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AN ABSTRACT OF THE THESIS OF Warren Jon Winters for the Master of Science in Geology presented May 16, 1984.

Title: Stratigraphy and sedimentology of Paleogene arkosic and volcanoclastic strata, Johnson Creek - Chambers Creek area, southern Cascade Range, Washington.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Paul E. Hammond, Chairman

Robert O. Van Atta

Richard E. Thoms

Over 1150 m of middle to late Eocene nonmarine arkose, lithic arkose, mudstone, and siltstone, referred to here as the Chambers Creek beds, are interstratified with, and overlain by over 1600 m of late Eocene-Oligocene(?) andesitic volcanoclastic and subordinate volcanic rocks assigned to the Ohanapecosh Formation, in a dissected structural high in the southern Washington Cascade Range, ~18 km south-southeast of the town of Packwood.

Where well exposed, the Chambers Creek beds are dominated by fine-

grained strata. Mudstone, siltstone, and very fine-grained arkosic sandstone form 10 to 19 meter thick coarsening-upward intervals interpreted as nonmarine regressive sequences.

Lateral to, and intercalated with these fine-grained intervals are thick, relatively coarse-grained sand bodies, characterized by half meter- to meter-scale planar and trough cross bedding. Paleocurrent patterns, sand body geometry, and fining-upward intervals indicate these originated in a nonmarine channel environment.

The intercalation of regressive and channel sequences implies a common depositional setting. The former probably originated by infilling of lakes or lagoons adjacent to major distributaries. The latter represent deposition in and adjacent to these paleochannels. The thickness of the regressive cycles, their rarity of emergence, and the low width/depth ratio of the channels suggest rapid basin subsidence.

The lowermost ~700 m of the Ohanapecosh Formation, studied in detail, is dominated by volcanic arenite, mudrocks, and diamictite. Medium- to very coarse-grained cross-bedded, graded, and less common massive volcanic arenite units formed in and adjacent to paleochannels. Volcanic diamictite forms thick, massive to weakly graded, very poorly sorted intervals interpreted as lahars. Volcanic mudrocks form a locally thick (~145 m) sequence that apparently reflects density-flow dominated sedimentation in a long-lived lake.

The composition and sedimentology of the Chambers Creek beds indicate an easterly provenance dominated by crystalline rocks. Ohanapecosh volcanic sediments were derived from the erosion of more proximal andesitic volcanic highlands. Intercalations of arkosic sandstone up to

~ 650 m above the base of the Ohanapecosh Formation indicate that vigorous, interior-draining streams were able to maintain their westerly course well into the time of Ohanapecosh deposition.

The Chambers Creek/Ohanapecosh sequence is folded into a northwest-trending, faulted anticline that was not active at the time of deposition of the mapped sequence. Abundant shallow intrusions of basaltic to andesitic composition pre(?) - and post-date deformation.

Intrusive events were followed by late Miocene(?) - Pliocene uplift and deep erosional dissection of northwest-trending structures. Plio-Pleistocene High Cascade lavas of calc-alkaline pyroxene andesite and hornblende-pyroxene dacite lap over the older rocks and locally fill ancestral and modern valleys.

STRATIGRAPHY AND SEDIMENTOLOGY OF PALEOGENE
ARKOSIC AND VOLCANICLASTIC STRATA,
JOHNSON CREEK - CHAMBERS CREEK AREA,
SOUTHERN CASCADE RANGE,
WASHINGTON

by

WARREN JON WINTERS

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

MASTER OF SCIENCE
in
GEOLOGY

Portland State University

1984

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of Warren Jon Winters presented May 16, 1984.

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Gene Pierson and Chris Burke of the P.S.U. Geology Department provided logistical support at many key times.

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CHAPTER I

INTRODUCTION

PURPOSE OF STUDY

A stratigraphic section of over 1,150 m of nonmarine arkose, lithic arkose, mudstone and siltstone, and over 1,600 m of superjacent andesitic volcanoclastic and subordinate volcanic rocks are exposed in a dissected structural high in the Cascade Range of southeastern Lewis County, Washington. The primary purpose of this study is to characterize the sedimentology of the arkosic rocks and the lower portion of the andesitic sequence, and relate this information to regional paleogeography. Mapping and interpretation of geologic structure, and of younger intrusive and volcanic rocks, was also completed as part of the first detailed geologic study of this area.

This site was selected for a detailed study because it comprises the largest previously unmapped inlier of Eocene arkosic rocks in the southern Washington Cascade Range. The depositional setting of Eocene rocks in and around the Cascade Range is critical in determining the relationship of nonmarine rocks east of the range with the dominantly marine rocks to the west.

METHODS OF INVESTIGATION

Approximately 3 months were spent in the field during August through October, 1982, and in August, 1983. Field work included:

- 1) geologic mapping at a scale of 1:24,000
- 2) detailed field study of sedimentary rocks to define lithofacies, and compilation of a representative sandstone suite for petrographic study
- 3) recording of all observed paleocurrent indicators
- 4) measuring of stratigraphic sections with steel tape; thick units and covered intervals were measured by pace and compass methods
- 5) collection of samples for palynologic, floral, microfaunal, and maturation studies
- 6) sampling of vitric tuffs for fission-track age dating
- 7) field description and sample collection of intrusive and volcanic rocks to compile a representative suite for chemical analysis.

Laboratory work consisted of detailed thin section study of arkosic and volcanic sandstones, including point counts of selected samples, petrographic reconnaissance of volcanoclastic, volcanic, and intrusive rocks, disaggregation of mudstone samples for microfauna, and disaggregation and grain-mount examination of selected vitric tuffs. Data from additional laboratory services, including palynologic analysis, vitrinite reflectance, and diagenetic studies were generously released by Amoco Production Company, Denver.

Twenty-two representative intrusive and volcanic rock samples were analyzed by x-ray fluorescence for major oxides by Dr. Peter Hooper and associates at Washington State University. A single vitric tuff with abundant euhedral zircon was dated by fission-track methods by Geoff Clayton at the University of Washington.

LOCATION AND ACCESS

The study area is located in Gifford Pinchot National Forest and

is ~18 km south-southeast of Packwood, Washington (Figure 1). USFS (U.S. Forest Service) roads 21 (Johnson Creek Road) and 22 (North Cispus Road) provide access to key outcrops and are usually open mid-May through late October. Food and lodging are available in Packwood; several Forest Service campgrounds are located immediately south and east of the map area.

Annual precipitation exceeds 165 cm (65 inches). Much of the study area is forested with old growth timber and light underbrush, making cross-country travel relatively easy. Elevations range from 670 to 1,737 m, and steep stream gradients provide discontinuous bedrock exposures along most tributaries. Nearly vertical natural outcrops are present on the east flank of Mission Mountain. South of Elk Creek, the 1902 Cispus Burn affords nearly continuous, although deeply weathered ridgetop outcrops. Road cuts locally provide excellent, continuous, and relatively unweathered exposures. Man's activities in this area are limited to logging and recreation.

GEOMORPHOLOGY

Drainage patterns in the study area (Plates, back pocket) exhibit strong structural control. Moderately dipping sandstones and mudstones are intruded by numerous cuesta-forming sills. Most first-order streams flow down dip slopes and escarpments, while some first and most second-order streams parallel strike, and follow the tops of sills. The area east of Chambers Creek is underlain by flows of undeformed High Cascades andesite, and drainages appear to follow flow margins. A flat-topped mesa of dacite immediately north of Jordan Creek is an intracanyon flow

that now forms a resistant ridge (D.A. Swanson, pers. comm., 1982).

The profiles of the North and South Cispus valleys strongly suggest alpine glaciation. Numerous small erratics mantle the ground at ~1,250 meters elevation on USFS Road 22 in the Chambers Creek drainage.

Johnson Creek appears to be underfit, and flows northward in a spectacular V-shaped valley locally exceeding 1,100 meters in relief. Fault displacement along this trend in the map area appears to be minor, so the relief of the valley is enigmatic. Quaternary glaciation of the Cowlitz River valley to the north probably lowered the local base level, possibly resulting in rapid downcutting of tributary streams, including Johnson Creek.

