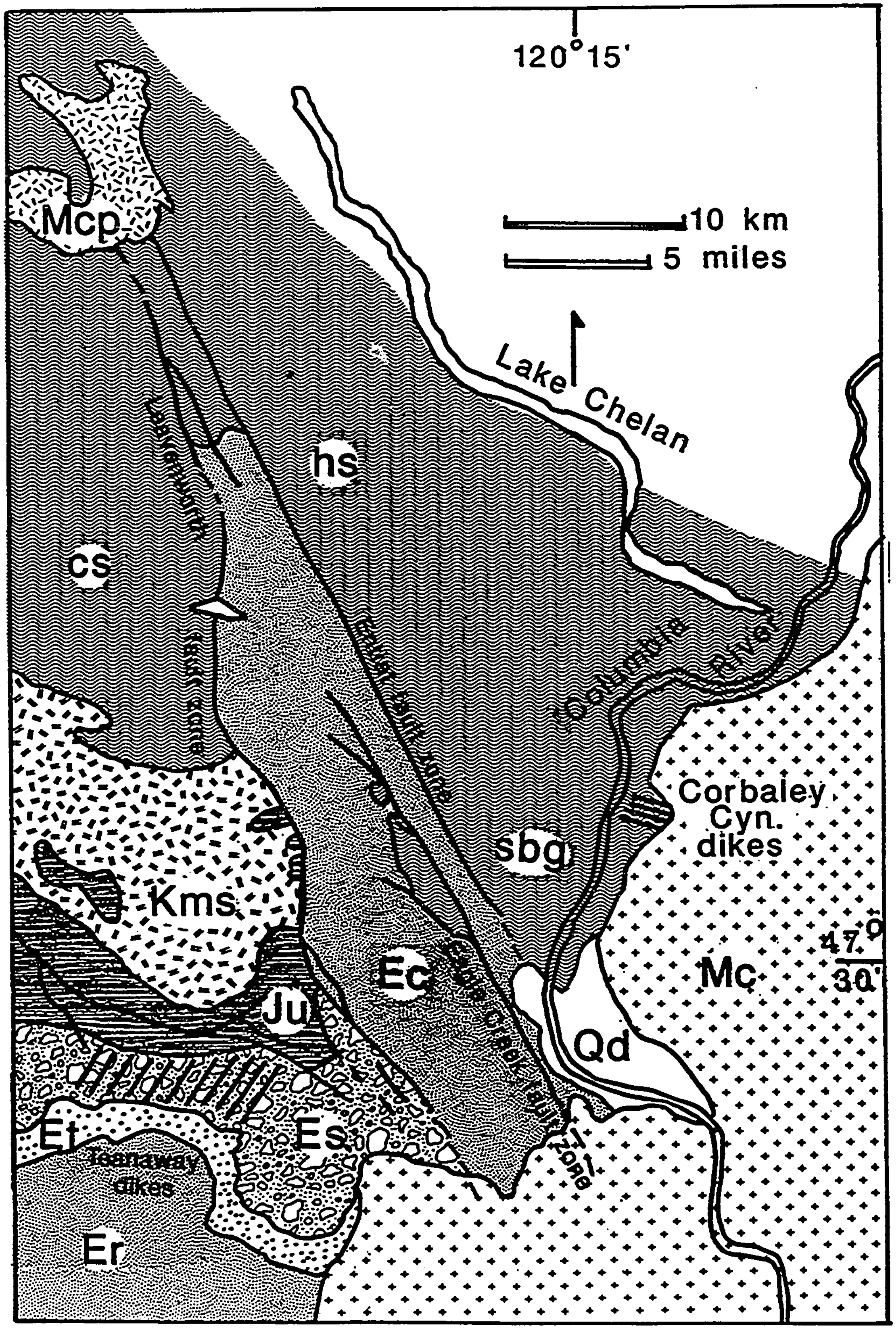
Criterion	Western Sub-basin	Eastern Sub-basin
Gravity Study: (Silling, 1983)	approx. 2 km	approx. 1 km
Thermal Maturity Indicators:		
Zeolite Minerals	0.9 - 1.5	0.9 - 1.5
Vitrinite Reflectance	1.8 - 2.3 km	1.0 - 1.6 km
Discordant Apatite & Zircon Fission Track Ages	1.0 - 2.1 km	not available
Stratigraphic Thickness:	approx. 12 km	approx. 2 km

Figure 4.1--Generalized geologic map of northwestern Washington State and southwestern British Columbia showing major faults of known Mesozoic and Paleogene displacement and Paleogene sedimentary basins. Abbreviations used on map: Ch - Chumstick Formation, Ck - Chuckanut Formation, M - Manastash Formation, N - Naches Formation, P - Puget Group, R - Roslyn Formation, S - Swauk Formation, T - Teanaway Formation.



122°
120°
49°
47°
N
Settler Fault
Hozameen
Chewack - Pasayten Fault
British Columbia
Washington
Canada
U.S.A.
Ross Lake Fault
Ck
Straight Creek Fault
Puget
Seattle
Sound
Leavenworth
Entiat Fault
Ch
S
T
R
N
M
Fault
Cle Elum Fault
P
P
0
50
100
150 km

Figure 4.2--Generalized geologic map of the Chumstick basin ("Chiwaukum graben") and related rocks, based upon mapping by Tabor et al., 1980, 1982. Abbreviations used on map: cs - Chiwaukum schist, Ec - Chumstick Formation, Er - Roslyn Formation, Es - Swauk Formation, Et - Teanaway Formation, hs - heterolithic schist, Ju - Ingalls Tectonic Complex, Kms - Mount Stuart Batholith, Mc - Columbia River Basalt, Mcp - Cloudy Pass Batholith, Qd - alluvium, sbg - Swakane Biotite Gneiss.



120°15'
10 km
5 miles
Lake Chelan
Mcp
hs
cs
Leavenworth fault zone
Entiat fault zone
Columbia River
Corbaley Cyn. dikes
sbg
Kms
Ec
Ju
Mc
47° 30'
Qd
Eagle Creek fault zone
Et
Es
Teanaway dikes
Er

Figure 4.3--Regional stratigraphic relations of Paleogene sedimentary and volcanic units in central and western Washington, based upon data compiled by Johnson, 1985 and Tabor et al., 1984. Chumstick Formation data modified from Evans (chapter 3, this study). Abbreviations used-- Tb = Basalt of Frost Mountain, Th = Huntingdon Formation, Tm = Manastash Formation, Tt = Teanaway Formation, Tta = Taneum Formation, Tw = Wenatchee Formation.

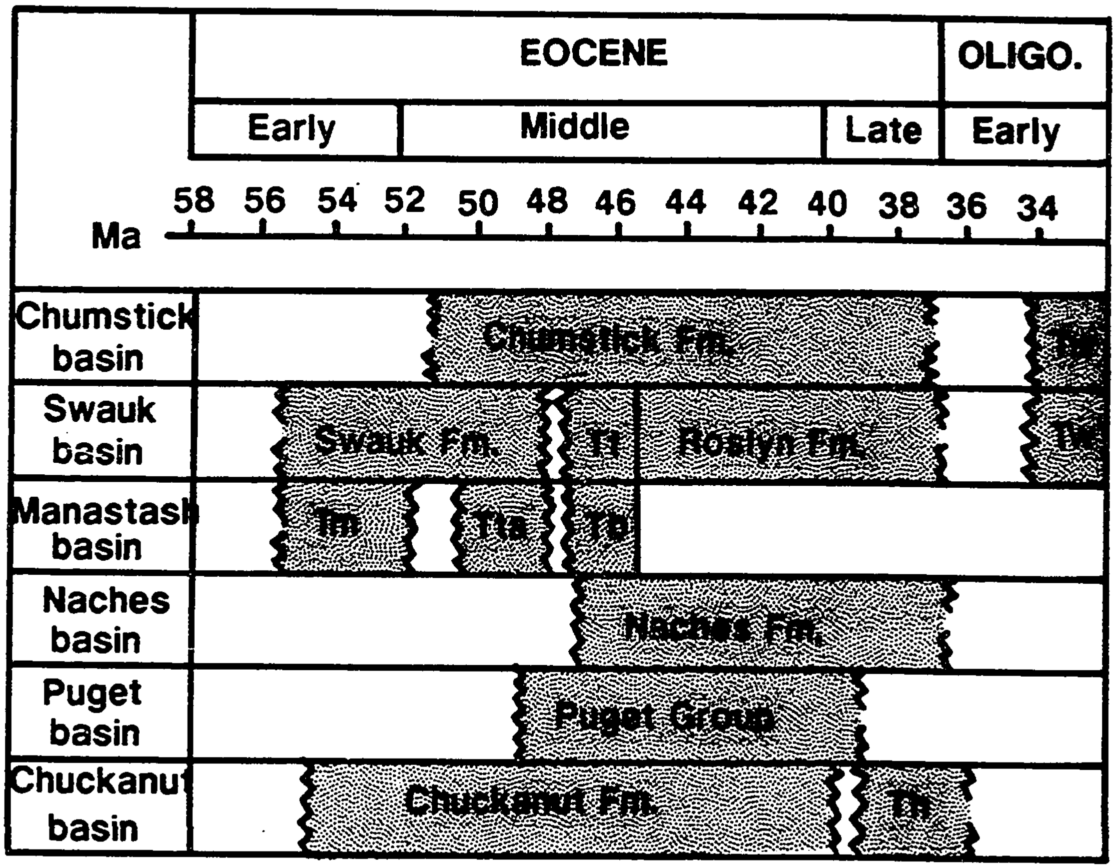

EOCENE
OLIGO.
Early
Middle
Late
Early
58 56 54 52 50 48 46 44 42 40 38 36 34
Ma
Chumstick basin
Swauk basin
Manastash basin
Naches basin
Puget basin
Chuckanut basin
Chumstick Fm.
Swauk Fm.
Tt
Roslyn Fm.
Tm
Tta
Naches Fm.
Puget Group
Chuckanut Fm.
Th

Figure 4.4--Stratigraphic relationships of depositional phases in the Chumstick Formation. Tephrostratigraphy based upon McClincy, 1986. Zircon fission track ages of tuffs from Gresens etal., 1981; Gresens, 1983; Tabor et al., 1980, 1982; this study.

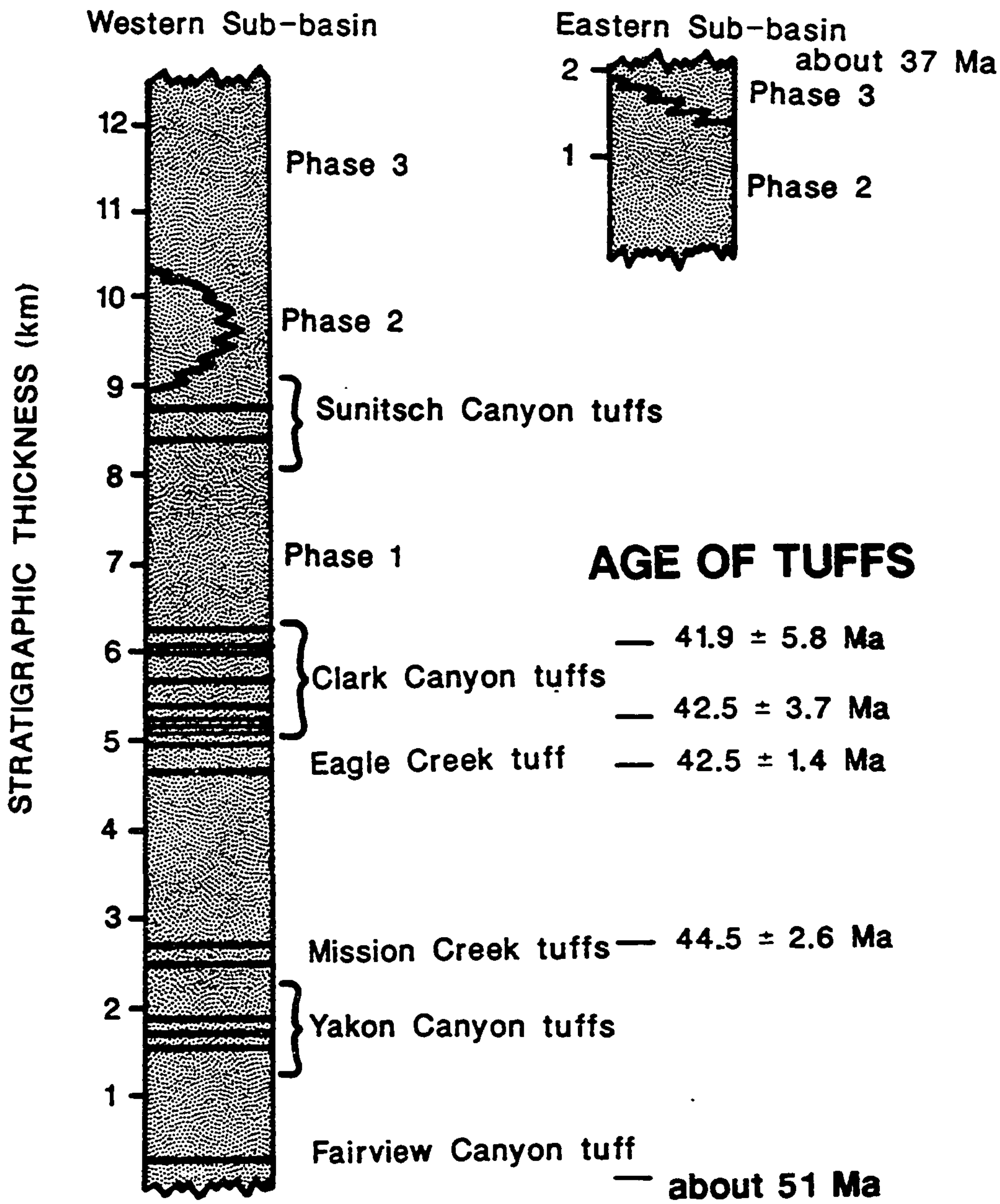
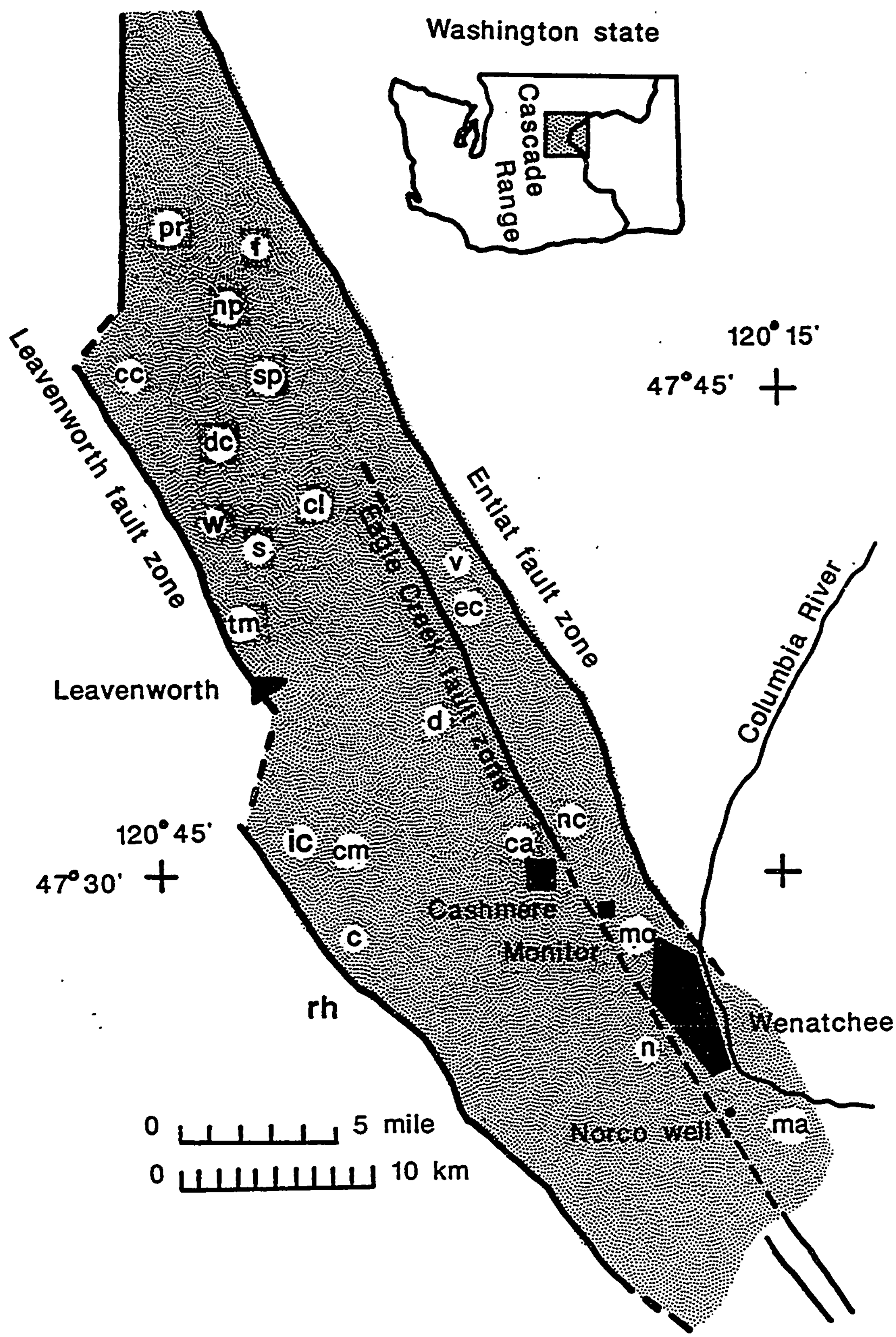

Western Sub-basin
Eastern Sub-basin
about 37 Ma
Phase 3
Phase 2
STRATIGRAPHIC THICKNESS (km)
Phase 3
Phase 2
Sunitsch Canyon tuffs
Phase 1
AGE OF TUFFS
Clark Canyon tuffs
41.9 ± 5.8 Ma
42.5 ± 3.7 Ma
Eagle Creek tuff
42.5 ± 1.4 Ma
Mission Creek tuffs
44.5 ± 2.6 Ma
Yakon Canyon tuffs
Fairview Canyon tuff
about 51 Ma

Figure 4.5--Map showing the location of major fault zones, towns (Leavenworth, Cashmere, Monitor, and Wenatchee) and stratigraphic sections discussed in this paper. Abbreviations for stratigraphic sections-- c = Camasland, ca = Cashmere, cc = Cole's Corner, cl = Clark Canyon, cm = Camas Creek, d = Derby Canyon, dc = Deadhorse Canyon, ec = Eagle Creek, f = Fish Lake, ic = Ingalls Creek, ma = Malaga Road, mo = Monitor, n = Number 2 Canyon, nc = Nahahum Canyon, np = North Plain, pr = Pole Ridge, rh = Red Hill, s = Sunitsch Canyon, sp = South Plain, tm = Tumwater Mountain, v = Van Canyon, w = Wright Canyon.

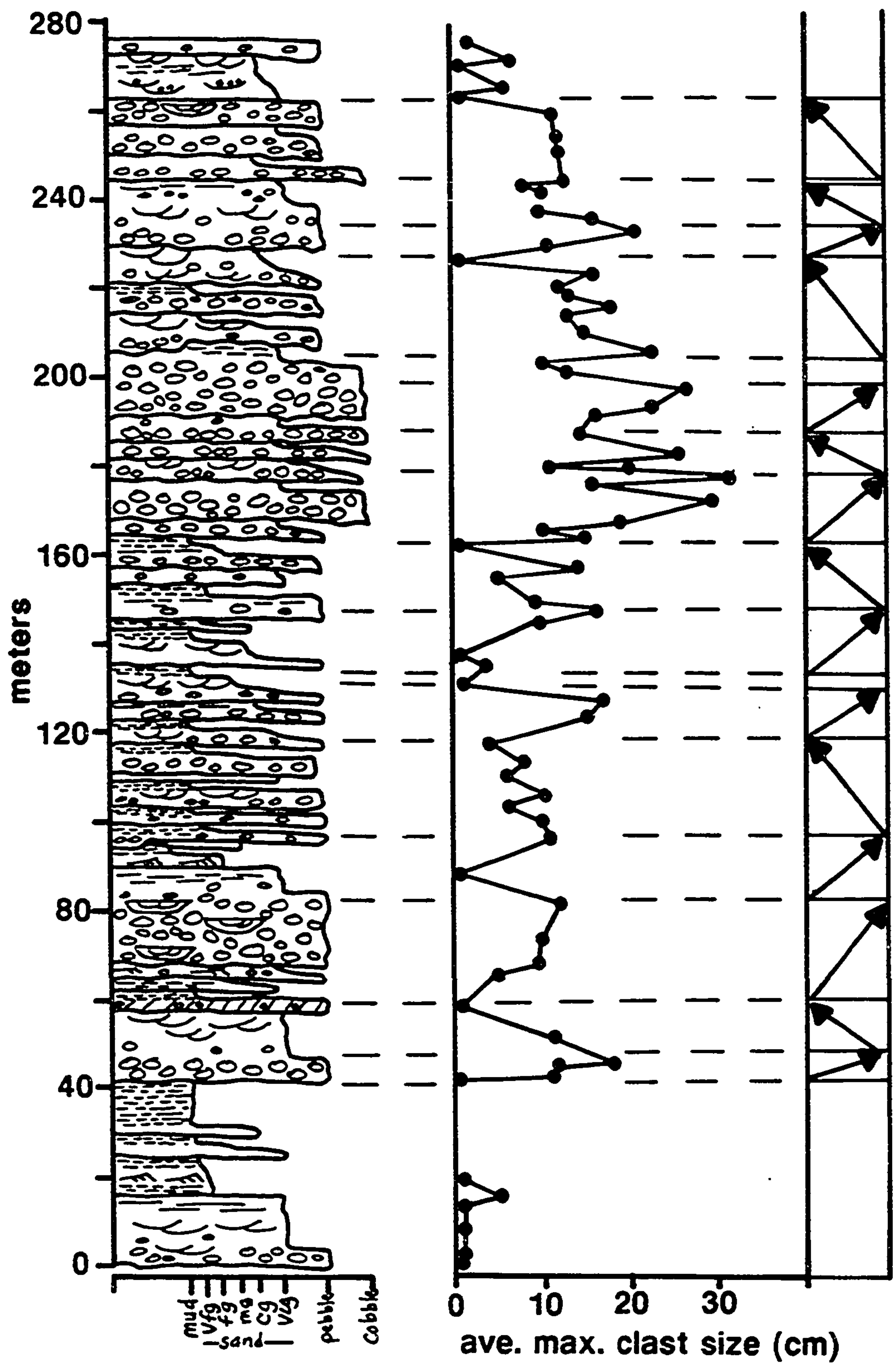


Washington state
Cascade Range
120° 15'
47°45'
120° 45'
47°30'
Leavenworth fault zone
Entiat fault zone
Eagle Creek fault zone
Columbia River
Leavenworth
Cashmere
Monitor
Wenatchee
Norco well
pr
f
np
cc
sp
dc
cl
w
s
v
ec
tm
d
nc
ic
cm
ca
c
mo
rh
n
ma
0 5 mile
0 10 km

Figure 4.6--Stratigraphic section of proximal fan deposits at the Camasland section. Meter-scale, fining-upward depositional units are organized into mega-sequences 15 to 40 meters thick. Average maximum clast size represents average of 10 largest clasts per bed. Symbols used:

exoclasts
intraclasts
parallel bedding
parallel lamination
trough x-bedding
planar x-bedding
ripple x-lamination
climbing ripple x-lam.
convoluted bedding

plant macrofossil
rootlets
slumps/logs
bioturbation:
infaunal
bedding surface
clastic dike
concretion layer
fining-upward sequence



280
240
200
160
120
80
40
0
meters
mud
vfg
fg
mg
cg
vcg
—sand—
pebble
cobble
0
10
20
30
ave. max. clast size (cm)

Figure 4.7--Stratigraphic section of distal fan deposits, Clark Canyon section, showing lateral continuity of gravel longitudinal-bar deposits separated by broadly lenticular inter-bar channels. The lateral continuity of soil horizons indicates intervals of non-deposition on the fan. Layers of intraclasts, which represent channel bank failures and slumps, can also be traced laterally. Symbols are as given in Figure 4.6.

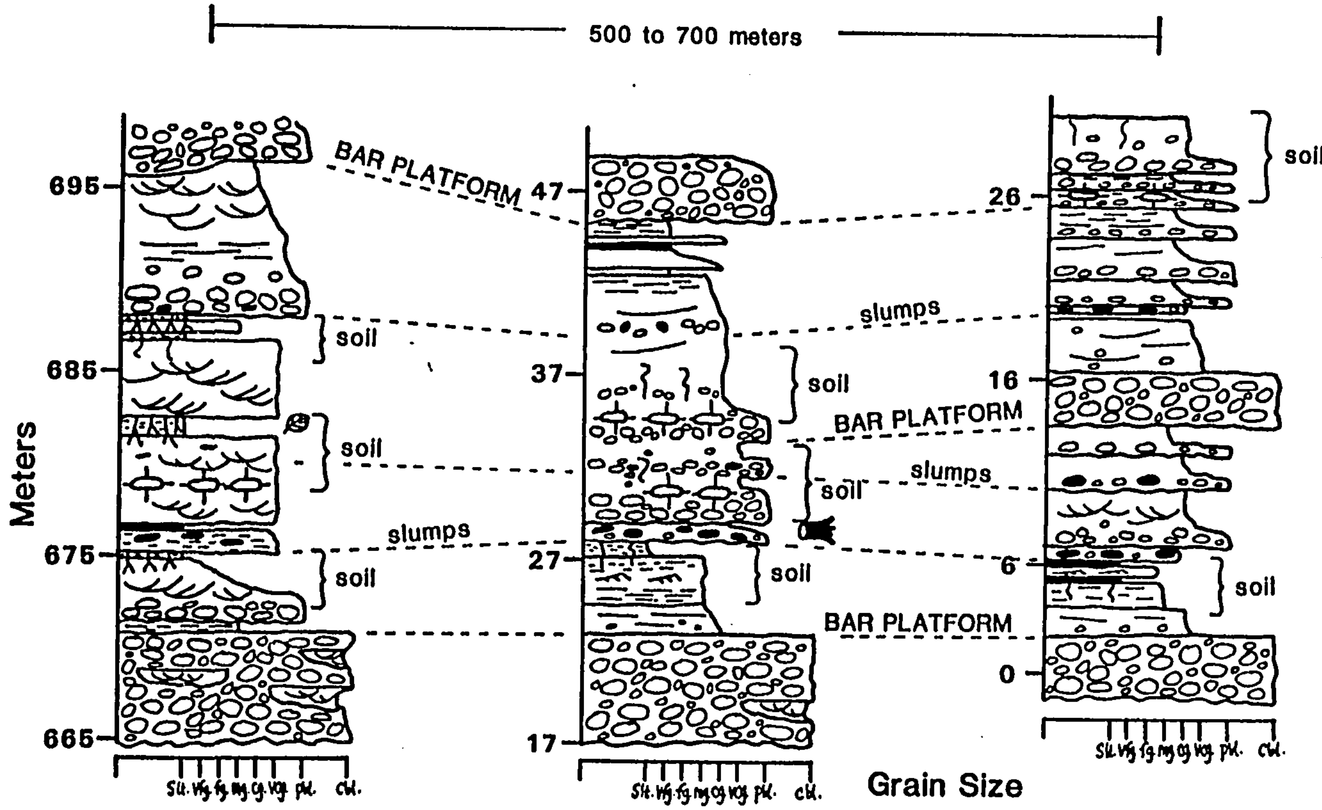
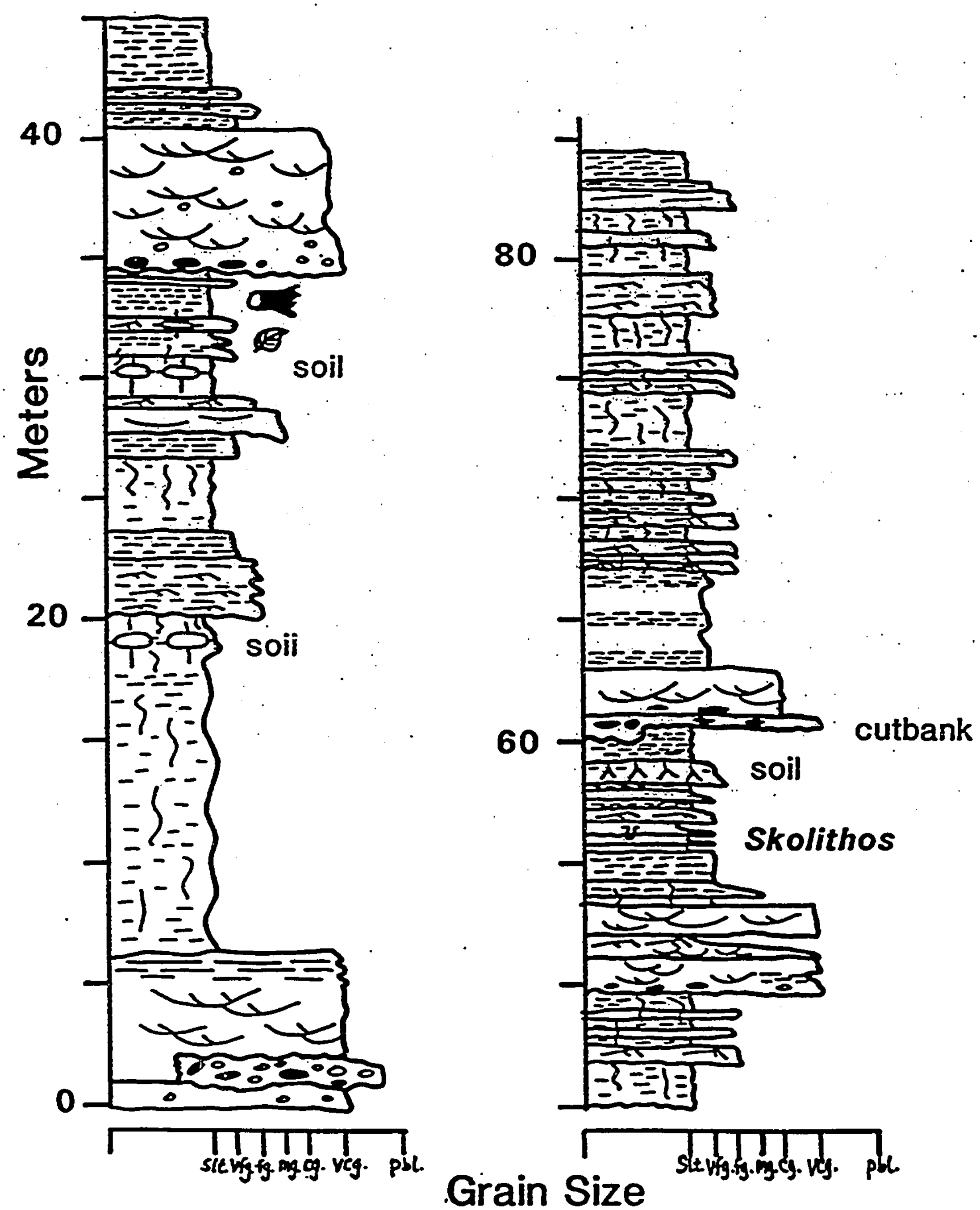
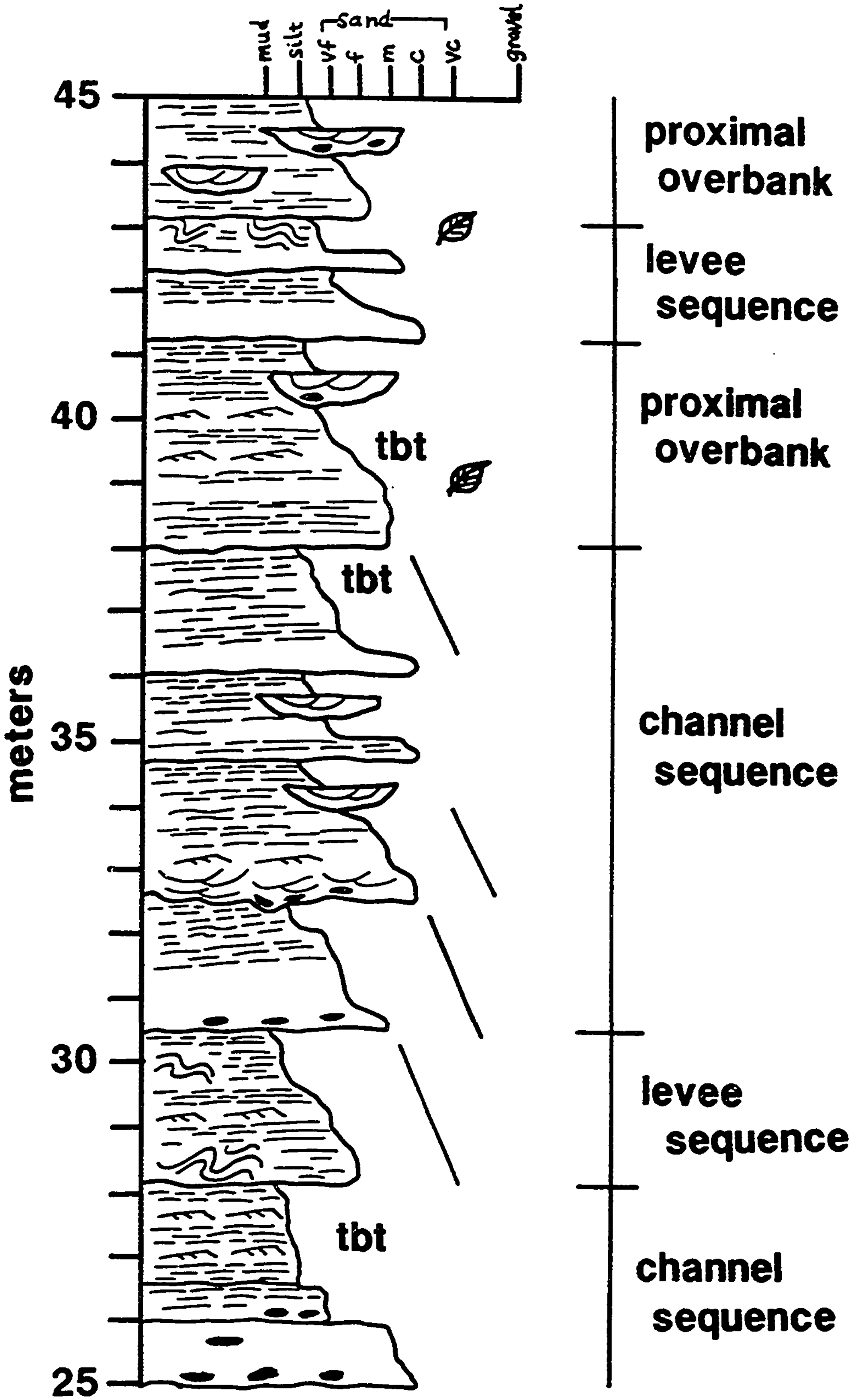

500 to 700 meters
Meters
695
685
675
665
47
37
27
17
26
16
6
0
BAR PLATFORM
soil
slumps
Grain Size
Slt. vfg. fg. mg. cg. vcg. pbl. cbl.

Figure 4.8--Stratigraphic section of basin-fill deposits. The Pole Ridge section consists of vertically stacked, multistory-channel deposits encased in proximal- and distal-overbank sequences. See Figure 4.5 for location of section. Symbols used are the same as in Figure 4.6.



40
20
0
Meters
soil
soii
80
60
cutbank
soil
Skolithos
Slt. vfg. fg. mg. cg. vcg. pbl.
Slt. vfg. fg. mg. cg. vcg. pbl.
Grain Size

Figure 4.9--Stratigraphic section of lacustrine delta-front deposits. The Sunnyslope Road section consists of lenticular, isolated channels and vertically stacked multistory channels surrounded by thin-bedded turbidites. Channel-fill sequences include turbidites, dune deposits, massive beds, and channel-margin slumps. Symbols are the same as in Figure 4.6.



mud
silt
sand
vf
f
m
c
vc
gravel
45
40
35
30
25
meters
tbt
tbt
tbt
proximal overbank
levee sequence
proximal overbank
channel sequence
levee sequence
channel sequence

Figure 4.10--Photographs of soft-sediment deformation structures in the Chumstick Formation. These are interpreted as soft-sediment structures that were induced by paleo-earthquake events. Top: large-scale sand clastic dikes, hammer for scale (30 cm). Bottom: sand flame structures, scale is 15 cm.

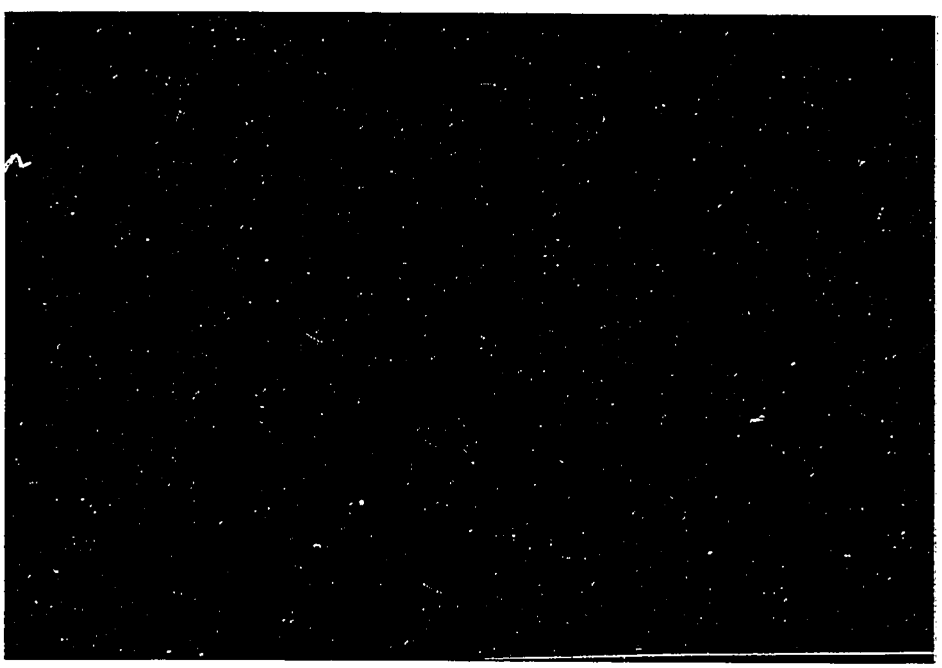
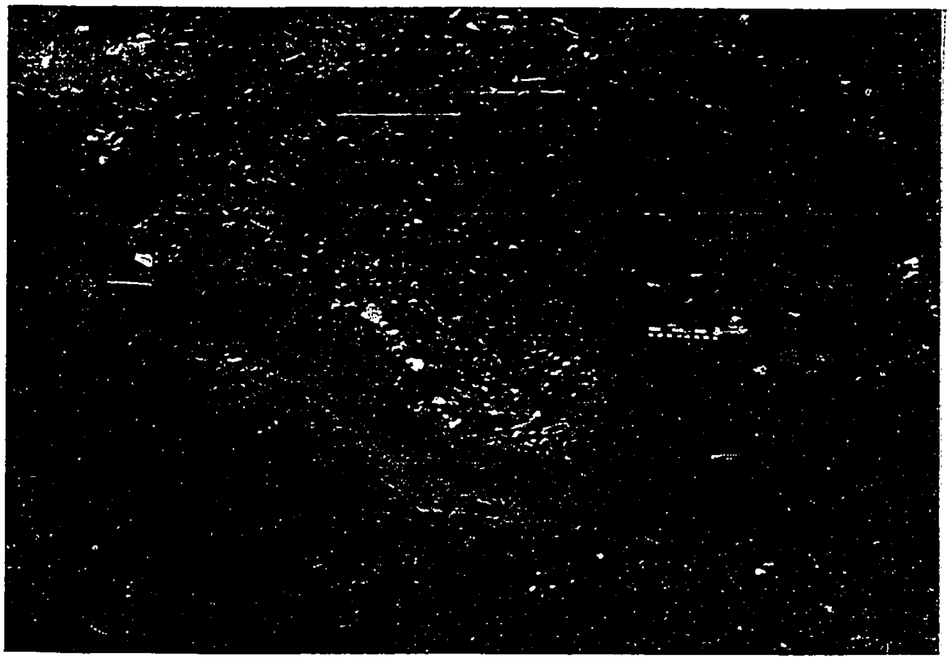


Figure 4.10 (con't.)--Top: unusual gravel scour pits into underlying sand, note vertical scour-pit wall, scale is 15 cm. Bottom: small mud diapirs into overlying sand, scale is 15 cm.



