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PETROLOGY AND STRATIGRAPHY OF PALEOGENE NONMARINE SANDSTONES, CASCADE RANGE, WASHINGTON

by

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This report is preliminary and
has not been edited or reviewed
for conformity with Geological
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ABSTRACT

The Cascade Range of Washington north of 47° latitude is composed of probable Paleozoic and Mesozoic metamorphic rocks and Mesozoic and Tertiary plutonic rocks. Several Paleogene nonmarine arkosic sandstone units fringe and in part occur within the complex crystalline core.

The early to middle Eocene Chuckanut Formation is present on the west side of the crystalline core in the western foothills of the Cascades. The early to middle Eocene Swauk Formation partially encircles the Mt. Stuart massif of the central Cascades. In the western foothills of the Cascades, between the main body of Chuckanut Formation near Bellingham and the main outcrop area of the Swauk Formation south of Mt. Stuart, many smaller bodies of arkosic sandstone have variously been referred to either the Swauk or Chuckanut Formations. The early Eocene Manastash Formation occurs locally in an area south of the Yakima River. The middle to late Eocene Chumstick Formation is mostly confined to the Chiwaukum graben within the crystalline core and is separated from the Swauk Formation on the southwest by the Leavenworth Fault. The Oligocene Wenatchee Formation unconformably overlies the Chumstick Formation near Wenatchee. The middle to late Eocene Roslyn Formation crops out north of the Yakima River and is underlain by the Teanaway Basalt which separates the Roslyn from the older Swauk Formation. The middle Eocene to early Oligocene Naches Formation forms a north-trending body that crosses the Yakima River and is in fault contact with both the Swauk and Manastash Formations. The middle to late Eocene Puget Group underlies the Quaternary deposits of the Puget Lowland southeast of Seattle on the western flank of the Cascades.

The various formations are all composed predominantly of fine- to medium-grained sandstones with lesser amounts of interbedded shale, conglomerate and coal. Compositionally, the units are predominantly either feldspathic or litho-feldspathic subquartzose sandstones. Volcanic rocks are important constituents of the Puget Group, the Chumstick and Naches Formations, and the isolated arkosic bodies. The three older units, however, contain relatively less volcanic lithics to total lithics than do younger units, indicating perhaps the initiation of more widespread volcanic activity in middle Eocene time. Ratios of framework grain parameters show that the terrestrial sandstone units were derived from a mixed plutonic and tectonic source terrane of continental block tectonic provenance with an overprint of magmatic arc provenance.

Modal analysis was performed on samples from the various sedimentary units to establish petrologic compositions, and to provide data with which to compare the different units and discuss clast provenance and tectonic regimen. Although the arkosic sandstones have generally uniform framework clast compositions, minor yet significant differences do exist between the units. Basal or basement-onlap portions of the units in particular are locally derived and differ markedly from the overall compositions of the individual units.

Many coincidences of composition, age, structure, and bedrock indicate that the Chuckanut and Swauk may have originally been deposited as a single unit that since has been offset approximately 160 kilometers by right lateral strike slip motion starting about 48 Ma. If this hypothetical offset did occur, then major movement on the Straight Creek Fault is bracketed between about 48 Ma and Oligocene time.

INTRODUCTION

The Cascade Range north of 47° latitude is composed of probable Paleozoic and Mesozoic metamorphic rocks and Mesozoic and Tertiary plutonic rocks, locally overlain by Tertiary sedimentary and volcanic rocks (Figures 1 and 2) (Misch, 1966; and McKee, 1974). Several Paleogene nonmarine arkosic sandstone units fringe and in part occur within the complex crystalline core. The fascinating problems of the basement terrane of the Cascade Range have, for the most part, long lured geologists past the outcrops of the Paleogene sandstone that fringe it. Although some workers, primarily from the University of Washington, have studied and established stratigraphic relationship between the units as part of various mapping projects, few attempts have been made to correlate all the units or describe in detail the composition of these geographically separated sandstone units.

In this thesis, using data derived from the literature, and from field work, and fission track and potassium argon ages, I describe and correlate the sandstone units. I also present detrital modal data with which I compare the different units and discuss clast provenance and tectonic regimen.

The research stems from an ongoing U.S. Geological Survey mapping project in the area covered by the Wenatchee 2° sheet (120-122 W, 47-48 N). The goal of the project is to enlarge the body of knowledge of the local stratigraphy and structural features, particularly for the Tertiary.

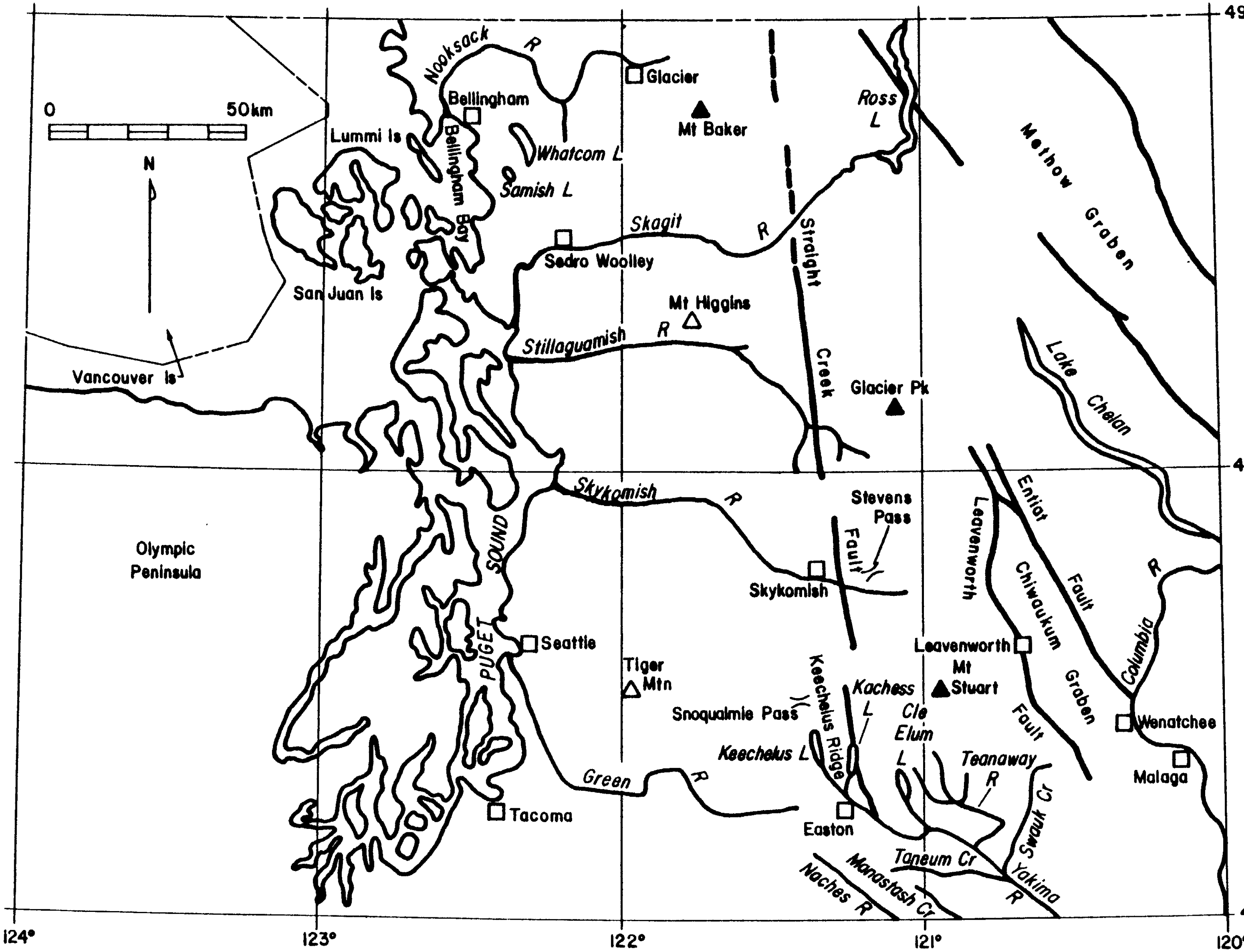


Figure 1. Map with place names for northwest Washington.

REGIONAL GEOLOGY AND TECTONIC SETTING

Regional Geology

The pre-Tertiary crystalline core of the Cascades is a complex collage of variously aged rocks and associations of rocks which formed in different locations both environmentally and geographically, and which have been juxtaposed by poorly understood mechanisms. Misch (1966) outlined the rock units and the basic relationships between them, and several recent workers have summarized, with varying emphasis, the regional geology including Davis (1977) and Davis, Monger, and Burchfiel (1978). I have drawn heavily from these and other sources to summarize the regional geology (Figure 2).

Pre-Tertiary Stratigraphy of Selected Geological Units

The north Cascades and adjoining western foothills are divided by the Straight Creek Fault into two differing, but equally complex terranes. East of this major north-south trending fault, the terrane is predominantly underlain by the Skagit Metamorphic Suite (Misch, 1966). This unit consists of upper Paleozoic to lower Mesozoic strata metamorphosed before the middle Cretaceous according to Misch (1966, p. 113), but Pb-u and Pb-Pb dates derived from the Skagit Gneiss by Mattinson (1972, p. 3778-3779) indicate the metamorphism may be as young as Middle or Late Cretaceous. The migmatitic Skagit Gneiss (Misch, 1966) predominates and contains concordont remnants of the Cascade River Schist (Misch, 1966), made up of isochemical metasedimentary rocks with subordinate volcanic rocks and carbonates that were subjected to Barrovian type metamorphism.

The Chiwaukum Schist of Page (1939), roughly correlatable with parts of the Skagit Metamorphic Suite of Misch (1966), crops out north

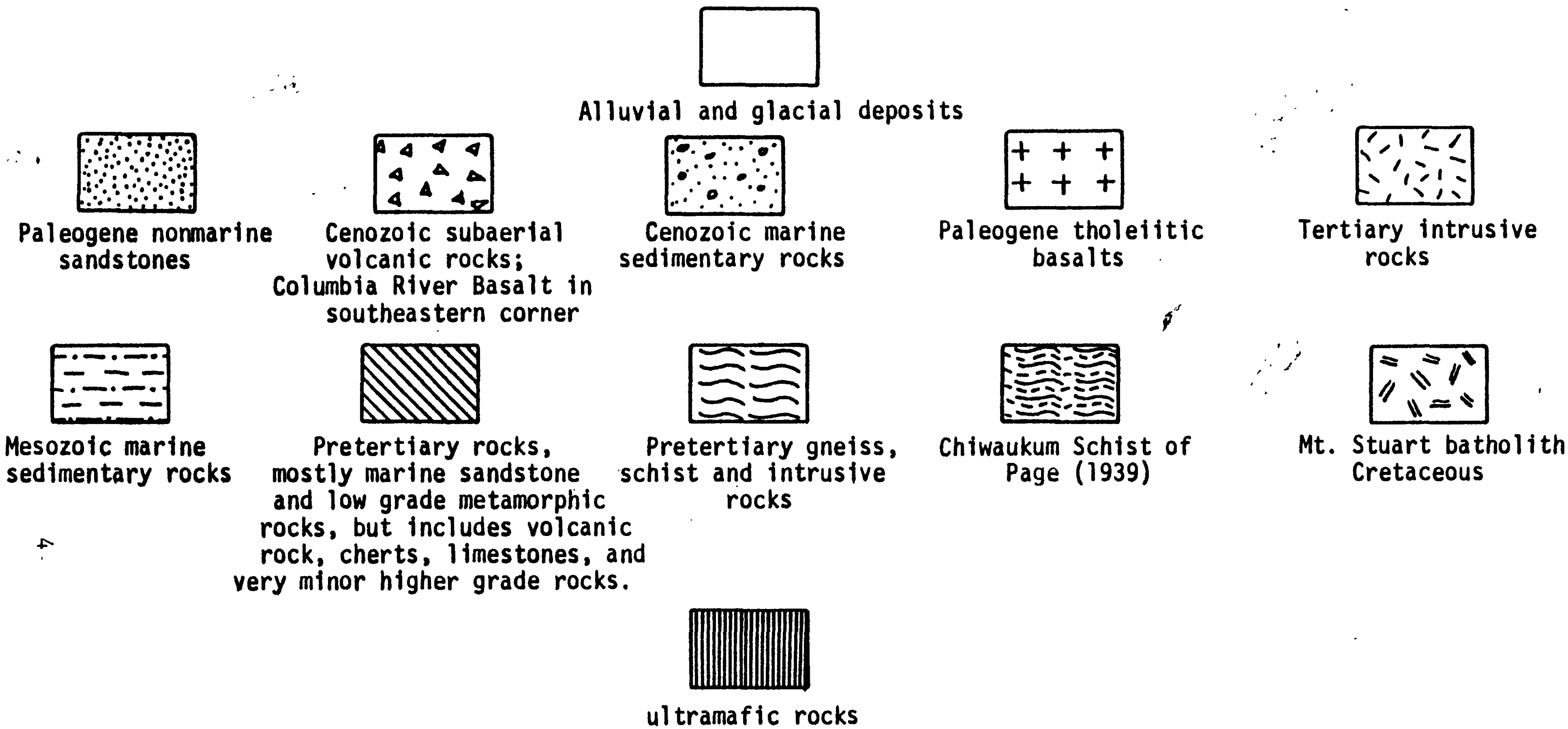
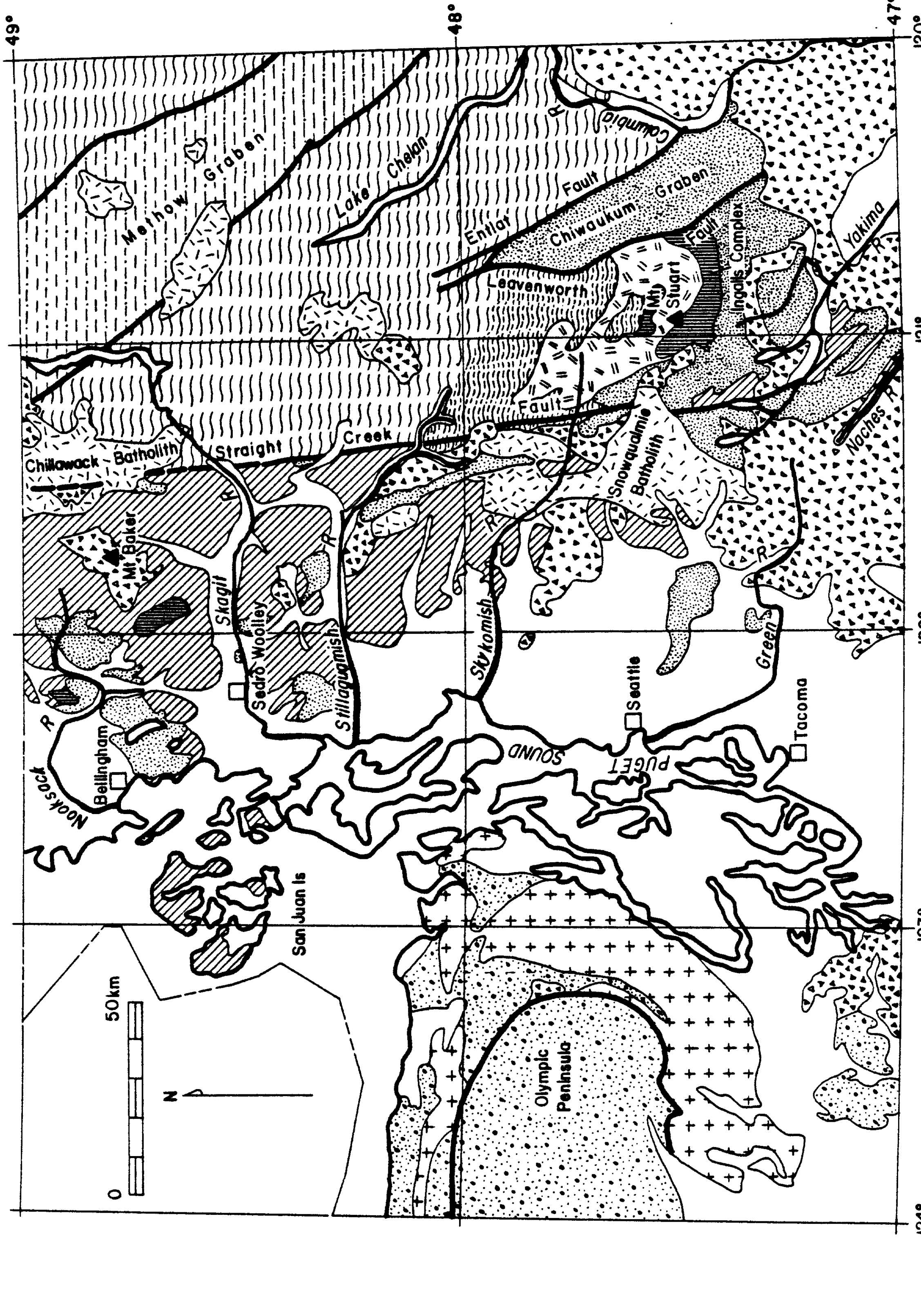


Figure 2. Sketch map showing generalized geology of northwestern Washington.


49°
48°
47°
120°
121°
122°
123°
124°
Methow Graben
Lake Chelan
Entiat Fault
Chiwaukum Graben
Columbia
R
Leavenworth
Fault
Mt Stuart
Ingalls Complex
Yakima
R
Naches
R
Straight Creek
Fault
Chillawack Batholith
Snoqualmie Batholith
Mt Baker
Skagit
R
Sedro Woolley
Stillaguamish
R
Skykomish
R
Seattle
Green
R
Tacoma
PUGET SOUND
Bellingham
Nooksack
R
San Juan Is
Olympic Peninsula
0
50 km
N

of Mt. Stuart. These isochemical and allochemical metasedimentary rocks (commonly kyanite, staurolite, and garnet bearing quartz biotite schists) and minor metavolcanic rocks (amphibolite, hornblende gneiss) were intruded by synkinematic quartz diorite stocks (Van Diver, 1964 and Getsinger, 1978). A sequence of Lower Jurassic through Upper Cretaceous marine sandstone, shale, and conglomerate occupy the Methow graben east of the schists and gneisses (Tennyson and Cole, 1978, p. 499-508).

West of the Straight Creek Fault heterogeneous pre-Tertiary rocks ranging in age from Precambrian to lower Cretaceous have been grouped into four units separated by thrust faults of middle to late Cretaceous age (Misch, 1966). The upper Jurassic and lower Cretaceous Nooksack Formation is stratigraphically the youngest and structurally the lowest unit. The Nooksack consists of marine volcanic sandstone, siltstone, subordinate conglomerate with minor intercalations of dacitic volcanic rocks (Misch, 1978).

The Church Mountain thrust separates the Nooksack Formation from two overlying but older units, the Yellow Aster Complex and the Chilliwack Group. The Yellow Aster Complex consists of Precambrian and lower Paleozoic metaplutonic rocks representative of continental crust (Misch, 1966, and 1978 p. 3; Mattinson, 1972). The Chilliwack Group (named in Canada by Daly, 1912) is a mixed assemblage including clastic sedimentary, volcanic sedimentary, and pyroclastic rocks, volcanic rocks, ribbon cherts, and limestone. Limestone yields fossils ranging in age from Devonian to Triassic (Danner, 1966 p. 71; Evans and Savage, 1979 p. 77). The Trafton Group (Danner, 1966, p. 68, and 1977, p. 497) contains Permian fossils with Tethyan affinity, indicating to Danner (1977 p. 500) that the rocks originated in a Paleozoic ocean and did not become part of North America until at least mid-Mesozoic. The relationship of the Trafton Group to the thrusts is poorly understood.

The Shuksan thrust separates the Yellow Aster Complex and Chilliwack Group from the overlying Shuskan Metamorphic Suite of Misch (1966 p. 109). This suite is composed of metaclastic rocks, the Darrington Phyllite of Misch (1966), overlain by metabasaltic rocks, the Shuksan Greenschist of Misch, (1966). Phyllites, greenschist, and blue amphibole schist were first described by Smith (1904 p. 3) near Easton on the Yakima River. From there they occur in a discontinuous belt stretching to the Canadian border, but the outcrops of the blue schist near Easton along Lake Kachess are the only ones east of the Straight Creek Fault.

The San Juan Islands, located between the North Cascades, Vancouver Island, and the Olympic Peninsula, are made of five thrust bounded terranes consisting predominantly of Mesozoic age rocks that were tectonically juxtaposed in post mid Cretaceous time (Whetten and others, 1978, and Whetten and others, in press). See Vance (1975 and 1977) for a different approach to the geology of the San Juan Islands. Thrust faults dip to the east. The westernmost terrane and structurally the lowest, contains rocks ranging in age from probable Pre-Cambrian through Jurassic (Whetten and others, 1978, p. 123). On the basis of faunal affinity, Danner (1966) considered part of the Permian limestones as Tethyan, and more recently stated that they are allochthonous to North America (Danner, 1977, p. 500).

Whetten and others (in press) hypothesize that an extensive thrust (the Haystack thrust) marks the base of a dismembered Jurassic ophiolite and infer that the klippen stretches from the southeastern San Juan

Islands nearly to the Straight Creek Fault bordered on the south by the Oligocene Devil's Mountain Fault. They consider it the structurally highest thrust to have occurred during the period of thrusting that produced the Church Mountain and Shuksan thrusts. Whetten and others (in press) consider the Ingalls Complex of Frost (1973), a late Jurassic dismembered ophiolite adjacent to Mt. Stuart on the east side of the Straight Creek Fault, a possible outlier of the Haystack thrust.

Overlying the five terranes described by Whetten and his colleagues and stacked together by a sequence of south dipping imbricate thrusts are three well bedded and relatively undeformed sedimentary units (Johnson, 1979; Vance, 1977; Cowan and Whetten, 1977; and Whetten and others, 1978) that from south to north, are structurally lower and stratigraphically higher in the section. These include, from structurally highest to lowest, the upper Triassic Haro Formation and the upper Jurassic to lower Cretaceous Spieden Formation which are mainly volcaniclastic rocks deposited in mixed shallow marine environments adjacent to a nearby volcanic source terrane (Johnson, 1979). While no suitable source terrane is known for the Haro, appropriate source rocks were available for the Spieden (Johnson, 1979). The upper Cretaceous Haslam Formation of the Nanaimo Group is composed of conglomerate and sandstone of mixed provenance. The rocks include clasts of volcanic rock, intrusive rock, chert, and sandstone, indicating that the San Juan Islands, the Coast Mountains of British Columbia, and possibly the western North Cascades may have been the source terrane (Johnson, 1979).

Vancouver Island is west of the San Juan Islands and is composed predominantly of a thick pile of middle to upper Triassic basaltic rocks that overlie middle Triassic shales which in turn overlie late Paleozoic carbonates. The basaltic rocks are overlain by upper Triassic carbonates, completing a sequence that is more or less repeated at four other west coast localities and named Wrangellia by Jones, Silberling, and Hillhouse (1977). These workers consider Wrangellia an allochthonous terrain which formed at low paleolatitudes (within 15 of the paleo equator) that was juxtaposed by late Jurassic to mid Cretaceous against dissimilar Triassic rock more closely tied to North America.

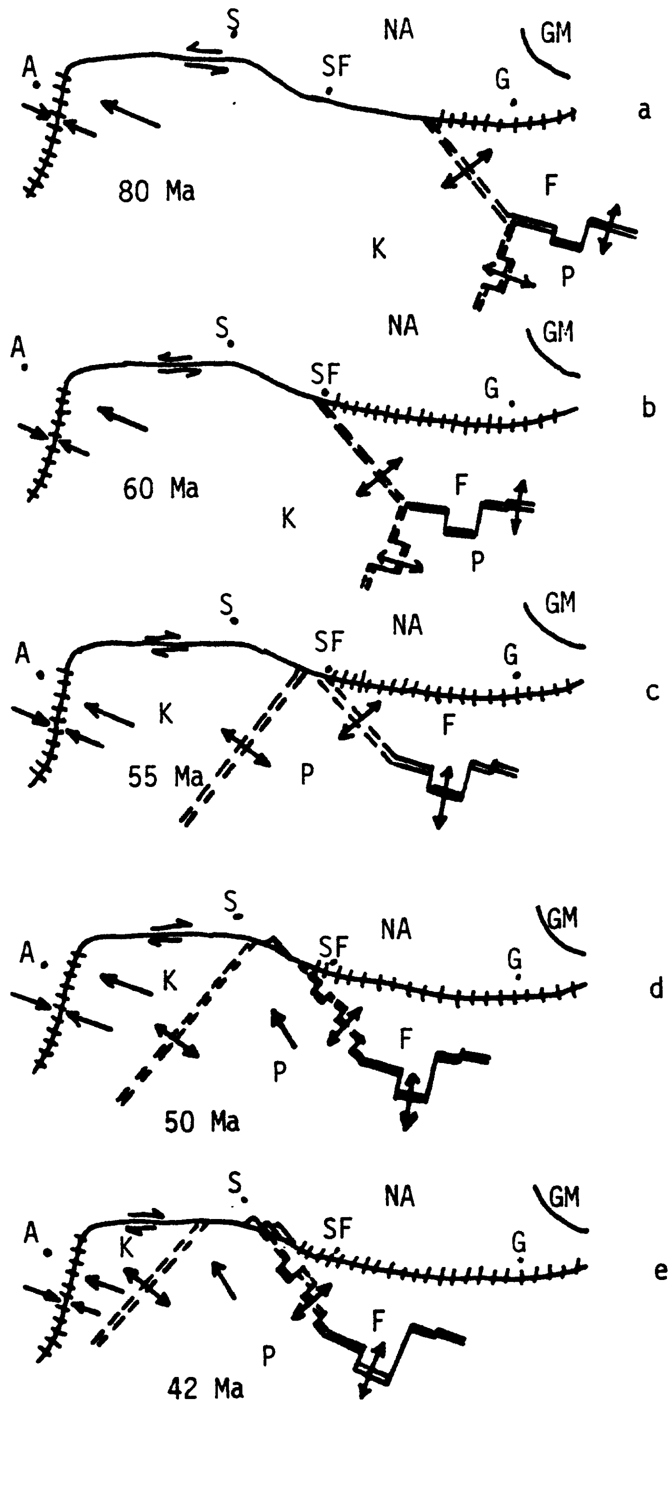
The Olympic Peninsula is south of Vancouver Island and subequal in size to it and the North Cascades. The peninsula is predominantly made of two geologic terranes (Tabor and Cady, 1978); peripheral rocks consist predominantly of tholeiitic basalts of the early and middle Eocene Crescent Formation of Brown, Gower, and Snavely (1960) and intercalated deep-water clastic deposits overlain by upper Eocene to Miocene marine sedimentary rocks of marginal basin facies (P. Snavely, pers. commun., 1979) that form a horseshoelike belt surrounding the core on three sides. These intercalated sedimentary rocks include clasts of continental affinity that indicate to Cady (1975, p. 57) a close proximity to North America at time of deposition.

The core consists of bathyal marine turbidite deposits of Eocene to Oligocene age that show various amounts of disruption, ranging from coherent blocks in a broken formation to completely disrupted melanges. The combination of oceanic basalts and melange-like rocks suggest "that the core rocks were emplaced during subduction of oceanic lithosphere" (Tabor and Cady, 1978, p. 3, and others cited therein).

Plate Tectonic Setting

Evolution of plate geometry back to the late Cretaceous can be deduced from magnetic lineations in the ocean floor, ages of the lineations, and extrapolation of rates and directions of current plate movement. Coney (1978) and Dickinson (1979 and 1976), using data about these oceanic events and features from Larson and Pitman (1972) and Cooper and others (1976), among others, have synthesized a model for the tectonic setting adjacent to North America from Late Cretaceous to present. In their model, an 80 Ma plate configuration (Figure 3, a) involves subduction at a Farallon-North American trench extending from Mesoamerica to Alaska and a Kula-Farallon spreading center stretching from the mid Pacific to a position near the present Aleutian Trench. A late Cretaceous magmatic arc is inferred to have been present, the front of which stretched from northwestern to southeastern Washington (Snyder and others, 1976, fig. 2). Dickinson (1976, p. 1278) considers the Nanaimo basin a fore-arc basin adjacent to the arc. Between 80 and 40 Ma subduction continued with the Kula plate being consumed at the Aleutian Trench (DeLong and others, 1978). At about 55 Ma the Kula-Pacific Ridge probably ceased spreading (Byrne, 1978) thus, enlarging the Pacific plate (Figure 3, b). The magmatic arc widened in early Tertiary, and by late Eocene it included most of the area between the present Cascade Range of Washington through central Montana, with the Chuckanut, Swauk, and associated sandstone units representing terrestrial fore-arc basins. A subduction zone is inferred to lie along the Willamette Valley--Puget Sound trend east of the lower to middle Eocene basalts and associated sediments of the continental borderland (Dickinson, 1976, p. 1279-1280).