Mass wasting in the study area includes slumping, landslides, and rock slides. The rock slide shown northwest of Chambers Lake (Plate I) moved more than 1.3 km on a slope of about 10 degrees. A landslide northeast of Mission Mountain involves rotation of large bedrock blocks, has diverted Johnson Creek to the east, and created the irregular topography that allowed Wright Lake to form.

PREVIOUS WORK

This report is the first detailed investigation of the geology of the study area. Reconnaissance mapping by V.E. Livingston (1958) is shown on the 1:500,000 Geologic Map of Washington (Hunting and others, 1961). Hammond (1980) includes the study area on his 1:125,000 reconnaissance map of the southern Washington Cascade Range, and provides a geologic summary for the region.

The geology of the area immediately to the east, including the

Goat Rocks Wilderness and White Pass, is described in detail in two recent reports (Clayton, 1983; Swanson and Clayton, 1983). The Ohanapecosh Formation has been the subject of several studies and diverse interpretations, including those of Fiske (1963), and Clayton (1983).

The stratigraphic section most comparable with the rocks of the study area crops out in the western foothills of the Cascade Range, between the Puget Sound lowland and Mount Rainier. This thick sequence of nonmarine arkosic sandstone, siltstone, and mudstone has been subject to intermittent study since the late 1800's due to the presence of small economic coal deposits. Bailey Willis first described these rocks in 1886, and White (1889) referred to them as the Puget Group. A series of divisions adopted by Willis were either redefined or abandoned by Gard (1968), who divided the Puget Group in the Lake Tapps Quadrangle into the Carbonado, Northcraft, and Spiketon Formations. The Northcraft Formation and the Tukwila Formation near Seattle consist of andesitic volcanic complexes, underlain and locally overlain by arkosic sediments.

Buckovic (1974) completed a detailed study of the Puget Group and Ohanapecosh Formation in the area just west of Mount Rainier, and later summarized the regional Eocene paleogeography (1979). Fisher (1957, 1961) described a correlative sequence in the Ashford area, and mapped by reconnaissance almost 1,500 km² between the Nisqually and Cowlitz Rivers. Schreiber (1981), and Clayton (1983) described the stratigraphy and structure of lower Tertiary arkosic sediments in the Nelson Butte and White Pass areas, respectively, east of the Cascade crest.

CHAPTER II

REGIONAL GEOLOGY

REGIONAL STRATIGRAPHIC FRAMEWORK

The arkosic sandstone, and associated siltstone and mudstone exposed in the study area is part of a series of early to late Eocene arkosic sediments that underlie much of southern Washington and northwestern Oregon. Paleocurrent patterns and sandstone mineralogy indicate an eastern, crystalline source, or sources, and sediment transport across a low-lying alluvial plain by westward to southwestward flowing rivers.

The oldest arkosic rocks are exposed in central Washington (Swauk Formation), suggesting east-to-west progradation (Armentrout and Franz, 1983). Eocene sediments prograded over a diverse continental basement, and thin considerably over paleohighs. Lateritic paleosols over basement rocks, and thin (meter scale) zones of locally derived detritus suggest passive onlap of Eocene sediments over basement blocks. Off-shore, Eocene arkoses enveloped an accreting chain of basaltic seamounts, and infilled the newly constructed fore-arc basin (Armentrout and Franz, 1983).

The "magmatic null" (Dickinson, 1979) that allowed these crystalline-derived sediments to accumulate was interrupted by several volcanic episodes, including bimodal volcanism in central Washington (Teanaway and Naches Formations, Tabor and others, 1984) and andesitic volcanism

in western Washington (Northcraft and Tukwila Formations, Buckovic, 1979). These episodes were accompanied and followed by continuing arkosic sedimentation, which buried the more distal volcanic facies under a blanket of arkose.

In latest Eocene(?) time, new andesitic volcanic centers appeared, between latitudes 47° and 46° N, and generally west of the present-day crest of the Washington Cascade Range (Hammond, 1980). Andesitic flows accumulated near vents, but the most extensive deposits are the great thicknesses of nonmarine volcanoclastic rocks (Ohanapocosh Formation, Fiske and others, 1963), and marine tuffaceous strata (Lincoln Creek and Keasey Formations, Van Atta, 1971). Relatively close to the Ohanapocosh volcanic centers, coarse volcanic sediments were locally deposited in and adjacent to energetic, westward-flowing, arkosic sediment-bearing drainages, which were able to maintain their westward course well into the time of active volcanism (this report). This resulted in inter-stratification of arkosic and volcanoclastic rocks in a broad belt circling the western and southern margins of this volcanic source area (Buckovic, 1974; and this report). East-to-west arkose transport across Washington was eventually blocked by eruptive products of continued volcanism, but continued to the south, resulting in deposition of tuffaceous arkose in northwestern Oregon (Pittsburg Bluff Formation, Van Atta, 1971). Deposition of andesitic to rhyodacitic volcanic sequences (middle Western Cascade Group, Hammond, 1980) continued in the Cascade Range, while quartzose sandstones accumulated in lowlands east of the mountains (Wenatchee Formation, Hauptman, 1983).

In Miocene time, flood basalts of the Yakima Basalt Subgroup were

erupted from fissures near the Oregon-Idaho-Washington border, covering lowlands east of the Cascade Range and following paleodrainages across the Cascade volcanic high, locally intercalating with the upper part of the Western Cascade Group (Hammond, 1980).

Pliocene to Holocene basalt and basaltic andesite shield volcanoes and subordinate andesitic to dacitic composite cones of the High Cascades Group are the youngest bedrock units exposed in the southern Washington and northern Oregon Cascade Range.

LOCAL GEOLOGIC SETTING

The study area is located in the southwestern portion of the White Pass region of the southern Washington Cascade Range (Figure 2). The primary bedrock units of this area are the Jurassic and Cretaceous(?) rocks of the Rimrock Lake inlier (Russell Ranch Formation, shown as Jr, and the Indian Creek crystalline complex), lower Eocene(?) volcanic rocks, Eocene arkosic sediments (Chambers Creek beds, Tcc), Paleogene volcanoclastic and subordinate volcanic strata (Ohanapecosh Formation, To), and Plio-Pleistocene High Cascades basaltic to dacitic lavas (ruled areas).

High angle north-trending faults cut the pre-Tertiary rocks and predate deposition of Tertiary units. Lower Tertiary units form broad, north-northwest-trending folds, and are locally cut by high angle faults parallel to this trend. These structures are deeply eroded, and are locally overlain by undeformed High Cascades rocks.

The Rimrock Lake inlier (Miller, 1982, Clayton, 1983) forms the southernmost exposure of pre-Tertiary basement in western and central

Figure 2. Generalized geologic map of the southwestern portion of the White Pass region, southern Cascade Range, Washington; geology from Hammond (1980), Swanson and Clayton (1983), and this report: Jr, Russell Ranch Formation; Tcc, Chambers Creek beds; To, Ohanapecosh Formation; ruled areas, High Cascade lavas; CCF, projection of Cortright Creek fault.

Washington, and is exposed about 15 km east-northeast of the study area. Paleocurrent data in this report places it directly "upstream" from the mapped Paleogene sequence, therefore its geology is briefly described here, and later interpreted in light of the new data.

Pre-Tertiary rocks form five lithological belts bounded by high angle pre-Eocene faults, and are shown by Clayton (1983, p. 11) as underlying about 430 km² east of White Pass. Sheared and boudinaged argillite and lithic arkose are the dominant lithologies, and along with subordinate chert, conglomerate, tuff, pillow basalt, and greenstone, make up the deep marine Russell Ranch Formation. Plutonic rocks from tonalitic to gabbroic composition, and their metamorphic equivalents (units comprising the Indian Creek crystalline complex) make up relatively thin tectonic blocks within and adjacent to the Russell Ranch Formation. The projection of the ~N10°W-trending Cortright Creek fault, interpreted by Hammond (1980) as the western boundary of the Rimrock Lake inlier, lies between the pre-Tertiary outcrops and the Johnson Creek - Chambers Creek area (Figure 2).