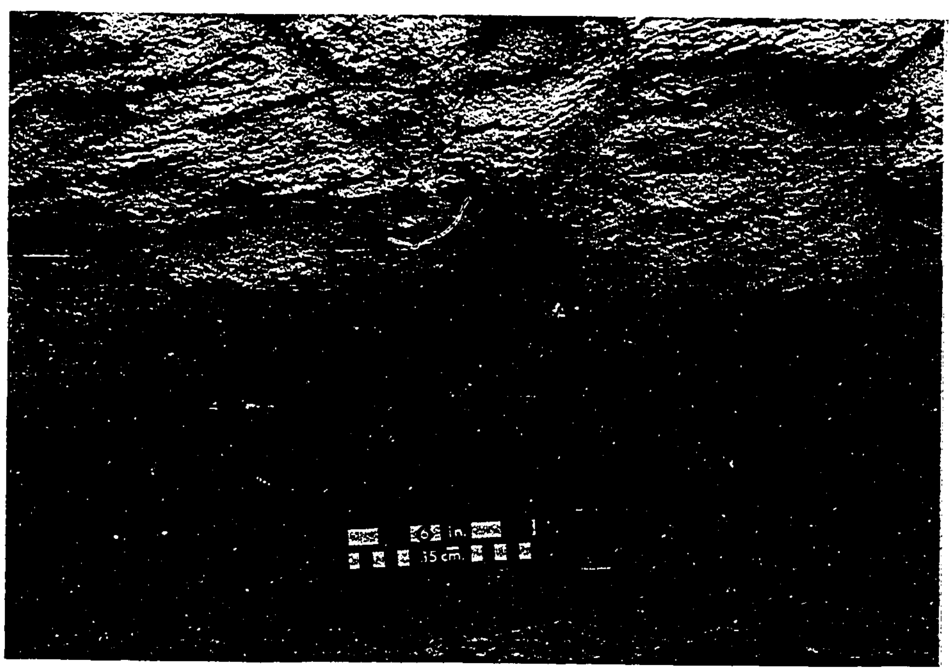
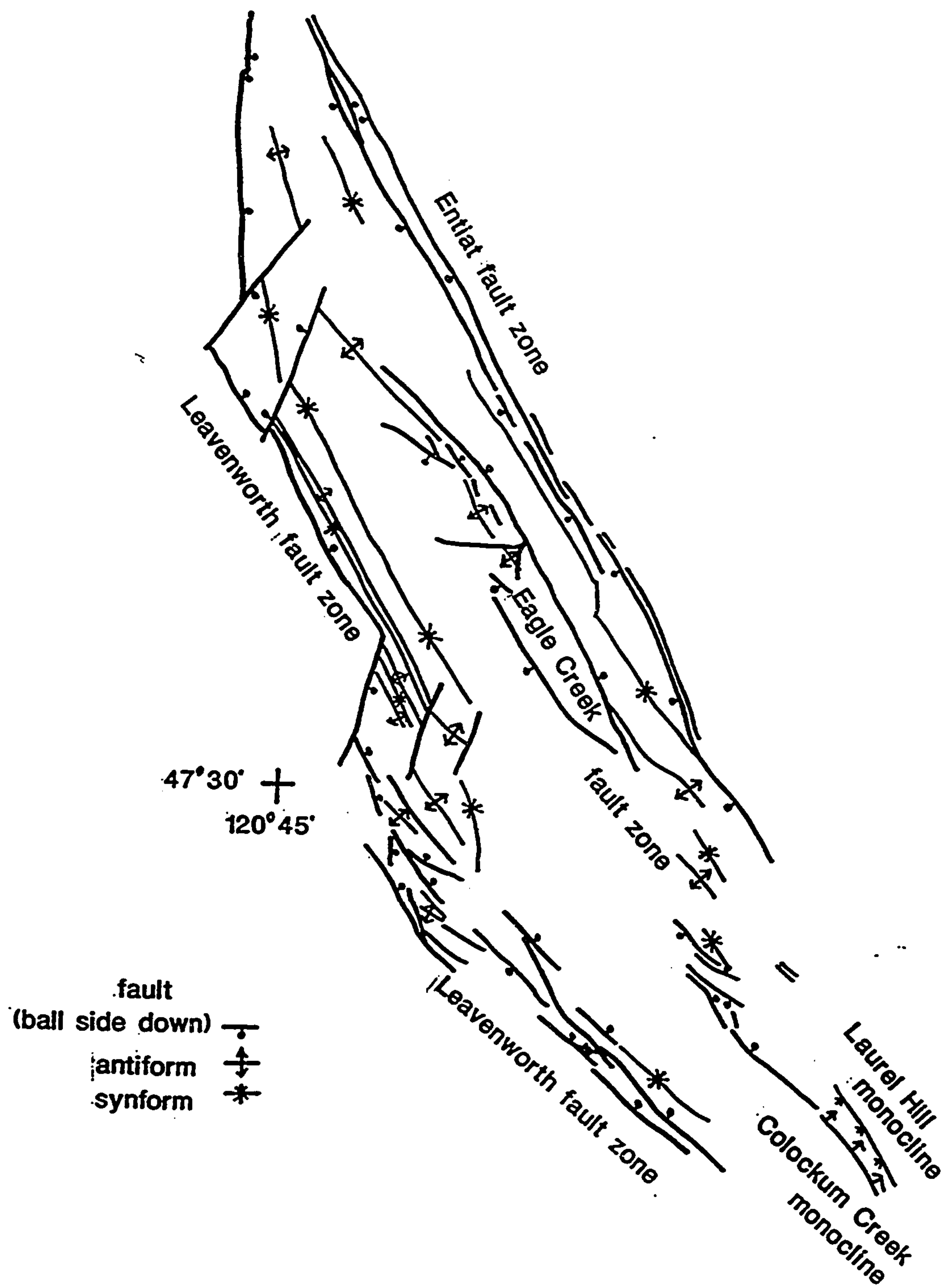
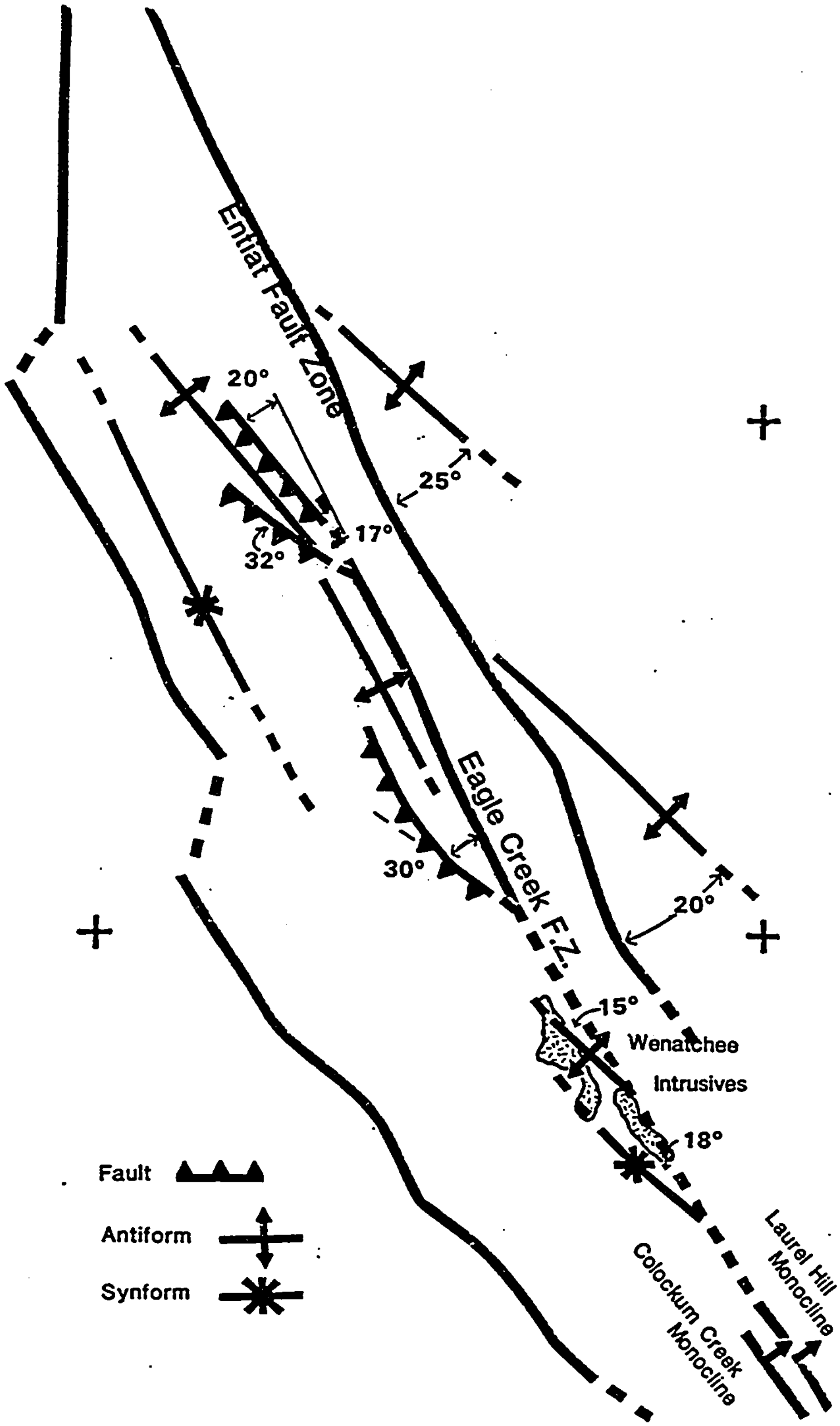

in.
cm.

Figure 4.11-- Map showing the structural geology of the Chumstick Formation. The Chumstick basin is divided into two sub-basins by a set of fault herein called the Eagle Creek fault zone. The northern terminus of the Eagle Creek fault zone consists of secondary faults and folds forming a horsetail splay structure. Fold axes have a strong northwest-trend, parallel to the trend of the Entiat and Eagle Creek fault zones, and to the two right-stepping bends on the Leavenworth fault zone (near location of labels). See text for discussion of fold axes.



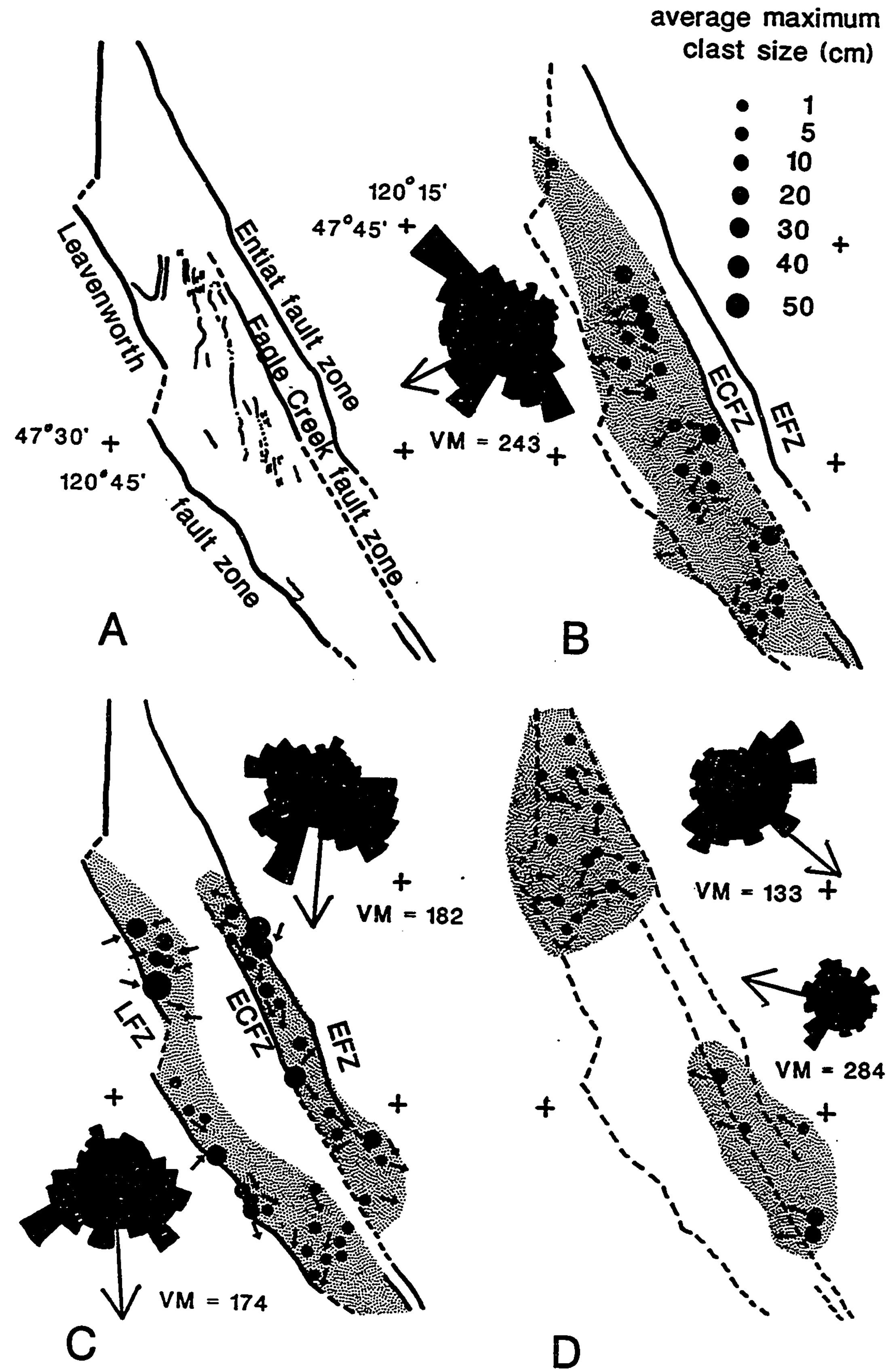
Entiat fault zone
Leavenworth fault zone
Eagle Creek
fault zone
47°30'
120°45'
Leavenworth fault zone
Laurel Hill
monocline
Colockum Creek
monocline
fault
(ball side down)
antiform
synform

Figure 4.12--Simplified structural map that emphasizes features in the Eagle Creek and Entiat fault zones. The Eagle Creek fault zone is proposed to be a major, through-going, fault zone that parallels and partly overlaps the Entiat fault zone. The intrusive complex near Wenatchee was emplaced into the trend of the Eagle Creek fault zone. Structural and sedimentological data suggest that the eastern sub-basin opened in the step-over zone between these two overlapping, dextral faults. Mapping based on Tabor et al., 1980, 1982.



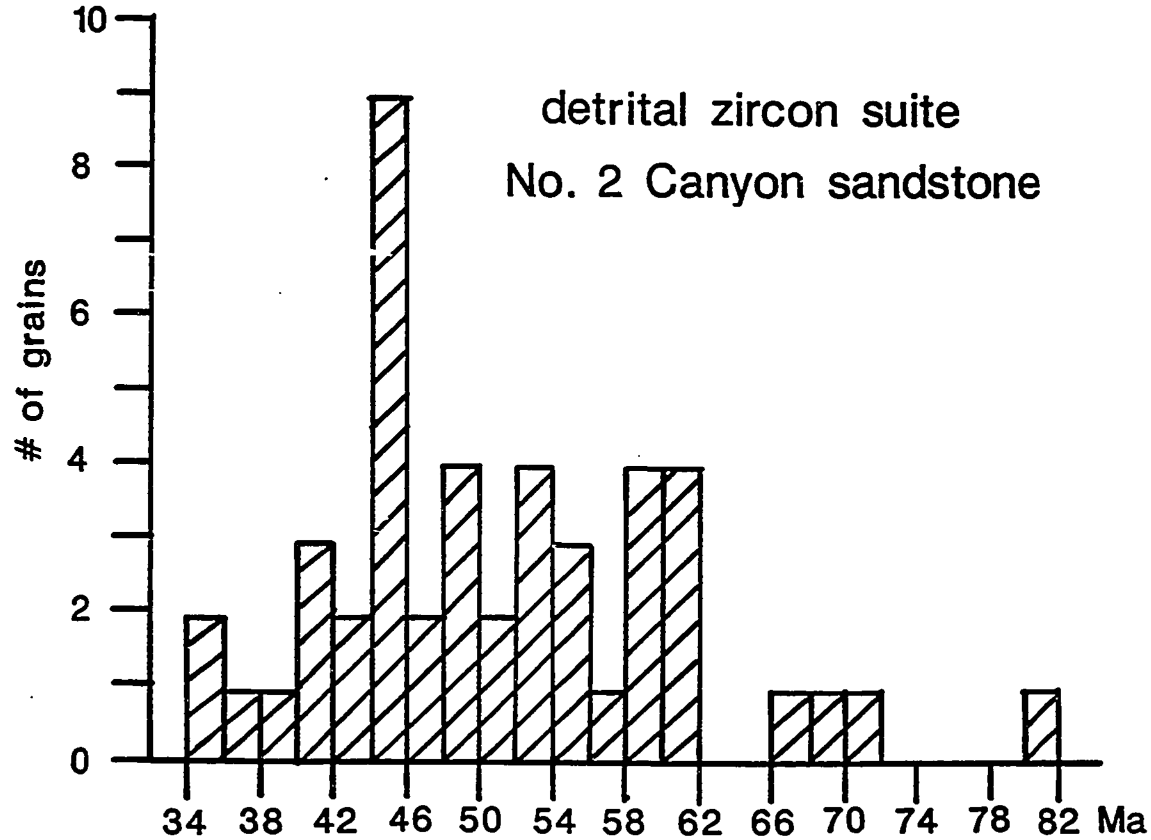
Entiat Fault Zone
Eagle Creek F.Z.
20°
25°
17°
32°
30°
20°
15°
18°
Wenatchee
Intrusives
Laurel Hill
Monocline
Colockum Creek
Monocline
Fault
Antiform
Synform

Figure 4.13--Map showing paleocurrent and provenance data from the Chumstick Formation. A: Map showing the distribution of interstratified tuffs in the Chumstick Formation (based on mapping by McClincy, 1986). Tuffs are restricted to Phase 1 deposits in the western sub-basin, and young to the northwest. B: Phase 1 deposition (>51 Ma to about 42 Ma). C: Phase 2 deposition (about 42 Ma to about 40 Ma). D: Phase 3 deposition (about 40 Ma to about 37 Ma). Symbols used: small arrows are vector means of paleocurrent distributions; paleocurrent rose shows summary of paleocurrent data for each phase; circles indicate the average maximum clast size at outcrops (key in Fig. 4.7b).



average maximum clast size (cm)
1
5
10
20
30
40
50
Leavenworth fault zone
Entiat fault zone
Eagle Creek fault zone
47°30'
120°45'
120°15'
47°45'
A
VM = 243
ECFZ
EFZ
B
VM = 182
LFZ
ECFZ
EFZ
VM = 174
C
VM = 133
VM = 284
D

Figure 4.14--Histogram of the zircon fission-track ages from two samples in the Chumstick Formation. Top: detrital zircons recovered from a sandstone in Number 2 Canyon, near the city of Wenatchee, indicating a depositional age of 46 to 44 Ma. Bottom: zircons recovered from the Eagle Creek tuff, indicating a depositional age of about 43 Ma.


detrital zircon suite
No. 2 Canyon sandstone
# of grains
0
2
4
6
8
10
34 38 42 46 50 54 58 62 66 70 74 78 82 Ma

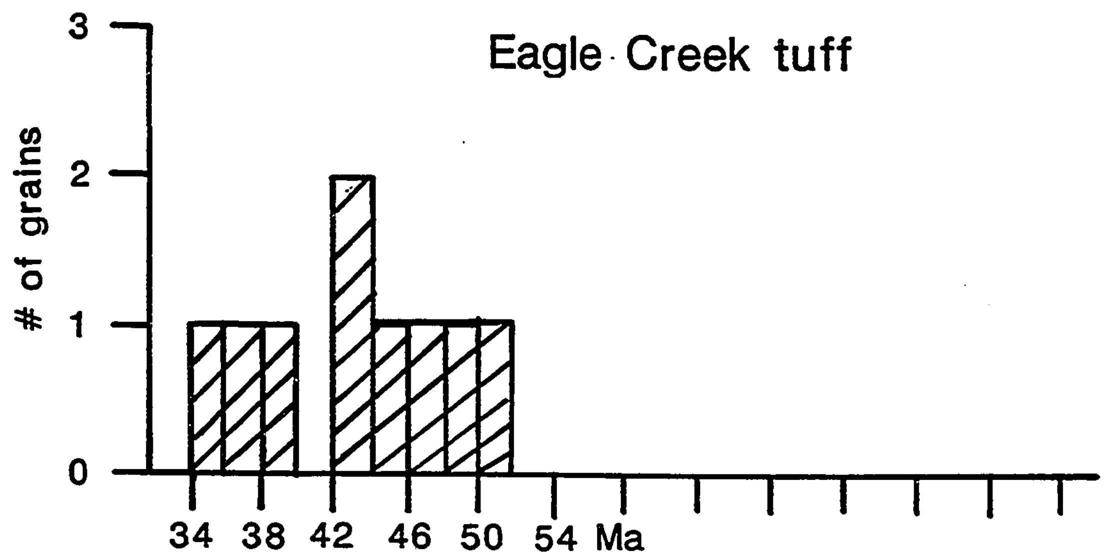

Eagle Creek tuff
# of grains
0
1
2
3
34 38 42 46 50 54 Ma

Figure 4.15--Compilation of zircon fission-track (circles) and potassium-argon (triangles) radiometric dates for tuffs, flows, and intrusives in the region around the Chumstick Formation. Circles and triangles are shown at mean of each age distribution, and bars represent analytical precision (one standard deviation). Data compiled from Tabor et al., 1980, 1982, 1984; Gresens et al., 1981; and Ott et al., 1986.

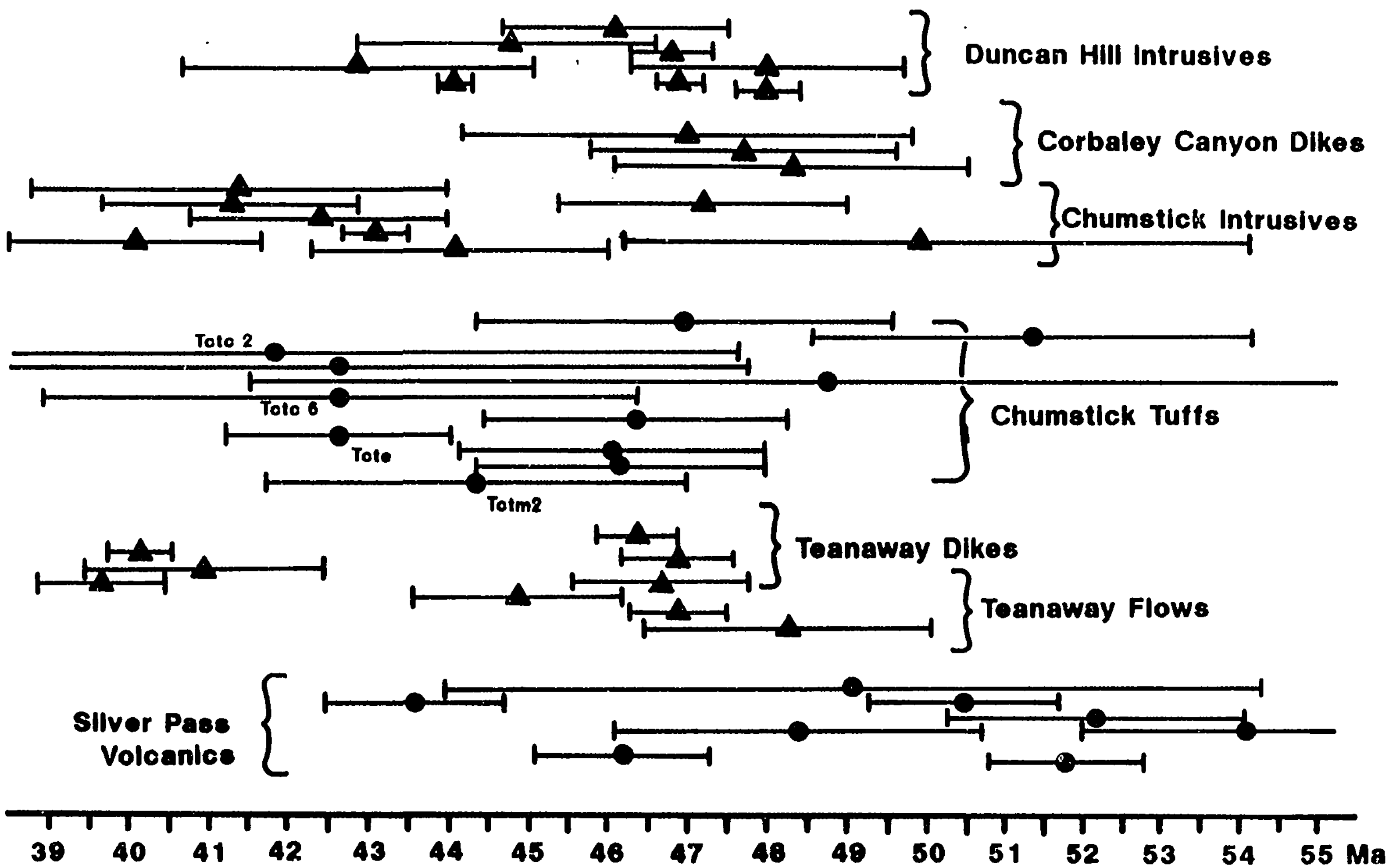
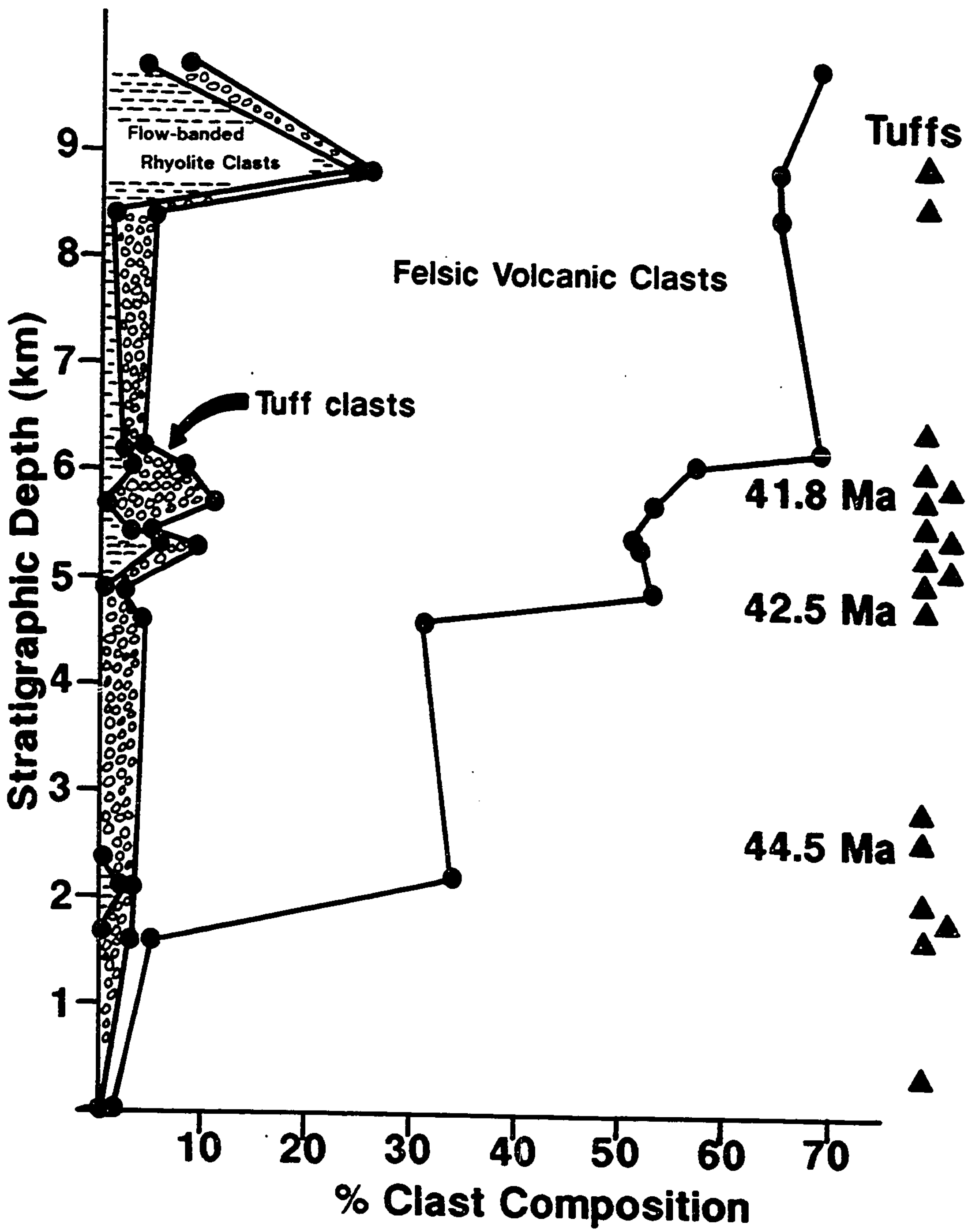
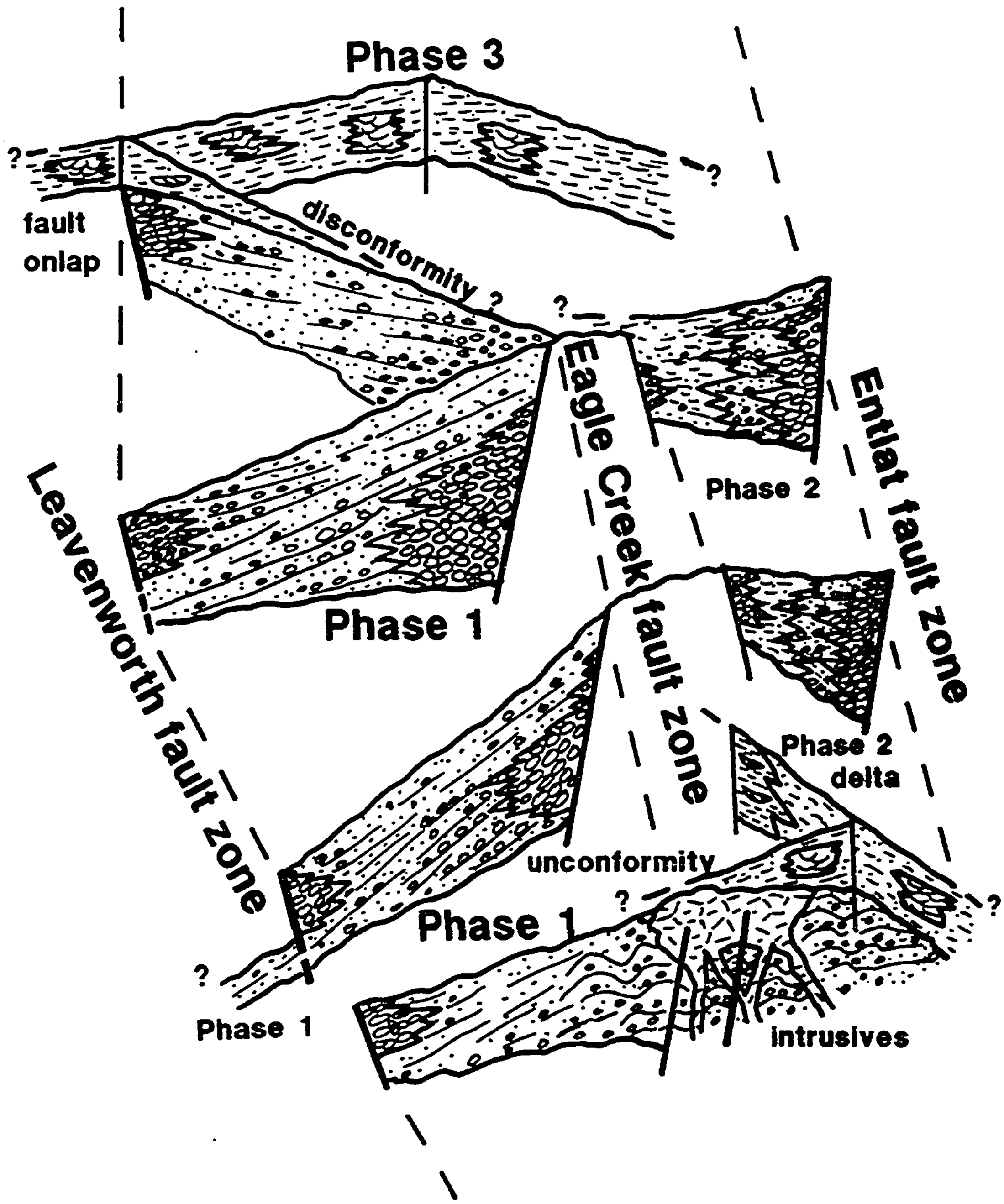

Duncan Hill Intrusives
Corbaley Canyon Dikes
Chumstick Intrusives
Chumstick Tuffs
Toto 2
Toto 6
Tote
Totm2
Teanaway Dikes
Teanaway Flows
Silver Pass Volcanics
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55 Ma

Figure 4.16--Volcanic-clast composition of Phase 1 deposits. The stratigraphic column shows the upward increase in three lithologies: flow-banded rhyolite, tuff, and porphyritic rhyodacite. At each stratigraphic level, the set of data points represent a sample of 300 to 500 clasts. The stratigraphic position and radiometric ages of tuffs are shown on the right.



Flow-banded
Rhyolite Clasts
Felsic Volcanic Clasts
Tuff clasts
Tuffs
41.8 Ma
42.5 Ma
44.5 Ma
Stratigraphic Depth (km)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
% Clast Composition

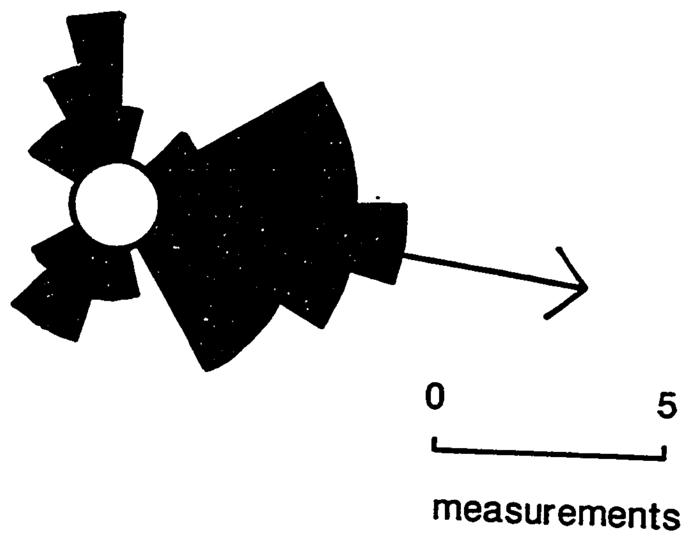
Figure 4.17--Fence diagram showing the stratigraphic relationship of Chumstick deposits. Phase 1 deposits are thickest on the west side of the Eagle Creek fault zone (ECFZ), and overtopped the trend of the Leavenworth fault zone (LFZ). An intrusive complex was injected into the ECFZ during Phase 1 time, and locally deformed and hydrothermally altered the deposits. Later uplift in the LFZ resulted in west-derived sediments (Phase 2) that overlie Phase 1 deposits in the western sub-basin. Sediments in the eastern sub-basin were mostly derived from the east, with minor sources along the ECFZ. Phase 3 deposits conformably overlie earlier deposits in the western sub-basin, and onlap the LFZ. Phase 3 deposits in the southern part of the basin unconformably overlie the intrusives and older Chumstick deposits.



Phase 3
?
?
fault
onlap
disconformity
?
?
Eagle Creek fault zone
Entiat fault zone
Phase 2
Leavenworth fault zone
Phase 1
Phase 2
delta
unconformity
?
Phase 1
?
?
Phase 1
intrusives

Figure 4.18--Paleocurrents in the region near Wright Canyon (north of Tumwater Mountain) showing eastward-directed coarse-grained fluvial deposits interbedded with northwestward-directed finer-grained fluvial deposits. The latter are interpreted as onlaps of basin-fill into the Leavenworth fault zone during intervals of tectonic quiescence.

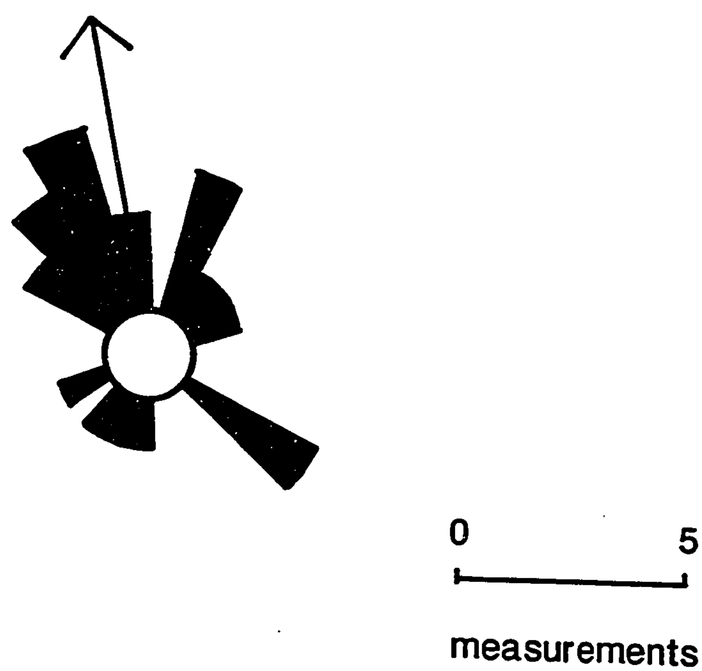
CLAST IMBRICATION



O = 099

n = 39

CROSS-BEDDING

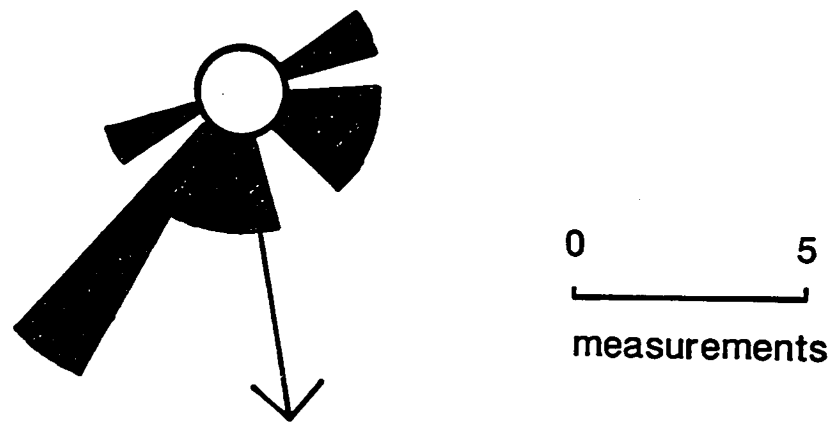


O = 351

n = 24

Figure 4.19--Paleoslope and paleocurrent data from delta-front deposits at Sunnyslope Road (see Figure 4.5 for location). Paleoslope data was obtained from the corrected orientation of slump folds, and is shown here as the trend of the slope. Mean paleoflow direction was approximately perpendicular to mean paleoslope (i.e., it was approximately parallel to the trend of the slope, as shown here).