Figure 3. Inferred plate configuration for Late Cretaceous and early Tertiary. Initials are: G, Guaymas; SF, San Francisco; S, Seattle; A, Anchorage; GM, Gulf of Mexico; NA, North America plate; F, Farallon Plate; P, Pacific Plate; K, Kula Plate. Single lines are transform faults; double lines are spreading centers; and hatched lines are subduction zones. Figure modified after Dickinson (1979, Figure 1) and Coney (1979, Figure 2-4).

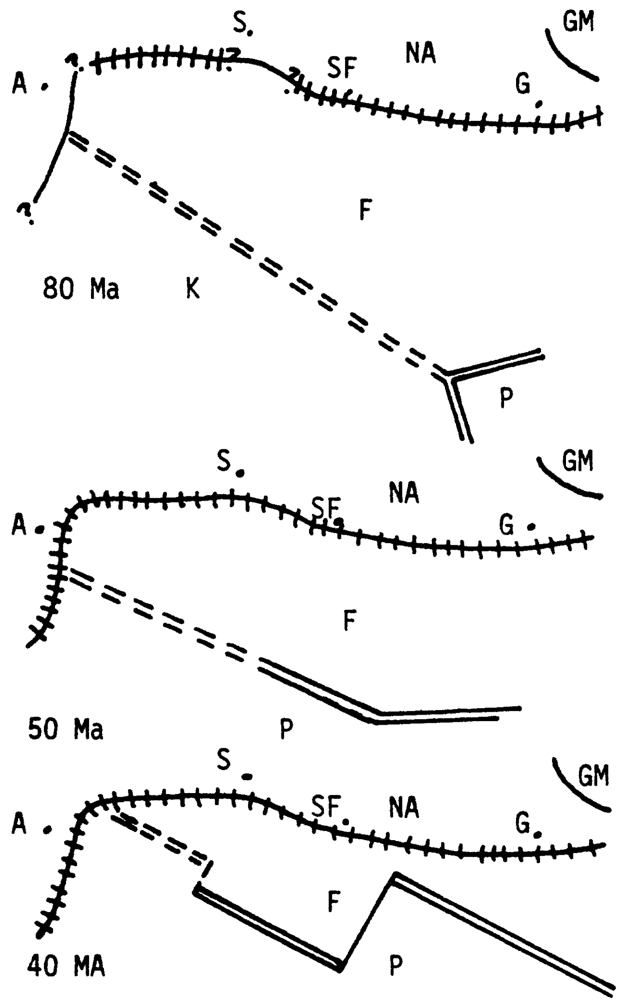


S
NA
GM
A
SF
G
a
80 Ma
F
K
P
S
NA
GM
A
SF
G
b
60 Ma
F
K
P
S
GM
NA
SF
A
G
c
K
F
55 Ma
P
S
NA
GM
A
SF
G
d
K
F
P
50 Ma
S
NA
GM
A
SF
G
e
K
F
P
42 Ma

Starting in late Eocene the magmatic arc narrowed and occupied a position colinear with the trend of the present Cascades with various amounts of apparent seaward and landward migration of its axis through time (Dickinson, 1976, p. 1281). Throughout the period 80 to 40 Ma the vector of convergence of the Farallon plate to the American Plate was oriented obliquely to the North American margin, and involved a prominent component of dextral strike slip motion (Dickinson, 1979, p. 3).

In a currently evolving manuscript Kenneth Fox (written commun., 1979) has produced a synthesis of the plate tectonic setting adjacent to North America from the late Cretaceous (Figure 4, a) to the present that is at variance with the one proposed by Coney and Dickinson. Hopefully without damaging the threads of logic, I present a summary of his ideas. Fox, synthesizing published data of others with his own ideas, states that in early Tertiary (Figure 4, b) time the Kula, Farallon, and Pacific plates were joined at a triple junction that consisted of three spreading ridges from which the respective plate grew (Pitman and Hayes, 1968). The Kula and Farallon plates flanked the North American plate (Grow and Atwater, 1970, and McKenzie and Morgan, 1969); and all three oceanic plates moved right laterally past the North American plate, while at the same time moving in various directions with respect to each other. The union of the North American, the Kula and the Farallon plates was a Humboldt type triple junction (Fox, 1976) consisting of a transform fault (NA-K), a spreading ridge (K-F), and an oblique subduction zone (F-NA) (Atwater, 1970, Fig. 18). This regime continued until about 55 Ma (Figure 4, c) at which time the Kula-Pacific ridge jumped northward Fox prefers the "jump" for structural reasons, others

Figure 4. Hypothesized Late Cretaceous and early Tertiary plate geometry. Initials and symbols same as Figure 3. Figure after Atwater (1970), and Fox (written commun., 1979).


S
GM
NA
SF
A
G
a
F
80 Ma
K
P
S
GM
NA
SF
A
G
b
F
50 Ma
P
S
GM
SF
NA
A
G
F
c
40 MA
P

favor the ridge simply vanishing (Byrne, 1976, p. 98 and Anonymous, 1978).

The portion of the Kula plate that became "attached" to the Pacific Plate subsequent to the possible jump in the Kula-Pacific ridge presumably would have to adjust to the inertia of the Pacific plate. While the relative motion between the Kula and North America plate previous to the jump may have been strike slip as assumed by Atwater (1970, p. 3531), Fox suggests that because the Pacific and North American plates were not in mutual contact, they could have had convergent paths. Assuming that the North American and Pacific Plates were convergent implies that the new amalgamated super-Pacific plate would impinge on North America ("side swipe" is Fox's term) prior to deflection caused by the impact and the subsequent adjustment to motions paralleling their bounding transform faults (Figure 4, d). Because of the physical properties of the plates and the distances involved the causal action (in this case, the ridge jump) may preceed the effect (impingement on North America) by several millions of years. Fox suggests that the 42 Ma path change relative to the Hawaian hot spot (Dalrymple and Clague, 1976) marks the end of that period of convergence and collision between the North American and Pacific plates (Figure 4, e). In the meantime, all oceanic plates continued to move north relative to North America, and the subduction zone between the Farallon and North American plates continued to grow in length.

Although they were derived from a more or less similar data set, the models presented above start with two opposing tectonic settings at 80 Ma. The problem is that enough degrees of freedom exist in the data that neither model can be discounted (A. K. Cooper, personal communication, 1979). The model by Fox is appealing because it supplies tectonic regimens that could have been responsible for temporally related events on land.

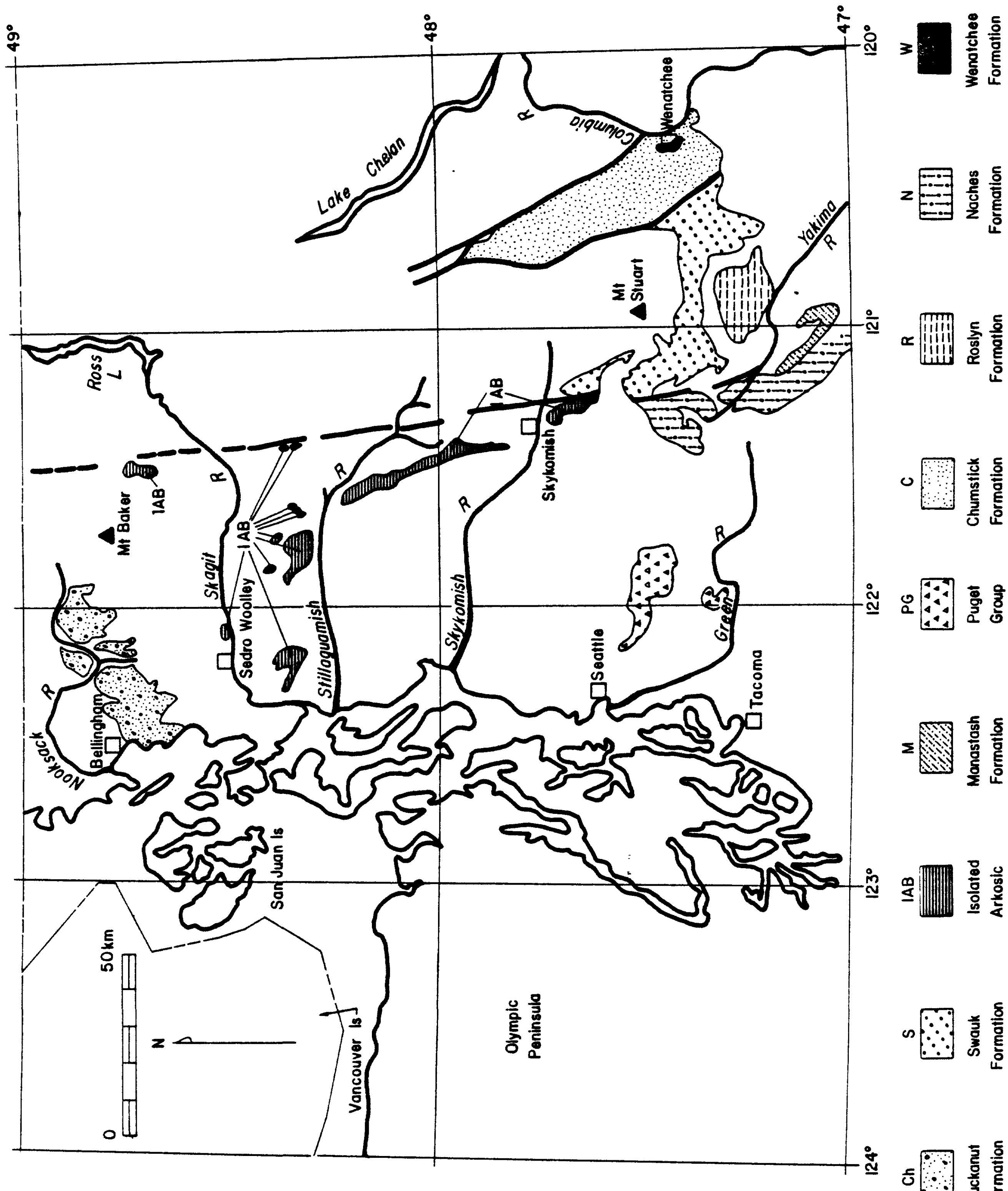
STRATIGRAPHIC UNITS

Introduction to Stratigraphic Units

The Chuckanut Formation is present on the west side of the crystalline core in the western foothills of the Cascades (Figure 5). The Swauk Formation partially encircles the Mt. Stuart massif on the south. In the western foothills of the Cascades, between the main body of Chuckanut Formation near Bellingham and the main outcrop area of the Swauk Formation south of Mt. Stuart, are many smaller bodies of arkosic sandstone which have variously been referred to as either Swauk or Chuckanut. For convenience and because the affinity of some of these bodies is questionable, they are here referred to informally as isolated arkosic bodies and are treated separately. The Manastash Formation is isolated in an area south of the Yakima River. The Chumstick Formation is mostly confined to the intracrystalline core Chiwaukum graben and is separated from the Swauk Formation on the southwest by the Leavenworth Fault. The Wenatchee Formation unconformably overlies the Chumstick Formation near Wenatchee. The Roslyn Formation crops out north of the Yakima River and is underlain by the Teanaway Basalt which separates the Roslyn for the older Swauk Formation. The Naches Formation forms a north-trending body of rock that crosses the Yakima River and is in fault contact with both the Swauk and Manastash Formations. The Puget Group underlies the Quaternary deposits of the Puget Lowland southeast of Seattle.

The arkosic sandstone units are all predominantly composed of fine- to medium-grained sandstone with lesser amounts of interbedded shale, conglomerate and coal. Volcanic rocks are important constituents of the Puget Group and Naches Formations.

Figure 5. Map showing generalized outcrop pattern for nonmarine Paleogene sandstone units in Washington. Ch, Chuckanut Formation; S, Swauk Formation; IAB, Isolated Arkosic Bodies; M, Manastash Formation; PG, Puget Group; C, Chumstick Formation; R, Roslyn Formation; N, Naches Formation; W, Wenatchee Formation.



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Because of early reconnaissance work (Willis, 1886; White, 1888; Russell, 1893, 1900), the existence of all the units was known by the turn of the century.

Chuckanut Formation

McLellan (1927, p. 136) named the Chuckanut Formation for rocks "occurring on the northern part of Lummi Island and in the vicinity of Bellingham Bay." Although McLellan described no stratigraphic section, he indicated that the rocks were well exposed along Chuckanut Drive, a roadway cut into the seacliff south of Bellingham.

Glover (1935) measured two sections in the Chuckanut Formation, one referred to by McLellan along Chuckanut Drive and the other along the west side of Lake Whatcom. Based on his measured sections and their relationship to the overlying Bellingham Coal Bed, Glover estimated that the total probable thickness of the Chuckanut was in excess of 16,000 feet; this estimate was supported by Miller and Misch (1963, p. 170), who estimated 15,000 to 20,000 feet of section east of the American Sumas Mountains. Glover's measured sections indicate that more than 80 percent of the Chuckanut Formation is sandstone, 10 to 20 percent is shale, and 1 to 2 percent is conglomerate (it is important to note that both sections are half concealed). Other than the coal beds, no internal marker beds are known to exist in the Chuckanut, and no subdivisions have been made within the formation.

An early study of the fossil flora present in the Chuckanut Formation lead Knowlton (in Smith and Calkins (1904), p. 34, 97) to continue a correlation with the Puget Formation, which was then considered Eocene in age. (The term Paleocene had not yet come into common use). Pabst (in Miller and Misch, 1963, p. 170) identified a

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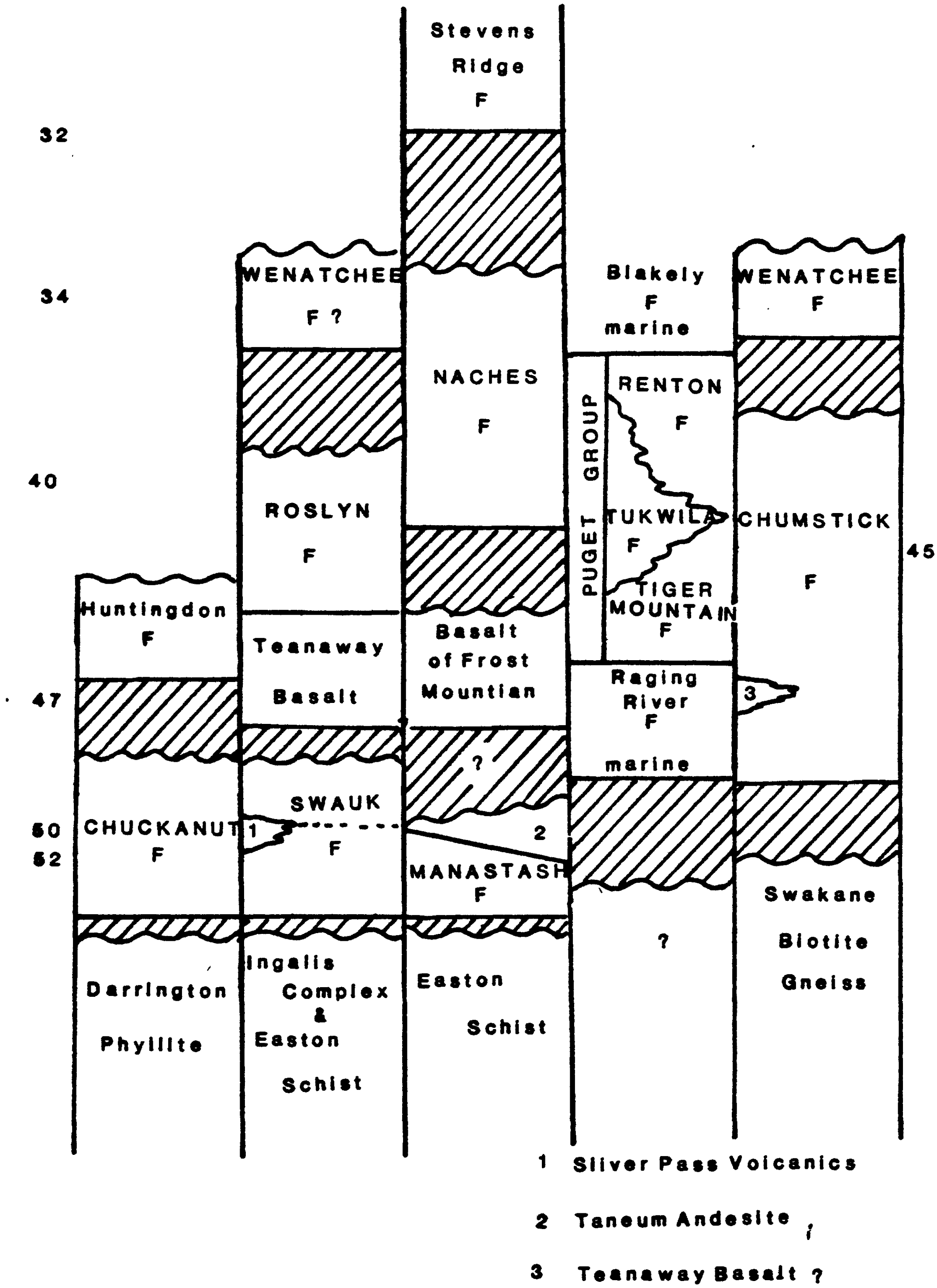
Figure 6. Correlation chart for Paleogene nonmarine arkoses and related rocks, Washington.


Stevens Ridge F
32
34
40
47
50
52
45
WENATCHEE F ?
Blakely F marine
WENATCHEE F
NACHES F
RENTON F
PUGET GROUP
ROSLYN F
TUKWILA F
TIGER MOUNTAIN F
CHUMSTICK F
Huntingdon F
Teanaway Basalt
Basalt of Frost Mountian
Raging River F marine
SWAUK F
CHUCKANUT F
MANASTASH F
Swakane Biotite Gneiss
Darrington Phyllite
Ingalls Complex & Easton Schist
Easton Schist
1 Silver Pass Volcanics
2 Taneum Andesite
3 Teanaway Basalt ?

flora collected by Misch from the base of the unit near Glacier as Upper Cretaceous. More recently, Griggs (1970), on the basis of palynomorphs, assigned an age of Late Cretaceous to early Eocene to the lower half of the Chuckanut Formation along Chuckanut Drive.

Zircons separated from a rhyolitic clast collected by John Whetten from a conglomerate bed near the top of Glover's Chuckanut Drive Section, however, have a fission track age of about 50 m.y. (See Appendix I), indicating that the conglomerate is no older than latest early Eocene and, allowing time for erosion and deposition of the clast, may be middle Eocene (Figure 6). Such an age is permissible according to Griggs (1970).

The Chuckanut Formation overlies the pre-Jurassic Darrington Phyllite at the south end of Glover's Lake Whatcom section and just east of Lake Samish where basal Chuckanut was studied by Kelley (1970). Moen (1962, Plate 1) shows a small outlier of Chuckanut overlying the mixed Chilliwak Group which has recently yielded Triassic conodonts from the nearby Hilltop quarry (Evans and Savage, 1979). On Lummi Island, the Chuckanut Formation unconformably overlies mafic metaplutonic rocks, silicic dikes, and pillow basalts postulated by Whetten and others (in press) to be a klippe of the Haystack thrust.

McLellan (1927, p. 136) and Miller and Misch (1963, p. 170) correlated the lower part of the Chuckanut Formation with the upper part of the mostly marine Nanaimo Group. Nowhere, however, are the units interbedded, and fold axes in Chuckanut on Lummi Island are at right angles to those of the Nanaimo (John Whetten, oral commun., 1979).

Nonmarine arkose of the Huntingdon Formation, considered to be middle Eocene (based on palynomorphs, Fischer, in Miller and Misch, 1963, p. 171), unconformably overlies the Chuckanut Formation south of the Nooksack River and east of Bellingham.

Swauk Formation

Russell (1900, p. 118-119) first applied the name Swauk sandstone to the sedimentary rocks exposed along Swauk Creek, and suggested that the Swauk could be subdivided into the Camas sandstone (northeast of what is now known as the Leavenworth fault) and the Wenatchee sandstone (southwest of the Leavenworth Fault), but refrained from doing so upon the advice of B. Willis and G. O. Smith, who were doing more detailed work in the area. Smith (1904, p. 5) and Smith and Calkins (1906, p. 4-5) extended the formational name from the Swauk Creek drainage to include similar sandstones in the upper Teanaway and Cle Elum drainages. Waters (1930), Chappell (1936), Page (1939), Willis (1953), and Cater and Crowder (1967) mapped the Swauk Formation into the Chiwaukum graben and northward. Spurr (1901), Smith (1916), Pratt (1958), Galster (1956), Ellis (1959) and Yeats (1958) mapped the sedimentary and volcanic rocks to the northwest, and Vance (1957), Jones (1959), and Misch (1966) found remnants of Swauk-like sedimentary rocks north to the Canadian border.

Estimates of the thickness of the Swauk Formation range from 4000 feet (Foster, 1960, p. 104) to 10,000 feet (Ellis, 1959). Alexander (1956, p. 18) estimated the minimum total thickness in the Swauk Creek area to be 7,000 feet. A minimum of about 7500 feet of section are present between the base of the Swauk in the vicinity of the North Fork of the Teanaway River and thin beds of mafic tuff near the unconformable contact with the Teanaway basalt. A similar amount of section is exposed above the tuff on the south limb of a major syncline in the vicinity of Liberty (Tabor and others, 1977). Pratt (1958, p. 28) estimated correctly that exposures of Swauk Formation are composed of 80 percent sandstone, 10 percent shale, and 10 percent conglomerate.

The formation has been subdivided into several mappable facies based upon the predominant clast size and bedding characteristics (Tabor and others, 1977). East of the type area, along Swauk Creek the unit becomes more shaley and evenly and thinly bedded upward in the section (Frizzell and Tabor, 1977 p. 421). Several facies including shale, arkosic sandstone, conglomerate, an ironstone deposit, and white arkosic sandstone have been mapped in the vicinity of Swauk Pass (Pratt, 1958, p. 30, and Tabor and others, 1977), while the predominantly arkosic sandstone, subordinate conglomerate, and only locally present ironstone have been mapped west of there. With the exception of the mafic tuff described below, no marker beds have been found in the Swauk Formation.

As with the Chuckanut Formation, the age assignment for the Swauk Formation has been revised several times. Willis (1886, p. 76) referred to the Swauk as upturned Laramie beds. F. H. Knowlton (in Smith, 1904, p. 5) studied fossil leaves from the unit and concurred, correlating them with the Eocene (now Paleocene) Fort Union and Laramie Beds. Duror (in Smith, 1916, p. 566) concurred also and stated that the Swauk Formation was correlative with the Lower Puget Group. Newman (1971, p. 397-398 and 1975, p. 158), on the other hand, in consideration of palynomorph assemblages, interpreted the Swauk to be "no older than early Eocene and as young as middle Eocene" (1975, p. 158).

A tuff interbedded in the Swauk near Liberty yields a zircon fission track age of 50.4 ± 2.7 Ma (C. Naeser, written commun., 1976). Similar tuffs interbedded in Swauk in the Swauk Creek-Swauk Pass area have fission track ages of 51, 49, and 44 Ma (Appendix II). Volcanic rocks east of Lake Cle Elum, named the Silver Pass by Foster (1960, p. 105) and considered to be unconformably overlying the Swauk by Foster and Lofgren (1974, p. 33-34), but now known to be interbedded with Swauk, have fission track ages of 51 ± 5 and 53 ± 5 Ma (J. Vance and C. Naeser, written commun. 1976 and 1977). The Swauk near these interbeds (probably halfway to three quarters up the unit) of volcanic rock is about 50 Ma old, that is, early Eocene, with the shale of Tronson Ridge to the east somewhat younger.

The Swauk Formation is in depositional contact with pre-Tertiary rocks including serpentinite in the Ingalls Complex of Frost (1973), phyllite of the Easton Schist, and granitic rocks of the Mt. Stuart massif. Fault contacts with subadjacent units are found southeast of Mt. Stuart adjacent to the Leavenworth Fault zone but, except for probably minor basement/sediment faulting ("shearing off" of Misch, 1966, p. 137), most other contacts are depositional.

The Teanaway basalt unconformably overlies folded Swauk Formation. Russell (1900, p. 130-131) described the Teanaway as basalt and andesite, and Clayton (1973) noted that it included much basaltic pyroclastic material, some rhyolite, and some arkosic material. A whole rock potassium argon date for the Teanaway Basalt of 47 Ma (R. Tabor, pers. commun., 1979) supplies an approximate time by which the Swauk was deformed and eroded.

Isolated Arkosic Bodies

The affinities of bodies of Tertiary sediments (Figure 5) scattered between the main outcrop areas of the Chuckanut and Swauk Formations are not well understood.

Coal bearing arkosic sedimentary rocks underlie much of the westernmost foothills of the Cascades between the Stillaguamish and Skagit Rivers. Rhyolitic(?) volcanic rocks are apparently interbedded with arkosic sandstones in the easternmost part of this body where the sandstones dip east into a fault zone that separates them from greenstones correlated with the Fidalgo Ophiolite of Whetten and others (in press). Further west, Jenkins (1924) described the sedimentary rocks and coal workings and, although he found shell bearing beds indicative of a marine environment (p. 53), he correlated the entire package of sandstones with the soon to be named Chuckanut Formation. Lovseth (1974) remapped the area and divided the sedimentary rocks into two units separated by the Devil's Mountain fault: the Chuckanut Formation on the north and the Rocks of Bolson Creek on the south. Marine fossils found in the coal bearing and predominantly terrestrial rocks of Bolson Creek indicate an Oligocene age and very shallow marine environment (J. Yount, oral commun., 1979).

Jones (1959) described the geology of the Finney Peak and Mt. Higgins area north of the Stillaguamish River in southeastern Skagit county and indicated that an 8,000 foot section of sandstone (which he called Swauk) is made of two units that differ in bedding characteristics and clast size (Jones, 1959, p. 116-118). The predominate unit is a massive arkose in which beds 8 to 10 feet thick are common; the other unit, presumed by Jones to be the upper part of the sandstone section, is thinly bedded and contains more shale and carbonaceous matter. Jones states that within three of the fault bounded blocks, the sedimentary rocks are either over- or underlain by altered, light brown to green, aphanitic dacites. David R. Peaver (written commun., 1979) states that while shard bearing tuffs apparently unconformably overlie the sandstones near Mt. Higgins some evidence indicates that tuffs may also be locally interbedded.

Milnes (1976) and Dotter (1977) mapped small tectonic slices of sedimentary rocks (which they called Swauk) in the Straight Creek Fault zone east of the confluence of the Suiattle with the Stillaguamish River.

Vance (1957 p. 231-238) described an elongate body of sandstone stretching from the headwaters of the South Fork of the Stillaguamish River to a point 25 km to the northwest. While Vance stated that the rocks (he called them Swauk) are "moderately strongly folded" and that relationships between the sedimentary rocks and some adjacent units are not definitely established, he did describe intrusion into the sedimentary rocks by both the Squire Creek quartz diorite and three dunite bodies. On the eastern side of the sandstone body indirect evidence indicates that the Barlow Pass volcanics overlie the sedimentary rocks, but locally the two units are in fault contact. Barlow Pass volcanic have yielded a 35 Ma zircon fission track date (Vance and Naeser, 1977 p. 520).

Galster (1956) and Yeats (1958) mapped light gray, medium grained arkoses with intercalations of pebbly sandstone in the Skykomish area west of a projection of the Straight Creek Fault. Well bedded shales occur higher in the section to the west. Galster (1956, p. 62) correctly described the interbedded relationship between the sedimentary rocks and calc-alkalic volcanics he called Temple Mountain andesites. Yeats (1977, p. 273) informally calls these volcanics the Skykomish unit and considers them late Oligocene based on a 28 Ma fission track date (Vance and Naeser, 1977). This locality is so close to the nearby Snoqualmie Batholith, though, that the zircons almost certainly were subject to annealing, and thus the age is a minimum.

This brief summary of the various isolated bodies of sedimentary rocks indicates that they are by no means unequivicably assignable to either the Swauk or Chuckanut Formations.

