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GEOLOGY AND LOW-GRADE METAMORPHISM OF THE GREENWATER RIVER AREA, CENTRAL CASCADE RANGE, WASHINGTON

by

Donald Albert Hartman

A dissertation submitted in partial fulfillment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY
UNIVERSITY OF WASHINGTON
1973

Approved by John T Whetten
(Chairman of Supervisory Committee)

Department Department of Geological Sciences
(Departmental Faculty Sponsoring Candidate)

Date November 30, 1973

UNIVERSITY OF WASHINGTON

Date: November 9, 1973

We have carefully read the dissertation entitled Geology and Low-grade Metamorphism of the Greenwater River Area, Washington submitted by Donald Albert Hartman in partial fulfillment of the requirements of the degree of Doctor of Philosophy and recommend its acceptance. In support of this recommendation we present the following joint statement of evaluation to be filed with the dissertation.

Mr. Donald A. Hartman has mapped, described, and interpreted the geology of the Greenwater River area, Washington, in a precise and scholarly manner. Prior to Mr. Hartman's work, the area was very poorly known geologically. However, the area is important because it is a connecting link between other areas that are much better known and there are problems within the area that shed light on the evolution of the Central Cascades.

Mr. Hartman's main contributions include (1) careful delineation of the stratigraphy of the area, (2) a consideration of the environment on which the rocks were deposited, (3) an investigation of the relationships between the volcanic and intrusive events in the area, (4) a consideration of the post-depositional environments during diagenesis and low grade metamorphism, and (5) an investigation of the absolute age of some of the rocks.

Mr. Hartman's finding that the low grade metamorphism is not the product of deep burial, but rather the result of hydrothermal alteration caused by thermal gradiants and circulating waters in rocks adjacent to and overlying the intrusions is of particular significance.

It is likely that some of the information in this dissertation will cause some of our earlier ideas on the geology of the Cascades to be re-evaluated and reinterpreted.

We commend Mr. Hartman for having completed a very large undertaking in excellent fashion. His dissertation shows unusual thoroughness and perception.

DISSERTATION READING COMMITTEE: John T. Whetten
Joseph A. Vance
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Doctoral Dissertation

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INTRODUCTION

Alteration of Tertiary rocks in the central Cascade Range was first mentioned by Smith and Calkins (1906) in their description of the Keechelus Andesite. The lower portion of this assemblage shows considerable alteration whereas the upper part is relatively unaltered. Subsequent workers have used variation in alteration as a criterion for stratigraphic differentiation of the Keechelus and related units (Coombs, 1936; Warren, 1941; Foster, 1960; Waters, 1961, Fiske and others, 1963; and Stout, 1964). In Mount Rainier National Park the alteration assemblages are characteristic of the zeolite facies (Fiske and others, 1963). The intensity of alteration increases with stratigraphic depth and its origin was attributed to burial metamorphism. The pattern of mineral zonation is complicated by thermal metamorphism accompanying igneous intrusions (Fiske and others, 1963; and Race, 1969, unpubl, M.S. Thesis). No thorough study of the Tertiary alteration has been made.

Waters (1961) and Fiske and others (1963) have divided rocks previously mapped as Keechelus Andesite (Coombs, 1936) in the park into the Ohanapecosh, Stevens Ridge and Fifes Peak Formations which they consider to be, in part, equivalent to the "lower" Keechelus of Smith and Calkins (1906). The stratigraphy in the park can be extended into adjacent areas and provides a useful framework for evaluation of stratigraphic variation in alteration.

During 1971 and 1972 six months were spent in field investigations in the central Cascades. The geology of the

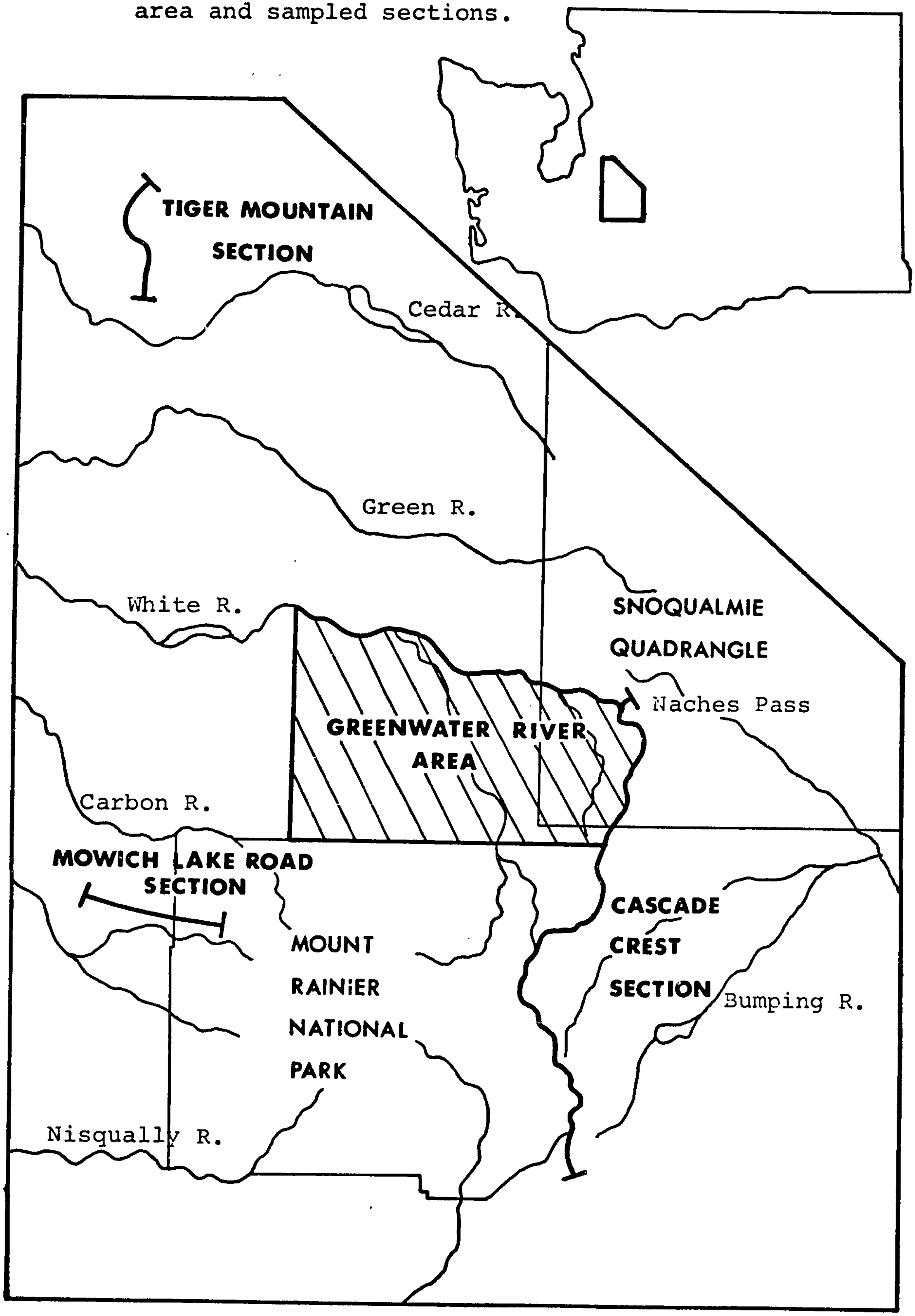
Greenwater River area (Figure 1; Plate 1) was mapped to determine the relationship between the stratigraphic divisions of the "lower" Keechelus in the park to the "upper" Keechelus exposed at Naches Pass. Nearly 15,000 feet of Late Eocene (?) to Quaternary volcanogenic rocks are exposed in this area. Tertiary units include the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations and the "upper" Keechelus Andesite. Radiometric dates for the Stevens Ridge and Fifes Peak Formations were obtained to define the timing of volcanic events. Since all major divisions of the Keechelus are present and the direct effects of contact metamorphism are mininal, an evaluation of stratigraphic variation in alteration was possible. Sections through the Tertiary interval in adjacent areas (Figure 1) were sampled to evaluate regional variations in alteration. Alteration assemblages were determined using petrographic and X-ray techniques, and compositions of rocks and minerals were determined by electron microprobe analyses. In addition to probe analyses, plagioclase compositions were estimated from extinction angles using curves of Wahlstrom (1955). The nature and origin of low-grade metamorphism are interpreted from geological, experimental and theoretical data.

General Tertiary Geology of the Central Cascade Range of Washington

Stratigraphy

The Tertiary section in the central Cascade Range is a complex assemblage of rocks including arkosic sandstones, siltstones, shales, and coals; volcaniclastic rocks including ash-

Figure 1: Index map showing the location of the Greenwater River area and sampled sections.

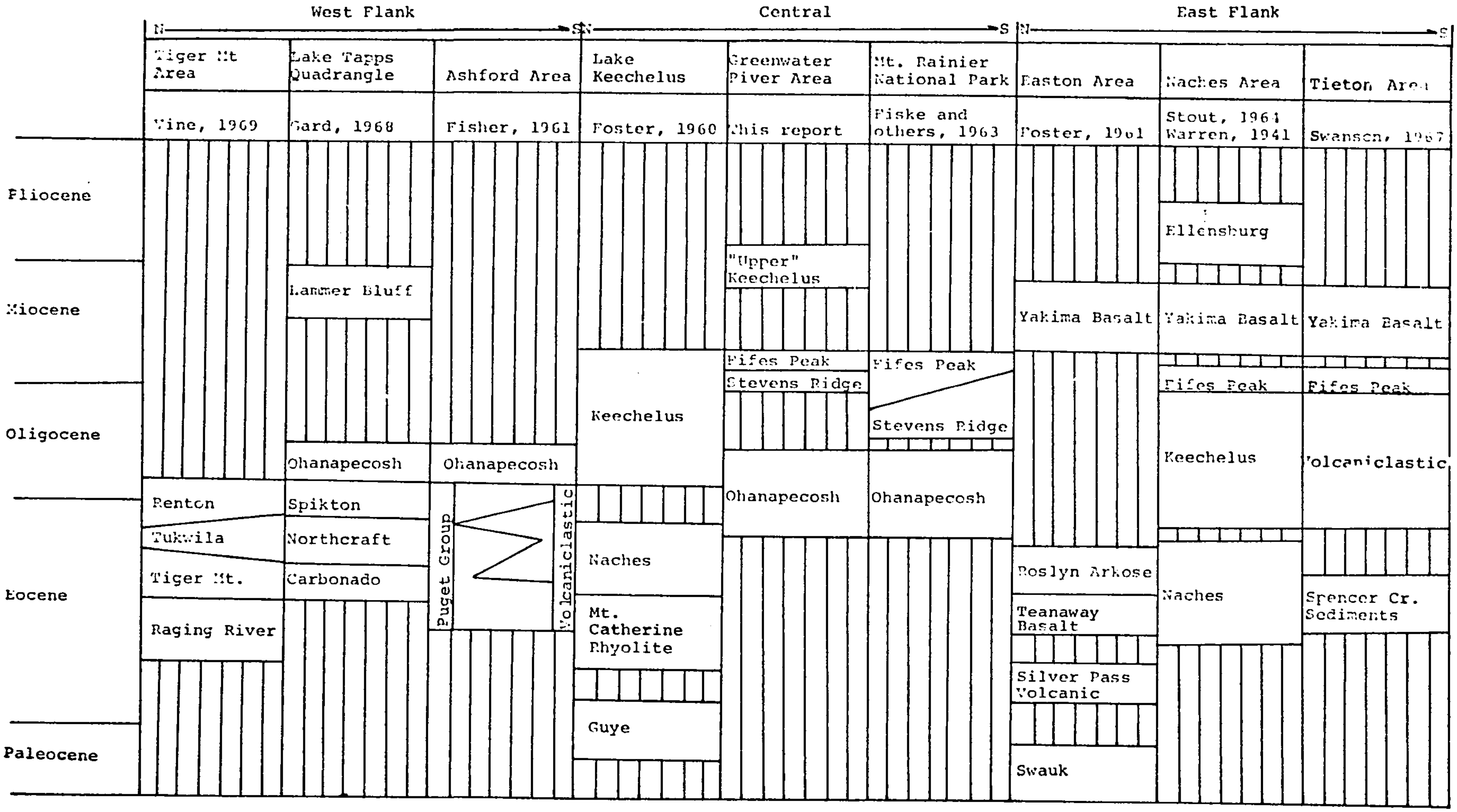


flow and air-fall tuffs, volcanic breccias, conglomerates, sandstones, and siltstones; and extrusive rocks ranging in composition from rhyolite to basalt. The sedimentary rocks largely accumulated in a continental environment, but a few marine units intertongue along the western margin of the range. Thick stratigraphic intervals are assigned to all epochs of the Tertiary. The Tertiary rocks unconformably overlie or are in fault contact with Pre-Tertiary weakly to highly metamorphosed sedimentary and volcanic rocks and granitic rocks, and are overlain by Quaternary volcanic rocks and surficial deposits.

Stratigraphic nomenclature of the Tertiary section (Table 1) is somewhat confused and contradictory. Excellent discussions of nomenclature problems are given by Waters (1961), Hammond (1963, unpubl. Ph.D. Thesis) and Gard (1969). The nomenclature used by Fiske and others (1963) in the park was followed in this study.

Lower Tertiary arkosic sandstones, siltstones, carbonaceous shales and coals are widely exposed along both flanks of the range and in small exposures within the range, and include parts of the Puget Group, Naches Formation and the Roslyn Arkose. These rocks are commonly at the base of the Tertiary section and interbedded with volcanogenic rocks along the flanks of the range. The core of the range and by far the bulk of the section is composed of Lower and Middle Tertiary volcaniclastic rocks which are largely the product of contemporaneous volcanism and deposition. Lava flows, predominantly andesite, are found throughout the section and near eruptive centers form thick

Table 1: Stratigraphic nomenclature in the central Cascades of Washington.



stratigraphic intervals. The volcanogenic assemblage is commonly referred to as the Keechelus Andesite. Younger Tertiary volcanogenic rocks within and along the flanks of the range include the Yakima Basalt and the Ellensburg and Hammer Bluff Formations.

Structure

At least four episodes of Tertiary folding are recognized in the central Cascade Range (Table 2). Older structures are deformed by younger folding events due to different stress fields. This is best displayed by the superposition of E-W trending folds on N-S trending folds which has resulted in the arcuate bending of the axial traces of the N-S folds. Pre-Tertiary rocks along the east flank of the range lie along the axial culminations of the Late Eocene to Early Oligocene N-S trend and the Middle Miocene E-W trend. Multiple folding has caused considerable deformation of the older Tertiary rocks which is displayed in the field by secondary faults and drag folds and petrographically by grain deformation and disruption of grain fabric.

Faulting in the Tertiary section is difficult to evaluate because of poor exposures and lack of detailed stratigraphic control. Numerous faults are mapped in the coal fields in the Puget Group, but involve only small amounts of displacement. In the volcanogenic section within the range, faults are recognized in road cuts but cannot be traced far laterally. Some dikes may be emplaced along faults.

Table 2: Tertiary episodes of deformation in the central Cascade Range.

Age of Folding	Dominant Trend	Type of folding	Units in which folding is displayed	Examples of Major Folds
Middle Eocene	East-West	tight folds dips greater than 50° common	Swauk Fm.	Unnamed folds in Swauk Fm. south of Mt. Staurt.
Late Eocene to Early Oligocene	North-South	tight folds dips greater than 50° common	Puget Group Ohanapecosh Fm. Teanaway Basalt Naches Fm.	Skate Cr. Anticline, Taylor Syncline, Lawson Anticline, Kummer Syncline, Unicorn Peak Syncline, Chinook Pass Anticline, Carbon River Anticline.
Middle Miocene	East-West	broad open folds dips generally less than 40°	Keechelus Andesite Stevens Ridge Fm. Fifes Peak Fm.	Roslyn Syncline, Newcastle Hills Anticline (?), many broad folds within the central Cascades but most are not formally named.
Plio-Pleistocene	North-South	broad open arching dips are less than 20°	Ellensburg Fm. Yakima Basalt	Marks the present uplif of the Cascade Range. The uplift appears to b asymmetric with the steeper flank to the east. Axis of this uplif lies to the east of the present Cascade Crest.

Intrusive Rocks

The larger plutons in the central Cascades (Figure 2; Table 3) are the Snoqualmie Batholith, Carbon Stock, Tatoosh and Bumping Lake Plutons. Chemical trends from the Snoqualmie Batholith (Erikson, 1969) are typical of the calc-alkaline suite and similar to trends in Cascade lavas (Carmichael, 1964). Detailed study of the Tatoosh Pluton (Fiske and others, 1963) and the Snoqualmie Batholith (Erikson, 1969; and Fuller, 1925, unpubl. M.S. Thesis) indicates they were emplaced at shallow depths and associated with contemporary comagmatic volcanism. Radiometric ages and stratigraphic evidence indicate that the major episode of plutonism occurred in the Middle Miocene. Because of the similarities of the plutons, Fiske and others (1963) suggest they may be connected at depth to form a continuous mass underlying the central Cascades.

Small intrusions are exceedingly abundant. Stocks, plugs, dikes and sills may be composed of diabase, pyroxene diorite, hornblende diorite, pyroxene andesite, basalt, rhyodacite, rhyolite, and various porphyries and vitrophyres. Some intrusions are genetically associated with phases of Miocene plutonism as hypabyssal dike and sill swarms or as conduits of contemporary volcanism. Others are related to older intrusive and volcanic events and a few are related to Pliocene and Quaternary volcanism.

Figure 2: Map showing location of Tertiary intrusions and distribution of Pre-Tertiary rocks and Pleistocene volcanics in the central Cascade Range of Washington.

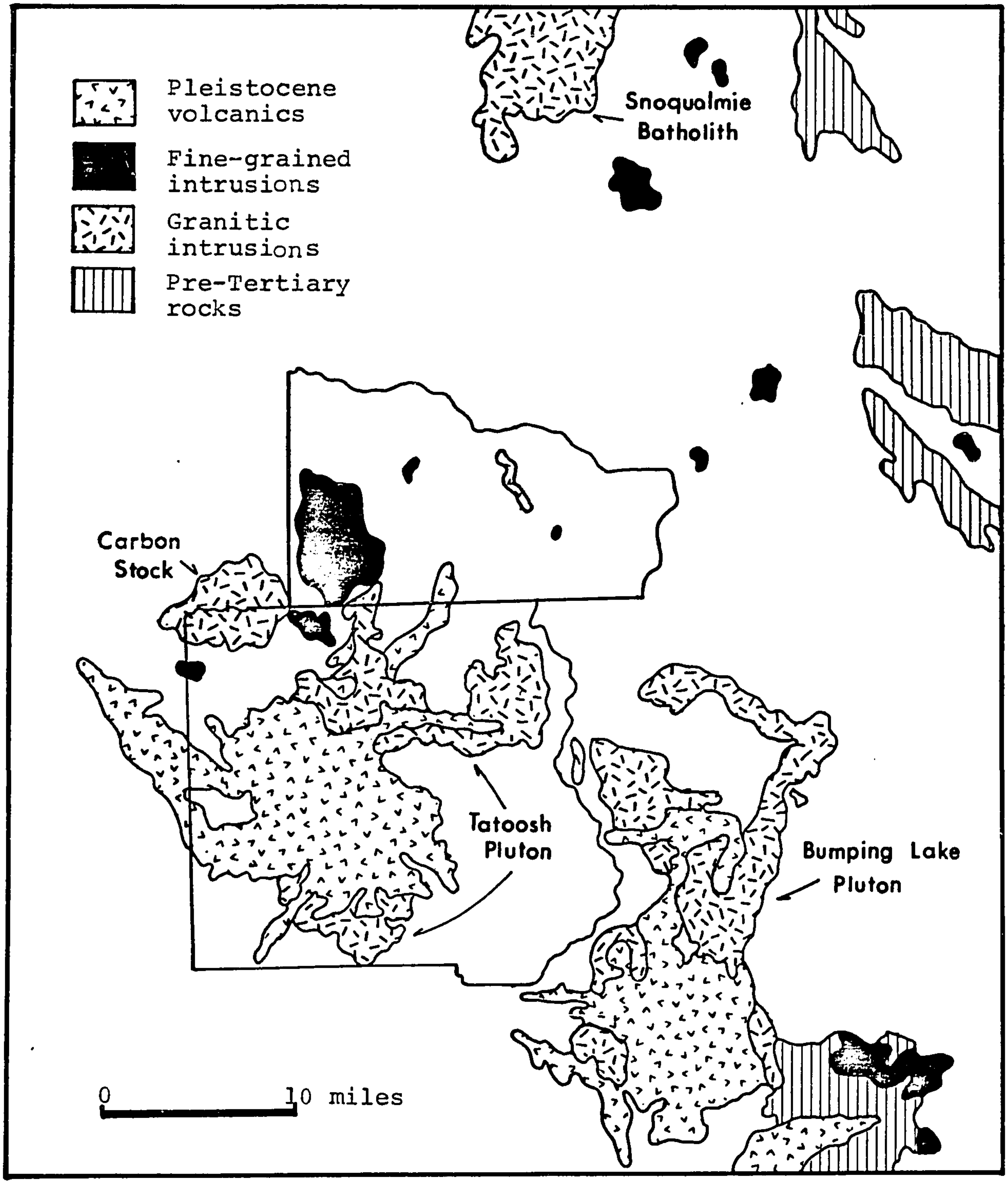


Table 3: Summary of larger Tertiary granitic intrusions in the central Cascades of Washington.

Intrusion	Age	Lithology	Tertiary Formations Intruded
Snoqualmie Batholith (1,2)	18 m.y. (3) 17 m.y. (4)	composite batholith, initial calcic gabbros, followed by diorites, minor quartz diorites, and abundant granodiorites, quartz monzonites, and biotite aplite alaskites	Swauk Formation Guye Formation Mt. Catherine Rhyolite Naches Formation Keechelus Andesite
Carbon River Stock (5)	Miocene	granodiorite and minor quartz diorite	Puget Group Ohanapecosh Formation Stevens Ridge Formation Fifes Peak Formation
Tatoosh Pluton (5)	14.7 1 m.y. 13.1 m.y.	hornblende-biotite granodiorite and quartz monzonite most abundant, and pyroxene quartz diorite and granophyre less common	Ohanapecosh Formation Stevens Ridge Formation Fifes Peak Formation
Bumping Lake Pluton (6)	Miocene	granodiorite, quartz diorite and dacite porphyry	Puget Group Keechelus Andesite Fifes Peak Formation

(1) Fuller, 1925, unpub. M.S. Thesis
(2) Erikson, 1969
(3) Baadsgaard and others, 1961
(4) Curtis and others, 1961
(5) Fiske and others, 1963
(6) Abbott, 1953, unpub. Ph.D. Thesis

GEOLOGY OF THE GREENWATER RIVER AREA

Stratigraphy

Ohanapecosh Formation

Upper Eocene(?) to Oligocene volcaniclastic rocks and interbedded lava flows of the Ohanapecosh Formation are the oldest rocks in the area (Figure 3; Table 4). The rocks which were mapped as the Ohanapecosh Formation (Plate 1) are a northward extension of the upper part of this extremely thick sequence described in Mount Rainier National Park (Fiske and others, 1963). All rocks of this formation are weakly to highly altered, and as a result most of the original textural and mineralogic characteristics have been altered. The dominant green and less common brown and maroon colors are due to alteration of glass and rock fragments to chlorite and clay.

Tuff breccia, consisting of angular andesite, basalt and pumice fragments "floating" in a volcanic sandstone or siltstone groundmass, is the most common rock type. Exposures are massive and lack internal stratification. Epiclastic volcaniclastic rocks (Table 5), consisting of well-bedded volcanic breccia, conglomerate, sandstone and siltstone units, are interbedded with tuff breccias, but are less frequently exposed. Abrupt lateral variation in bedding and grain size in the thinner bedded units is common. Andesite and basalt flows are interbedded with the volcaniclastic rocks and locally, as in the Byron Creek area, may comprise more than one third of the section. Most flows are in the range of 10 to 60 feet thick. Intrusive (?) rhyolite and rhyolite flows are present in the

Figure 3: Composite section of the Greenwater River area.