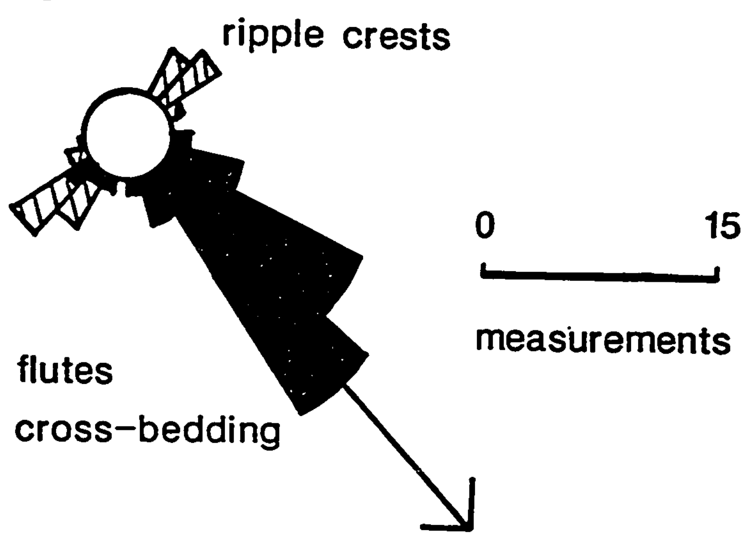
PALEOSLOPE



θ = 171

n = 10

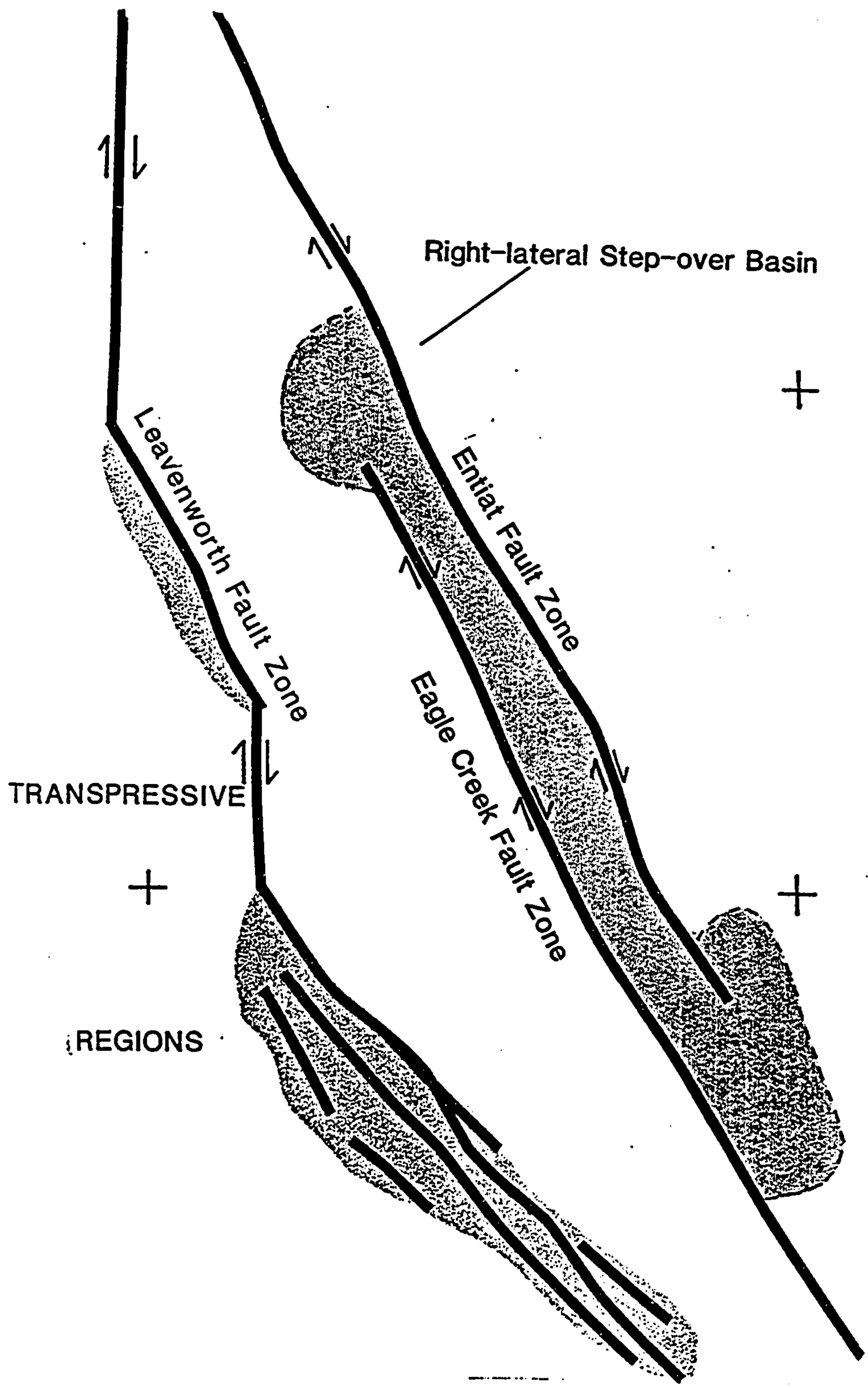
PALEOCURRENTS



θ = 141

n = 54

Figure 4.20--Proposed relationship of faults to sedimentation during Phase 2. Right-lateral movement on the Leavenworth fault zone caused transpression and uplift on the right-stepping, Leavenworth fault zone. The shaded areas indicate the uplifted regions that served as sediment sources during Phase 2 time. Coeval right-lateral movement on the overlapping Eagle Creek and Entiat fault zones resulted in the formation of the eastern sub-basin as a transtensional step-over basin (stipled area).



Right-lateral Step-over Basin
Leavenworth Fault Zone
Entiat Fault Zone
Eagle Creek Fault Zone
TRANSPRESSIVE
REGIONS

Figure 4.21--Schematic cross-section of positive and negative flower structures (from Harding, 1985). It is proposed that uplift of biotite gneiss blocks in the center of the Chumstick basin was a result of reverse faulting out of the principle displacement zone, in this case the Eagle Creek fault zone to the east of the uplift.

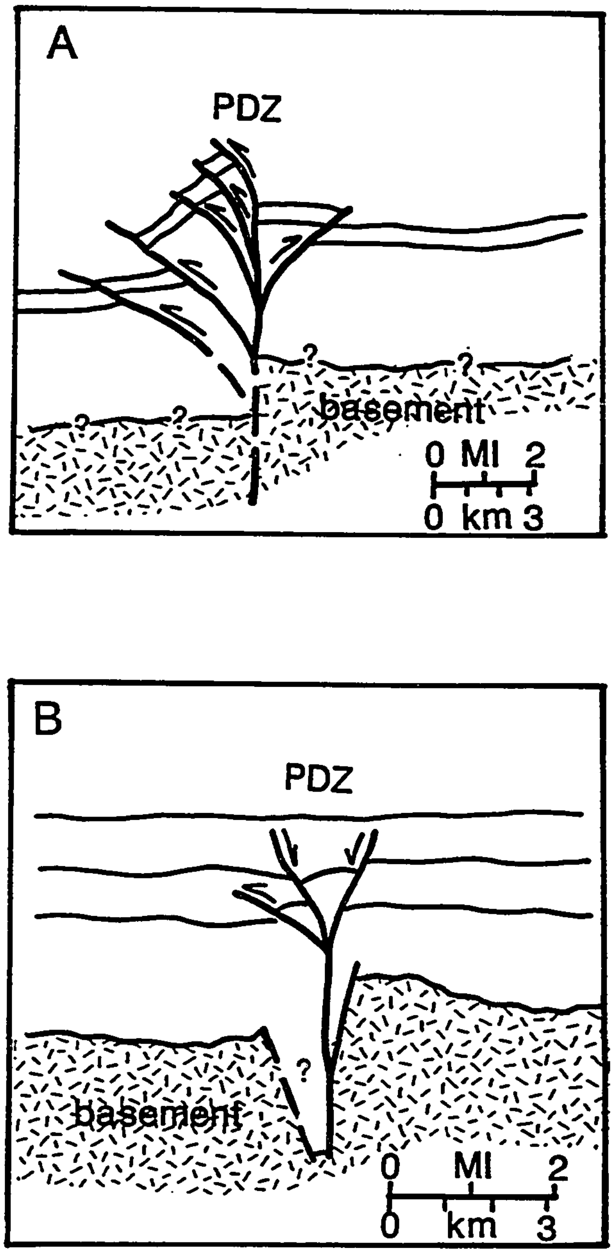
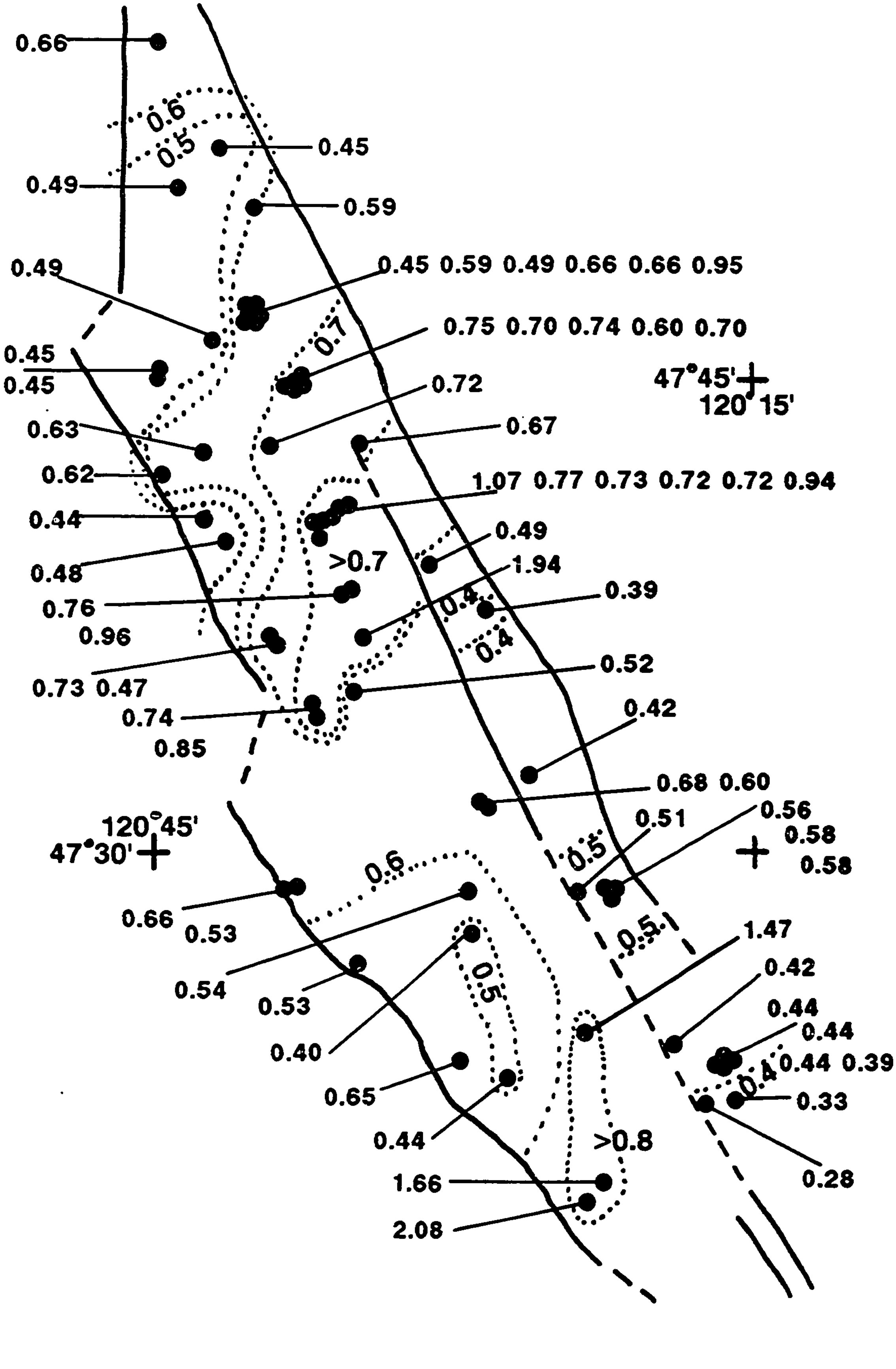
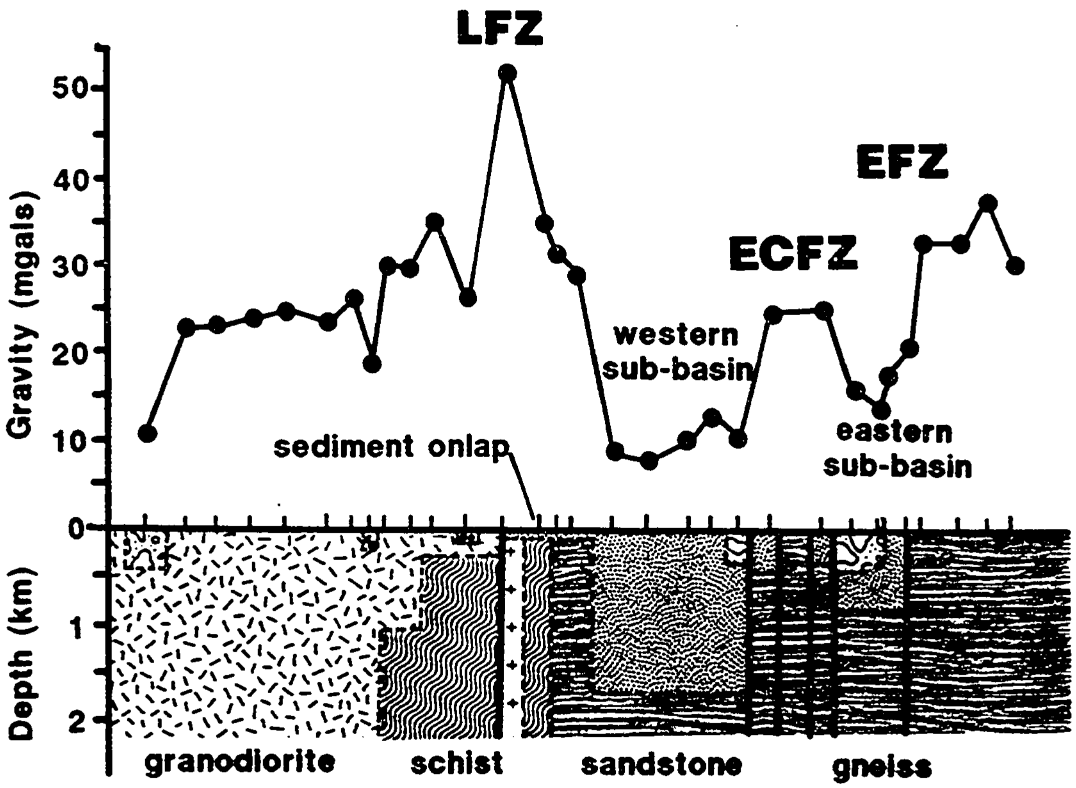

A
PDZ
basement
0 MI 2
0 km 3
B
PDZ
basement
0 MI 2
0 km 3

Figure 4.22--Contour plot of the vitrinite reflectance values of surface outcrops in the Chumstick Formation. This contour plot shows that the basin depocenter in the western sub-basin was immediately west of the Eagle Creek fault zone. Inliers of lower values along the Leavenworth fault zone correspond to younger (Phase 2) sediments. Thermal data in the eastern sub-basin are suggestive of cross-cutting structures that may have controlled deposition in the lacustrine-deltaic system. See text for discussion. Data from Evans and Walsh, in preparation.



0.66
0.6
0.5
0.45
0.49
0.59
0.49
0.45 0.59 0.49 0.66 0.66 0.95
0.7
0.75 0.70 0.74 0.60 0.70
0.45
0.45
47°45'
120°15'
0.72
0.63
0.67
0.62
1.07 0.77 0.73 0.72 0.72 0.94
0.44
0.49
0.48
>0.7
1.94
0.76
0.4
0.39
0.96
0.4
0.73 0.47
0.52
0.74
0.85
0.42
0.68 0.60
120°45'
47°30'
0.51
0.56
0.58
0.58
0.5
0.6
0.66
0.53
0.5
1.47
0.54
0.53
0.5
0.42
0.44
0.44
0.40
0.44 0.39
0.4
0.65
0.33
0.44
>0.8
0.28
1.66
2.08

Figure 4.23--Gravity transect across the northern part of the Chumstick basin. Top: gravity profile, modified from Silling (1979) to show separation of the basin into eastern and western sub-basins, the location of the Eagle Creek fault zone, and proximal onlap of Phase 3 deposits near the Leaven-worth fault zone. Bottom: map showing location of transect.


LFZ
EFZ
ECFZ
Gravity (mgals)
50
40
30
20
10
0
western
sub-basin
eastern
sub-basin
sediment onlap
Depth (km)
1
2
granodiorite
schist
sandstone
gneiss

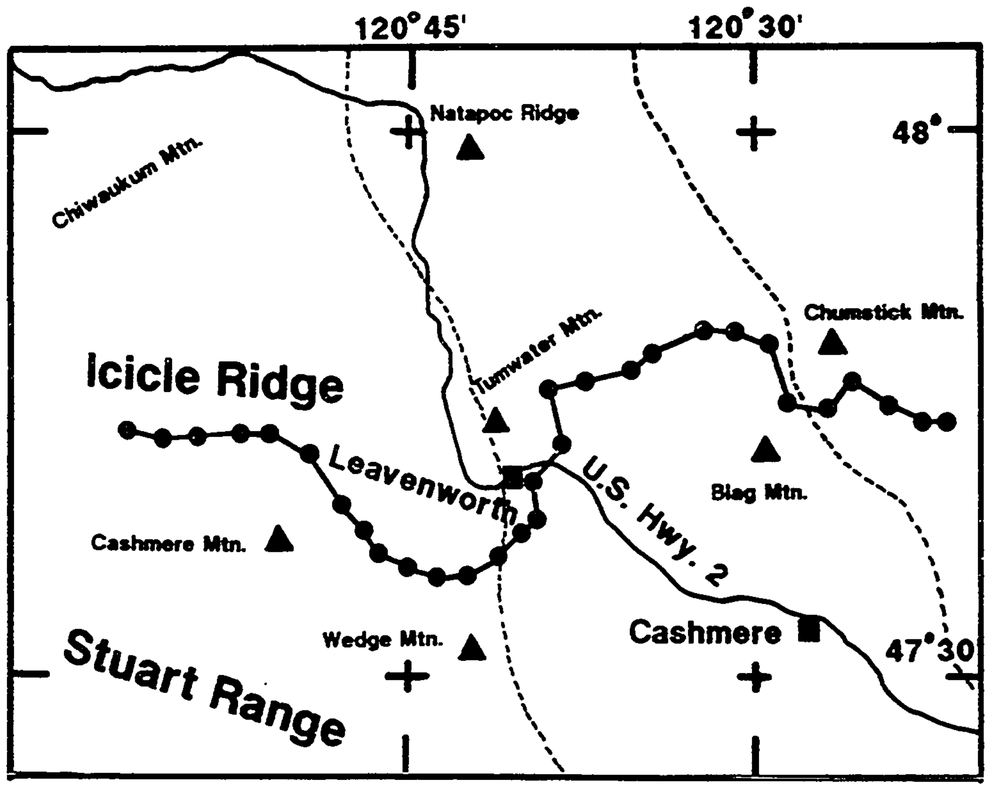

120°45'
120°30'
48°
Natapoc Ridge
Chiwaukum Mtn.
Tumwater Mtn.
Chumstick Mtn.
Icicle Ridge
Leavenworth
U.S. Hwy. 2
Blag Mtn.
Cashmere Mtn.
Wedge Mtn.
Cashmere
47°30
Stuart Range

Figure 4.24--Models of conveyor-belt sedimentation, from Crowell (1982). Top: map view showing offlapping and shingling of depositional units due to lateral offset of sediment source regions. Bottom: cross-sectional views showing how the summation of stratigraphic thickness of these imbricated depositional packages is much greater than the actual basin-fill thickness measured in the vertical direction.

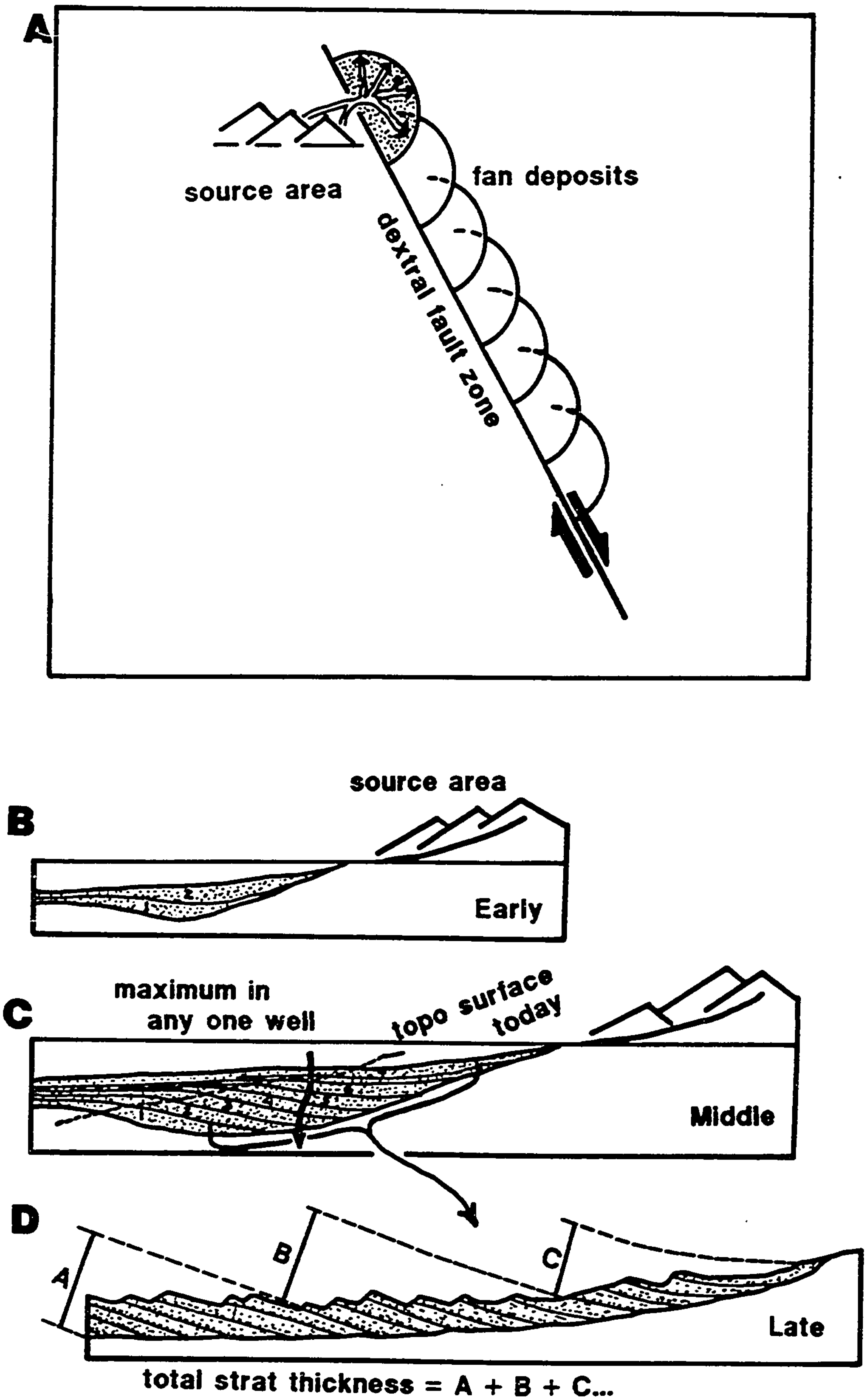
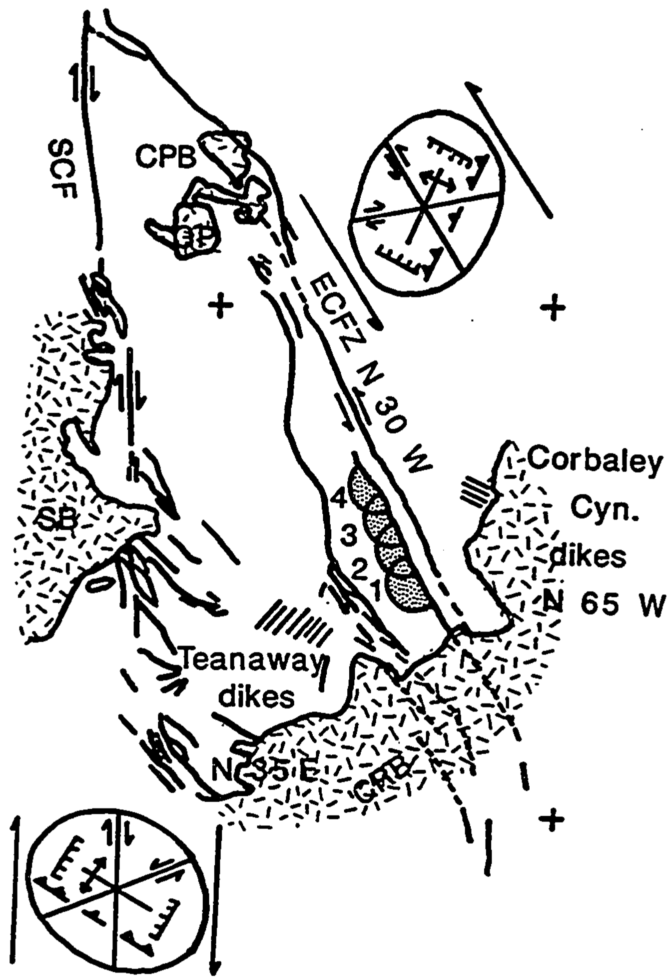

A
source area
fan deposits
dextral fault zone
B
source area
Early
C
maximum in
any one well
topo surface
today
Middle
D
A
B
C
Late
total strat thickness = A + B + C...

Figure 4.25--Proposed alternatives for the opening of the western sub-basin at about 51 Ma, and related movement on the Eagle Creek fault. A: shows model for left-lateral movement on the Eagle Creek fault, and the orientation of Teanaway Basalt and Corbaley Canyon dikes. B: shows the preferred model for right-lateral movement on the Eagle Creek fault coupled with oblique-slip in the fault zone. See text for discussion.

A


SCF
CPB
CP
ECFZ N 30 W
4
3
2
1
Corbaley
Cyn.
dikes
N 65 W
SB
Teanaway
dikes
N 35 E
GRB

B

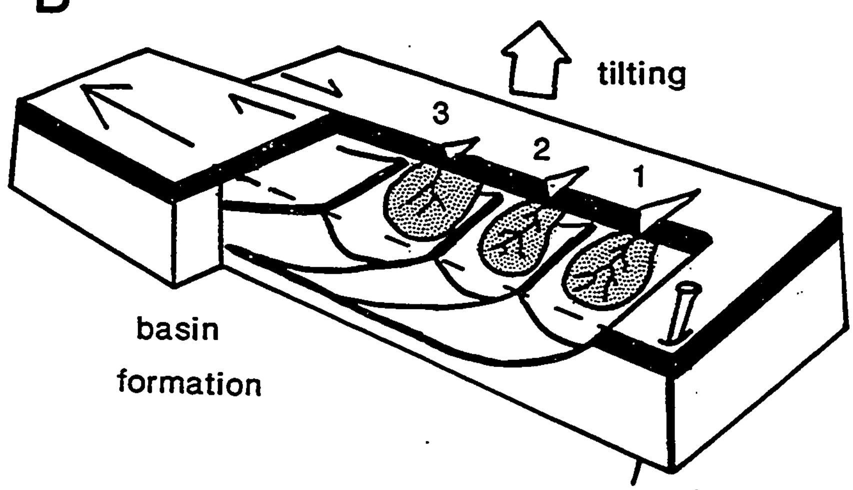
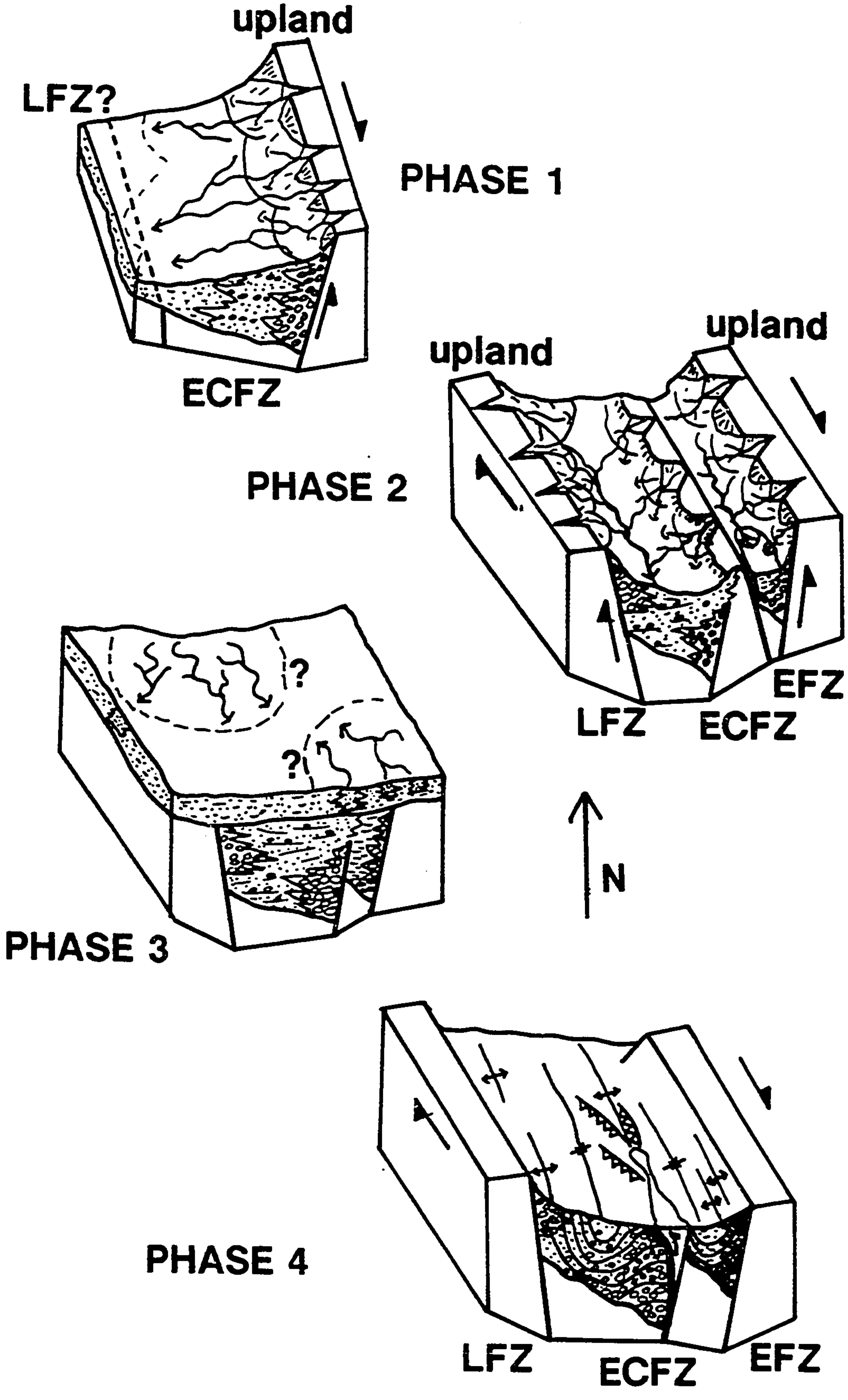

tilting
3
2
1
basin
formation

Figure 4.26--Block diagrams showing the basin evolution of the Chumstick Formation. A: Phase 1 deposition in a half-graben west of the Eagle Creek fault zone. B: Phase 2 deposition during an interval of dextral faulting resulting in uplift along the Leavenworth fault zone, and formation of the eastern sub-basin. C: Phase 3 deposition during an interval of tectonic quiescence. D: basin deformation in a zone of dextral transpression, with uplift and exposure of basement blocks in the center of the basin resulting in a localized Phase 4(?) of debris-flow deposition.


upland
LFZ?
PHASE 1
ECFZ
upland
upland
PHASE 2
LFZ
ECFZ
EFZ
?
?
PHASE 3
N
PHASE 4
LFZ
ECFZ
EFZ

REFERENCES

Abbott, P.L. and Peterson, G.L., 1978, Effects of abrasion durability on conglomerate clast populations: examples from Cretaceous and Eocene conglomerates of the San Diego area, California: Journal of Sedimentary Petrology, v. 48, p. 31-42.

Alexander, F., 1956, Stratigraphic and structural geology of the Blewett-Swauk area, Washington [M.S. Thesis]: Seattle, University of Washington, 62 p.

Alexander, J. and Leeder, M.R., 1987, Active tectonic control on alluvial architecture, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., editors, Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication no. 39, p. 243-252.

Allen, J.R.L., 1974, Studies in fluviatile sedimentation: implications of pedogenic carbonate units: Lower Old Red Sandstone, Anglo-Welsh outcrop: Geological Journal, v. 9, p. 181-208.

Allen, J.R.L., 1978, Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion-controlled alluvial suites: Sedimentary Geology, v. 21, p. 129-147.

Andrews, E.D., 1983, Entrainment of gravel from naturally sorted riverbed material: Geological Society of America Bulletin, v. 94, p. 1225-1231.

Andrews, E.D., 1984, Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado: Geological Society of America Bulletin, v. 95, p. 371-378.

Axelrod, D.I., 1966, The Eocene Copper Basin flora of northeastern Nevada: University of California Publications in Geological Science, v. 59, 125 p.

Aydin, A. and Nur, A., 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v.1, p. 91-105.

Aydin, A. and Page, B.M., 1984, Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California: Geological Society of America Bulletin, v. 95, p. 1303-1317.

Bailey, I.W. and Sinnott, E.W., 1915, A botanical index of Cretaceous and Tertiary climates: Science, v. 41, p. 831-834.

Bailey, I.W. and Sinnott, E.W., 1916, The climatic distribution of certain types of Angiosperm leaves: American Journal of Botany, v. 3, p. 24-39.

Ballance, P.F. and Reading, H.G., editors, 1980, Sedimentation in Oblique-slip Mobile Zones: International Association of Sedimentologists, Special Publication no. 4, 265 p.

Barker, C.E. and Pawlewicz, M.J., 1986, The correlation of vitrinite reflectance with maximum paleotemperature in humic organic matter, in Buntebarth, G. and Stegena, L., editors, Paleogeothermics. New York: Springer-Verlag, p. 79-93.

Biddle, K.T. and Christie-Blick, N., editors, 1985, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, 386 p.

Bluck, B.J., 1979, Structure of coarse-grained braided stream alluvium: Transactions of the Royal Society of Edinburg, v. 70, p. 181-221.

Bogue, S.W. and Evans, J.E., 1986, Discordant paleomagnetic component from the Eocene Chumstick Formation, central Washington state [abstract]: Geological Society of America, Abstracts with Programs, v. 18, p. 88.

Boothroyd, J.C. and Ashley, G.M., 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, in McDonald, B.C. and Jopling, A.V., editors, Glaciofluvial and Glaciolacustrine Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication no. 23, p. 193-222.

Boothroyd, J.C. and Nummedal, D., 1978, Proglacial braided outwash: a model for humid alluvial fan deposits, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 641-668.

Bown, T.M., and Kraus, M.J., 1981, Lower Eocene alluvial paleosols (Willwood Formation, northwest Wyoming, U.S.A.) and their significance for paleoecology, paleoclimatology, and basin analysis: Paleogeography, Paleoclimatology, Paleoecology, v. 34, p. 1-30.

Bracken, B. and Picard, M.D., 1984, Trace fossils from Cretaceous/Tertiary North Horn Formation in central Utah: Journal of Paleontology, v. 58, p. 477-487.

Bradley, W.C., 1970, Effects of weathering on abrasion of granitic gravel, Colorado River, Texas: Geological Society of America Bulletin, v. 81, p. 61-80.

Bridge, J.S., 1985, Paleocurrent patterns inferred from alluvial deposits: a critical evaluation: Journal of Sedimentary Petrology, v. 55, p. 579-589.

Brown, M.B.,1983, Two-way tables, empty cells, and departures from independence, in Dixon, W.J. and Brown, M.B., editors, BMDP-83, Biomedical Computer Programs, P Series: Los Angeles, University of California Press, p. 278-296.

Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 147-163.

Buza, J.W., 1979, Dispersal patterns and paleogeographic implications of lower to middle Tertiary fluviatile sandstones in the Chiwaukum graben, east-central Cascades, Washington in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 63-74.

Bull, W.B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geological Survey Professional Paper no. 352-E, p. 89-129.

Bull, W.B., 1977, The alluvial fan environment: Progress in Physical Geography, v. 1, p. 222-270.

Burnham, R.J., 1986, Foliar morphological analysis of the Ulmoidae (Ulmaceae) from the early Teriary of western North America: Palaeontographica, v. 201, p. 135-167.

Byrnes, M.E., 1985, Provenance study of late Eocene arkosic sandstones in southwest and central Washington

[M.S. Thesis]: Portland, Oregon, Portland State University, 65 p.

Campbell, N.P., 1987, Structural and stratigraphic relationships between the northwestern Columbia River Basalt margin and recent sub-basalt gas wells [abstract]: Geological Society of America, Abstracts with Programs, v. 19, p. 364.

Carr, T.R., 1982, Log-linear models, Markov chains, and cyclic sedimentation: Journal of Sedimentary Petrology, v. 52, p. 905-912.

Cashman, S.M., 1974, Geology of the Peshastin Creek area, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 29 p.

Cashman, S.M. and Whetten, J.T., 1976, Low-temperature serpentinization of peridotite fanglomerate on the west margin of the Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 87, p. 1773-1776.

Castano, J.R. and Sparks, D.M., 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals, in Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.A., editors, Carbonaceous Materials as Indicators of Metamorphism: Geological Society of America Special Paper no. 153, p. 31-52.

Cater, F.W. and Crowder, D.F., 1967, Geologic map of the Holden quadrangle, Washington: U.S. Geological Survey, Geological Quadrangle Map 646.

Chaney, R.W. and Sanborn, E.I., 1933, The Goshen flora of west-central Oregon: Carnegie Institute of Washington Publication, v. 439, 103 p.

Chappell, W.M., 1936, Geology of the Wenatchee quadrangle [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 249 p.

Christie-Blick, N. and Biddle, K.T., 1985, Deformation and basin formation along strike-slip faults, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 1-34.

Crowell, J.C., 1974a, Sedimentation along the San Andreas fault, California, in Dott, R.H., Jr. and Shaver, R.H., editors, Modern and Ancient Geosynclinal Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication no. 19, p. 292-303.

Crowell, J.C., 1974b, Origin of the Cenozoic basins in southern California, in Dickinson, W.R., editor, Tectonics and Sedimentation, Society of Economic Paleontologists and Mineralogists Special Publication no. 22, p. 190-204.

Crowell, J.C., 1982, The tectonics of Ridge Basin, southern California, in Crowell, J.C. and Link, M.H., editors, Geological History of Ridge Basin, Southern California, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 25-42.

Crowell, J.C. and Link, M.H., editors, 1982, Geologic history of the Ridge Basin, southern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, 304 p.

Davies, D.K., Vessell, R.K., Miles, R.C., Foley, M.G., and Bonis, S.B., 1978, Fluvial transport and downstream sediment modifications in an active volcanic region: in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 61-84.