Manastash Formation

The Manastash Formation was named by Smith (1904, p. 7) but later included in the Naches by Stout (1964, p. 324). The arkosic sandstones are older than the Naches and are mappable, so the Manastash Formation is an appropriate term (Tabor and others, 1977 and in press). Saunders (1914, p. 119) correctly stated that the Manastash has a minimum thickness of 1900 feet but about 2400 feet of section is exposed in the faulted northern limb of the westnorthwest trending syncline on Manastash Creek. The unit is composed predominantly medium to coarse grained, in part, quartz-rich, sandstone, shale, and minor coal.

No leaf species in the Manastash Formation are known to occur in either the Swauk or the Roslyn Formations. Knowlton (in Smith, 1904, p. 7) correlated the Manastash with the Clarno beds in Oregon, now thought to be upper Eocene to lower Oligocene (Hergert, 1961, Wolfe and Hopkins, 1967, p. 69-73; Swanson and Robinson, 1968, p. 159-160). The age assignment of fossil leaves collected by Stout (1964, p. 327) agrees with Knowlton's Eocene and possibly Oligocene age for this unit. Newman

(1977, p. 1113), on the other hand, reports preliminary palynomorph data suggesting that the Manastash Formation along Taneum Creek is equivalent to the Swauk Formation.

Overlying the Manastash Formation with apparent conformity are andesitic to rhyolitic lavas and pyroclastic rocks which Smith (1904, p. 7) and Smith and Calkins (1906, p. 7) referred to the Taneum Andesite. Most of these rocks were called Keechelus Formation by Stout (1964, p. 329). Zircon fission track ages from a rhyolite ash flow tuff from this unit are 45 and 52 Ma. (Appendix I). The basalt of Frost Mountain which overlies the Taneum Andesite appears to be correlative with the Teanaway Basalt and has a whole rock potassium argon age of 47 m.y. (R. Tabor, pers. commun., 1979).

Based upon these ages, and the gross lithologic similarities of the Manastash, Taneum, and Basalt of Forest Mountain sequence to the Swauk, Silver Pass, and Teanaway sequence, Tabor and others (in press) tentatively and with explicit reservation suggest a direct correlation.

In the headwaters of Manastash and Taneum Creeks, the Manastash Formation was deposited on phyllites of the Easton Schist, while further to the west the unit was deposited upon hornblende quartz diorite gneiss. At its western limit, the Manastash Formation is in fault contact with the Naches Formation.

Puget Group

The Puget Group underlies the southern Puget Lowland area south and southeast of Seattle. The part of the Puget Group studied herein lies between Seattle and the Green River area. Throughout most of this area the Puget Group rocks are covered with unconsolidated glacial deposits.

Willis (1886, p. 760) referred to these rocks as the Coal Measures of Puget Sound. White (1888, p. 446) while discussing the estuarine nature of fossil mollusks, first used the term Puget Group for the coal bearing arkosic sedimentary rocks in the Puget Sound Lowland. Subsequent workers continued this usage until Waldron (1962) named the Eocene volcanic rocks in the Seattle area the Tukwila Formation and included the formation in the Puget Group. Waldron (1962) also named the Renton Formation for the overlying coal bearing arkosic sedimentary rocks and included them in the Puget Group. Arkosic sandstones that underlie volcanics of the Tukwila Formation on Tiger Mountain east Seattle were included in the Puget Group and named the Tiger Mountain Formation by Vine (1962 p. 12). The three interbedded units, Tiger Mountain, Tukwila, and Renton Formations, from oldest to youngest, comprise the Puget Group. This sequence is present between the Des Moines and Maple Valley quadrangles (Mullineaux, 1970) and is, in part, correlative with others to the south (cf. Gard, 1968; Snavely, and others, 1958; and Buckovic, 1979).

The thickness of the Puget Group, and as is most likely for all the nonmarine sedimentary units, is variable and changes over short distances. A minimum composite thickness of the Puget Group is 11,000 feet in the vicinity of Tiger Mountain (Vine, 1969, p. 17, 20, 24). In the Green River, on the other hand, a minimum thickness of about 6,200 feet was estimated for the Puget Group (Vine, 1969, p. 6). Much of the difference likely is due to the absence or thinning of the volcanic unit south of an inferred hinge line separating the two areas (Vine, 1968, p. 36). Buckovic (1979, fig. 5-7) illustrates the interbedded nature of the formations and lithologies. Arkosic sandstone predominants in the Tiger Mountain and Renton Formation, and the Tukwila Formation is composed of volcanic sandstone, tuff, volcanic conglomerate, and some flow rock.

The Puget Group is "an unusually complete section of Paleogene nonmarine rocks containing abundant plant fossils." Thus Wolfe described the unit in which he assigned epochal and subepochal boundaries to four plant stages which he established (Wolfe, 1968 and 1977, p. 8). Wolfe stated that undifferentiated Puget Group in the Green River area contains flora indicative of an age span from early Eocene to early Oligocene. In the Tiger Mountain area, however, Wolfe assigned the Tiger Mountain Formation a middle Eocene age, the Tukwila Formation a middle Eocene to early Oligocene age, and the overlying Renton Formation a late Eocene to early Oligocene age (Wolfe, 1968, p. 11-12 and 1977, p. 8).

I obtained a fission track age of 41 m.y. (Appendix I) from an andesite breccia near the upper part of the Tukwila Formation, and R. Tabor and M. Hetherington (written commun., 1979) obtained a potassium argon age on hornblende from the same breccia of 45.9± m.y., indicating that part of the Tukwila is indeed middle Eocene.

Marine volcaniclastic rocks both overlie and underlie the terrestrial rocks of the Puget Group in the vicinity of Tiger Mountain. The Tiger Mountain Formation overlies marine volcanic siltstones, sandstones and conglomerates of the Raging River Formation with apparent conformity. Foraminifera from the Raging River Formation indicate a middle Eocene age (Vine, 1969, p. 15). Northwest of Tiger Mountain the contact between the Renton Formation and the overlying volcaniclastic rocks is apparently conformable. Here the volcaniclastics are mostly marine and are tentatively correlative with the Blakeley Formation on Bainbridge Island. Just south of Samish Lake these rocks yield shallow water foraminifera of early Oligocene age (H. Gower, oral commun., 1979). The base of the Puget Group in the vicinity of the Green River is not exposed and the upper part of the unit is interbedded with an unnamed volcanic unit (Vine, 1969, p. 28).

Chumstick Formation

The Chumstick Formation is confined to the northnorthwest-trending Chiwaukum graben. Russell (1900, p. 118-119) stated while naming the Swauk Formation (s.l.) that it could be subdivided into the Camas sandstone (now the Chumstick Formation) and the Wenatchee sandstone (Swauk Formation of Swauk Creek), but, as I mentioned earlier, refrained from doing so upon the advice of B. Willis and G. O. Smith. Page (1939) described the Swauk Formation in the Chiwaukum graben, as did Chappell (1936). Willis (1950, 1953) described the Leavenworth fault and noted that this fault separated the graben fill from basement. The extension of this fault is now known to separate the graben fill from the Swauk Formation to the west. Alexander (1956, p. 16) studied the Swauk Formation in the type area and the Camas sandstone of Russell (1900) and concluded "that Russell's division of the two units (was) justified". The Chumstick Formation was named (by Whetten in Gresens and others, in press) for Chumstick Creek, north of Leavenworth.

Lupe (1971, p. 6) estimated that the Chumstick Formation is 28,000 feet thick while Whetten (1976) more conservatively, and perhaps more correctly, estimated the thickness to be about 18,000 feet thick. Whetten also has suggested that thickness may be extremely variable (Gresens and others, in press).

Lupe (1971) estimated that 80 percent of the Chumstick is composed whitish medium-grained sandstone. Whetten divided the sequence into several units including a fanglomerate unit, a sandstone unit, a conglomerate unit, tuffs, and a fine grained lacustrine unit (Whetten and Laravie, 1976; Whetten and Waitt, 1978; and Gresens and others, in press). The tuff beds interbedded in the lower part of the Chumstick Formation are marker beds that have aided greatly in delineating structures.

Although fossil leaf collections from the Chumstick Formation indicate that it is the same age as the Swauk (Brown _in_ Waters, 1930, and La Motte _in_ Chappell, 1936, p. 73-76), the tuffs yield zircon fission track ages of about 45 m.y. or middle Eocene (Whetten, 1976, p. 420, and Gresens and others, in press, Table 1). In the case of La Motte's correlation of the rocks with the Laramie beds, the comparisons were based on composite samples collected from both the Chumstick and the Swauk Formations (Chappell, 1936, p. 70). Palynomorphs from rocks in the Chumstick Formation indicate a late Eocene age (Newman 1975, p. 158).

The Chumstick Formation was deposited upon and is faulted against Swakane Biotite Gneiss. The Entiat Fault separates the Chumstick from Swakane Biotite Gneiss on the northeast, and the Leavenworth Fault separates it from several crystalline units and the Swauk Formation on the west. Both the Wenatchee Formation and the Columbia River basalt unconformably overlie the Chumstick. The Chumstick Formation may be equivalent, in part, to the Roslyn Formation, which overlies Teanaway Basalt near the Yakima River. It also may be equivalent, in part, to upper Swauk Formation (Tabor and others, in press).

Roslyn Formation

Willis (1886) mentioned the development of coal in the Roslyn beds which were, he said, similar to those of Puget Sound. Russell (1900, p. 123) proposed the name Roslyn sandstone for the entire system of sedimentary beds including the coal mine at Roslyn but proposed no type sections. The unit was described by Smith (1904, p. 6-7) and most definitively studied by Bressler (1951 and 1956).

Bressler (1951, Table IV) divided the Roslyn Formation into three units with over 6500 feet of total thickness. The unit consists of 80 percent white to weathering yellow, medium to coarse grained arkosic sands with about 16 percent finer grained sands, and 3 percent conglomerate; the upper part contains 0.6 percent coal (Bressler, 1951, Fig. 12).

Fossil leaves collected from the Roslyn indicate to Knowlton (in Smith, 1904, p. 5) that no species are common to both the Swauk and Roslyn and that the Roslyn is younger than the Swauk Formation. Newman (1975, p. 158) assigned a late Eocene age to the palynomorph assemblage present in the upper part of the Roslyn Formation and felt that the Roslyn was equivalent to the Franklin Coal Zone in the middle Puget Group.

Although Bressler (1951, p. 441) felt that the Roslyn was disconformable on the Teanaway Basalt, interbedded basaltic pyroclastic materials and arkose (Clayton, 1973, p. 35), indicate that the units are conformable. Probable interbeds of Teanaway basalt in sandstone of the Chumstick Formation suggest that at least the lower part of the Roslyn may be equivalent to part of the Chumstick. Limited exposures of variegated shales and nearby tuffaceous sands on and near the Teanaway

River are reminiscent of the Wenatchee Formation. A single zircon fission track age of 33 Ma (Appendix I) tends to confirm this tentative correlation. Exposures are poor and no contact with an underlying unit is exposed but the Wenatchee-like beds probably overlie the Roslyn Formation.

Naches

Because the Naches Formation is heterogeneous and has undergone several nomenclatural changes, it is one of the more confusing Tertiary units in the Cascades.

Smith and Calkins (1906, p. 4) named the Naches Formation "for the river in whose basin it is most extensively developed". It is fair to say that most subsequent workers have not studied this type area. Stout (1964, p. 324) included the Manastash Formation of Smith (1904) in his newly defined Naches Formation. Foster (1960, p. 114-118) redefined the Guye Formation of Smith and Calkins (1906), and identified the pre-Tertiary Denny Formation, the Guye Formation, the Mt. Catherine Rhyolite, and Naches Formation. The Naches as used here is a predominantly volcanic unit that includes several intercalated subunits including widespread arkosic sandstone, locally occurring black shale and chert pebble conglomerate (Guye Formation of Foster, 1960), basalt, andesite, basaltic tuff and breccia, and crystal tuff and flows of rhyolitic composition (rhyolite tuff includes Mt. Catherine Rhyolite of Foster, 1960).

Foster (1960, p. 16) reported 5,000 feet of section and Stout (1964, p. 324) reported a minimum thickness of 8,000 feet while estimating that thickness is in excess of 10,000 feet. Our mapping suggests approximately 10,000 feet of section are present in the northeast limb of a northwest-trending anticline on Keechelus Ridge.

As may be expected with a unit that has undergone several nomenclatural changes the age is somewhat of a controversy. Based upon stratigraphic and paleobotanical arguments, Smith and Calkins (1906, p. 4 and 5) thought the Naches equivalent to Swauk. Foster (1960, p. 116) used lithologic, stratigraphic, and paleobotanical arguments, to conclude that Naches is equivalent to part of the Puget Group.

Rhyolite ash flow tuffs in the lower part of the Naches have zircon fission track ages of 35 to 39, and possibly 42 m.y. (J. Vance and C. Naeser, written commun., 1977). Whole rock potassium argon ages of basalt, presumably from near the base, are 40 and 43 m.y. old (R. Tabor, oral commun., 1979). Unconformably overlying the Naches are Late Oligocene pyroclastic rocks probably equivalent to the Stevens Ridge Formation (Waters, 1961 p. 52, and Fiske and others, 1963 p. 20-26). These two ash flow tuffs yield zircon fission track ages of 29.5 ± 3.0 and 29.3 ± 2.9 Ma (J. Vance and C. Naeser, written commun., 1977,) and 32 Ma (Appendix I). Because of these ages and relationship the Naches Formation is considered upper Eocene and Oligocene here and by Tabor and others (1978).

The Naches Formation unconformably overlies three pre-Tertiary units: south of the Yakima River, quartz dioritic rocks and the metasediments of the Lookout Mountain Formation (Stout, 1964 p. 320-321); on the Yakima, phyllite of the Easton Schist; and near Snoqualmie Pass, marbles, cherts, and greenstones of the Denny Formation (Foster, 1960 p. 111 and Chitwood, 1976).

The Naches is in fault contact with both the Swauk Formation and the Manastash, Taneum, and Basalt of Frost Mountain sequence on its eastern side; to the north it is cut off by the Snoqualmie batholith. At its southern end, it is unconformably overlain by Columbia River Basalt.

Wenatchee Formation

The Wenatchee Formation crops out in the area immediately west of the town of Wenatchee. Chappell (1938 p. 93-94) described an unconformity between the folded Chumstick Formation (which he called Swauk) and an overlying sandstone unit. The Wenatchee Formation has more recently been studied in detail by Gresens (1976, p. 376-377 and 1975; Gresens and others, 1977, p. 114-123; and Gresens and others, in press) who subdivided the unit into several members.

The Wenatchee Formation is somewhat more than 360 m thick at its type section and is distinguished from the underlying Chumstick Formation by its mild deformation, quartz rich composition, and varigated shales.

Leaves collected from the Wenatchee Formation suggest a middle Eocene age and are different from assemblages in the Swauk and Chumstick Formations (J. A. Wolfe, written commun., 1976). On the other hand, palynomorph assemblages yield an Oligocene age (Newman, 1975, p. 158). Tuffaceous beds in the Wenatchee Formation yield zircon fission track ages of about 34 m.y., about early to early late Oligocene (Gresens and others, in press).

Rocks between Stemilt Creek and Malaga and in landslide blocks near there have a variegated appearance and appear to be in the appropriate structural position to be Wenatchee, although Gresen and others (in press) consider these rocks to be younger. An apatite age of 36 m.y. (Appendix I) was obtained from tuffaceous beds in the Malaga slide, but due to the very low uranium content the error is quite large. The usefulness of this age is questionable.

Vertical beds of sandstone underlying the Chopper Hill Reference Section (Gresens, 1976, Gresens and others, 1977, and Gresens and others, in press) have been correlated with the Swauk Formation. The composition of sandstone collected from this locality, however, does not support the correlation (see section on Other Modal Analyses).

SANDSTONE PETROLOGY

Introduction to Sandstone Petrology

Modal analyses were performed on samples from the various sedimentary units to establish petrologic composition, and to provide data with which to compare the different units and discuss clast provenance and tectonic regimen. Methodology and modal data are detailed in Appendices II and III, respectively. I have presented part of the data and a preliminary analysis elsewhere (Frizzell, 1979a, b, c).

Pongsapich (1970) initiated the first petrographic comparison of the various nonmarine sandstone units in Washington. His results and those of others are summarized on Figure 7. Lupe (1971) studied the composition of the Chumstick Formation from near Chumstick Creek. Dotter (1977) analyzed four sandstone samples from an isolated arkosic body along the Straight Creek fault; Buckovic (1979, Fig. 4) summarized his petrographic data from Washington and north-central Oregon arkosic sandstones.

Framework grain parameters (Figure 8) were calculated using methods outlined by Dickinson (1970), Graham and others (1976) and K. Helmold (personal commun., 1978). Total quartz (Q) was derived by adding chert and polycrystalline quartz grains (collectively symbolized as Q_P) to monocrystalline quartz grains (Q_M). Total feldspar (F) was derived by adding plagioclase (P) to potassium feldspar (K). Sedimentary and metasedimentary lithic fragments (L_S) added to volcanic lithic fragments (L_V) yielded lithics (L) which when added to Q_P produced total lithics (L_T).

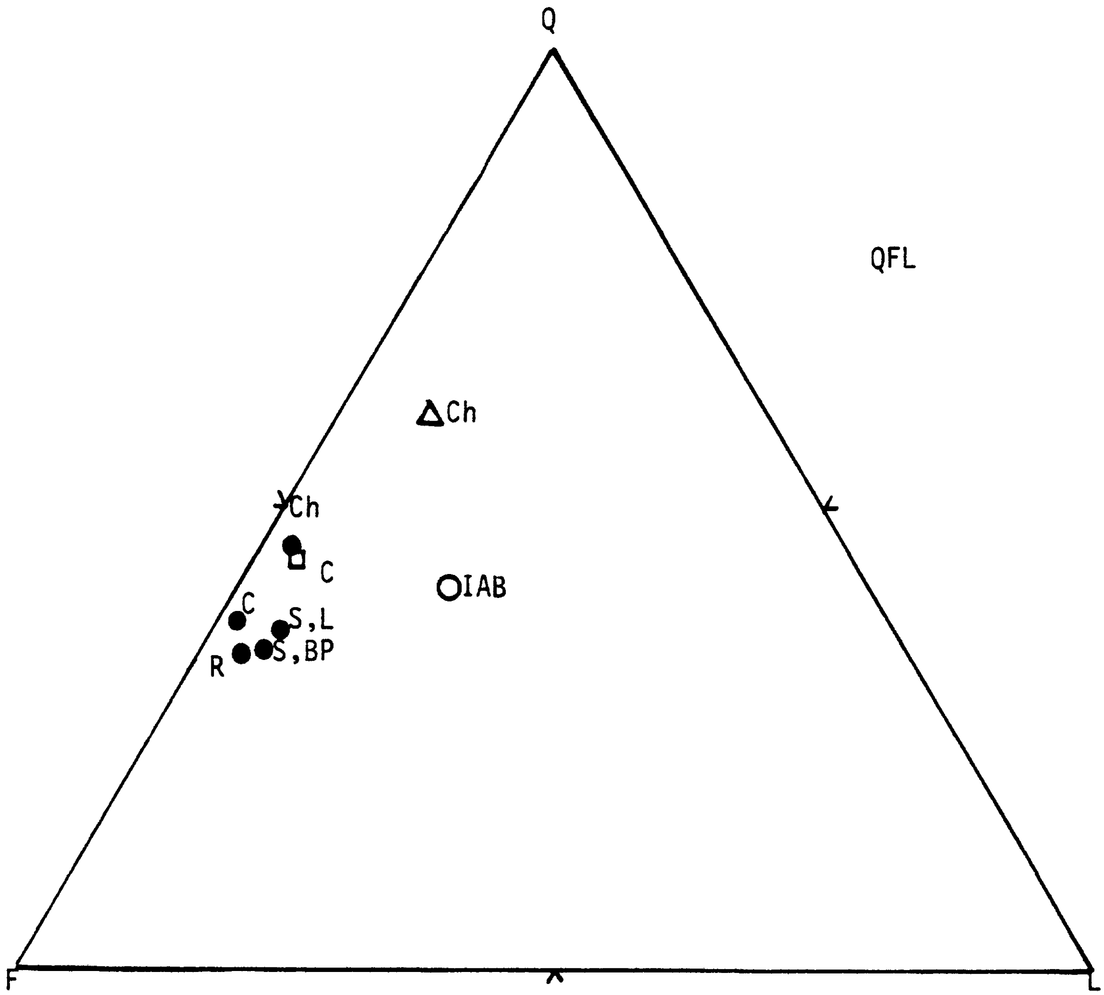
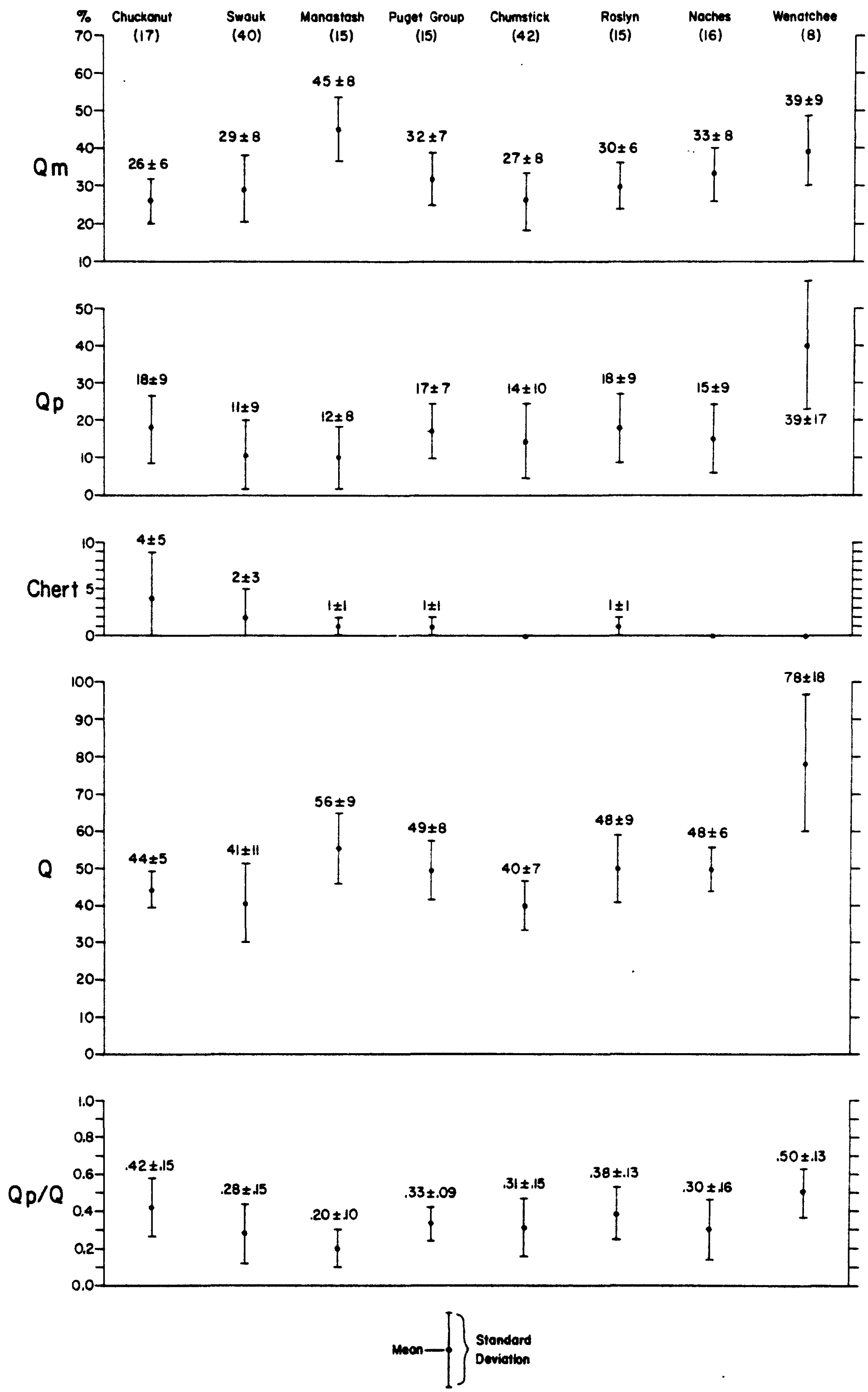
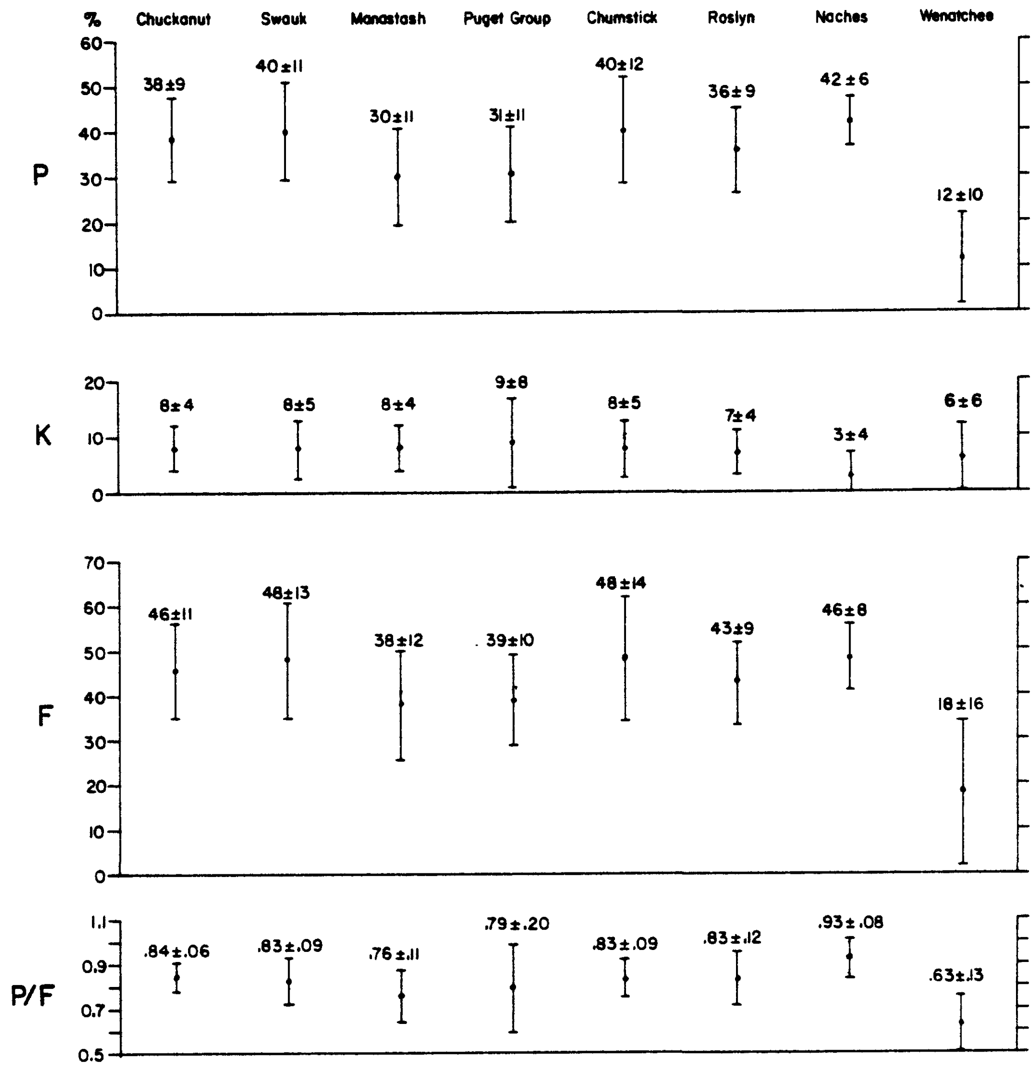


Figure 7. QFL diagram for modal data for Paleogene sandstone literature sources. Filled circles from Pongsapich (1970): Ch, Chuckanut, ten samples; S, BP, Swauk at Blewett Pass, 24 samples; S, L, Swauk at Liberty, 8 samples; C. Chumstick, 14 samples; and R, Roslyn, 8 samples. Open triangle, Kelley (1970) ten samples of basal Chuckanut. Open circle, Dotter (1977) isolated arkosic body along Straight Creek Fault, 4 samples.