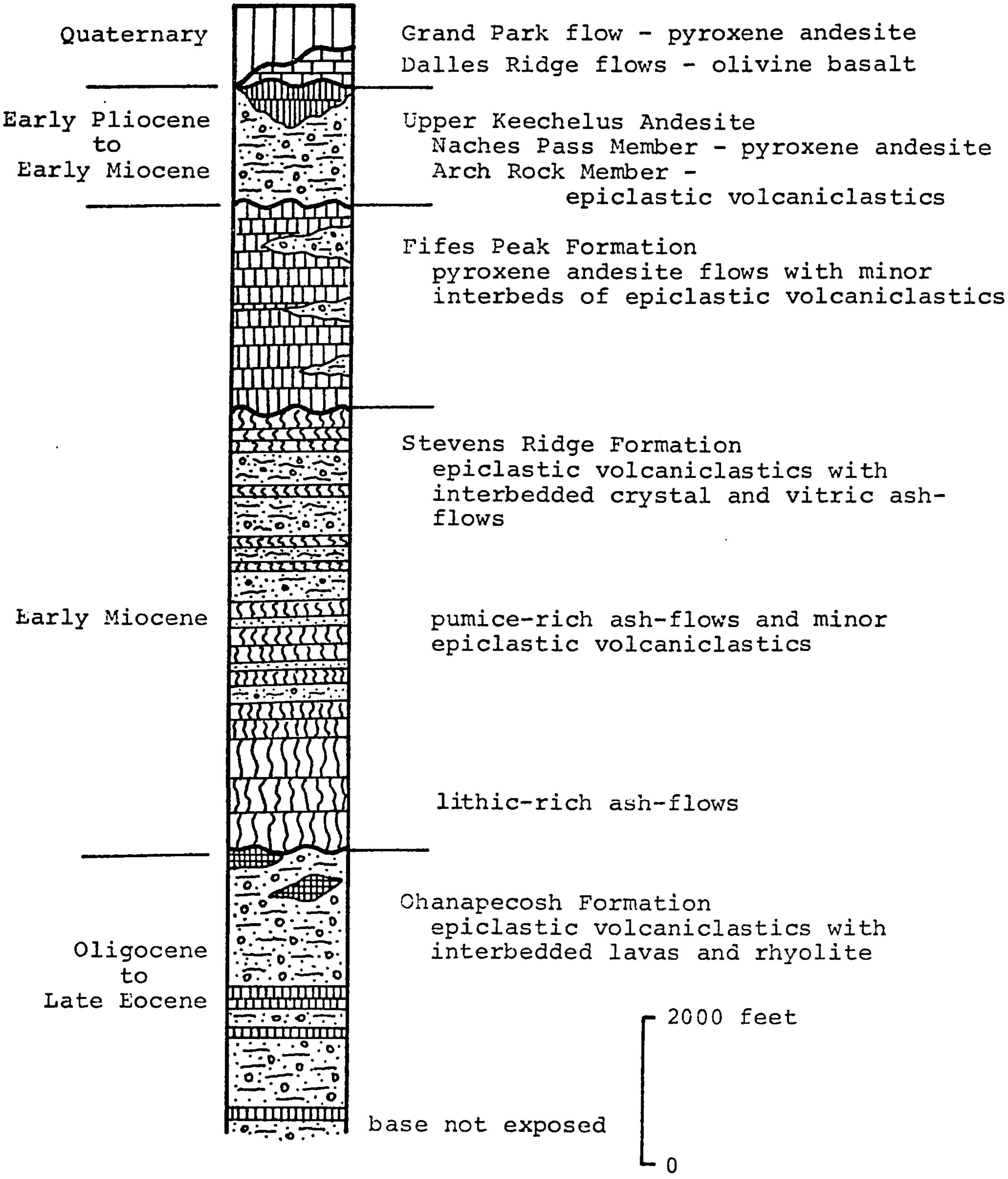


Table 4: Summary of the Ohanapecosh Formation

Lithology	The formation consists dominantly of volcaniclastic rocks with local accumulations of andesite and basalt flows and minor rhyolite. Volcaniclastic rocks include tuff breccia, volcanic breccia, conglomerate, sandstone, and siltstone. All lithic grains are of volcanic origin. The strata are well-indurated.
Distribution:	Mainly exposed along the southern portion of the map area. Best exposed along the Corral Pass, Buck Creek and Huckleberry Creek roads and in logging roads in the Byron Creek area. The formation is more widely exposed to the south and underlies nearly one-half of Mount Rainier National Park (Fiske and others, 1963).
Thickness:	Only the upper 3,500 feet of this formation is exposed in the area. To the south in the park, the formation exceeds 10,000 feet in thickness (Fiske and others, 1963) and much farther to the south at Columbia Gorge it is nearly 19,000 feet thick (Wise, 1970).
Contacts:	The basal contact is not exposed in the area. Southeast of the park at Carlton Pass and along the west flank of the range the Ohanapecosh Formation concordantly overlies the Puget Group. In the area the Ohanapecosh is unconformably overlain by the Stevens Ridge and Fifes Peak Formations and Quaternary lavas.
Age:	No diagnostic fossils were found in the area. On stratigraphic and paleobotanic evidence Fiske and others (1963) assign a Middle Eocene to Early Oligocene age to this formation. Wolfe (1961, 1968) considers the Ohanapecosh to be of Oligocene age based on paleobotanic evidence.
Origin:	Volcaniclastic rocks represent deposits of pyroclastic volcanism and accumulations of fluviatile deposits. Local accumulations of lava flows, sills and rhyolite may indicate the location of volcanic vents.

Table 5: Characteristics of epiclastic volcaniclastic rocks.*

	Breccia and Conglomerate	Sandstone	Siltstone
Bedding	very thick- to medium-bedded	thick- to very thin-bedded rarely very thick-bedded, may be laminated	medium- to very thin-bedded, commonly laminated
Bedding Character	massive to well-bedded, may display abrupt change in lithology	well-bedded, lenticular	well-bedded, usually present in thin intervals, may be laterally persistent
Clasts	mainly fragments of lavas, some pumice clasts, rare intrusive rocks	grains of lavas, pumice, plagioclase, augite, hornblende, hypersthene, biotite and rare quartz	grains of plagioclase, augite and quartz
Matrix	sandstone or siltstone	siltstone, ash or clay	ash and clay
Sorting	very poor	poor to good	good
Contacts	sharp to gradational, often erosional	sharp to gradational	usually gradational
Structures	imbricate clasts, channels and lenses, graded bedding	graded bedding, load casts, channel structures, slump structures, rare cross-bedding and ripple marks	load and slump structures, cross-bedding and ripple marks

*Epiclastic volcaniclastic rocks of the Ohanapecosh, Stevens Ridge and Fifes Peak Formations and the "upper" Keechelus are grossly similar except for differences in bedding thickness and character, clasts content, and changes resulting from alteration.

southeastern part of the Greenwater quadrangle. These rocks have well-developed flow banding which is often highly contorted and marked by trains of spherulites and lithophysae.

Although the source of the volcanic detritus has not been determined, the debris was most likely the product of concurrent volcanism and deposition. Abundant pumice indicates pyroclastic eruptions which were possibly explosive. Angular, very coarse-grained lithic clasts indicate a relatively close source. Tuff breccias may represent subaqueous volcanic mudflows (Fiske, 1963) or aubaerial ash-flows. The epiclastic volcaniclastic rocks are water deposited as indicated by their lithology, bedding, and sedimentary structures (Fiske, 1963). The Ohanapecosh depositional environment was probably a broad coastal floodplain, similar to that interpreted for the underlying Puget Group (Gard, 1968; and Vine, 1969), which was continuously subsiding during deposition. The major difference from the Puget Group environment was the presence of volcanic centers which supplied debris that replaced or displaced the deposition of arkose detritus. The volcanoes emitted large quantities of pyroclastics which flowed out on floodplains as ash-flows or into lakes as subaqueous mudflows, and contributed debris which was subsequently deposited by fluvial systems to form the epiclastic deposits. This environment is further suggested by interbedding of the Puget Group and the Ohanapecosh Formation along the western flank of the range (Fisher, 1961).

Stevens Ridge Formation

Lithic-, pumice-, and crystal-rich ash-flows and interbedded epiclastic volcaniclastic rocks of the Stevens Ridge Formation (Figure 3; Table 6) unconformably overlie the Ohanapecosh Formation. The Stevens Ridge Formation was described by Waters (1961) and Fiske and others (1963) for exposures along Stevens Ridge in the southcentral portion of Mount Rainier National Park. In the study area the Stevens Ridge Formation may be divided into basal, middle and upper members based on characteristics of the ash-flows (Table 7) and the distribution of epiclastic deposits. The basal member (Figure 4) is a densely welded, lithic-rich, composite ash-flow sheet which consists of at least three cooling units; the middle member consists of very thick-bedded, pumice-rich ash-flows and minor interbedded epiclastic rocks; and the upper member is dominantly epiclastic volcaniclastic rocks with interbedded ash-flows. The dominant epiclastic volcaniclastic rocks are light-colored sandstones and siltstones rich in glassy constituents. They commonly contain carbonaceous material and thin-bedded coals are present in the upper member.

Although the contact between the Ohanapecosh and Stevens Ridge Formations is not clearly exposed, the geometry of the basal member indicates an unconformity. In the southeastern part of the Greenwater quadrangle, the thickness of the cooling units and the overall thickness of the basal member decreases to the southeast along the Dalles Ridge and to the south toward the park. In the park the basal member is not present and pumice-rich ash-flows, similar to the middle member, overlie soil horizons developed on the Ohanapecosh Formation (Fiske and

Table 6: Summary of the Stevens Ridge Formation

Lithology:	The basal member is a lithic-rich composite ash-flow sheet with at least three cooling units; the middle member consists of pumice-rich, very thick-bedded ash-flows and minor interbedded epiclastic deposits; and the upper member is dominantly epiclastic volcaniclastic rocks with interbedded ash-flows.
Distribution:	The formation crops out in a northwest trending band through the area. The best exposures of the basal member are along the southwest slope of the Dalles Ridge and to the east and south of Sun Top; the middle member in the Sun Top and Lightning Creek areas; and the upper member in logging road cuts west of Huckleberry Creek, near the Palisades, and in the Lightning Creek and Rocky Run Creek areas. North of the area the formation is exposed along the Green River and its tributaries (Waters, 1961), and to the south it is present in the park (Fiske and others, 1963) and in the Camp Creek area (Simons, 1972, unpubl. M.S. Thesis).
Thickness:	The cumulative thickness of this formation is approximately 6,000 feet; basal member - 1,400 feet, middle member - 1,400 feet, and upper member - 3,200 feet. In the park the formation thickness varies from 450 to 3,000 feet (Fiske and others, 1963).
Contacts:	The formation unconformably overlies the Ohanapecosh Formation and is unconformably overlain by the Fifes Peak Formation and Quaternary lavas.
Age:	Radiometric dates, 20.5 ± 1.5 m.y. and 19.5 ± 1.8 m.y., on plagioclase from the basal member indicate an Early Miocene time of extrusion and crystallization.
Origin:	Ash-flow deposits represent pyroclastic eruptions which buried the pre-Stevens Ridge erosional surface and repeatedly inundated the fluviatile environments represented by the interbedded epiclastic rocks.

Table 7: Characteristics of Stevens Ridge ash-flows.

	Basal Member	Middle Member	Upper Member
Color	dark gray to brown	pale green to tan	pale green to tan
Major Clasts	lavas, intrusive rocks, plagioclase, and hornblende	pumice and plagioclase	variable: pumice, lavas, plagioclase, and biotite
Minor Clasts	quartz, augite, hypersthene, biotite, and pumice	quartz, hornblende, augite, lavas and carbonized wood	quartz, hornblende, biotite, augite, hypersthene, and carbonized wood
Matrix	devitrified glass	mostly altered to secondary quartz, clay, chlorite, and zeolites	variable: mostly altered to clay, chlorite, quartz and zeolites; devitrified glass; some relict glass with shard textures
Induration	densely welded	moderately well indurated	variable: densely welded to weakly indurated
Bedding Thickness	very thick, cooling units of the composite sheet are greater than 400 feet thick	very thick, some units are nearly 200 feet thick	thin, most units less than 10 feet thick
Jointing	good columnar jointing	blocky jointing	blocky jointing, and columnar jointing
Structures		flow alignment of clasts, graded	flow alignment of clasts, baked basal contacts, deformation of underlying units

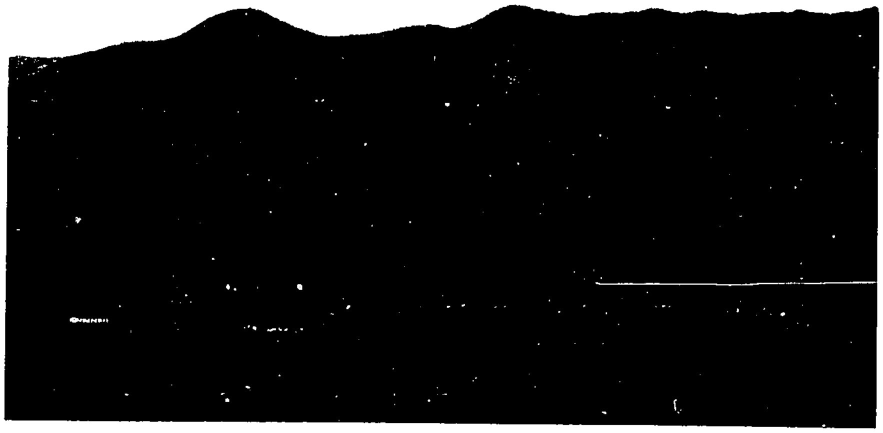


Figure 4: Basal member of the Stevens Ridge Formation exposed along the southwest flank of the Dalles Ridge. The thickness of the composite ash-flow and of the cooling units decrease to the southeast (to the right) along the ridge.

others, 1963). The basal member was deposited in a depression which was topographically lower than elevations in the park, and its distribution indicates at least 1,400 feet of relief on the pre-Stevens Ridge erosional surface. The filling of topographic irregularities by the basal member provided a more uniform depositional surface and allowed a wider distribution of the overlying pumice-rich ash-flows.

The Stevens Ridge volcaniclastic rocks represent widespread explosive eruptions of large amounts of pyroclastic debris from unknown volcanic centers. Many of the ash-flow eruptions, especially those of the basal and middle members, were catastropic events. Interbedded epiclastic volcaniclastic rocks become increasingly more abundant in younger intervals of the formation. Abundant carbonaceous material, coals, soil horizons, as well as the lithology, bedding, and sedimentary structures of the epiclastic deposits clearly indicate deposition in continental environments, presumably in fluviatile systems. Even-bedded, laminated, very fine-grained volcaniclastic rocks may represent air-fall tuffs or lacustrine deposits. During accumulation of the epiclastic deposits, however, the continental environments were repeatedly overwhelmed and buried by ash-flows. The change in composition of the ash-flows, the decrease in abundance and thickness of the units, and increased accumulation of epiclastic deposits in younger intervals of the formation may reflect waning intensity of explosive volcanism.

On stratigraphic and weak paleontologic evidence, Fiske and others (1963) suggest that the Stevens Ridge Formation was deposited during the Middle Oligocene to Early Miocene. To obtain a more precise control of the age of the Stevens Ridge Formation a sample collected from the basal member at the Dalles was submitted for a radiometric age determination. The rock contains clasts of basalt and andesite and crystals of plagioclase, quartz, hornblende, biotite, clinopyroxene, hypersthene, and iron oxide in a groundmass of devitrified glass. K/Ar dates of 20.5 ± 1.5 m.y. and 19.5 ± 1.8 m.y. on plagioclase indicate the basal member is Early Miocene in age. Since the overlying Fifes Peak Formation is also Early Miocene, the volcaniclastic rocks of the Stevens Ridge Formation were accumulated in a relatively short period of time.

Fifes Peak Formation

The Fifes Peak Formation (Figure 3; Table 8) is a sequence of andesite and basalt flows with minor interbeds of light-colored volcaniclastic rocks. Warren (1941) named this formation for exposures in the Mount Aix quadrangle and considered it equivalent to the "upper" Keechelus. Fiske and others (1963) redefined the Fifes Peak Formation to exclude silicic ash-flows (now assigned to the Stevens Ridge Formation) at the base of this formation in the Mount Aix quadrangle. In a reconnaissance study, Waters (1961) found the Fifes Peak Formation to be correlative with the "lower" Keechelus. Mapping in the Greenwater River area (Plate 1) indicates the Fifes Peak Formation underlies the "upper" Keechelus of Smith and Calkins (1906).

Although the contact between the Fifes Peak and Stevens

Table 8: Summary of the Fifes Peak Formation.

Lithology:	The rocks consist dominantly of porphyritic andesite and basalt lava flows with minor interbeds of coarse-grained, poorly sorted, epiclastic volcaniclastic rocks.
Distribution:	The formation is best exposed in the southwestern part of the Lester quadrangle, especially the Castle Mountain and Mutton Mountain areas and along the Cascade Crest. In the Camp Creek area and along Huckleberry Ridge, lava flows cap ridges and form dip slopes. This formation is also exposed in the park (Fiske and others, 1963), in the Mount Aix quadrangle (Warren, 1941; Abbott, 1953, unpubl. Ph.D. Thesis) and near the Tieton Reservoir (Swanson, 1966).
Thickness:	Nearly 2,800 feet of this formation are exposed in the southwestern part of the Lester quadrangle. In the Camp Creek area and along Huckleberry Ridge, the formation is relatively thin, less than 600 feet and 800 feet respectively. The formation is less than 2,400 feet thick in the park (Fiske and others, 1963). At the Tieton volcano, the formation is nearly 10,000 feet thick (Swanson, 1966).
Contacts:	The formation unconformably overlies the Ohanapecosh and Stevens Ridge Formations and is unconformably overlain by the "upper" Keechelus and Quaternary lavas.
Age:	On stratigraphic evidence, Fiske and others (1963) suggest the Fifes Peak Formation to be Early Miocene in age. Radiometric dates of 21.7 ± 1.9 m.y. and 23.4 ± 1.4 m.y. on a sample of Castle Mountain and 20.3 ± 2.6 m.y. and 16.7 ± 4.3 m.y. from a sample collected near Mowich Lake confirm the Early Miocene age.
Origin:	The lava flows accumulated as products of volcanism which led to the construction of shield volcanoes. Epiclastic deposits accumulated as the result of surficial processes on the flanks of the growing volcanos.

Ridge Formation is considered concordant and probably conformable in the park (Fiske and others, 1963), it is unconformable in the Greenwater River area. This is best displayed along the Dalles Ridge where the formation overlies both the Stevens Ridge and Ohanapecosh Formations. Along the western and southern parts of the area Fifes Peak lava flows overlie the Ohanapecosh Formation.

Basalt and andesite lava flows, ranging from 40 to 100 feet thick, are the dominant rocks. Most rocks are porphyritic with abundant large (up to 1 cm.) phenocrysts of plagioclase and some phenocrysts of augite and hypersthene. Weathered surfaces are commonly brown to reddish brown, whereas fresh surfaces are dark gray to black. In small exposures the flows have a sheet-like layering, however, the geometry of the flows in large outcrops is more irregular and many show lensoid-profiles. The geometry of the flows was largely controlled by the topography on which the lava was deposited. Platy jointing is common and oriented parallel to the margins of flows. Some flows are vesicular and the vesicles are often filled with chlorite, calcite or zeolites. Flow breccias are common. Thin intervals of epiclastic deposits are interbedded with the lava flows. Epiclastic deposits become thicker with increasing distance from the eruptive centers. The rocks are dominantly cobble and pebble conglomerates and breccias, sandstones and minor siltstones. Lithic clasts are mainly fragments of Fifes Peak lavas and pumice is uncommon. Vertical and lateral variations in grain size and bedding are often abrupt. The units are characteristically very poorly sorted.

The thick accumulations of Fifes Peak lavas are remnants of shield volcanoes, similar to the Tieton volcano (Swanson, 1966). The thick accumulation of flows and abundance of dikes in the Castle Mountain area indicate a similar eruptive center. Along the Dalles Ridge, a small plug and radial dike system lithologically similar to Fifes Peak lavas intrudes the Stevens Ridge Formation and represents the intrusive base of a second eruptive center. These vents probably contributed many flows and are, in part, the source of the thick accumulation of Fifes Peak Formation in the southwestern part of the Lester quadrangle. Vents for the Fifes Peak Formation in the Camp Creek area and along Huckleberry Ridge have not been located. Epiclastic deposits interbedded with the lava flows accumulated along the flanks of growing volcanoes largely as stream deposits. Some unsorted conglomerates and breccias may be mudflow or slurry flood deposits.

On stratigraphic evidence, Fiske and others (1963) estimate the age of the Fifes Peak Formation to be Early Miocene. K/Ar whole rock dates of 21.7 ± 1.9 m.y. and 23.4 ± 1.4 m.y. were obtained from a porphyritic andesite, consisting of phenocrysts of plagioclase and pyroxenes in a granular groundmass of plagioclase, pyroxenes and iron oxides, collected from the Castle Mountain area. A porphyritic andesite, composed of plagioclase and pyroxene phenocrysts in groundmass consisting mainly of plagioclase, pyroxene and iron oxides, collected from the Fifes Peak Formation exposed near Mowich Lake in the northwestern part of the park yields K/Ar plagioclase dates of 16.7 ± 4.3 m.y. and 20.3 ± 2.6 m.y. The radiometric dates confirm the Early Miocene age estimated from stratigraphic evidence for the Fifes Peak Formation.

"Upper" Keechelus Andesite

The andesite flows at Naches Pass and underlying volcaniclastic rocks which unconformably overlie the Fifes Peak Formation are informally assigned to the "upper" Keechelus Andesite (Figure 3; Table 9: Plate 1). This assignment is essentially the same as made by Smith and Calkins (1906). The sequence deserves designation as a formation, but its northerly and easterly distribution should be defined prior to naming units. In the study area this sequence is divided into the Arch Rock and Naches Pass members.

The Arch Rock member consists of well-bedded epiclastic deposits. Dominant rocks include, in decreasing order of abundance, pebble conglomerates and breccias, sandstones, siltstones, and cobble conglomerates and breccias. Lithic clasts are mainly fragments of lavas similar in composition to Fifes Peak lavas. Although pumice clasts are rare, glass is common in the groundmass. The Naches Pass member consists of 2 or 3 flows of fine-grained porphyritic pyroxene andesite. The rocks are composed of small phenocrysts of plagioclase, augite, and hypersthene set in a fine-grained groundmass of granular pyroxenes, iron oxides, plagioclase laths and glass. In the east-facing cliffs north of Rods Gap, the flows have a lensoid cross-section indicating they filled a valley in the underlying volcaniclastic

Table 9: Summary of the "upper" Keechelus Andesite.

Lithology:	The Arch Rock member consists of well-bedded, epiclastic volcaniclastic rocks including, in decreasing order of abundance, pebble conglomerates and breccias, sandstones, siltstones and cobble-conglomerates and breccias. The Naches Pass member consists of fine-grained, porphyritic andesite flows.
Distribution:	This formation is exposed in the northeastern part of the area. The Arch Rock Member is best exposed in cliffs north of Arch Rock and along logging roads in the Pyramid Creek and Meadow Creek areas. Lava flows of the Naches Pass member underlie the tableland at Naches Pass and extend south to Rods Gap.
Thickness:	The Arch Rock member is approximately 400 feet thick north of Greenwater Lakes and increases in thickness to the south to nearly 1,200 feet at Arch Rock. The maximum thickness of the Naches Pass member is approximately 400 feet.
Contacts:	The Arch Rock member unconformably overlies the Fifes Peak Formation. The Naches Pass member is interbedded (?) and overlain by the Ellensburg Formation.
Age:	On stratigraphic evidence the "upper" Keechelus is assigned to the interval ranging from Early Miocene to Early Pliocene.
Origin:	Epiclastic volcaniclastic rocks of the Arch rock member accumulated as fluvial deposits in valleys carved in the underlying Fifes Peak Formation and older rocks. Lava flows of the Naches Pass member accumulated as valley-filling flows.

rocks (Waters, 1961).

The volcaniclastic rocks were deposited by fluvial processes in valleys carved in the underlying Fifes Peak Formation. Whether the source of glassy debris was erosion of older pyroclastic deposits or contemporary volcanism is unknown, however, no ash-flows or air-fall tuffs were recognized in this interval. The composition of the clasts indicates erosion of the underlying Fifes Peak Formation provided much of the detritus. The lava flows at Naches Pass were extruded from unknown vents and were deposited as valley-filling flows on the underlying epiclastic deposits.

The age of the "upper" Keechelus may be approximately determined from stratigraphic relations. The volcaniclastic rocks unconformably overlie the Lower Miocene Fifes Peak Formation. East of Naches Pass along the ridge north of the Middle Fork of the Little Naches River, lava flows of the "upper" Keechelus are interbedded (?) and overlain by pumice-rich volcaniclastics of the Ellensburg Formation which is Late Miocene to Early Pliocene. Because of the close chemical similarity of the "upper" Keechelus lava flows and the rhyodacite welded tuff of the Tatoosh Pluton, Waters (1961) suggested the flows may represent an eruptive volcanic phase of this plutonic event (13 ± 1 m.y. and 14.7 ± 1 m.y.).

Tertiary Intrusive Rocks

Clear West Peak Rhyodacite

The Clear West Peak Rhyodacite is the largest intrusive body in the area (Plate 1) and intrudes the Ohanapecosh, Stevens

Ridge and Fifes Peak Formations. It was first described by Fiske and others (1963) who believe it to be a plug and contemporaneous welded tuff associated with the Tatoosh Pluton. The intrusive contacts are sharp, steeply dipping, and often marked by a reddish oxidation zone. North of Frog Mountain, blocks of highly altered country rocks, probably roof pendants, are incorporated in the rhyodacite.

The rocks are light colored, commonly shades of red, light-gray, bluish gray, and light brown. The rhyodacite contains phenocrysts of plagioclase and minor amounts of hornblende, augite, hypersthene, and biotite in a fine-grained devitrified groundmass (Table 10). Cumuloporphyritic aggregates of phenocrysts are common. Oliogclase and andesine phenocrysts often have well-developed normal zoning and less commonly oscillatory zoning. Most ferromagnesian phenocrysts are altered to chlorite, epidote, sphene and quartz. The groundmass is extremely fine-grained and spherulitic devitrification forming a mosaic of small domains (.1 to .2 mm. in diameter) is the most common texture. Staining with sodium cobaltinitrate indicates K-bearing constituents are present in the groundmass, but there are no K-feldspar phenocrysts. Columnar jointing and planar flow banding are characteristic structures. The columnar jointing has variable trends and horizontal to subhorizontal orientations of the columns are common. Flow banding is present in most exposures and is marked by aligned phenocrysts and segregations in the groundmass, probably due to compositional variation in the viscous magma.

Table 10: Modal analyses of the Clear West Peak Rhyodacite

Sample	136	444	446	447	177	441
Groundmass	94.3	88.3	92.1	91.1	90.3	91.4
Phenocrysts						
Plagioclase	5.0	7.7	5.1	7.3	6.5	6.7
Ferromagnesian Minerals	0.4	1.4	1.0	1.2	1.7	0.6
Opaques	0.3	--	0.3	0.4	0.5	0.1
Lithic Clasts	--	2.6	1.0	--	1.0	1.2
	100.0	100.0	100.0	100.0	100.0	100.0

Note: Samples 136, 444, 446, and 447 are vitrophyric rocks from the main body of the Clear West Peak Rhyodacite. Samples 177 and 441 are from extrusive equivalents.

Rhyodacitic rocks compositionally similar (Table 10) to the Clear West Peak Rhyodacite overlie the Ohanapecosh, Stevens Ridge and Fifes Peak Formations north of the intrusion (Plate 1). Flow banding is highly contorted and markedly different from the planar flow banding in the intrusion. Columnar jointing is absent, but platy jointing parallel to flow banding is common. The rhyodacitic rocks north of the intrusion represent contemporaneous surface extrusives.