Davis, G.A., Monger, J.W.H., and Burchfiel, B.C., 1978, Mesozoic construction of the Cordilleran "collage," central British Columbia to central California, in Howell, D.G. and McDougall, K.A., editors, Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 2, p. 1-32.

Denny, C.S., 1965, Alluvial fans in the Death Valley region, California and Nevada: U.S. Geological Survey Professional Paper no. 466, 62 p.

Duchaufour, P., 1977, Pedology: Pedogenesis and Classification. London: George Allen and Unwin, 448 p.

Engels, J.C., Tabor, R.W., Miller, F.K., and Obradovich, J.D., 1976, Summary of K-Ar, Rb-Sr, U-Pb, and fission track ages of rocks from Washington state prior to 1975 (exclusive of Columbia Plateau Basalts): U.S. Geological Survey, Miscellaneous Field Studies, no. 710.

Ethridge, F.G. and Schumm, S.A., 1978, Reconstructing paleochannel morphologic and flow characteristics: methodology, limitations, and assessment: in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 703-721.

Evans, J.E. and Walsh, T., in preparation, Thermal evolution, maturity, and petroleum potential of the Eocene Chumstick Formation, a wrench-fault basin in the Cascade Range, Washington.

Ewing, T.E., 1980, Paleogene tectonic evolution of the Pacific Northwest: Journal of Geology, v. 88, p. 619-638.

Flach, K.W., 1978, Soil Taxonomy: approved amendments and clarification of definitions: Soil Conservation Service, Washington, D.C.

Fraser, G.T., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation in the Swauk Pass area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 219 p.

Friend, P.F., 1978, Distinctive features of some ancient river systems, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 531-542.

Friend, P.F., Slater, M.J., and Williams, R.C., 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of Geological Society London, v. 136, p. 39-46.

Frizzell, V.A., 1979, Petrology of Paleogene non-marine sandstone units in Washington, in Armentrout, J.M., Cole, M.R., and TerBest, H., Jr., editors, Cenozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Symposium 3, p. 113-118.

Frizzell, V.A., Jr. and Tabor, R.W., 1977, Stratigraphy of Tertiary arkoses and their included monolithological fanglomerates and breccias in the Leavenworth fault zone, central Cascades, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 9, p. 421.

Gibling, M. and Rust, B.R., 1984, Channel margins in a Pennsylvanian braided fluvial deposit: the Morien Group near Sydney, Nova Scotia, Canada: Journal of Sedimentary Petrology, v. 54, p. 773-872.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1965, The K horizon: a master soil horizon of carbonate accumulation: Soil Science, v. 99, p. 74-82.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences in carbonate accumulation in desert soils: Soil Science, v. 101, p. 347-360.

Gloppen, T.G. and Steel, R.J., 1981, The deposits, internal structure, and geometry in six alluvial fan-fan delta bodies (Devonian-Norway) - a study in the significance of bedding sequence in conglomerates, in Ethridge, R.G. and Flores, R.M., editors, Recent and Ancient Nonmarine Depositional Environments: Models for Exploration: Society of Economic Paleontologists and Mineralogists Special Publication no. 31, p. 49-69.

Gole, C.V. and Chitale, S.V., 1966, Inland delta building activity of Kosi River: Journal of Hydraulics Division, American Society of Civil Engineers, Proceedings, Paper 4722, v. HY 2, p. 111-126.

Gresens, R.L., 1980, Deformation of the Wenatchee Formation and its bearing on the tectonic history of the Chiwaukum graben, Washington, during Cenozoic time: Geological Society of America Bulletin, v. 91, p.4-7, 115-155.

Gresens, R.L., 1982a, Early Cenozoic geology of central Washington state: I. Summary of sedimentary, igneous, and tectonic events: Northwest Science, v. 56, p. 218-229.

Gresens, R.L., 1982b, Early Cenozoic geology of central Washington state: II. Implications for plate tectonics and alternatives for the origin of the Chiwaukum graben: Northwest Science, v. 56, p. 259-264.

Gresens, R.L., 1983, Geology of the Wenatchee and Monitor quadrangles, Chelan and Douglas Counties, Washington: Washington Division of Geology and Earth Resources, Bulletin 75, 75 p.

Gresens, R.L., Naeser, C.W., and Whetten, J.T., 1981, Stratigraphy and age of the Chumstick and Wenatchee Formations- Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: Geological Society of America Bulletin, v. 92, p. 233-236, 841-876.

Gresens, R.L. and Stewart, R.J., 1981, What lies beneath the Columbia Plateau? Oil and Gas Journal, v. 79, p. 157-164.

Harding, T.P., Gregory, R.F., and Stephens, L.H., 1983, Convergent wrench fault and positive flower structure, Ardmore Basin, Oklahoma, in Bally, A.W., editor, Seismic Expression of Structural Styles: American Association of Petroleum Geologists, Studies in Geology, Series 15, v. 3, p. 4.2-13 to 4.2-17.

Harding, T.P., Vierbuchen, R.C., and Christie-Blick, N., 1985, Structural styles, plate-tectonic settings, and hydrocarbon traps of divergent (transtensional) wrench faults, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 51-77.

Harland, W.B., 1971, Tectonic transpression in Caledonian Spitsbergen: Geological Magazine, v. 108, p. 27-42.

Hauptman, J.L., 1983, The sedimentology of the Wenatchee Formation: Late Paleogene fluvial and lacustrine strata of the east-central Cascade Range, Washington state [M.S. Thesis]: Seattle, Washington, University of Washington, 164 p.

Hickey, L.J. and Wolfe, J.A., 1975, The basis of Angiosperm phylogeny: vegetative morphology: Annals of the Missouri Botanical Garden Society, v. 62, p. 538-589.

Hood, A., Gutjahr, C.C.M., and Heacock, R.L., 1975, Organic metamorphism and the generation of petroleum: American Association of Petroleum Geologists Bulletin, v. 59, p. 986-996.

Hooke, R. LeB., 1967, Processes on arid-region alluvial fans: Journal of Geology, v. 75, p. 438-460.

Hopkins, W.S., Jr., 1966, Palynology of Tertiary rocks of the Whatcom Basin, southwestern British Columbia and northwestern Washington [Ph.D. Dissertation]: Vancouver, British Columbia, University of British Columbia, 184 p.

Johnson, P.E., 1983, The origin of the Chiwaukum graben, Chelan County, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 96 p.

Johnson, S.Y., 1982, Stratigraphy, sedimentology, and tectonic setting of the Chuckanut Formation, North Cascades, Washington [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 221 p.

Johnson, S.Y., 1984a, Evidence for a margin-truncating transcurrent fault (pre-Late Eocene) in western Washington: Geology, v. 12, p. 538-541.

Johnson, S.Y., 1984b, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, p. 92-106.

Johnson, S.Y., 1984c, Cyclic fluvial sedimentation in a rapidly subsiding basin, northwestern Washington: Sedimentary Geology, v. 38, p. 361-392.

Johnson, S.Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington, in Biddle, K.T. and Christie-Blick, N., editors, Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication no. 37, p. 283-302.

Kellerhals, R., Shaw, J., and Arora, V., 1975, On grain size from thin sections: Journal of Geology, v. 83, p. 79-96.

Kesel, R.H., 1985, Alluvial fan systems in a wet-tropical environment, Costa Rica: National Geographic Research, v. 1, p. 450-469.

Knight, K.L., 1987, Rhizolite/calcrete: nonpedogenic plant root diagenesis (Middle Pennsylvanian) from Kansas [abstract]: American Association of Petroleum Geologists Bulletin, v. 71, p. 578.

Kochel, R.C. and Johnson, R.A., 1984, Geomorphology and sedimentology of humid-temperate alluvial fans, central Virginia: in Koster, E.H. and Steel, R.J., editors, Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists, Memoir 10, p. 109-122.

Kuenzi, W.D., Horst, O.H., and McGehee, R.V., 1979, Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala: Geological Society of America Bulletin, v. 90, p. 827-838.

Laravie, J.A., 1976, Geologic field studies along the eastern border of the Chiwaukum graben, central Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 55 p.

Leeder, M.R., 1975, Pedogenic carbonates and flood sediment accretion rates: a quantitative model for alluvial arid-zone lithofacies: Geological Magazine, v. 112, p. 257-270.

Lingley, W.S., Jr. and Walsh, T.J., 1986, Issues relating to petroleum drilling near the proposed high-level nuclear waste repository at Hanford: Washington Division of Geology and Earth Resources, Geologic Newsletter, v. 14, p. 10-19.

Lupe, R.D., 1971, Stratigraphy and petrology of the Swauk Formation in the Wenatchee Lake area [M.S. Thesis]: Seattle, Washington, University of Washington, 27 p.

MacGinitie, H.D., 1941, A Middle Eocene flora from the central Sierra Nevada: Carnegie Institute of Washington, Publication 534, 178 p.

MacGinitie, H.D., 1969, The fossil flora of the Green River beds in northwestern Colorado and northeastern Utah: University of California, Publications in Geological Science, v. 83, 140 p.

MacGinitie, H.D., 1974, An early Middle Eocene flora from Yellowstone-Absaroka Volcanic Province, northwestern Wind River Basin, Wyoming: University of California, Publications in Geological Science, v. 108, p. 1-103.

Machette, M.N., 1985, Calcic soils of the American Southwest, in Weide, D.L. and Faber, M.L., editors, Soils and Quaternary Geology of the Southwestern United States, Geological Society of America, Special Publication no. 203, p. 1-21.

Maizels, J.K., 1983, Paleovelocity and paleodischarge determination for coarse gravel deposits, in Gregory, K.J., editor, Background to Paleohydrology, John Wiley and Sons, Ltd., p. 101-139.

Margolis, J., 1987, Hydrothermal alteration and structure associated with epithermal gold mineralization, Wenatchee Heights, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 120 p.

McClincey, M., 1986, Tephrostratigraphy of the Chumstick Formation [M.S. Thesis]: Portland, Oregon, Portland State University, 127 p.

McFadden, L.D. and Tinsley, J.C., 1985, Rates and depth of pedogenic-carbonate accumulation in soils: formulation and testing of a compartment model, in Weide, D.L. and Faber, M.L., editors, Soils and Quaternary Geology of the Southwestern United States, Geological Society of America, Special Publication no. 203, p. 23-41.

McPherson, J.G., 1979, Calcrete (caliche) paleosols in fluvial redbeds of the Aztec Siltstone (Upper Devonian) southern Victoria Land, Antarctica: Sedimentary Geology, v. 22, p. 267-285.

Miall, A.D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v.13, p. 1-62.

Miall, A.D., 1978, Lithofacies types and vertical profile models in braided river deposits: a summary, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 597-604.

Mohrig, D., 1987, Facies and paleohydrology of a floodplain-dominated btaided fluvial system: Cretaceous Ventura redbeds, Washington, U.S.A. [M.S. Thesis]: Seattle, Washington, University of Washington, p.

Monger, J.W.H. and Price, R.A., 1979, Geodynamic evolution of the Canadian Cordillera- progress and problems: Canadian Journal of Earth Sciences, v. 16, p. 770-791.

Mukherji, A.B., 1976, Terminal fans of inland streams in Sutlej-Yamuna plain, India: Zeitschrift fur Geomorphologie, v. 20, p. 190-204.

Naeser, C.W., 1979, Fission-track dating and geologic annealing of fission tracks, in Jager, E. and Hunziker, J.C., editors, Lectures in Isotope Geology. New York: Springer-Verlag, p. 154-169.

Newman, K.R., 1981, Palynologic biostratigraphy of some early Tertiary nonmarine formations in central and western Washington, in Armentrout, J.M., editor, Pacific Northwest Cenozoic Biostratigraphy: Geological Society of America Special Paper no. 184, p. 49-65.

Ott, L.E., Groody, D., Follis, E.L., and Siems, P.L., 1986, Stratigraphy, structural geology, ore mineralogy, and hydrothermal alteration at the Cannon Mine, Chelan County, Washington, in MacDonald, A.J., editor, Gold '86, An International Symposium on the Geology of Gold Deposits, Proceedings Volume, p. 425-435.

Page, B.M., 1939, Geology of a part of the Chiwaukum quadrangle [Ph.D. Dissertation]: Palo Alto, California, Stanford University, 203 p.

Parkash, B., Awasthi, A.K., and Gohain, K., 1983, Lithofacies of the Markanda terminal fan, Kurukshetra District, Haryana, India, in Collinson, J.D. and Lewin, J., editors, Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication no. 6, p. 337-344.

Parrish, R.R., 1983, Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia, 1. Fission-track dating, apparent uplift rates, and patterns of uplift: Tectonics, v. 2, p. 601-631.

Pierson, T.C., 1980, Erosion and deposition by debris flows at Mt. Thomas, New Zealand: Earth Surface Processes, v. 5, p. 227-247.

Plescia, J.B. and Golombek, M.P., 1986, Origin of planetary wrinkle ridges based on the study of terrestrial analogs: Geological Society of America Bulletin, v. 97, p. 1289-1299.

Plint, A.G., 1985, Possible earthquake-induced soft-sediment faulting and remobilization in Pennsylvanian alluvial strata, southern New Brunswick, Canada: Canadian Journal of Earth Sciences, v. 22, p. 907-912.

Plint, A.G., 1986, Slump blocks, intraformational conglomerates, and associated erosional structures in Pennsylvanian fluvial strata of eastern Canada: Sedimentology, v. 33, p. 387-399.

Pongsapich, W., 1970, A petrographic reconnaissance of the Swauk, Chuckanut, and Roslyn Formations, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 63 p.

Potter, C.J., Sanford, W.E., Yoos, T.R., Prussen, E.I., Keach, R.W., II, Oliver, J.E., Kaufman, S., and Brown, L.D., 1986, COCORP deep seismic reflection traverse of the interior of the North American Cordillera, Washington and Idaho: implications for orogenic evolution: Tectonics, v. 5, p. 1007-1025.

Powers, D.W. and Easterling, R.G., 1982, Improved methodology for using embedded Markov chains to describe cyclical sediments: Journal of Sedimentary Petrology, v. 52, p. 913-923.

Price, R.A. and Carmichael, D.M., 1986, Geometric test for Late Cretaceous-Paleogene intracontinental transform faulting in the Canadian Cordillera: Geology, v. 14, p. 468-471.

Raisz, E., 1945, The Olympic-Wallowa Lineament: American Journal of Science, v. 243, p. 479-485.

Ratcliffe, B.C. and Fagerstrom, J.A., 1980, Invertebrate lebensspuren of Holocene floodplains: their morphology, origin, and paleoecological significance: Journal of Paleontology, v. 54, p. 614-630.

Raunkiaer, C., 1934, The Life Forms of Plants and Statistical Plant Geography. Oxford: Clarendon Press, 632 p.

Reeves, C.C., Jr., 1970, Origin, classification, and geologic history of caliche in southern high plains, Texas and eastern New Mexico: Journal of Geology, v. 78, p. 352-362.

Retallack, G.J., 1981, Fossil soils: indicators of ancient terrestrial environments, <u>in</u> Niklas, K.J., editor, Paleobotany, Paleoecology, and Evolution, v. 1, p. 55-102.

Retallack, G.J., 1984, Trace fossils of burrowing beetles and bees in an Oligocene paleosol, Badlands National Park, South Dakota: Journal of Paleontology, v. 58, p. 571-592.

Retallack, G.J., 1986, Fossil soils as grounds for interpreting long-term controls on ancient rivers: Journal of Sedimentary Petrology, v. 56, p. 1-18.

Richards, P.W., 1952, The Tropical Rain Forest. Cambridge: Cambridge University Press, 450 p.

Riedel, S.P., 1984, The Saddle Mountains: the evolution of an anticline in the Yakima fold belt: American Journal of Science, v.284, p. 942-978.

Roberts, J.W., 1985, Stratigraphy, sedimentology, and structure of the Swauk Formation along Tronsen Ridge, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 188 p.

Rosenmeier, F.J., 1968, Stratigraphy and structure of the Table Mountain - Mission Peak area in the Wenatchee Mountains, central Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 44 p.

Russell, I.C., 1900, A preliminary paper on the geology of the Cascade Mountains in northern Washington: U.S. Geological Survey, Annual Report, v. 20, p. 83-110.

Rust, B.R., 1978, Depositional models for braided alluvium, in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 605-625.

Rust, B.R., 1984, Proximal braidplain deposits in the Middle Devonian Malbaie Formation of Eastern Gaspe, Quebec, Canada: Sedimentology, v. 31, p. 675-695.

Ruxton, B.P., 1970, Labile quartz-poor sediments from young mountain ranges in northeast Papua: Journal of Sedimentary Petrology, v. 40, p. 1262-1270.

Schumm, S.A.,1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.

Silling, R.M., 1979, A gravity study of the Chiwaukum graben, Washington [M.S. Thesis]: Seattle, Washington, University of Washington, 100 p.

Smith, D.G. and Putnam, P.E., 1980, Anastomosed river deposits: modern and ancient examples in Alberta, Canada: Canadian Journal of Earth Sciences, v. 17, p. 1396-1406.

Smith, D.G. and Smith, N.D., 1980, Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta: Journal of Sedimentary Petrology, v. 50, p. 157-164.

Smith, G.O., 1904, Description of the Mount Stuart quadrangle, Washington: U.S. Geologic Atlas Folio 86, 10 p.

Smith, N.D., 1972, Flume experiments on the durability of mud clasts: Journal of Sedimentary Petrology, v. 42, p. 378-383.

Soil Survey Staff, 1975, Soil Taxonomy: Agricultural Handbook 436, Soil Conservation Service, Washington, D.C.

Stanley, K.O. and Fagerstrom, J.A., 1974, Miocene invertebrate trace fossils from a braided river environment, western Nebraska, U.S.A.: Paleogeography, Paleoclimatology, Paleoecology, v. 15, p. 63-82.

Steel, R.J., 1974, Cornstone (fossil caliche)- its origin, stratigraphic and sedimentological importance in the New Red Sandstone, western Scotland: Journal of Geology, v. 82, p. 351-369.

Steel, R.J. and Aasheim, S.M., 1978, Alluvial sand deposition in a rapidly subsiding basin (Devonian, Norway), in Miall, A.D., editor, Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 385-412.

Steel, R.J. and Gloppen, T.G., 1980, Late Caledonian (Devonian) basin formation, western Norway: signs of strike-slip tectonics during infilling, in Ballance, P.F. and Reading, H.E., editors, Sedimentation in Oblique-slip Mobile Zones: International Association of Sedimentologists, Special Publication no. 4, p. 79-103.

Tabor, R.W., Frizzell, V.A., Jr., Whetten, J.T., Swanson, D.A., Byerly, G.R., Booth, D.B., Hetherington, M.J., and Waitt, R.B., Jr., 1980, Preliminary geologic map of the Chelan quadrangle, Washington: U.S. Geological Survey, Open-File Report no. 80-841.

Tabor, R.W., Waitt, R.B., Jr., Frizzell, V.A., Jr., Swanson, D.A., Byerly, G.R., and Bentley, R.D., 1982, Geologic map of the Wenatchee quadrangle, Washington: U.S.

Geological Survey, Miscellaneous Geological Investigations I-1311.

Tabor, R.W., Frizzell, V.A., Jr., Vance, J.A., and Naeser, C.W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault: Geological Society of America Bulletin, v. 95, p. 26-44.

Taylor, S.B., 1985, Stratigraphy, sedimentology, and paleogeography of the Swauk Formation in the Liberty area, central Cascades, Washington [M.S. Thesis]: Pullman, Washington, Washington State University, 199 p.

Taylor, S.B., Johnson, S.Y., Fraser, G.T., and Roberts, J.W., in press, Sedimentation and tectonics of the Swauk Formation, eastern Swauk basin- significance for hydrocarbon exploration in central Washington: American Association of Petroleum Geologists Bulletin.

Tempelman-Kluit, D. and Parkinson, D., 1986, Extension across the Eocene Okanogan crustal shear in southern British Columbia: Geology, v. 14, p. 318-321.

Turk, G., 1979, Transition analysis of structural sequences: discussion and reply: Geological Society of America Bulletin, v. 90, p. 989-991.

Turner, D.L., Frizzell, V.A., Jr., Triplehorn, D.M., and Naeser, C.W., 1983, Radiometric dating of ash partings in coal of the Eocene Puget Group, Washington: implications for paleobotanical stages: Geology, v. 11, p. 527-531.

Vance, J.A., 1957, The geology of the Sauk River area in the Northern Cascades of Washington [Ph.D. Dissertation]: Seattle, Washington, University of Washington, 333 p.

Vance, J.A. and Miller, R.B., 1981, The movement history of the Straight Creek fault in Washington state, in Monger, J.W.H., editor, The Last 100 Million Years (Mid-Cretaceous to Holocene) of Geology and Mineral Deposits in the Canadian Cordillera: Geological Association of Canada, Program with Abstracts, p. 39-41.

Vessell, R.K. and Davies, D.K., 1981, Nonmarine sedimentation in an active arc basin, in Ethridge, F.G. and Flores, R.M., editors, Recent and Ancient Nonmarine Depositional Environments: Models for Exploration: Society of Economic Paleontologists and Mineralogists, Special Publication no. 31, p. 31-45.

Vine, J.D., 1969, Geology and coal resources of the Cumberland, Hobart, and Maple Valley quadrangles, King County, Washington: U.S. Geological Survey Professional Paper no. 624, 67 p.

Waters, A.C., 1930, Geology of the southern half of the Chelan quadrangle [Ph. D. Dissertation]: New Haven, Connecticut, Yale University, 265 p.

Waters, A.C., 1932, A petrographic and structural study of the Swakane Gneiss, Entiat Mountains, Washington: Journal of Geology, v. 40, p. 604-633.

Webb, L.J., 1959, Physiognomic classification of Australian rain forests: Journal of Ecology, v. 47, p. 551-570.

Wells, N.A., 1984, Sheet debris flow and sheetflood conglomerates in Cretaceous cool-maritime alluvial fans, South Orkney Islands, Antarctica, in Koster, E.H. and Steel, R.J., editors, Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists, Memoir 10, p. 133-145.

Wells, N.A. and Dorr, J.A., Jr., 1987a, Shifting of the Kosi River, northern India: Geology, v. 15, p. 204-207.

Wells, N.A. and Dorr, J.A., Jr., 1987b, A reconnaissance of sedimentation on the Kosi alluvial fan of India, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., editors, Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists, Special Publication no. 39, p. 51-61.

Wells, S.G. and Harvey, A.M., 1987, Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England: Geological Society of America Bulletin, v. 98, p. 182-198.

Whetten, J.T., 1976, Tertiary sedimentary rocks in the central part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 8, p. 420-421.

Whetten, J.T., 1977, Sedimentology and structure of part of the Chiwaukum graben, Washington [abstract]: Geological Society of America, Abstracts with Programs, v. 9, p. 527.

Whetten, J.T., 1980a, Preliminary geologic map, Chiwaukum 4 NW quadrant: U.S. Geological Survey, Open-File Report no. 80-456.

Whetten, J.T., 1980b, Preliminary geologic map, Chiwaukum 4 Sw quadrant: U.S. Geological Survey, Open-File Report no. 80-616.

Whetten, J.T., 1980c, Preliminary geologic map of the east half of Chiwaukum 4 SE quadrant: U.S. Geological Survey, Open-File Report no. 80-723.

Whetten, J.T. and Laravie, J.A., 1976, Preliminary geologic map of the Chiwaukum 4 NE quadrangle, Chiwaukum graben, Washington: U.S. Geological Survey, Miscellaneous Field Studies, no. MF-794.

Whetten, J.T. and Waitt, R.B., Jr., 1978, Preliminary geologic map of the Cashmere quadrangle, Chiwaukum lowland, Washington: U.S. Geological Survey, Miscellaneous Field Studies, no. MF-908.

Wiberg, P.L. and Smith, J.D., 1987, Calculations of the critical shear stress for motion of uniform and heterogeneous sediments: Water Resources Research, v.

Williams, G.E., 1973, Late Quaternary piedmont sedimentation, soil formation, and paleoclimate in arid South Australia: Zeitschrift fur Geomorphologie, v. 17, p. 102-125.

Williams, G.E. and Polach, H.A., 1971, Radiocarbon dating of arid-zone calcareous paleosols: Geological Society of America Bulletin, v. 82, p. 3069-3085.

Willis, B., 1903, Physiography and deformation of the Wenatchee-Chelan district, Cascade Range: U.S. Geological Survey Professional Paper no. 19, p. 41-97.

Willis, C.L., 1950, Geology of the northeastern quarter of Chiwaukum quadrangle [Ph. D. Dissertation]: Seattle, Washington, University of Washington, 158 p.

Willis, C.L., 1953, The Chiwaukum graben, a major structure of central Washington: American Journal of Science, v.251, p. 789-797.

Wing, S.L., 1984, Relation of paleovegetation to geometry and cyclicity of some fluvial carbonaceous deposits: Journal of Sedimentary Petrology, v. 54, p. 52-66.

Wolfe, J.A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: U.S. Geological Survey Professional Paper no. 571, 33p.

Wolfe, J.A., 1971, Tertiary climatic fluctuations and methods of analysis of Tertiary floras: Paleogeography, Paleoclimatology, Paleoecology, v. 9, p. 27-57.

Wolfe, J.A., 1977, Paleogene floras from the Gulf of Alaska region: U.S. Geological Survey Professional Paper no. 997, 108 p.

Wolfe, J.A., 1978, A paleobotanical interpretation of Tertiary climates in the northern hemisphere: American Scientist, v. 66, p. 694-703.

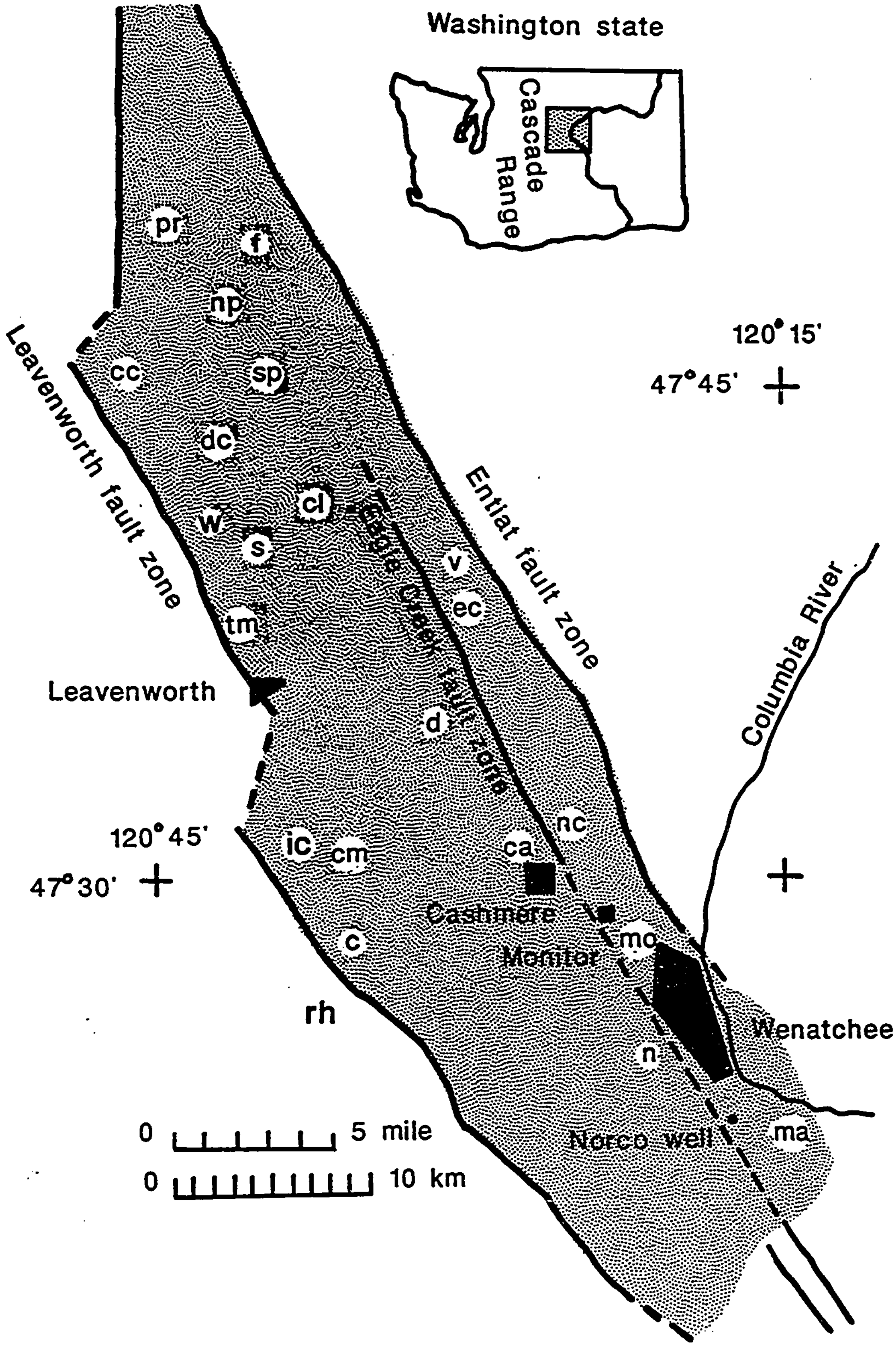
Wolfe, J.A. and Hopkins, D.M., 1967, Climatic changes recorded by Tertiary land flora in northwestern North America, in Kotora, H., editor, Tertiary correlations and climatic changes in the Pacific, Pacific Science Congress, Symposium no. 25, p. 67-76.

Wolfe, J.A. and Wehr, W., 1986, Middle Eocene dicotyledonous plants from Republic, northeastern Washington: U.S. Geological Survey Professional Paper no. 1597, 74 p.

Young, R.E., 1963, Geology of the Swauk Formation in the Leavenworth, Washington area [B.S. Thesis]: Seattle, Washington, University of Washington, 49 p.

APPENDIX A: DETAILED MEASURED SECTIONS OF THE CHUMSTICK FORMATION

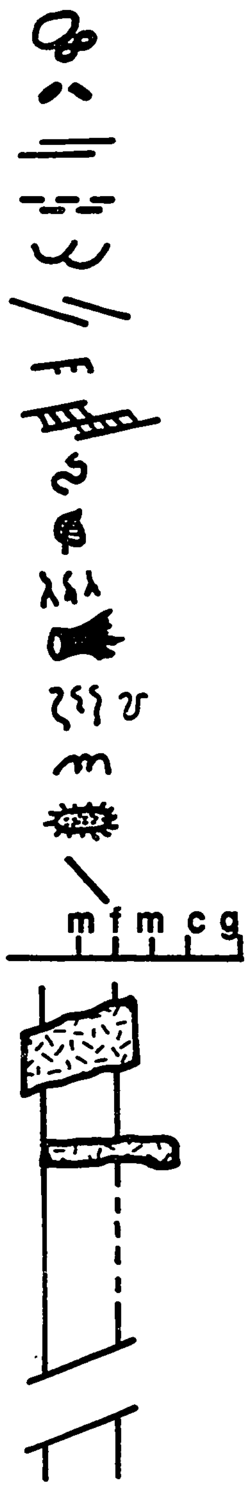
Figure A.1-- Location map showing major regional faults, towns (black), and the locations of measured sections. Abbreviations used: c - Camasland, ca - Cashmere, cc - Cole's Corner, cl - Clark Canyon, cm - Camas Creek, d - Derby Canyon, dc - Deadhorse Canyon, ec - Eagle Creek, f - Fish Lake, ic - Ingall's Creek, ma - Malaga Road, mo - Monitor, n - Number Two Canyon, nc - Nahahum Canyon, np -North Plain, pr - Pole Ridge, rh - Red Hill, s - Sunitsch Canyon, sp - South Plain, tm - Tumwater Mountain, v - Van Canyon, and w - Wright Canyon.



Washington state
Cascade Range
pr
f
np
cc
sp
dc
cl
w
s
tm
v
ec
d
nc
ca
ic
cm
c
mo
n
ma
rh
Leavenworth fault zone
Entiat fault zone
Eagle Creek fault zone
Columbia River
Leavenworth
Cashmere
Monitor
Wenatchee
Norco well
120° 15'
47°45'
120° 45'
47°30'
0 5 mile
0 10 km

Figure A.2--Key to symbols used in measured sections. Grain size indicated by bar (abbreviations used: M = mud and silt, F = very fine-grained and fine-grained sand, M = medium-grained sand, C = coarse-grained and very coarse-grained sand, G = gravel).

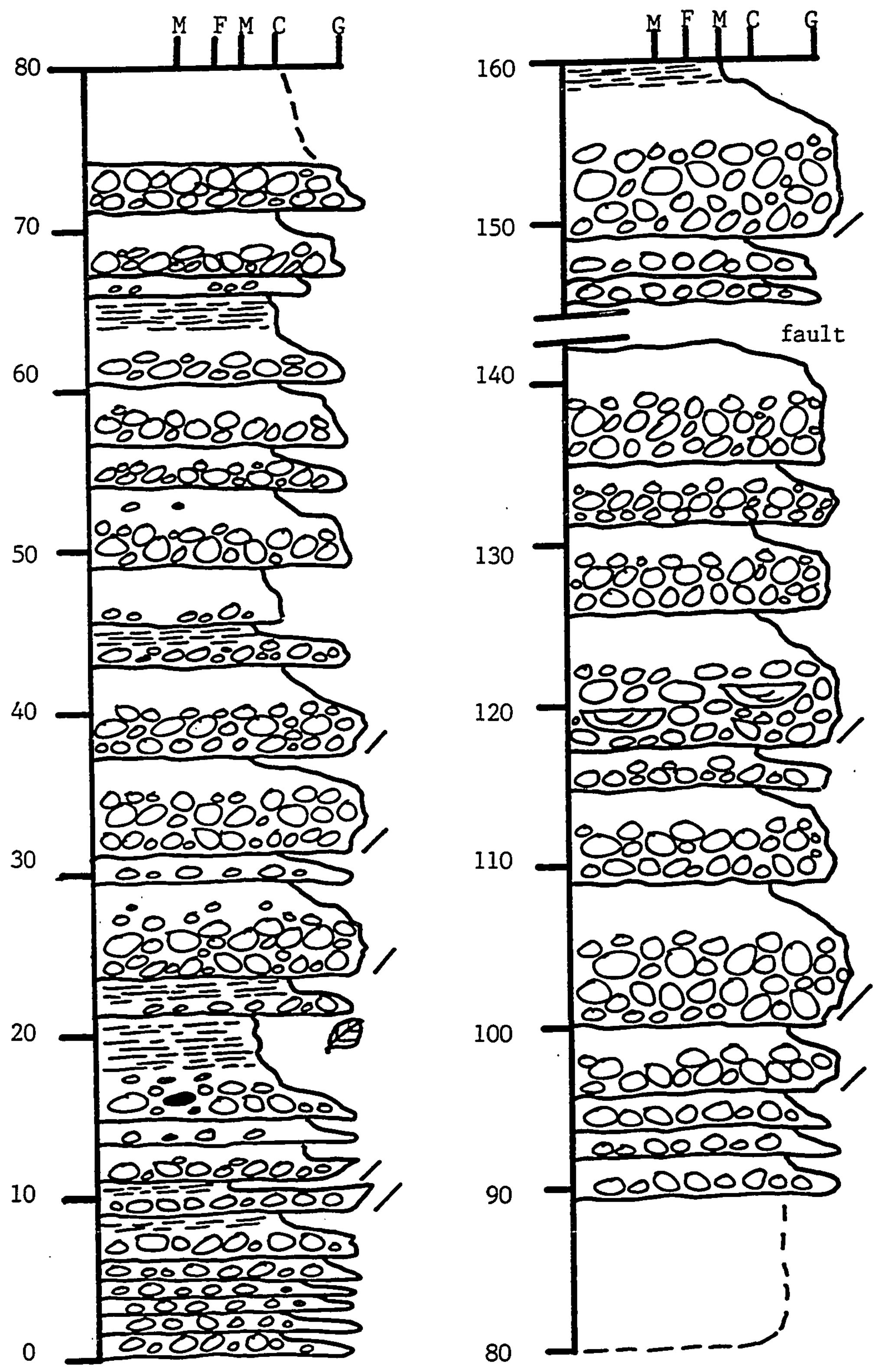
KEY TO SYMBOLS



85JE135 — sample locality

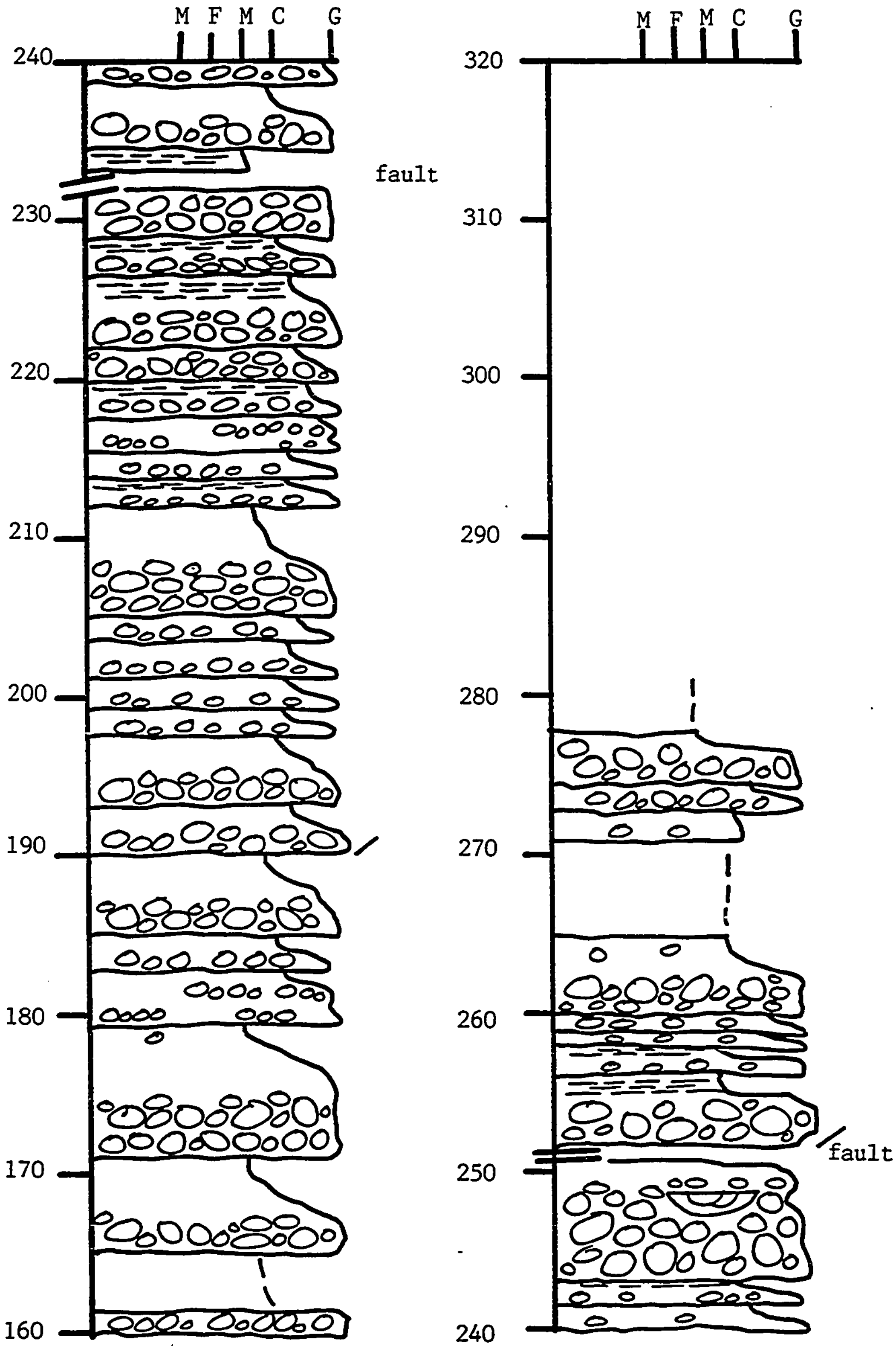
- exoclasts
- intraclasts
- parallel bedding
- parallel lamination
- trough cross-bedding
- planar cross-bedding
- ripple cross-lamination
- climbing ripple cross-lamination
- convoluted bedding
- plant macrofossil
- rootlets
- stumps/logs
- infaunal bioturbation
- bedding-plane trace fossils
- pedogenic concretions
- fining-upward sequence
- grain size (see caption)
- discordant igneous rocks
- concordant igneous rocks
- covered section (to scale)
- covered section (not to scale)

Figure A.3--Cashmere section, near U.S. Highway 2 and the town of Cashmere (T.24N., R.19E., Section 33 SW1/4SW1/4). See Figure A.2 for symbols used.