Laterally discontinuous sequences of lower Tertiary rocks (not shown in Figure 2) locally overlie the Rimrock Lake inlier, and consist mainly of subaerial basalt flows, arkosic sandstones, and silicic lavas and tuffs. These rocks may have originally been more extensive, and were probably locally eroded before deposition of the disconformably-overlying Ohanapecosh Formation (Clayton, p. 31). Post-Ohanapecosh vertical uplift of the Rimrock Lake inlier is inferred because of steep doming of Paleogene rocks along its margins. The evidence therefore points to repeated Tertiary uplift of the Rimrock Lake inlier.

CHAPTER III

STRATIGRAPHY

OUTLINE OF LITHOSTRATIGRAPHIC UNITS

Four bedrock units are mapped in the study area: arkosic sediments of the Chambers Creek beds (informal name, introduced here), volcaniclastic strata assigned to the Ohanapecosh Formation, basaltic to andesitic intrusions, and High Cascades andesitic to dacitic lavas, which unconformably overlie all the other units.

Only the most extensive surficial units are shown on the geologic map (Plate I, back pocket). Three large landslides, and an extensive apron of talus surrounding an erosionally isolated High Cascades dacite flow, are shown. Recent alluvium and alpine glacial drift are locally present, and thin colluvium mantles much of the map area, but these are not shown.

The Chambers Creek beds are the stratigraphically lowest unit, and consist of quartzose, micaceous arkose to lithic arkose, siltstone, mudstone, and sparse interbeds of coal, lapilli-tuff, tuff, and tuffaceous sediments. Where well exposed, the Chambers Creek beds are characterized by fine-grained, coarsening-upward intervals (lithofacies A,B intervals, this chapter), associated rhythmically bedded, fine-grained strata (lithofacies C), and relatively coarse-grained, cross-bedded sand bodies (lithofacies D). The Chambers Creek beds are correlated with the Spike-ton Formation of Gard (1968) on the basis of lithology and stratigraphic

position (Chapter VIII).

The most continuous exposures of the Chambers Creek beds are in road cuts corresponding to the Chambers Creek and Road 21 measured sections (locations on Plate II, back pocket), and in cliffs on the east flank of Mission Mountain (SE 1/4 of section 4, T 11 N, R 10 E).

Volcanic sandstone, siltstone, mudstone, lapilli-tuff, tuff, conglomerate, and diamictite, assigned to the Ohanapecosh Formation, overlies, and are interstratified with, the Chambers Creek beds. Figure 3 shows that the base of this volcanoclastic sequence is lower in the section in the northern portion of the map area, where it consists primarily of volcanic arenite (lithofacies P, this chapter), and locally thick mudstone intervals (lithofacies R). In the southern portion of the field area (Figure 3), the base of the Ohanapecosh is also mostly arenaceous, but here the volcanic sediments pass upward into thick intervals of volcanic diamictite (lithofacies Q). Throughout the map area, arkosic sandstone forms minor intercalations in the lower portion of the Ohanapecosh Formation.

Assignment of these rocks to the Ohanapecosh Formation of Fiske and others (1963) is warranted by their stratigraphic position, and general similarity of lithofacies to the type section, which is ~32 km to the north. The most continuous exposures of these strata are in road cuts corresponding to the North Cispus and Middle Fork measured sections, and along the crest of Elk Ridge (Plate II).

The Chambers Creek and Ohanapecosh strata are intruded by a large volume of basaltic to andesitic sills, dikes, and stocks, described in Chapter V. Only the larger intrusive features are shown on Plate I.

Figure 3. Stratigraphic cross section of the Johnson Creek - Chambers Creek area; shows general stratigraphic relationship between the Chambers Creek beds (Tcc) and the Ohanapecosh Formation (To), local facies change in Ohanapecosh Formation, and locations of measured sections: R 21, Road 21 section; CC, Chambers Creek section; NC, North Cispus section; and MF, Middle Fork section.

High Cascades pyroxene andesite and hornblende-pyroxene dacite locally laps over the Chambers Creek, Ohanapecosh, and intrusive rocks. These flows are recognized by their fresh, unaltered appearance; their lithology and texture are described in Chapter VI. Good exposures of andesite occur in a road cut on USFS Road 2152 a few hundred meters north of its junction with Road 2160 (station HG-200 on Plate II); exposures of dacite form cliffs just south of the Jordan Creek trail (station JOR-102).

LITHOFACIES OF THE CHAMBERS CREEK BEDS

Introduction

Four types of lithologic intervals are distinguished in the well-exposed portion of the Chambers Creek beds. Each is characterized by a distinct association of lithologies, bedding styles, and sedimentary structures, implying each represents a particular set of depositional conditions.

According to Walther's Principle, superposed lithologies in a conformable stratigraphic sequence represent the deposits of laterally adjacent sedimentary environments. Superposition of lithologic intervals in the field area, as described in the text, is taken as evidence of lateral equivalence of these intervals. This assumption is required to presume these lithologies represent facies, as limitations of exposure do not permit direct establishment of their lateral equivalence.

The characteristics of these presumed lithofacies are summarized in Table I, then described in detail. Inferred environments of deposition are discussed in Chapter X.

TABLE I

SUMMARY OF LITHOFACIES OF CHAMBERS CREEK BEDS,
JOHNSON CREEK - CHAMBERS CREEK AREA

<u>lithofacies</u>	<u>thickness of intervals</u>	<u>contacts between intervals</u>	<u>grain size trend</u>	<u>type of stratification</u>	<u>other features</u>	<u>depositional processes</u>	<u>inferred environment*</u>
A	4-17 m	A → B: gradational B → A: sharp or gradational	mudstone, uppermost half meter coarsens into B	massive, except for thin, tabular intercalations of lapilli-tuff, tuff, and coal	locally abundant small iron oxide concretions	deposition of mud from suspension; volcanic air-fall	open lacustrine and/or open lagoonal
B	1-9 m	see above	very fine-grained arkose to lithic arkose	alternation of ripple- and parallel-laminated cosets common	burrows, bioturbation, wave ripples, roots; carbonaceous concretions	tractive currents in relatively shallow water	shallow lacustrine and/or shallow lagoonal
C	4 m (only one interval observed)	not observed	very fine-grained arkose & mudstone	composite sets, each composed of a mud/sand rhythmite coset and a flaser to lenticular bedded coset of sub-equal thickness	sand laminae are rippled, indicating deposition by currents, not from suspensions	intermittent current or wave activity in a regime of variable sand supply	lacustrine delta
D	to 50 m	base sharp, top not observed	mostly medium-grained, two intervals fine upward to very fine-grained	meter-scale, medium- to coarse-grained planar cross-sets, and half meter-scale medium- to fine-grained planar and trough cross-sets that grade upward into thinner, fine- to very fine-grained sets	unimodal paleocurrents, sand body elongate parallel to paleoflow, reactivation surfaces	tractive currents	fluvial or deltaic distributary channel

Detailed work was, by necessity, limited to the approximately 400 meter thick interval of the Chambers Creek beds that is well exposed in road cuts. Therefore, the lithofacies described here may or may not be characteristic of all of the 1,150 meter total thickness of this unit. However, the lithology of small natural outcrops throughout the map area suggest the well-exposed interval is typical.

Lithofacies A

Dark gray to light olive gray mudstone makes up almost half of the clastic strata exposed in the Chambers Creek measured section (Figure 4). Most mudstone intervals are 4 to 8 m in thickness, but one unit exceeds 17 m. These rocks are generally massive, except for uncommon tabular intercalations of coaly carbonaceous siltstone, claystone (altered vitric tuff), and crystal to lithic lapilli-tuff (Figure 5). The presence of abundant euhedral, unabraded crystals in the lapilli-tuff and tuff units indicates these interbeds probably originated as volcanic air-fall.