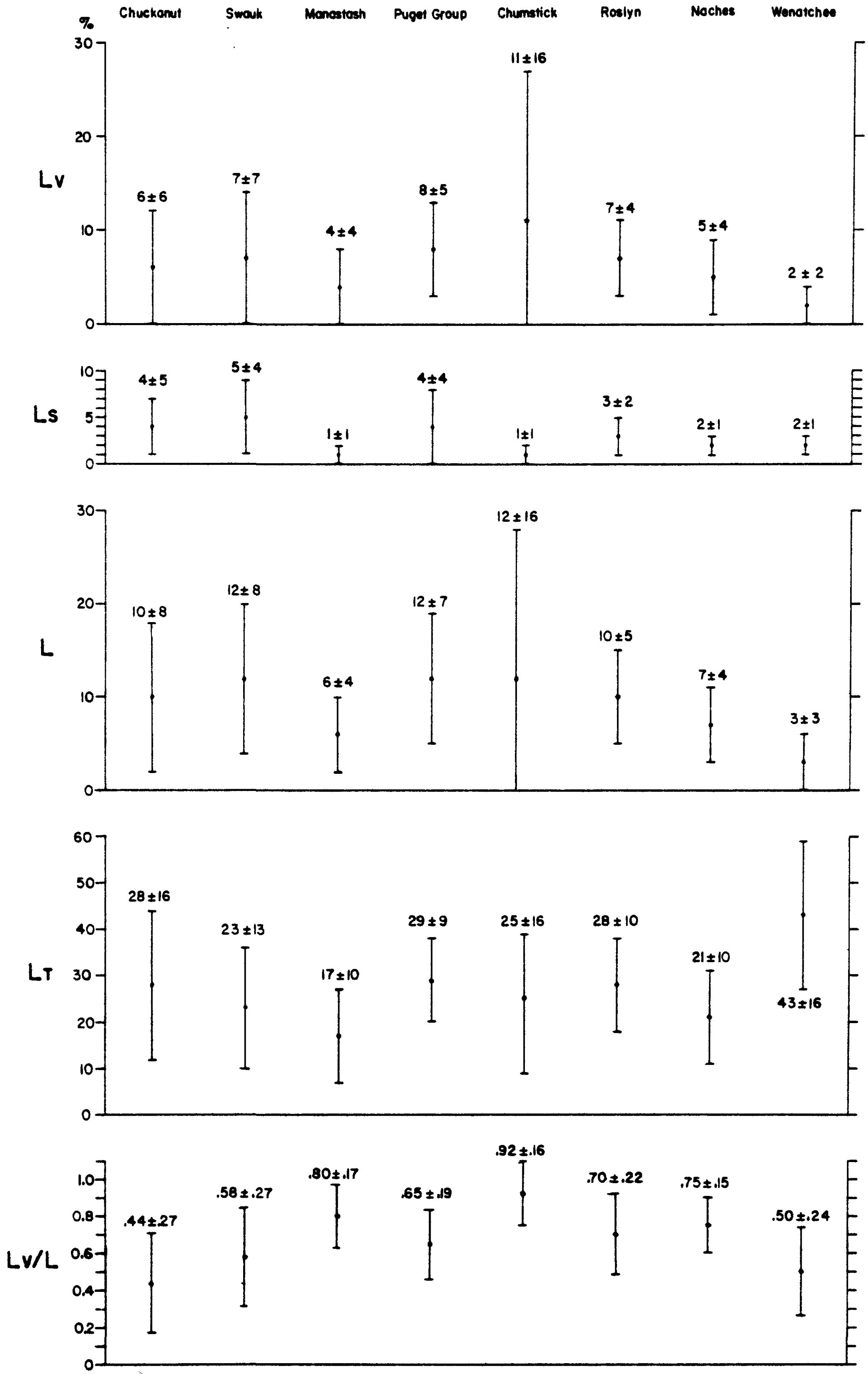
Figure 8. Mean and standard deviations of framework grain parameters. See text for definitions and Appendix II for derivations of parameters. Dots represent means, and bars, standard deviations. (Three pages.)



%
Chuckanut (17)
Swauk (40)
Manastash (15)
Puget Group (15)
Chumstick (42)
Roslyn (15)
Naches (16)
Wenatchee (8)
Qm
26 ± 6
29 ± 8
45 ± 8
32 ± 7
27 ± 8
30 ± 6
33 ± 8
39 ± 9
Qp
18 ± 9
11 ± 9
12 ± 8
17 ± 7
14 ± 10
18 ± 9
15 ± 9
39 ± 17
Chert
4 ± 5
2 ± 3
1 ± 1
1 ± 1
1 ± 1
Q
44 ± 5
41 ± 11
56 ± 9
49 ± 8
40 ± 7
48 ± 9
48 ± 6
78 ± 18
Qp/Q
.42 ± .15
.28 ± .15
.20 ± .10
.33 ± .09
.31 ± .15
.38 ± .13
.30 ± .16
.50 ± .13
Mean
Standard Deviation



%
Chuckanut
Swauk
Manastash
Puget Group
Chumstick
Roslyn
Naches
Wenatchee
P
K
F
P/F
38±9
40±11
30±11
31±11
40±12
36±9
42±6
12±10
8±4
8±5
8±4
9±8
8±5
7±4
3±4
6±6
46±11
48±13
38±12
39±10
48±14
43±9
46±8
18±16
.84±.06
.83±.09
.76±.11
.79±.20
.83±.09
.83±.12
.93±.08
.63±.13


Chuckanut
Swauk
Manastash
Puget Group
Chumstick
Roslyn
Naches
Wenatchee
%
Lv
6±6
7±7
4±4
8±5
11±16
7±4
5±4
2 ± 2
Ls
4±5
5±4
1±1
4±4
1±1
3±2
2±1
2±1
L
10±8
12±8
6±4
12±7
12±16
10±5
7±4
3±3
LT
28±16
23±13
17±10
29±9
25±16
28±10
21±10
43±16
Lv/L
.44±.27
.58±.27
.80±.17
.65±.19
.92±.16
.70±.22
.75±.15
.50±.24

These framework-grain parameters were variously combined to form ternary ratios (Table 1) and triangular diagrams (Figures 9 through 21). Such ternary ratios have been used to compare suitable sandstone units (Graham and others, 1976) and to discriminate between sandstone units from different tectonic regimens (Dickinson and Suczek, 1978 and in press). The components of the Ternary ratios QFL and QFL_T were taken directly from the percentage derived from the point-count data and should sum to 100 percent. The components of the ratios Q_MQpL, QpL_VL_S, and Q_MPK, however, were summed and recalculated to sum to 100 percent before they were plotted on triangular diagrams. Ternary diagrams are shown in Figures 9 through 16. The results in Figure 8 and Table 1 differ somewhat from those published elsewhere (Frizzell, 1979a) for two reasons: (1) data here contains more samples, and (2) differing methods of calculating L_V were used. The previously published L_V included granitic lithic fragments whereas such fragments are here distributed to either Q_M, P, or K depending upon which species was counted within the plutonic grain.

Three secondary parameters, essentially ratios of six of the above mentioned framework grain parameters, are suggested by Dickinson (1970) as refinements which may help describe a given unit. These include polycrystalline quartz to total quartz (Q_M/Q), designated C/Q in Dickinson (1970); plagioclase to total feldspar (P/F); and volcanic lithic to lithics (L_V/L). These ratios are shown in Figure 8 and Table 1.

	Chuckanut Formation	Swauk Formation	Manastash Formation	Puget Group Formation	Chumstick Formation	Roslyn Formation	Naches Formation	Wenatchee Formation
No. Samples	(17)	(40)	(15)	(15)	(42)	(15)	(16)	(8)
QFL	44,46,10	40,48,12	56,38,6	49,39,12	40,48,12	48,43,10	48,46,7	78,18,4
Q_MFL_T	26,46,28	29,48,23	45,38,17	32,39,29	27,48,25	30,43,28	33,46,21	39,18,43
Q_MQpL	48,33,19 (26,18,10)	56,21,23 (29,11,12)	71,19,10 (45,12,6)	52,28,20 (32,17,12)	51,26,23 (27,14,12)	52,31,17 (30,18,10)	60,27,13 (33,15,7)	48,48,5 (39,39,4)
QpL_VL_S	64,21,14 (18,6,4)	48,30,22 (11,7,5)	71,24,6 (12,4,1)	59,28,14 (17,8,4)	54,42,4 (14,11,1)	64,25,11 (18,7,3)	68,23,9 (15,5,2)	91,5,5 (39,2,2)
Q_MPK	36,53,11 (26,38,8)	38,52,10 (29,40,8)	54,36,10 (45,30,8)	44,43,13 (32,31,9)	36,53,11 (27,40,8)	41,49,10 (30,36,7)	42,55,4 (33,42,3)	68,21,11 (39,12,6)
C/Q	.42	.28	.20	.33	.31	.38	.30	.50
P/F	.84	.83	.76	.79	.83	.83	.93	.67
L_V/L	.44	.58	.80	.65	.92	.70	.75	.50

Table 1. Ternary and secondary ratios for nonmarine sandstone units from Washington. Numbers in parentheses in top line are number of samples per unit. Numbers in parentheses in body of table are recalculated to sum to 100 percent. See text and Appendix II for definition and derivation of ratios.

Description of Basal Beds

While the arkosic sandstones generally have similar framework clast compositions, minor yet significant differences do exist between the units. Basal or basement-onlap portions of the units, in particular, are locally derived and differ markedly from the overall composition of the units.

The basal Chuckanut Formation near the south end of Lake Whatcom is a thin sandstone unit rich in schist clasts overlain by a 72 foot thick quartz pebble conglomerate (Glover, 1936, p. 10). Kelley (1970, p. 7) reports a similar quartz pebble conglomerate as the basal unit near Lake Samish. Ten sandstone samples from basal Chuckanut in the vicinity of the pebble conglomerate counted by Kelley (1970, p. 41 and Appendix 2) are relatively quartz rich and apparently reflect the basement source. The mean of these ten samples is shown on Figure 7. Basal Chuckanut at the south end of the Chuckanut Drive section appears to be a weathered laterite(?) containing small pisoliths. Basal beds on Lummi Island contain clasts of basalt (J. Whetten, oral commun., 1979).

Nickeliferous iron deposits form discontinuous basal beds where Swauk Formation overlies serpentinite. Lupher (1944) named these deposits the Cle Elum Formation and noted some reworking of the clastic material. The deposits were compared convincingly with Cuban-type laterite iron deposits by Lamy and Hotz (1951, p. 57-58) and were, therefore, considered residual laterite. Pratt (1958, p. 36) pointed out that this indicates that the earliest Swauk was deposited on a surface of low relief that had undergone a long period of chemical weathering. The chemical weathering which formed the laterite may have been related to a warm/cold oceanographic boundary present off the west coast about 55 Ma. This northward excursion of warm water would have changed the climate to a tropical monsoon-type and increased the overall humidity thus, perhaps, inducing the formation of laterite (J. Ingle, oral commun., 1978). Serpentinite sandstone derived from the laterite (cf. RWT-11-75, Appendix III, Table 2) grades rapidly upward into a more typical arkosic sandstone with serpentinite clasts (cf. RWT-12-75) and then into a serpentinite free arkosic sandstone.

Galster (1956, p. 39) reported coarse-grained-to-pebbly feldspathic sandstone with fragments of schist, phyllite, quartz, and basic igneous rock overlying schist in a railroad cut five miles east of Skykomish. Basal beds on phyllite in the Easton Schist near the north end of Lake Kachess are pebbly sandstones with quartz and phyllite clasts that also rapidly grade upward into the more predominant arkosic sandstones. Likewise, basal Chumstick is a reddish fanglomerate/diamictite composed of gnessic and vein quartz clasts in a sandy matrix (Gresens and others, in press).

The quartzose sandstones from the Naches Formation (cf. VF-78-246 and 247, Appendix III,Table 7) while not basal were probably locally derived from the Denny Formation, a pre-Tertiary unit composed of marble, chert, and greenstone. Samples of obviously local source such as these, while shown in the appendices, have been excluded from the calculations of mean composition.

Description of Subquartzose Sandstone Units

The nonvolcanic sandstone units are predominantly either feldspathic or lithofeldspathic subquartzose sandstones (terminology after Crook, 1960, and Dickinson, 1970). The Wenatchee Formation and some samples of both the Manastash and Naches Formations, however, are quartzose sandstones (more than 75 percent of framework grains are quartzose); and the Chumstick Formation contains samples more properly called feldspathiolithic or lithic subquartzose sandstone.

Description of Compositions

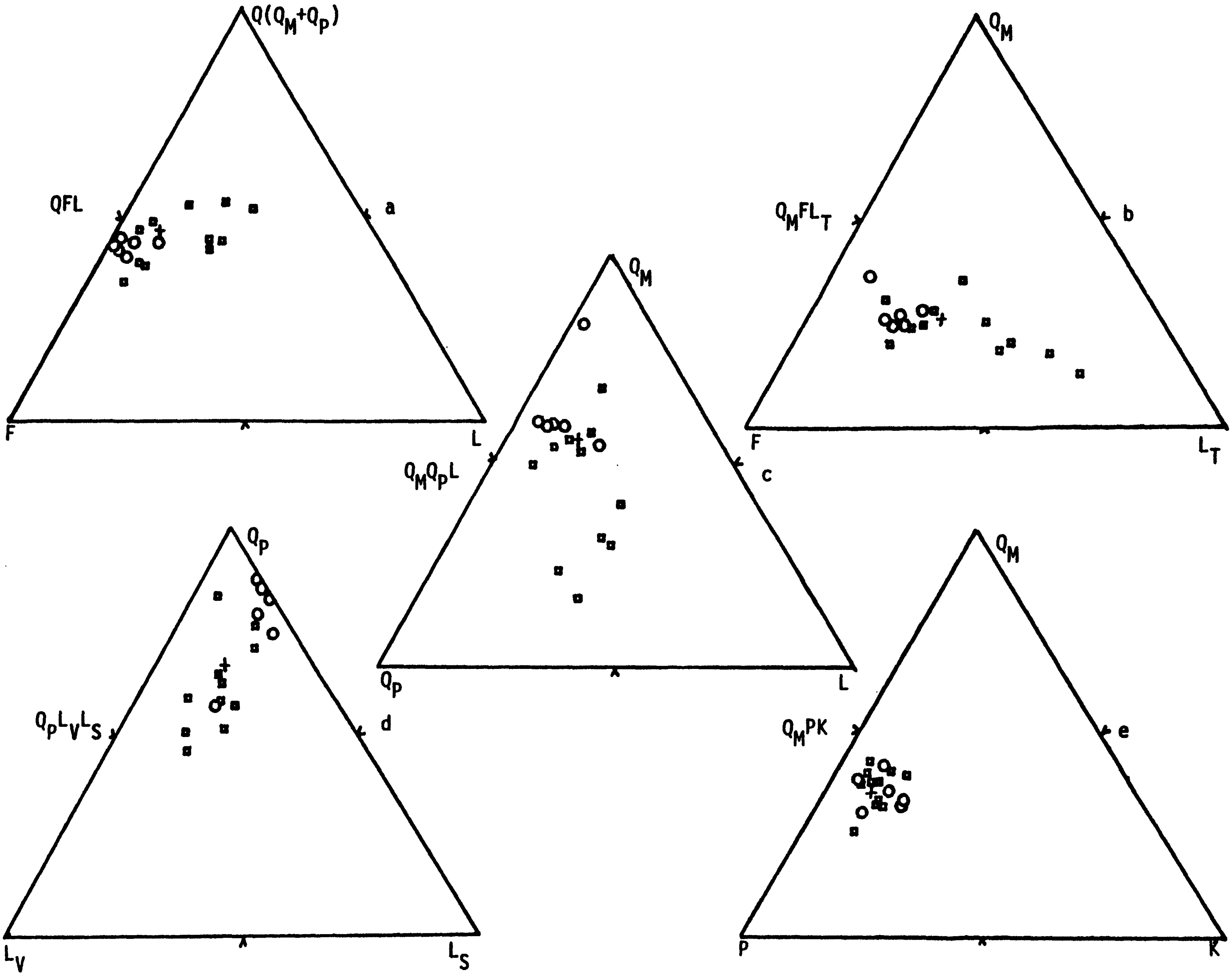
The amount of monocrystalline quartz (Q_M) (Figure 8) ranges from 27 to 45 percent, with the Manastash Formation containing the most. The Wenatchee Formation has equal amounts of Q_M, Q_P (39 percent), and the most total quartz (78 percent). The Chuckanut and Swauk Formations contain four and two percent chert, respectively. All other units contain one percent or less chert. Most units contain 30 to 42 percent plagioclase with the exception of the Wenatchee Formation which contains only 12 percent. The Naches Formation has the lowest amount of potassium feldspar (three percent) and the Chuckanut has highest 10 percent. Total feldspar ranges from an extremely low 18 percent in the Wenatchee Formation, to 38 percent in the next lowest unit, the Manastash Formation, to a high of 48 percent for both the Swauk and Chumstick Formations.

The Chuckanut and Swauk Formations and the Puget Group contain more than three percent sedimentary and metasedimentary lithic grains. The Chumstick contain only one half percent sedimentary lithics but contains the greatest amount of volcanic lithic grains.

Source Terrane and Tectonic Regimes

Pre-Tertiary rocks including the low grade metasedimentary rocks, schists, gneisses, and intrusives discussed above and Tertiary volcanic rocks were source rocks for the Paleogene nonmarine sandstones. Knowledge of these source terranes and the data presented here verify, for these rocks, schemes which attempt to use modal data to define

Figure 9. Triangular diagrams for detrital modes of Chuckanut Formation, Washington. a. QFL plot; b. $Q_M F L_T$ plot; c. $Q_M Q_P L$ plot; d. $Q_P L_V L_S$ plot; e. $Q_M PK$ plot. Circles from lower in section (?), relatively L_V poor; squares remainder of samples; + indicates mean.



Q(QM+QP)
QFL
a
F
L
QM
QMFLT
b
F
LT
QM
QMQPL
c
QP
L
QP
QPLVLS
d
LV
LS
QM
QMPK
e
P
K

Figure 10. Triangular diagrams for detrital modes of Swauk Formation, Washington. Format similar to Figure 9.

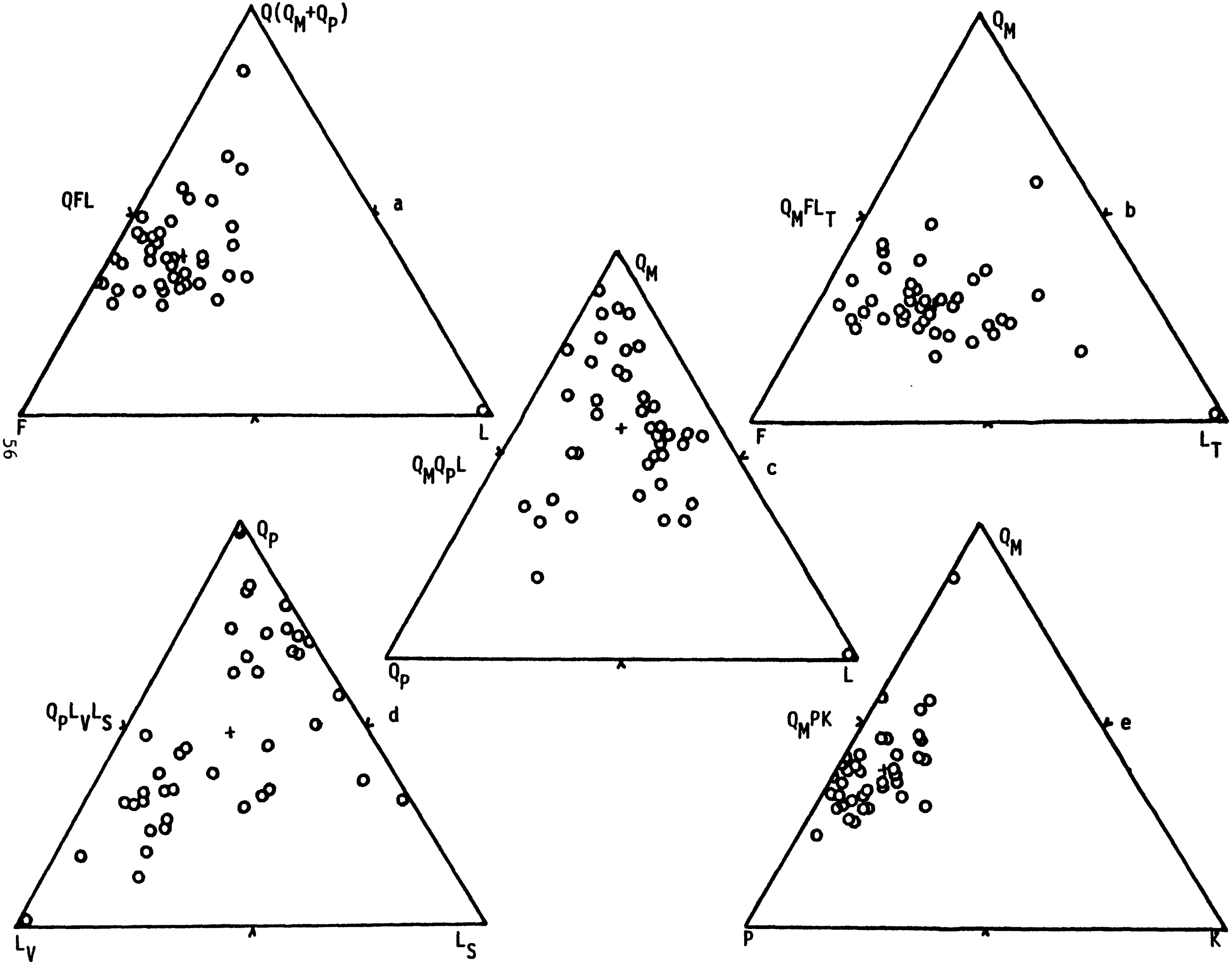

Q(Q_M+Q_P)
QFL
a
F
L
Q_M
Q_MFL_T
b
F
L_T
Q_M
Q_MQ_PL
c
Q_P
L
Q_P
Q_PL_VL_S
d
L_V
L_S
Q_M
Q_MPK
e
P
K

Figure 11. Triangular diagrams for detrital modes of Manastash Formation, Washington. Format similar to Figure 9.

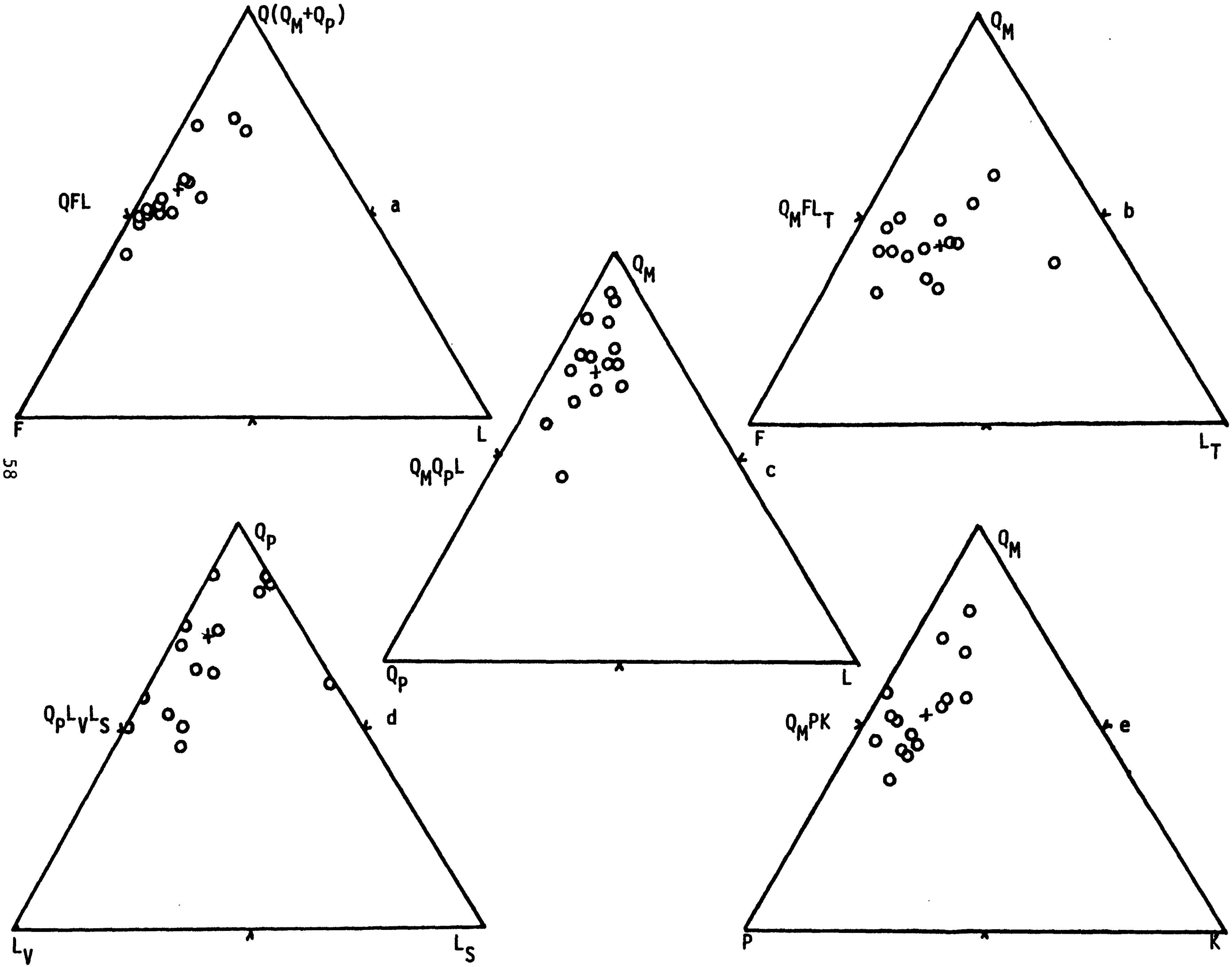

QFL
$Q(Q_M+Q_P)$
F
L
a
Q_MFL_T
Q_M
F
L_T
b
Q_MQ_PL
Q_M
Q_P
L
c
$Q_PL_VL_S$
Q_P
L_V
L_S
d
Q_MPK
Q_M
P
K
e

Figure 12. Triangular diagrams for detrital modes of Puget Group arkoses, Washington. Format similar to Figure 9. Circles, Tiger Mountain Formation; triangles, Tukwila Formation; squares, Renton Formation.