Intrusive contacts, roof pendants, extreme thickness of the body, consistent mineralogic composition, and lack of pyroclastic textures indicate an intrusive origin for the Clear West Peak Rhyodacite. The very fine-grained rocks and oxidized intrusive contacts indicate the rhyodacite was emplaced at very shallow depths. Variation in flow banding trends (Plate 1) suggest the magma may have been emplaced from more than one subsurface conduit. Whether the intrusion was wholly subsurface or, in part, an extrusive dome is not clear. Contemporaneous extrusive rhyodacitic rocks north of the intrusion indicate the magma breached the surface.

The Clear West Peak Rhyodacite intrudes the Fifes Peak Formation and therefore cannot be older than Early Miocene. A K/Ar whole rock date of 18.6 ± 0.4 m.y. was obtained from a sample collected from outcrops near the base of Clear West Peak along the West Fork of the White River. This late Early Miocene date is older than the age suggested by Fiske and others (1963).

Granitic Rocks

Medium-grained intrusive rocks are exposed in three small outcrops (Plate 1). The two exposures along the West Fork of the White River are mesocratic pyroxene diorites, composed of altered plagioclase, augite, highly altered hypersthene, and minor hornblende. Rocks of southern exposure intrude the Ohanapecosh and Fifes Peak Formations and those of the northern exposure intrude the Stevens Ridge Formation. The contacts of these intrusions are sharp. A small, poorly exposed hornblende quartz diorite body intrudes lava flows of the Fifes Peak Formation on the Dalles Ridge near the headwaters of Twentyeight Mile Creek (Plate 1). It consists mainly of plagioclase and hornblende with minor augite, biotite and quartz.

Fine-grained Intrusive Rocks

Fine-grained intrusive rocks are common in the area (Plate 1). They are mostly porphyritic pyroxene andesites consisting of plagioclase, hypersthene, augite and, less commonly, hornblende phenocrysts in a holocrystalline groundmass of plagioclase, augite and hypersthene. Minor quartz is present in some samples between plagioclase grains or embaying crystals. Pyrite and other sulfides are common to these rocks and the altered country rocks. Some intrusions may represent conduits for surface volcanism (see page 24). Dikes and sills are the most abundant intrusive bodies and are especially common in the Ohanapecosh and Stevens Ridge Formations. They are mainly very fine-grained to porphyritic andesites and basalts and range from a few inches to more than 200 feet in thickness. Dikes are frequently exposed in road cuts, but most cannot be traced laterally for substantial distances. One northeasterly trending dike east of Haller Pass was traced for nearly 2 miles. Sills are very common in the Stevens Ridge Formation. The high south-facing cliffs of the Palisades (Plate 1) are formed by a thick sill in this formation.

Miocene Volcanism and Plutonism

Beginning with the Upper Cretaceous and continuing to the Pliocene, large masses of granitic rocks were emplaced in the Cascade Range of Washington. Continuing intrusive activity is suggested by Quaternary volcanism. The intrusive chronology (Grant, 1969) suggests the plutonic events become younger from north to south and that the granitic rocks of the southern and central belts were emplaced mainly in the Miocene. Fuller (1925, unpubl. M.S. Thesis), Cater (1960), Tabor (1963), and Fiske and others (1963) describe explosion breccias and other features which indicate the intrusions were emplaced at high levels in the crust and in some cases broke through to the surface.

Radiometric ages (Table 11) and spatial relations of the Miocene volcanic and plutonic rocks in the central Cascades suggest they may be products of separate processes of the same magmatic event. The close similarity in ages of the Stevens Ridge and Fifes Peak Formations indicates the Early Miocene was a period of extensive volcanism and represents the emplacement of a magmatic body with the crust. First, large volumes of pyroclastic materials and, then, lavas were extruded to the surface. Initial deposits of the magmatic event are pyroclastic rocks of the Stevens Ridge Formation which represent explosive

Table 11: Radiometric ages of Miocene plutonic and volcanic rocks.

Tatoosh Pluton[1]	13 ± m.y. and 14.7 ± 1 m.y.
Snoqualmie Granodiorite[2,3]	17 m.y. and 18 m.y.
Clear West Peak Rhyodacite	18.6 ± 0.4 m.y.
Fifes Peak Formation	
Mowich Lake area	20.3 ± 2.6 m.y. and 16.7 ± 4.3 m.y.
Castle Mountain area	23.4 ± 1.4 m.y. and 21.7 ± 1.9 m.y.
Stevens Ridge Formation	20.5 ± 1.5 m.y. and 19.5 ± 1.8 m.y.

[1] Fiske and others, 1963

[2] Baadsgaard and others, 1961

[3] Curtis and others, 1961

volcanic eruptions resulting from degassing of the magma body. After degassing, quieter volcanic eruptions began in which Fifes Peak lavas were extruded to form shield volcanoes. As the magma body crystallized, silicic magmas were mobilized to form intrusive bodies like the Clear West Peak Rhyodacite. Radiometric dates of the Snoqualmie Granodiorite and Tatoosh Pluton record the final crystallization and cooling of the magma body and define the end of this magmatic event.

Quaternary Volcanic Rocks

Grand Park Flow

The Grand Park flow represents an early eruption of Mount Rainier which emitted lavas that filled valleys carved in Tertiary rocks (Fiske and others, 1963). The most northerly remnant of this flow forms the ridge between Huckleberry and Eleanor Creeks (Plate 1). The flow overlies the Ohanapecosh and Fifes Peak Formations and the contact is marked by a reddish oxidation zone. At the southern edge of the area the flow caps the ridge at an elevation of 4,700 feet, and at the most northerly exposure its base is at an elevation of 3,000 feet. The flow filled an ancient valley which had a gradient of approximately 150 feet/mile and valley walls with a 30% slope, similar to the present valley of Huckleberry Creek. The flow was ponded in the valley and had sufficient time during cooling to form well-developed vertical columnar jointing.

The flow is a light-colored, porphyritic pyroxene andesite, containing phenocrysts of plagioclase, augite, and hypersthene (Table 12). Plagioclase phenocrysts (up to 1.25 cm. in length)

Table 12: Modal analyses of the Grand Park flow and the Dalles Ridge flows

Sample	Grand Park Flow 126	384	The Dalles Ridge Flows 415	417	543	544
Groundmass						
Plagioclase	47.5	46.8	54.6	--	52.1	45.8
Ferromagnesian Minerals	6.7	6.4	29.0	--	30.4	34.0
Opaques	4.6	7.4	7.2	3.9	6.1	7.8
Phenocrysts						
Plagioclase	28.7	29.7	--	62.5	--	--
Olivine	tr	--	9.2	6.8	11.4	12.4
Hypersthene	5.5	4.0	--	--	--	--
Clinopyroxene	7.0	5.7	--	26.8	--	--
	100.0	100.0	100.0	100.0	100.0	100.0

126 & 384 Porphyritic pyroxene andesites

415, 543 & 544 Fine-grained, microporphyritic olivine basalts

417 Coarse-grained, diktytaxitic olivine basalt

Table 13: Microprobe chemical analysis of the Dalles Ridge flows. Analysis is anhydrous determined from a fused glass bead.

Sample	415
SiO_2	51.96
TiO_2	1.47
Al_2O_3	15.79
Fe_2O_3*	8.72
MgO	7.91
CaO	9.00
Na_2O	3.15
K_2O	0.83
Total	98.83

*Total iron given as Fe_2O_3

are most abundant and consist of unzoned and normally zones crystals ranging from An_{55} in the core to An_{40} at the rim. Some show minor resorbtion at their borders and others have rims clouded by inclusions of glass and opaques. Pale green to neutral augite (2V 45-50°) and prismatic crystals of hypersthene are present in equal amounts. The groundmass is a felted mass of plagioclase laths with subordinant grains of augite, hypersthene and small crystals of opaques.

The Dalles Ridge Flows

The Dalles Ridge flows are exposed for nearly four miles along the crest of the Dalles Ridge (Plate 1). Their highest exposure is approximately 5,040 feet about one mile southeast of the Dalles Lake and at the northwest end of the ridge the flows are found as low as 3,200 feet. The sinuous outcrop pattern suggests the flows filled a stream valley carved in the Fifes Peak and Stevens Ridge Formations, and if the present distribution of flows occupy the lowest portions of the valley its gradient was approximately 320 feet/mile. The flows overlie a soil horizon and the contact may be marked by a bright red oxidation zone, cinder layers, and/or a scoriaceous zone at the base of the flows. The preserved remnants of these flows are no more than 300 feet thick.

The initial eruption was a crystal-pumice ash-flow which displays excellent flow banding, marked by alignment of plagioclase crystals and flattened lenses of pumice. This was followed by at least five lava flows which range from 10 to 80 feet thick. The flows are fine-grained, light-colored olivine basalts which contain microphenocrysts of subhedral olivine (about 0.5 mm. in length) in a pilotaxitic groundmass of plagioclase laths, abundant opaques and lesser amounts of clinopyroxene and olivine (Table 12). One flow is coarse-grained and has a diktytaxitic texture. Columnar jointing is displayed by each flow. Although the flows have scoriaceous bases and tops, soil zones and clastic intervals between the flows are absent indicating only short intervals of time elapsed between eruptions.

The Dalles Ridge flows (Table 13) are different from the lavas of Mount Rainier volcano and are more similar to the high-alumina olivine basalts and andesites found farther south in the Cascade Range (Wise, 1970; and Waters, 1973). The vent for the flows was not located but it probably lies southeast of Dalles Lake. The flows are lithologically similar to lavas associated with Quaternary volcanoes in the Cascade Range and for this reason are believed to be Quaternary. Since the flows have undergone considerable topographic inversion, they probably represent a relatively old Quaternary volcanic event.

Surficial Deposits

Deposits of alluvium, glacial drift and mudflows cover the valley floors in the Greenwater River area (Plate 1), but have not been mapped in this study. Landslides are common in areas underlain by volcanclastic rocks and in areas of hydrothermal alteration. Thick soils cover most slopes, especially in areas underlain by volcaniclastic rocks at lower elevations.

LOW-GRADE METAMORPHISM IN THE CENTRAL CASCADE RANGE

Nature of Alteration

Low-grade metamorphism of the Tertiary section in the central Cascades is of hydrothermal origin. The abundant occurrences of hydrated secondary minerals are clear evidence of the activity of water. In many cases, however, the alteration shows no relationship to igneous intrusions and the origin of the hydrothermal fluids is uncertain. Whether the hydrothermal fluids result from increasing rock temperatures due to deep burial or are due to dissipation of heat from cooling intrusions is the major question. The abundance of igneous intrusive rocks (Figure 2; Plate 1) indicates the availability of cooling igneous bodies. Similarly, the total thickness of the Tertiary section, greater than 26,000 feet, is sufficient to attain temperatures to produce low-grade burial assemblages.

The alteration is transitional from diagenesis to assemblages characteristic of the zeolite and prehnite-pumpellyite facies of metamorphism as defined by Turner (1968). Alteration products replace primary phases and fill cavities, vesicles, and veins. Progressive alteration is displayed by the stratigraphic and areal zonation of secondary minerals. The rocks are not pervasively altered and original textures, relict minerals, and relatively unaltered rocks are commonly preserved. Volcaniclastic rocks are invariably more highly altered than interbedded lava flows or arkosic rocks. Samples of volcaniclastic rocks collected at the same locality show varying characteristics of alteration suggesting that local evironmental conditions played an important role. The local variability in alteration is largely related to inherent original lithologic characteristics (e.g., porosity, permeability, grain size, and relative chemical stability of primary phases). The alteration assemblages appear to be in equilibrium on a mm. or cm. scale. The relatively short duration of the Tertiary low-grade metamorphic processes has resulted in incomplete adjustment of the rocks and the development of highly varied assemblages.

Stratigraphic Variation in Alteration

Central Cascades Section

The central Cascades section is a composite section which includes sampled intervals in the Greenwater River area and the Cascade Crest section (Figure 1) and contains volcanogenic and sedimentary rocks ranging from Middle Eocene to Early Pliocene (Figure 5). Sampled intervals in the Greenwater River area include the "upper" Keechelus Andesite, Fifes Peak and Stevens Ridge Formations and the upper part of the Ohanapecosh Formation. Additional units present in the Cascade Crest section are the Ellensburg Formation, a complete section of the Ohanapecosh Formation, and the Puget Group. The stratigraphic variation in secondary minerals (Figure 5) shows a definite pattern. The upper part of the section is characterized by low density, highly hydrated minerals, zeolites and clays. Higher density and less hydrated minerals, prehnite, epidote, calcite, and mica are more abundant in the lower part of the section.

Figure 5: Stratigraphic distribution of alteration minerals in the central Cascades Section.

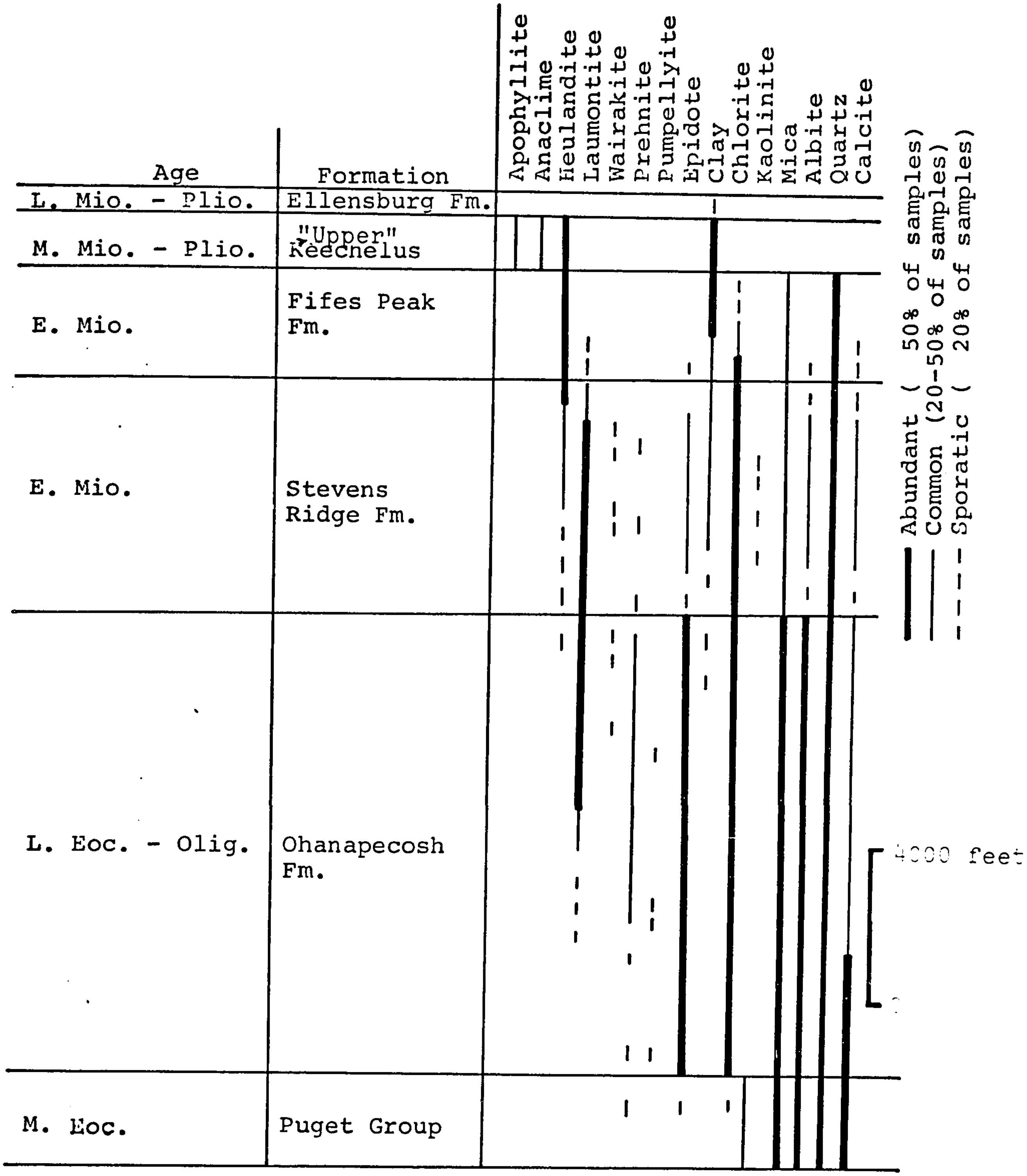


Table 14: Alteration assemblages in the central Cascades section. Ab, albite; An, analcime; Ap, apophyllite; Ca, calcite; Ch, chlorite; C, clay; Ep, epidote; He, heulandite; Ka, kaolinite; La, laumontite; M, mica; Pr, prehnite; Pu, pumpellyite; Q, quartz; Sp, sphene, Wa, wairakite.

Formation	Volcaniclastics	Lavas
Ellensburg Formation	Unaltered	None
"Upper" Keechelus	He-C (An, Ap)	Unaltered
Fifes Peak Formation	He-C•Ch-Q (M, Ab) He-La-C•Ch-Q (M) La-Ch-Q (M, Ca)	He-C•Ch-Q (M) La-C•Ch-Q (Ep, M, Ab, Ca) Ca-C•Ch-Q (M, Ep)
Stevens Ridge Formation	He-C•Cl-Q (M, Ca, Sp) He-La-Cl-Q (M, Ab, Sp) La-Ch-Q (M, Ab, Ca, Sp) La-Wa-Ch-Q (Ep, Pr, M, Ab, Ca) Pr-La-Ch-Q (Ep, M, Ab, Ca, Sp) Ep-La-Ch-Q (Ab) Ep-Pr-Ch-Q (Ab, Ca, Sp, K) Ep-Cl-Q (M, Ca, Sp) Ca-Ch-Q (M, Ab, K)	None
Ohanapecosh Formation	He-Ch-Q (Ca, Sp) La-Ch-Q (Ab, Ca) La-Wa-Ch-Q (Ep, M, Ca, Sp) Pr-La-Ch-Q (Ep, M, Ab, Sp) Ep-La-Ch-Q (Pu, M, Ab, Sp) Pr-Ch-Q (M, Ca, Sp) Ep-Pr-Ch-Q (M, Ab, Sp) Ep-Ch-Q (Pu, M, Ab, Ca, Sp) Ca-Ch-Q (M, Ab, Sp)	La-Ch-Q (Ab) Pr-La-Ch-Q (Ep, Pu, M, Ab) Ep-Pr-Ch-Q (Ab, Sp) Ep-Ch-Q (M, Ab, Ca) Ca-Ch-Q (M, Ab)
Puget Group	Ca-M-Q (Ca, Ab)	Ep-Pr-Ch-Q (Ab, Ca, Sp) Ep-Ch-Q (M, Ab, Ca, Sp) Ca-M-Q (Ch, Ab)

Alteration assemblages are complex, commonly consisting of 4 or more phases, and highly variable (Table 14). The relatively shallow depths of burial of the low-grade assemblages suggest the Tertiary section was subjected to steep thermal gradients of metamorphism.

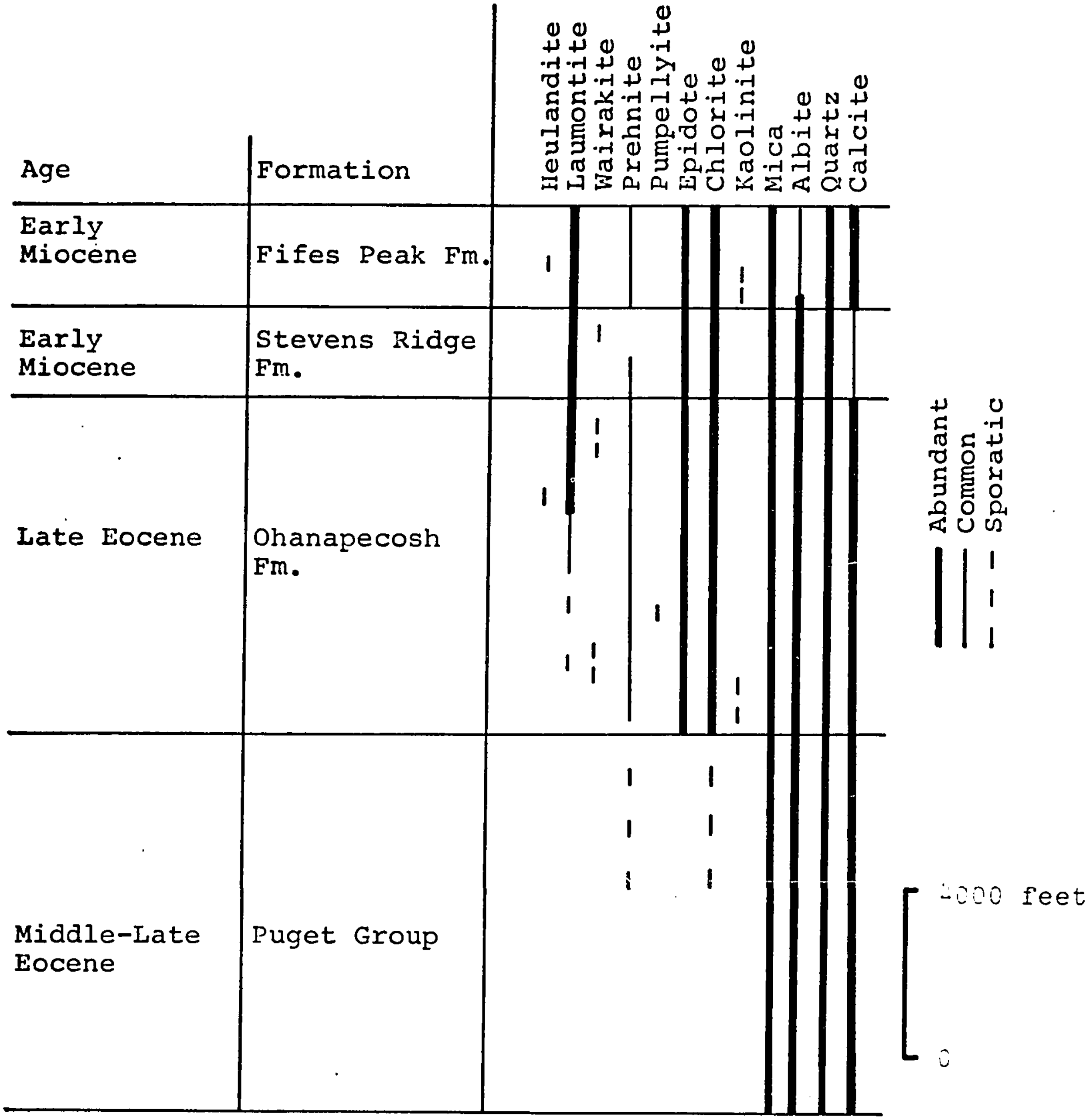
Mowich Lake Road Section

At the northwest corner of Mount Rainier National Park nearly 22,000 feet of volcanogenic and sedimentary rocks ranging from Middle Eocene to Early Miocene in age are exposed in the Mowich Lake road section (Figure 1). Sampled units include the Puget Group, Ohanapecosh, Stevens Ridge and Fifes Peak Formations. The distribution of secondary minerals in this section (Figure 6) is similar to that observed in the central Cascades section. The major difference is that higher density alteration minerals are more abundant in the Stevens Ridge and Fifes Peak Formations in the Mowich Lake road section than in the central Cascade section which suggests even steeper metamorphic gradients in this area.

Tiger Mountain Section

Interbedded arkosic and volcanogenic rocks of the Tiger Mountain section (Figure 1) were studied to determine the role of lithologic composition in the development of alteration assemblages. In this section, Middle Eocene to Lower Oligocene nonmarine rocks of the Puget Group unconformably overlie Middle Eocene marine rocks of the Raging River Formation (Vine, 1969). The Tiger Mountain and Renton Formation, lower and upper members of the Puget Group, respectively, consist of arkosic sandstones

Figure 6: Stratigraphic distribution of alteration minerals in the Mowich Lake Road Section.



and interbedded carbonaceous siltstones, shales and coals. The Tukwila Formation, the middle member, consists of epiclastic volcaniclastic rocks.

In this section (Figure 7) variation in alteration assemblages is related to increased depth of burial and differences in rock type. The burial metamorphic alteration is best displayed by the matrix of the arkosic sandstones. Micaceous matrix[1] increases in abundance with depth whereas kaolinitic matrix decreases in abundance, similar to the pattern observed in many thick accumulations of arkosic sediments (Burst, 1957; Maxwell and Hower, 1967; Powers, 1969; Muffler and White, 1969; and Schmidt, 1973). Arkosic rocks are characterized by a kaolinite-mica alteration assemblage. Locally, calcite or laumontite may occur as cement. Volcaniclastic rocks are characterized by a mica-chlorite (± laumontite or kaolinite assemblage). Laumontite occurs replacing plagioclase, glassy groundmass, or as cement.

Minimum metamorphic conditions may be estimated from the degree of coal metamorphism. In the Renton Formation, coals from the Taylor area have an average volatile matter content of 36.2% (d.a.f.) and rank as high-volatile B to high-volatile A bituminous coals (Beikman and others, 1961). Coal metamorphism curves of Teichmuller and Teichmuller (1968) indicate this grade of coal was subjected to no less than 7,000 feet of burial and rock temperatures of at least 80°C.