Mudstone units contain locally abundant small iron oxide cemented concretions, and pyrite nodules were noted in a few beds. The dark gray color of most mudstone beds suggests a high organic content. All mudstones were carefully inspected in the field for microfauna. Five samples selected for disaggregation were barren. Faunal remains, if present, are sparse.

Lithofacies A mudstone units were deposited in relatively deep water, distant from terrigenous sand sources. This is evident from the thickness of the units (averaging 4 to 8 m), and the absence of sandy intercalations except for tabular, tuffaceous interbeds of probable air-fall origin.

meters

Figure 4. Chambers Creek measured section. Key on following page.

Lithologies

	mudstone		planar cross beds (tabular)
	siltstone		planar cross beds (wedge shaped)
	massive sandstone		trough cross beds
	laminated sandstone		intrusive
	small-ripple bedded sandstone		crystal to lithic-crystal lapilli-tuff
	coal		lithic to crystal-lithic lapilli-tuff

Symbols

	leaf fossils		rhythmic stratification
	mollusk impressions		graded bedding
	concretions, with type		alternating feldspathic and lithic layers
	burrows		epsilon cross-stratification
+++	claystone (altered tuff)		intraformational recumbent fold
	calcareous cement		wave ripples
#	pyrite		fining-upward interval
	possible erosional surface		coarsening-upward interval
	carbonaceous
	roots		

ss: scour surface

A: lithofacies discussed in text (example)

Small numbers refer to field designations for beds; some of these are referred to in the text.

Figure 5. Mudstone assigned to lithofacies A with two to three centimeter thick, tabular intercalations of crystal to lithic-crystal lapilli-tuff; lower part of unit 30, Chambers Creek measured section.

Lithofacies B

Beds of very fine-grained arkose to lithic arkose are intercalated with lithofacies A in the Chambers Creek measured section (Figure 4). These units are dark gray to light brownish gray, ripple- to parallel-laminated, and locally burrowed to bioturbated. Wave ripples and root scars are locally present. Most of these beds range in thickness from 1 to 5.4 meters, and display some type of repeating stratification, including alternation of parallel- and ripple-laminated cosets, small-scale coarsening-upward intervals, and intercalation of parallel- to ripple-laminated cosets with thinner flaser- to wavy-bedded cosets.

All of these units are carbonaceous, and contain angular wood fragments, leaf fossils, or carbonaceous laminations along bedding. No macrofauna was noted. Calcium carbonate cement is usually present, either throughout the bed, or more commonly localized in layers of concretions. These are generally 20 to 45 cm long, and form layers parallel to bedding in the middle to lower portion of a sandstone unit.

Several features of lithofacies B indicate relatively shallow water depositional conditions. The repeating stratification described indicates sand deposition by tractive currents of varying strength. Root scars indicate emergent to very shallow water conditions. Bioturbation and wave ripples occur in a variety of environments, but are more characteristic of shallow water.

Lithofacies A,B Coarsening-upward Intervals

Much of the mudstone and very fine-grained arkose in the Chambers Creek measured section (Figure 4) forms coarsening-upward intervals. Five such intervals from 10 to 19 meters in thickness are indicated.

The similarity of these intervals indicates they probably originated through a similar, recurring set of depositional conditions.

An idealized A,B interval is shown in Figure 6. Mudstone predominates, making up the lower 55 to 80 percent of the interval. This passes upward into a half meter thick gradational zone, of either thinly interlayered mudstone and sandstone, or a transitional siltstone member, that grades upward into ripple- to parallel-laminated very fine-grained arkose.

Lithofacies A,B coarsening-upward intervals are regressive sequences, reflecting a gradual transition from relatively deep water mudstone deposition to shallow water sandstone deposition. The gradational to sharp contacts between these intervals suggests that resubmergence could be either slow or relatively rapid.

The absence of marine fauna and the presence of abundant well preserved plant debris and occasional root scars suggest that lithofacies A,B intervals represent deposition in a low energy nonmarine environment. Several possible depositional settings are discussed in Chapter X.

Lithofacies C

A relatively minor stratigraphic interval in the Chambers Creek measured section that displays an unusual type of stratification is described here as lithofacies C. This occurs in a single, four meter thick exposure, and corresponds to unit 34 in Figure 4. This unit is separated from the underlying facies by a sill, but its attitude indicates it is part of the same conformable stratigraphic sequence.

Unit 34 of the Chambers Creek section displays a highly cyclic stratification style. It is made up of a series of composite sets,

Figure 6. Idealized lithofacies A,B coarsening-upward interval; symbols identified on page 19.

each 10 to 35 cm in thickness, and each composed of a parallel-laminated coset and a cross-laminated coset of subequal thickness. The latter generally displays a rippled top, with parallel laminations of the overlying coset filling the ripple troughs. Mud is abundant; parallel-laminated cosets are composed of about 3 mm thick alternating layers of mud and sand (Figure 7), and cross-laminated cosets are flaser- to lenticular-bedded.

Alternating layers of mud and sand (rhythmites) can originate either by short term processes (e.g. current fluctuations, tidal changes) or long term processes such as seasonal fluctuations in discharge (Reineck and Singh, 1980, p. 123), and can be the products of either currents or suspensions (e.g. varves). The slightly rippled appearance of many sandy layers in lithofacies C parallel-laminated cosets suggests deposition by currents.

Flaser to lenticular bedding requires conditions of current or wave action alternating with slack water conditions (Reineck and Singh, p. 115). Therefore, both the thinly interlayered parallel-laminated sets, and the flaser- to lenticular-bedded cross-laminated sets described here reflect intermittent current or wave activity.

Sandy layers in the cross-laminated cosets are much thicker than those in the parallel-laminated cosets. Muddy layers are about the same thickness. This suggests that the two types of cosets reflect two conditions of sand supply. Composite sets therefore reflect a cycle of sand supply, most likely annual stream discharge cycles, or progradational cycles. Stacking of these composite sets indicates autocyclicity.

In summary, the stratification style of lithofacies C requires an

Figure 7. Lithofacies C: cosets of slightly rippled interlayered mud and sand alternate with cosets of flaser- to lenticular-bedded very fine-grained arkosic sandstone (white strata adjacent to pencil); unit 34, Chambers Creek measured section.

environment with short term energy fluctuations (waves or intermittent currents), longer term fluctuations in sand supply (discharge cycles or progradational cycles) and autocyclic renewal of depositional conditions. Environments that meet these criteria are discussed in Chapter X.

Lithofacies D

Dominantly medium- to fine-grained lithic arkose with half meter- to meter-scale planar and trough bedding characterizes lithofacies D. Sediment size ranges from coarse- to very fine-grained sand; gravel and mud are notably absent. Unit 23 of the Chambers Creek measured section (Figure 4), and all of the clastic rocks of the Road 21 measured section (Figure 9, p. 29) are assigned to this facies.

Lithofacies D is inferred to be laterally equivalent to the other three facies described because of its intercalation with these rocks in the Chambers Creek section, and its occurrence in the Road 21 section, which lies 1.2 km to the south along strike.

Cross bedding in lithofacies D falls into three ranges of thicknesses. The largest cross sets are 0.8 to 2.5 meters thick, medium- to coarse-grained, and almost all planar cross bedded (Figure 8). A few sets with truncated tops are thinner. Foreset laminae are one half to two centimeters thick, inclined 16 to 23 degrees, and are readily visible due to differences in grain size (micaceous laminae) or composition (feldspathic and lithic layers). These largest-scale cross sets probably formed by slip face avalanching of active bars in distributary channels.

Thirty to fifty centimeter thick medium- to fine-grained planar and trough cross sets are the most common type, and formed by migration of straight-crested megaripples (sand waves) and undulatory to lunate

Figure 8. Planar cross bedding in medium-grained lithic arkose assigned to lithofacies D; unit 23, Chambers Creek measured section. Note steeply dipping (23°), ~ 1 cm thick foreset laminae. Set is 63 cm thick, with erosional top (visible), and probably formed by slip-face avalanching on an active bar.

megaripples, respectively (Reineck and Singh, 1980, p. 40-43). Most sets show truncated tops, indicating recurrent scour.