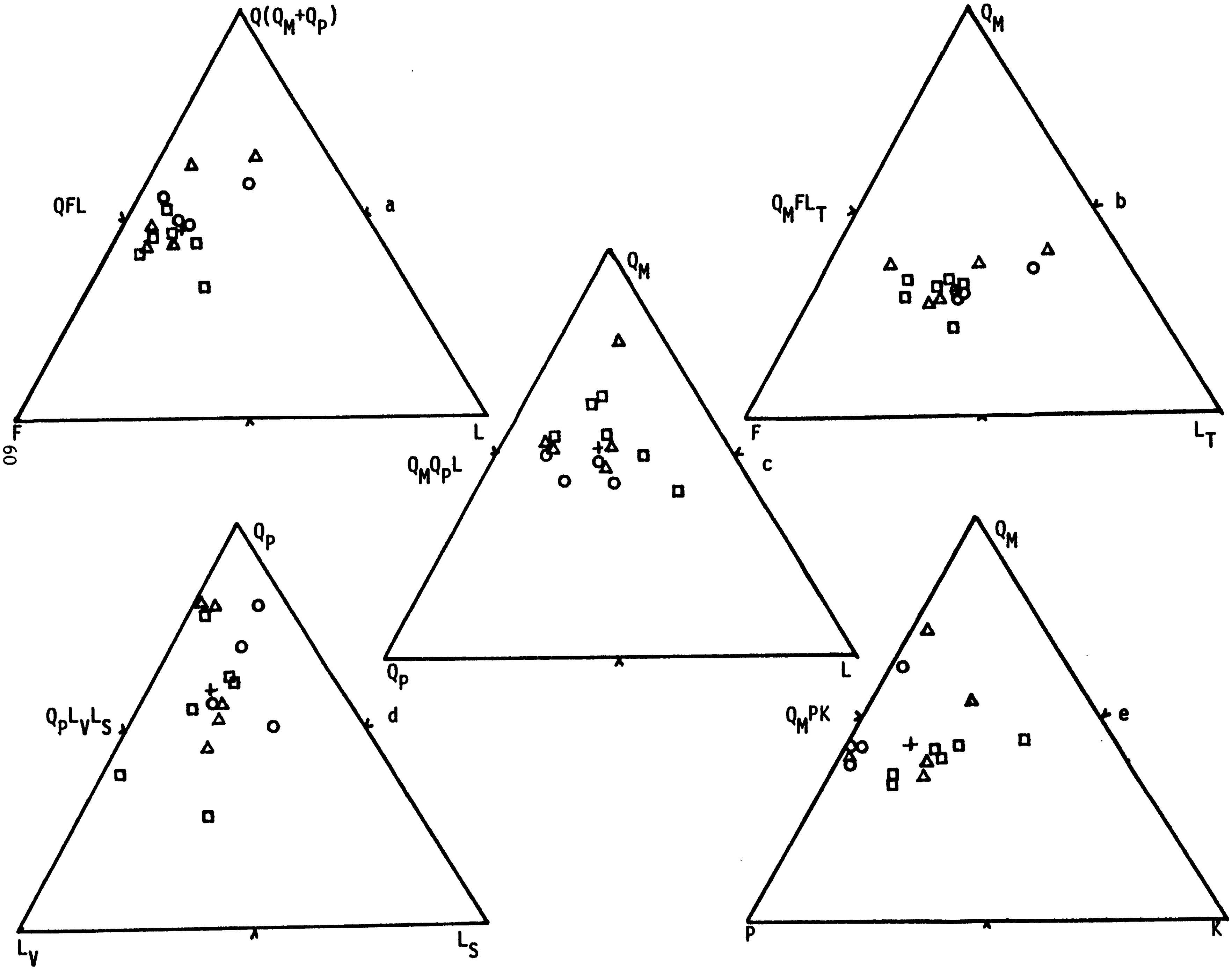
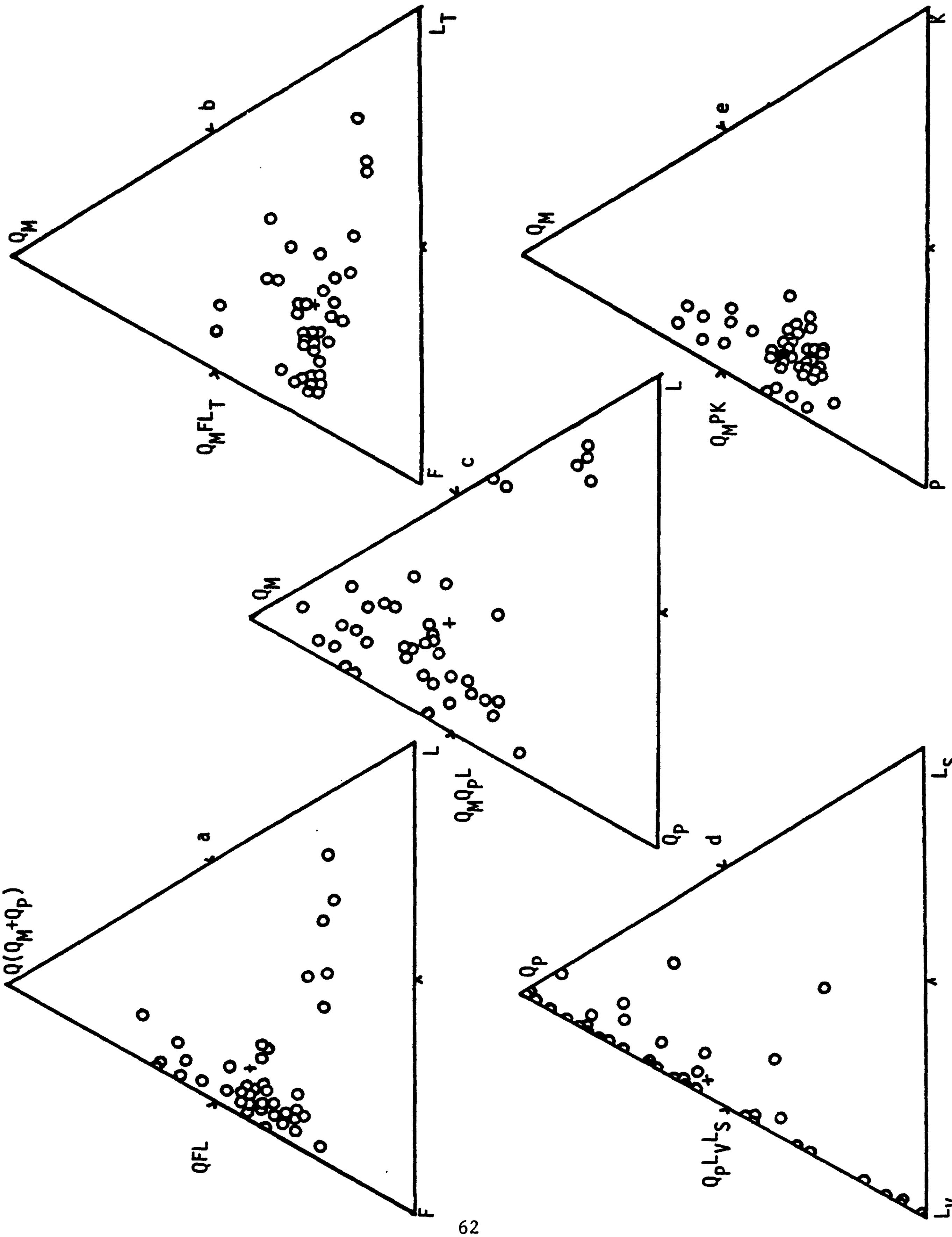

Q(Q_M+Q_P)
QFL
a
F
L
Q_M
Q_MFL_T
b
F
L_T
Q_M
Q_MQ_PL
c
Q_P
L
Q_P
Q_PL_VL_S
d
L_V
L_S
Q_M
Q_MPK
e
P
K

Figure 13. Triangular diagrams for detrital modes of Chumstick Formation, Washington. Format similar to Figure 9.



Q(QM+QP)
QFL
a
F
L
QMFLT
b
QM
LT
F
QMQPL
c
QM
QP
L
QPLVLS
d
QP
LV
LS
QMPK
e
QM
P
K

Figure 14. Triangular diagrams for detrital modes of Roslyn Formation, Washington. Format similar to Figure 9.

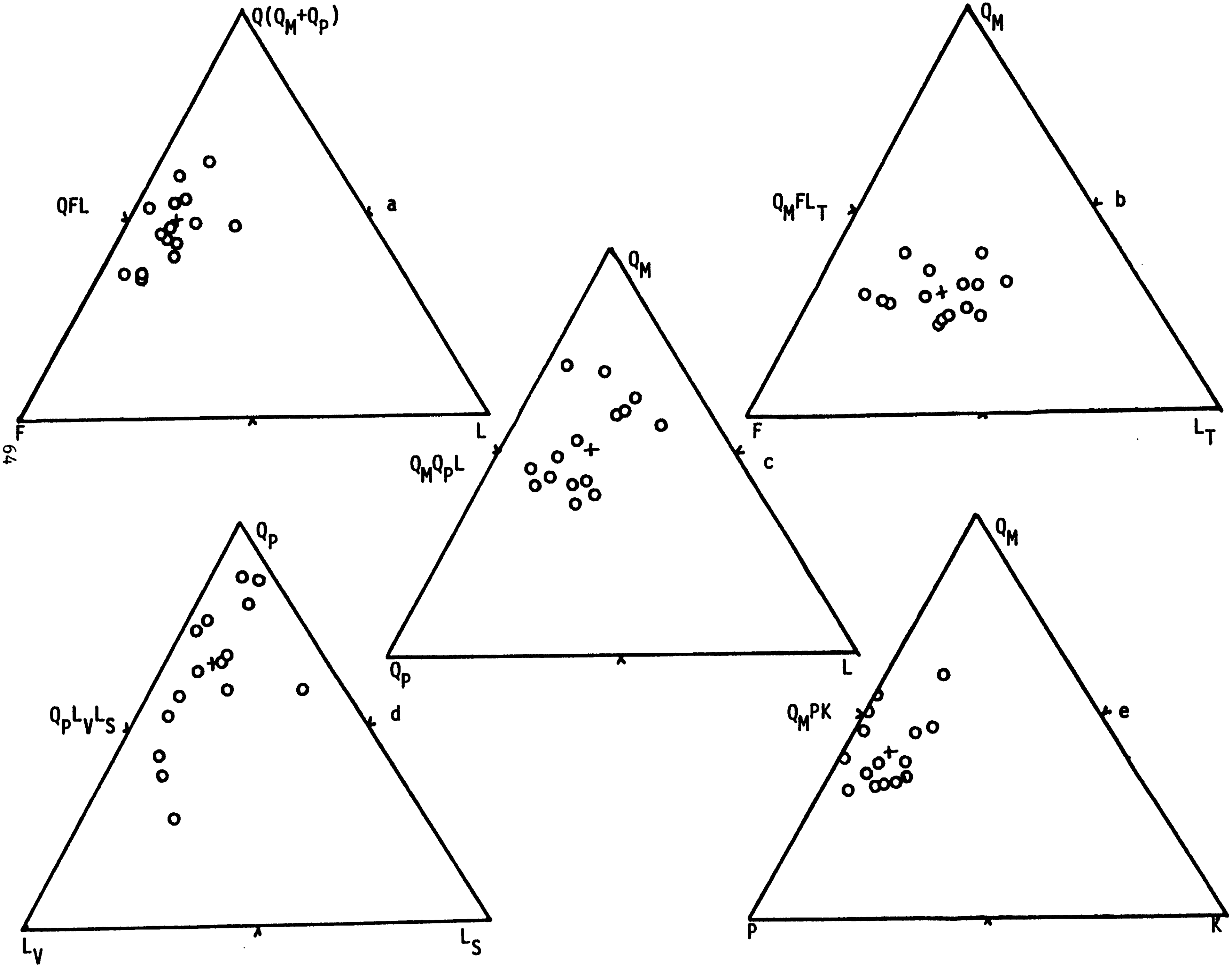
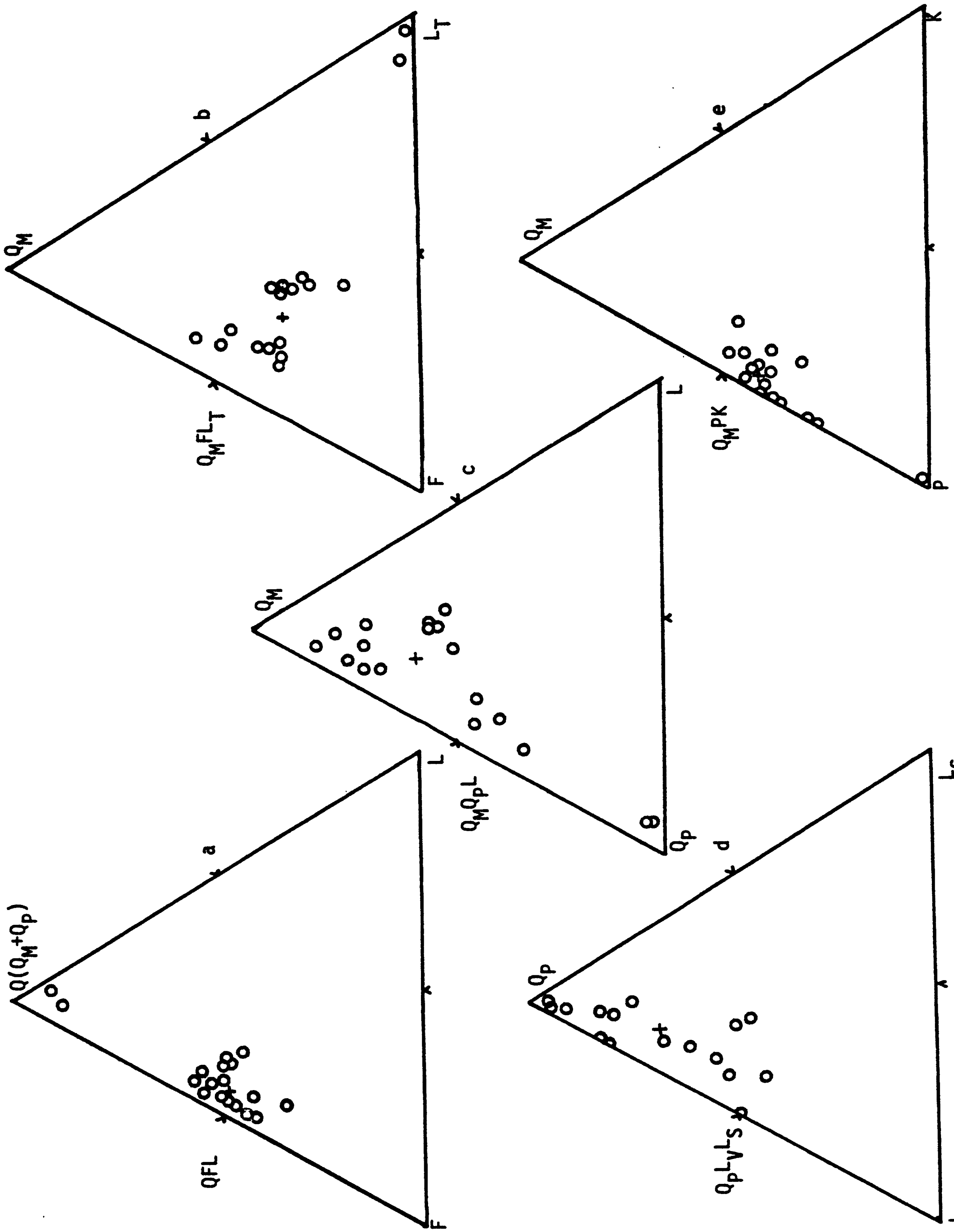
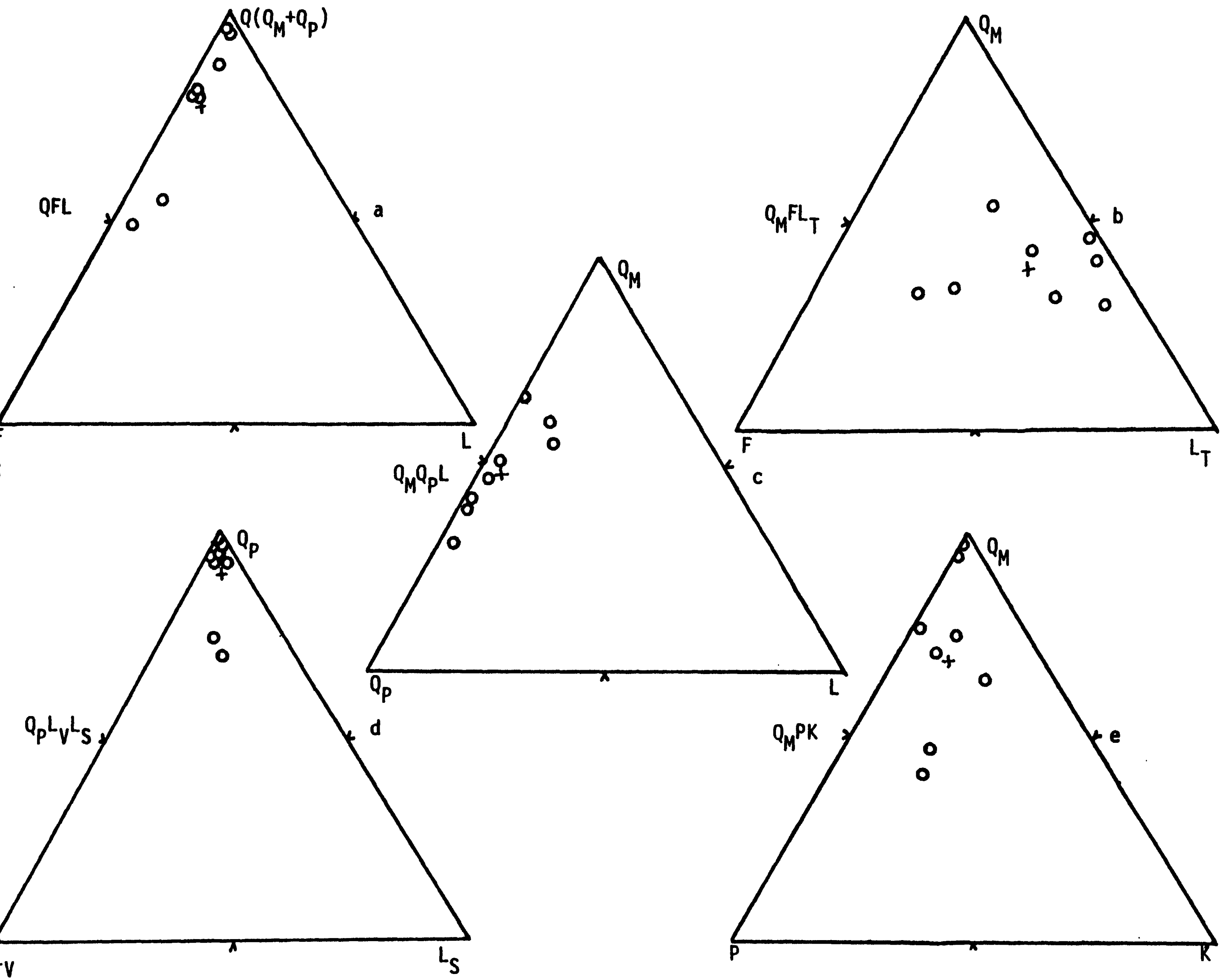

QFL
Q(QM+QP)
F
L
a
QMFLT
QM
F
LT
b
QMQPL
QM
QP
L
c
QPLVLS
QP
LV
LS
d
QMPK
QM
P
K
e

Figure 15. Triangular diagrams for detrital modes of Naches Formation, Washington. Format similar to Figure 9.



a
QFL
$Q(Q_M+Q_P)$
F
L
b
$Q_M F L_T$
Q_M
L_T
c
$Q_M Q_P L$
Q_P
d
$Q_P L_V L_S$
L_V
L_S
e
$Q_M P K$
P
K

Figure 16. Triangular diagrams for detrital modes of Wenatchee Formation, Washington. Format similar to Figure 9.



QFL
$Q(Q_M+Q_P)$
F
L
a
Q_MFL_T
Q_M
F
L_T
b
Q_MQ_PL
Q_M
Q_P
L
c
$Q_PL_VL_S$
Q_P
L_V
L_S
d
Q_MPK
Q_M
P
K
e

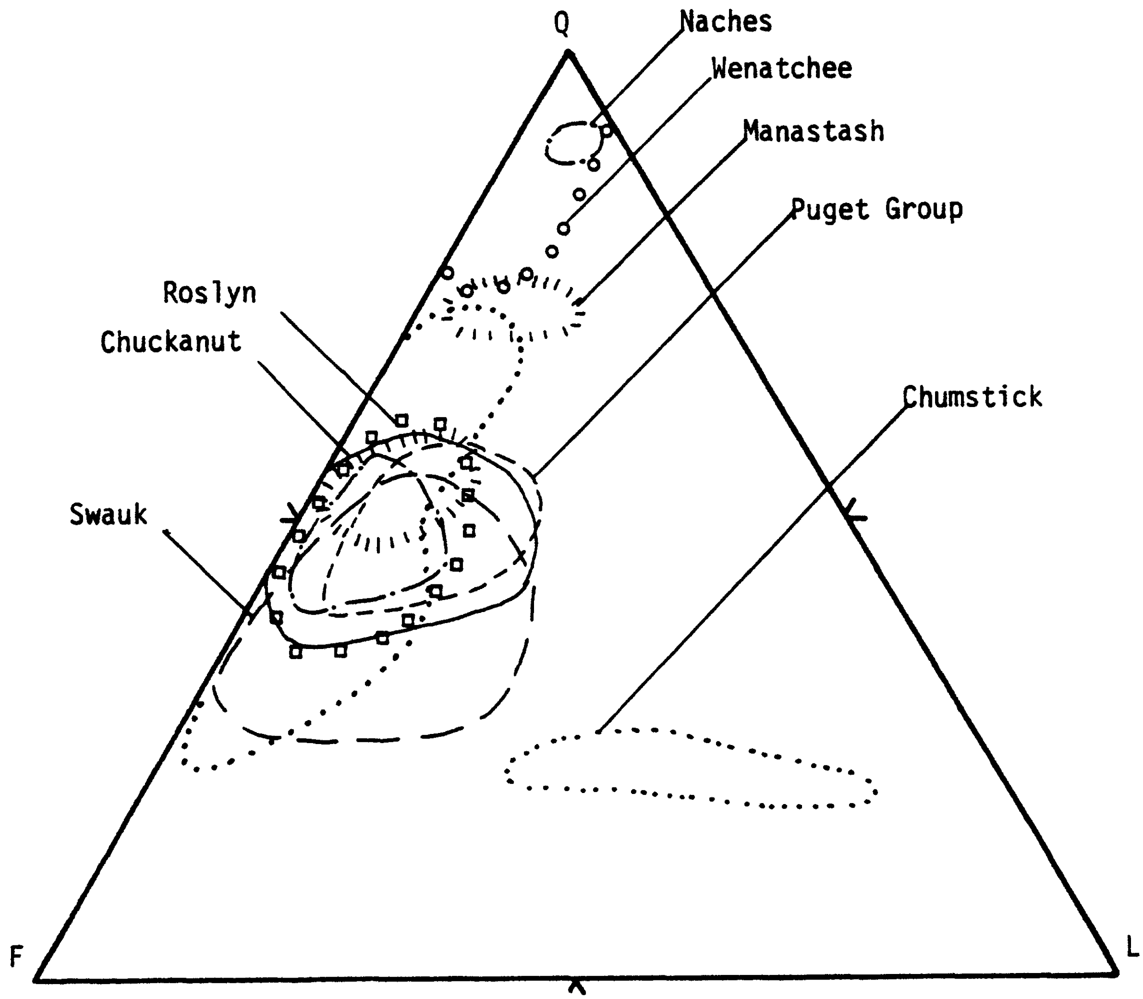


Figure 17. Triangular diagram comparing QFL plots of eight nonmarine sandstone units from Washington. Outlined are domains which include 90 percent or more of sample modes for each unit.

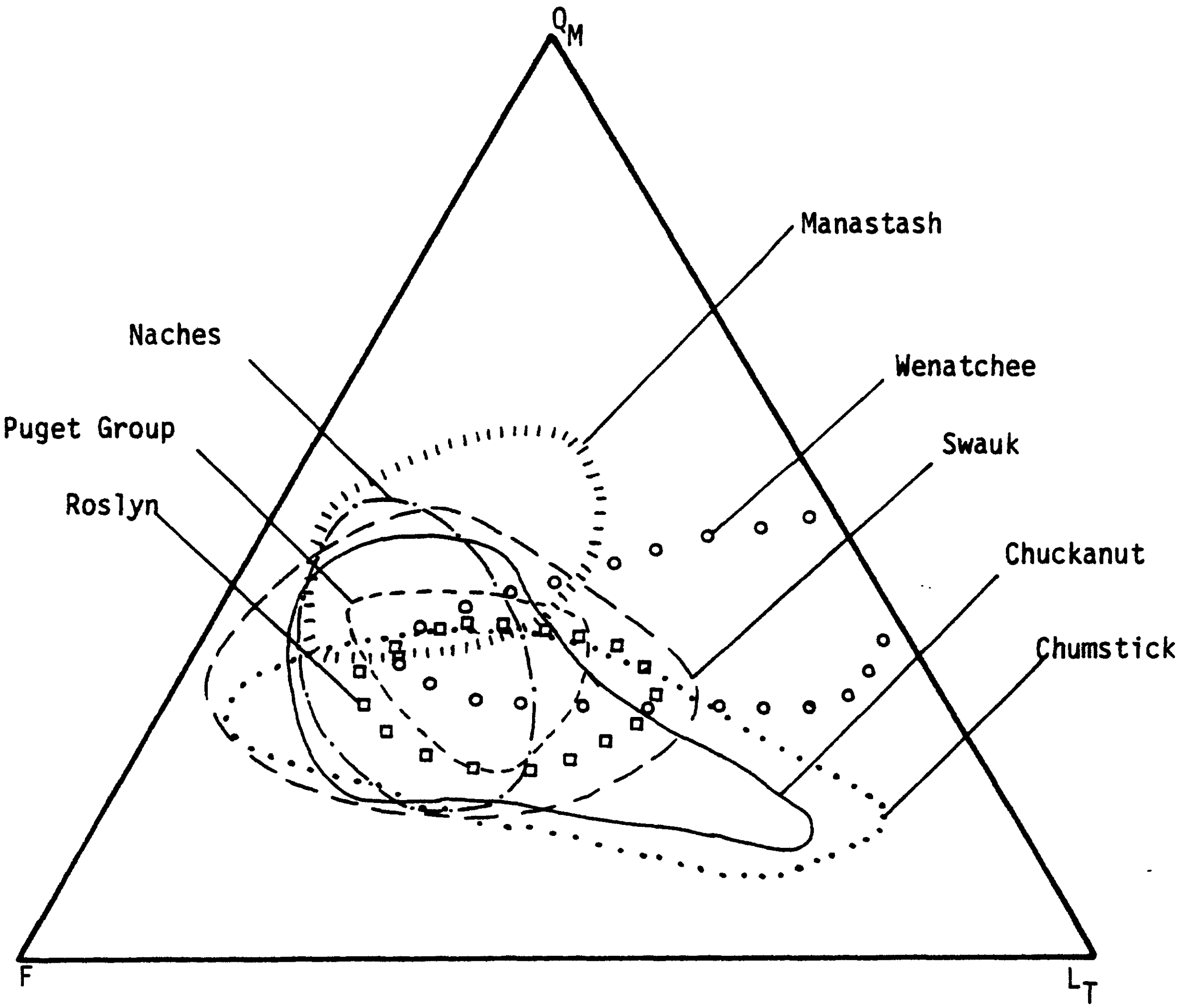


Figure 18. Triangular diagram comparing Q_MFL_T plots of eight nonmarine sandstone units from Washington.

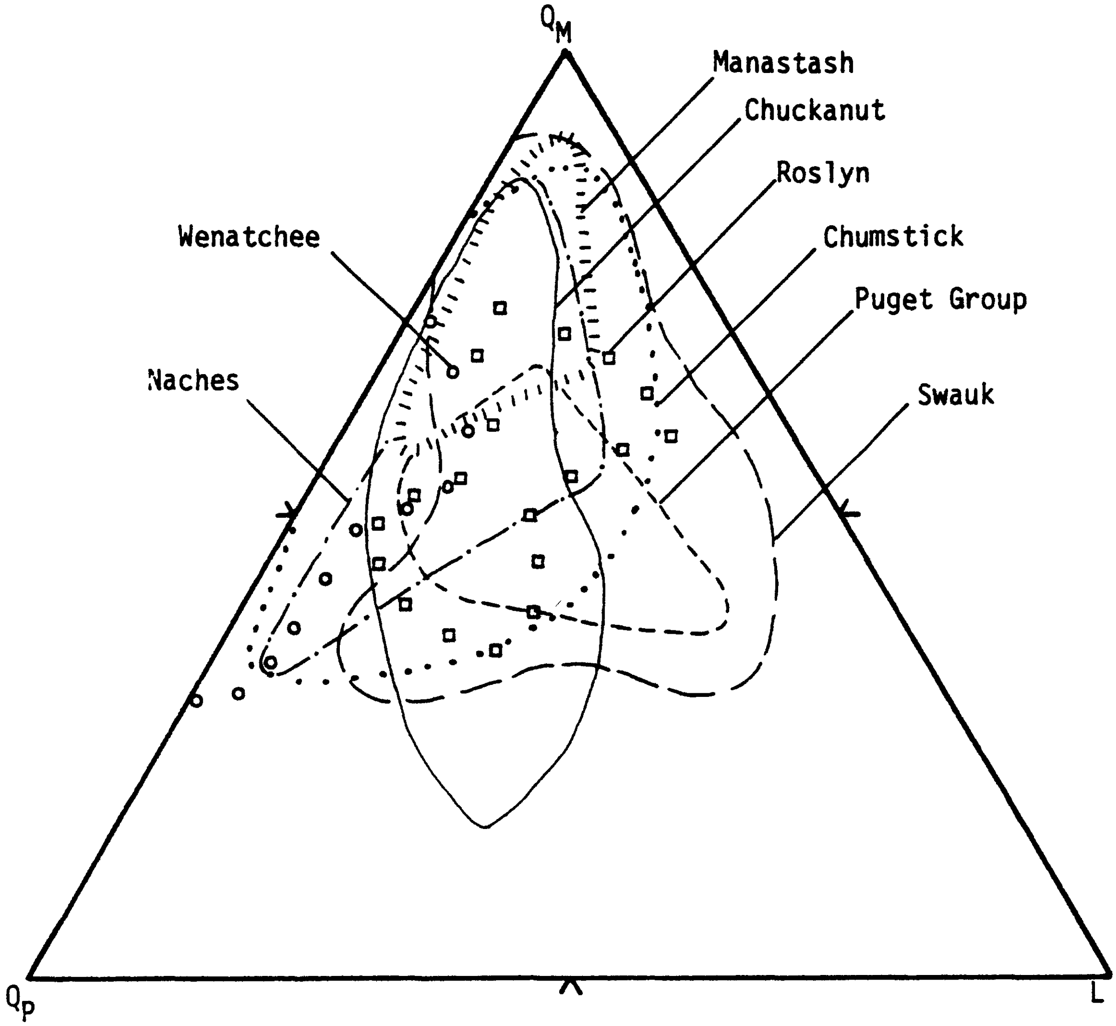


Figure 19. Triangular diagram comparing Q_MQpL plots of eight nonmarine sandstone units from Washington.