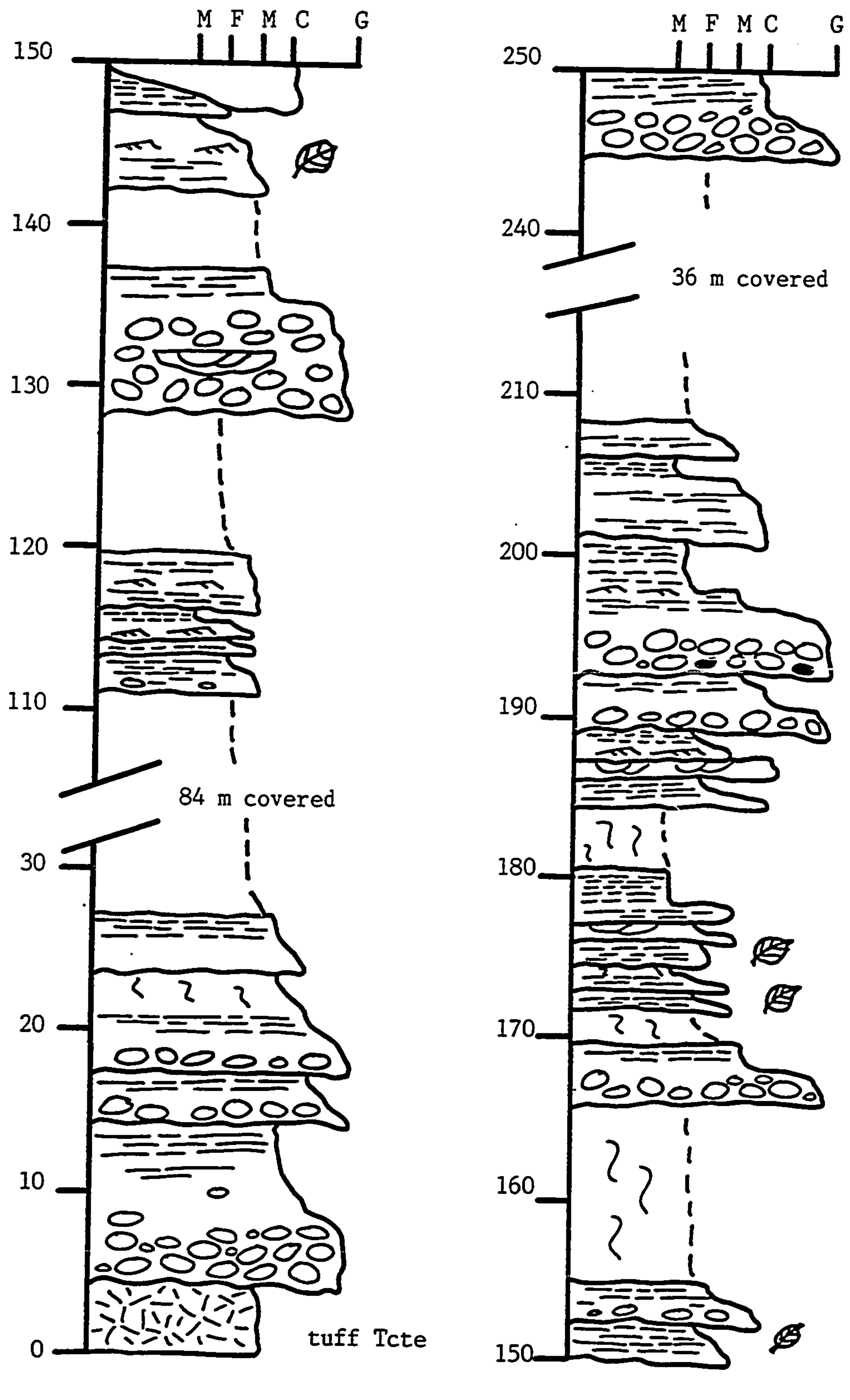
M F M C G
80
70
60
50
40
30
20
10
0
M F M C G
160
150
fault
140
130
120
110
100
90
80

Figure A.3 (con't.)-- Cashmere section.



M F M C G
240
230
220
210
200
190
180
170
160
fault
M F M C G
320
310
300
290
280
270
260
250
240
fault

Figure A.4-- Clark Canyon section #1, Clark Canyon Road (T.25N., R.18E., Section 10 NW1/4NW1/4 to Section 8 NW1/4SE1/4). See Figure A.2 for symbols used.



M F M C G
150
140
130
120
110
84 m covered
30
20
10
0
tuff Tcte
M F M C G
250
240
36 m covered
210
200
190
180
170
160
150

Figure A.4 (con't.)-- Clark Canyon section #1.

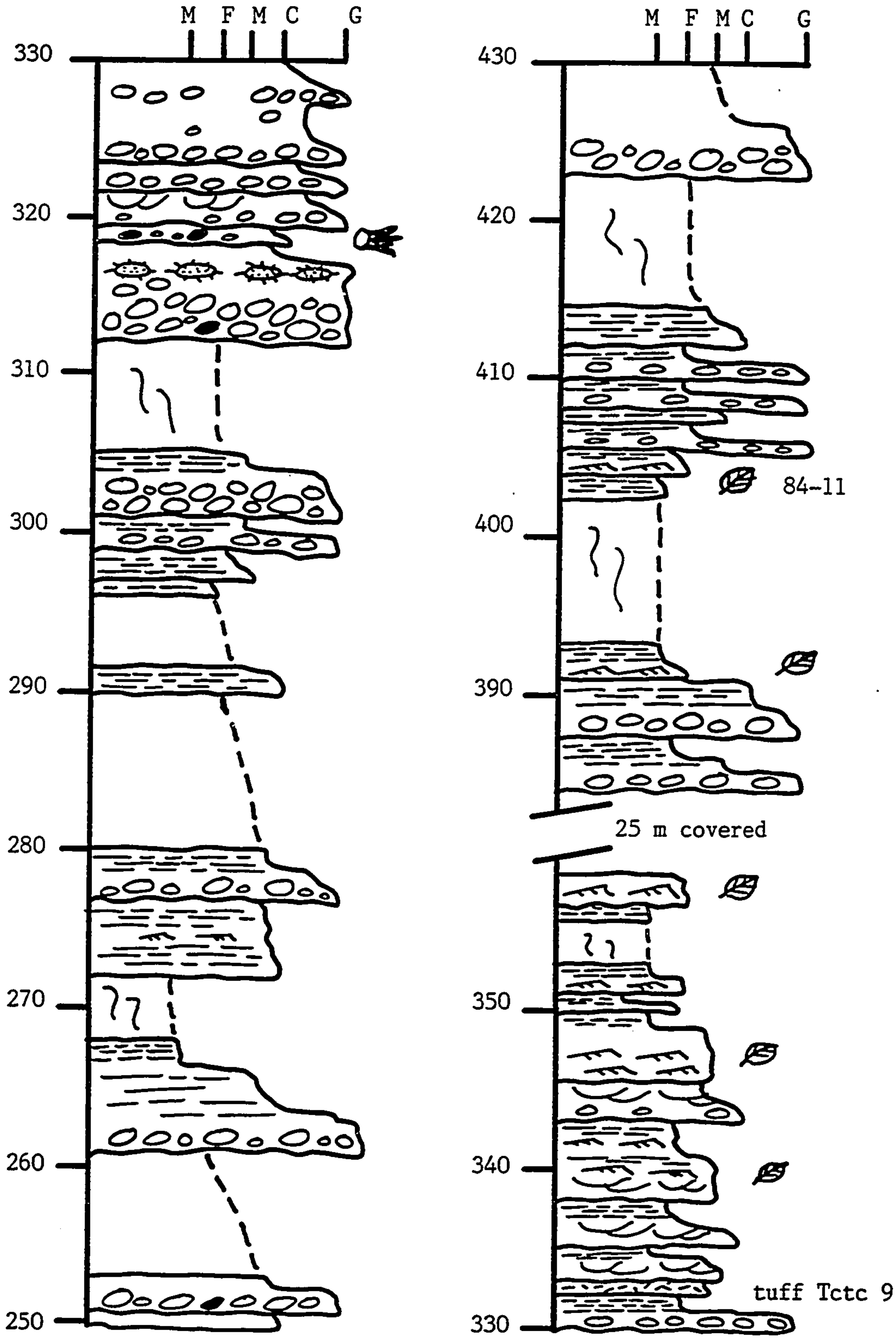
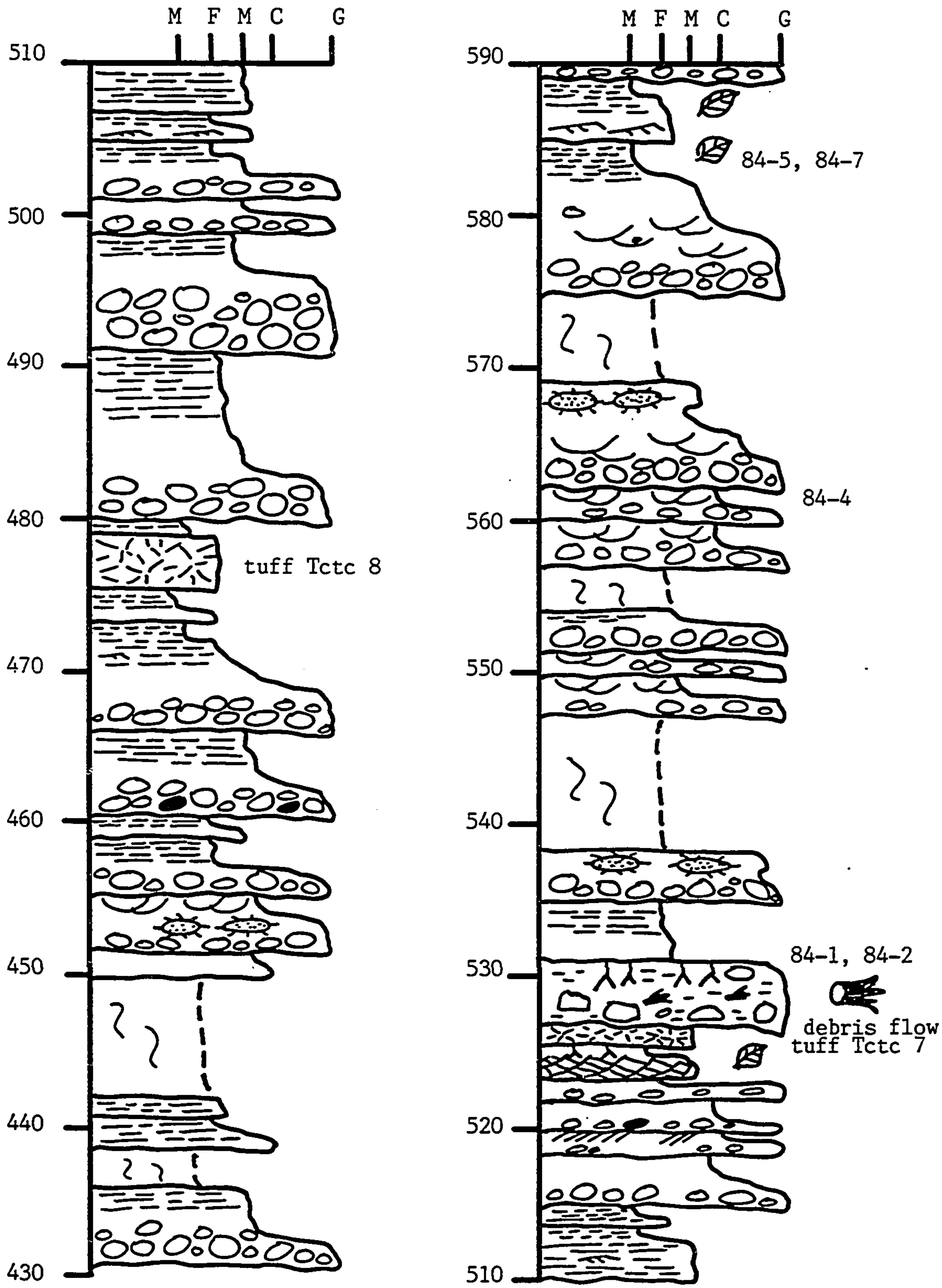

M F M C G
330
320
310
300
290
280
270
260
250
M F M C G
430
420
410
84-11
400
390
25 m covered
350
340
tuff Tctc 9
330

Figure A.4 (con't.)-- Clark Canyon section #1.



M F M C G
510
500
490
480
470
460
450
440
430
tuff Tctc 8
M F M C G
590
580
570
560
550
540
530
520
510
84-5, 84-7
84-4
84-1, 84-2
debris flow
tuff Tctc 7

Figure A.4 (con't.)-- Clark Canyon section #1.

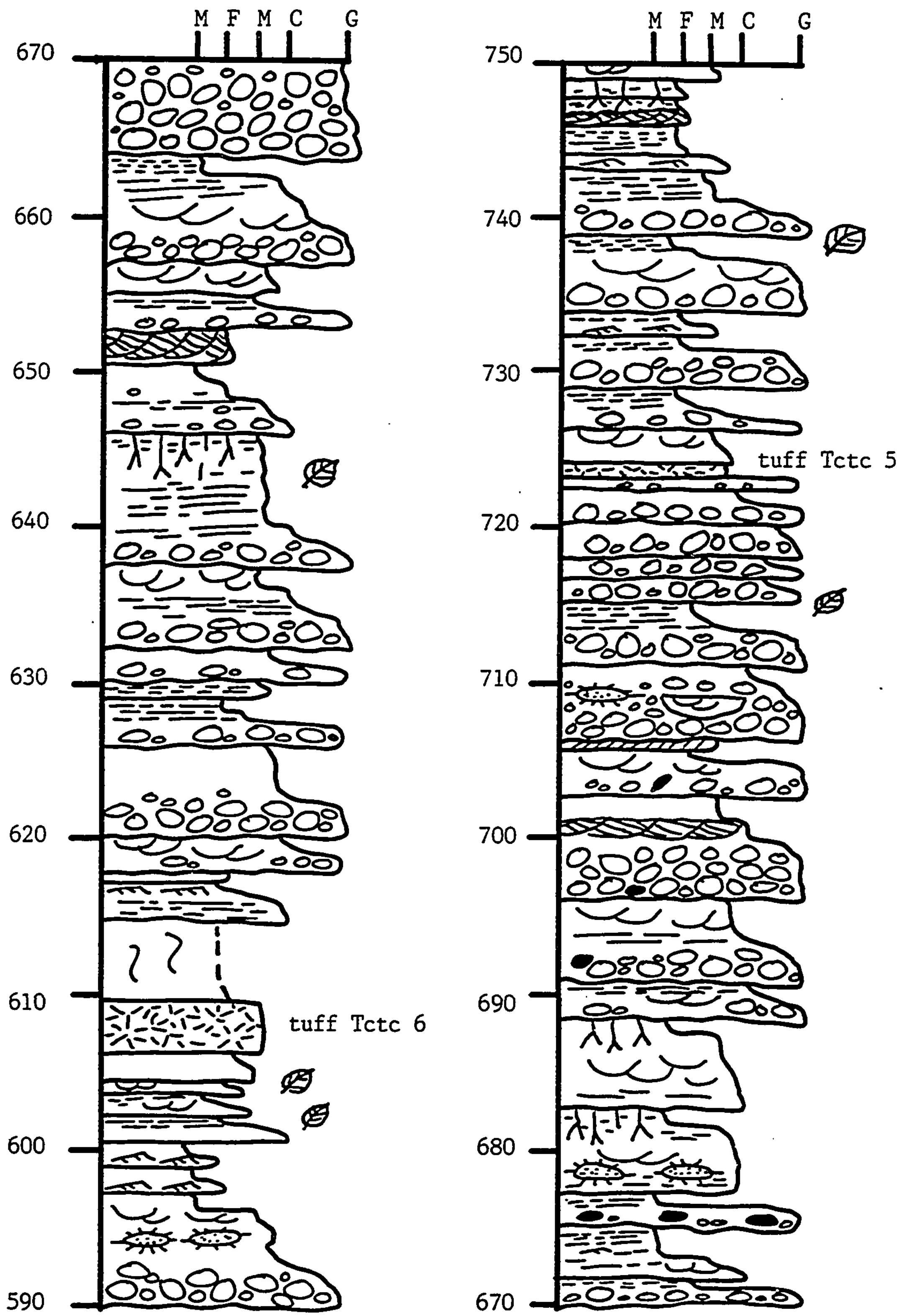
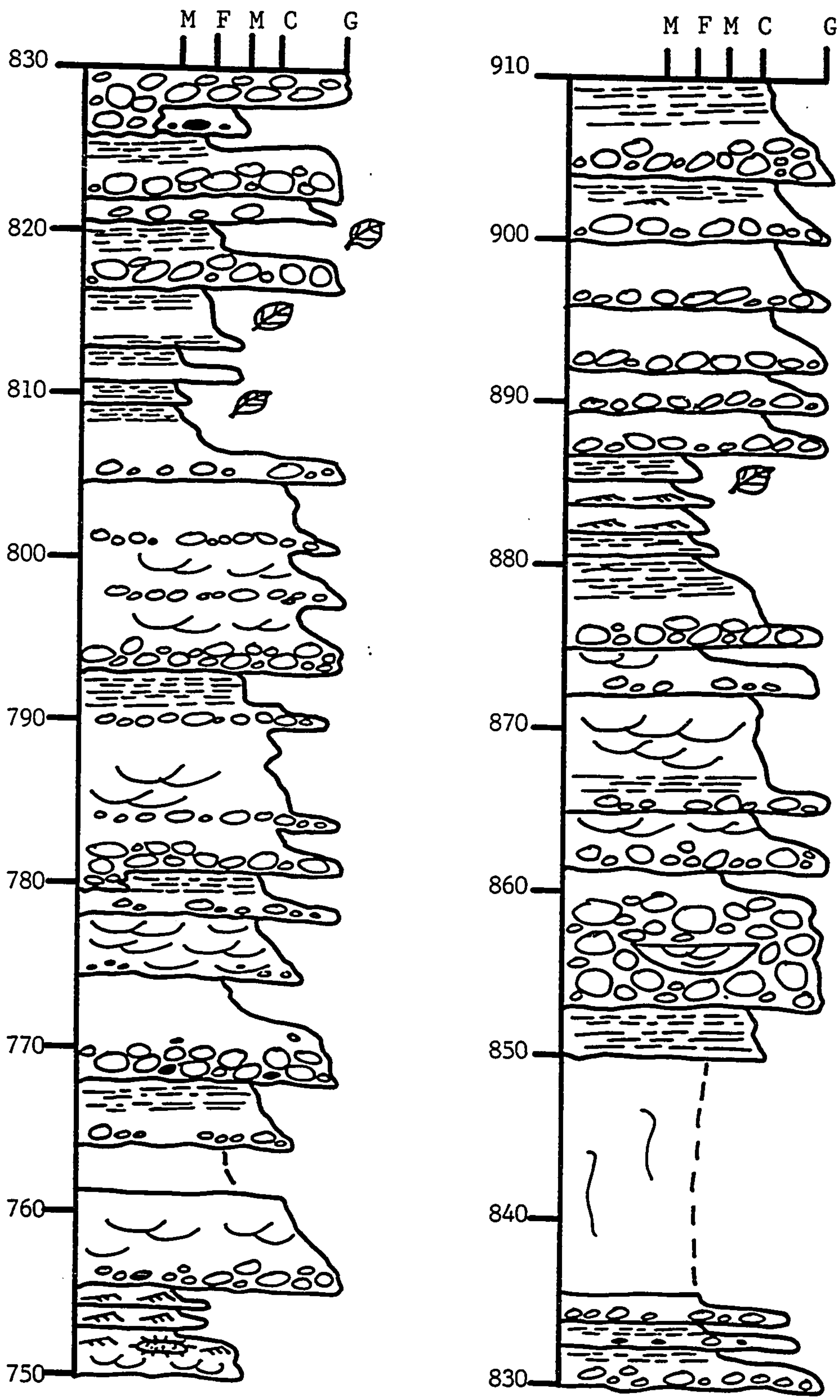
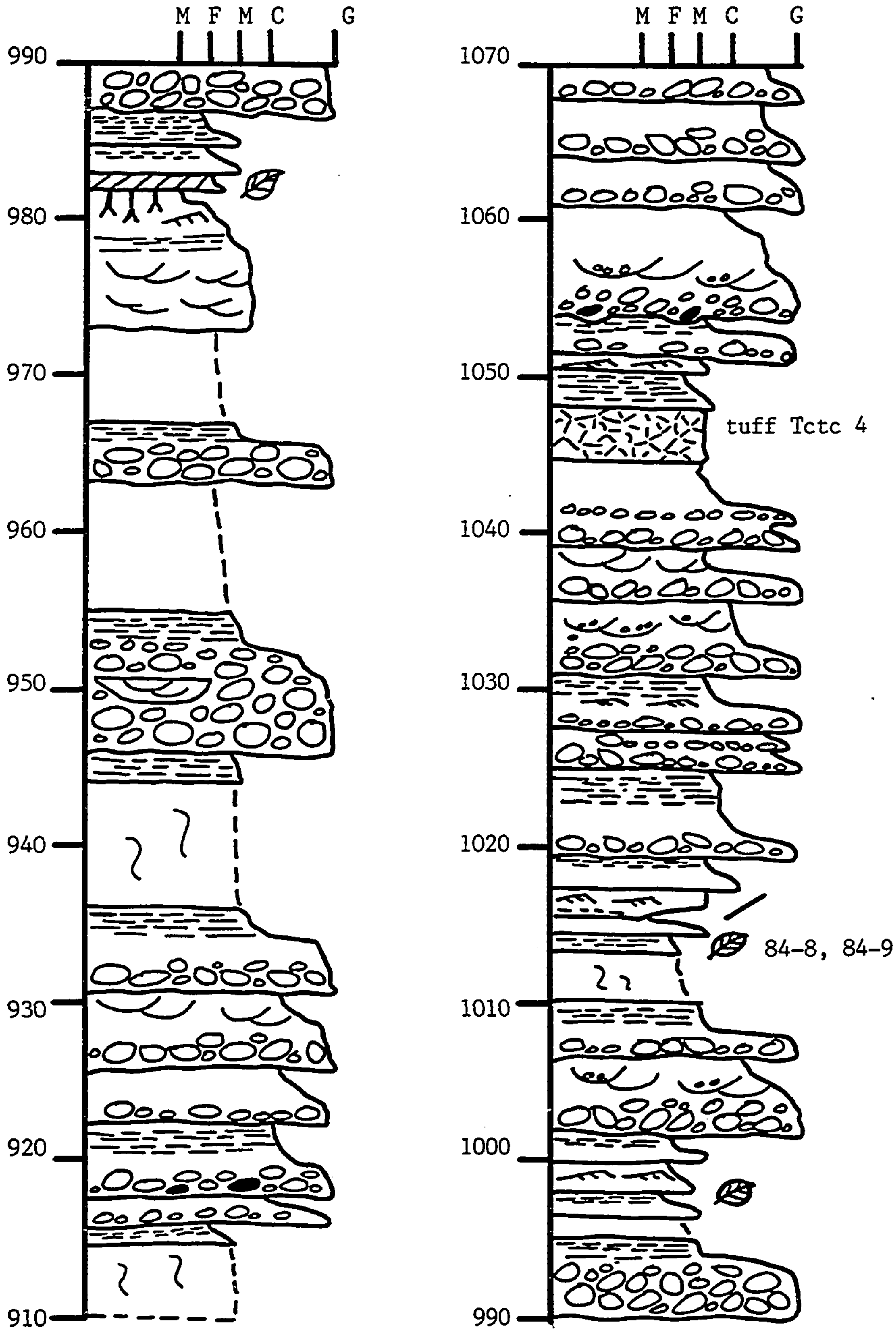

M F M C G
670
660
650
640
630
620
610
600
590
tuff Tctc 6
M F M C G
750
740
730
720
710
700
690
680
670
tuff Tctc 5

Figure A.4 (con't.)-- Clark Canyon section #1.



M F M C G
830
820
810
800
790
780
770
760
750
M F M C G
910
900
890
880
870
860
850
840
830

Figure A.4 (con't.)-- Clark Canyon section #1.



M F M C G
990
980
970
960
950
940
930
920
910
M F M C G
1070
1060
1050
tuff Tctc 4
1040
1030
1020
84-8, 84-9
1010
1000
990

Figure A.4 (con't.)-- Clark Canyon section #1.

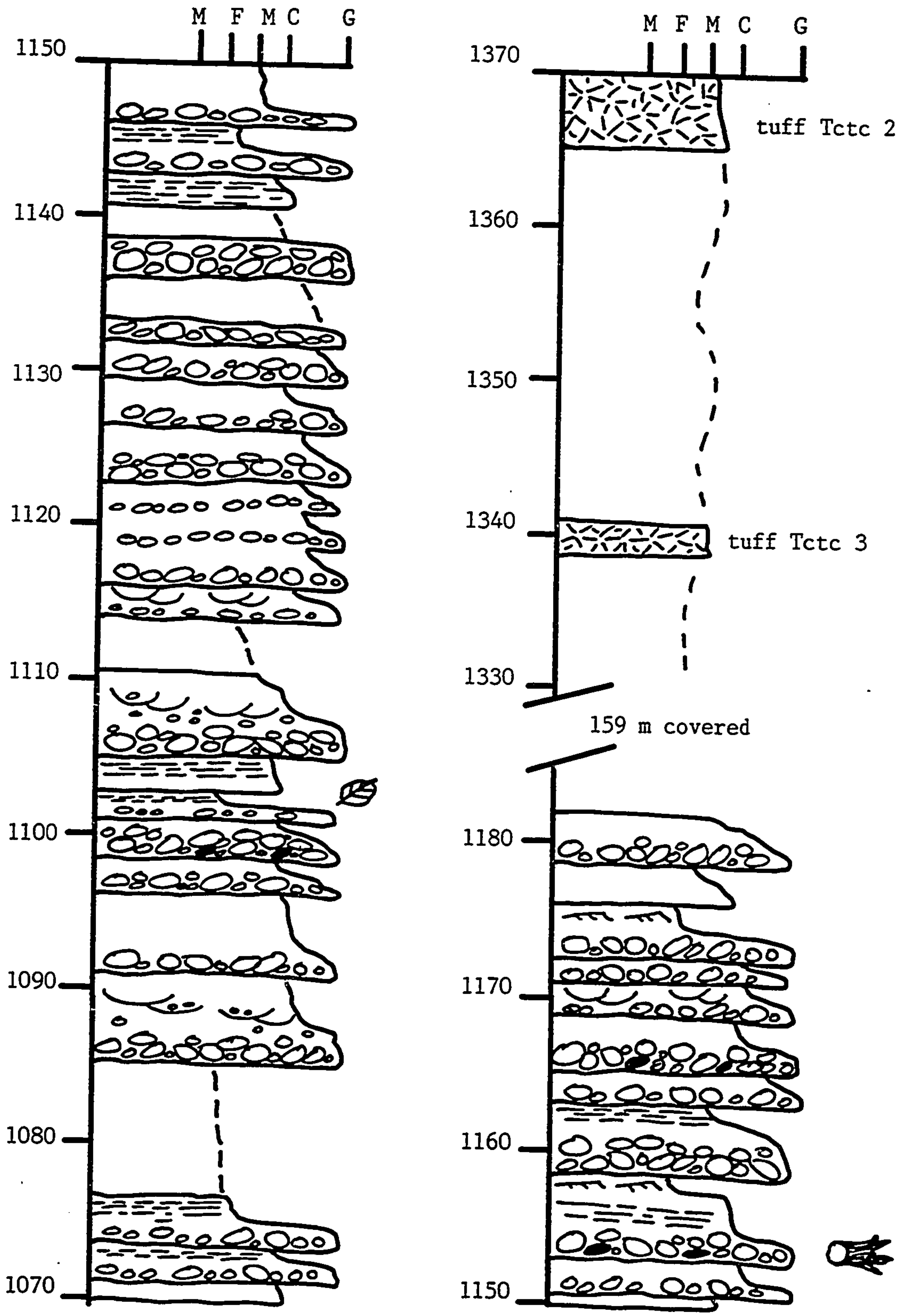
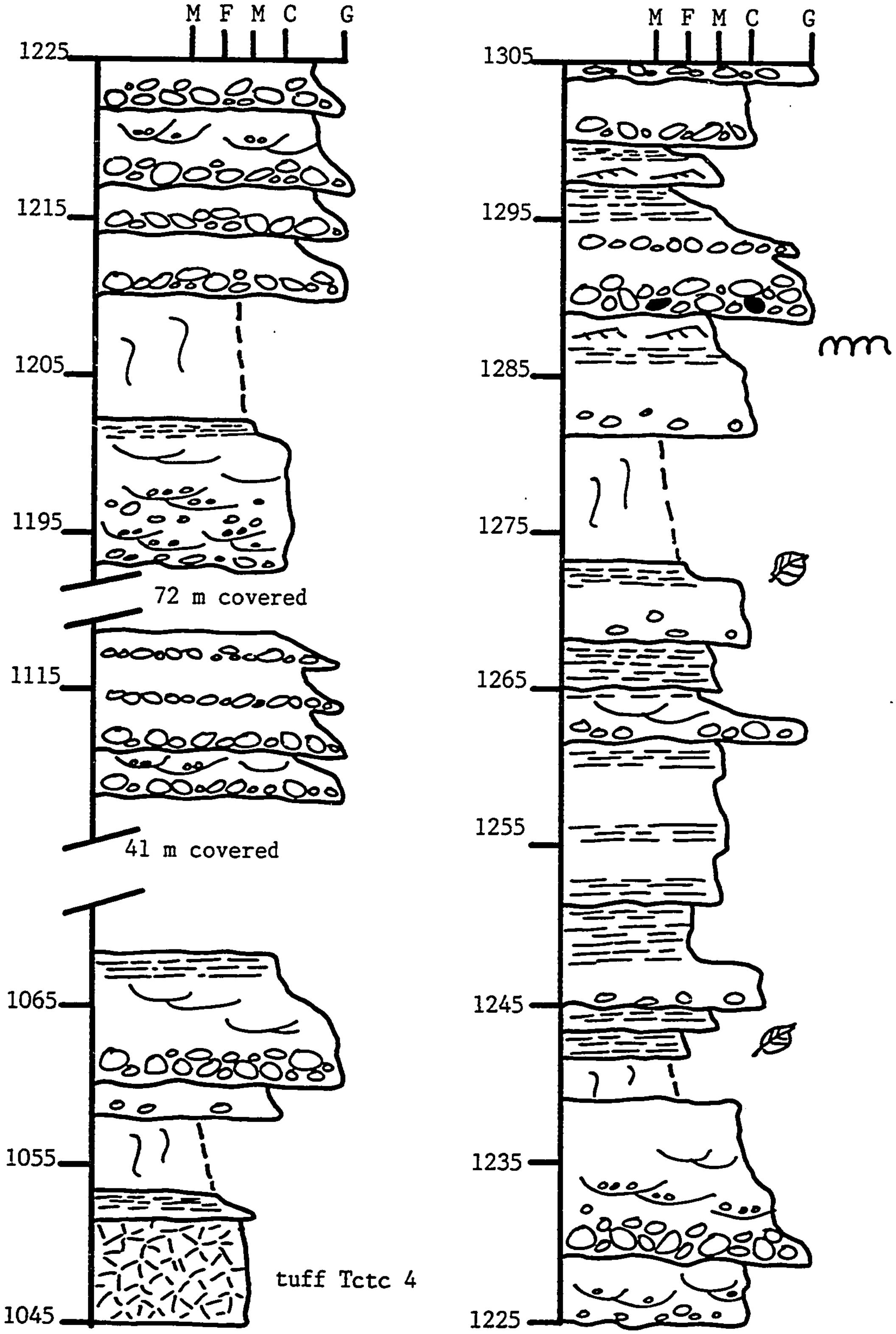
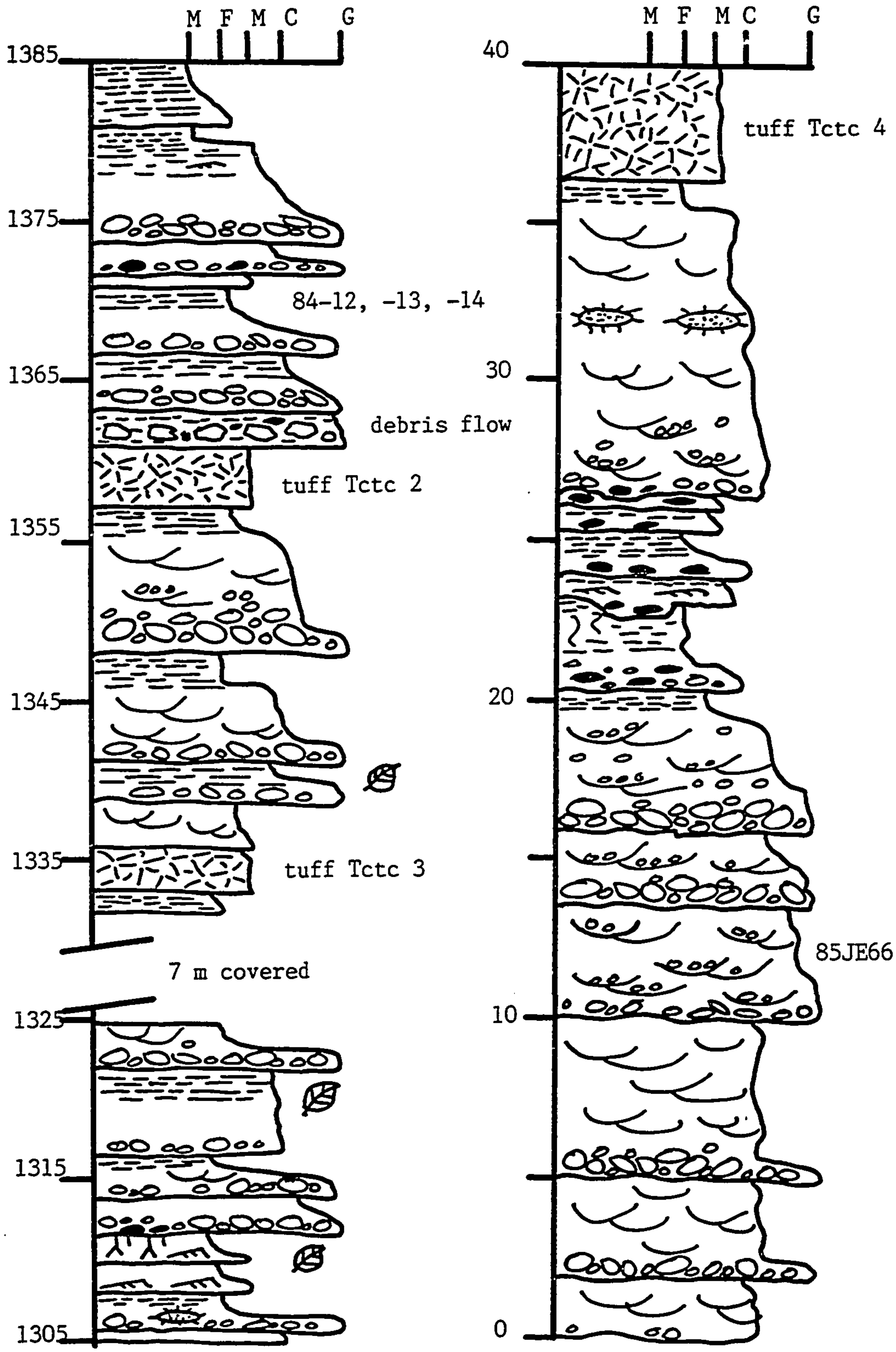

M F M C G
1150
1140
1130
1120
1110
1100
1090
1080
1070
M F M C G
1370
tuff Tctc 2
1360
1350
1340
tuff Tctc 3
1330
159 m covered
1180
1170
1160
1150

Figure A.5--Clark Canyon section #2, Walker Canyon Road (T.25N., R.18E., Section 9 SW1/4SW1/4 to Section 8 SE1/4SE1/4). See Figure A.2 for symbols used.



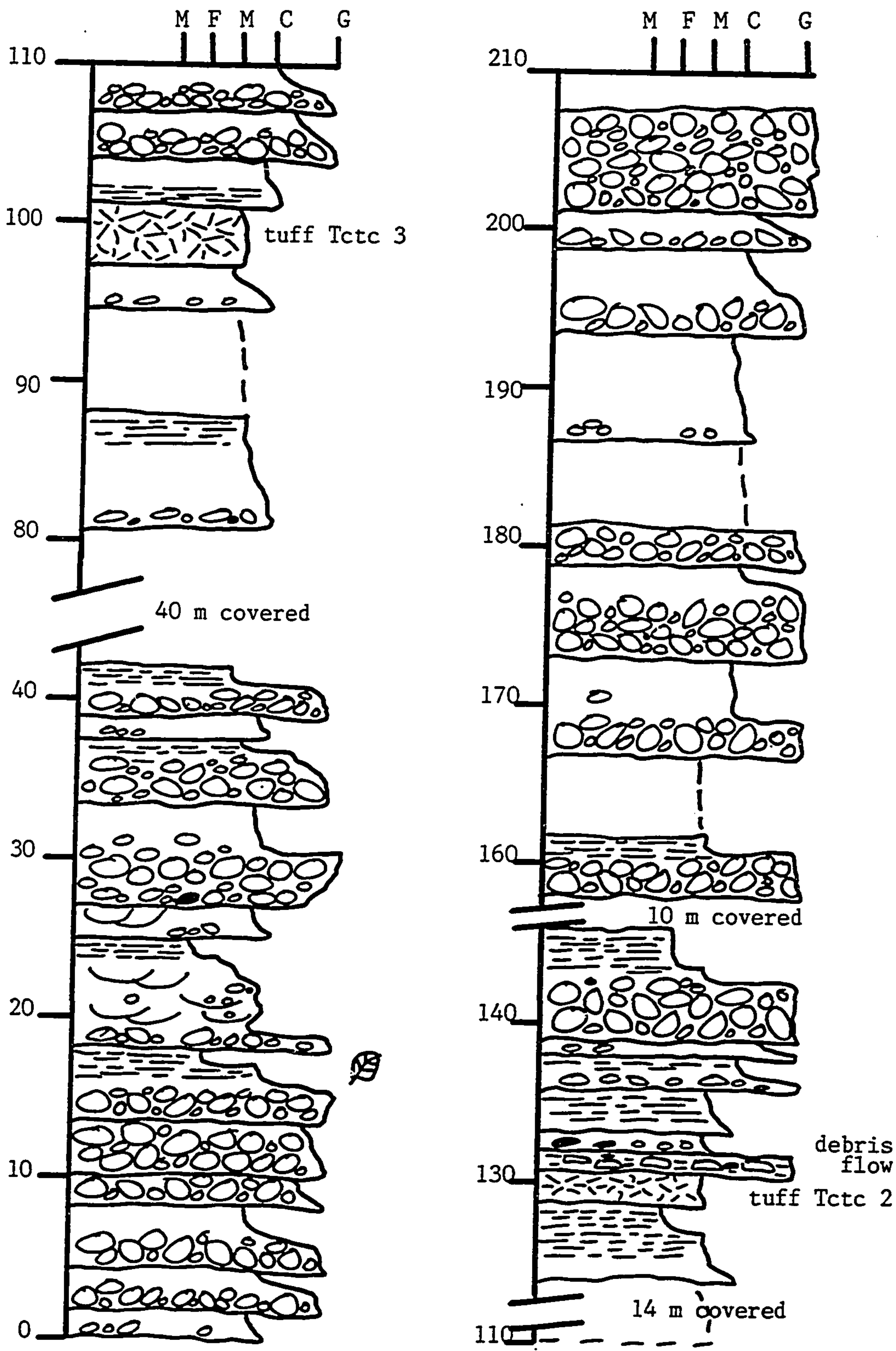
M F M C G
1225
1215
1205
1195
72 m covered
1115
41 m covered
1065
1055
1045
tuff Tctc 4
M F M C G
1305
1295
1285
1275
1265
1255
1245
1235
1225

Figure A.5 (con't.)--
LEFT COLUMN: completion of Clark Canyon section #2.
RIGHT COLUMN: Eagle Creek Road section (T.25N., R.18E., Section 27 NW1/4NW1/4). See Figure A.2 for symbols used.