Ten to twenty centimeter thick fine- to very fine-grained cross sets are exposed at the tops of two ~15 meter thick fining-upward intervals. These planar and trough cross sets were formed by megaripples under conditions of declining flow.

Unit 23, Chambers Creek Measured Section (Figure 4). The lower ~9 meters of this 17 meter thick lithic arkose unit is composed of half meter- to meter-scale tabular and wedge-shaped planar cross sets (Figure 8) and a 1.2 meter thick epsilon cross set. This interval grades upward into thinner and finer sets; first, 15 to 20 centimeter thick fine-grained planar and trough cross sets, then, 10 to 15 centimeter thick very fine-grained planar and trough cross sets. Calcite cement and distinctive brown patches of manganese oxide are irregularly distributed throughout the units. The basal contact with siltstone is sharp and planar; the top of unit 23 is not exposed. Lateral relationships are also not exposed.

Several features of unit 23 are features normally associated with channels, including a sharp base, cross beds that thin and fine upwards, and epsilon cross bedding. Cross sets have erosional contacts (reaction surfaces), but laterally extensive scours were not noted.

Road 21 Measured Section (Figure 9). Poorly exposed medium-grained lithic arkose with sparse thin (centimeter scale) coal seams passes upward into medium-grained rocks with half meter to almost two meter thick wedge-shaped and tabular planar and subordinate trough cross sets. Above a laterally extensive scour surface, the cross sets thin to 20 to 60 cm

meters

Figure 9. Road 21 measured section. Key on page 19.

in thickness. Cross beds overlying a long poorly exposed interval fine and thin upwards; a 2.5 meter thick medium- to coarse-grained planar cross set is overlain by about 7 meters of 30 to 100 cm thick wedge-shaped and tabular mostly planar sets. Ten to twenty centimeter thick sets of very fine- to fine-grained sandstone form the upper four meters of the exposed sequence.

The upward-fining and -thinning trend in the upper 14 meters of this interval suggests that the top of the sandstone body is exposed, or nearly so. Small-scale cross bedding in this interval parallels trends in the rest of the sand body, indicating currents of decreasing strength, and a large intraformational recumbent fold records intense scour, probably associated with a flood event (Reineck and Singh, p.99).

Nine paleocurrent readings in the Road 21 section all lie within the third quadrant, indicating southwestward paleoflow. The ~290 meter long exposure along Road 21 is, therefore, a nearly longitudinal cross section of the sandstone body. In a true vertical section this sandstone body could be considerably thinner than the ~50 m measured thickness.

The scour surface shown on Figure 9 truncates numerous cross sets, but appears to lack any lag deposits. Wood, carbonaceous laminations, and leaf fossils are scarce in the Road 21 section. Carbonate cement is widespread. Patchy brown stain, originally thought to be dead oil, was identified by energy-dispersive x-ray analysis as a manganese oxide compound.

Features of the Road 21 section typical of channels include large-scale planar cross beds, a laterally extensive scour, unimodal paleo-

currents, an intraformational recumbent fold, elongation parallel to paleoflow, and a fining-upward interval at the presumed top of the sequence.

Correlation of the Road 21 and Chambers Creek Measured Sections.

An attempt to physically correlate the Road 21 and Chambers Creek sections was unsuccessful. Descriptive geometry allowed the stratigraphic relationship of the two sections to be determined approximately (Billings, 1972, p. 500-501). The base of the Road 21 section is equivalent to a portion of the 49 meter thick covered interval between units 14 and 16 of the Chambers Creek section (see Figure 4); the top of the Road 21 section corresponds to a portion of unit 23 (lithofacies D lithic arkose). It is therefore possible that unit 23 is part of the same sandstone body that is exposed along Road 21, 1.2 km to the south along structural and depositional strike. This would give a width/depth estimate for this sand body of about 80, assuming the maximum thickness is about 50 meters. Exposure along Road 21 parallel to depositional dip may have exaggerated the sand body thickness, as discussed; conversely, this unit may be locally thicker. It is also possible the Road 21 sandstone body pinches out to the south of unit 23 (i.e. there is no continuity between the two units). The width/depth ratio of the Road 21 sandstone body therefore probably lies between 50 and 120, depending upon the assumptions made. The significance of this estimate is discussed in Chapter X.

In summary, lithofacies D is dominated by medium- to fine-grained, planar, trough, and epsilon cross bedded lithic arkose, with many reactivation surfaces, a laterally extensive scour, and a prominent intraformational recumbent fold. Fining-upward intervals, unimodal paleo-

currents, and sand body elongation parallel to paleoflow support the interpretation of lithofacies D as the product of sedimentation in and adjacent to westerly- to southwesterly-flowing paleochannels.

LITHOFACIES OF THE OHANAPECOSH FORMATION

Introduction

The estimated thickness of the Ohanapecosh Formation in the Johnson Creek - Chambers Creek area is over 1600 meters. Reconnaissance indicates that pyroclastic rocks dominate the upper half of this interval; epiclastic strata are subordinate. Andesitic extrusive rocks were only noted in a single exposure (Plate II), but increase in abundance near vent complexes outside the map area (Swanson and Clayton, 1983). I limited my work to the primarily epiclastic, lowermost ~ 700 meters of the Ohanapecosh Formation, and studied its sedimentology and stratigraphic relation to the underlying arkosic sediments.

Three main types of lithologic intervals are distinguished in the lowermost Ohanapecosh Formation. Vertical and lateral relations described in the text suggest these represent lithofacies. Table II summarizes the most important characteristics of these presumed facies; it is followed by more complete descriptions.

Classification of Volcaniclastic Rocks

The classification of volcaniclastic rocks used in this report (Figure 10) generally follows the classification given by Le Bas and Sabine (1980). Stratigraphic units in the field area composed almost entirely of pyroclasts ($\geq 75\%$) are named according to this scheme. Pyroclasts noted include angular lithic fragments, pumice, and crystals,

TABLE II

SUMMARY OF LITHOFACIES OF OHANAPECOSH FORMATION,
JOHNSON CREEK - CHAMBERS CREEK AREA

<u>lithofacies</u>	<u>thickness of intervals</u>	<u>contacts between intervals</u>	<u>grain size trend</u>	<u>type of stratification</u>	<u>other features</u>	<u>depositional processes</u>	<u>inferred environment*</u>
P	0.2-4.0 m; (0.5-1.5 m average)	base sharp but non-erosional, top sharp or gradational	generally medium- to very coarse-grained (and less commonly fine-grained)	cross-bedded, graded, (and less commonly massive), epsilon cross-stratification	wave ripples, current ripples; scattered volcanic and non-volcanic pebbles; associated with finer-grained volcanic arenite, siltstone, and mudstone	tractive currents; channel sequence	fluvial channel
Q	3-23 m (about 6-15 m average)	base and top usually sharp, but may also grade into conglomerate	25-50% lapilli and pebbles, and scattered blocks and cobbles, in an abundant (50-75%) matrix; very poor sorting	generally massive; may show carbonaceous layers and weakly graded intervals within units	most are lithic lapilli-tuff; subangular to rounded clasts far exceed angular clasts; intercalated with cross-bedded sandstone	mass flow; lahar sequence	fluvial channel
R	1-5 m	base and top sharp; a few are gradational	0.3 to 2.0 m thick beds of very fine-grained volcanic arenite, siltstone, or sandy mudstone fine upward into generally thicker finer-grained beds	lithologies are massive, graded, or parallel laminated; cross bedding is notably absent	intercalated 10-60 cm thick medium to very coarse-grained massive arenite, and 50-145 cm thick pebbly diamictite	deposition of suspended sediment and density flows	open lacustrine and/or open lagoonal

* discussed in Chapter 10

Figure 10. Classification of pyroclastic deposits (after Le Bas and Sabine, 1980).

of presumed juvenile and accessory volcanic origin.