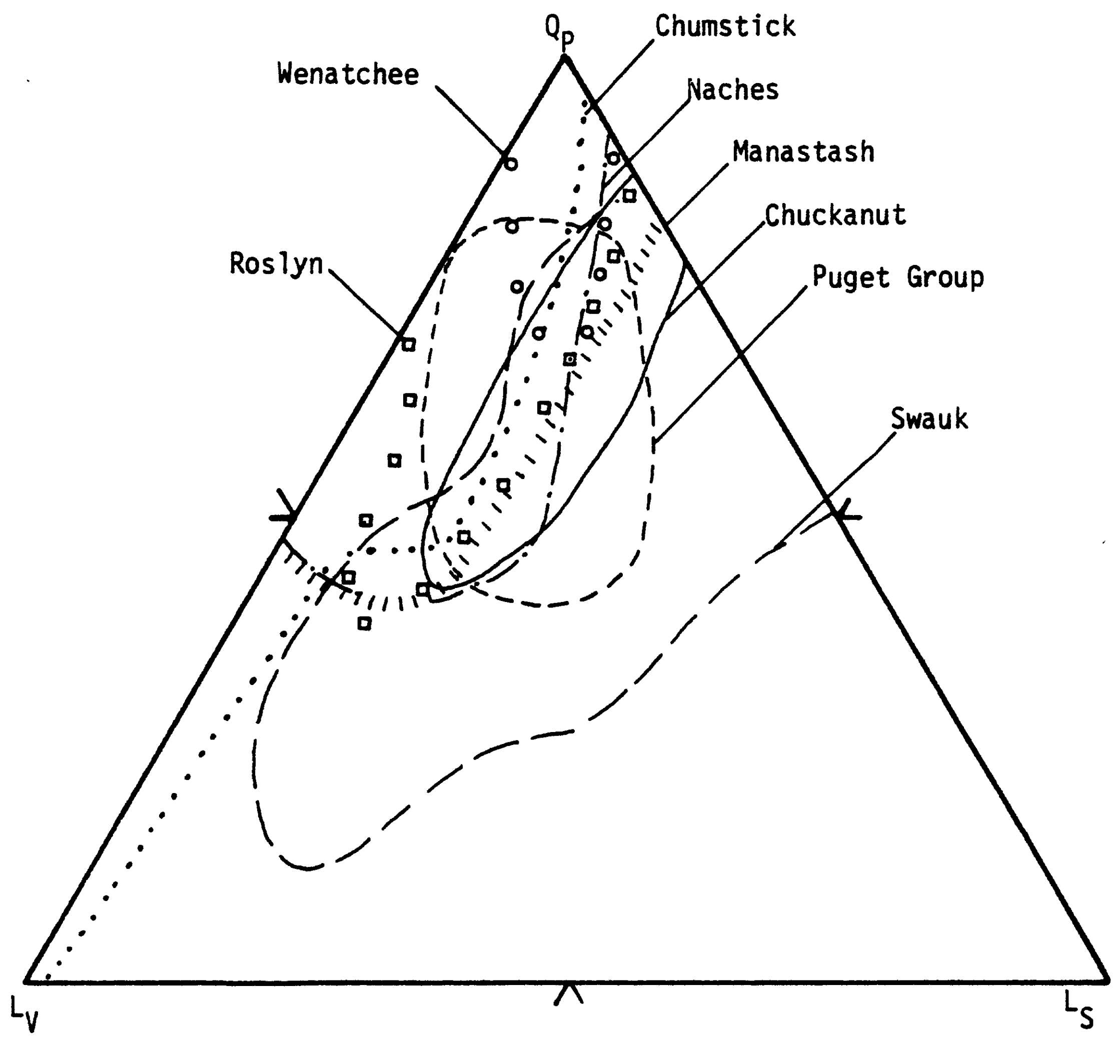


Figure 20. Triangular diagram comparing $Q_pL_VL_S$ plots of eight nonmarine sandstone units from Washington.

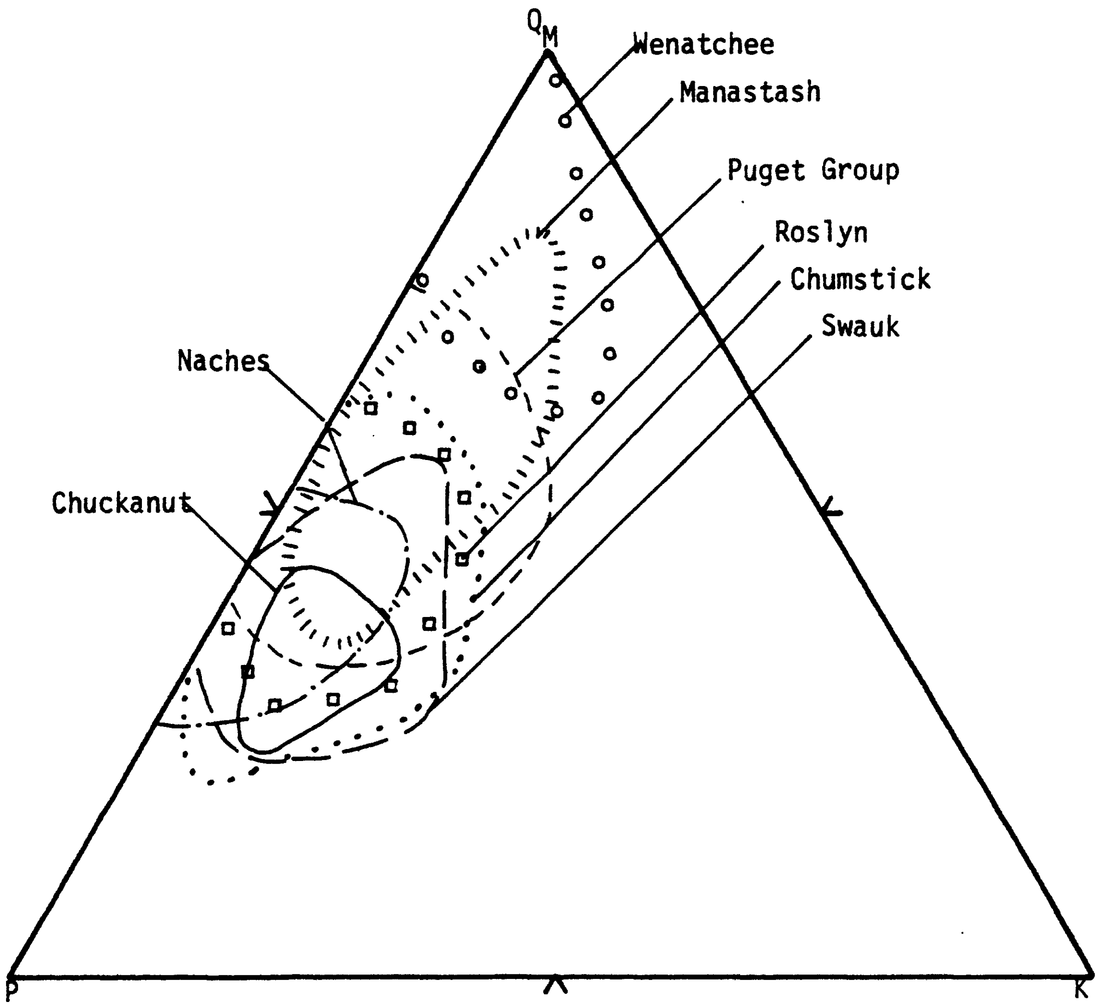


Figure 21. Triangular diagram comparing Q_MPK plots of eight nonmarine sandstone units from Washington.

source terrane and tectonic regimen in the source terrane.

Dickinson (1970, p. 704-706 and Table 4 reproduced here as Table 2) gives "typical" values for the various grain parameters in subquartzose sandstones derived from either idealized volcanic, plutonic, or tectonic provenances or mixtures of different types of provenances within orogenic belts. Dickinson (1970) describes tectonic provenances as uplifted supracrustal strata composed mostly of chert, sediments, and metasediments. Dickinson and Suczek (1978, and in press) go one step further in stating that various triangular plots jointly discriminate the chief tectonic provenance types, namely: magmatic arc, continental block, and recycled orogen. Based upon their criteria alone, the following generalizations can be made about the western Washington arkosic units.

Total quartz content (40 to 56 percent, and 78 percent for the Wenatchee) and special parameters such as mica and chert (the mean amount of total mica, biotite plus muscovite, not shown in Figure 8, ranges from 4 to 9 percent) indicate a combination of plutonic and tectonic provenances.

With the exception of the Wenatchee Formation, feldspar content (45 percent overall mean) and lithic content (10 percent overall mean) suggest a plutonic source. The ratio of polycrystalline quartz to total quartz (Q_p/Q) average 0.32 overall. This value is between the plutonic (near 0) and tectonic (0.5+) values.

Values for the ratio of plagioclase to total feldspar (P/F) are all between 0.75 and 1.0, which could be indicative of volcanic source terrane. The P/F values for the other two terrane types, however, are cited as variable by Dickinson (1970), so evidence for a volcanic source

	Volcanic	Plutonic	"Tectonic"
Q	low, <25	high, 50±25	mod, 25–50
F	mod, 25–50	high, ~50	low, <25
L	high, 50–75	low, <25	mod, ~50
C/Q	low, near 0	low, near 0	high, 0.5+
P/F	high, 1.0–0.75(?)	variable	variable
V/L	high, near 1.0	variable	mod, ~0.5
Special	pyriboles	mica	"chert-grain"

Table 2. Typical values for grain parameters in subquartzose sandstones derived from volcanic, plutonic, and tectonic provenances within orogenic belts. From Dickinson, 1970, Table 4.

terrane must be considered inconclusive.

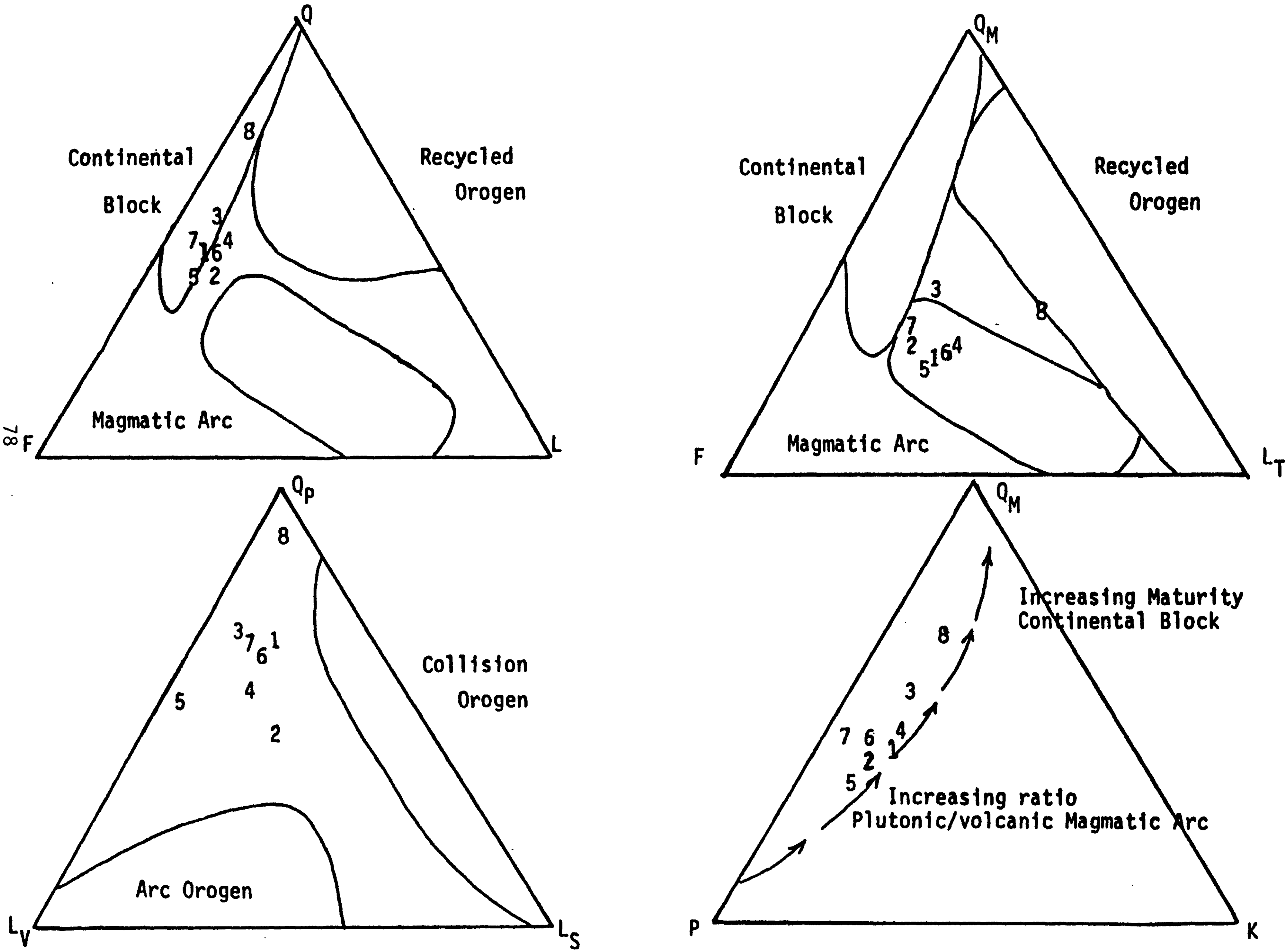
A volcanic source terrane overprint for the Chumstick Formation is emphasized by its high volcanic lithic to lithics ratio (L_V/L) of 0.92. The Chuckanut, the Swauk, and the Wenatchee Formations, on the other hand, have L_V/L ratios of 0.44, and 0.58, and 0.50 respectively, indicative of tectonic provenances. (Plutonic source terranes have "variable" L_V/L ratios.) L_V/L ratios for the other units with the exception of Swauk(?) are between these extremes.

Comparison of mean framework grain modes from the nonmarine subquartzose sandstone units of Washington with triangular plots for 75 selected sandstone suites from different types of tectonic provenances compiled by Dickinson and Suczek (in press) also indicate a combination of source terranes.

The mean QFL ternary ratios (Figure 22) plot within and adjacent to the continental block domain delineated by Dickinson and Suczek. Removal of the Q_P from the Q_M corner and placing it into the L_T corner yields a $Q_M FL_T$ triangular in which the Washington sandstone means fall predominately within the magmatic arc province. Note, however, that there is a merger of fields for plutonic basement and the roots of magmatic arc.

Plots of the $Q_P L_V L_S$ ratios of Washington sandstones on the triangular diagram of Dickinson and Suczek are somewhat confusing (Figure 22). The few sandstone suites from their original diagram shown in the area where most of the Washington sandstone means are plotted are from subduction complex sources. While such terranes may have been in part sources for some of the units, they certainly did not predominate. These modes probably indicate that the method of treatment

Figure 22. Triangular diagrams for mean framework modes for Paleogene nonmarine sandstone units, Washington. Provenance boundaries from Dickinson and Suczek (Figure 1, in press). Numerals indicate mean framework modes for: 1, Chuckanut Formation; 2, Swauk Formation; 3, Manastash Formation; 4, Puget Group; 5, Chumstick Formation; 6, Roslyn Formation; 7, Naches Formation; 8, Wenatchee Formation.


Q
Continental
Block
Recycled
Orogen
8
3
7 1 6 4
5 2
Magmatic Arc
F
L
Q_M
Continental
Block
Recycled
Orogen
3
8
7
2
5 1 6 4
Magmatic Arc
F
L_T
Q_P
8
3 7 6 1
4
5
2
Collision
Orogen
Arc Orogen
L_V
L_S
Q_M
Increasing Maturity
Continental Block
8
3
7 6 4
2 1
5
Increasing ratio
Plutonic/volcanic Magmatic Arc
P
K

of polycrystalline quartz grains used here treats more grains as Q_P relative to Q_M than the method used by Dickinson and Suczek.

The triangular plot of Q_MPK emphasizes the relative maturity of the Wenatchee Formation. The quartz rich Manastash Formation also is of relatively mature.

The modal data suggests that the sandstone units were derived from a mixed plutonic and tectonic source terrane of continental block tectonic province. A strong overprint of debris from a magmatic arc is also indicated, especially for the middle Eocene and younger units.

Volcanic Rocks in Early Eocene Arkosic Sandstones

It is interesting to note that the lack of volcanics has been suggested as a useful characteristic for distinguishing the Swauk and Chuckanut Formations from younger units (Yeats, 1958, p. 150). Since the Silver Pass Volcanics is now known to be interbedded with the Swauk and since volcanic rocks are apparently interbedded in the upper(?) parts of three of the isolated arkosic bodies (once believed to be Swauk), there appears to be problems with this generalization. I do not feel, however, that the generalization should be completely discounted. It is probably significant that the older Chuckanut and Swauk Formations have relatively low and subequal L_V/L ratios (Figure 8 and Table 1). Furthermore, the Chuckanut appears to have different compositions in different areas.

Six of the seventeen samples collected from the main outcrop area south of the eastwest line shown on Plate 1 have an average L_V/L ratio of 0.18 ± .24; while north of the line eleven samples have an average L_V/L ratio of 0.58 ± .16. The one exceptional sample to the low L_V/L ratio for the southern samples has a L_V/L ratio of 0.6. This sample is near the axis of a syncline not far from the locality that yielded the datable rhyolite clast. Because of the small numbers of samples involved and the unconfirmed assumption that the section becomes younger to the north, the apparent difference in composition may only be a statistical artifact, but it certainly indicates a possible direction for further investigation.

The fact that the Manastash Formation, which was presumably deposited coevally with the Swauk, fails to share a low L_V/L ratio with the Swauk and Chuckanut Formations is somewhat enigmatic. Several possible answers to the problem are possible. Perhaps the Manastash had a separate basin and its own source terrane including the quartz diorite gneiss and Lookout Mountain Formation of Stout (1964). The relative quartz and volcanic clast enrichment of the Manastash could be explained by chemical and physical elimination of feldspars and sedimentary lithic fragments. Or, perhaps the Manastash was emplaced tectonically. Of the three, the second or perhaps a combination of the first and second seem the most probable.

Volcanic Rocks in Younger Units

The importance of the contribution of volcanic detritus to the Puget Group, Chumstick, and Naches Formations is not only evident from the intercalations of tuffs, flows, and breccias in those units, but is also indicated by the $Q_pL_VL_S$ triangular plots (Figures 12d, 13d, 15d) on which the domains for each of the units partially share the Q_p-L_V edge as a common boundary. The Roslyn Formation, while lacking extensive intercalations of volcanic rocks, also contains relatively large amounts of volcanic detritus.

As I noted above, the Naches Formation is composed predominantly of volcanic rocks with subordinate intercalations of arkosic sands. This fact makes it difficult to understand why the Naches should have a lower L_V/L ratio than the Chumstick, for instance, which is predominantly sandstone with minor intercalations of tuff. In the case of the Chumstick, much of its source area was the metasedimentary(?) Swakane Biotite Gneiss terrane to the east, and clasts derived from it were probably mostly mineral grains not sedimentary lithic fragments. This, and the fact that volcanic clasts seemingly never leave distributional systems, would produce relatively high L_V/L ratio.

The relatively low L_V/L ratio in the predominantly volcanic Naches Formation is not as easy to explain. Although not completely satisfactory, the only way to rationalize the low L_V/L ratio seems to be in keeping volcanic clasts from getting into the fluvial system from which the arkosic sands were deposited. The presence of arkosic sands throughout the Naches indicates that such sands were always available. Disributional systems may have been disrupted during periods of volcanic activity so that arkosic materials were not deposited as descrete beds. The volcanic flows and debris filled drainage channels and low areas and may have been covered by subsequent deposition of arkosic sands. If the streams remained in a depositional mode with little erosion, they could inundate volcanic highs while eroding little volcanic material from their flanks.

A similar model, that is one which keeps volcanic material out of an arkosic distributional system, has been suggested for the Puget Group.

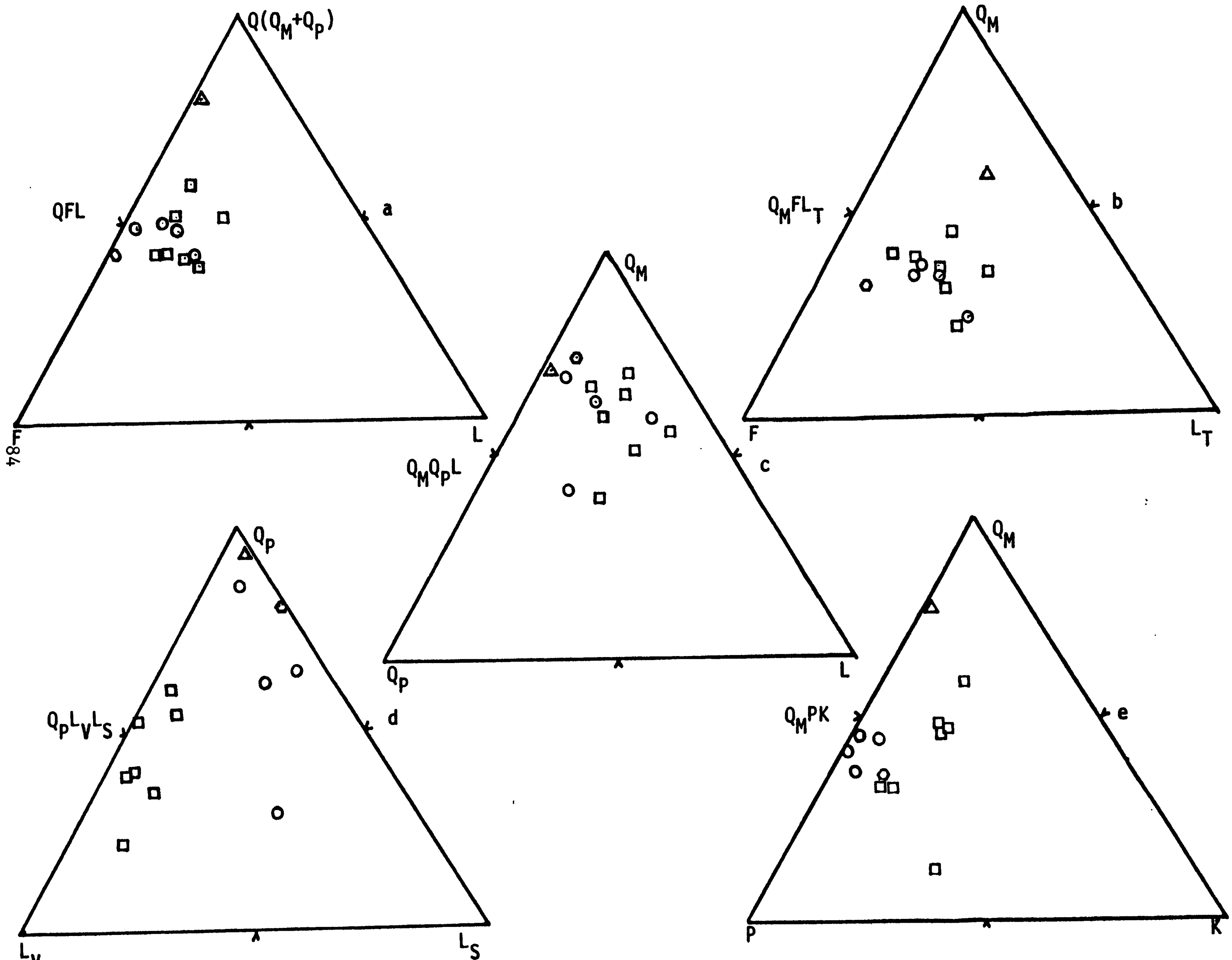
Hartman (1973) noted a systematic increase in L_V/L in stratigraphically younger intervals of the Puget Group. This increase may be reflected in Figure 12d where the Renton Formation is relatively more rich in volcanic clasts than is the Tiger Mountain Formation. Considering that volcanic rocks of the Tukwila Formation were being deposited at the same time as the arkosic rocks of the Renton Formation, the L_V/L ratio for these rocks is relatively low. Buckovic (1979, p. 156) proposes Yazoo-like stream courses between the volcanic rocks and the arkosic deltaic system to explain the lack of mixing between these two source types.

Description of Isolated Arkosic Bodies

I counted 13 samples of sandstone from the isolated arkosic bodies; the modal data presented in Table 9 of Appendix III. The data for all samples is summarized in triangular diagrams in Figure 23, while the data for the bodies near Sedro Woolley and near Skyomish have been converted to ternary and secondary ratios presented in Table 3. Small numbers of samples prevent rigorous analysis, but some points are notable. Sample DP-8 is quite quartz rich and lithic poor, and if it is representative of the sandstones from Mt. Higgins, than the average modal composition certainly would be quite different from either the Swauk or Chuckanut. RWT-525-76 collected north of Sedro Woolley is also somewhat lithic poor relative to either Chuckanut or Swauk.

The seven samples collected from the isolated arkosic body south of Sedro Woolley have relatively more monocrystalline quartz than the Chuckanut or Swauk, apparently at the expense of both lithics and feldspar. Interestingly, while the unit appears to have volcanic interbeds near its eastern boundary, the L_V/L ratio is 0.60 or the same

Figure 23. Triangular diagrams comparing modes of four isolated Paleogene arkosic bodies; Western Cascade Foothills, Washington. Format similar to Figure 9. Triangle, near Mt. Higgins; hexagon, north of Sedro Woolley; circles, southwest of Skykomish; squares, south of Sedro Woolley.


QFL
Q(QM+QP)
F
L
a
QMFLT
QM
F
LT
b
QMQPL
QM
QP
L
c
QPLVLS
QP
LV
LS
d
QMPK
QM
P
K
e

	South of Sedro Woolley (7)	Southwest of Skykomish (4)
QFL	53,42,5	47,43,9
Q_MFL_T	38,42,20	33,43,23
Q_MQ_PL	66,26,9 (38,15,5)	59,25,16 (33,14,9)
$Q_PL_VL_S$	75,15,10 (15,3,2)	61,9,30 (14,2,7)
Q_MPK	48,34,19 (38,27,15)	43,54,3 (33,41,2)
Q_P/Q	.28	.30
P/F	.64	.95
L_V/L	.60	.36

Table 3. Ternary ratios and secondary parameters for two isolated arkosic bodies, Washington. See text for discussion of units and definitions of parameters.

as the overall ratio for Swauk or the "upper" part of the Chuckanut discussed above. In addition, the unit south of Sedro Woolley is relatively rich in potassium feldspar.

While the arkosic unit southwest of Skykomish has interbedded volcanics high in the section, it too has a quite low L_V/L ratio; that is 0.36. Apparently the framework clast composition of these units emphasizes the relative overall homogenity of a given unit irregardless of the contribution from local sources.