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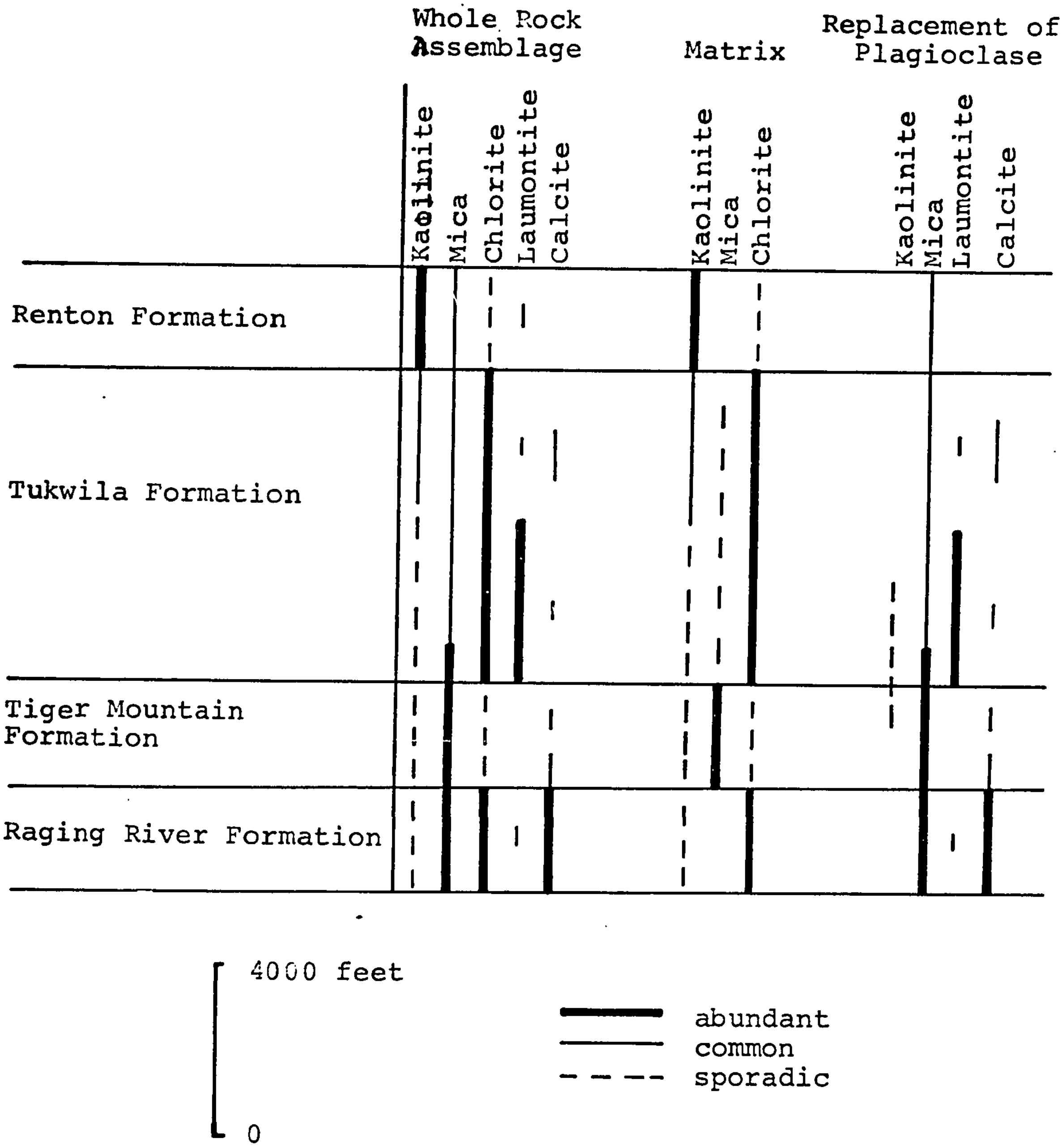
[1] The micaceous matrix has a sharp 10 Å peak on X-ray diffraction traces and is interpreted to be a highly ordered illite.

Figure 7: Stratigraphic distribution in alteration minerals in the Tiger Mountain area.



Stratigraphic Zonation of Mineral Associations

Stratigraphic distribution of secondary minerals displays a similar sequence in each of the sections studied. The central Cascades section contains the most complete range in mineral associations and may be divided into 6 alteration zones based on the dominant Ca-silicates and phyllosilicates which occur as replacement phases (Figure 8). These zones in order of increasing rank are:

I. Unaltered[1]
II. Heulandite-clay (analcime, apophyllite, calcite)
III. Heulandite-clay·chlorite-quartz (laumontite, sphene, calcite, mica, albite)
IV. Laumontite-chlorite-quartz (heulandite, wairakite, prehnite, epidote, sphene, calcite, clay, mica, albite)
V. Epidote-prehnite-chlorite-quartz (laumontite, pumpellyite, sphene, calcite, mica, albite)
VI. Mica-calcite-quartz (Chlorite, kaolinite, albite).

Alteration assemblages indicate hydration of the primary phases of rocks. The most hydrous secondary minerals, zeolites and clays, occur in the lowest grades of alteration and with increasing stratigraphic depth (increasing temperature) more strongly dehydrated assemblages are formed with the highest grade assemblages containing the least hydrous phases, epidote, prehnite and mica (Figure 9). The density of the secondary minerals also increases with increasing grade of alteration (Figure 10.) Because of the overlap in the distribution of alteration minerals, the boundaries of the zones are indefinite and can only be approximately located.

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[1] The unaltered zone contains some alteration of ferromagnesian minerals and glass to clay, but the alteration present in this zone is indistinguishable from the effects of weathering.

Figure 8: Stratigraphic Zonation in the Central Cascades Section.

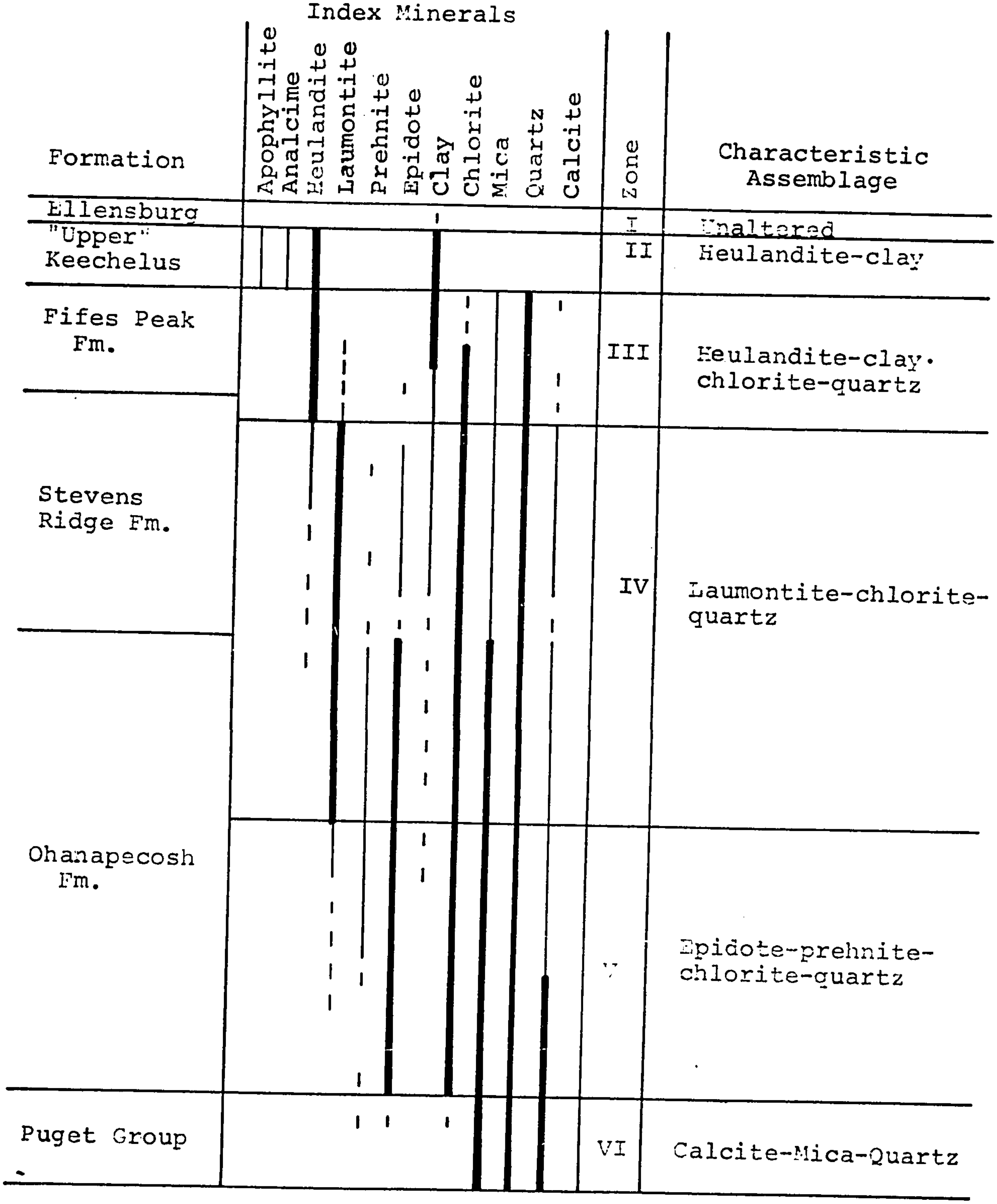


Figure 9: Water content of hydrous alteration minerals in alteration zones.

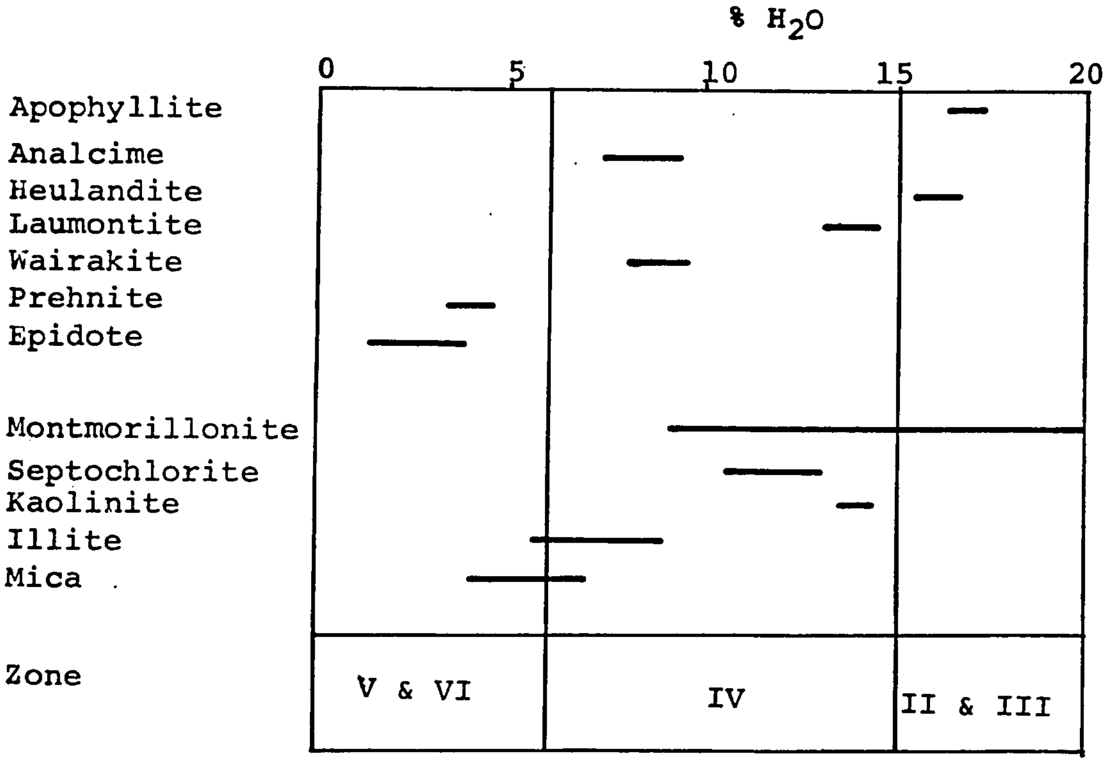
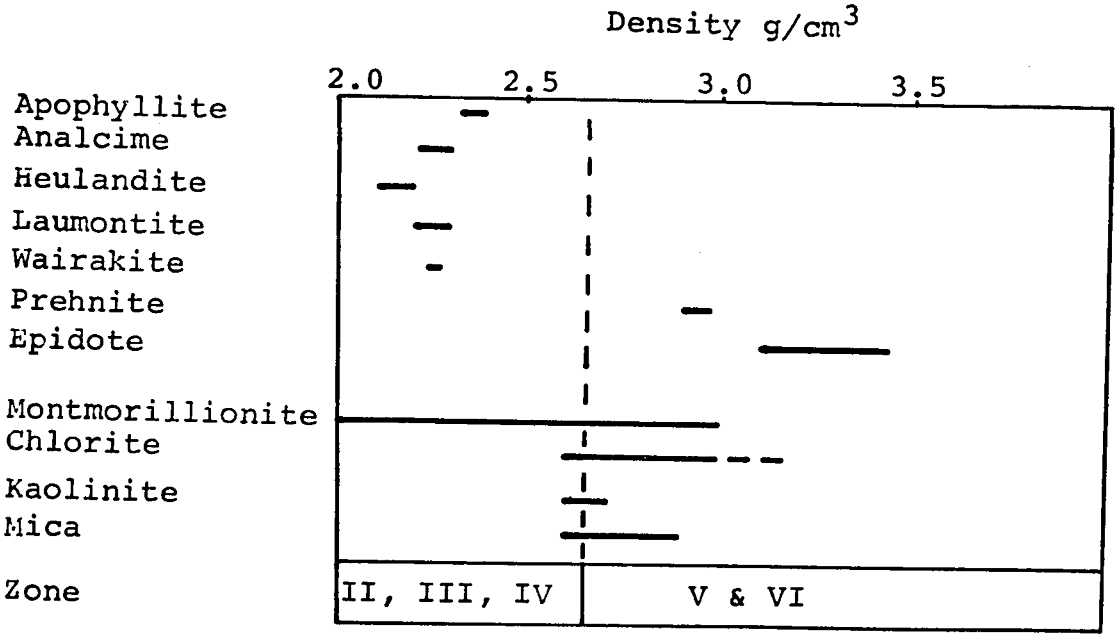


Figure 10: Density of alteration minerals in alteration zones.



Areal Distribution of Alteration Minerals

In the Greenwater River area the alteration zones are roughly parallel to stratigraphic boundaries. However, comparison of the central Cascades section (Figure 5) with the Mowich Lake road section (Figure 6) indicates the alteration zones are not confined to the same stratigraphic intervals. Regional stratigraphic variation in alteration is readily apparent in the areal distribution of the secondary minerals (Figures 11 and 12). The minerals have overlapping fields of occurrence and indicate a northerly decrease in grade of alteration. Zones of epidote and prehnite (Figure 11) and then laumontite, heulandite, analcime and apophyllite (Figure 12) are encountered progressively proceeding northeasterly from the park. In part, the areal distribution of alteration minerals reflects the stratigraphic zonation in that the northeastern part of the area is underlain by Lower Miocene and younger rocks containing zeolitic assemblages and the southern part of the area is underlain largely by older Tertiary rocks and contain higher grade assamblages. However, younger Tertiary rocks in the southern part of the area also contain higher grade assemblages (e.g. Stevens Ridge and Fifes Peak Formations in the Mowich Lake road section). The discordance of alteration zones and stratigraphy and the higher grade of alteration to the south are probably due to the close proximity of the Carbon Stock and Tatoosh Pluton.

Alteration of Primary Phases

The analysis of diagnetic and low-grade metamorphic trans-

Figure 11: Areal distribution of epidote, prehnite and pumpellyite.

Explanation

▨ Granitic intrusive rocks

⊞ Fine-grained intrusive rocks

○ Samples of Tertiary rocks

● With epidote

ϕ With prehnite

⊖ With pumpellyite

┬┬┬ Outer limit of abundant epidote

░ Area of abundant prehnite

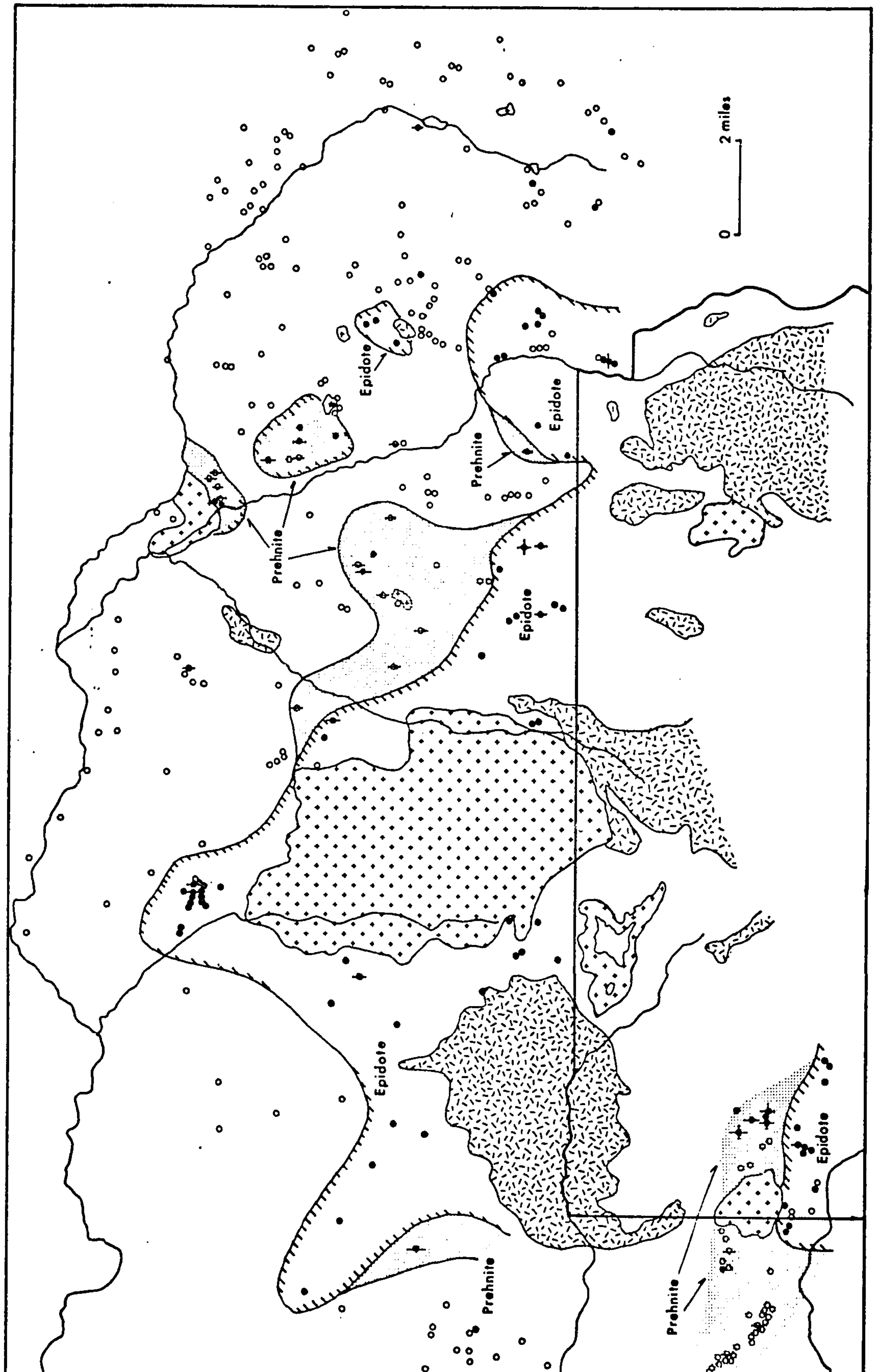

Epidote
Prehnite
Prehnite
Epidote
Prehnite
Epidote
Epidote
Prehnite
Prehnite
Epidote
0
2 miles

Figure 12: Areal distribution of Wairakite, laumontite, heulandite, analcime and apophyllite. Identification of zeolite minerals determined from X-ray diffraction traces.

Explanation

▨ Granitic intrusive rocks

⊞ Fine-grained intrusive rocks

o Samples of Tertiary rocks

⦵ With wairakite

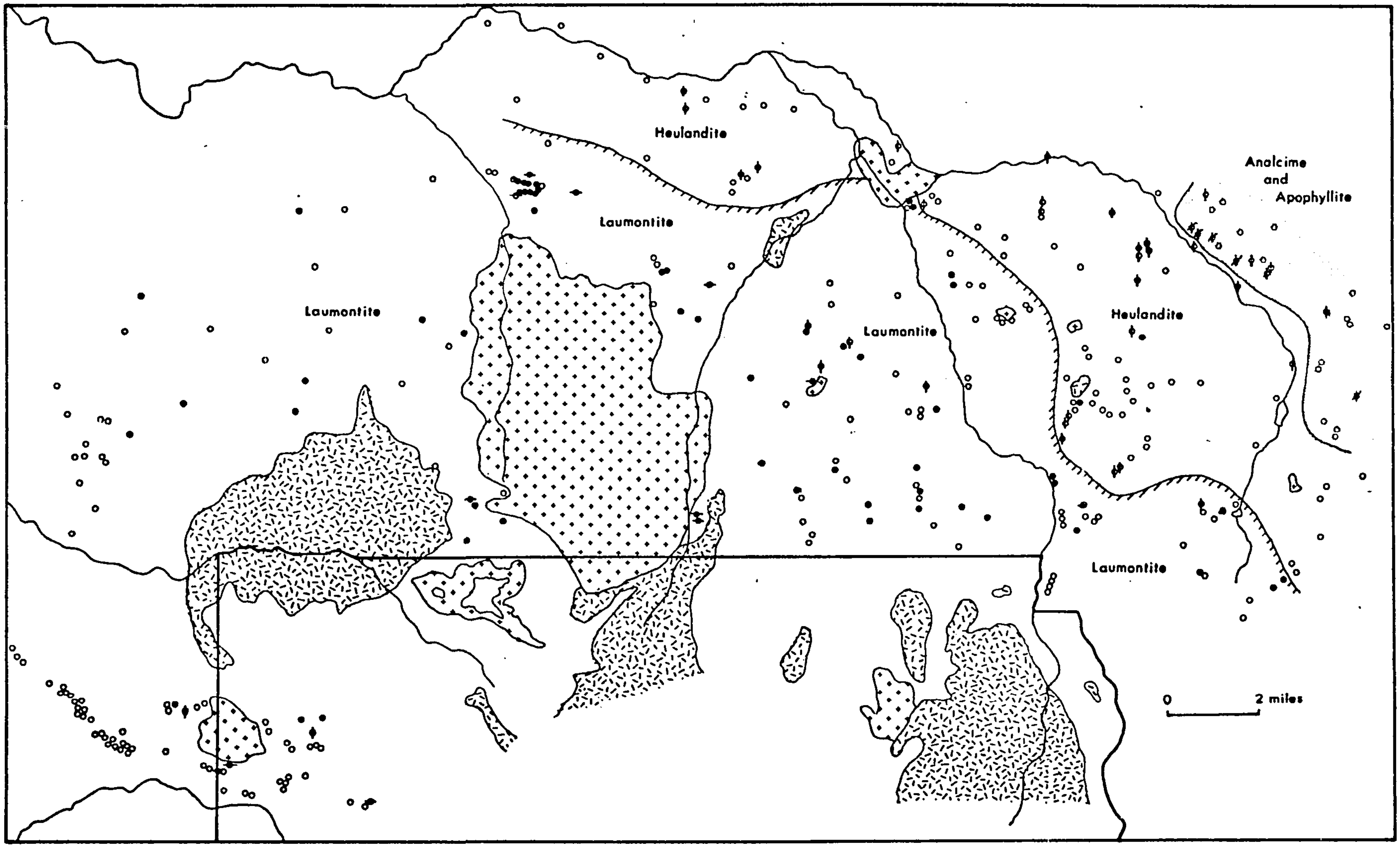
● With laumontite

ϕ With heulandite

ø With analcime and/or apophyllite

┬┬┬┬ Outer limit of abundant laumontite

▦ Area of abundant analcime and apophyllite



Heulandite
Analcime
and
Apophyllite
Laumontite
Laumontite
Laumontite
Heulandite
Laumontite
0
2 miles

formations involves investigation of four parameters (Crook, 1963):

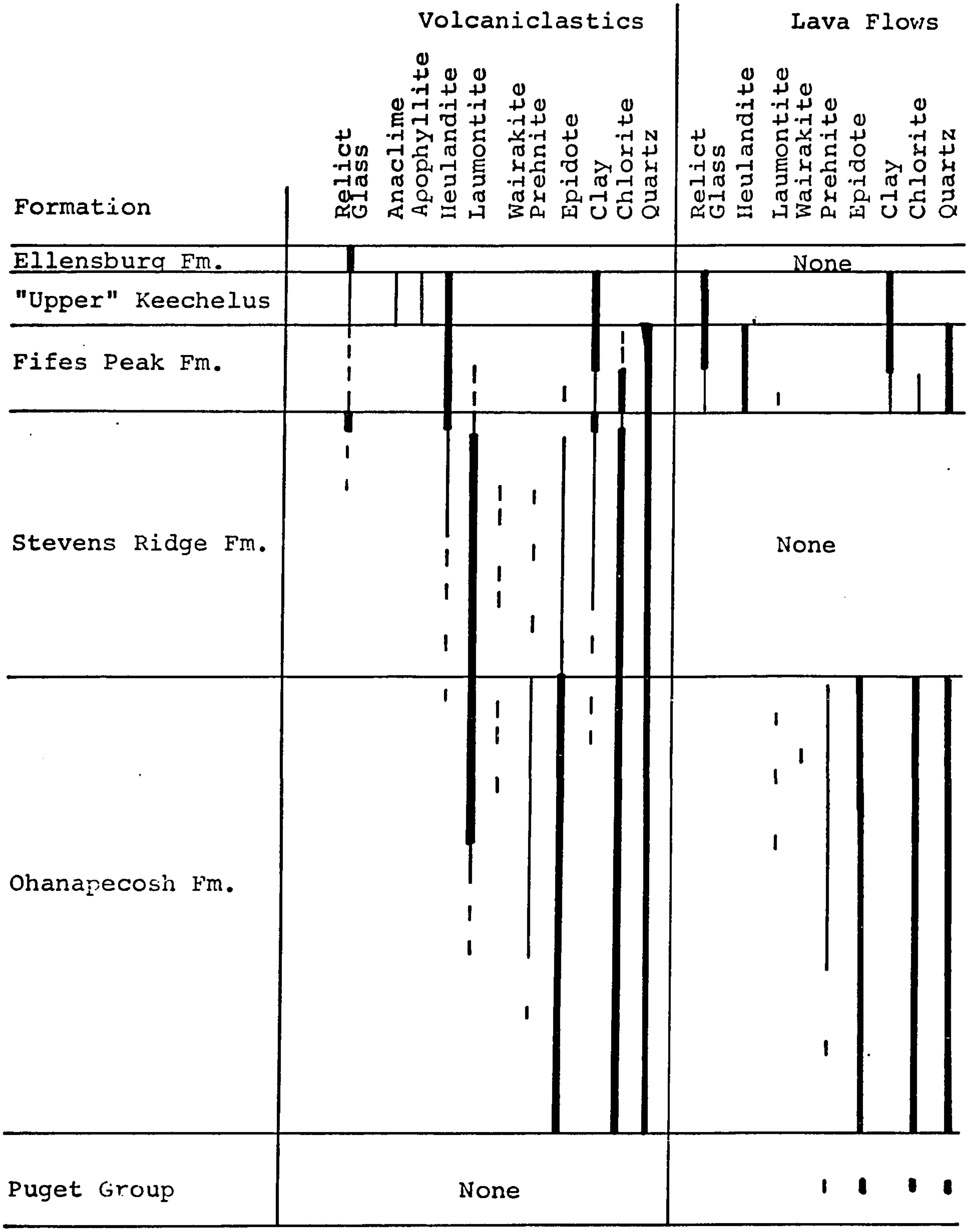
1) primary phases (relict phases)
2) replacing phases
3) new growth phases (filling of pores and vesicles)
4) vein phases.