The classification of mixed pyroclastic-epiclastic rocks given by Le Bas and Sabine has been deviated from. Poorly sorted, polymodal deposits composed of angular to rounded clasts (mostly volcanic) surrounded by a diagenetically altered fine-grained matrix (lithofacies Q, this chapter) are referred to as volcanic diamictite. This term expresses the composition and texture, and does not require a difficult estimation of the proportion of pyroclastic material. These rocks are given a supplemental name according to Figure 10a because of their inferred volcanic (laharic) origin. By contrast, clast-supported rudites dominated by volcanic clasts are called volcanic conglomerate.

Sandstones seen under a hand lens to be dominated by volcanic components ($\geq 75\%$ volcanic rock fragments and crystals) are referred to as volcanic arenite or volcanic wacke. Arkose refers to intercalations of sandstone similar in composition to arkose of the underlying Chambers Creek beds.

Siltstone and mudstone is called "volcanic" if it is either part of a volcanoclastic sequence, or contains numerous intercalations of pyroclasts.

Lithofacies P

Medium- to very coarse-grained volcanic arenite, and subordinate finer-grained volcanic arenite to siltstone of lithofacies P forms much of the lower portion of the Ohanapecosh Formation in the field area. This widespread facies is well exposed in road cuts at stations EMM-200, KTR-300, and MMR-103 (Plate II, back pocket).

In the North Cispus measured section (Figure 12, p. 39), sandstone

units assigned to lithofacies P are interstratified with volcanic diamictite of facies Q (next section), and arkosic sandstone similar to facies D of the Chambers Creek beds. This relationship suggests these lithologies are local facies equivalents. On the western flank of the Johnson Creek anticline, volcanic sandstones assigned to facies P are on strike with a thick section of volcanic mudrocks assigned to facies R (Middle Fork section, this chapter), suggesting lateral equivalence of these two lithologic types.

Sandstone assigned to facies P forms 0.2 to 4.0 meter thick cross-bedded, graded, and less common massive beds. Half meter to 1.5 meter thick beds are the most common. Lower contacts with associated finer-grained rocks are usually sharp but non-erosional. Large-scale wave ripples (Figure 31, p. 91) and current ripples are locally well developed. One outcrop (Figure 11) exposes a small, complete point bar.

Most medium-grained volcanic arenite shows compositional sorting; foreset laminae and graded laminae are composed of same-sized grains of feldspathic and lithic compositions. Coarser-grained arenites contain rounded granules to small pebbles of andesite, vein quartz, and chert. These are usually scattered within the sand bed, but are locally concentrated into ~10 cm thick lenses.

The orientations of cross-bedding and current ripples in facies P parallel those in sandstones of the underlying Chambers Creek beds, and indicate westward paleoflow.

Lithofacies Q

The thickest coarse-grained intervals in the mapped portion of the Ohanapecosh Formation consist of 3 to 23 meter thick beds of volcanic

Figure 11. Lithofacies P: medium-grained volcanic arenite with thin, complete point bar (lateral to head of hammer), station KTR-300, Windy Pass. Note epsilon cross-stratification, fine-grained drape, and graded bedding in overlying tabular sandstone unit. Maximum thickness of bar is about 50 cm, and it is about 6.3 meters wide in cross-section.

diamictite assigned to lithofacies Q. Good exposures of these rocks are found in road cuts between mileposts 13 and 14 of USFS Road 22 (North Cispus measured section, Figure 12). Volcanic diamictite forms prominent cliffs in an outcrop belt extending from peak 4896' (just south of Mission Mtn., Plate I), south 7 km along strike to Elk Ridge. In most outcrops, volcanic diamictite is intercalated with volcanic arenite of facies P, or arkosic sandstone similar to facies D of the Chambers Creek beds.

Most facies Q diamictites are lithic lapilli-tuffs, and consist of 25 to 50 percent subangular to rounded andesitic lapilli and pebbles (average long diameter 3-5 cm), and scattered andesitic blocks and cobbles (8-50 cm), in an abundant (50-75%) well-indurated crystal-lithic matrix of altered sand-sized andesitic rock fragments, and euhedral feldspar and pyroxene (Figure 13). These units are massive and very poorly sorted, but a few show carbonaceous layers and weakly graded intervals; one unit shows reverse grading (Figure 12, unit 13). All units studied display a sharp base, and some overlie finer-grained sediments with slight erosional disconformity. Most display a sharp upper contact, but two well-exposed diamictite beds (units 13 and 17, Figure 12) grade upward into granule to pebble polymict orthoconglomerate.

Most volcanic diamictites are greenish-gray to grayish-olive, and weather to a brownish- or yellowish-gray. The greenish cast is due to extensive replacement of matrix and lithic clasts by authigenic minerals, probably chlorite and smectitic clays. Clast shape and composition are most visible on weathered surfaces (Figure 13).

Abundant fine-grained matrix, poor sorting, and poorly developed

Figure 12. North Cispus measured section. Key on following page.

Lithologies

	mudstone		granule orthoconglomerate
	siltstone		pebble to cobble orthoconglomerate
	massive sandstone		volcanic diamictite
	laminated sandstone		diamictite with granule to pebble layers
	small-ripple bedded sandstone		crystal to lithic-crystal lapilli-tuff
	coal		lithic to crystal-lithic lapilli-tuff
	planar cross beds		intrusive
	trough cross beds		

Symbols

	interbed of volcanic sandstone or lapilli-tuff
	claystone (altered vitric tuff)
	carbonaceous
	wood
	graded bedding
	concretions, with type
	calcareous cement

Q: lithofacies discussed in text (example)

Small numbers and letters refer to field designations for beds;
some of these are referred to in the text.

Figure 13. Lithofacies Q pyroclastic breccia of probable laharc origin; subangular to angular blocks and lapilli of phyrlic and aphyric andesite float in a crystal-lithic matrix. Note the degree of induration. Unit 21, North Cispus measured section.

stratification indicate the lithofacies Q diamictites represent lahars. Many volcanic diamictites are ignimbrites, but features characteristic of ignimbrites, such as compositional zoning and pumice-rich layers (Sparks and others, 1973) are absent. Supporting features for a laharic origin include a strongly bimodal grain size distribution, and subangular to rounded clasts (accessory) far in excess of angular clasts (juvenile?).

Associated Lithologies - North Cispus Measured Section. In the North Cispus section (Figure 12), lahars are intercalated with thinner units of parallel- to cross-laminated arkosic sandstone that are similar to facies D of the Chambers Creek beds. Lahars are locally underlain by volcanic orthoconglomerate. This ~158 meter thick interval of diamictite, conglomerate, and arkose (units 11 through 23, Figure 12) comprises the middle portion of a ~211 meter thick sequence of diamictite, conglomerate, and very coarse- to medium-grained volcanic and arkosic arenite (units 9 through 26). This thick coarse-grained pyroclastic-epiclastic interval is underlain by at least 30 meters of mudstone, and overlain by several hundred meters of fine- and coarse-grained pyroclastic rocks with few clearly sedimentary interbeds (based on reconnaissance of lithologies between top of section and St. John Creek, Plate II).

Lithofacies R

Volcanic mudrocks and very fine-grained volcanic arenite make up many relatively thin intervals (< 5 meters thick) throughout the map area. Most of these are not assigned to a described facies. An exceptionally thick (~145 meter) fine-grained sequence exposed in road cuts on USFS Road 2140 (Middle Fork Measured section, Figure 14) is assigned

meters

Figure 14. Middle Fork measured section. Key on page 40.

to lithofacies R. This interval lies on strike with arenaceous rocks on the western flank of the Johnson Creek anticline assigned to facies P; the two lithologies may be facies equivalents. Rocks similar to those in the Middle Fork section form a ~ 30 m thick interval at the base of the North Cispus section (Figure 12).

Lithofacies R is made up of 0.3 to to 2.0 meter thick beds of very fine-grained volcanic arenite, siltstone, and sandy mudstone, that fine upward into generally thicker beds of sandy mudstone or mudstone. Over twenty five of these one to five meter thick, fining-upward, silty/muddy couplets are recorded (Figure 14).