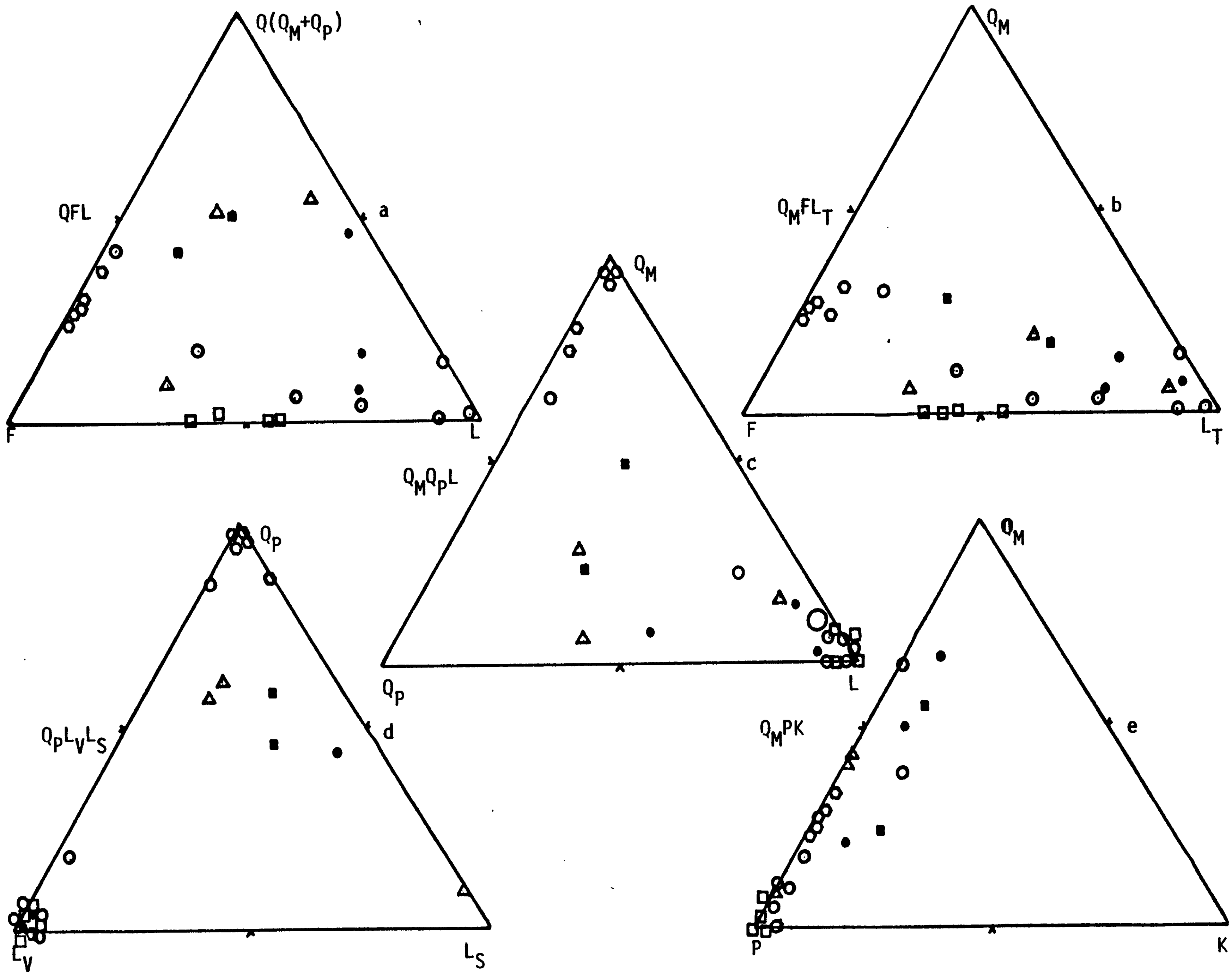
Other Modal Analyses

I produced 24 additional analyses (Appendix III, Table 10) predominantly from tuff and tuffaceous sandstone samples from Paleogene units not otherwise herein treated so that they might be compared with the units under studies, these include: the Huntingdon Formation, rocks underlying the Wenatchee Formation referred to as Swauk(?) by Gresens and others (in press), the Raging River and Tukwila Formations, rocks of Bolson Creek of Lovseth (1975), and the Blakeley Formation. Triangular diagrams are shown in Figure 24, and ternary and secondary ratios are shown in Table 4.

The two Huntingdon Formation samples are relatively lithic rich and feldspar poor compared with the Chuckanut Formation which underlie it. Differences in Q_M, Q_P, chert, and mica between the two samples must reflect varying supply from different source areas. The low L_V/L ratio indicates that no nearby volcanic source area existed or that contributions from volcanic source areas were minor during the time of deposition of beds represented by these samples.

The unit underlying the Wenatchee Formation at the Chopper Hill reference section is referred to as Swauk(?) by Gresens (1975, 1976, p.

Figure 24. Triangular diagrams comparing detrital modes of six Paleogene arkosic and volcaniclastic sandstone units, Washington. a. QFL plot; b. $Q_M F L_T$ plot; c. $Q_M Q_P L$ plot; d. $Q_P L_V L_S$ plot. Closed squares, Huntington Formation; open hexagons, Swauk(?) of Gresens near Wenatchee; open triangles, Raging River Formation; open squares, Tukwila Formation; closed circles, rocks of Bolson Creek; open squares, Blakeley Formation.


Q(QM+QP)
QFL
a
F
L
QM
QMFLT
b
F
LT
QM
QMQPL
c
QP
L
QP
QPLVLS
d
LV
LS
QM
QMPK
e
P
K

	Huntington Formation (2)	Swauk(?) Formation (5)	Raging River Formation (3)	Tukwila Formation (4)	Rocks of Bolson Creek (3)	Blakeley Formation (7)
QFL	46,34,19	30,69,0	38,33,28	1,45,52	24,13,63	10,28,62
Q_MFL_T	23,34,42	27,69,3	10,33,56	1,45,52	9,13,78	7,28,65
Q_MQ_PL	35,35,30 (23,23,19)	90,10,0 (27,3,0)	15,42,42 (10,28,28)	2,0,98 (1,0,52)	10,17,72 (9,15,63)	10,4,86 (7,3,62)
$Q_PL_VL_S$	55,17,29 (23,7,12)	100,0,0 (3,0,0)	50,38,12 (28,21,7)	0,100,0 (0,52,0)	13,68,19 (9,49,14)	5,95,0 (3,62,0)
Q_MPK	40,47,12 (23,27,7)	28,72,0 (27,69,0)	23,77,0 (10,33,0)	2,98,0 (1,45,0)	41,50,9 (9,11,2)	26,66,8 (10,25,3)
C/Q	.5	.1	.61	.13	.71	.15
P/F	.79	1.0	1.0	1.0	.82	.89
L_V/L	.37	--	.75	1.0	.72	1.0

Table 4. Ternary and secondary ratios for three arkosic and three volcaniclastic units, Washington.

376 and 377, and Gresens and others, in press) based on lack of potassium feldspar, chlorinization of biotite, and steep dips. The rocks are predominantly composed of plagioclase, quartz, and mica, however, and contain neither chert nor lithic fragments which are commonly found in the Swauk. The Swauk and Chumstick Formations have identical average potassium feldspar content. Because of the lack of chert and lithic fragments present in most Swauk sandstones, and because the composition is mostly plagioclase, quartz, and mica, the rocks are probably potassium feldspar poor, debris flows similar in mode of origin to those found in the Chumstick east of the Leavenworth fault.

The remaining four units have obvious volcanic affinities; average total quartz is low; L_V predominates in QpL_VL_S ratios; P/F and L_V/L are near 1.0. The volcaniclastic Raging River and Blakeley Formations underlie and overlie, the Puget Group, respectively, and are both at least partially marine in origin. Some of the samples included in the modal data for the Blakeley Formation are from rocks assumed to be correlative with the Blakeley. The modal values for the rocks of Bolson Creek indicate a mixed source terrane.

SIGNIFICANCE OF PALEOGENE SEDIMENTS TO THE STRAIGHT CREEK FAULT

The Straight Creek Fault

The Straight Creek Fault is a nearly north-south trending fault that juxtaposes two differing terranes. Vance (1957, p. 302) first mapped the fault in the vicinity of Darrington where it separates higher grade metamorphic rocks on the east from sedimentary rocks and low grade metamorphics on the west. Subsequently Misch (1966, p. 108) mapped the fault northward where it is cut off by Chilliwack Batholith. North of the batholith, the fault continues as the Hope fault, the western fault of the southern extension of Fraser River Fault system (McTaggart and Thompsen, 1967, p. 1226). Yeats (1958, p. 237) mapped an en echelon continuation, the Evergreen Fault, to the south. Ellis (1959) and Foster (1960) mapped the southernmost extension, the Kachess Fault, to the Yakima River. The fault has recently been the part of a controversy from which several studies have resulted (including Vance, 1977; and Clayton and Miller, 1977).

Misch (1977, p. 37) compared rocks on the west side of the fault near Harrison Lake in Canada with similar rocks on the east side of the fault near Stevens Pass and suggested that right lateral strike slip had separated the two areas. In Canada Lowes (1972) mapped the Settler Schist which is composed of pelitic schists with porphyroblasts of garnet, staurolite, and kyanite and he commented (p. 17) upon the remarkable similarity between them and the Chiwaukum Schist (Page, 1939) in Washington. Lowes also mapped quartz diorite intrusives which he correlated with nearby Middle to Late Cretaceous intrusions and, in addition, he mapped locally present mafic and ultramafic rocks. While the association of garnet staurorite kyanite schists, Late Cretaceous quartz diorite intrusions, and ultramafic is present on opposite sides of the fault, an estimate of offset was obtained by me by summing the presumed offset of projections of both the northern and southern contacts of the Settler Schist and the Chiwaukum Schist to the Straight Creek Fault (shown diagramtically Figure 25) and dividing by two. The estimated offset is 160 km.

Timing of strike slip movement has been variously estimated. Misch (1977) noted that while demonstratably offset is Eocene, earlier movement was possible. While Anderson (1977) and Tipper (1977) suggest Jurassic or early Cretaceous movement, the late Cretaceous plutons may indicate that faulting occurred subsequent to their intrusion. Large strike slip movement has not occurred subsequent to the intrusion of the Chilliwack and Snoqualmie batholiths.

Swauk-Chuckanut Offset

Numerous simularities of composition, age, structure, and bedrock indicate that the Chuckanut and Swauk Formations may have originally been deposited as a single unit that has since been offset approximately 160 km by right lateral strike slip motion starting about 48 Ma (Figure 25). Darrington Phyllite underlie much of the Chuckanut Formation, and phyllite bodies can be found between Bellingham and near Easton where rocks with similar lithologies, the Easton Schist, underlie much of the Swauk Formation adjacent to the southern continuation of the Straight Creek Fault, the Kachess Fault of Foster (1960). The outcrops of Chuckanut, Swauk, and the isolated arkosic bodies has a distribution similar to these basement rocks. Both the Swauk and Chuckanut Formations are early Eocene in age, apparently older than any of the

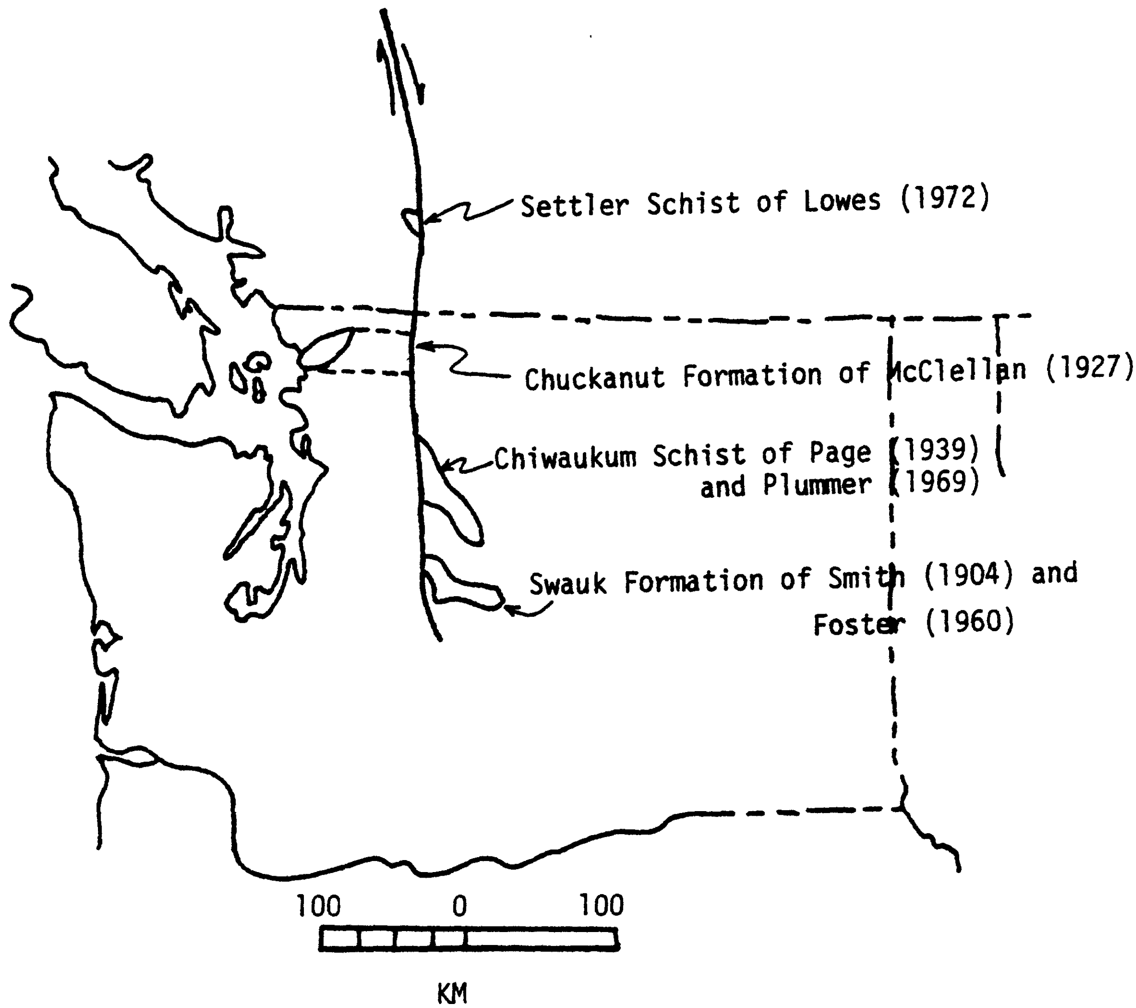


Figure 25. Right lateral strike slip offset along Straight Creek Fault. About 160 kilometers of offset is shown by aluminum-excess schists with a similar metamorphic history as suggested by Misch (1977). About 160 kilometers offset is also shown by offset of early Eocene Chuckanut and Swauk Formations.

other Paleogene sandstone units. Both have northwest trending folds which are permissive of right lateral strike slip movement. The Swauk Formation was folded and eroded prior to the extrusion of the Teanaway Basalt, and northeast trending feeder dikes for the Teanaway Basalts cut the Swauk Formation, permissive evidence that the rocks were still being subjected to the stress field responsible for right lateral offset, but no rocks correlative with the Teanaway have yet been found west of the fault.

Framework grain compositions of the Chuckanut and Swauk Fomations are quite similar (Figure 8 and Table 1). Chert composition is 4 and 2 percent for the Chuckanut and Swauk Formations, respectively. No other unit averages greater than 1 percent chert, and three contain essentially none. The ratio of volcanic lithics to volcanic plus sedimentary lithics for both units is lower than any other unit except the quartzose Wenatchee Formation.

The hypothesized 160 km offset of the early Eocene Chuckanut and Swauk Formations may help bracket age of much of the movement on the Straight Creek Fault. The lack of fanglomerates similar to those reported in the Chumstick Formation adjacent to the Leavenworth Fault by Cashman (1974) and Frizzell and Tabor (1977) along the Straight Creek indicates that deposition did not coincide with movement. Thus movement may have began sometime between eruption of the 50 Ma Silver Pass Volcanics of Foster (1960) and extrusion of the 47 m.y. Teanaway Basalt. Mildly deformed late(?) Oligocene volcanic rocks, abundant west of the fault, also occur in isolated areas east of the fault. Their occurrence on both sides of the fault suggest that major relative offset has not occurred since late Oligocene (Tabor and Frizzell, 1979).

While the hypothesized offset does not appear unreasonable, several unanswered questions remain. For instance, only a small amount of the area between the main outcrop body of the Chuckanut Formation and the Straight Creek Fault is underlain by Paleogene sandstone. The combined affects of uplift of the Chilliwack batholith, erosion, and burial by volcanic rocks might explain the absence.

Also troublesome is the lack of any marker beds which could firmly tie the units together. The discovery of rocks equivalent to the Silver Pass in the Chuckanut would greatly enhance the credibility of the hypothesized offset. But since the Silver Pass is thickest near the Straight Creek fault and the Chuckanut has been eroded from its possible position adjacent to the Straight Creek fault, the discovery of a more distal mafic tuff bed in the Chuckanut would be fortuitous.

The distribution of the isolated arkosic bodies is seemingly difficult to explain by movement solely in the Straight Creek fault. Movement on that fault was almost certainly accompanied by movement along en echelon faults, though. Additionally, the isolated arkosic bodies only occur north of the east-west trending left lateral strike slip Devil's Mountain Fault of Oligocene age described by Whetten (1978, p. 153). Complex structural relationships between undiscovered faults en echelon to the Straight Creek or to the Devils Mountain faults may explain this distribution.

Discussion

By the beginning of the Eocene time the basement terranes for the Paleogene sediments had been amalgamated. The area now called the San Juan Islands was somewhat southwest of the present site of Mt. Stuart. The laterite developed on serpentinites of the Ingalls Complex may indicate that the region was relatively stable and perhaps of low relief. At about 55 Ma two temporally related events took place: the Kula-Pacific spreading ridge "jumped" an undetermined distance north, and the Mt. Stuart batholith rose to a level at which apatite would begin to keep fission track (Erikson and Williams, 1976). A fault bonded block composed of the Mt. Stuart batholith and the suprajacent Ingalls Complex and Chiwaukum Schist became an upland source area for the Swauk and Chuckanut Formation, and deposition of these units began. About 50 Ma the Silver Pass Volcanics erupted and volcanic rocks became intercalated with sandstones as deposition of arkosic sediments continued. By about 48 Ma the change in plate motion due to the ridge jump caused right lateral strike slip faulting.

The Swauk Formation and intercalated Silver Pass volcanics were folded and eroded prior the eruption of the Teanaway Basalt. Northeast trending Teanaway dikes in folded Swauk Formation sandstones may indicate that the region was still in a strike-slip-type regimen during Teanaway time. The same stress field may have been responsible for the formation of the Chiwaukum graben.

Deposition within the graben evolved from coarse fanglomerates to fine grained lacustrine deposits. Tuffs in the Chumstick, the intercalation of a tongue of Teanaway Basalt in lower parts of the Chumstick Formation, and interbeds of arkosic sandstone in the Teanaway indicate that arkosic sedimentation and volcanism were coeval.

These interbedded relationships and the volcanic affinities of the middle Eocene Raging River Formation attest to widespread, but perhaps not dominating, volcanic activity during middle Eocene, but whether the volcanics were magmatic arc related is difficult to determine. Marine fossils in the Raging River Formation indicate that the shoreline was within forty miles of the Straight Creek Fault. The fluvial-deltaic Puget Group prograded over these marine rocks and provided, apparently coevally with volcanic activity, environments conducive to the formation of coal.

South of Mt. Stuart, the middle(?) to upper Eocene Roslyn Formation was deposited conformably on the Teanaway as volcanism waned. In upper Roslyn time supply of arkosic materials became sporatic and interbeds of coal resulted.

Volcanic activity became dominant over arkosic sedimentation sometime after late Eocene. The predominantly volcanic nature of the Naches Formation, with relatively minor arkosic sands, and the volcaniclastic sands in the Blakeley which overlies the Puget Group attest to this change. These and subsequent volcanic rocks are almost certainly arc related. If the Pacific-Farallon ridge were complicated by variously offset transforms, arc activity would likewise be complicated by periods of activity and quiescence as the Pacific-Farallon-North American triple junction changed its position along the margin of North America.

Appendix I.

Methodology for producing fission track ages.

Ten fission track dates (Table 1) were produced from volcanic rocks intercalated in the Paleogene sedimentary rocks. These dates, when combined with those recently produced by C. Naeser and J. Vance, and potassium argon ages produced by R. Tabor, provide a reasonable basis for assigning ages and relationships to the various units.

More than 40 samples were collected for fission track dating. Because of a general paucity of zircons, a minimum of 50 pounds was collected for each sample. At the outset, the primary concentration of heavies subsequent to crushing and pulverizing was done with a gold pan. Later this concentration was done with a Wilfly table.

Methylene Iodide (S.G. 3.32) was used at full density and at lesser densities (diluted with acetone) to produce sequential heavy liquid separates. A large hand magnet was used to separate magnetite and roller mill chips from the heavy liquid separate preceding magnetic separation using a Franz Isodynamic magnetic separater. The final Franz separate was examined for zircon or apatite at which time the decision was made to either continue sample preparation or dispose of the sample.

If a suitable quantity of zircon was available, the sample was hand picked and zircons were mounted in teflon, ground, and polished using techniques described by Naeser (1976) and C. Meyer (oral communs., 1975-1979). The single apatite sample was etched using a 7 percent HNO_3 solution as suggested by Naeser (1976). The zircons were etched using a NaOH-KOH eutectic melt developed by Gleadow, Hurford, and Quaife (1976). Zircon fission tracks were counted using the external detector method while the population method was used to count apatite tracks.

Raw fission track numbers were manipulated using age equations described by Naeser (1976) which were programed for use on a computer by C. Meyer (pers. commun., 1976) using constants from Steiger and Jager (1977). The two sigma values, estimates of analytical uncertainty, were derived using methods described by Naeser, Johnson, and McGee (1978).

Sample	Unit	Mineral	$\rho_s \times 10^6$ τ/cm^2	$\rho_i \times 10^6$ τ/cm^2	ϕ $\times 10^{15}$ n/cm^2	T $\times 10^6$ years	$\pm 2\sigma$ $\times 10^6$ years	U ppm	grains counted	date counted	comments
VF-75-633	Chuckanut	zircon	5.95 (400)	6.45 (217)	0.906	49.8	1.4	216	4	2-20-79	
VF-77-101	Silver Pass in Swauk	"	7.45 (715)	8.42 (404)	0.957	50.5	1.2	267	4	2-12-79	
VF-76-450	"	"	5.64 (198)	8.50 (150)	1.23	48.6	2.3	209	3	10-10-77	
ER-76-75	"	"	5.55 (808)	9.35 (680)	1.23	43.6	1.1	230	5	9-30-77	Age too young
VF-77-305	Taneum Andesite	"	3.95 (898)	6.09 (692)	1.34	51.8	1.0	138	4	2-15-79	
RWT-469a-76	"	"	3.71 (851)	5.80 (665)	1.21	45.3	1.1	145	5	10-5-77	Age too young
VF-78-115	Tukwila	"	6.38 (781)	8.66 (535)	0.939	41.3	2.3	28	5	2-23-79	
RWT-644-77	Wenatchee(?)	"	8.91 (1759)	1.55 (1529)	0.956	32.8	0.65	492	5	2-5-79	
VF-77-149	"	apatite	2.27 (5)	7.26 (3)	0.954	35.6	20.3	0.12	50	3-6-79	U conc. too low
VF-78-323	Stevens Ridge(?)	zircon	2.29 (1033)	4.04 (959)	0.956	32.4	0.6	128	5	2-26-79	

Table 1. Fission track data. $\lambda_F = 7.03 \times 10^{-17}$ year^{-1}; ( ) = number of tracks counted.

Appendix II.

Methodology of point counting and calculating modal data.

While texts such as Cheyes (1956) and Carver (1971) and articles such as Kelly (1971) and Galehouse (1971) are helpful in developing an appreciation for the point counting technique, they are not directed to the problem of how to actually do point counting.

Numerous studies using point count data have been done which incorporate point counting techniques as a major component. Recent west coast examples include Ingersoll (1978); Jacobson (1978); and Tennyson and Cole (1978). However, these too, for the most part, avoid the "how to" issue.

One of the most recent applications of point count data is the comparison of modal characteristics with tectonic setting (Dickinson and Suczek, in press). Such comparisons are most useful if each set of data produced by different authors is produced using similar or comparable techniques. With this ideal situation as a goal, briefly set out below are the techniques followed in the production of such data.

Sample selection should be done with the future point counting in mind. Ideally, samples should have consistent grain size and, where possible, should be collected from the same relative position within the various beds sampled.

If possible, sample locations should be collected systematically with equal distribution of localities throughout the unit or units from which the samples are being collected. Unfortunately this is often not done, because most mapping and therefore sample collecting is done in areas of structural interest.

Standard petrographic thin sections should be prepared using epoxy for impregnation where required. Staining for potassium feldspar and plagioclase can be done to sections or to slabs using techniques outlined by Laniz, Stevens, and Norman (1964).

Various staining schemes are available. One involves staining one half of a thin section for both feldspar species, with the remaining half unstained. Each half is counted separately. The unstained half is counted first to determine the combined proportion of quartz, plagioclase and potassium feldspar to other components (the various lithics, other minerals, and matrix) and then the stained half is counted to determine the relative proportions of quartz, plagioclase, or potassium feldspar. Seemingly this method gives the best of both worlds: lithic fragments are not masked under layers of yellow and red, and very accurate ratios of the main mineral components are produced. One drawback is the obverse: no stain is available to help determine lithic types. For instance, potassium feldspar strain is one of the most useful characteristics in determining whether some grains are felsitic volcanic rock fragments or chert.

Another method, developed by R. J. McLaughlin (pers. commun., 1978), is to count a completely unstained section, thus determining the ratio of quartz, plagioclase, and potassium feldspar to other clast types. Then the thin section chips stained for both species are counted thereby determining the ratio between the three species.

The method used here was one which used sections stained only for potassium feldspar. The advantage over doubly stained sections is that lithic clasts are not masked by the double stain, yet the K-spar stain is present for volcanic rock fragment determinations. While the HF etch preceding the K-spar stain does cause a textural change on the surface of plagioclase, some untwinned plagioclase is undoubtedly missed and counted as quartz.

Subsequent to preparation of the thin sections an informal point count of representative sections should be made to determine what groupings to use when counting. Since the production of modal data that is comparable with that produced by other workers is an end goal, a minimum list of constituents should be counted in all cases with enlargements of these skeletal groupings as needed.

Dickinson (1960, Table 1) elaborated on the apices of the standard Q, F, L triangular diagrams. These three detrital grain parameters (quartz, feldspar, and lithics) are the minimum number of countable categories. In the same paper, however, Dickinson (1960, Table 2) introduced three useful secondary parameters that require differentiating: 1) polycrystalline quartz and chert from monocrystalline quartz, 2) plagioclase from potassium feldspar, and 3) volcanic rock fragments from other lithic fragments.

Thus there already are nine categories that should be counted, namely: monocrystalline quartz, polycrystalline quartz, plagioclase, potassium feldspar, volcanic lithic fragments, other lithic fragments, matrix, other, and unknown. Yet even these could be subdivided, as needed, to "fine tune" the point counting and several possible subdivisions are defined by Dickinson (1960, Table 3 and p. 701) and Graham and others (1976, p. 628). Examples of various grain types as observed in thin section are illustrated in Scholle (1979), Zimmerle (1976), and Vuagnat (1952).

The preliminary point counting of the feldspathic to lithofeldspathic subquartzose sandstones done for this research indicated that twenty-five categories of grain type could be counted. These categories and the modal data produced are shown in Appendix III.

A brief description of each category is as follows:

monocrystalline quartz: single crystal quartz grains with straight to undulose extinction, with or without overgrowths

foliated quartz aggregate: polycrystalline quartz with straight crystal boundaries and elongate crystals

equidimensional quartz aggregate: polycrystalline quartz with straight or curvilinear boundaries; equidimensional nonoriented fabric

undifferentiated polycrystalline quartz aggregate: all other polycrystalline quartz aggregates; probably ends up including some questionable chert

chert: microcrystalline, microgranular or chalcedonic monomineralic silica aggregates; may include very fine grained "dust" but when "dust" exceeds 50 percent noted as sedimentary rock fragment; may include ghosts of tests or spicules; never stains with potassium feldspar stain

plagioclase: monocrystalline to polycrystalline plagioclase; twinned or untwinned; often altered or replaced by either kaolinite, laumontite, muscovite, calcite or seiricite; most often eteched by HF bath preceding sodium cobaltinitrite strain for potassium feldspar potassium feldspar: monocrystalline to polycrystalline potassium feldspar; most easily determined in twinned or untwinned state by sodium colbaltinitrite stain

sedimentary rock fragments: angular to rounded microgranular mineral or lithic grains in matrix

quartz mica tectonite: metamorphic clasts composed of varying proportions of mica and quartz; planar oriented fabric

microgreanular hornfels: quartz with variable amounts of mica; equidimensional nonoriented fabric

felsitic volcanic rock fragment: siliceous fine grained, microgranular to devitrified; subordinate feldspar laths surrounded by microcrystalline groundmass of siliceous glass, quartz, and feldspar; potassium feldspar stain is great aid for differentiating these from detrital chert

microlitic volcanic rock fragment: intermediate; subordinate feldspar laths surrounded by microlites; felted

miscellaneous volcanic rock fragments: siliceous to mafic; lathwork, vitric; clasts not easily placed in other two volcanic fragment catagories

granitic rock fragment: polycrystalline, polymineralic; quartz, plagioclase, potassium feldspar, mica; not framework grain; numbers added to respective species for final figures

micas: biotite, muscovite, biotite often altered or replaced by chlorite, calcite; often occurs as psuedomatrix

pyroboles: amphibole, pyroxene

epidote:

garnet:

calcite:

kaolinite(?): most often aggregates of very fine grained colorless radiating platlets or piles of platelets; often with blocky outline of altered feldspar; may form psuedomatrix

chlorite: green, pleochroic; often with anomalous interference colors

alteration products: various intergranular(?) alteration products

matrix: material filling interstices between grains; Dickinson(1970) defines several categories

miscellaneous: clasts other than those listed above; i.e., opagues or various minerals

unknown: clasts of unknown affinity

Raw point count data are converted to percentages (Table 1) using methods modified from Dickinson (1970), Graham and others (1976), and K. Helmold (pers. commun., 1978). The sum of total points counted is divided into the unknown category which yields percentage of total points which were unknown when counted. The number of unknown counts are subtracted from total points counted which yield a figure that is divided into miscellaneous and matrix. This yields the percentage of the known components of the rock which are either matrix or miscellaneous.