Parameters 2,3, and 4 were used to determine alteration assemblages (Table 14) and the replacing phases have been used to define zones of alteration (Figure 8). Relict phases, which decrease in abundance with increasing grade of alteration, are present in nearly all altered rocks. The occurrence of relict phases indicates incomplete alteration and suggests equilibruim was not achieved during low-grade metamorphism. The alteration of glass, ferromagnesian minerals and plagioclase was given special emphasis in this study.

Glass

Volcanic glass is particularly susceptible to alteration and relict glass decreases in abundance with increasing depth of burial (Figure 13). In the most highly altered rocks, relict glass is absent. Apparently, the alteration of glass proceeds more rapidly in volcaniclastic rocks than in lavas. The alteration is mainly a replacement process involving solution of the original material followed by precipitation of secondary phases. The distribution of secondary minerals replacing glass (Figure 13) is similar to that found in the stratigraphic zones of alteration (Figure 8). Devitrification of glass was observed only in the densely welded ash-flows of the Stevens Ridge Formation.

Figure 13: Alteration of volcanic glass in the central Cascades.



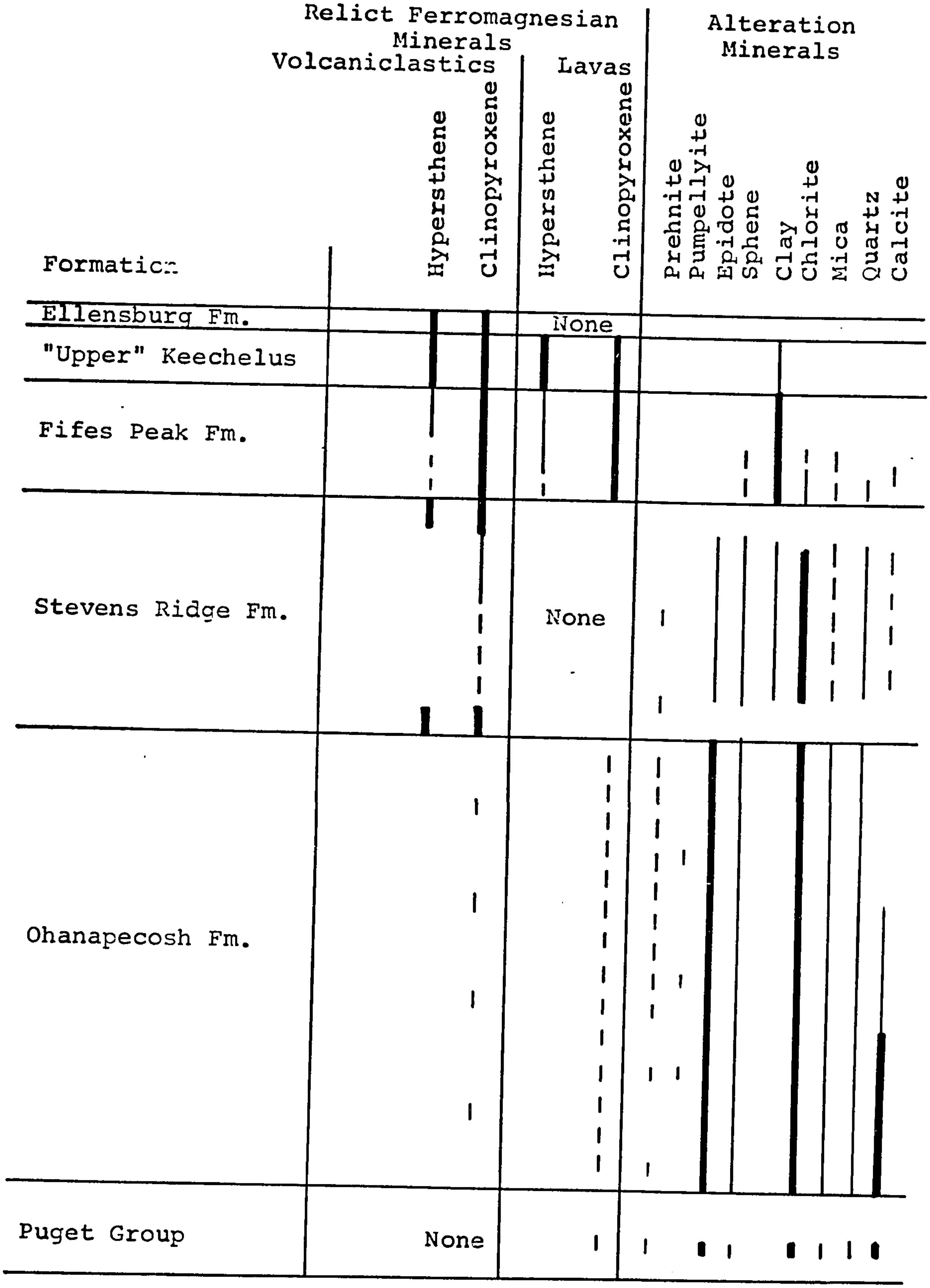
Ferromagnesian Minerals

Ferromagnesian minerals in the volcanogenic rocks include clinopyroxene, hypersthene, hornblende, biotite and olivine, but only clinopyroxene and hypersthene are sufficiently abundant to be studied systematically. Like glass, relict clinopyroxene and hypersthene decrease in abundance with increasing grade of alteration (Figure 14), but the ferromagnesian persist to somewhat deeper stratigraphic levels. Alteration of clinopyroxene and hypersthene is more rapid in volcaniclastic rocks than in lavas; and, given similar rock types, hypersthene shows a greater tendency to be altered than clinopyroxene. Abundant ferromagnesian minerals are preserved in the densely welded ash-flows of the Stevens Ridge Formation. Mineral alteration initially occurs as replacement along fractures and edges of crystals and grains and ultimately leads to the formation of pseudomorphs. Replacement by clay, chlorite, sphene, calcite and quartz occurs in shallow stratigraphic levels and epidote, pumpellyite, prehnite, chlorite, mica, sphene, calcite and quartz occur at higher grades (Table 14).

Plagioclase

Primary plagioclases range from albite to labradorite, but oligoclase and andesine are most common. Alteration begins at grain margins or as small patches or stringers within grains and at higher degrees of alteration the grains are wholly replaced. The replacing phases are mostly confined to individual grains. Within a single rock sample, individual grains may range from

Figure 14: Alteration of pyroxenes in the central Cascades.



unaltered to completely replaced, and the alteration assemblages in adjacent grains are frequently different. The percentage of samples in a stratigraphic interval with altered plagioclase and the percentage of samples with albitized plagioclase increase with increasing depth of burial (Figure 15). Secondary albite only partially replaces grains and is generally accompanied by additional secondary minerals. Common minerals replacing plagioclase include analcime, heulandite, laumontite, wairakite, epidote, prehnite, kaolinite, mica, and calcite. The stratigraphic distribution of the replacing phases (Figure 15) is similar to the alteration of glass (Figure 13).

Plagioclase alteration is mainly the result of hydration reactions involving the breakdown of the anorthite component (Table 15). For most replacement reactions, the few additional components necessary are probably readily available in the associated fluids. Heulandite, laumontite, and prehnite need additional Si; prehnite and epidote, additional Ca; and mica, additional K. Reactions forming mica and kaolinite release Ca to the reacting system. Plagioclase alteration assemblages and variation in assemblages in individual grains in the same sample suggest some replacement reactions bear reciprocal relationships. Calcite is commonly found with prehnite, epidote, mica and kaolinite but rarely with heulandite or laumontite.

Textural Alteration of Volcaniclastic Rocks

Most studies of low-grade metamorphic rocks have focused on the development of secondary mineral assemblages and little attention has been given to textural changes other than veins.

Figure 15: Alteration of plagioclase in the central Cascades section.

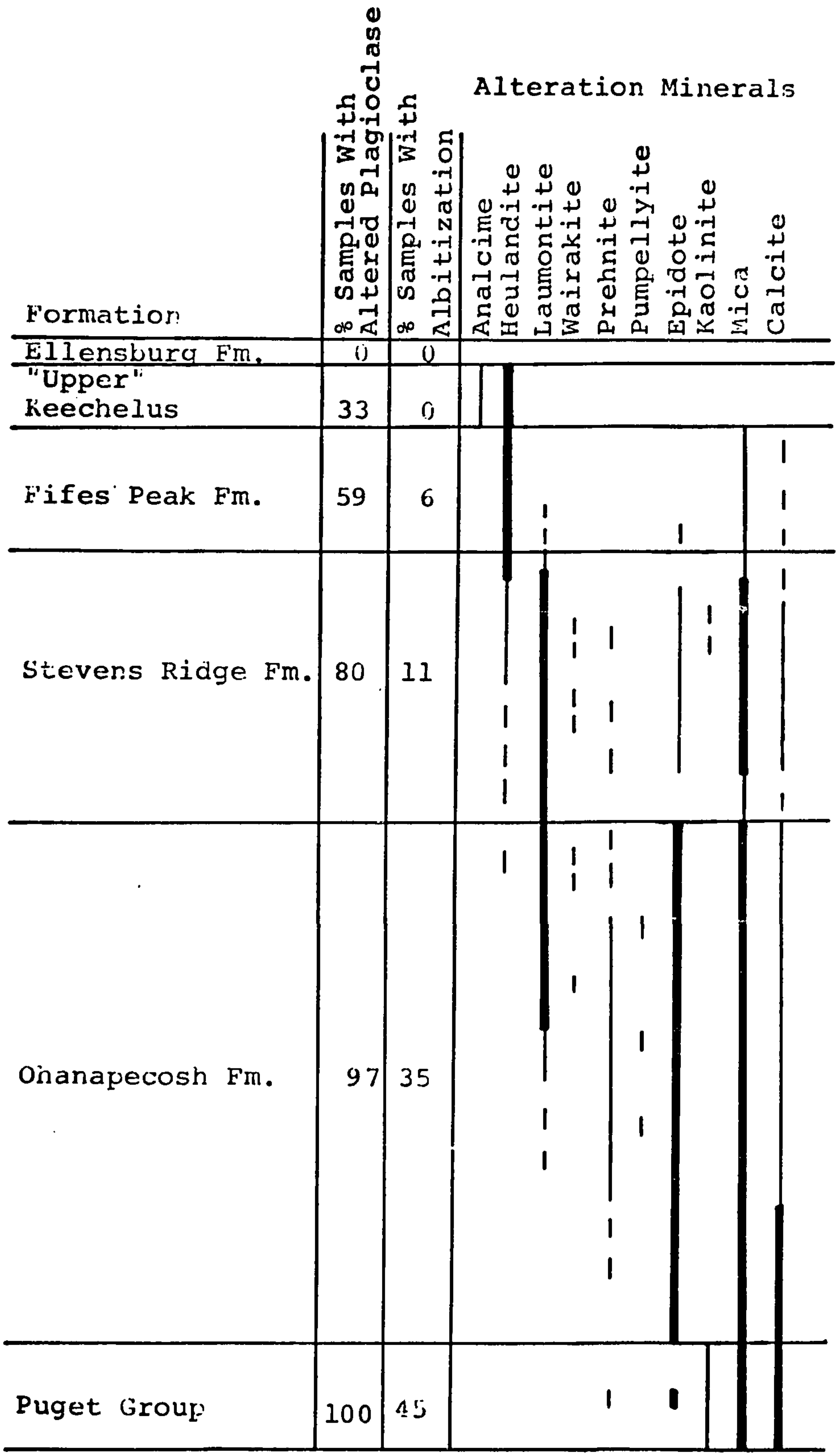


Table 15: Anorthite replacement reactions

Heulandite

(1) $CaAl_2Si_2O_8 + 6\ H_2O + 5\ SiO_2 \longrightarrow CaAl_2Si_7O_{18} \cdot 6\ H_2O$

Laumontite

(2) $CaAl_2Si_2O_8 + 4\ H_2O + 2\ SiO_2 \longrightarrow CaAl_2Si_4O_{12} \cdot 4\ H_2O$

Prehnite

(3) $CaAl_2Si_2O_8 + \underset{Ca^{++}}{CaCO_3} + \underset{2\ H_2O}{H_2O} + SiO_2 \longrightarrow Ca_2Al_2Si_3O_{10}(OH)_2 + \underset{2\ H^+}{CO_2}$

Epidote

(4) $3\ CaAl_2Si_2O_8 + \underset{Ca^{++}}{CaCO_3} + \underset{2\ H_2O}{H_2O} \longrightarrow 2\ Ca_2Al_3Si_3O_{12}(OH) + \underset{2\ H^+}{CO_2}$

Mica

(5) $3\ CaAl_2Si_2O_8 + \underset{2\ K^+}{2\ KOH} + \underset{4\ H^+}{H_2O} + 3\ CO_2 \longrightarrow 2\ KAl_3Si_3O_{10}(OH)_2 + \underset{3\ Ca^{++}}{3\ CaCO_3}$

Kaolinite

(6) $2\ CaAl_2Si_2O_8 + \underset{2\ H_2O}{4\ H_2O} + \underset{4\ H^+}{2\ CO_2} \longrightarrow Al_4Si_4O_{10}(OH)_8 + \underset{2\ Ca^{++}}{2\ CaCO_3}$

Because volcaniclastic rocks are particularly sensitive to alteration, several recognizable trends in textural modification accompany increasing grades of metamorphism. The textural changes are an excellent measure of the extent of alteration and provide some evidence of the alteration processes. Replacement of primary grains and crystals is confined within original grain boundaries and the characteristics of this alteration have been discussed previously. In addition, alteration of groundmass, lithic grains, and fillings of pores, vesicles and veins show marked textural and mineralogic changes with increasing alteration.

The volcaniclastic rocks of the Ellensburg Formation and the occurrence of relatively unaltered rocks within altered intervals in other units provide a base with which to compare textural changes associated with increasing alteration. The unaltered rocks may contain minor clay replacement of ferromagnesian minerals and glass, or some etching of detrital grains, but this alteration is indistinguishable from the effects of weathering. Three major lithologic components are recognized in the unaltered rocks:

1) detrital grains - mineral, pumice and lithic clasts,
2) matrix - mainly glass,
3) voids - pores and vesicles.

In unaltered rocks, recognition of the individual components is easily made, but with increasing alteration differentiation of detrital grains and matrix, or matrix and void fillings becomes more difficult.

Color may also reflect the degree of alteration. Colors of rocks in the Ellensburg Formation reflect the colors of the detrital components. Lithic detrital rocks contain multicolored lithic fragments and the color of the rock is determined by the dominant clasts. Glass-rich rocks are very light-colored and contain multicolored lithic clasts. Altered rocks with zeolite and clay assemblages are mostly light-colored, tan and light brown, and frequently contain dark lithic clasts. Higher grade rocks, especially those of the Ohanapecosh Formation, are greenish colored due to replacement of groundmass and lithic clasts by chlorite.

The progressive alteration of volcaniclastic rocks with burial is, in part, reflected in their relative degree of induration (Table 16). Weakly to moderately indurated rocks break around detrital grains but across the groundmass. Highly indurated rocks break across all lithic components. Compaction and grain deformation proceed rapidly with burial. Detrital grains in matrix-poor rocks of the Ellensburg Formation have point contacts and less than 1 grain contact/grain. Matrix-poor rocks of the Fifes Peak Formation have longitudinal and concave-convex grain contacts and 3 to 5 grain contacts/grain. The increased compaction and induration with burial is paralleled by an increase in bulk rock density (Figure 16).

Groundmass

The fine-grained clastic matrix in rocks of the Ellensburg Formation consists mainly of glass which commonly displays shard textures. Glass is readily altered to secondary minerals with burial (Figure 13). Altered matrix can be clearly differ-

Table 16: Stratigraphic variation in induration and density of volcaniclastic rocks.

Formation	Induration	Density	
		Range	Average
Ellensburg Formation	friable, very weakly indurated	1.83-2.12	1.94
"Upper" Keechelus Andesite	friable, weakly to moderately indurated	1.80-2.03	1.95
Fifes Peak Formation	friable, weakly to moderately indurated	2.08-2.33	2.19
Stevens Ridge Formation	weakly to highly indurated	2.08-2.42	2.24
Ohanapecosh Formation	highly indurated	2.20-2.60	2.41

entiated from interstitial pore fillings only in rocks of the "upper" Keechelus Andesite. Pore fillings contain secondary minerals arranged in radial or concentric patterns with respect to the margins of the void spaces, whereas the matrix alteration generally displays no preferred orientation. At higher degrees of alteration, the two lithologic components are thoroughly recrystallized and fine-grained intergranular material is referred to collectively as groundmass. Shard textures which are conspicuous in the Ellensburg Formation rarely survive in the "upper" Keechelus and are absent at lower stratigraphic levels, except for the relatively unaltered ash-flows near the top of the Stevens Ridge Formation. In some samples shard textures are pseudomorphed by clay and/or zeolite.

The groundmass in volcaniclastic rocks of the Fifes Peak Formation consists of irregular, intergranular patches of secondary minerals, including clay, chlorite, mica, heulandite, laumontite, calcite, sphene and quartz. At higher grades of alteration, the earlier formed secondary minerals are recrystallized to form mosaic textures consisting of 2 or 3 minerals. Porphyroblasts of laumontite and prehnite form across groundmass-grain boundaries. In many samples alteration assemblages in groundmass and associated detrital grains are similar and recognition of the contact between the two lithologic components is not possible.

Alteration of Lithic Clasts

Lithic clasts are unaltered and have sharp grain boundaries in volcaniclastic rocks of the Ellensburg Formation. In the "upper" Keechelus, lithic grains remain relatively unaltered but develop "dirty" rims (Figure 16). Similar rims occur in the the Fifes Peak Formation and rarely in the Stevens Ridge and Ohanapecosh Formations. The rims appear to be clay minerals adhering to grain surfaces and, in a few cases, alteration of the outer margin of the grain. Since the rims coat feldspars and other detrital grains in addition to the lithic clasts, they must have formed after deposition and are not a weathering rind. Furthermore, it is unlikely the rims could have survived fluvial transport.

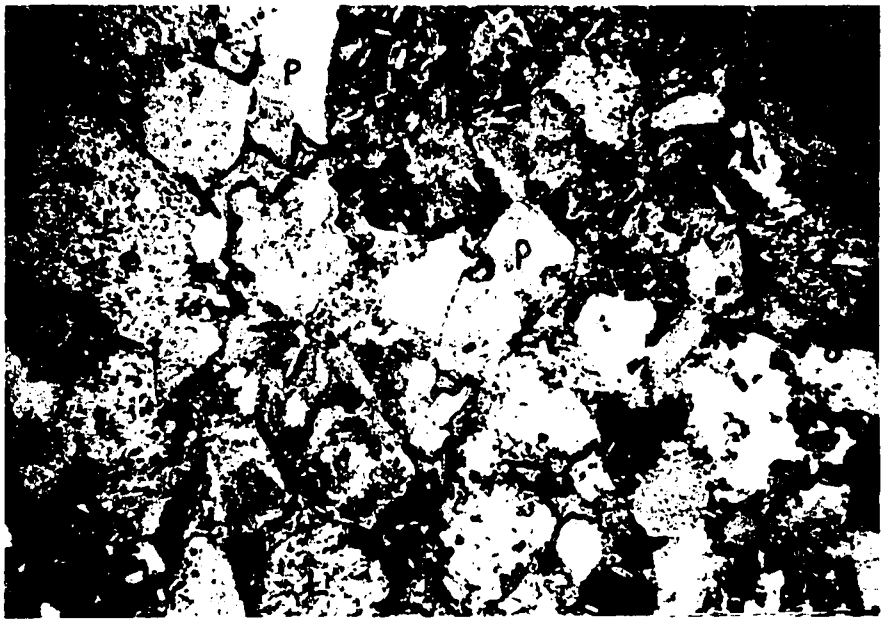
In the Fifes Peak Formation lithic clasts are altered with intersertal glass and ferromagnesian minerals replaced by assemblages similar to those occurring in the groundmass. Grain boundaries remain sharp and the clasts are easily distinguished from the groundmass. At higher grades of alteration, lithic grain degradation (alteration of grains to matrix) is common (Figure 17). Marginally or wholly, the grains are altered to assemblages texturally and mineralogically indistinguishable from the groundmass. In highly altered rocks, relict textures, such as vesicles, may be the only evidence of former lithic clasts. Grain degradation accounts for the high matrix content observed in highly altered rocks.

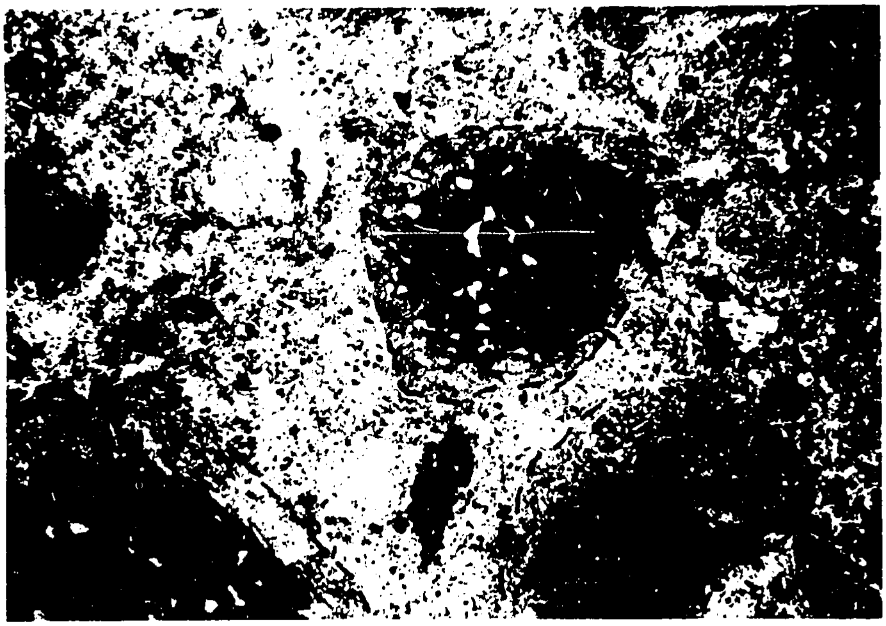
Cavity Fillings

Secondary minerals in pores and vesicles are the product of precipitation of ionic species from an associated fluid phase. Pores and vesicles in lithic clasts in the volcaniclastic rocks of the Ellensburg Formation contain no secondary minerals. In

Figure 16: "Dirty" rims on the detrital grains in a volcanic sandstone of the "upper" Keechelus Andesite. The rims consist largely of clay minerals adhering to the outer surface of grains. (L) - lithic grains, (P) - plagioclase.

Figure 17: Grain degradation in a volcanic sandstone of the Ohanapecosh Formation. At higher grades of alteration outer portions of lithic grains are altered to materials indistinguishable from the surrounding groundmass. Dashed lines indicate the outer margins of the lithic grains.


P
P



contrast, every sample from the "upper" Keechelus has cavity filling minerals (Table 17). Zonal patterns of secondary minerals in cavity fillings are common and form a distinct textural characteristic of the alteration (Figure 18). Concentric and radial patterns indicate inward filling of the void spaces. The concentric distribution of secondary minerals reflects compositional changes in the fluids during alteration. In the Fifes Peak Formation and older stratigraphic units vesicle fillings are common (Table 17), but the zonal patterns of cavity fillings are uncommon. Rarely do more than 2 minerals occur in the cavity filling assemblage and frequently all cavities in a rock are filled by the same mineral.

Veins

Veins form as fracture fillings after initial lithification and are the product of low-grade metamorphism. The veins are mostly small, 1 or 2 mm. wide, the largest veins being less than 1 cm. wide. Orientations perpendicular or subparallel to bedding are most common. The frequency of occurrence of veins and grade of vein assemblages (Table 17) increase with depth of burial.

Lithologic Controls of Alteration

Interbedding of volcaniclastic rocks and lavas allows evaluation of differences in alteration resulting from variation in lithology. Since both rock types have similar ranges in chemical composition (Table 18) and contain essentially the same minerals, the variation in alteration is related to inherent characteristics other than composition. The extent to which

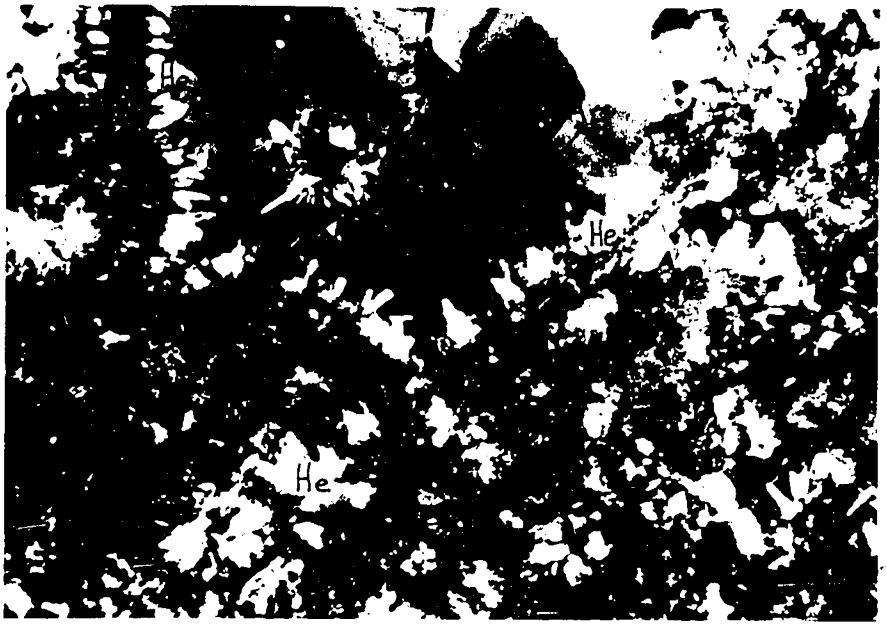


Figure 18: Zonal cavity filling in a volcanic sandstone of the "upper" Keechelus Andesite. Radial and concentric distribution of the secondary minerals indicate inward filling of the cavities.
(Ap) - apophyllite, (He) - heulandite

Table 17: Cavity filling minerals and vein assemblages in volcaniclastic rocks.