Sandy mudstone is massive to graded, and consists of sand-sized angular plagioclase crystals and volcanic lithic fragments floating in a muddy matrix. Volcanic arenite is thinly parallel-laminated, graded, or massive; cross bedding is notably absent. This lithology is composed of volcanic rock fragments, plagioclase grains, accessory quartz, and uncommon muscovite. Scattered pebbles of chert and andesite occur in a few beds.

Intercalated with these fine-grained rocks are 10 to 60 cm thick beds of medium- to very coarse-grained, generally massive, well-sorted volcanic arenite, and 50 to 145 cm thick beds of polymict granule to pebble diamictite (Figure 14, units HD and I, also see Figure 15). Diamictite beds are massive, except for a few discontinuous layers in which the long axes of pebbles show subparallel alignment. Two diamictite beds grade upward into pebbly sandstone units, otherwise these diamictite and volcanic arenite beds are massive, and display sharp contacts. Several of these units show rapid pinch outs, and most have irregular, load-

Figure 15. Lithofacies R, Middle Fork measured section. About 15 meters of section is shown, from about 75 m to 90 m above the base (refer to Figure 14). Note the predominance of greenish-gray volcanic mudstone. A 1.4 m thick bed of pebbly coarse-grained volcanic arenite (just below center of frame), and a 0.6 m thick bed of white, coarse-grained volcanic arenite (top of frame) are inferred grain-flow deposits.

deformed bases.

Lithofacies R silty/muddy couplets represent quiet water deposition of mud, silt, and very fine-grained sand. Parallel lamination, grading, and angular grains floating in a muddy matrix all suggest sediment deposition from suspension rather than by traction. The absence of cross lamination supports this idea. Several interbeds of very coarse- to medium-grained volcanic arenite, and granule to pebble diamictite, reflect sporadic influx of coarse sediment.

Associated Lithologies - Middle Fork Measured Section. Lithofacies R, including coarse-grained intercalations, makes up about 145 meters of the Middle Fork measured section. This interval is overlain by 3.5 m of well-sorted fine- to medium-grained cross bedded arkose (unit L, Figure 14) similar in composition to the Chambers Creek beds, 3.5 m of typical lithofacies P mudstone and sandy mudstone, and 8 m of medium- to fine-grained massive to graded volcanic arenite.

Lateral Relations. Rocks exposed in the Middle Fork section cannot be traced to the east due to their truncation by a northwest-trending reverse fault. However, similar lithologies are exposed 0.5 km along strike to the southwest, at milepost 10.65 on USFS Road 21.

At this exposure, 2 to 3 meter thick sharply-bounded beds of medium- to coarse-grained, massive-appearing volcanic arenite are intercalated with siltstone beds of subequal thickness. Pebbly lenses and cut-and-fill occur locally in the sandstone, and complete plant fossils, including large leaves, are locally abundant in the siltstone. Compared with lithofacies R in the Middle Fork section, these features suggest relative proximity to sediment sources.

Angry Mountain Road Sequence

This well-exposed sequence of pyroclastic rocks in the northern portion of the map area is described briefly here to contrast it with the other Ohanapecosh sections. Its base lies several hundred stratigraphic meters above the top of the Middle Fork section.

Over 400 m of relatively well-sorted lapilli-tuff and tuff is exposed in road cuts along USFS Road 2120. Stratigraphic units noted in a reconnaissance of this section include: 1) a ~ 10 meter thick lapilli-tuff unit with a normally graded base, composed of subangular to angular lithic and subordinate pumice lapilli (station AMR-101, Plate II), 2) a thin bed of green volcanic mudstone with accretionary lapilli (underlies unit I), and 3) many ~ 0.5 to 2.0 meter thick lapilli-tuff beds with highly angular pumice and lithic fragments (station AMR-103).

The stratigraphic sequence along Road 2120 is unique in the map area because it is dominated by units with a high proportion of angular lithic and pumiceous lapilli that probably represents juvenile or accessory material of eruptive origin. Clearly epiclastic rocks such as cross bedded volcanic arenite form only thin intercalations within this sequence.

CHAPTER IV

SEDIMENTARY PETROLOGY

FIELD DISTINCTION OF LITHOSTRATIGRAPHIC UNITS

Except for some mudstone units, rocks of the Chambers Creek beds and the Ohanapecosh Formation are readily distinguished in the field.

Sandstone of the two units superficially appears similar, but quartzose lithic arkose and arkose of the Chambers Creek beds are typically light gray, weather to moderate yellowish brown, and are seen under a hand lens to be composed of well sorted subangular to subrounded quartz and feldspar grains with minor dark lithic fragments, biotite, and muscovite. By contrast, feldspathic to lithic subquartzose volcanic arenite^{*} of the Ohanapecosh Formation is dark olive gray to olive brown, well to moderately sorted, and is composed almost entirely of plagioclase feldspar and volcanic rock fragments.

Mudrocks of the Chambers Creek beds are generally dark gray, whereas Ohanapecosh lutites are olive gray to dark gray. Micaceous laminae are prominent in Chambers Creek siltstones, but are rare to absent in siltstones of the Ohanapecosh Formation. Mudstone units of the two formations are generally massive except for thin, tabular intercalations of coal, lapilli-tuff, tuff, and tuffaceous sediments.

^{*}The classification of Crook (1960) is used to name these rocks because their low quartz count makes use of the term "arkose" inappropriate (see Williams, Turner, and Gilbert, 1982, p. 328).

SEDIMENTARY PETROLOGY - CHAMBERS CREEK BEDS

The Chambers Creek beds are dominated by very fine- to fine-grained arkose and lithic arkose, and mudstone to siltstone. Medium- to coarse-grained lithic arkose is locally present, and is restricted to a single facies (lithofacies D). Coaly carbonaceous siltstone, lapilli-tuff, tuff, and tuffaceous sediments form minor intercalations.

Rudites

Rudaceous rocks are notably absent in the outcrop belt of the Chambers Creek beds. Scours and reactivation surfaces in inferred channel deposits (lithofacies D) do not contain pebbly lag deposits. The only beds observed within the Chambers Creek beds that were coarser than sand size were minor interbeds of lithic lapilli-tuff and volcanic pebble orthoconglomerate.

Mudrocks

Mudstone comprises a substantial portion of the Chambers Creek beds where they are well exposed (~48% of Chambers Creek measured section, Figure 4, p. 18). It is generally dark gray, massive to faintly laminated, and contains locally abundant small iron oxide cemented concretions and less common partings of coal, claystone (altered vitric tuff), and graded beds of lapilli-tuff and coarse volcanic sandstone. Siltstone is relatively minor, forming thin parallel- to ripple-laminated transitional zones in some lithofacies A,B coarsening-upward intervals (Chapter 3). Siltstone and mudstone were not examined in thin section, nor analyzed by x-ray diffraction.

Sandstones

Arkose and lithic arkose of the Chambers Creek beds are light gray, weathering to moderate yellowish brown, and are recognized in the field by their quartzose, micaceous composition. Very fine- to fine-grained beds are generally parallel-laminated to small ripple-bedded, with carbonaceous laminae, carbonized wood fragments, leaf imprints, carbonate-cemented concretions, and less common smooth-walled burrows and root scars. Cement is clay and/or carbonate. Medium- to coarse-grained beds generally show thick planar and subordinate trough cross-bedding, and patchy carbonate cement.

A detailed study of the framework mineralogy of the Chambers Creek arkosic sandstones was undertaken to allow comparison with published data for age-equivalent units, and to evaluate the provenance of these rocks.

Sampling Procedure. Approximately 40 samples of arkosic sandstone were collected and described. Sample localities are shown on Plate II (in back pocket). The 19 sandstone samples that were selected for thin sections appeared to be compositionally typical, and covered the stratigraphic thickness and outcrop extent of the Chambers Creek beds. Extensive alteration made several of these unsuitable for accurate modal analysis; the 15 least altered samples were selected for point counting. These cover the section fairly well (Plate II), but are biased toward fine to medium grain sizes. Despite their abundance, only two very fine-grained arkoses were counted, due to the increased difficulty of identifying grains in altered samples.