The components micas, pyriboles, epidote, garnet, calcite, kaolinite (?), chlorite, and alteration products are divided individually by the subtotal remaining after the miscellaneous and matrix components were subtracted from their divisor. After the percentages of the above eight categories are derived, the sum of the eight categories is subtracted from their divisor.

The resulting difference consists of total framework clasts. The framework clast total is then divided into all remaining categories of grain types. From these percentages, framework grain parameters can be derived using methods outlined by Dickinson (1970) and Graham and others (1976).

Total quartz (Q) is derived by adding chert and polycrystalline quartz grains (collectively symbolized as Q_p) to monocrystalline quartz grains (Q_m). Total feldspar (F) is derived by adding plagioclase (P) to potassium feldspar (K). Sedimentary and metasedimentary lithic fragments (L_S) added to volcanic lithic fragments (L_V) yield lithics (L) which when added to Q_p produce total lithics (L_T).

These framework-grain parameters are variously combined to form ternary ratios. Such ternary ratios have been used to compare suitable sandstone units (Graham and others, 1976) or possibly to discriminate between sandstone units from differing tectonic regimens (Dickinson and Suczek, 1978). The components of the ternary ratios QFL and QFL_T are taken directly from the percentages derived from the point-count data. The components of the ratios Q_MQpL, QpL_VL_S, and Q_MPK however, are summed and recalculated to 100 percent before they can be plotted on triangular diagrams.

Three secondary parameters, essentially ratios of six of the above mentioned framework grain parameters, are suggested by Dickinson (1970) as refinements which may help describe a given unit. These include polycrystalline quartz to total quartz (Q_M/Q), designated C/Q in Dickinson (1970); plagioclase to total feldspar (P/F); and volcanic lithic to lithics (L_V/L).

Appendix III

Detrital Modes, Paleogene Sandstones, Washington State

Contents

Key to Tables 1-10

1 Map Number
2 Field Sample Number
3 (Total Points Counted)
4 monocrystalline quartz
5 foliated quartz aggregate
6 equidimensional quartz aggregate
7 undifferentiated polycrystalline quartz aggregate
8 chert
9 plagioclase
10 potassium feldspar + microcline
11 sedimentary rock fragments
12 quartz mica tectonite
13 microgranular hornfels
14 felsitic volcanic rock fragment
15 microlitic volcanic rock fragment
16 miscellaneous volcanic rock fragment
17 granitic rock fragment
18 micas (biotite + muscovite)
19 pyroxenes + amphiboles
20 epidote
21 garnet
22 calcite (some with hematite stain)
23 koalinite (?)
24 chlorite
25 miscellaneous alteration products
26 matrix
27 miscellaneous
28 unknown

List of Tables

1	CH-1	CH-2	CH-3	CH-4	CH-5	CH-6	CH-7	CH-8	CH-9	CH-10	CH-11	CH-12	CH-13
2	VF78-143	VF78-144	VF78-145	VF78-146	VF78-147	VF78-149	VF78-150	VF78-151	VF78-152	VF78-153	VF78-155	VF78-158	VF78-159
3	(476)	(553)	(460)	(478)	(449)	(443)	(501)	(424)	(625)	(653)	(598)	(485)	(445)
4	26	29	29	27	38	27	18	26	20	37	19	25	31
5							1	1					
6	2			1		1		1			1	1	
7	13	10	14	12	5	13	19	9	11	16	14	12	8
8		3	1	1	1		16	7	12		8	1	
9	49	43	41	40	45	42	24	32	31	27	31	44	45
10	7	4	11	14	9	14	3	4	2	9	6	9	9
11	1	2	2	3	1	1	8	5	6	3	8	4	3
12	2	2	1	1				1	1	1	1	1	
13						1				1	1		
14		6	1	1			3	3	5	3	4		1
15							1				1		
16							8	12	11	4	7	2	2
17	4	2	4	2	1	1	4	2	3	2	5	1	2
18	8	4	11	9	13	13	4	9	4	21	7	10	6
19													
20	1	2		1	1		2	1	1		1	1	1
21	1												
22		5											
23									1	12	3		
24						1							
25													
26	4	14	2	2	13	3	2	6	16	8	2	3	7
27	1	2			1	1	1	2	2	1		1	1
28	1	3	1	1		1	5	4	4	2	1	2	1

Table 1. Detrital Modes, Chuckanut Formation.

1	CH-14	CH-15	CH-16	CH-17
2	VF78-160	VF78-161	VF78-162	VF78-163
3	(470)	(489)	(481)	(525)
4	29	25	21	13
5				
6		2	1	
7	18	17	11	25
8	1	2		13
9	34	41	51	19
10	11	8	8	3
11	4	1	3	4
12			1	
13			1	
14		1	2	
15			1	
16	2	3	3	17
17	5	6	4	7
18	4	4	4	5
19				
20		3	1	1
21				
22				
23				
24				
25				
26	2	2	5	2
27		1		
28		1	1	2

Table 1. Continued.

1	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12
2	RWT11-75	RWT12-75	RWT186-76	RWT223-76	RWT275-76	RWT334-76	RWT500-76	RWT503-76	VF75-151	VF75-234	VF75-328	VF75-3456
3	(304)	(590)	(483)	(500)	(530)	(500)	(522)	(531)	(612)	(479)	(414)	(455)
4		29	29	48	24	29	40	58	24	22	35	32
5			1						1			1
6		1							4	3	1	2
7		11	5	5	4	4	8	24	6	6	3	2
8			4					2	18	1		1
9		43	29	28	46	57	34	9	31	48	49	46
10		9	12	9	10	10	11		2	3	13	3
11			2	2	2		1	3	7	5		4
12		3	2	2	1	1				1		1
13		1	1	4	1				1	5		2
14			7		4				2	6		4
15			2		2				4	1		2
16	79	3	5	1	7		8	2	1	1		1
17		9	6	3	5	8	1		2	3		2
18		14	1	4	3	8		1	1	4	9	14
19			2	4	2	3						
20			2	3	2	1			2			
21										1		
22	20	1		14								
23												
24		1										
25												
26		9			3			9	11	13	1	5
27	46	1	1	2	1	2	3	1	2	1	8	1
28		2	7	1	1				4	4		3

Table 2. Detrital Modes, Swauk Formation.

1	S-13	S-14	S-15	S-16	S-17	S-18	S-19	S-20	S-21	S-22	S-23	S-24
2	VF75-381	VF75-440	VF75-443	VF76-143	VF76-167	VF76-173	VF76-176	VF76-177	VF76-180	VF76-209	VF76-242	VF76-244
3	(506)	(350)	(445)	(439)	(521)	(463)	(511)	(626)	(529)	(453)	(533)	(628)
4	26	38	25	28	31	24	21	25	28	44	23	29
5		1	2				2					
6	2		3		2			1	5			
7	2	5	8	4	3	6	6	5	2	4	5	3
8		1	4	5	1	4	6		2			
9	42	38	49	39	38	44	41	51	39	45	58	42
10	21	15	1	11	10	7	7	9	3	6	9	2
11	2	1	4	5	1	5	4	1	2			2
12	1	1	2		1	1		1		2	2	2
13	2	1	1	3			1		1	1	2	1
14	2			1	4	3	7	3	10			9
15				1	3	2	4	2	3			1
16			1	3	3	5	2	3	4		1	6
17	3		2		1		1	2	2	2	11	4
18	10	3	6	11	6	4	1	10	2	15	9	4
19	2											
20	2			2	2	1	6	2				1
21							3					
22									3			8
23												
24												
25												
26	8	2	1	5	6	6	14	1	2		2	
27	1	2	5	2	7	3	13	5	14	1		2
28	2	2	2	2	2	3	3	3	1		1	1

Table 2. Continued.

1	S-25	S-26	S-27	S-28	S-29	S-30	S-31	S-32	S-33	S-34	S-35	S-36
2	VF76-245	VF76-256	VF76-262	VF76-319	VF76-348	VF76-351	VF77-106	VF77-236	VF77-327	VF77-465	VF77-510	VF77-588
3	(480)	(601)	(532)	(510)	(536)	(507)	(420)	(325)	(601)	(465)	(565)	(603)
4	27	34	25	30	20	24	26	19	36	40	25	35
5					1	1			1			
6	1	1			1		2	1	1		1	2
7	3	8	8	8	3	2	3	8	2	3	2	10
8					9	7	1	1	6		2	
9	48	34	60	52	30	26	41	40	24	38	48	47
10	2	4	7	8	8	7	14	4	7	13	6	1
11		1			6	7		4	4	1	4	
12	1	12		1			1	2				1
13		7		1			1	1				2
14	6				12	8	5	18	13	3	9	
15					5	7	7	1	2		2	1
16	11				4	9		1	3			3
17	4	7	19	6	1		1	5	1		4	4
18	4	8	13	9	1	3	3	7	1	2	1	1
19				2								
20		3		3						1	3	4
21												4
22									18			
23												
24												
25												
26				2	1	3	3	3		2	4	
27	1	2	3	2	3	2	4		6	1	2	6
28	1	1		2	2	2	2	6	2	1	2	5

Table 2. Continued.

1	S-37	S-38	S-39	S-40	S-41
2	VF77-644	VF78-364	VF78-365	VF78-366	VF78-383
3	(489)	(258)	(464)	(454)	(457)
4	30	17	30	23	15
5	1		1		
6		1	3		
7	4	39	28	33	23
8	3	3	2		
9	39	21	23	38	50
10	10				3
11	7	1	4	2	1
12		13	5	2	2
13	1	2	1		
14	2				
15	2				
16	3		2	3	5
17	2	2		2	4
18	1	5	4	6	5
19					
20	2				3
21					1
22	14	2	1		2
23					
24					2
25					
26					
27	2				1
28		3	2	1	3

Table 2. Continued.

1	M-1	M-2	M-3	M-4	M-5	M-6	M-7	M-8	M-9	M-10
2	RWT354-75	RWT420-76	RWT463-76	RWT467-76	RWT313-77	RWT324-77	VF76-512	VF76-515	VF76-567	VF76-570
3	(430)	(562)	(509)	(481)	(553)	(477)	(540)	(441)	(599)	(589)
4	36	61	51	45	33	43	39	42	43	45
5										1
6	3	1		1	1	2	4	1	2	1
7	12	9	3	7	19	5	27	10	6	12
8		2		2			1			
9	35	10	28	19	35	45	12	35	35	23
10	9	6	13	14	9	3	3	10	5	11
11		1		2	3		1	1		1
12									1	1
13				1				1	1	
14		9	3	9	1		12		6	4
15							1			
16	5				1	1				2
17		1	1	1	3	1	1	2		1
18	2	1	4	4	4	3		8	11	12
19										
20								1		
21										
22			3							
23										
24										
25										
26	2	2		1	1	3		6	11	2
27	2	1		6		2	4	2	5	1
28	2	1				1	1	2	4	1

Table 3. Detrital Modes, Manastash Formation.

1	M-11	M-12	M-13	M-14	M-15
2	VF76-616	VF76-617	VF77-258	VF77-265	VF77-322
3	(461)	(516)	(520)	(535)	(364)
4	33	43	54	50	49
5					
6	4	2	3	3	
7	4	3	13	5	3
8			2		
9	45	38	15	33	40
10	11	12	9	33	6
12		1	1	1	2
12					
13	1		2		2
14	1	1		5	
15	1	1		1	
16		1			1
17	10	4	6		9
18					
19			1		1
20					
21				19	
22					
23					
24					
25					
26	2	1	14		1
27	2	13	1		2
28			1		1

Table 3. Continued.

1	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-10
2	V-H19	V-H20	V-H22	V-H56	V-H72	V-H77	V-H333	VF78-106	VF78-114	VF78-124
3	(348)	(475)	(376)	(152)	(250)	(432)	(320)	(447)	(592)	(658)
4	35	26	31	29	40	30	38	23	31	34
5	1	1				1			1	
6			2					3	2	2
7	18	19	22	14	25	17	5	5	9	8
8	3	3				1		1		1
9	19	38	38	31	14	38	50	34	13	32
10	1	1	2	13				9	25	16
11	5	2		5	5	3	2	9	1	3
12	5	2	4	1	3	2				
13	4	1								
14	1			2		1		12	12	3
15				1		1		1		
16	8	5	2	5	12	7	4	2	6	1
17	2	3	2		1	1			1	3
18	5	2	5	8	23	9	20	6	4	9
19										
20										
21										
22		32	18				2			37
23		3	9		15	1		3	1	
24						1	1	3	1	2
25										13
26	3				8	2		4	39	
27	15			1				3	1	
28	7	1	1	5	2	2	2	5		2
Formation Name	TM	TM	TM	T	T	TM	T	R	R	R

Table 4. Detrital Modes, Puget Group. R, Renton Formation; T, Tukwila Formation; TM, Tiger Mountain Formation

1	P-11	P-12	P-13	P-14	P-15
2	VF78-125	VF78-127	VF78-128	VF78-129	VF78-131
3	(482)	(558)	(610)	(533)	(553)
4	32	27	37	32	30
5				1	
6	2	3	5	3	3
7	12	17	20	17	7
8					1
9	29	32	17	23	41
10	14	14	13	17	10
11	3	1		1	3
12					
13					
14	6	4	6	5	3
15					
16	3				1
17	4	3	4	2	1
18	12	4	3	6	1
19					
20					
21					
22			4	1	15
23	1	5	19	12	5
24	1				
25	46	17	7		8
26		1			
27					
28	3	2	2	1	2
Formation Name	R	T?	T?	R?	R?

Table 4. Continued.

1	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11
2	RWT104-76	RWT218-76	RWT347-76	RWT355-76	VF76-108	VF76-111	VF76-280	VF76-288	VF76-289	VF76-379	VF76-404
3	(490)	(512)	(366)	(522)	(418)	(444)	(444)	(491)	(575)	(404)	(477)
4	31	26	30	29	29	25	38	31	24	29	35
5				1	1		2				1
6					3	1	10	2	1	3	5
7	29	7	9	9	8	4	15	3	2	10	18
8											
9	26	52	40	40	44	44	32	40	28	42	27
10	6	11	7	6	9	16	3	21	7	11	9
11			1	1	1					1	
12			2								
13			1								
14			3	4	3	4				1	5
15		1	1	6	2	2		1			
16	7	2	7	6		5		2	37	2	
17	18	7	12	13	2	1	2	2		2	5
18	8	6	10	2	8	15	3	6	4	6	13
19				1	1						
20		1			1	2		1			
21	1										
22	21		1						9		
23											
24											
25											
26		2	2	6	1	7	3	3	18	6	2
27	3	1	2	2	2	1	2		3	1	1
28		1	2	1	3	1		1	2	1	1

Table 5. Detrital Modes, Chumstick Formation.

1	C-12	C-13	C-14	C-15	C-16	C-17	C-18	C-19	C-20	C-21	C-22
2	VF77-132	VF77-161	VF77-208	VF77-211	VF77-212	VF77-214	VF77-216	VF77-217	VF77-218	VF77-221	VF77-222
3	(394)	(399)	(415)	(564)	(417)	(515)	(423)	(459)	(457)	(462)	(528)
4	26	35	26	51	51	24	29	27	25	26	28
5	2	1				2	1			2	
6	4	2	2		8	13	3	1		3	1
7	5	4	3	8	5	5	5	1	5	7	4
8					1	1					
9	40	55	51	33	27	45	56	53	56	40	53
10	15	2	15	7	7	8	5	11	7	13	9
11	1		2			1		2		1	
12											
13	1					1		1			
14	3		1						4	3	1
15	2									1	4
16	2	1		1				3	3	4	1
17		2	1	1		11	2	1	2	3	7
18	7	11	7	24	10	6	20	17	4	4	7
19											
20			3								1
21											
22						21		5	12	3	
23							2	6	4	8	
24											
25											
26	3	5	4		6		5	2	1	3	4
27	1	2	10	8	2	8	5	3	4	1	
28	1	1	1	1		1	1	1	2	1	1

Table 5. Continued.

1	C-23	C-24	C-25	C-26	C-27	C-28	C-29	C-30	C-31	C-32	C-33
2	VF77-223	VF77-226	VF78-174	VF78-175	W-75-96	W-75-97	W-75-105	W-75-117	W-75-130	W-75-141	W-76-47
3	(522)	(506)	(495)	(491)	(499)	(457)	(538)	(463)	(530)	(515)	(434)
4	25	22	28	24	27	20	16	19	19	21	23
5						1	1	1			
6	1										
7	5	1	16	12	11	21	21	22	33	26	
8											
9	54	67	44	53	53	42	34	43	43	38	36
10	10	6	8	5	3	9	10	11	1	11	9
11			1								
12											
13											
14	1	1	1	3	2		3	1		1	18
15	2				2		1	1		1	8
16	4	1	2	4	1	5	12	3	2	2	6
17	2	4	3	4	1	6	5	5	8	8	5
18	7	13	8	10	5	5	5	9	2	8	8
19					4						
20	1	1	2	1	1						
21			1					1			
22			19							3	2
23									9	5	1
24											1
25											
26	4	2		3	4	1	3	1			6
27	1	3			1				10	2	
28	1	1	1	1	1		1				1

Table 5. Continued.

1	C-34	C-35	C-36	C-37	C-38	C-39	C-40
2	W-76-65	W-76-66	W-77-51	W-77-84	W-77-86	W-77-104	W-77-113
3	(399)	(394)	(454)	(513)	(464)	(488)	(528)
4	12	22	37	13	15	15	30
5		1					
6							
7	11	15	31	7	6	6	17
8							
9	22	47	20	20	26	11	45
10	4	9	2	3	11	1	
11			2				
12			2				
13							
14	18	1	1	32	15	29	5
15	1	1		1		1	
16	32	3	5	25	25	37	3
17	11	5	4	10	3	2	7
18	3	10	12	5	5	2	12
19			9				1
20		2	2	2			1
21			5	1			
22							
23							
24		1					1
25							
26		3	1		1		5
27			1				
28	1		1	1			1

Table 5. Continued.

1	R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10
2	VF75-261	VF77-331	VF77-466	VF78-425	VF78-426	VF78-427	VF78-428	VF78-429	VF78-613	VF78-614
3	(595)	(466)	(478)	(539)	(408)	(528)	(462)	(321)	(514)	(464)
4	40	28	35	26	24	24	24	31	29	26
5	1		1	1		1	1	1		
6	1	4	5			2				
7	4	2	4	27	18	17	23	21	17	9
8	2				1	1	1	1		1
9	19	43	31	39	38	39	32	35	35	46
10	9	13	10	?	9	6	5	1	11	9
11	4	1		3	2	2	2	1	3	1
12	1		2	1		1	1		1	
13	1	1				1				
14	1	2	10		3				1	
15	1									1
16	14	6	1	3	6	7	11	7	4	6
17	5	4	1		3	4	3	3	4	7
18	2	7	4	12	11	8	4	14	7	8
19										
20	1	1	1		1	2	1	1	1	1
21										
22				(7)		18	11			20
23		2		(25)						
24		2				1	1			1
25										
26	30	3			2				6	
27	1	1	1							
28	1	1		1	2	1		1		

Table 6. Detrital Modes, Roslyn Formation.

1	R-11	R-12	R-13	R-14	R-15
2	VF78-615	VF78-616	VF78-618	VF78-619	VF78-620
3	(466)	(550)	(585)	(469)	(565)
4	33	31	24	40	29
5	2	1			1
6					
7	29	28	17	13	6
8		1	2		
9	26	34	33	31	55
10	?	?	11	14	4
11	2	3	4	1	4
12			1		
13					
14	1		1		
15					
16	7	1	7	1	1
17	2	2	4		4
18	10	3	4	8	9
19					5
20					3
21					
22		(17)	21		
23	(16)	(12)	2	2	1
24			3		3
25	7	5		4	
26	1				
27					1
28	1	1	1		1

Table 6. Continued.

1	N-1	N-2	N-3	N-4	N-5	N-6	N-7	N-8	N-9	N-10
2	BL105-78	BL115-78	VF77-299	VF77-301	VF77-338	VF77-366	VF77-378	VF77-384	VF77-405	VF77-410
3	(414)	(429)	(527)	(525)	(430)	(627)	(460)	(556)	(533)	(620)
4	28	18	34	46	48	32	33	39	33	36
5						1			1	1
6	1			3	2	7	6	1	5	3
7	28	32	7	3	4	10	7	8	5	8
8							1		1	
9	40	47	46	42	43	38	36	47	30	35
10			10			3	4	1	9	3
11		1	1		1	2	2		1	4
12	1			1		1		2	2	1
13										
14			1	3			2		6	3
15				1		1	2		2	1
16	2	2	2		1	8	7	2	5	4
17			2	1		1	5	3	1	
18	3	1	19	2	13	12	8	18	8	11
19										
20							1	4	1	1
21										
22										
23										
24	4	3								
25										
26	1		8	7	9		2	1	1	2
27			12	1	6			1	3	5
28	8	1	5	1	1	1	2	1	3	3

Table 7. Detrital Modes, Naches Formation.

1	N-11	N-12	N-13	N-14	N-15	N-16	N-17	N-18
2	VF77-411	VF77-417	VF77-535	VF77-540	VF78-201	VF78-241	VF78-246	VF78-247
3	(499)	(574)	(518)	(520)	(466)	(419)	(223)	(453)
4	34	25	34	36	26	25	3	2
5			1	1		1		
6		1			1			
7	10	8	11	5	23	29	17	33
8							69	56
9	49	47	48	46	42	39	7	2
10	5	9	2	4				
11			1	2	1	1	2	3
12				1		1		
13								
14	2	3						
15		1		1				
16		5	2	3	6	4	3	3
17	3	7	4	6	1			
18	13	4	13	5	6	2		
19								
20		1	1	6	1			
21		1						
22					2	7		
23								
24	4				1	1		
25								
26	2	1	1		7	10	9	5
27	5	1	1	1	2	1		
28	8	2	3	2	2	2	3	3

Table 7. Continued.

1	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8
2	CHSS	CHCG	LS-6B	MS-4B	YS-7D	WF-12A	WF-12B	WF-6
3	(556)	(472)	(496)	(555)	(503)	(528)	(558)	(433)
4	28	46	32	42	33	41	54	34
5	1	1						
6		1						
7	59	48	48	38	16	55	27	19
8						1		1
9	8	1	7	12	31	2	11	25
10			10	4	15		6	12
11	1	2	1	2	2	1		4
12								
13								
14	1							
15								
16	2	1	1	1	3			4
17								
18	6	5	8	9	3	1	9	9
19			1					
20								
21								
22	7				6		18	1
23	8			3	7			6
24								
25	8	1		2	7		9	2
26		1	13	5				12
27		1	1					
28	1	1	1	2	1		1	2

Table 8. Detrital Modes, Wenatchee Formation.

	South of Sedro Woolley							North of Sedro Woolley	Near Mt. Higgins Figure 1
1	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	
2	JY76-36	JY76-38	JY76-58	JY77-34	JY77-35	JY77-37	VF78-142	RWT525-76	DP-8
3	(692)	(603)	(577)	(598)	(528)	(541)	(597)	(606)	(627)
4	42	40	24	43	44	49	21	33	60
5							1		
6			17				1		
7	17	13		8	6	13	23	9	19
8		1	1	1		1	3		3
9	9	29	37	30	29	19	33	48	16
10	25	15	11	15	17	14	7	9	
11	2		3	1	1		4	1	1
12			2		1	1	1	1	
13									
14			3			1			
15			1				3		
16	4	1	2	1	1	2	2		
17	1	2	3	2		2	7		
18	4	4	3	2	13	1	4	6	6
19									
20									
21									
22			15	3		2			3
23	13	8	3	8	7	3	1		
24									
25									
26									14
27	20	8	1	8	2	1	1		1
28	2		2		2	1	2	1	3

Table 9. Detrital Modes, Isolated Arkosic Bodies.

Southwest of Skykomish

1	CS-10	CS-11	CS-12	CS-13
2	VF77-666	VF78-520	VF78-524	VF78-526
3	(578)	(562)	(482)	(560)
4	37	36	34	24
5	1			
6	4			
7	7	12	7	23
8	1			
9	39	48	38	37
10	4		1	3
11	1	1	10	8
12	2			1
13	2			1
14	3		1	
15				
16		1	6	2
17	5	1		1
18	2	2	2	9
19				
20		4	2	
21				1
22				
23				
24	5		1	2
25				
26		8	3	1
27				3
28	5		2	1

Table 9. Continued.

	Rocks of Bolson Creek			Huntingdon		Swauk(?) near Wenatchee				
1	BC-1	BC-2	BC-3	H-1	H-2	SW-1	SW-2	SW-3	SW-4	SW-5
2	JY77-8	VF78-165	VF78-166	VF78-154	VF78-156	RWT95-76	RWT96-76	VF76-400	VF76-401	VF76-402
3	(519)	(545)	(480)	(584)	(655)	(466)	(498)	(457)	(469)	(542)
4	8	13	6	28	18	25	28	28	24	32
5					1					1
6										1
7	17	5	2	13	20	5	1	1	1	4
8	22				12					
9	3	11	20	33	21	68	70	72	74	60
10	1	2	3	8	6					
11	42			7	14	1				
12				1	1					
13				1						
14	1	17	15	1	1					
15	1	14	3		1					
16	6	36	53	5	6					
17		1		1	1	4			1	2
18				36	8	9	10	5	6	10
19		2	2							
20		1					1		1	1
21				1						
22					12				3	6
23	2			1						
24	1						6	9		
25										
26	19	18	18	1	1					
27				1		3	4	1	6	7
28	1	1	1	1	2		1			

Table 10. Detrital Modes, Other Modal Analyses.

	Raging River Formation			Tukwila Formation			
1	RR-1	RR-2	RR-3	T-1	T-2	T-3	T-4
2	V-H15b	V-H16a	V-H313	V-H177	VF78-104	VF78-116	VF78-118
3	(196)	(472)	(458)	(387)	(310)	(443)	(464)
4	20	6	6	1		1	
5			1				
6			1				
7	26	2	21			1	
8	6	1	27				
9	29	61	8	43	38	54	45
10							
11	7		13			1	
12	1						
13							
14	1	4		1		17	49
15		4				3	4
16	11	21	23	56	61	24	3
17	1		1				
18	1					1	
19						5	
20							
21							
22			37	4			
23							
24		2		7			
25							6
26	3	7			10		
27				1	3		1
28	4	1					2

Table 10. Continued.

Blakeley Formation

1	BF-1	BF-2	BF-3	BF-4	BF-5	BF-6	BF-7
2	VF78-101	VF78-108	VF78-110	VF78-112	VF78-120	VF78-132	VF78-134
3	(601)	(444)	(220)	(314)	(553)	(606)	(383)
4	3			2	30	11	4
5							
6							
7					13	6	1
8							
9	24	15	9	1	38	48	37
10					16	2	1
11						1	1
12							
13							
14	11	6			1	4	3
15	5	4				5	3
16	56	74	91	97		22	51
17							
18	5						
19	4	5	3			1	3
20							
21							
22	41				10		
23	1				5	8	
24							
25					7	12	
26	1				1	3	
27		3				2	6
28	4				2	4	3

Table 10. Continued.

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