Formation	Cavity Filling Minerals	Vein Assemblages
Ellensburg Formation	none	none
"Upper" Keechelus Andesite	heulandite apophyllite calcite clay	none
Fifes Peak Formation	heulandite laumontite chlorite calcite quartz	heulandite calcite
Stevens Ridge Formation	heulandite laumontite wairakite prehnite chlorite calcite quartz	heulandite laumontite laumontite-quartz calcite calcite-quartz chlorite-quartz
Ohanapecosh Formation	laumontite wairakite prehnite epidote chlorite calcite quartz	laumontite-quartz laumontite-calcite-quartz calcite calcite-quartz calcite-epidote-quartz epidote-quartz chlorite-quartz

Table 18: Microprobe analyses of chemical compositions of Tertiary lavas and volcaniclastic rocks. Analyses are anhydrous determined from fused glass beads.

	193	210	142	237	254	185
SiO_2	68.65	54.76	58.66	63.02	63.84	63.07
TiO_2	0.56	1.30	2.06	1.38	0.63	0.79
Al_2O_3	16.16	18.01	15.96	15.82	16.45	16.21
Fe_2O_3*	5.98	9.93	11.16	8.48	5.54	6.72
MgO	0.82	5.12	2.03	1.85	2.10	2.88
CaO	3.00	6.43	5.32	4.64	4.43	5.86
Na_2O	2.23	2.61	3.49	3.09	3.53	3.23
K_2O	0.85	0.73	0.72	0.82	2.33	2.04
Total	98.40	98.89	99.40	99.10	98.85	100.80

	351	382	431	208	264
SiO_2	55.27	62.72	63.61	58.80	55.63
TiO_2	1.32	0.95	1.07	1.19	1.26
Al_2O_3	18.58	15.39	15.80	15.27	16.60
Fe_2O_3*	8.60	5.71	6.29	8.69	8.91
MgO	2.50	2.47	2.85	4.75	3.26
CaO	9.44	7.94	5.01	7.60	8.86
Na_2O	3.28	2.80	3.53	2.14	3.22
K_2O	0.63	1.04	0.98	1.86	1.28
Total	99.62	99.02	99.14	100.30	99.02

*Total iron given as Fe_2O_3

193 - Ohanapecosh Formation; tuff breccia
210 - Ohanapecosh Formation; volcanic sandstone
142 - Ohanapecosh Formation; volcanic sandstone
237 - Ohanapecosh Formation; volcanic conglomerate
- Stevens Ridge Formation; lithic-crystal ash-flow
185 - Stevens Ridge Formation; lithic-crystal ash-flow
351 - Fifes Peak Formation; porphyritic basaltic andesite
382 - Fifes Peak Formation; porphyritic andesite
431 - Fifes Peak Formation; porphyritic andesite
208 - "upper" Keechelus Andesite; volcanic sandstone
264 - "upper" Keechelus Andesite; porphyritic andesite

replacement reactions proceed is largely dependent upon the availability and access of the fluid phase. Fluid content and mobility, in turn, are largely controlled by the porosity and permeability of the rocks.

As one would suspect, the volcaniclastic rocks are generally more highly altered than the associated lavas. The greatest differences in degree of alteration occur in the lowest grade zones. Volcaniclastic rocks of the "upper" Keechelus and the Fifes Peak Formation are relatively porous and permeable, and the associated lavas have low porosities and are nearly impermeable. In both stratigraphic units greater alteration of primary phases (Figures 13 and 14) and higher degrees of alteration (Table 19) are observed in the volcaniclastic rocks than in the lava flows. In deeper stratigraphic levels, the volcaniclastic rocks become more highly indurated and have lower porosities and permeabilities. As alteration progresses, the degree of alteration and alteration assemblages in the volcaniclastic rocks and lavas become similar.

Local variations in alteration of volcaniclastic rocks may result from small scale changes in porosity and permeability. In part, grain size is important in that the finer grained rocks expose more surface area and allow greater accessibility of the fluids. Within the same sample, lithic pebbles are frequently less altered than lithic sand grains. However, very fine-grained rocks are often only weakly altered because of their low permabilities.

Compositional control of alteration assemblages is best

Table 19: Comparison of alteration of volcaniclastic rocks and lava flows of the Fifes Peak Formation.

	Volcaniclastic Rocks	Lava Flows
% samples unaltered	none	25%
% samples with heulandite	65%	20%
% samples with laumontite	40%	15%
% samples with relict hypersthene and clinopyroxene	50%	80%

displayed in the interbedded arkosic sandstones and volcanogenic rocks at the base of the Tertiary section (Figures 5 and 6). The arkosic sandstones contain a mica-calcite-quartz assemblage whereas the associated dikes and sills and overlying volcanogenic rocks have assemblages characterized by Ca-silicates (epidote and prehnite) accompanied by chlorite, sphene, mica, calcite, and quartz. In the Tiger Mountain area (Figure 7), arkosic and volcanogenic rocks have similar assemblages except the volcanogenic rocks contain laumontite replacing phases and abundant chlorite.

Chemical Compositions of Alteration Minerals

Partial chemical analyses for analcime, apophyllite, heulandite, laumontite, wairakite, prehnite and epidote (Appendix) were determined using the electron microprobe. Standard corrections for absorption and fluorescence were made (program BAEDR; Univ. of Washington). Volatilization of light elements, particularly Na, was reduced by using low sample currents (.02-.05μA at 15 kV), large beam spots (greater than 10 microns), and short counting times (less than 9 secs.).

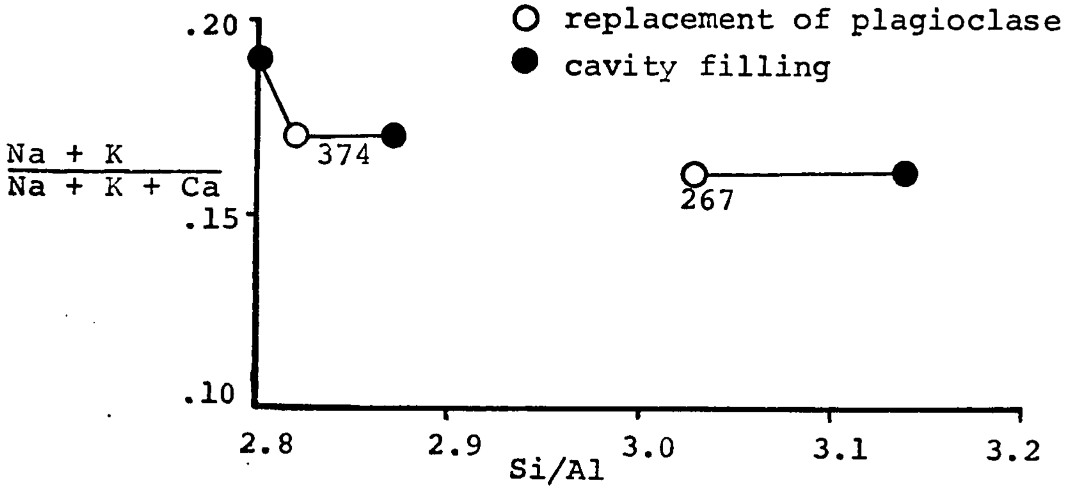
Analcime replaces plagioclase and glass in volcaniclastic rocks of the "upper" Keechelus Andesite. The analcimes have very minor substitution of Na by Ca and K, similar to other analcimes from sedimentary rocks (Sheppard, 1971). Si/Al ratios range from 1.93 to 2.11 which are low as compared to most analcimes (Si/Al ranging from 2.0 to 2.9) in sedimentary rocks (Coombs and Whetten, 1967). The "upper" Keechelus volcaniclastic rocks are andesitic in composition (Table 18) and are probably less siliceous than many sedimentary rocks containing analcime.

Apophyllite occurs as a cavity filling mineral (Figure 18) associated with heulandite, analcime and clay in volcaniclastic rocks of the "upper" Keechelus. The occurrence of apophyllite in clastic sedimentary rocks has not been previously described and the main occurrences of apophyllite are as amygdules in basalts, cavities in granites, fissures in metamorphic rocks, in limestones and in calc-silicate rocks (Deer and others, 1962). In Iceland, apophyllite is associated with zeolites in amygdules in basalts (Walker, 1960). Quartz is generally absent in these assemblages. In the "upper" Keechelus, quartz is also absent in the apophyllite-bearing rocks as confirmed by petrographic analyses and X-ray diffraction traces. The absence of quartz and the occurrence of apophyllite, low Si analcime and low Si heulandite in alteration assemblages in these volcaniclastic rocks suggest a low chemical potential of SiO_2 in the fluids associated with the alteration.

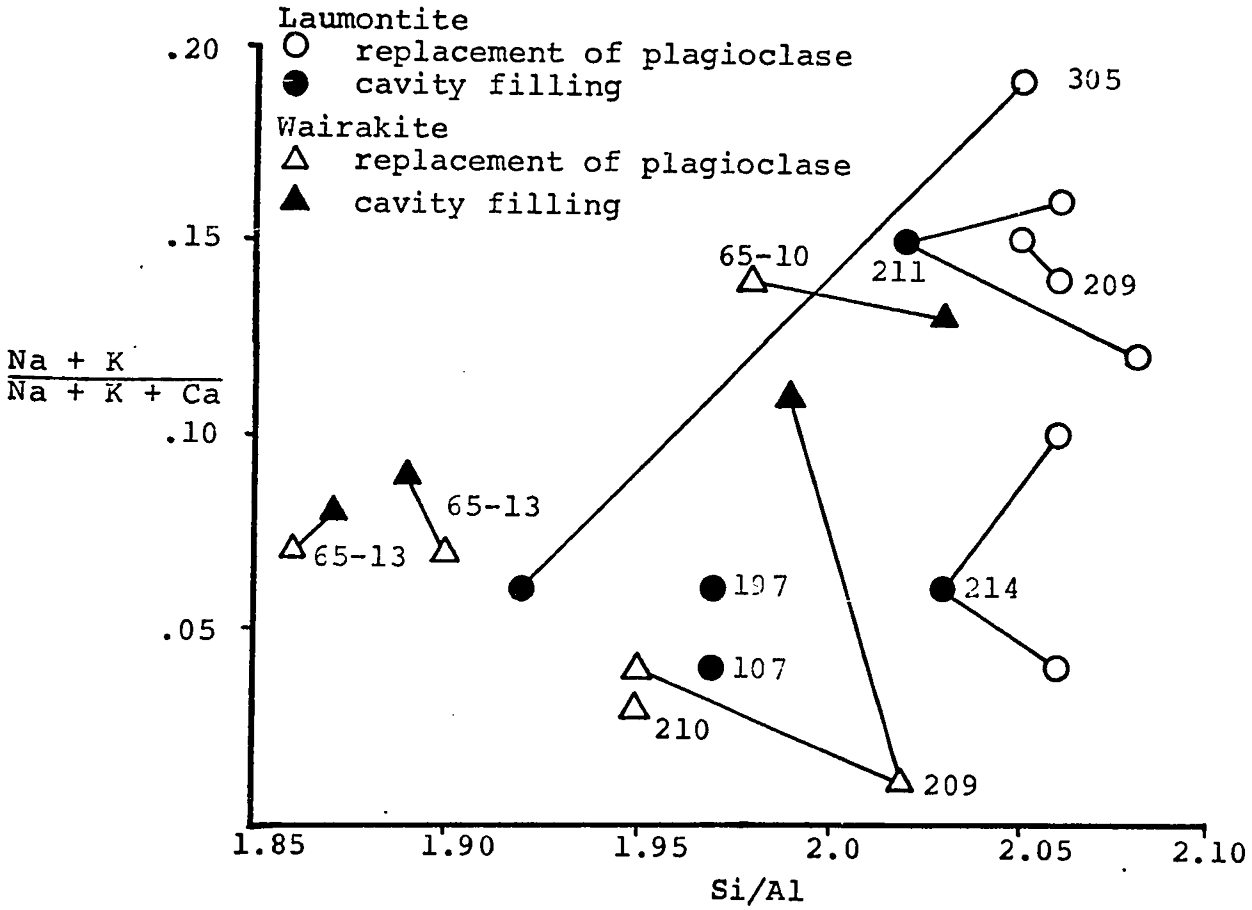
Heulandite, laumontite and wairakite occur replacing plagioclase, in groundmass assemblages and as cavity filling minerals. Heulandites have Si/Al ratios ranging from 2.80 to 3.14 and Na + K/Na + K + Ca ratios ranging from .16 to .19 (Figure 19) and are chemically similar to naturally occurring end-member heulandites (Boles, 1972). Laumontites have Si/Al ratios ranging from 1.92 to 2.08 and Na + K/Na + K + Ca ratios of .04 to .19 (Figure 19). Si/Al ratios (2.05 to 2.08) in laumontite replacing plagioclase are higher than coexisting cavity filling

Figure 19: Plots showing the compositional variation of heulandite, laumontite and wairakite.

A. Heulandite



B. Laumontite and Wairakite



laumontites. The relatively narrow range of Si/Al ratios (2.05 to 2.08) in laumontite replacing plagioclase is probably, in part, controlled by the composition of the host grains, whereas the greater variation and lower Si/Al of the cavity filling laumontites probably reflect compositional variations in the associated fluids. Wairakites have Si/Al ratios ranging from 1.86 to 2.03 and Na + K/Na + K + Ca ratios of .01 to .14 (Figure 19). With increasing grade of alteration Si/Al ratios of zeolites characteristic of the alteration zones decrease. Heulandite in the heulandite-bearing zones have Si/Al ratios of 2.80 to 3.14 and laumontite and wairakite in the laumontite zone have Si/Al ratios of 1.92 to 2.08 and 1.86 to 2.03 respectively. The decrease in Si/Al ratios of the zeolites reflects rising temperatures of alteration or a decrease in chemical potential of SiO_2 in the associated fluids. The chemical data also suggest a decrease in alkali substitution for Ca in the zeolites accompanying increase in grade. Variation in composition of the zeolites in the same sample is common and probably reflects local variation in composition of host grains or associated fluids, and further attest to the lack of attainment of bulk rock equilibrium.

Prehnite and epidote occur in groundmass assemblages, as a replacement of plagioclase and as porphyroblasts or aggregates in rocks of the laumontite-chlorite-quartz and epidote-prehnite-chlorite-quartz zones. Fe_2O_3 (total iron) ranges from 2.77 to 5.79% in prehnite and from 8.33 to 12.54% in epidote. Since the host plagioclase grains contain little Fe, the Fe in replacement prehnite and epidote is largely derived from the associated fluids. Increasing epidote replacement of glass (Figure 13) and plagioclase (Figure 15) is accompanied by increasing alteration of primary ferromagnesian minerals (Figure 14). Apparently the alteration of ferromagnesian minerals releases Fe which then combines with Ca and Al phases to form epidote. The alteration of ferromagnesian minerals, in part, accounts for the widespread occurrence of epidote in higher grade assemblages.

Mechanism of Alteration

The hydrous alteration assemblages characteristic of the volcanogenic rocks are largely the product of retrograde alteration of materials formed at high temperature. Volcanic materials in the epiclastic and pyroclastic volcaniclastic rocks and the lava flows exist as metastable phases in the cooler, aqueous surficial environment in which they are deposited. With time and burial the pyrogenic materials react with the associated fluid phase to form more stable low temperature secondary assemblages. Increasing temperatures with depth greatly enhance the rates at which the alteration reactions proceed and, in part, determine the nature of the secondary assemblages. The alteration is incomplete and bulk rock equilibrium is not achieved. Relict original materials persist throughout the Tertiary section.

In volcaniclastic rocks, the alteration proceeds in stages related to the stabilities of the detrital constituents. The sequence of susceptibility to alteration is 1) glassy groundmass, 2) lithic grains, and 3) mineral grains. Due to a higher content of glassy material, pumice clasts alter more readily than fragments of lavas. Of the mineral grains, hypersthene alters most rapidly, and clinopyroxene and feldspars undergo alteration at approximately the same rate. This sequence of alteration is similar to that observed in weathering, but the alteration products are different.

The replacement of anhydrous volcanic materials by hydrous assemblages clearly indicates the dependence of the alteration processes on the availability of water. Water is not only an essential reactant in the replacement reactions but is the necessary medium for the transfer of chemical components. The porosity and permeability of the rocks determine the availability and mobility of water and, in turn, determine the extent of alteration. In the initial alteration processes, the source of the waters was probably connate water or circulating groundwaters. "Dirty" rims, zonal cavity fillings, cements, and amygdules as well as the replacement reactions at low grades result from mobile fluids and/or chemical species within the fluids. The alteration is heterogenous on a microscopic scale with different assemblages developed in individual detrital components, probably reflecting many local chemical gradients. At higher grades of alteration the rocks are more compacted, greatly reducing their porosity, permeability and content of connate water. Much of the water for the alteration processes in these rocks is derived from dehydration reactions involving recrystallization of the initial alteration assemblages.

Increase in grade of alteration, dehydration of earlier alteration minerals, greater alteration of primary phases, and development of mosaic textures, porphyroblasts, and veins, take place with more advanced alteration. The alteration assemblages developed in all rocks and lithologic components become texturally and mineralogically similar. The local survival of anomalously unaltered rocks in altered units, persistence of relict phases, overlap in distribution of secondary minerals and the variable character of the alteration assemblages probably result, in part, from the unequal availability of water during the short duration of the low-grade metamorphic event.

Facies of Alteration

Diagenetic Facies

The boundary between diagenesis and low-grade metamorphism in sedimentary rocks is problematic and has not been precisely defined. In the central Cascades, the boundary between the diagenetic facies and the low-grade metamorphic zones is located at the stratigraphic level of the first development of zeolite facies assemblages in andesitic and basaltic lava flows interbedded with the volcaniclastic rocks. Since the flows are surface accumulated, but non-sedimentary, their burial to conditions appropriate for the development of zeolite facies minerals is considered to represent the transition to the environment of low-grade metamorphism. Initial alteration of lava flows to a heulandite-clay-quartz assemblage, characteristic of the lowest grades of the zeolite facies (Coombs, 1971), occurs in the upper part of the Fifes Peak Formation. The alteration of volcaniclastic rocks interbedded with these lavas and at deeper stratigraphic levels are, likewise, considered to be the product of low-grade metamorphism.

Rocks of the Ellensburg Formation and "upper" Keechelus Andesite are assigned to the diagenetic zone of alteration (Table 20). Volcaniclastic rocks of the Ellensburg Formation and lava flows of the "upper" Keechelus show little alteration other than that indistinguishable from weathering. Epiclastic rocks of the "upper" Keechelus are highly altered and display "dirty" rims on detrital grains, zonal cavity fillings, and abundant replacement of glassy groundmass and plagioclase. Diagenetic minerals include clay, heulandite, analcime, apophyllite, calcite, and quartz, in decreasing order of abundance. Although heulandite and analcime are common, they do not form the assemblages heulandite-quartz or analcime-quartz predicted from thermodynamic equilibrium which are characteristic of the lowest zones of the zeolite facies (Coombs, 1971). The diagenetic zeolite alteration in the "upper" Keechelus is similar to other occurrences in volcaniclastic rocks (Hay, 1966; and Sheppard, 1971). The zeolite and clay assemblages result from reactions between glass-rich volcanic materials and alkaline stratal waters. The alkalinity of the stratal waters is probably produced by the hydrolysis of glass.

Facies of Low-grade Metamorphism

Mineral assemblages characteristic of the zeolite and prehnite-pumpellyite facies occur in rocks of the Fifes Peak,

Table 20: Facies and zones of Tertiary alteration

Formation	Facies	Zone
Ellensburg Formation	Diagenetic Facies	Unaltered
"Upper" Keechelus Andesite		Heulandite-clay
Fifes Peak Formation	Zeolite Facies	Heulandite-clay·chlorite-quartz
Stevens Ridge Formation		Laumontite-chlorite-quartz
Ohanapecosh Formation	Prehnite-Pumpellyite Facies	Epidote-prehnite-chlorite-quartz
Puget Group		Mica-calcite-quartz

Thickness of units not to scale

Characteristic assemblages of the zones of low-grade metamorphism

Zeolite Facies

1) Heulandite-clay·chlorite-quartz zone
    a) heulandite-clay·chlorite-quartz
    b) heulandite-laumontite-chlorite-quartz
2) Laumontite-chlorite-quartz zone
    a) laumontite-chlorite-quartz
    b) laumontite-prehnite-chlorite-quartz
    c) laumontite-epidote-chlorite-quartz

Prehnite-pumpellyite Facies

1) Epidote-prehnite-chlorite-quartz zone
    a) epidote-prehnite-chlorite-quartz
    b) epidote-chlorite-quartz
    c) prehnite-chlorite-quartz
2) Mica-calcite-quartz zone
    a) mica-calcite-quartz

All assemblages may contain albite, mica or calcite.

Stevens Ridge and Ohanapecosh Formations and the Puget Group (Table 20). Progressive zonation of assemblages parallels an increase in stratigraphic depth. Zeolite facies metamorphism is represented by the heulandite-clay·chlorite-quartz, and laumontite-chlorite-quartz zones. Wairakite facies assemblages (Seki, 1969) occur sporadically near the base of the laumontite-chlorite-quartz zone and in local areas of hydrothermal alteration adjacent to intrusions. The boundary between the zeolite and prehnite-pumpellyite facies is approximately located at the stratigraphic level in which the occurrence of laumontite becomes rare and epidote and prehnite become the dominant Ca-silicates. The transition between the two facies is gradational and may span several thousand feet of stratigraphic interval. The prehnite-pumpellyite facies is represented by the epidote-prehnite-chlorite-quartz and mica-calcite-quartz zones (Table 20). Arkosic rocks of the mica-calcite-quartz zone are interbedded with anthracite coals and this grade of coal metamorphism is characteristic of the prehnite-pumpellyite facies (Kirsh, 1968).

Alteration assemblages within the low-grade metamorphic zones result from both retrograde alteration of the original high temperature materials and from progressive recrystallization of earlier formed alteration phases. Both processes proceed simultaneously and result in the development of complex secondary assemblages. The upper boundaries of the zeolite facies zones may be indicated by isograd reactions:

Heulandite-clay·chlorite-quartz zone;

$$\text{Heulandite} \longrightarrow \text{Laumontite} + 3\ SiO_2 + 2H_2O$$

Laumontite-chlorite-quartz zone;

$$\text{Laumontite} + \underset{(Ca^{++})}{\text{Calcite}} \longrightarrow \text{Prehnite} + SiO_2 + \underset{(2\ H_2O)}{3\ H_2O} + \underset{(2\ H^+)}{CO_2}$$

$$3\ \text{Laumontite} + \underset{(Ca^{++})}{\text{Calcite}} \longrightarrow 2\ \text{Zoisite} + \underset{(2\ H_2O)}{3\ H_2O} + \underset{(2\ H^+)}{CO_2}.$$

Since the characteristic minerals are normally very fine-grained, textural relations indicating one secondary phase replacing an earlier assemblage are not commonly recognized. The zones are largely determined from the stratigraphic distribution of the index minerals (Figure 8). The lack of sharp boundaries between the individual zones may, in part, be related to the kinetics of the reactions. Overlap in mineral distribution and variability of assemblages within zones may also result from independent reaction with relict materials such as plagioclase (Table 15), glass, or ferromagnesian minerals.

Environment of Low-grade Metamorphism

Recent experimental studies (Thompson, 1970a, 1970b, and 1971; and Liou, 1970, 1971a, 1971b, and 1971c) give some information on the stability fields of secondary minerals in low-grade assemblages. The physical conditions of metamorphism in the central Cascades cannot be directly inferred from the laboratory studies, however, since the alteration assemblages cannot be demonstrated to be in equilibrium with the rocks and additional physiochemical controls have affected the alteration. Active geothermal fields, such as Wairakei (Steiner, 1953 and

1955; and Coombs and others, 1959) Pauzhetsk (Averyev and others, 1962) and Onikobe (Seki and others, 1969) give useful data (Table 21) on the formation of similar alteration assemblages resulting from hydrothermal alteration associated with cooling igneous masses. Stratigraphic and field evidence as well as the distribution of alteration assemblages and textures in the central Cascades provide some limits to the low-grade metamorphic conditions.

Temperature

The cumulative thickness of stratigraphic units in the central Cascades section suggests a maximum burial of approximately 26,000 feet (nearly 8 km.). Assuming thermal gradients of 10-40° C/km., the maximum temperatures at the base of the section range from 100 to 340° C. (Figure 20). Normal thermal gradients in areas of thick accumulations of clastic sediments range from 10-20°C/km. (Fyfe, 1973). Temperature estimates using these gradients (Figure 20) appear too low to develop the alteration assemblages observed, and the additional burial necessary to achieve more realistic temperatures at these gradients cannot be justified from stratigraphic evidence. In comparison to the New Zealand section (Coombs, 1954), the relatively rapid increase in grade of alteration with depth in the central Cascades suggests a higher than normal thermal gradient. The thermal environment necessary to produce the alteration is likely to be similar to thermal gradients found in modern geothermal systems which range from 3 to 90° C/100 m.

Table 21: Distribution of zeolite and prehnite-pumpellyite facies minerals in active geothermal fields.