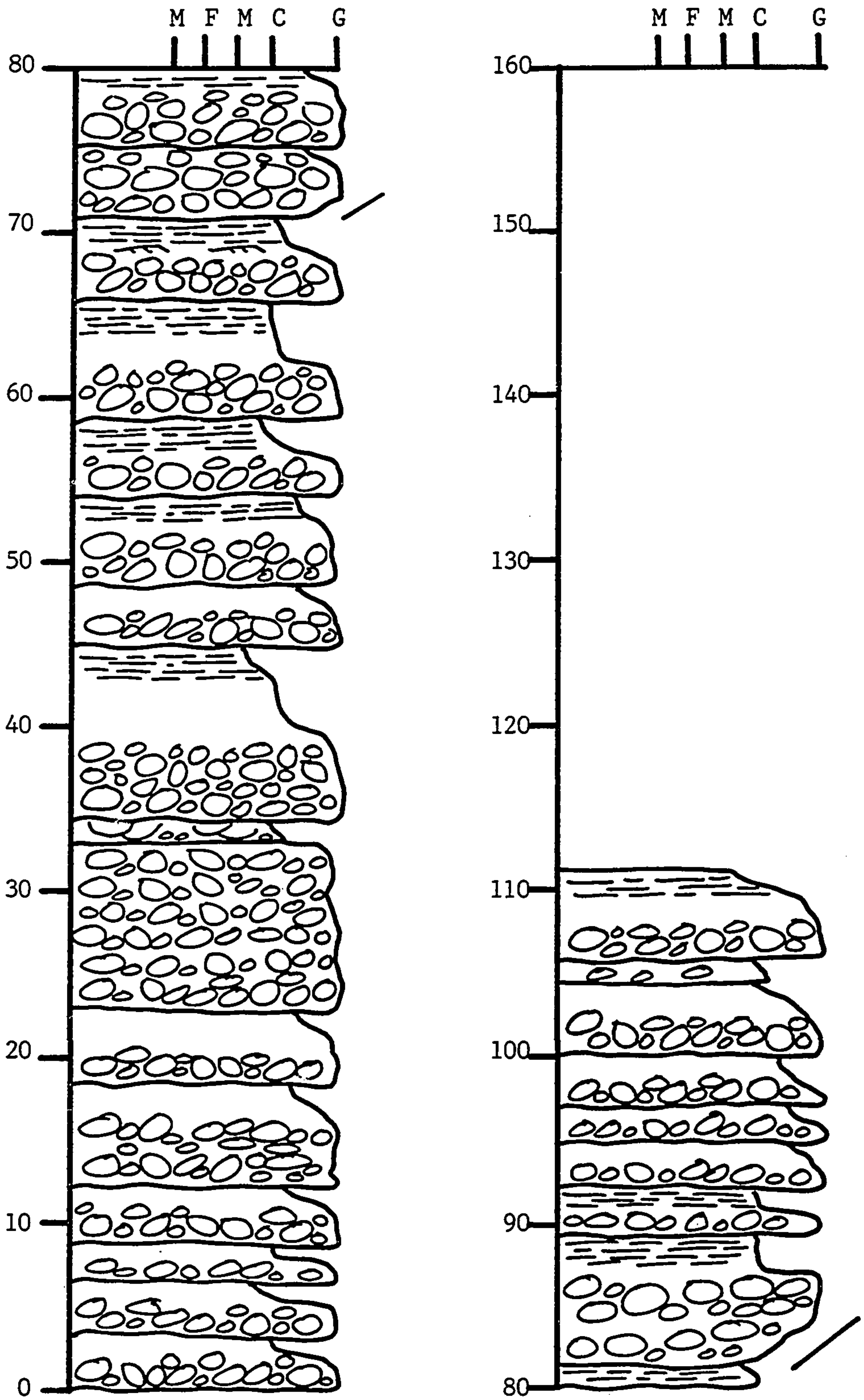
M F M C G
1385
1375
84-12, -13, -14
1365
debris flow
tuff Tctc 2
1355
1345
1335
tuff Tctc 3
7 m covered
1325
1315
1305
M F M C G
40
tuff Tctc 4
30
20
85JE66
10
0

Figure A.6--Chumstick Creek section, on Highway 209 near the BN railroad trestle (T.26N., R.18E., Section 31 NW1/4NE1/4). See Figure A.2 for symbols used.



M F M C G
110
100
tuff Tctc 3
90
80
40 m covered
40
30
20
10
0
M F M C G
210
200
190
180
170
160
10 m covered
140
debris flow
130
tuff Tctc 2
14 m covered
110

Figure A.7--Tumwater Mountain Section (T.25N., R.17E., Section 35 NW1/4SE1/4). See Figure A.2 for symbols used.



M F M C G
80
70
60
50
40
30
20
10
0
M F M C G
160
150
140
130
120
110
100
90
80

Figure A.8-- Camasland section, on Ruby Creek-Camas Creek road (T.23N., R.18E., Section 33 NW1/4SW1/4 to Section 34 SW1/4SE1/4). See Figure A.2 for symbols used.

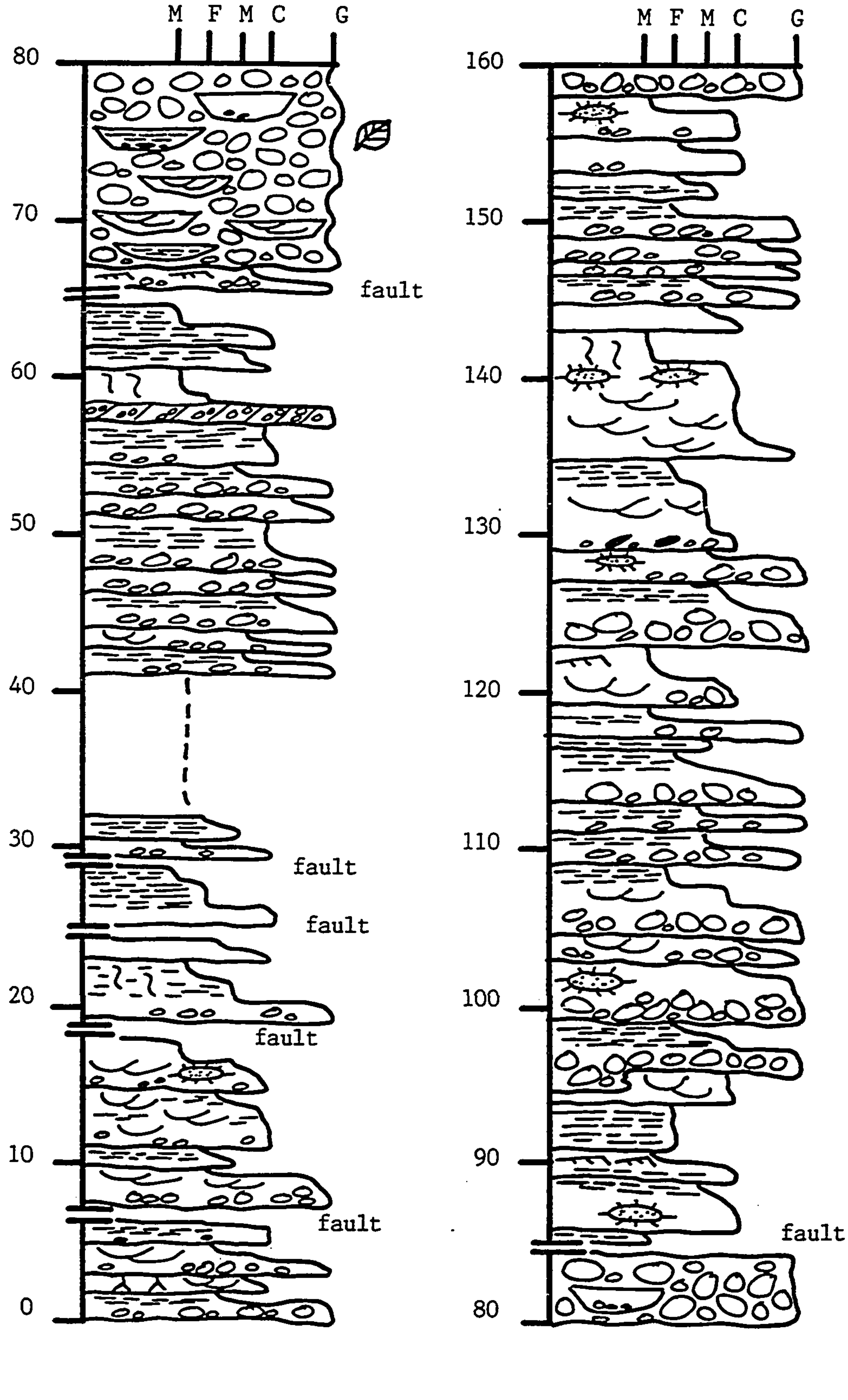
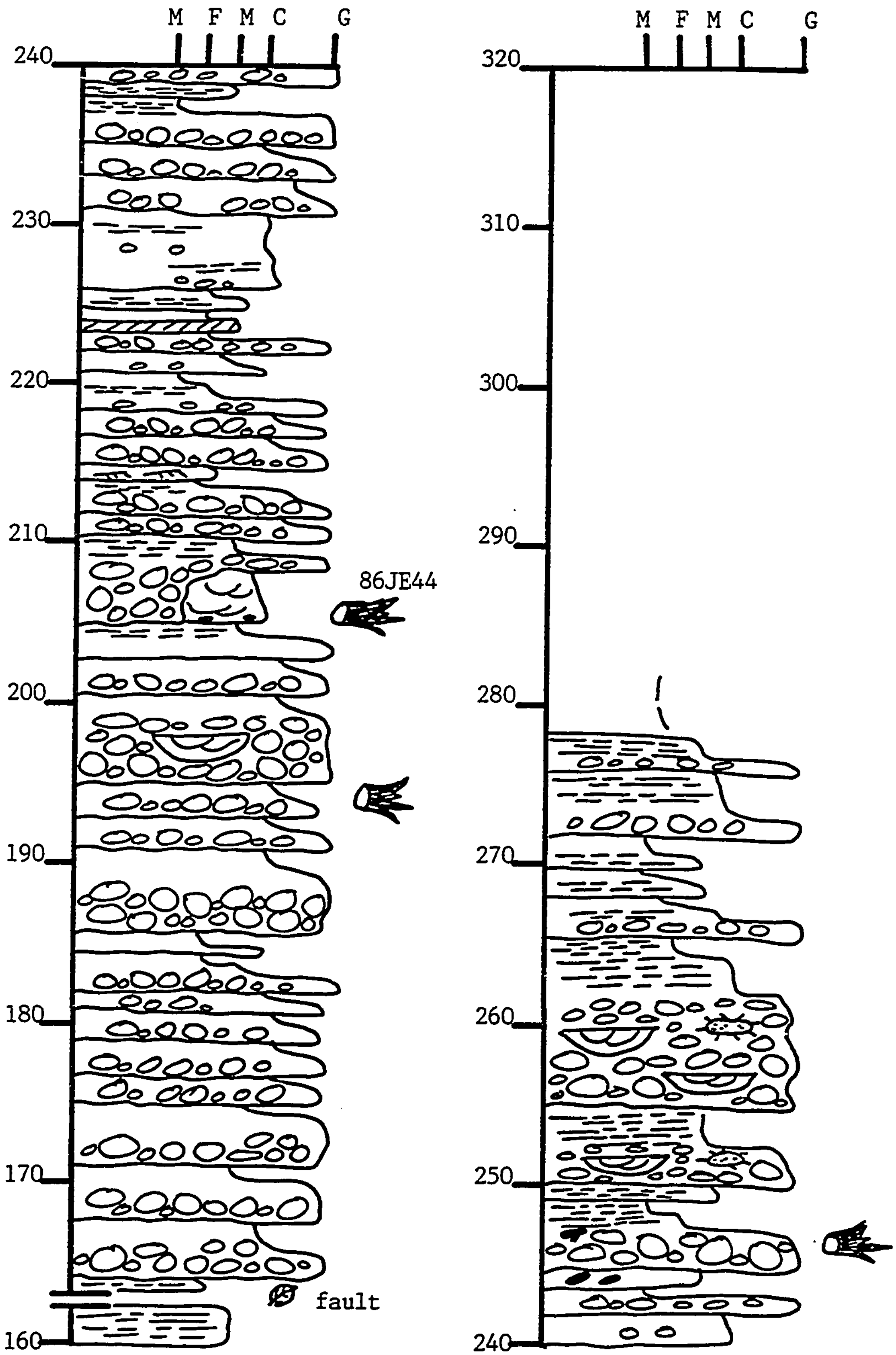

M F M C G
80
70
60
50
40
30
20
10
0
fault
fault
fault
fault
fault
M F M C G
160
150
140
130
120
110
100
90
80
fault

Figure A.8 (con't.)-- Camasland section.



M F M C G
240
230
220
210
200
190
180
170
160
86JE44
fault
M F M C G
320
310
300
290
280
270
260
250
240

Figure A.9--Camas Creek section, on road from Camas Creek to Tiptop Lookout (T.23N., R.18E., Section 20 NW1/4NW1/4 to Section 19 NE1/4NE1/4). See Figure A.2 for symbols used.

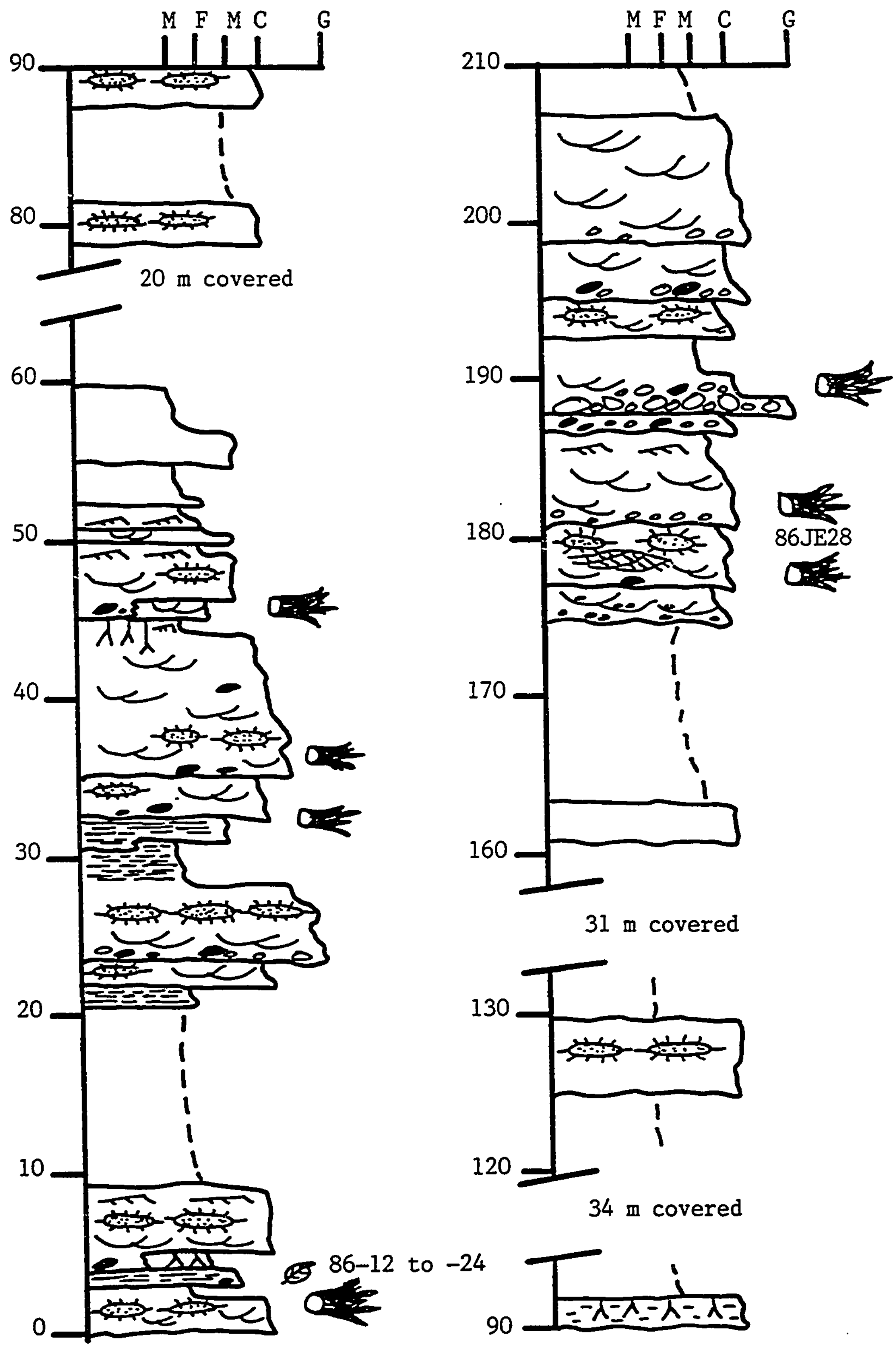
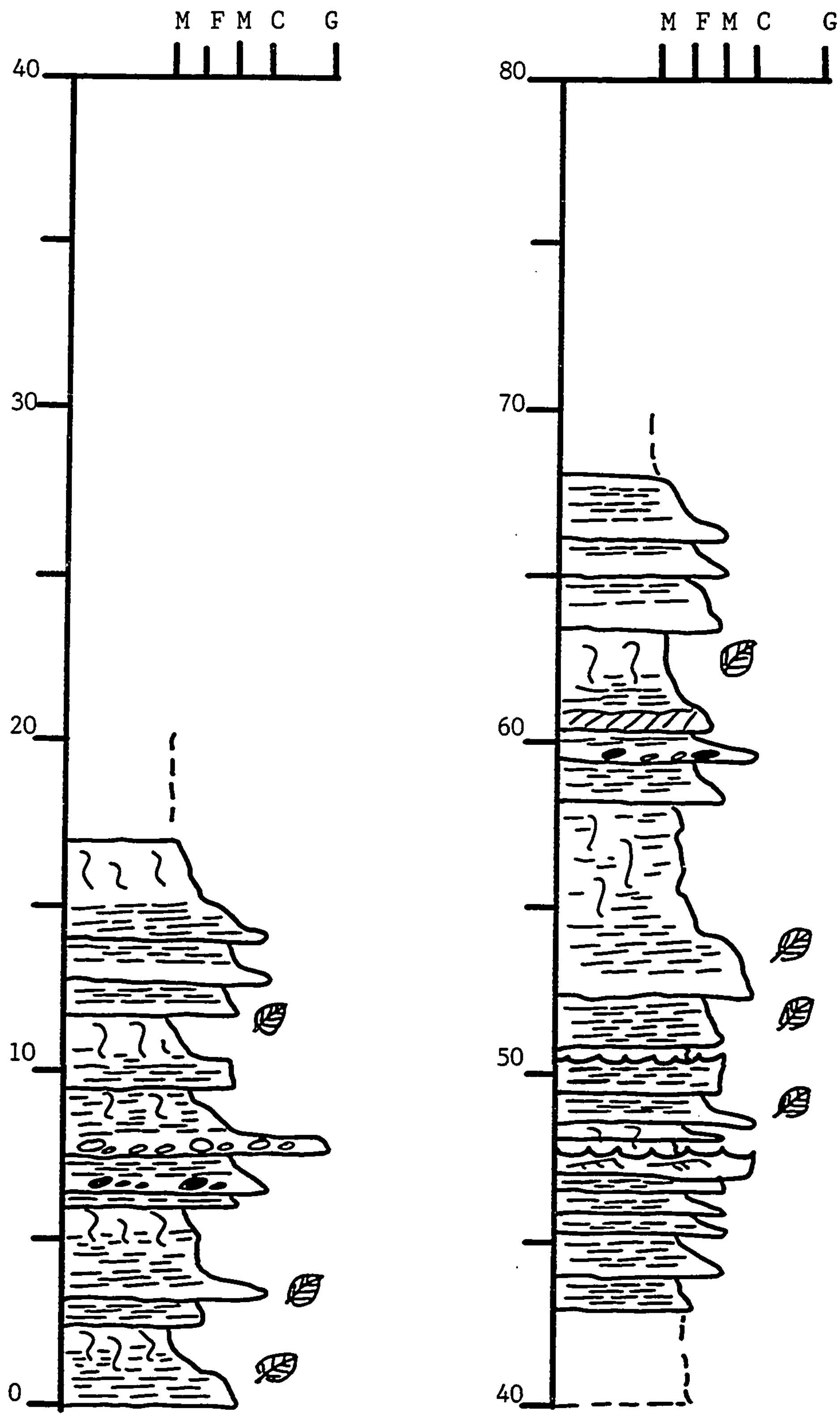
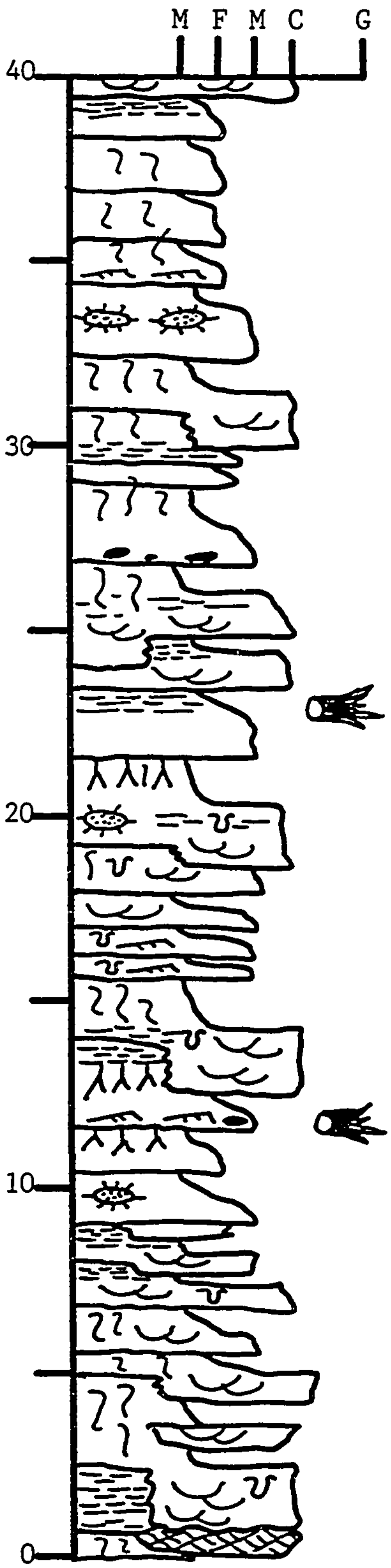

M F M C G
90
80
20 m covered
60
50
40
30
20
10
0
86-12 to -24
M F M C G
210
200
190
180
86JE28
170
160
31 m covered
130
120
34 m covered
90

Figure A.10--Railroad Canyon section (T.25N., R.18E., Section 2 SW1/4SW1/4). See Figure A.2 for symbols used.



M F M C G
40
30
20
10
0
M F M C G
80
70
60
50
40

Figure A.11--Monitor section (T.23N., R.19E., Section 24 NE1/4NW1/4 to Section 24 NW1/4NE1/4). See Figure A.2 for symbols used.


M F M C G
40
30
20
10
0

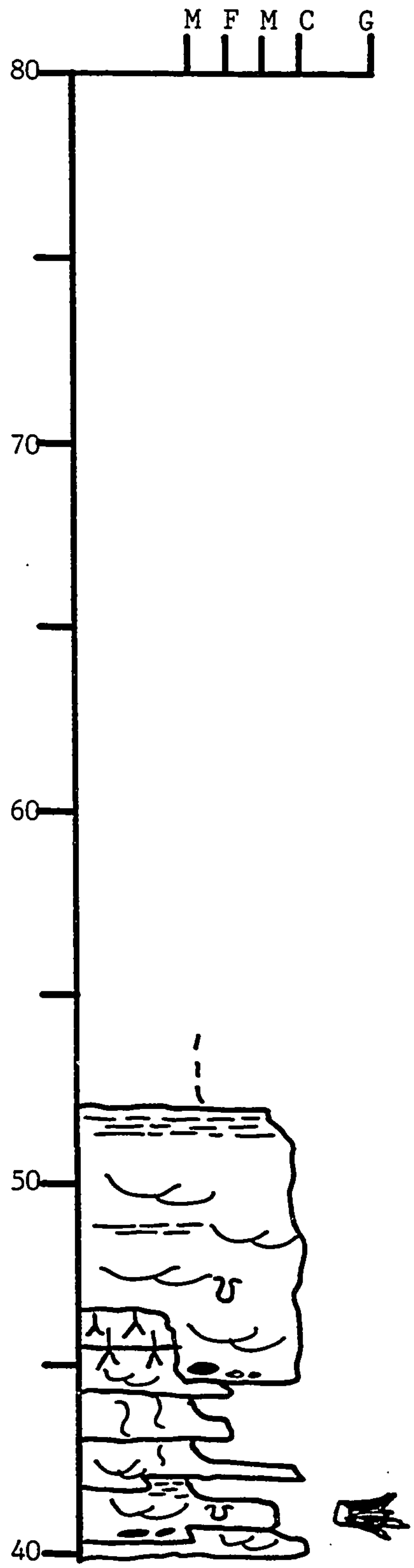
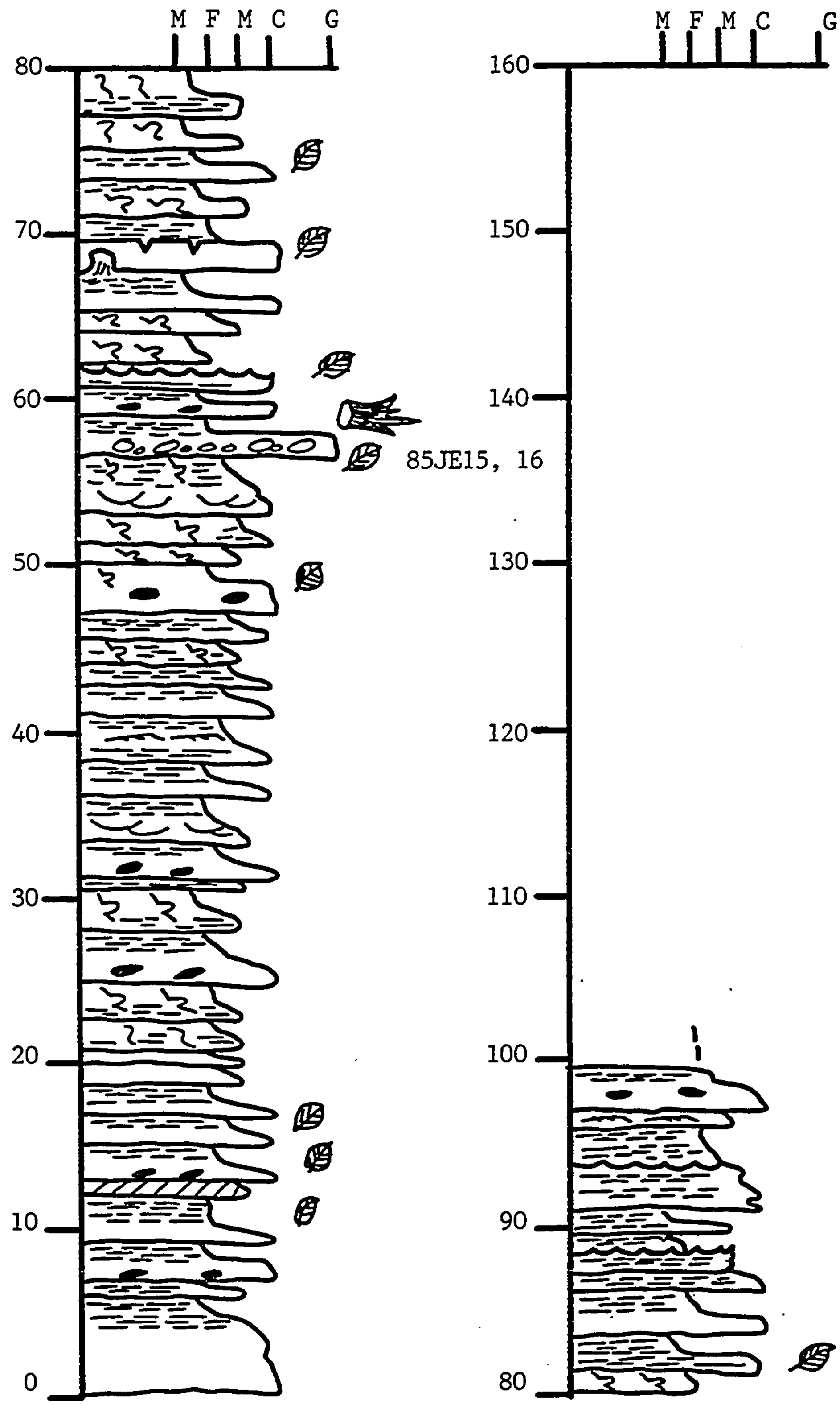

M F M C G
80
70
60
50
40

Figure A.12--Sunnyslope Road section, near interesction of U.S. Highway 2 and Sunnyslope Road (T.23N., R.20E., Section 19 NE1/4NE1/4). See Figure A.2 for symbols used.



M F M C G
80
70
60
50
40
30
20
10
0
85JE15, 16
M F M C G
160
150
140
130
120
110
100
90
80

Figure A.13--South Plain section, on Highway 209 (T.26N, R.18E., Section 18 NE1/4SW1/4). See Figure A.2 for symbols used.

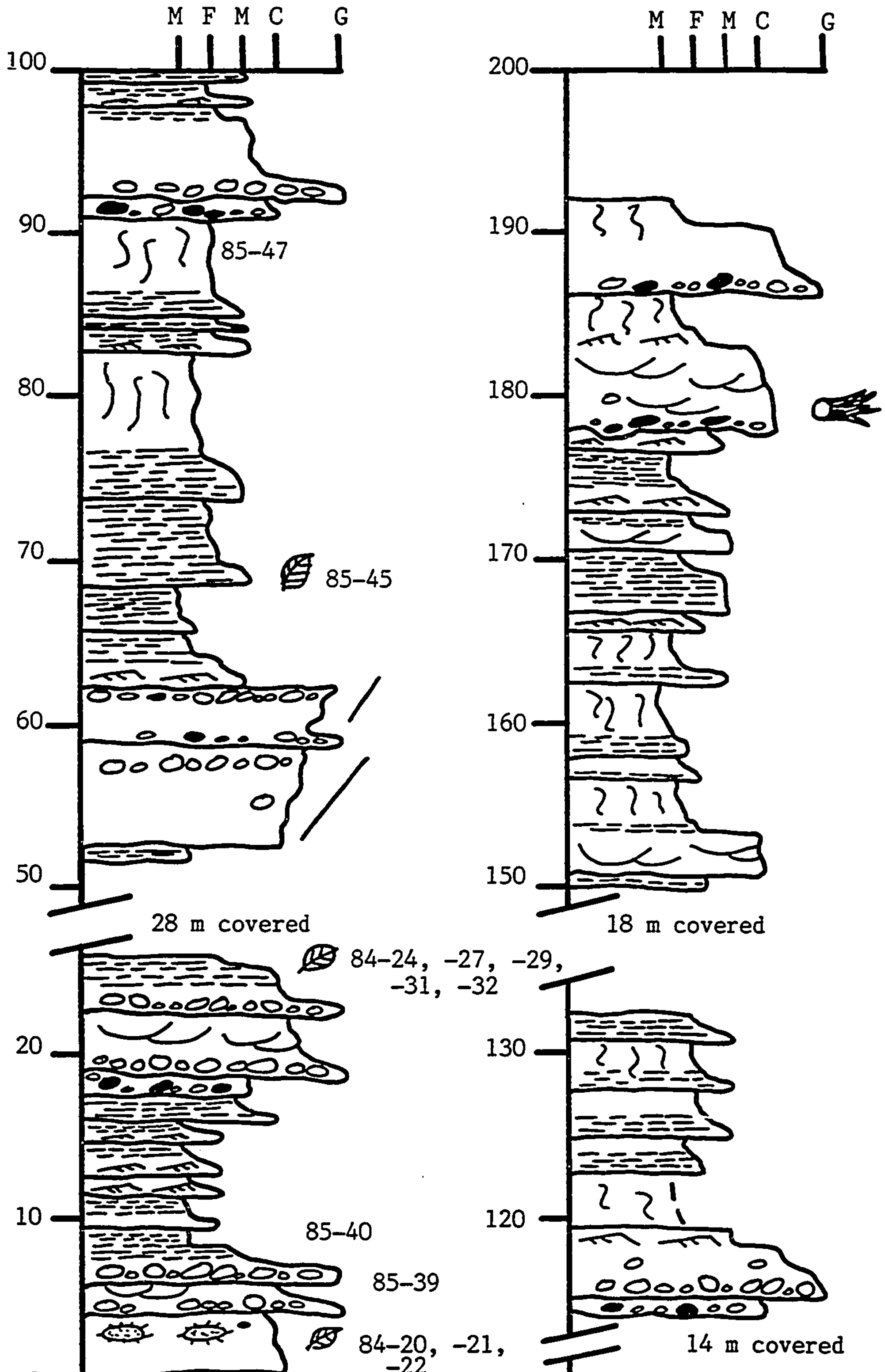
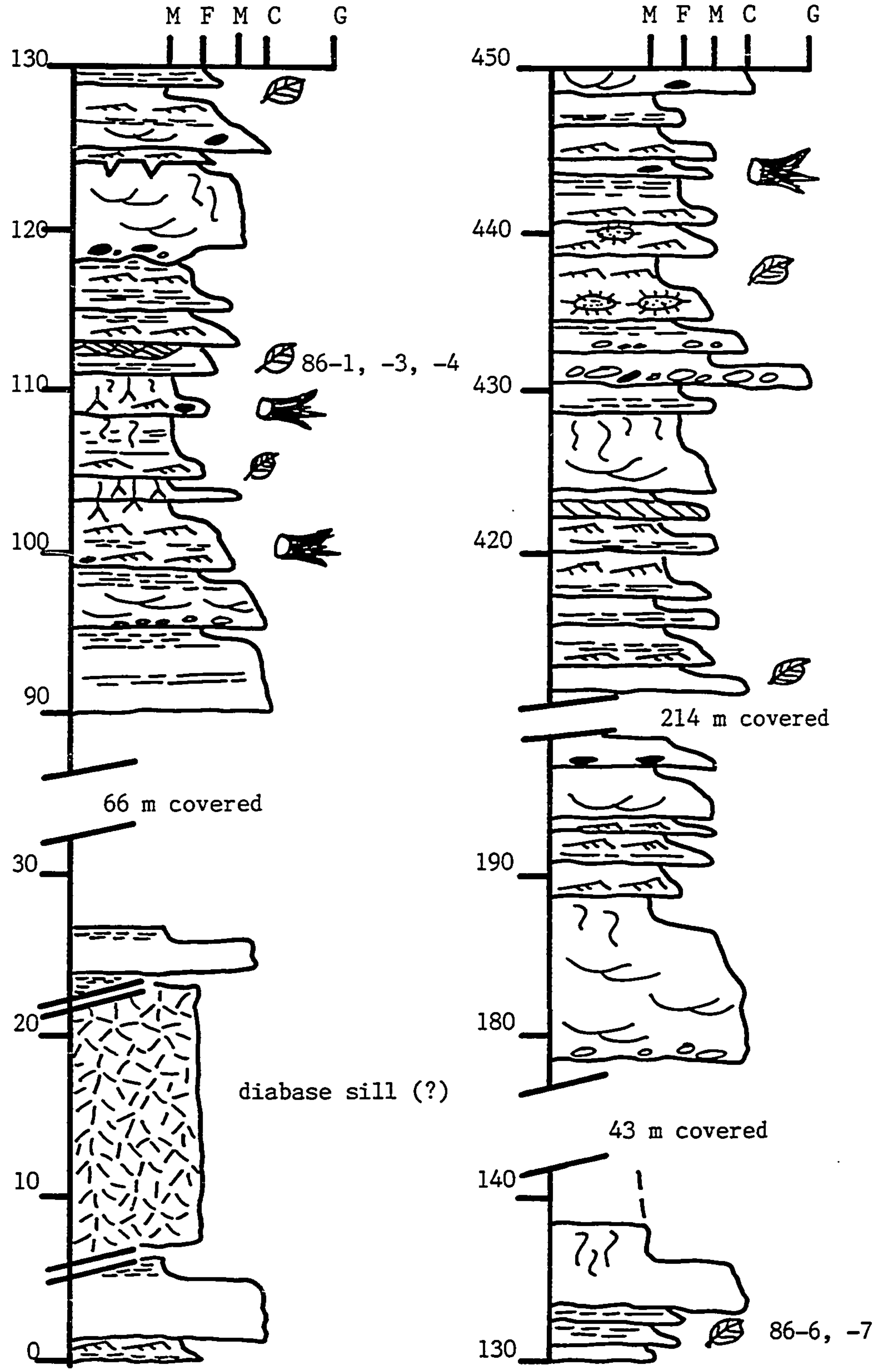
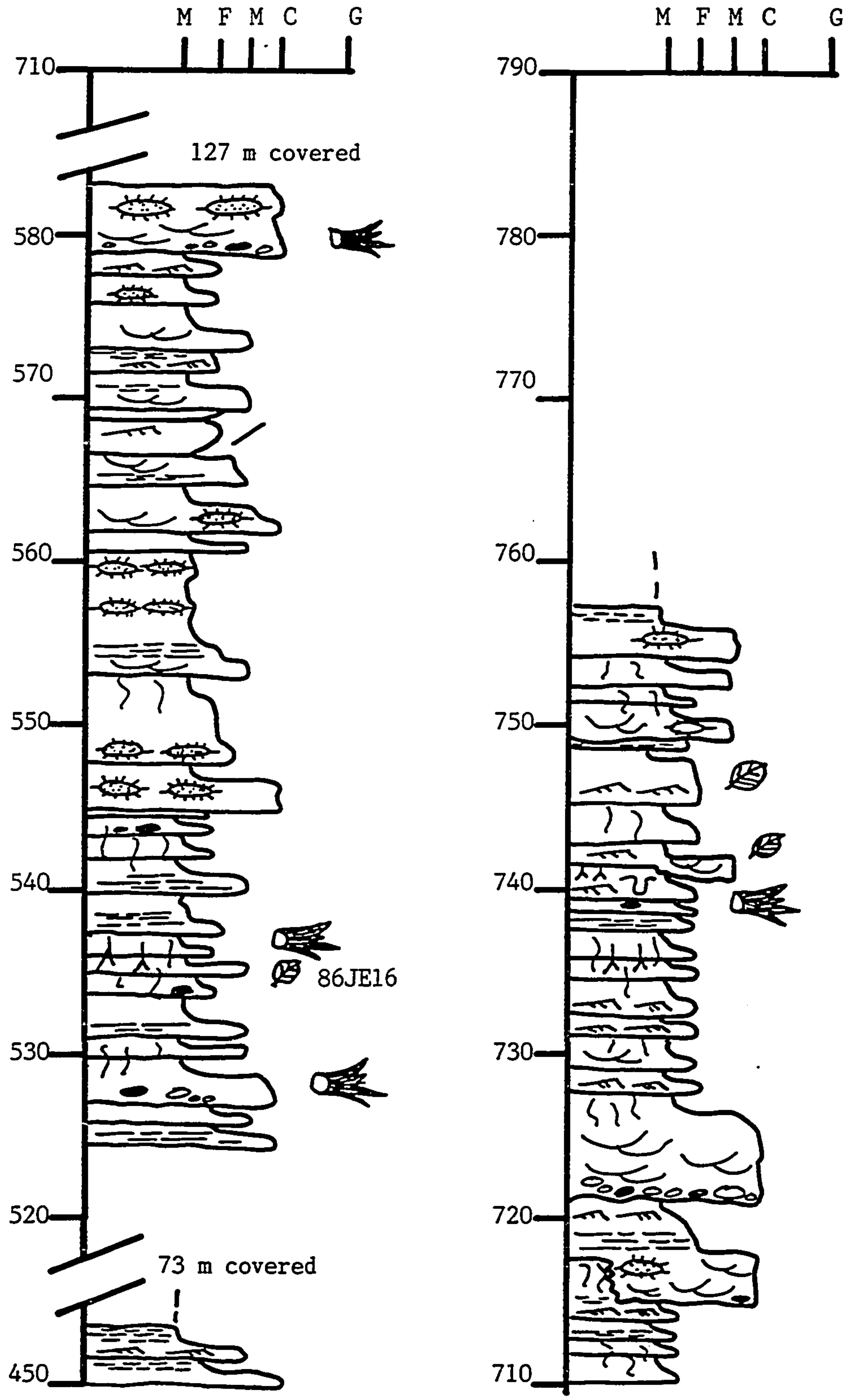

M F M C G
100
90
85-47
80
70
85-45
60
50
28 m covered
84-24, -27, -29,
-31, -32
20
10
85-40
85-39
84-20, -21,
-22
0
M F M C G
200
190
180
170
160
150
18 m covered
130
120
14 m covered
100

Figure A.14--Deadhorse Canyon section, along BN Railroad Tracks (T.26N., R.17E, Section 34 SE1/4NE1/4 to Section 34 NW1/4NW1/4). See Figure A.2 for symbols used.