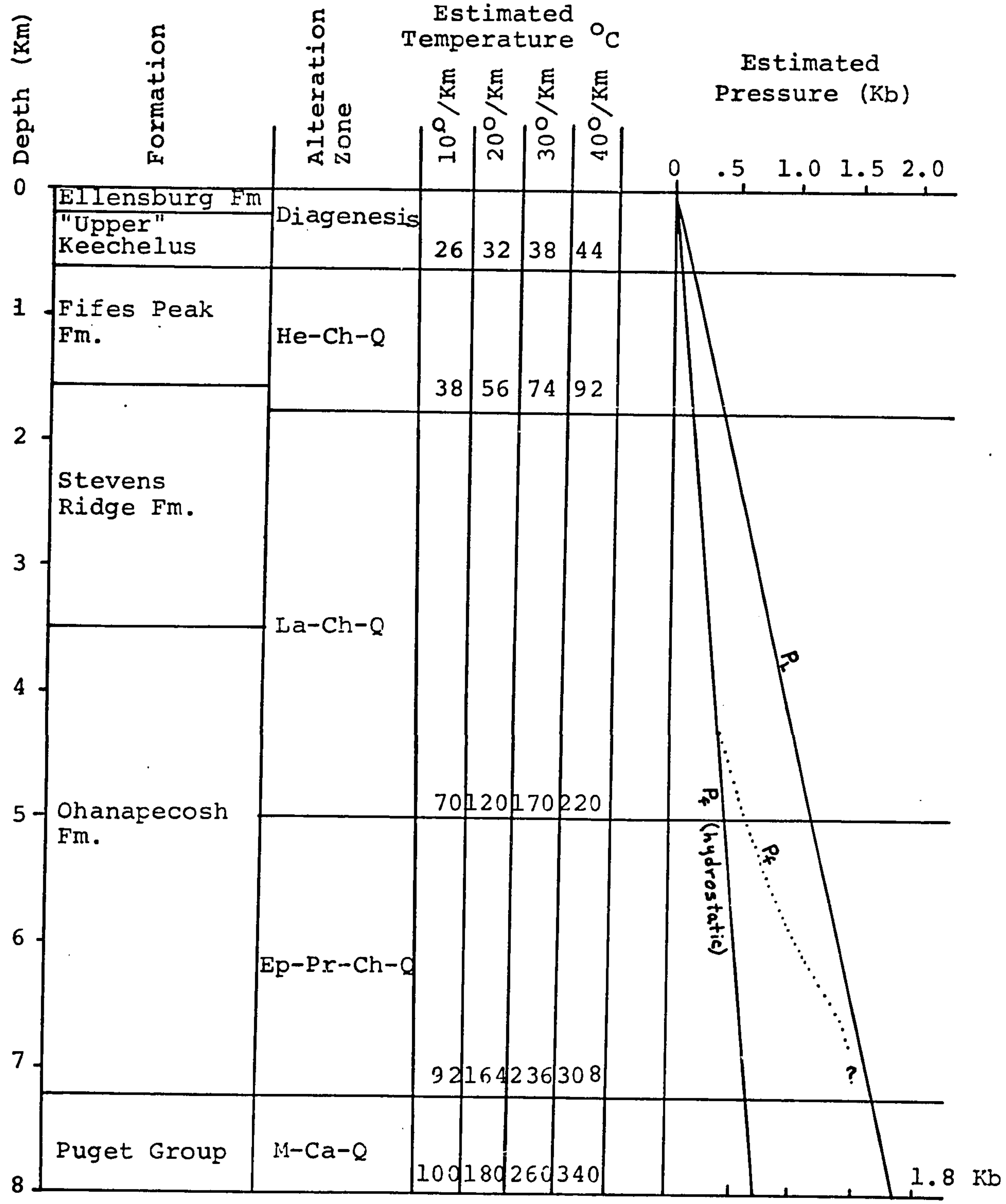
Zones	Temperature Range °C
I. Zeolite Zones	80 - 250
A. Heulandite Zone (Mordenite & Analcime)	80 - 200
B. Laumontite Zone	120 - 220
C. Wairakite Zone	150 - 250
II. Propylitic Zone (Epidote, Prehnite, Pumpellyite)	>180

Temperature ranges compiled from:

Averyev and others, 1962
Coombs and others, 1959
Muffler and White, 1969
Seki and others, 1969
Seki, 1970
Sigvaldson, 1963
Steiner, 1953
Steiner, 1955
White and Sigvaldson, 1963

Figure 20: Estimates of temperature and pressure conditions of low-grade metamorphism in the central Cascade Range.

P_l = load pressure, P_f = fluid pressure, dotted line represents probable increase in P_f during metamorphism



Pressure

Using stratigraphic thickness and density data, pressures for the alteration zones (Figure 20) have been estimated and the maximum pressure to which the central Cascade section was subjected is approximately 1.8 kb. In porous rocks at shallow depths of burial, fluid pressures (P_f) differ from lithostatic pressures (P_l). In the central Cascades, pore spaces in the volcaniclastic rocks, breccias, vesicle and amygdule zones in the lavas and veins indicate fluids could easily circulate and percolate toward the surface and allow P_f to drop well below P_l (Figure 20). Under such conditions, the equilibrium curves for the alteration reactions will be displaced to lower temperatures (Coombs and others, 1959). This effect is well-displayed by the lower temperatures of formation of zeolite assemblages in active geothermal areas as compared to temperatures determined in laboratory studies. Thompson (1955) has indicated that the projection of hydration-dehydration reactions in P_t-T space have positive slopes if the condition is $P_f = P_t$, but negative slopes where $P_f < P_t$. The distribution of alteration minerals in the Onikobe field (Seki and others, 1969) suggests the equilibrium curves for mordenite-laumontite and laumontite-wairakite reactions have negative slopes. Similar conditions are likely to have occurred during low-grade metamorphism in the central Cascades.

At higher grades of alteration, the condition $P_f = P_t$ (Figure 20) was approached and may have been approximately attained. The transition from the zeolite facies to the prehnite-pumpellyite facies is marked by an increase in density and lower water contents of the alteration minerals. Dehydration reactions resulting in a release of water in rocks of decreasing porposity and permeability may have developed P_f approaching P_t. Local variation in alteration assemblages may result from variations in P_f. Highly permable rocks ($P_f < P_t$) may develop higher grade assemblages than impermeable rocks ($P_f = P_t$) in the same zone. In some cases relatively impermeable rocks may escape alteration until reaching high grades.

Role of Volatiles

Since circulating water is a reactant and the active medium for the transfer of ions for the replacement reactions, variation in fluid composition directly effects the alteration processes and the nature of the alteration products. Chemically active fluids allow a wide variety of replacement reactions to occur. Decrease in the chemical potential of water resulting from dissolved ionic species or other volatiles has the same effect as increasing temperature in promoting the formation of less hydrous phases. Zen (1961) and Coombs and others (1970) have suggested that highly variable alteration assemblages may be related as a function of differing chemical potentials of water and carbon dioxide under isobaric and isothermal conditions. Experimental data by Liou (1971) and Thompson (1971) indicate high chemical potentials of Co_2 may inhibit the formation of characteristic minerals of the zeolite and prehnite-pumpellyite facies. The general absence of prehnite and abundant mica and calcite in the volcaniclastic rocks of the lowermost Ohanapecosh Formation may indicate metamorphism at high chemical potentials of CO_2:

$$\text{Prehnite} + 2\ CO_2 + H_2O \longrightarrow 2\ \text{Calcite} + \text{Kaolinite} + \text{Quartz}$$

or

$$3\ \text{Prehnite} + 2\ CO_2 \longrightarrow 2\ \text{Zoisite} + 2\ \text{Calcite} + 3\ \text{Quartz} + 2H_2O$$

The source of the CO_2 was possibly the metamorphism of bituminous coals to anthracite (Teichmuller and Teichmuller, 1968) in the underlying Puget Group which then permeated upwards into shallow stratigraphic levels. Because of lower porosities and permeabilities prehnite is preserved in altered lavas interbedded with the volcaniclastic rocks. Local concentrations of hematite may indicate high P_{O2}.

Origin of Low-grade Metamorphism

The metamorphism grade and the degree of alteration of original pyrogenic materials increase with stratigraphic depth. The progressive alteration zones developed as a result of conditions during burial and is similar to the zonation resulting from burial metamorphism (Coombs, 1954 and 1960; Packham and Crook, 1960; Smith, 1969; and Levi, 1970). Burial metamorphism by itself, however, is not sufficient to explain the pattern of alteration, because

1) the alteration zones are discordant to the stratigraphic units and the regional pattern of distribution of alteration minerals indicates a northward decrease in grade of alteration away from the cluster of medium-grained granitic rocks in the park, and

2) the relatively shallow depths of burial and distribution of alteration zones suggest steep thermal gradients, rather than low thermal gradients associated with areas of rapid sedimentary accumulation.

Large masses of granitic rocks (Figure 2) provide ample sources of heat to drive the metamorphism. During plutonism the geothermal gradients in the overlying Tertiary section were steeply elevated. Relatively narrow and low-grade contact aureoles suggest rapid conduction and dissipation of heat away from the intrusions by circulating waters in the relatively thin overlying section of porous rocks. Some heat was absorbed by the alteration reactions, particularly the dehydration reactions to produce the prehnite-pumpellyite facies assemblages, and may have effectively lowered the thermal gradient. In some cases the transfer of heat via the fluid phase enhanced alteration at great distances from exposed granitic rocks, as noted by Smith and Calkins (1906). The alteration of Tertiary rocks by circulating fluids adjacent to cooling intrusions in the central Cascades is similar to the model suggested by Taylor (1970) for alteration adjacent to Tertiary intrusions in the Cascade Range of Oregon.

Temporal, spatial and stratigraphic relations indicate the low-grade metamorphism resulted from a relatively short period of elevated thermal gradients associated with the Miocene intrusion of the Snoqualmie Batholith and related intrusions. Lower Miocene volcaniclastic rocks and lava flows of the Fifes Peak Formation are the youngest rocks to be altered by the metamorphic event. The Middle Miocene to Lower Pliocene "upper" Keechelus Andesite and Ellensburg Formation are altered only by diagenetic processes.

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APPENDIX I

Partial Chemical Analyses of Alteration Minerals

Microprobe analyses of polished thin sections.
(p) = replacement of plagioclase (c) = cavity filling

Analcime ($NaAlSi_2O_6 \cdot H_2O$)

Sample 374

	a(p)	b(p)	c(p)
SiO_2	53.52	56.21	57.62
Al_2O_3	23.56	22.64	23.49
CaO	0.28	0.06	0.17
Na_2O	13.67	13.32	13.20
K_2O	0.01	0.01	0.04
Subtotal	91.04	92.24	94.53
Si	1.979	2.038	2.036
Al	1.027	.968	.979
Ca	.011	.002	.006
Na	.980	.937	.905
K	.001	.001	.002
Si/Al	1.93	2.11	2.08

Apophyllite ($KFCa_4Si_3O_{20} \cdot 8H_2O$)

Sample 267

	a(c)	b(c)	c(c)
SiO_2	49.56	50.64	51.35
Al_2O_3	0.32	0.27	0.42
CaO*	22.91	23.08	23.22
Na_2O*	0.29	0.29	0.29
K_2O*	4.20	4.27	4.17
Subtotal	77.29	78.54	79.44

*Volatilization has probably resulted in low values for CaO, Na_2O and K_2O.

Heulandite ($CaAl_2Si_7O_{18} \cdot 6H_2O$)

	267		374		
	(p)	(c)	(p)	a(c)	b(c)
SiO_2	61.05	62.26	58.37	57.47	58.89
Al_2O_3	17.08	16.78	17.55	17.46	17.43
CaO	7.67	7.72	7.51	7.40	7.57
Na_2O	0.40	0.34	0.44	0.49	0.41
K_2O	0.62	0.56	0.63	0.73	0.65
Subtotal	86.81	87.66	84.50	83.55	84.95

Number of ions based on 18 (0)

Si	6.813	6.869	6.707	6.688	6.729
Al	2.247	2.182	2.377	2.396	2.348
Ca	.918	.912	.925	.922	.927
Na	.086	.073	.099	.111	.091
K	.088	.080	.092	.108	.094
Si/Al	3.03	3.14	2.82	2.80	2.87
$\frac{Na + K}{Na + K + Ca}$	0.16	0.16	0.17	0.19	0.17

Laumontite* ($CaAl_2Si_4O_{12} \cdot 4H_2O$)

	107(c)	197(c)	209(p)	209(p)	211(p)	211(p)	211(c)	214(p)
SiO_2	52.64	52.96	53.98	53.49	54.05	53.86	53.67	54.05
Al_2O_3	22.71	21.22	22.33	20.91	22.21	21.97	23.51	22.25
CaO	11.63	10.94	10.77	10.61	10.21	10.59	10.40	10.89
Na_2O	0.11	0.22	0.13	0.11	0.63	0.39	0.63	0.48
K_2O	0.23	0.18	1.13	1.09	0.70	0.61	0.61	0.29
Subtotal	87.32	85.52	88.36	86.22	87.80	87.41	87.81	87.96

Number of ions based on 12 (O)

Si	3.994	4.004	4.052	4.110	4.070	4.073	4.043	4.060
Al	2.032	2.028	1.977	1.994	1.971	1.959	1.999	1.971
Ca	.945	.920	.867	.874	.823	.858	.839	.876
Na	.016	.037	.019	.017	.092	.057	.092	.069
K	.022	.018	.108	.107	.067	.059	.059	.028
Si/Al	1.97	1.97	2.05	2.06	2.06	2.08	2.02	2.06
$\frac{Na + K}{Na + K + Ca}$	0.04	0.06	0.15	0.14	0.16	0.12	0.15	0.10

	214(p)	214(c)	305(p)	305(c)
SiO_2	53.15	53.60	53.99	50.76
Al_2O_3	21.93	22.35	22.30	22.38
CaO	11.03	11.45	9.86	11.11
Na_2O	0.38	0.28	0.31	0.03
K_2O	0.20	0.19	2.03	0.55
Subtotal	86.68	87.87	88.49	84.83

Number of ions based on 12 (O)

Si	4.052	4.035	4.060	3.971
Al	1.971	1.984	1.977	2.065
Ca	.901	.924	.794	.931
Na	.056	.040	.045	.005
K	.020	.018	.195	.054
Si/Al	2.06	2.03	2.05	1.92
$\frac{Na + K}{Na + K + Ca}$	0.04	0.06	0.19	0.06

*Fe_2O_3 and MgO contents are all less than 0.15

Wairakite ($CaAl_2Si_4O_{12}\cdot 2H_2O$)

	209 (p)	209 (p)	209 (c)	210 (p)	65-10 (p)	65-10 (c)
SiO_2	54.34	53.76	54.78	53.60	54.87	55.14
Al_2O_3	23.66	22.56	23.31	23.36	23.56	23.08
CaO	12.14	12.40	11.55	12.09	11.38	11.21
Na_2O	0.30	0.08	0.80	0.17	1.04	0.88
K_2O	0.00	0.00	0.00	0.00	0.00	0.04
Subtotal	90.44	88.80	90.44	89.22	90.84	90.34

Number of ions based on 12 (0)

Si	3.980	4.012	4.010	3.979	4.000	4.035
Al	2.043	1.985	2.012	2.045	2.025	1.991
Ca	.953	.992	.906	.962	.889	.880
Na	.042	.011	.114	.042	.147	.124
K	-	-	-	-	-	.004
Si/Al	1.95	2.02	1.99	1.95	1.98	2.03
$\frac{Na + K}{Na + K + Ca}$	0.04	0.01	0.11	0.03	0.14	0.13

	65-13 (p)	65-13 (c)	65-13 (p)	65-13 (c)
SiO_2	54.06	53.12	52.49	52.90
Al_2O_3	24.14	23.86	23.91	23.97
CaO	12.10	11.70	11.75	11.78
Na_2O	0.47	0.65	0.52	0.57
K_2O	0.00	0.00	0.00	0.00
Subtotal	90.77	89.33	88.68	89.22

Number of ions based on 12 (0)

Si	3.950	3.945	3.928	3.933
Al	2.080	2.089	2.110	2.102
Ca	.947	.931	.942	.939
Na	.067	.093	.075	.082
K	-	-	-	-
Si/Al	1.90	1.89	1.86	1.87
$\frac{Na + K}{Na + K + Ca}$	0.07	0.09	0.07	0.08

Prehnite ($Ca_2Al_2Si_3O_{10}(OH)_2$)

	107		197		
	a	b	a	b	c
SiO_2	42.86	44.43	45.13	44.09	45.05
Al_2O_3	23.31	23.25	22.04	19.69	22.22
Fe_2O_3	3.00	2.77	3.94	5.79	3.67
MgO	0.02	0.02	0.06	0.10	0.06
CaO	25.88	25.61	25.72	25.10	25.72
Na_2O	0.07	0.08	0.03	0.06	0.04
K_2O	0.02	0.02	0.01	0.02	0.02
Subtotal	95.16	96.17	96.93	94.85	96.79

Epidote*

	107 (p)	196 (v)	209 (p)	209 (p)	210 (p)	210 (p)
SiO_2	37.84	38.43	39.23	39.52	38.77	39.01
Al_2O_3	23.80	26.43	26.72	26.89	24.79	23.30
Fe_2O_3	12.54	10.39	8.71	8.33	9.30	10.33
MgO	0.18	0.07	0.04	0.05	0.16	0.19
CaO	23.05	23.57	23.44	23.79	23.99	23.79
Subtotal	97.41	98.91	98.14	98.15	97.01	96.62

	211 (p)	211 (p)	214 (p)	214 (p)
SiO_2	37.76	38.04	39.04	39.36
Al_2O_3	25.52	26.16	23.76	24.73
Fe_2O_3	8.90	9.18	10.09	9.58
MgO	0.15	0.05	0.19	0.05
CaO	23.26	23.29	23.22	23.62
Subtotal	95.59	96.72	96.30	97.34

*TiO_2 contents are less than 0.15 and Na_2O and K_2O contents are less than 0.05.

BIBLIOGRAPHICAL NOTE

Full Name of Author: Donald Albert Hartman

Date of Birth: June 12, 1943

Place of Birth: Bonners Ferry, Idaho

Father: Albert G. Hartman

Mother: Anna M. Hartman

Secondary Education: Bonners Ferry High School
Bonners Ferry, Idaho

Degrees Held: Bachelor of Science, University of Idaho
Master of Science, Oregon State University

GEOLOGY OF THE GREENV

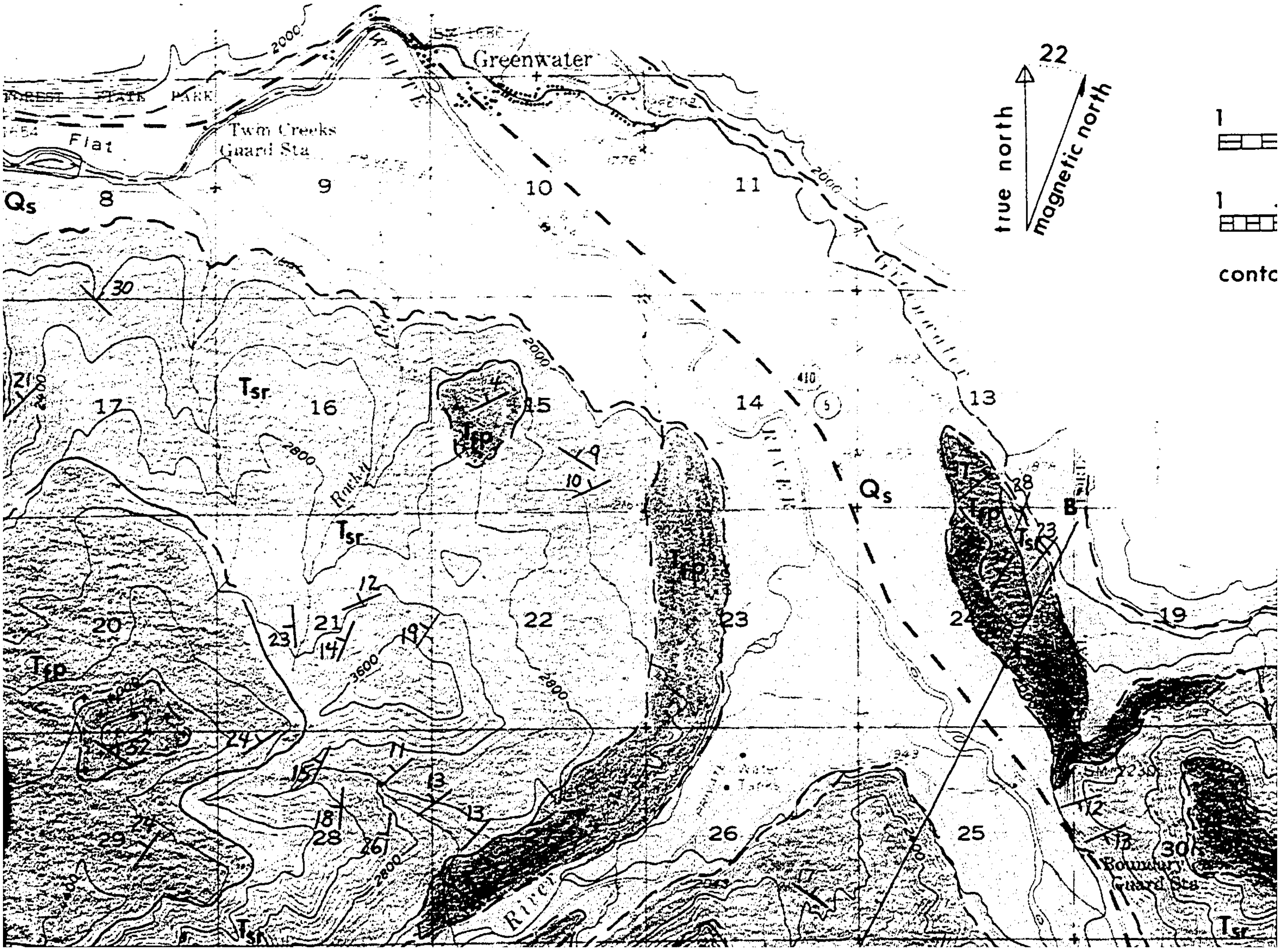
BY

DONALD A. HARTMA

1973

NWATER RIVER AREA

ARTMAN



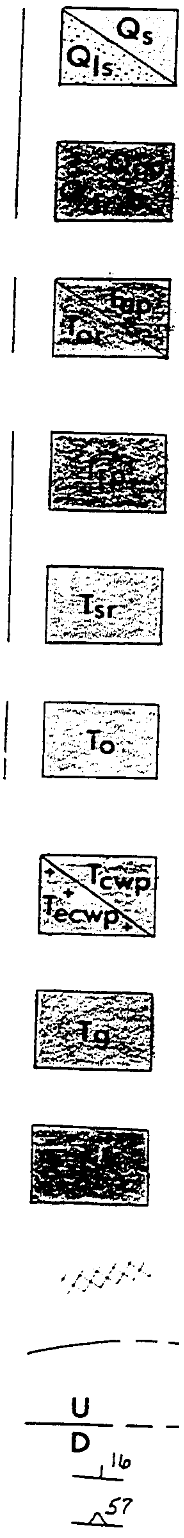
EXPLAN

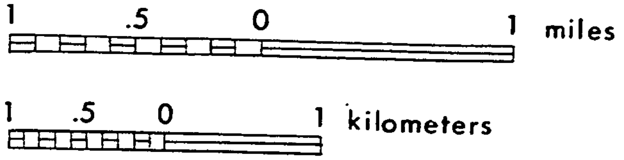
Quaternary

Early Pliocene to Early Miocene

Early Miocene

Oligocene to Late Eocene





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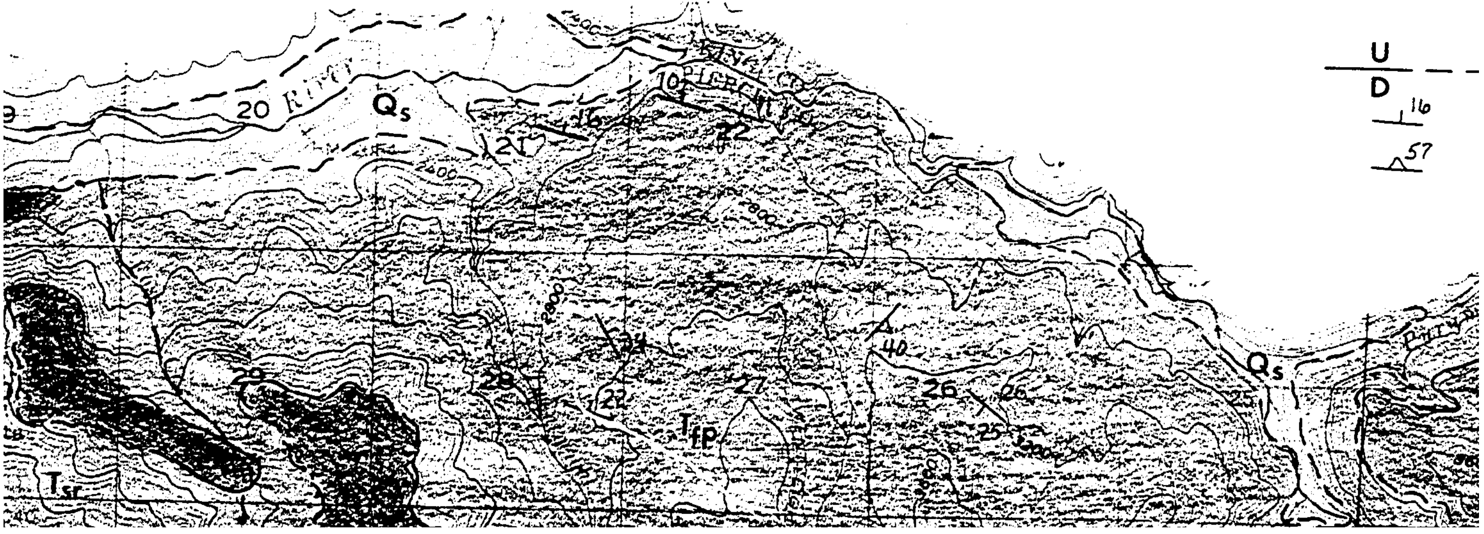
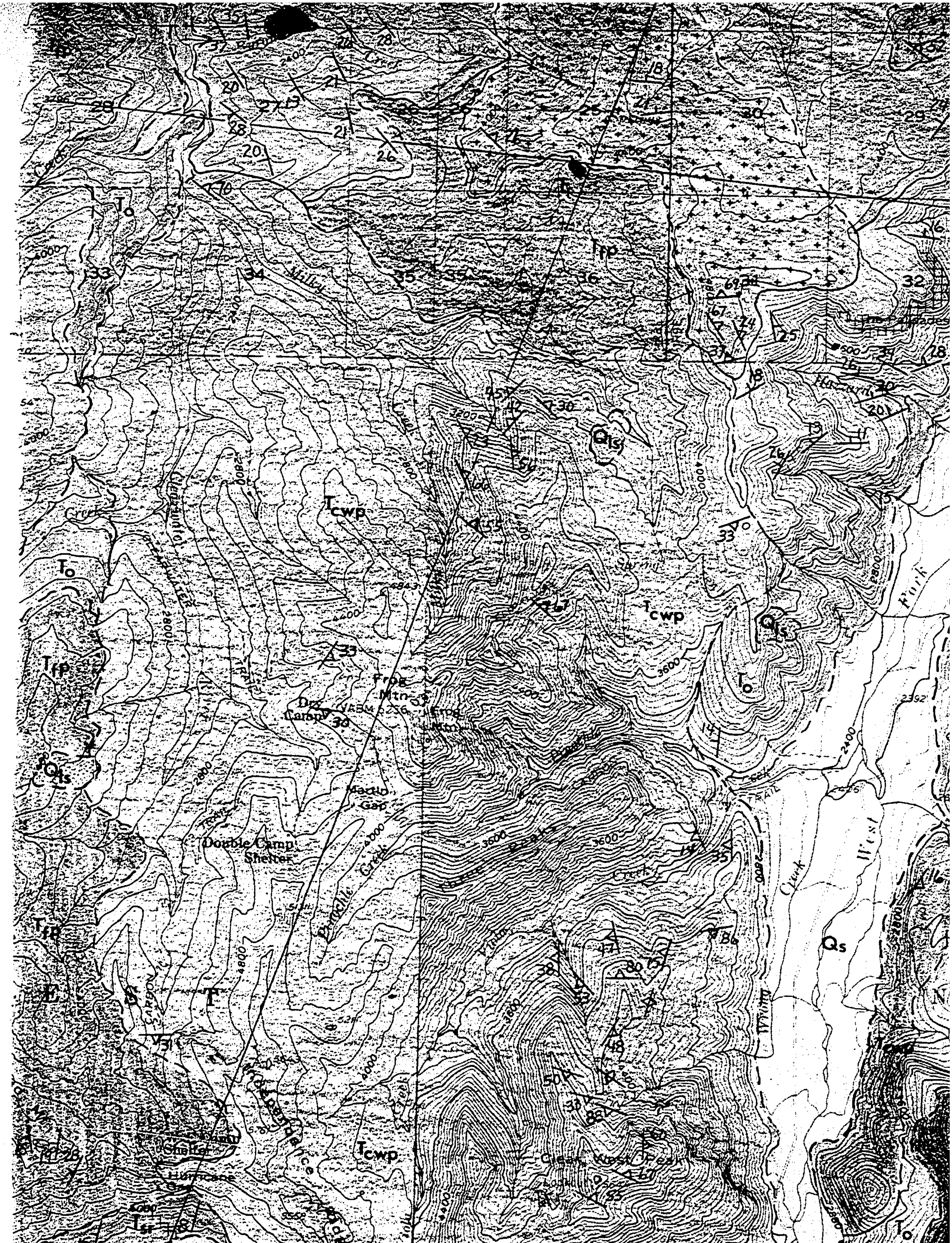