M F M C G
130
120
110
100
90
86-1, -3, -4
66 m covered
30
20
10
0
diabase sill (?)
M F M C G
450
440
430
420
214 m covered
190
180
43 m covered
140
130
86-6, -7

Figure A.14 (con't.)-- Deadhorse Canyon section.



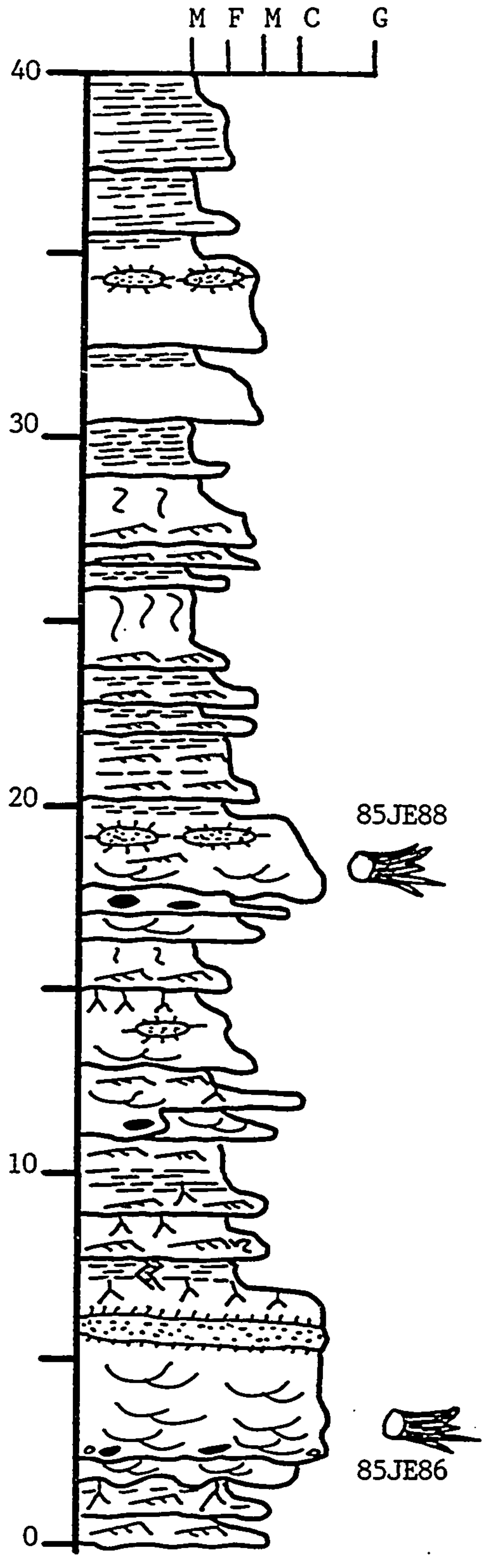
M F M C G
710
127 m covered
580
570
560
550
540
86JE16
530
520
73 m covered
450
M F M C G
790
780
770
760
750
740
730
720
710

Figure A.15--

LEFT COLUMN: Cole's Corner section, along BN Railroad Tracks (T.26N., R.17E., Section 17 SE1/4SE1/4).

RIGHT COLUMN: North Tumwater Canyon section, along U.S. Highway 2 (T.26N., R.17E., Section 32 NE1/4NE1/4).

See Figure A.2 for symbols used.


M F M C G
40
30
20
10
0
85JE88
85JE86

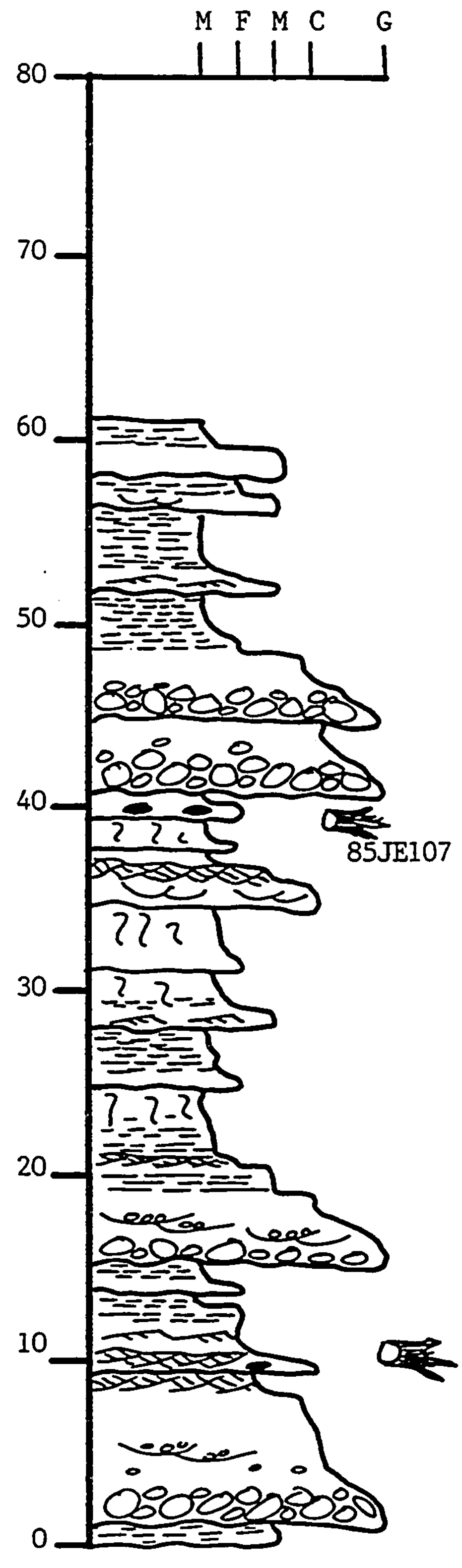
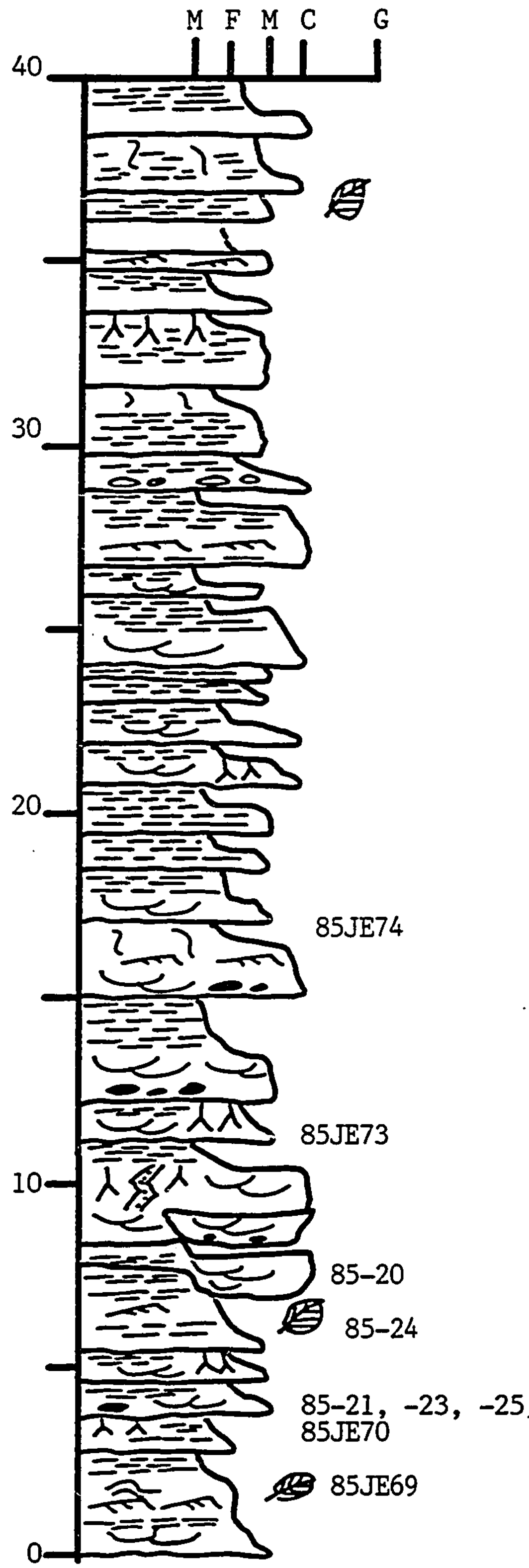

M F M C G
80
70
60
50
40
30
20
10
0
85JE107

Figure A.16--

LEFT COLUMN: North Plain section, on Highway 209 (T.26N., R.17E., Section 1 NE1/4NW1/4).

RIGHT COLUMN: Fish Lake section, near Chiwawa River bridge (T.27N., R.17E., Section 13 NW1/4NW1/4).

See Figure A.2 for symbols used.


M F M C G
40
30
20
10
0
85JE74
85JE73
85-20
85-24
85-21, -23, -25.
85JE70
85JE69

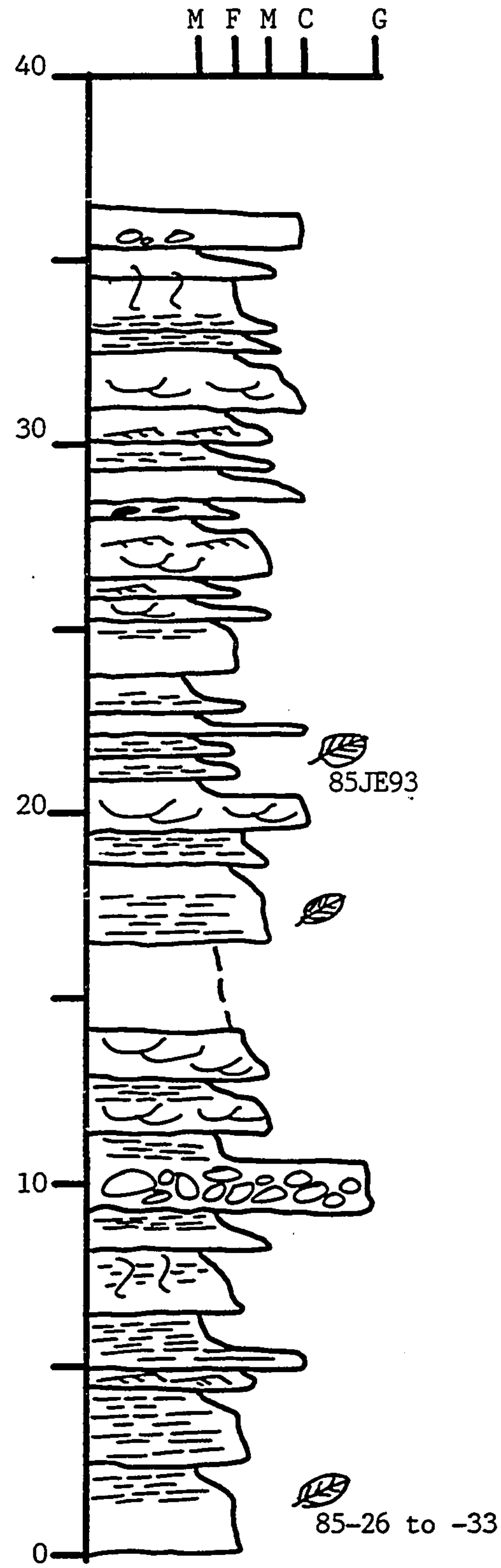

M F M C G
40
30
20
10
0
85JE93
85-26 to -33

Figure A.17--Pole Ridge section, (T.27N., R.17E., Section 9 SW1/4NE1/4). See Figure A.2 for symbols used.

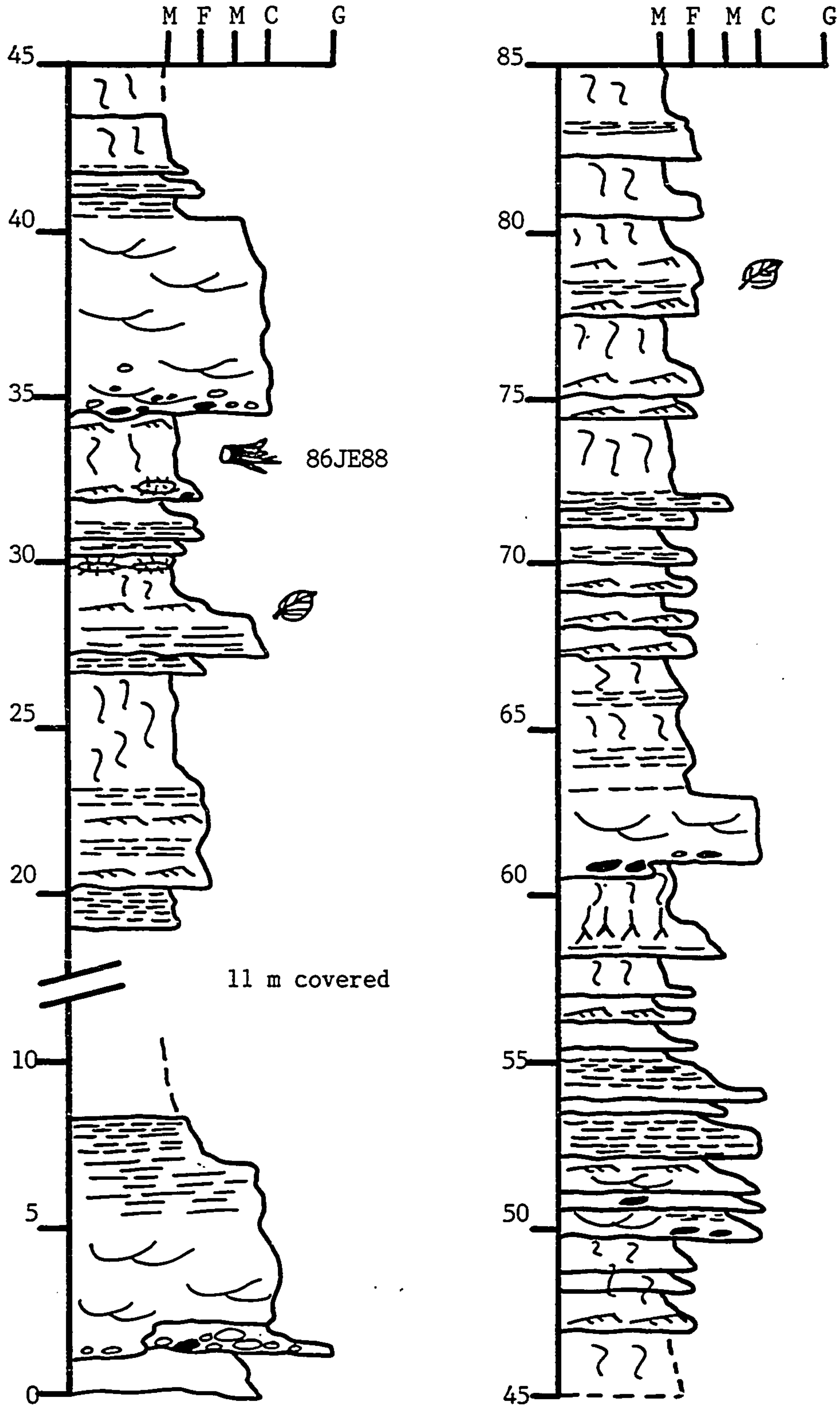
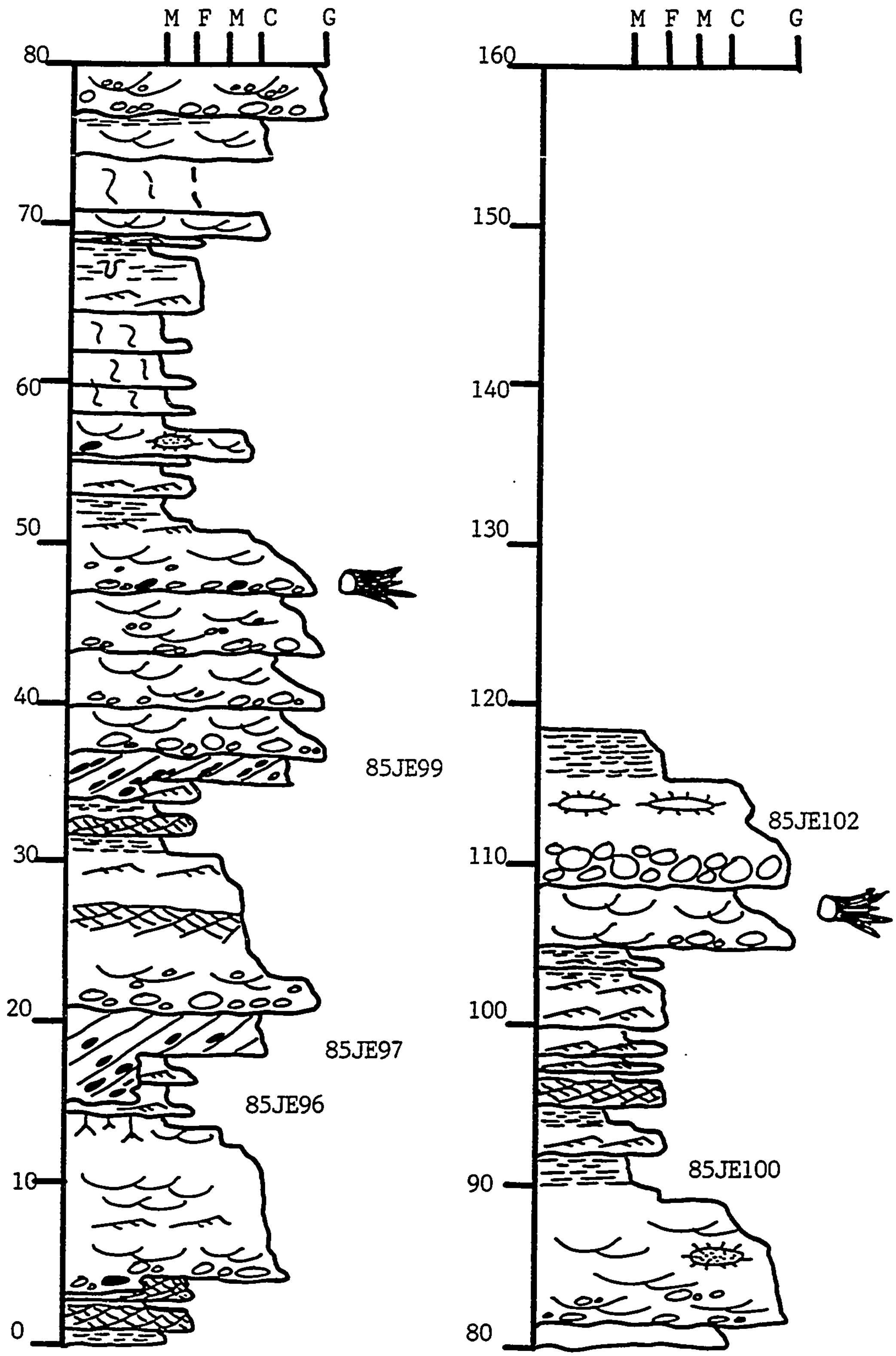

M F M C G
45
40
35
30
25
20
10
5
0
86JE88
11 m covered
M F M C G
85
80
75
70
65
60
55
50
45

Figure A.18--Malaga Road section, along Wenatchee-Malaga road (T.22N., R.20E., Section 23 SE1/4NE1/4). See Figure A.2 for symbols used.


M F M C G
80
70
60
50
40
30
20
10
0
85JE99
85JE97
85JE96
M F M C G
160
150
140
130
120
110
100
90
80
85JE102
85JE100

APPENDIX B: MARKOV CHAIN ANALYSIS DATA

Table B.1: Transition Count Matrix
Clark Canyon Section

	Gm	Gx	Gms	Ss	Se	Sh	St	Sl	Sr	Fl	Fm	P	T
Gm	0	83	0	1	2	32	14	12	2	3	0	1	0
Gx	46	0	0	5	2	16	6	20	2	6	2	4	3
Gms	1	0	0	0	0	1	0	0	0	0	0	0	0
Ss	20	3	0	0	3	4	2	0	0	0	0	0	0
Se	9	4	0	1	0	3	0	0	2	3	1	1	0
Sh	25	6	0	6	0	0	1	25	5	13	4	7	1
St	8	0	0	0	1	1	0	6	0	10	2	3	1
Sl	13	7	0	6	6	20	2	0	7	16	0	3	0
Sr	1	1	0	2	1	2	0	6	0	21	3	3	0
Fl	8	1	0	6	4	11	7	11	16	0	1	6	2
Fm	0	1	1	2	3	2	0	0	1	0	0	3	2
P	10	4	0	3	2	0	1	3	2	2	1	0	0
T	1	1	1	0	0	1	1	1	1	0	1	0	0

Table B.2: Transition Count Matrix
Camasland Section

	Gm	Gp	Ss	Se	Smc	Smf	Sh	St	Sp	Sr	Sl	Fl	Fm	P
Gm	0	0	10	0	39	6	19	4	0	0	1	3	3	0
Gp	1	0	0	0	0	0	0	0	0	0	1	0	0	0
Ss	34	1	0	2	11	0	6	5	0	0	0	0	0	0
Se	1	0	0	0	0	0	2	0	0	0	0	0	0	0
Smc	24	0	9	0	0	7	1	1	0	1	7	9	24	6
Smf	3	0	2	0	3	0	1	0	0	1	3	0	18	3
Sh	13	0	5	0	1	4	0	1	0	0	3	7	24	0
St	1	0	2	0	2	3	0	0	0	0	1	0	4	1
Sp	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Sr	0	0	0	0	1	0	1	0	0	0	2	1	2	0
Sl	2	0	2	0	3	2	8	1	0	0	0	3	8	1
Fl	0	0	0	0	5	1	5	1	1	1	3	0	4	2
Fm	3	0	15	1	19	9	14	0	0	5	5	0	0	9
P	3	0	11	0	2	2	1	0	0	0	2	0	0	0

Table B.3: Transition Count Matrix
Malaga Section

	Gm	Gt	Ss	Smc	Smf	Sh	Sl	St	Sp	Sr	Se	Fl	Fm	P	C
Gm	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Gt	0	0	0	3	0	0	0	5	0	0	0	0	1	0	0
Ss	0	1	0	0	0	0	0	0	0	1	3	0	0	0	0
Smc	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0
Smf	0	0	0	0	0	0	0	0	0	2	0	0	8	0	0
Sh	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
Sl	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
St	1	2	0	0	1	1	0	0	1	2	0	0	1	0	0
Sp	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Sr	0	0	3	0	1	0	0	3	0	0	0	6	16	0	1
Se	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0
Fl	0	0	0	0	0	0	0	0	0	6	0	0	3	0	1
Fm	0	0	2	0	5	0	1	0	0	16	1	3	0	4	0
P	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0

Table B.4: Transition Count Matrix
South Plain Section

	Gm	Gt	Ss	Se	Sh	St	Sl	Sr	Fl	Fm
Gm	0	0	0	0	6	2	0	0	0	0
Gt	0	0	0	0	0	1	0	0	0	1
Ss	2	0	0	0	1	0	0	0	0	0
Se	5	1	1	0	1	0	1	0	0	0
Sh	1	1	1	2	0	0	4	2	3	10
St	0	0	0	1	1	0	0	0	3	0
Sl	0	0	0	1	2	1	0	5	11	23
Sr	0	0	0	0	0	0	2	0	6	27
Fl	0	0	0	0	3	1	13	7	0	4
Fm	0	0	1	4	12	0	24	23	3	0

Table B.5: Transition Count Matrix
Deadhorse Canyon Section

	Ss	Se	Smc	Smf	Sh	St	Sp	Sr	Sl	Fl	Fm	P	C
Ss	0	9	2	2	1	7	0	2	1	0	0	0	0
Se	0	0	3	0	3	2	0	0	1	3	2	0	0
Smc	0	0	0	3	2	0	0	1	2	3	8	0	2
Smf	0	0	2	0	0	0	0	2	2	2	44	1	4
Sh	0	0	3	0	0	0	1	1	0	4	5	0	3
St	1	0	0	2	2	0	0	1	0	3	7	0	0
Sp	0	0	0	0	1	0	0	0	0	0	0	0	0
Sr	1	0	2	3	0	0	0	0	5	15	22	1	3
Sl	2	1	0	2	1	1	0	7	0	13	8	0	3
Fl	8	1	1	4	1	1	0	17	11	0	2	5	0
Fm	6	3	4	32	3	3	0	14	11	6	0	20	0
P	4	0	2	7	0	0	0	3	6	0	4	0	0
C	2	0	3	3	2	1	0	4	0	0	0	0	0

Table B.6: Transition Count Matrix
Monitor Section

	Ss	Se	Sh	St	Sr	Sl	Fl	Fm	P	Smf	Smc
Ss	0	2	0	17	1	0	0	0	0	1	1
Se	1	0	0	1	1	0	0	0	0	0	0
Sh	0	0	0	3	0	0	0	0	0	0	0
St	0	0	3	0	0	1	4	16	0	5	0
Sr	1	0	0	0	0	0	0	7	0	1	0
Sl	1	0	0	1	0	0	0	2	0	0	0
Fl	3	0	0	1	0	0	0	1	1	1	0
Fm	11	0	0	6	4	2	1	0	12	6	0
P	2	1	0	0	2	0	0	0	0	5	1
Smf	3	0	0	0	0	1	2	13	0	0	1
Smc	0	0	0	0	0	1	0	2	0	0	0

Table B.7: Transition Count Matrix
Sunnyslope Section

	Gm	Smc	Sh	Sl	Sp	St	Sr	Se	Ss	Fl	Sc	Fc
Gm	0	0	0	0	0	0	0	0	0	3	0	0
Smc	0	0	11	1	0	0	2	1	0	48	1	2
Sh	0	2	0	1	0	0	4	0	0	16	2	2
Sl	0	1	0	0	0	0	1	1	0	5	0	1
Sp	0	0	0	0	0	0	0	0	0	2	0	0
St	0	0	0	0	0	0	0	0	0	2	0	0
Sr	0	1	0	0	0	0	0	0	0	7	0	0
Se	0	0	1	1	0	0	0	0	0	3	0	1
Ss	0	5	0	0	0	2	0	3	0	0	0	0
Fl	2	59	13	6	2	0	1	1	3	0	4	0
Sc	1	1	2	0	0	0	0	0	0	3	0	1
Fc	0	3	0	1	0	0	0	0	1	1	0	0

APPENDIX C: PLANT MACROFOSSIL COLLECTION DATA

Table C.1: Paleoflora from Clark Canyon (T.25N., R.18E., Section 9 NE1/4SW1/4)

Sample No.	Identification
84-1	Calkinsia franklinensis
84-2	Tetracentron piperoides
84-4	Litseaphyllum (?) sp.
84-5	Litseaphyllum (?) sp.
84-7	Platanus (?) sp.
84-8	Aesculus (?) sp.
84-9	Carpinus sp.
84-11	Myristica sp.
84-12	Parashorea pseudogoldiana
84-13	Tetracentron piperoides
84-14a	Calkinsia franklinensis
84-14b	Parashorea pseudogoldiana

Table C.2: Paleoflora from Nahahum Canyon (T.24N., R.19E., Section 23 SW1/4NW1/4)

Sample No.	Identification
84-15	*Tetracentron piperoides*

Table C.3: Paleoflora from Van Creek Canyon (T.25N., R.18E., Section 13 NW1/4SW1/4)

Sample No.	Identification
84-17	*Mimosites (?) so.*
84-18	*Alnus sp.*

Table C.4: Paleoflora from South Plain Section (T.26N., R.18E., Section 18 NE1/4SW1/4)

Sample No.	Identification
84-20a	Salix sp.
84-20b	Populus sp.
84-20c	Salix sp.
84-21	Salix sp.
84-22	Salix sp.
84-24	Tetracentron piperoides
84-27	Salix sp.
84-29	Leguminosae
84-31	Tetracentron piperoides
84-32	pine needles

Table C.5: Paleoflora from North Plain Section (T.26N., R.17E., Section 1 NE1/4NW1/4)

Sample No.	Identification
84-33	Hamamelis inequalis (?)
84-34a	Chaetoptelea sp.
84-34b	Hamamelis sp.
84-35a	Myristica sp.
84-35b	Cyathea pinnata
84-36	Cyathea pinnata
84-37a	Chaetoptelea sp.
84-37b	Tetracentron piperoides
84-38	Chaetoptelea sp.
85-20a	Viburnum pugetensis
85-20b	Viburnum pugetensis
85-20c	Chaetoptelea sp.
85-21	Alnus sp.
85-23	Chaetoptelea sp.
85-24	Platanus appendiculata
85-25a	Viburnum pugetensis
85-25b	Populus sp.
85-25c	Myristica sp.

Table C.6: Paleoflora from Tumwater Mountain Section (T.25N., R.17E., Section 35 NW1/4SE1/4)

Sample No.	Identification
85-1	Dryopteris gibbsi
85-2	Cladrastis pugetensis
85-3	Macginitiea whitneyi
85-4	Myristica sp.
85-5a	Rhododendron (?) sp.
85-5c	Vinea pugetensis
85-6a	Tetracentron piperoides
85-6b	Macginitiea angustiloba
85-6c	Platanus macginitei
85-7	Myristica sp.
85-8	Dryopteris gibbsi
85-9	Phytocrene sordida
85-11	Viburnum (?) sp.
85-13	Dryopteris gibbsi
85-14	Macginitiea whitneyi
85-15a	Phytocrene sordida
85-15b	Tetracentron piperoides
85-16	Cocculus sp.
85-17	Myristica sp.
85-19	Phytocrene sordida

Table C.7: Paleoflora from Fish Lake Sectiom (T.27N., R.17E., Section 13 NW1/4NW1/4)

Sample No.	Identification
85-27a	Dryopteris gibbsi
85-27b	Parashorea pseudogoldiana
85-27c	Tetracentron piperoides
85-28	Cyathea pinnata (?)
85-29	Anemia (?) sp.
85-30	Rhus mixta
85-31	Carya sp.
85-32	Litseaphyllum katallaensis (?)
85-33	Parashorea pseudogoldiana

Table C.8: Paleoflora from Deadhorse Canyon Section (T.26N., R.17E., Section 34 NW1/4NW1/4)

Sample No.	Identification
86-1	_Litseaphyllum katallaensis_
86-3	_Macclintockia pugetensis_
86-4	_Fothergilla durhamensis_
86-6	_Salix sp._
86-7	_Salix sp._
86-10	_Dryopteris (?) sp._
86-11	_Salix sp._

Table C.9: Paleoflora from Camas Creek Section (T.23N., R.18E., Section 20 NW1/4NW1/4)

Sample No.	Identification
86-12	Salix sp.
86-13	Salix sp.
86-14	Salix sp.
86-15	Rhus (?) sp.
86-16	Eugenia americana
86-17	Eugenia americana
86-18	Eugenia americana
86-19	Eugenia americana
86-20	Eugenia americana
86-21a	Eugenia americana
86-21b	Eugenia americana
86-21c	Salix sp.
86-21d	Eugenia americana
86-22	Eugenia americana
86-23	Rhus (?) sp.
86-24	Rhus (?) sp.
86-25a	Artocarpus lessigiana (?)
86-25b	Thouinopsis myricaefolia
86-26	Pterocarya pugetensis

Table C.10: Paleoflora from Derby Canyon (T.24N., R.18E., Section 10 NW1/4SW1/4)

Sample No.	Identification
86-27	Aesculus sp.
86-28a	Dryophyllum pugetensis
86-28b	Myristica sp.
86-28c	Myristica sp.
86-28d	Aesculus sp.
86-29	Pterocarya pugetensis
86-30	Pterocarya pugetensis
86-31	Aesculus (?) sp. seed
86-32a	Tetracentron piperoides
86-32b	Aesculus sp.
86-33	Aesculus sp.
86-34	Platanus appendiculata

APPENDIX D: PALYNOLOGY COLLECTION DATA

TABLE D.1: PALYNOLOGY COLLECTION DATA

Location	Sample No.	Identification
Cashmere Section (T.24N., R.19E., Section 33 SW1/4SW1/4)	85JE116	Tilia sp. Alnus sp.
Wenatchee Cannon Mine (T.22N., R.20E., Section 22 NE1/4SW1/4)	COM-7A-271	Alnipollenites verus Cupuliferoipollenites sp. Caryapollenites inelegans Caryapollenites veripites cf. Celtis tschudyi Pesavis tagluensis
Malaga Section (T.22N., R.20E., Section 23 SE1/4NE1/4)	85JE100	Tilia sp. Alnus sp. ? Pesavis sp. Ulmus sp. Sciadopityspollenites sp. Pinus sp. Picea sp. Tsuga sp. Pityosporites sp. Retitricolpites sp. Retitricolporites sp. Pterocaryapollenites sp. Verrucatosporites sp.

APPENDIX E: VITRINITE REFLECTANCE DATA

TABLE E.1: OUTCROP SAMPLES

location name	legal description T	R	Section		sample no.	% vitrinite reflectance
PHASE 1 DEPOSITS						
No.2 Canyon	22N	20E	13	NENE	86JE113	1.47 ± 0.16
Cashmere	23N	19E	33	SWSW	TW-7	0.68 ± 0.04
Cashmere	23N	19E	33	SWSW	TW-8	0.60 ± 0.05
Mission Ck.	22N	19E	20	SESE	86JE121	0.54 ± 0.06
Mission Creek	23N	19E	29	SWSW	86JE119	0.40 ± 0.03
E. Mission Ck	22N	19E	28	NESW	86JE123	0.44 ± 0.03
Derby Cyn.	25N	18E	34	NESW	86JE56	1.94 ± 0.46
Derby Cyn.	24N	18E	16	NESE	86JE52	0.52 ± 0.03
Eagle Ck.	25N	18E	27	NWNW	85JE66	0.76 ± 0.06
Eagle Ck.	25N	18E	28	NENE	85JE143	0.96 ± 0.04
Peshastin	24N	18E	17	NENW	TW-9	0.74 ± 0.05
Peshastin	24N	18E	17	NENW	85JE113	0.85 ± 0.04
Leavenworth	24N	17E	1	NENE	85JE141	0.73 ± 0.09
Leavenworth	24N	18E	6	SWNW	86JE51	0.47 ± 0.04
Clark Cyn.	25N	18E	9	NESW	TW-4	1.07 ± 0.03
Clark Cyn.	25N	18E	9	NESW	TW-13	0.77 ± 0.05
Clark Cyn.	25N	18E	9	NWSW	TW-3	0.73 ± 0.06
Clark Cyn.	25N	18E	9	NWSW	TW-2	0.72 ± 0.05
Clark Cyn.	25N	18E	8	NESE	TW-1	0.72 ± 0.05
Clark Cyn.	25N	18E	9	SWSW	TW-5	0.94 ± 0.05
Chumstick Ck.	26N	18E	27	SWSW	86JE78	0.67 ± 0.06
Camp 12 Rd.	26N	17E	36	NENE	85JE154	0.72 ± 0.06
U.Miner's Run	21N	19E	14	NWNE	86JE107	2.08 ± 0.14
Squilchuck C.	21N	20E	18	NENE	86JE111	1.66 ± 0.48
PHASE 2 DEPOSITS (West)						
Wright Cyn.	25N	17E	15	NWNW	86JE96	0.44 ± 0.03
Spronberg Cy.	25N	17E	14	SWSW	86JE90	0.48 ± 0.09
Camasland Rd.	23N	18E	19	SENW	86JE28	0.66 ± 0.05
Camasland Rd.	23N	18E	19	NENE	86JE34	0.53 ± 0.04
Camasland Rd.	23N	18E	33	SESE	86JE44	0.53 ± 0.06
Devils Gulch	22N	19E	18	SESE	86JE129	0.65 ± 0.04

Table E.1 (con't.)

location name	legal description T	R	Section		sample no.	% vitrinite reflectance
PHASE 2 DEPOSITS (east)						
Eagle Creek	25N	18E	11	SESE	86JE97	0.49 ± 0.03
Ollala Cyn.	25N	19E	28	SESW	86JE100	0.39 ± 0.04
Nahahum Cyn.	24N	19E	34	NENW	86JE102	0.42 ± 0.03
Monitor	23N	19E	24	NWNE	86JE59	0.51 ± 0.04
Sunnyslope Rd.	23N	20E	19	NENE	85JE15	0.56 ± 0.05
Sunnyslope Rd.	23N	20E	19	NENE	85JE16	0.58 ± 0.04
Sunnyslope Rd.	23N	20E	19	NENE	TW-6	0.58 ± 0.04
PHASE 3 DEPOSITS (south)						
Malaga Rd.	22N	20E	23	SWNE	85JE96	0.44 ± 0.03
Malaga Rd.	22N	20E	23	SWNE	85JE97	0.44 ± 0.04
Malaga Rd.	22N	20E	23	SWNE	85JE99	0.44 ± 0.04
Malaga Rd.	22N	20E	23	SWNE	85JE102	0.39 ± 0.04
Stemilt Cyn.	22N	21E	30	SWNW	86JE-71	0.33 ± 0.05
Dry Gulch	22N	20E	16	SWSE	TW	0.42 ± 0.05
PHASE 3 DEPOSITS (north)						
South Plain	26N	18E	18	NESW	85JE39	0.75 ± 0.04
South Plain	26N	18E	18	NESW	85JE40	0.70 ± 0.03
South Plain	26N	18E	18	NESW	85JE45	0.74 ± 0.04
South Plain	26N	18E	18	NESW	85JE47	0.60 ± 0.03
South Plain	26N	18E	18	NESW	TW-10	0.70 ± 0.06
Deadhorse Cyn.	26N	17E	34	NWNW	86JE16	0.63 ± 0.04
N.Tumwater C.	26N	17E	32	NENE	85JE107	0.62 ± 0.04
Natapoc Mtn.	26N	17E	11	SWNW	86JE20	0.49 ± 0.04
North Plain	26N	17E	1	NENW	85JE69	0.45 ± 0.04
North Plain	26N	17E	1	NENW	85JE70	0.59 ± 0.05
North Plain	26N	17E	1	NENW	85JE73	0.49 ± 0.03
North Plain	26N	17E	1	NENW	85JE74	0.66 ± 0.05
North Plain	26N	17E	1	NENW	TW-11	0.66 ± 0.03
North Plain	26N	17E	1	NENW	TW-12	0.95 ± 0.06
Cole's Corner	26N	17E	17	SESE	85JE86	0.45 ± 0.03
Cole's Corner	26N	17E	17	SESE	85JE88	0.45 ± 0.02
Fish Lake	27N	17E	13	NWNW	85JE93	0.59 ± 0.04
Pole Ridge	27N	17E	9	SWNE	86JE88	0.49 ± 0.04
Meadow Ck.Rd.	27N	17E	3	NENE	86JE50	0.45 ± 0.03
Chiwawa R.Rd.	28N	17E	35	SWNW	86JE82	0.50 ± 0.03
Trinity	30N	16E	34	SWSW	86JE80	0.66 ± 0.05

TABLE E.2: VITRINITE REFLECTANCE DATA
FROM NORCO #1 WELL
WENATCHEE HEIGHTS AREA
(T.22N., R.20E., Section 26 NW1/4SW1/4)

Coal Seam Number	Stratigraphic Depth (m)	VR (%Ro)
1	290	n/a
2	480	n/a
3	534	0.38
4	579	0.39
5	687	0.51
6	732	0.50
7	762	0.48
8	820	0.32
9	884	0.28
10	960	n/a
11	1005	0.36
12	1007	0.47
13	1067	0.42
14	1126	0.51
15	1211	0.50
16	1283	0.77
17	1428	0.66
18	1450	n/a

APPENDIX F: FISSION-TRACK DATA

**TABLE F.1: ZIRCON FISSION-TRACK AGES
FROM SANDSTONE 85JE135**
(T.22N., R.20E., Section 8 SW1/4SW1/4)

sample no.	fossil tracks	induced tracks	age (m.y.)
1	427	198	67.42
2	589	327	56.36
3	373	170	68.58
4	429	305	44.05
5	304	155	61.34
6	534	373	44.83
7	349	229	47.71
8	402	253	49.74
9	414	233	55.60
10	410	280	45.85
11	253	225	35.24
12	252	185	42.66
13	310	216	44.94
14	596	321	58.08
15	290	156	58.15
16	327	246	41.64
17	497	297	52.37
18	497	258	60.25
19	532	335	49.71
20	372	339	34.39
21	499	430	36.36
22	133	71	58.60
23	268	216	38.87
24	320	200	50.08
25	518	347	46.74
26	274	160	53.59
27	395	202	61.16
28	268	165	50.84
29	435	339	40.20
30	203	119	53.39
31	691	308	70.12
32	394	249	49.02
33	291	115	79.03
34	458	298	48.12
35	500	349	44.86
36	502	296	53.08
37	584	334	54.73
38	241	167	45.19
39	477	366	40.83
40	453	235	60.29

Table F.1 (con't.)

sample no.	fossil tracks	induced tracks	age (m.y.)
41	702	479	45.96
42	471	330	44.70
43	342	181	59.10
44	469	324	45.33
45	491	276	55.66
46	393	293	42.01

Mean = 51.02 m.y.
Range = 79.03 to 34.39 m.y.
Standard Deviation = 9.60 m.y.