EXPLANATION

ernary	Q_s / Q_{ls}	Q_s	alluvium, mudflows and glacial drift
		Q_{ls}	landslides
	Q_{gp} / Q_{dr}	Q_{gp}	Grand Park flow
		Q_{dr}	Dalles Ridge flows
liocene	T_{np} / T_{ar}	T_{uk}	Upper Keechelus Andesite
iocene		T_{np}	Naches Pass Member
		T_{ar}	Arch Rock Member
	T_{fp}		Fifes Peak Formation
iocene			
	T_{sr}		Stevens Ridge Formation
ene Eocene	T_o		Ohanapecosh Formation

Intrusive Rocks

T_{cwp} / T_{ecwp}	T_{cwp}	Clear West Peak Rhyodacite
	T_{ecwp}	extrusive phase
T_g		Granitic Rocks
▓		Pyroxene Andesite
⁄⁄⁄⁄		Dikes and Sills
—— – – –		Contact: dashed where appoximately located
U —— D – –		Fault: dashed where approximately located
┴ 16		Strike and dip of bedding
△ 57		Strike and dip of flow banding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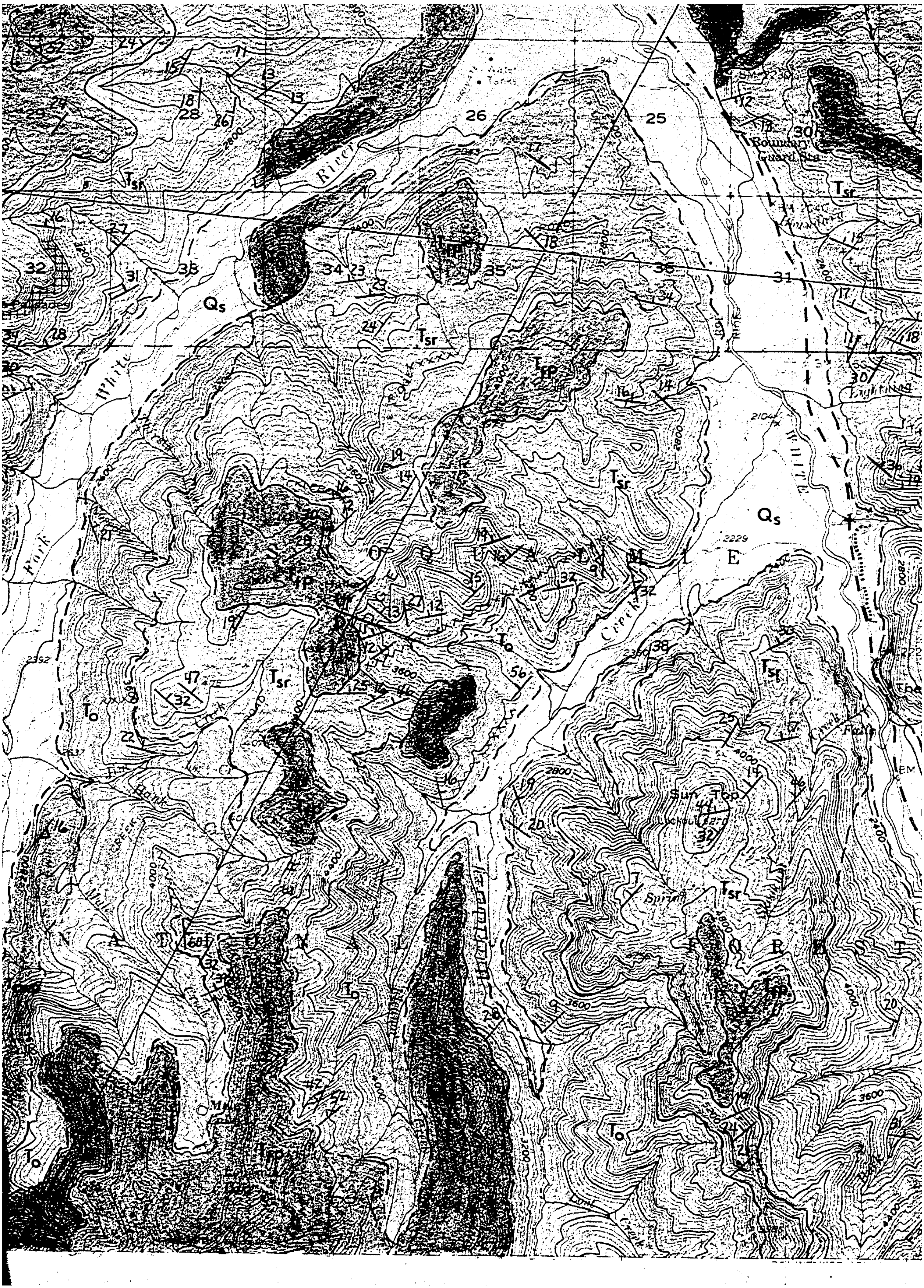

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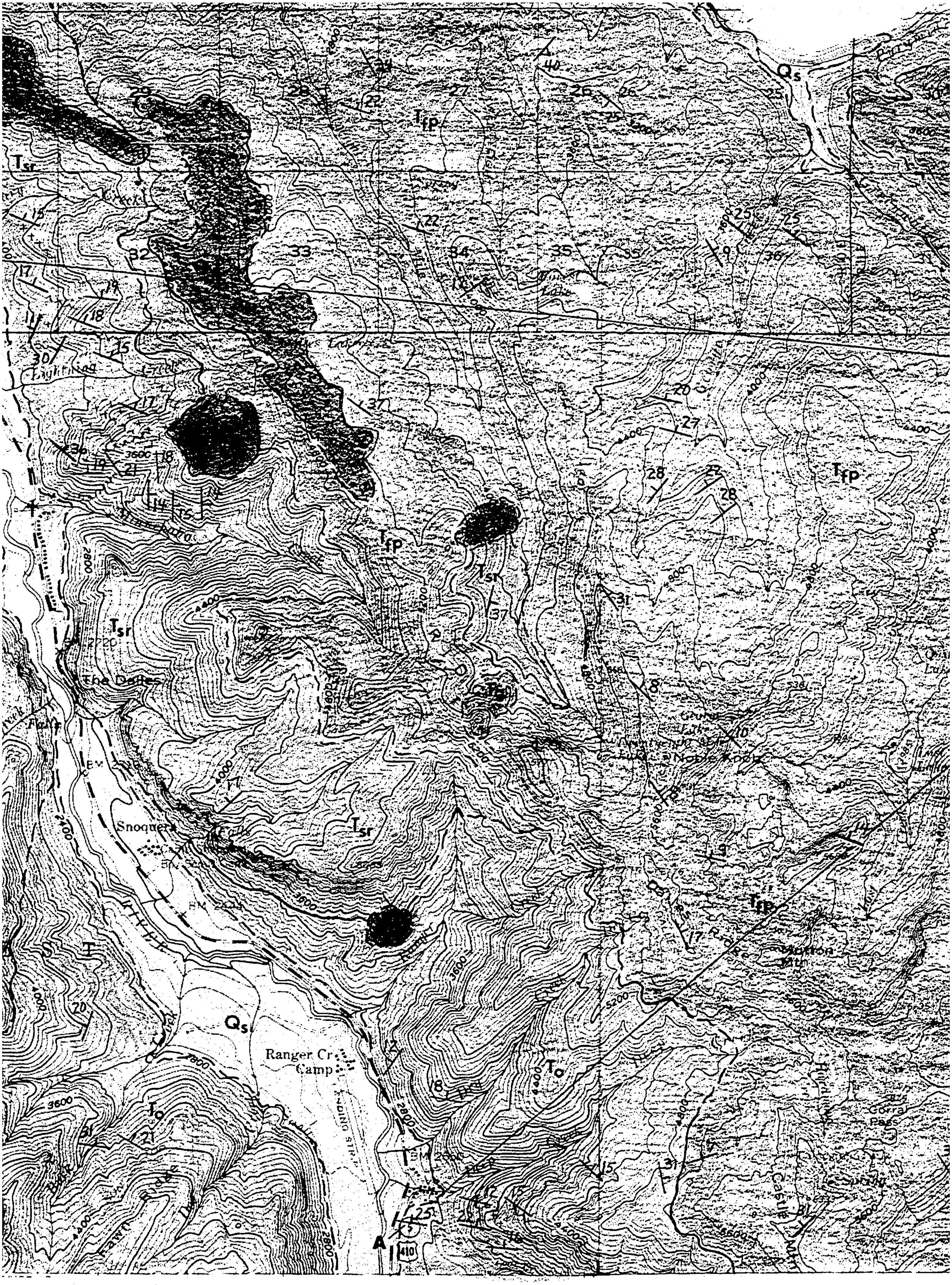
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Mutton Mtn
Gorra Pass
Castle
Hidden Lake
Quail Lake
Rods Gap
Saddle

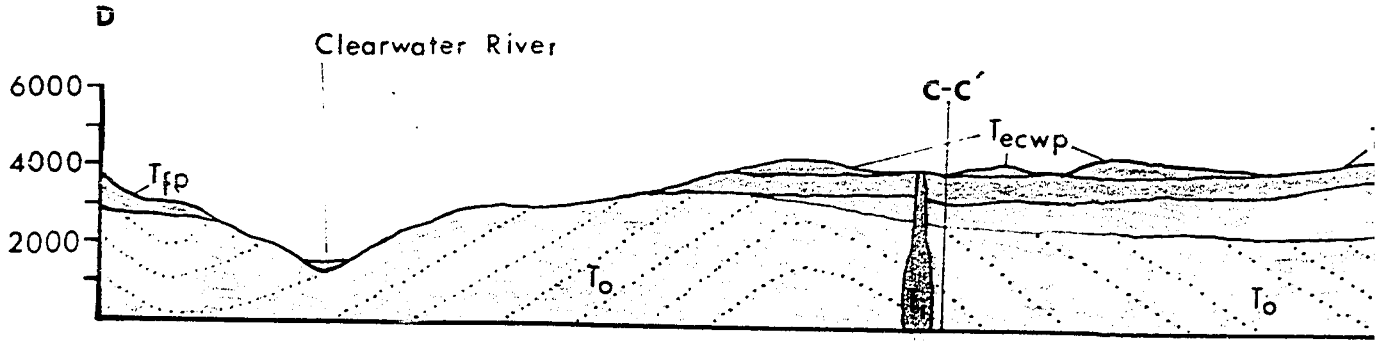
CROSS SECTIONS: GREENWA

BY

DONALD A. HARTMAN

Sections located on Plate 1

Explanation same as Plate 1



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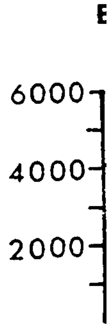

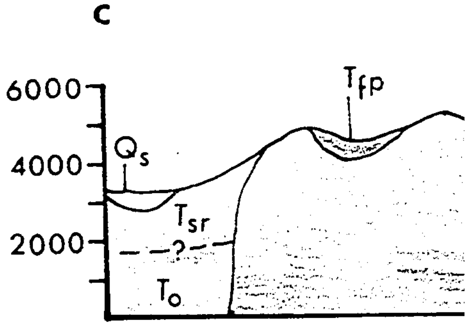

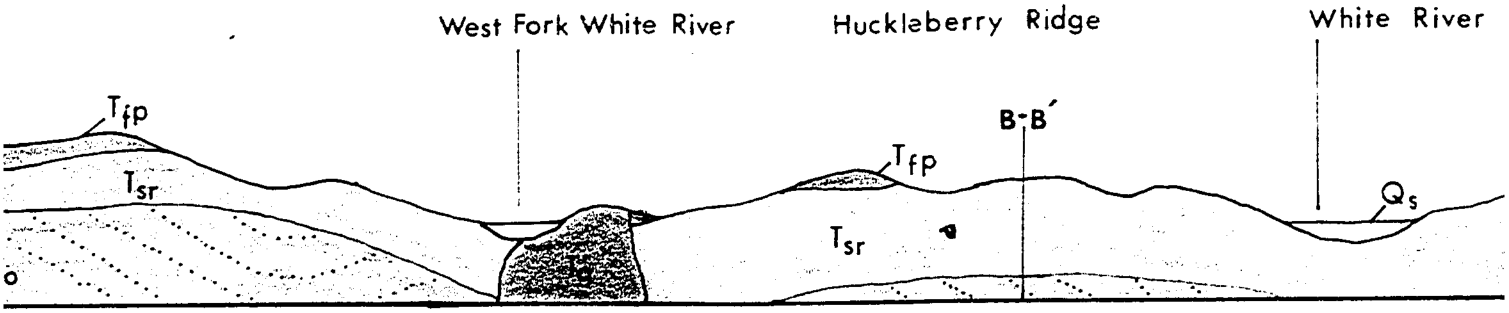

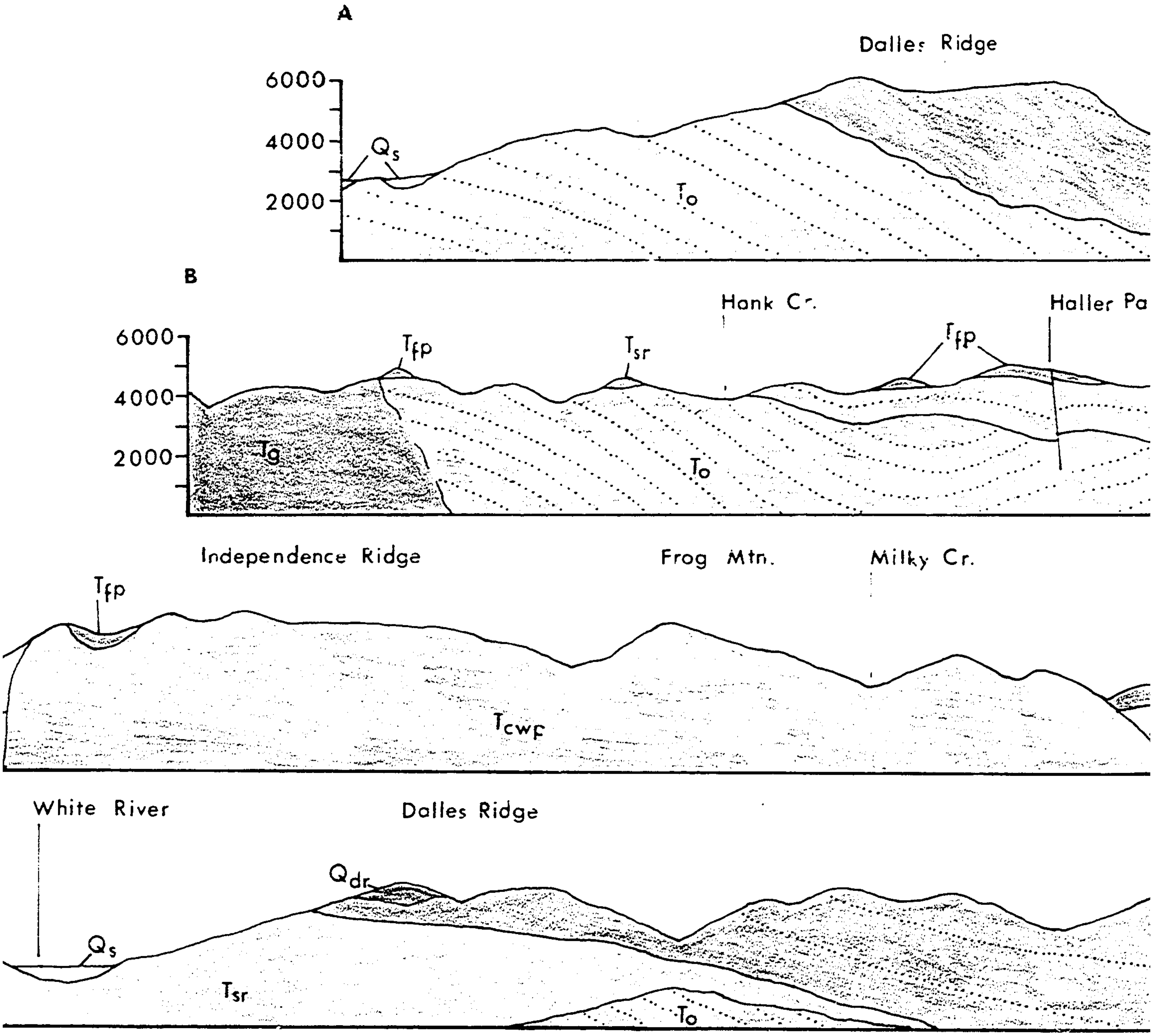
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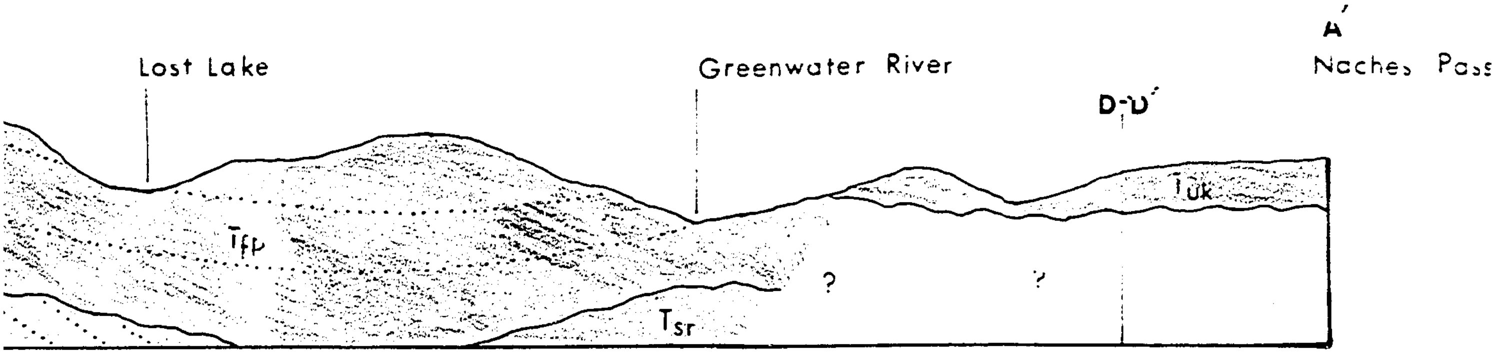
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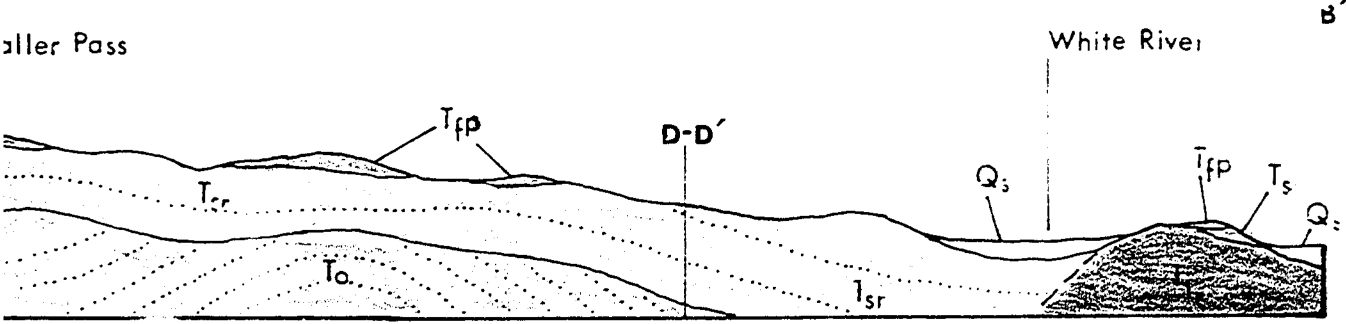
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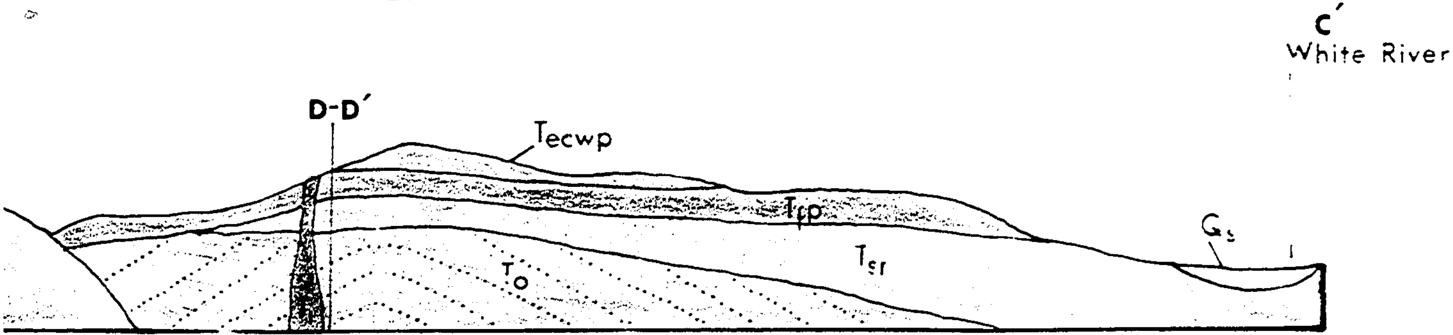
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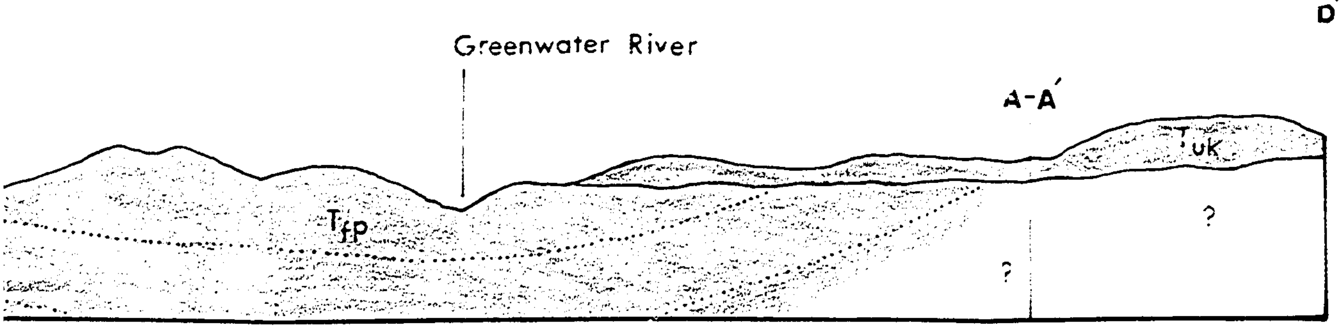
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Greenwater River
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