Estimated Depositional Age = 46 to 44 m.y.

Neutron flux = 0.99 x 10^{15}

**TABLE F.2: ZIRCON FISSION TRACK AGES
FROM EAGLE CREEK TUFF (Tcte)**
(T.25N., R.18E., Section 10 NE1/4SW1/4)

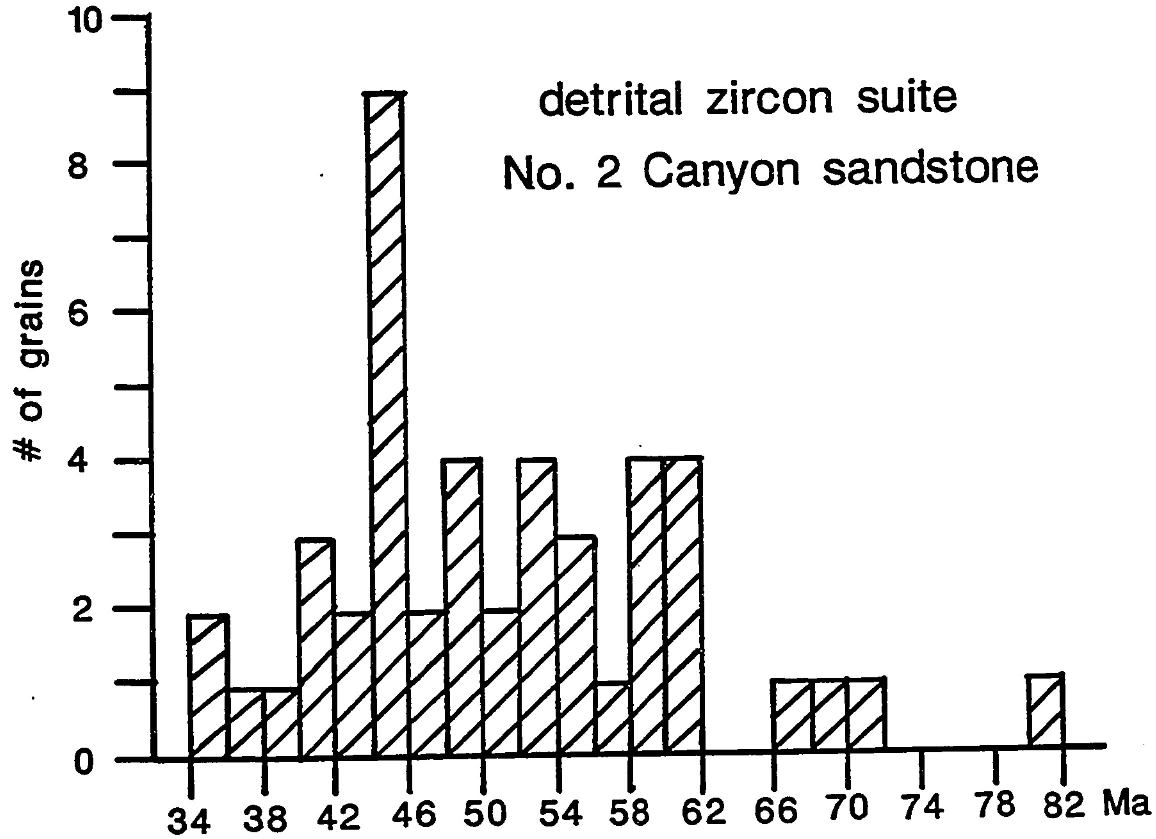
sample no.	fossil tracks	induced tracks	age (m.y.)
1	286	175	48.2
2	189	127	43.9
3	204	136	44.3
4	278	209	39.3
5	255	161	43.1
6	237	195	35.9
7	184	141	37.9
8	259	152	50.3

Mean = 42.9 m.y.
Range = 50.3 to 35.9 m.y.
Standard Deviation = 4.97 m.y.

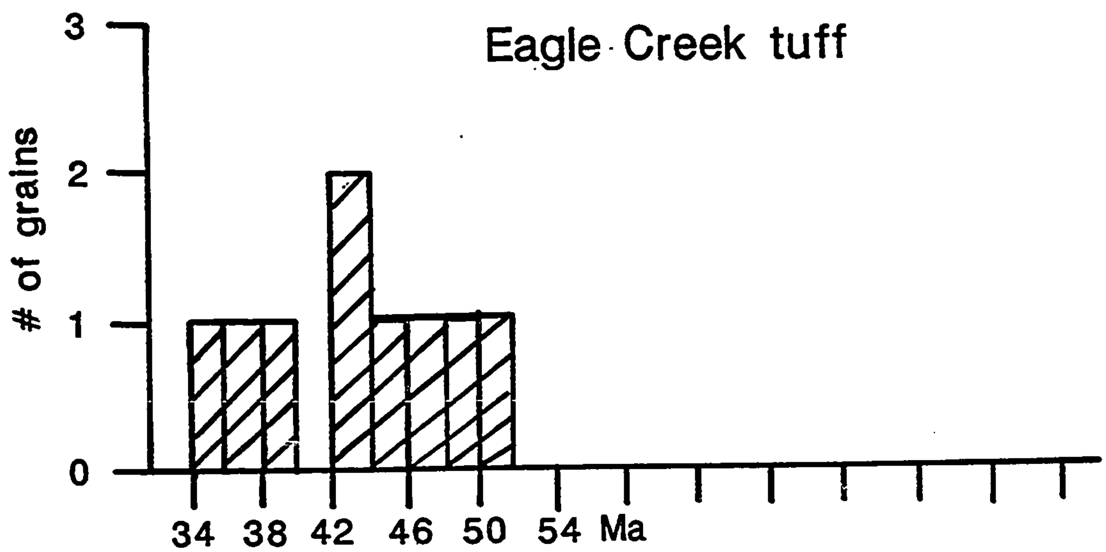
Estimated Depositional Age = 42.9 m.y.

Neutron flux = 0.99×10^{15}

Figure F.1--Histograms of fission-track dates. Top: histogram of zircon fission track dates from sample 85JE135, a sandstone from near the base of the Chumstick Formation. Bottom: histogram of zircon fission track dates from the Eagle Creek tuff (Tcte).



detrital zircon suite
No. 2 Canyon sandstone
# of grains
0
2
4
6
8
10
34 38 42 46 50 54 58 62 66 70 74 78 82 Ma



Eagle Creek tuff
# of grains
0
1
2
3
34 38 42 46 50 54 Ma

APPENDIX G: PALEOMAGNETIC DATA

Table G.1: Sample Locations

Sample Numbers	General Location	T	R	Section
5W001 to 5W007	Eagle Creek Rd.	25N	18E	28 SE1/4NW1/4
5W008 to 5W014	Eagle Creek Rd.	25N	18E	27 NW1/4NW1/4
5W015 to 5W021	Eagle Creek Rd.	25N	18E	13 SW1/4SE1/4
5W022 to 5W028	Eagle Creek Rd.	25N	19E	19 NW1/4NW1/4
5W029 to 5W036	Walker Cyn. Rd.	25N	18E	8 SE1/4SE1/4
5W037 to 5W063	Clark Cyn. Rd.	25N	18E	9 NE1/4 *
5W066 to 5W071	South Plain	26N	18E	18 NE1/4SW1/4
5W072 to 5W077	North Plain	26N	17E	1 NE1/4NW1/4
5W078 to 5W087	Sunnyslope	23N	20E	19 NE1/4NE1/4

* see Table G.2 for more detail

Table G.2: Normal Directions from the Clark Canyon section

Sample	Strat.Elev.	D,I in situ	strike/dip	D,I corrected
031	1350	307.7, 71.3	137/41S	252.6, 42.9
032	1350	292.5, 65.1	137/41S	254.8, 34.8
043	348	312.1, 28.3	154/49S	298.9, 03.6
044	348	330.2, 26.7	154/49S	311.0, 14.5
054	725	306.8, 43.5	161/50S	288.2, 07.5
055	864	347.5, 62.3	146/50S	273.3, 44.4
056	864	337.6, 42.6	146/50S	295.6, 33.3
059	984	344.8, 57.7	150/47S	284.5, 42.6
061	1051	288.0, 64.2	164/47S	269.1, 20.5
062	1176	312.4, 51.4	175/45S	293.3, 14.7

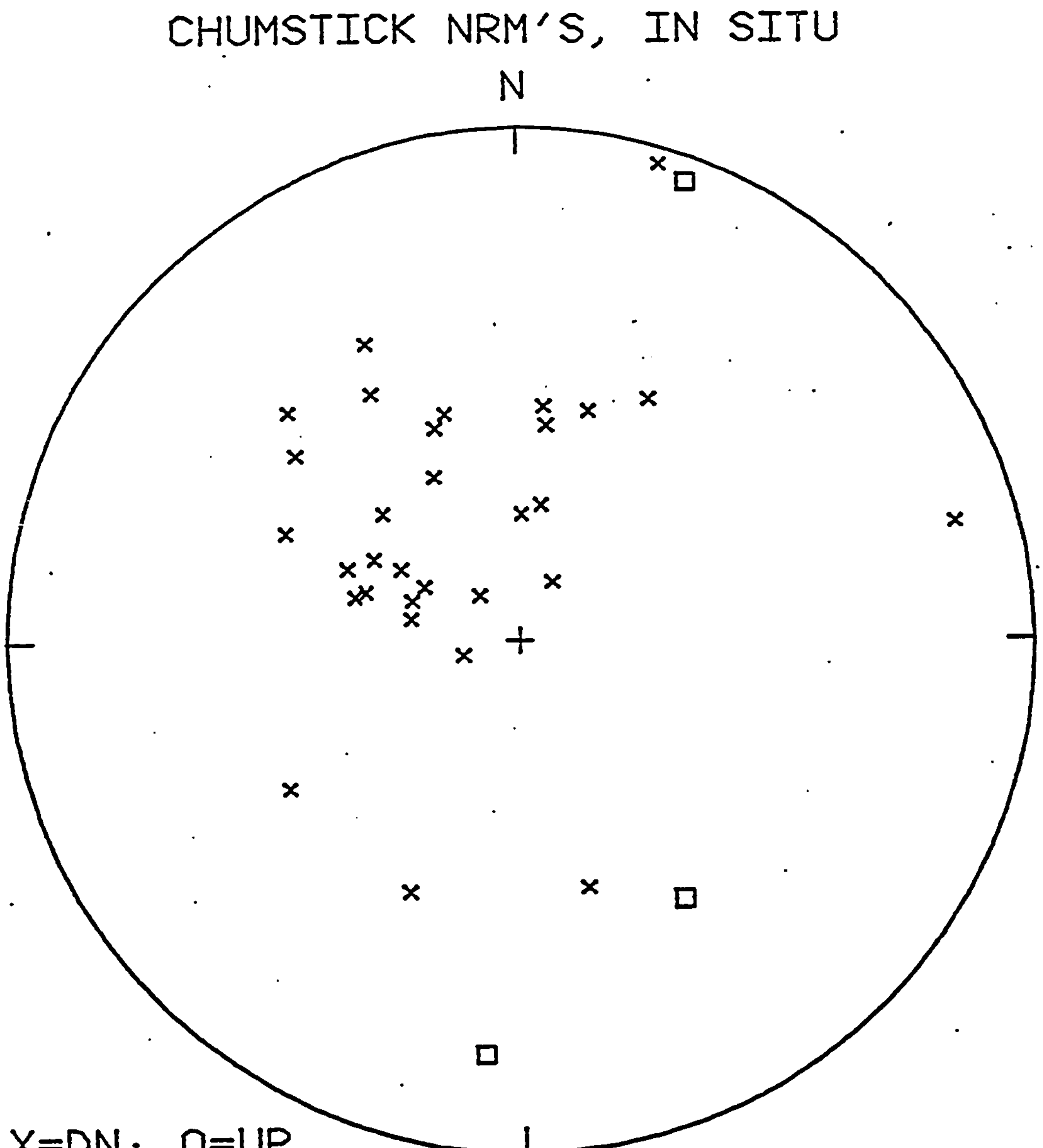
Mean in situ direction:
D = 319.6 I = 52.8 alpha-95 = 11.9 k = 17.4
Mean corrected direction:
D = 283.6 I = 27.0 alpha-95 = 14.1 k = 12.7

Table G.3: Reversed Directions from the Clark Canyon section

Sample	Strat.Elev.	D,I in situ	strike/dip	D,I corrected
035	1350	177.2,-56.7	156/37S	122.2,-51.9
036	1350	196.9,-43.3	156/37S	152.7,-56.6
037	115	191.2,-62.1	179/26S	145.9,-56.9
038	115	183.5,-63.6	179/26S	139.8,-55.1
058	984	198.5,-41.0	150/47S	139.3,-59.4
062	1176	203.6,-46.8	175/45S	149.7,-48.3

Mean *in situ* direction:
D = 193.2 I = -52.6 alpha-95 = 9.6 k = 50.0
Mean corrected direction:
D = 141.5 I = -55.1 alpha-95 = 6.3 k = 115.1

Figure G.1--Equal area plot of directions of natural remanent magnetization from the Clark Canyon section (uncorrected for tectonic tilt). Abbreviations: X = values in lower hemisphere (positive values), squares = values in upper hemisphere (negative values).



CHUMSTICK NRM'S, IN SITU
N
X=DN; O=UP

Figure G.2--Equal area plot of normal directions from the Clark Canyon section, obtained from straight line segments on orthogonal vector diagrams. Statistics: mean is shown as a circle of radius equal to alpha-95, n = 10.

CHUMSTICK NORMAL, IN SITU

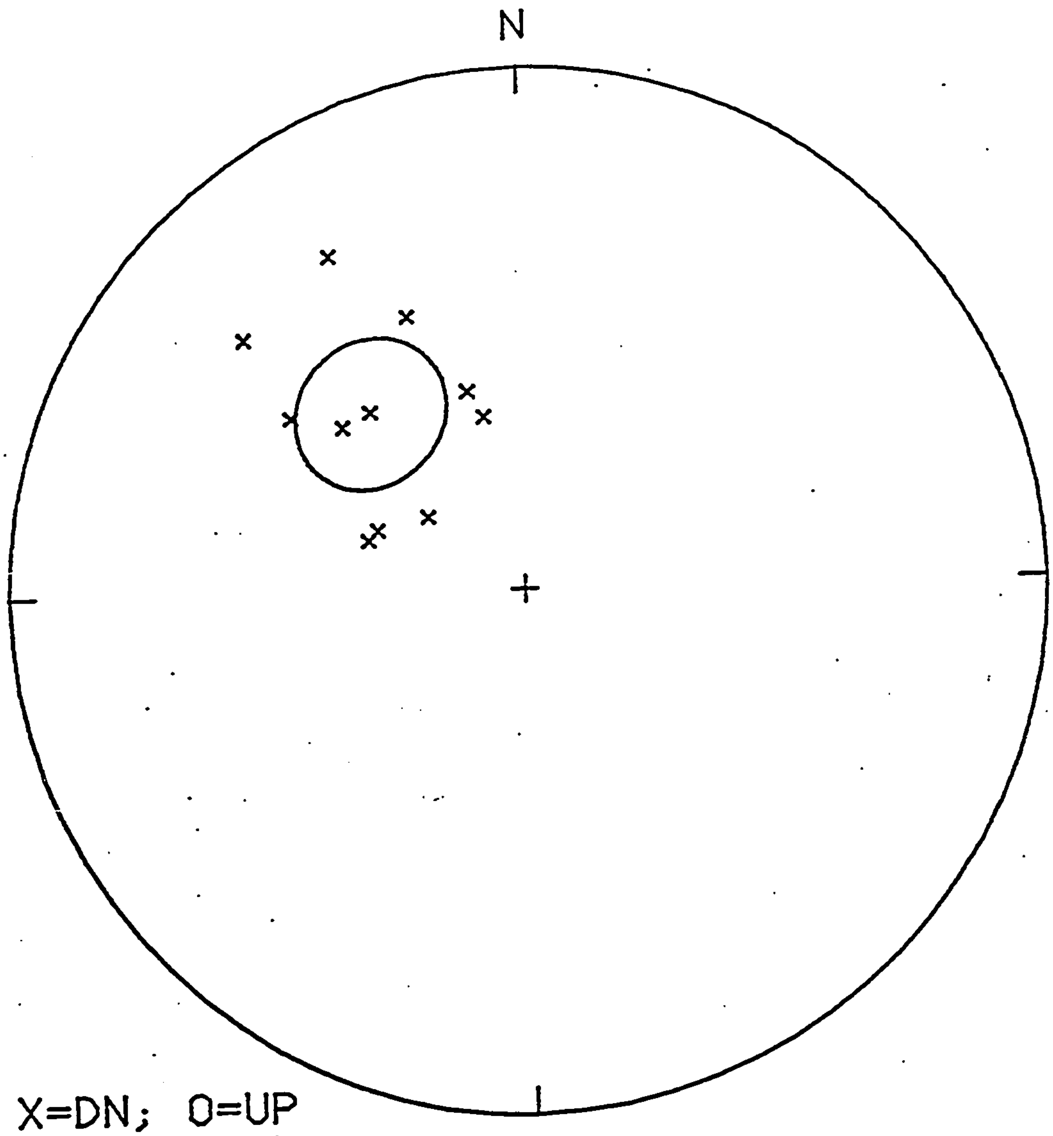


Figure G.3--Equal area plot of reverse directions from the Clark Canyon section, data obtained from straight line segments on orthogonal vector diagrams. Statistics: mean is shown as a circle of radius = alpha-95, n = 7.

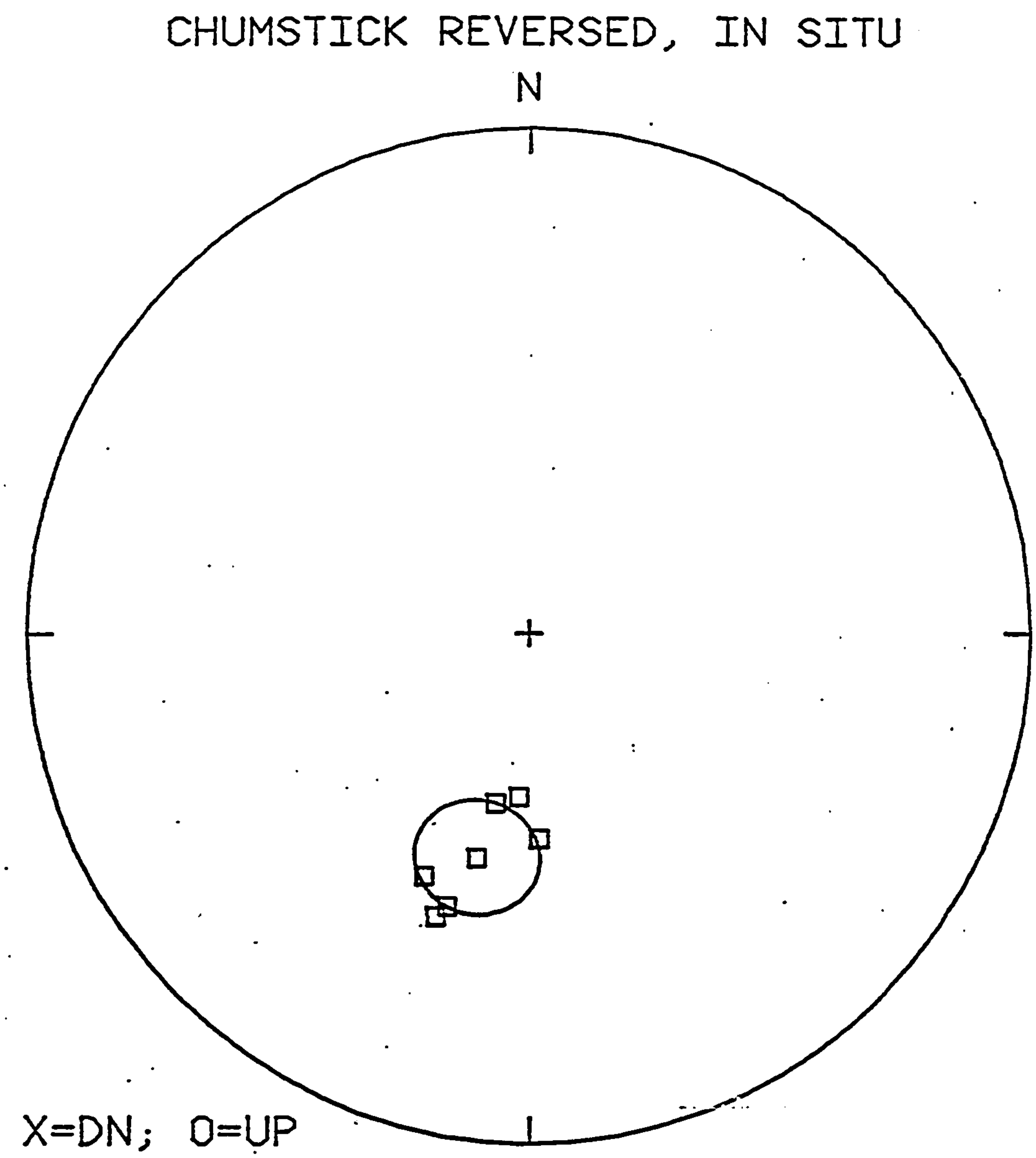

CHUMSTICK REVERSED, IN SITU
N
X=DN; O=UP

Figure G.4--Equal area plot for reverse directions in the Clark Canyon section, showing tilt correction. The reduction of dispersion suggests that this magnetization was pre-tilting.

CHUMSTICK REVERSED, CORRECTED

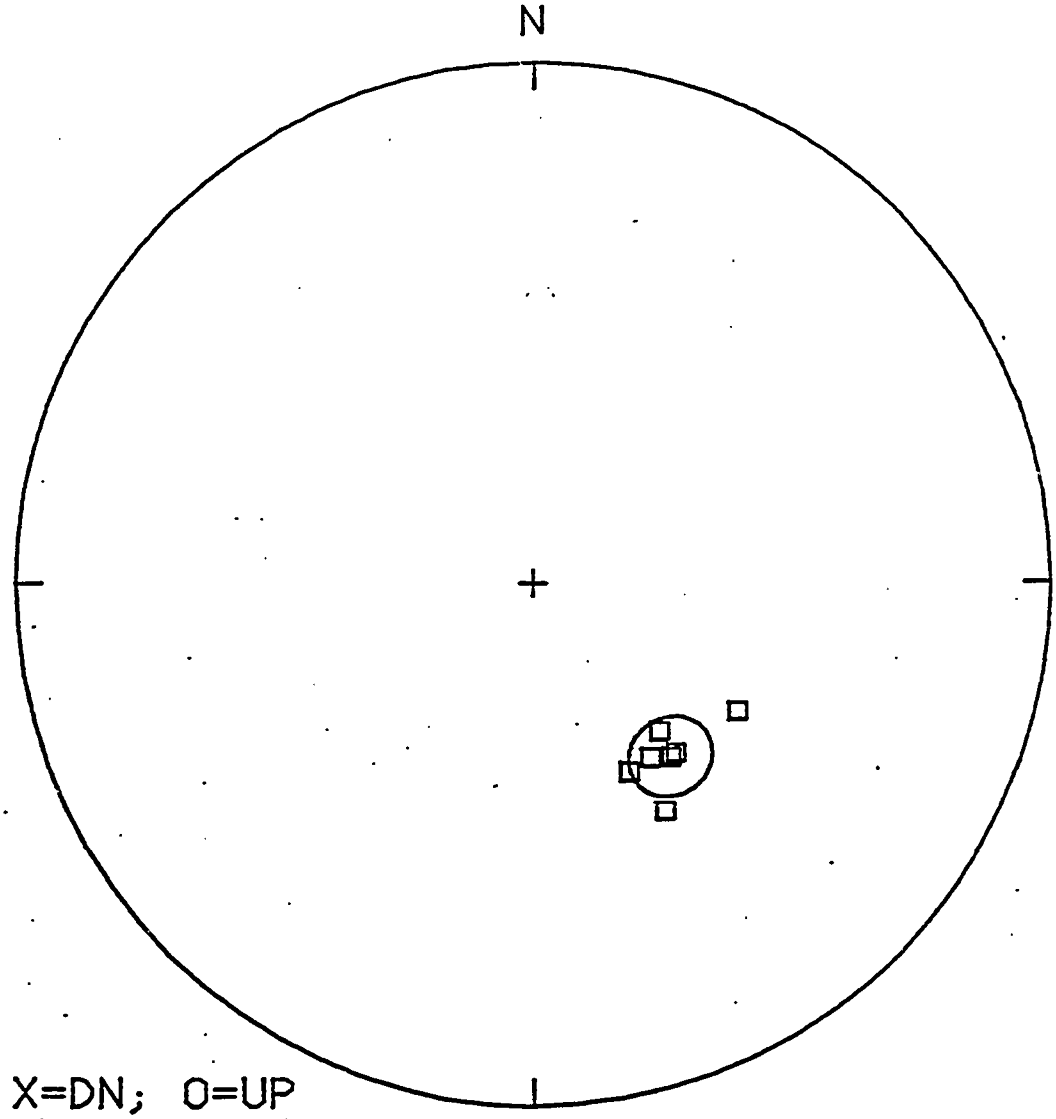


Figure G.5--Equal area plot showing data from six orthogonal vector diagrams in which straight line components can not be directly measured. Instead, a plane is fit to a portion of the vector endpoints on each orthogonal vector diagram, where each plane contains two or more vector components being removed simultaneously. The intersection of these planes in Fig. G.5 reveals a component common to all six planes (D = 320.4, I = 51.7). This component is identical to the values read directly, and shown in Fig. G.2.

CHUMSTICK GREAT CIRCLE FITS

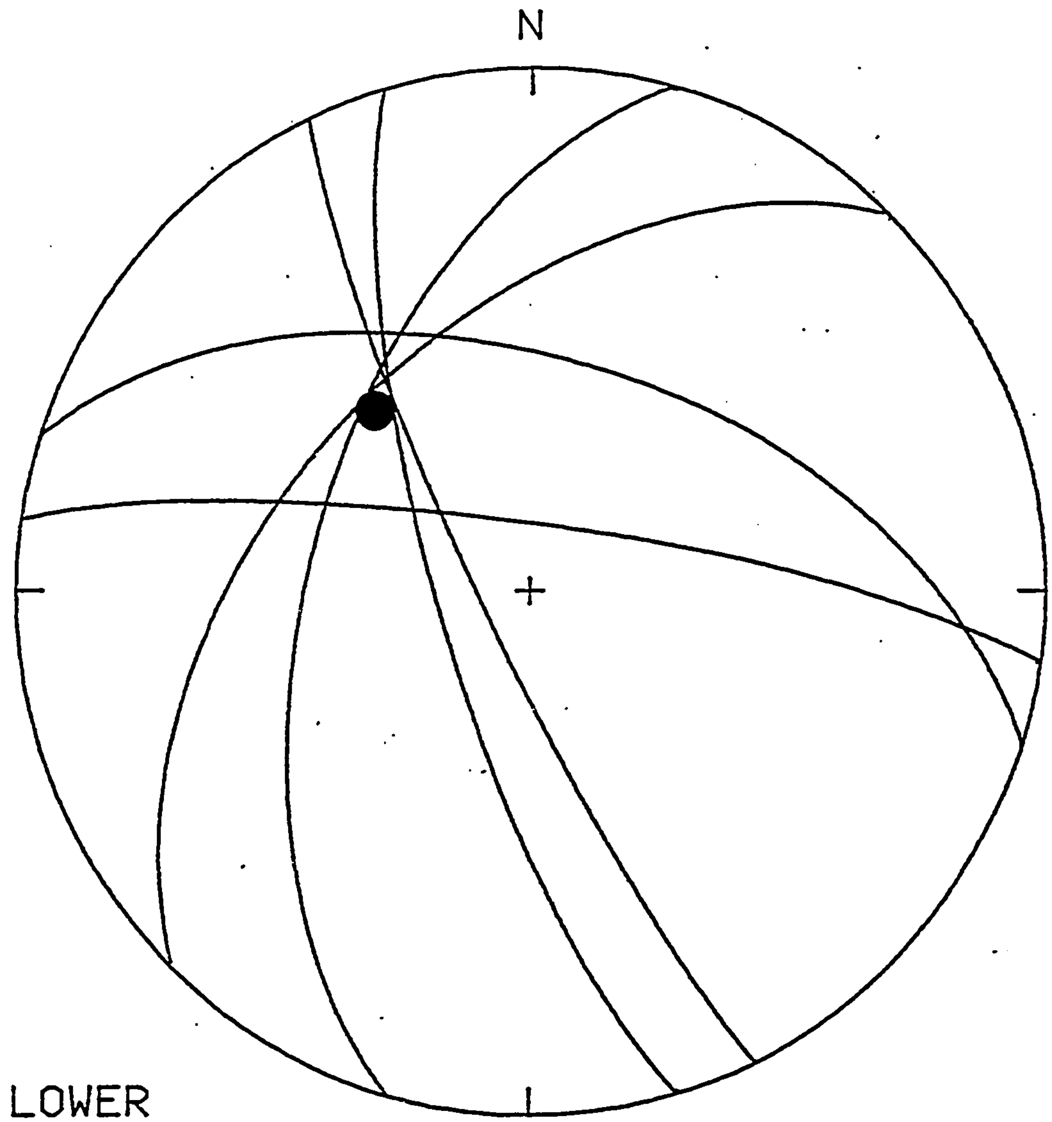
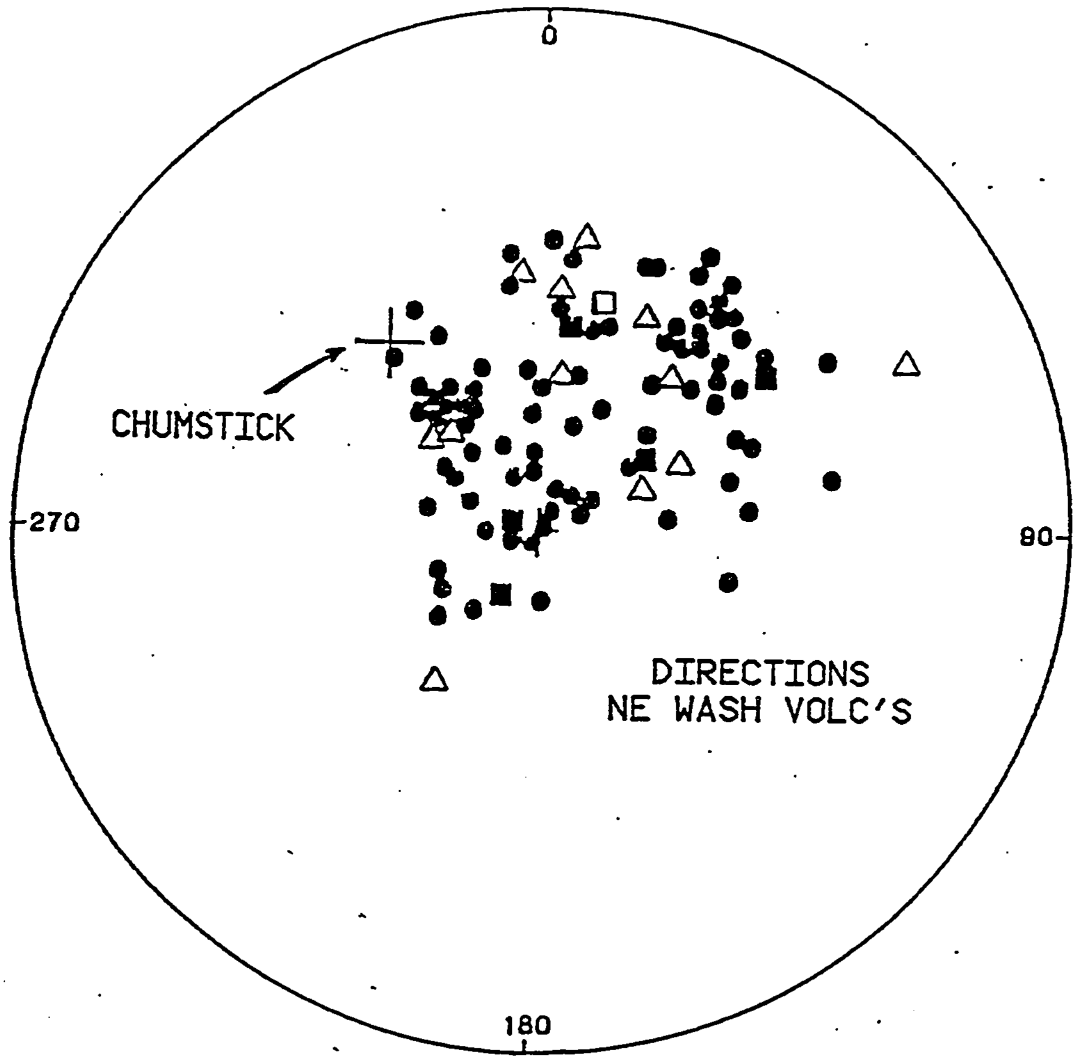


Figure G.6--Mean directions of magnetization from 102 sites of Eocene volcanic rocks of northeastern Washington (from Fox and Beck, 1985), showing the Chumstick Formation data. Abbreviations: solid symbols = normal polarity, open symbols = reverse polarity directions inverted through the center of the projection, circles = Sanpoil Volcanics, triangles = Klondike Mountain Formation, squares = O'Brien Creek Formation.


0
90
180
270
CHUMSTICK
DIRECTIONS
NE WASH VOLC'S

APPENDIX H: ORGANIC CARBON DATA

Table H.1: Organic Carbon Content of Mudrocks from the Chumstick Formation

Locality	Sample No.	Munsell Color		% TOC
No.2 Canyon	85JE136	5GY3/2	grayish olive green	0.49
Cashmere	85JE116	5Y4/2	light olive gray	1.39
Eagle Ck. Rd.	85JE147	5Y5/2	light olive gray	0.73
Eagle Ck. Rd.	85JE142	5Y5/2	light olive gray	0.22
Clark Canyon	85JE163	10GY5/2	grayish green	0.28
Clark Canyon	84CC40	5GY5/2	dusky yellow green	0.06
Clark Canyon	84CC79	5GY5/2	dusky yellow green	0.09
Peshastin	85JE110	5GY5/2	dusky yellow green	0.51
Mission Ridge	85JE127	5GY5/2	dusky yellow green	1.04
Beehive Res.Rd.	85JE130	5Y5/2	light olive gray	1.60
Camas Ck. Rd.	86JE31	5GY3/2	grayish olive green	3.58
Monitor	86JE60	5GY5/2	dusky yellow green	3.30
Monitor	86JE76	5G3/2	dusky green	5.18
Sunnyslope	85JE119	5GY3/2	grayish olive green	3.22
Sunnyslope	85JE122	N3	dark gray	5.04
Wenatchee	86JE67	5Y3/2	olive gray	3.43
South Plain	84JE19	5GY4/2	dusky yellow green	1.04
South Plain	85JE151	10Y4/2	grayish olive	0.34
Tumwater Cyn.	85JE108	N3	dark gray	3.71
Natapoc Ridge	86JE19	5Y3/2	olive gray	4.26
Cole's Corner	85JE87	5GY3/2	grayish olive green	0.21
Cole's Corner	86JE1	5GY3/2	grayish olive green	1.51
North Plain	85JE75	10GY5/2	grayish green	1.86
Fish Lake	85JE91	5G5/2	grayish green	0.21
Malaga	85JE100	5BG5/2	grayish blue-green	1.46

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Publications

Eisenreich, S.J., Hollod, G., Johnson, T.C., and Evans, J.E., 1979, Polychlorinated biphenyl and other micro-contaminant--sediment interactions in Lake Superior, _in_ R.A. Baker, editor, _Contaminants in Sediments_, v.1, Ann Arbor Science Publishing Company, Ann Arbor, Michigan, p. 67-94.

Johnson, T.C., Carlson, T., and Evans, J.E., 1980, Contourites in Lake Superior: Geology, v.8, p. 437-441.

Evans, J.E., Johnson, T.C., Alexander, E.C., Jr., and Lively, R.S., 1981, Sedimentation rates and depositional processes in Lake Superior using Pb-210 geochronology: Journal of Great Lakes Research, v.7, p. 299-310.

Johnson, T.C., Evans, J.E., and Eisenreich, S.J., 1982, Total organic carbon in Lake Superior sediments: comparison with hemipelagic and pelagic marine environments: Limnology and Oceanography, v.27, p. 481-491.