Petrographic Procedures. Frizzell (1979a, p. 104) distinguished 25 categories of mineral grains and rock fragments in his detailed study of Paleogene nonmarine sandstones of Washington. I have modified Frizzell's categories only slightly, and define 24 groups, which are given in Appendix A.

Arkosic sandstones were stained for potassium feldspar with sodium cobaltinitrite. Approximately 650 points were counted on each slide, in uniformly spaced rows which covered the entire slide. A mechanical stage ensured uniform point spacing.

Point count data, as tabulated in Appendix A, emphasizes the distinction between framework and non-framework components. In practice, this distinction was not easily made in samples with abundant alteration minerals. Relict grain outlines revealed with uncrossed nicols often made possible distinction between altered framework and interstitial alteration products.

Granitic, volcanic, and metasedimentary rock fragments in the sandstones examined commonly contain sand-sized mineral grains. The first type is relatively unstable and would be expected to break down along grain boundaries. Therefore, if the visible diameter of the grain under the cross hair was ≥ 0.0625 mm (lower limit of sand) the point was assigned to the respective mineral; otherwise, it was assigned to the felsite category (after Dickinson, 1970, p. 699).

Microlitic volcanic rock fragments commonly contained sand sized phenocrysts of plagioclase feldspar. The observed shapes of these phyrlic rock fragments does not suggest preferential breakage along the phenocryst/groundmass boundary. It therefore seems proper to tally

these phenocrysts as the associated volcanic rock fragment, as Frizzell did (pers. comm., 1983). Metasedimentary rock fragments are relatively stable, so were recorded as rock fragments regardless of grain size.

Composition. Sandstones of the Chambers Creek beds range in composition from arkose to lithic arkose (Figure 16a), and are dominantly composed of subangular monocrystalline quartz and feldspar (Figure 17). Point count data is given in Appendix A.

Unstrained to slightly strained monocrystalline plutonic(?) quartz is the most common type, but polycrystalline quartz and rare chert make up a few percent of every slide. Angularity and lack of overgrowths suggest that the monocrystalline quartz is dominantly first cycle.

The feldspar content of the arkosic sandstones ranges from 20 to 42 percent. Plagioclase makes up 60 to 70 percent of total feldspar in most of the Chambers Creek section, but drops to 25 to 50 percent in two stratigraphically high orthoclase-rich samples.

Detrital phyllosilicates comprise about 5 percent of the framework of most samples, but a few laminated very fine-grained sandstones contain three times this amount. The ratio of biotite to muscovite is variable, even within a single bed, and may depend upon local hydrodynamic conditions. Altered unidentifiable phyllosilicate grains are ubiquitous. If most of these represent the less stable biotite, it then exceeds muscovite in every slide. Minor detrital chlorite is present in most samples. Heavy minerals most regularly noted in thin sections were zircon, pyroxenes, and hornblende. Single grains of almandine, apatite, and pleonaste (green spinel) were observed.

Rock fragments make up from 3 to 19 percent of the framework of

Figure 16a Figure 16c Figure 16b

○ : Chambers Creek beds
 △ : Ohanapecosh Formation

Figure 16d

Figure 16. Composition of sandstones of the Chambers Creek beds and Ohanapecosh Formation, Johnson Creek - Chambers Creek area; components identified on page 61.

1 mm

Figure 17. Photomicrograph of a typical medium- to fine-grained arkosic sandstone from the Chambers Creek beds; plane polarized light. Sample is composed of subangular to angular quartz (clear, fractured grains), orthoclase (yellow stain), micas, and altered plagioclase feldspar (cloudy gray grains) and lithic fragments (brown to opaque). Sparry calcite cement (gray) fills pore-space and locally impinges upon grains, resulting in their highly angular appearance. (Sample JC-400U.)

the Chambers Creek sandstones. Metamorphic rock fragments of quartz and mica comprise 1 to 2 percent of the framework of the samples examined. Granitic rock fragments are rare, due to the relatively fine grain size of the samples. Distinctive grains of micrographic granite were noted in two slides. Sedimentary rock fragments include quartzose sandy mudstone, nondescript dark muddy grains, and outsized laminated siltstone clasts. Volcanic rock fragments are completely absent in many samples, comprise up to 10 percent of some stratigraphically high arkoses but are rare in others. Dark unidentified lithic grains are present in all samples. These are probably altered volcanic, or argillaceous, rock fragments.

Authigenic minerals are abundant in nearly every slide, and are discussed in a separate section (Sandstone diagenesis). Detrital matrix is sparse. Carbonized plant material makes up less than 2 percent of the sandstones studied, but comprises a higher percentage in the overall stratigraphic column due to the abundance of carbonaceous very fine-grained sandstone, siltstone, and mudstone.

SEDIMENTARY PETROLOGY - OHANAPECOSH FORMATION

In the map area, the Ohanapecosh Formation is composed of medium- to very coarse-grained volcanic arenite, volcanic siltstone and mudstone, lapilli-tuff, tuff, conglomerate, and diamictite. The nomenclature used for these rocks is given in Chapter III.

Rudites

Coarse-grained volcanoclastic rocks in the map area readily fall into two groups: orthoconglomerate and diamictite. Orthoconglomerate is

generally composed of subrounded to subangular andesite pebbles with a variable, lesser quantity of subrounded chert and vein quartz. Most clasts rest with their long axis parallel to bedding, but many lie normal to bedding; imbrication is rare. Most beds are between a half meter and a meter in thickness. Volcanic diamictite forms impressive 3 to 23 meter thick beds that are interpreted as lahars. These are described in detail in Chapter III (lithofacies Q).

Mudrocks

Volcanic mudstone and siltstone of the Ohanapecosh Formation is olive gray to dark gray, and is generally massive except for millimeter- to decimeter-scale graded to massive intercalations of sand-sized crystals, volcanic rock fragments, and pumice. Some of these interbeds show delicate deformational features along their soles, including load structures and ball-and-pillow structures. A ~170 meter thick mud-and-silt-dominated stratigraphic sequence (Middle Fork measured section, Figure 14) is described in detail in Chapter III (lithofacies R).

Volcanic Sandstones

Volcanic arenite of the Ohanapecosh Formation is dark olive gray to olive brown, well to moderately sorted, and composed almost entirely of plagioclase feldspar and volcanic rock fragments (Figure 18). These rocks are most commonly medium- to very coarse-grained, and comprise 0.2 to 4.0 meter thick cross bedded, graded, and massive beds. Wave and current ripples are locally prominent. Coarser-grained volcanic arenite is usually pebbly, with rounded granules to small pebbles of andesite, chert, vein quartz, and felsite(?). Volcanic arenite makes

1 mm

Figure 18. Photomicrograph of a poorly sorted volcanic arenite from the Ohanapecosh Formation; plane polarized light. Coarse-grained pilotaxitic to microgranular andesitic volcanic rock fragments are surrounded by fine- to medium-grained plagioclase feldspar and quartz. Irregular, clear areas are holes in the section. (Sample MCR-187W.)

up most of lithofacies P (Chapter III), and also forms massive to graded intercalations with the volcanic mudrocks of lithofacies R.

About twenty five samples of fine- to coarse-grained volcanic arenite were collected for study (Plate II, back pocket). Fourteen lithologically typical, stratigraphically representative samples were selected for thin section study; the five least altered of these were point counted. These five samples appeared to represent the observed range of compositions.

Approximately 450 points were counted on each slide, using evenly spaced lines and an automatic point counter. Grains were assigned to 23 categories (Appendix A). Lithic grains were classified according to conventions outlined on page 51. The Ohanapecosh sandstones were not stained for potassium feldspar, so as not to mask the very abundant lithic grains.

Point count data for these five volcanic sandstones is given in Appendix A, and summarized in Figure 16. These rocks are composed of subrounded microlitic to microgranular volcanic rock fragments (19-60%), subangular to angular feldspar (17-57%), and sparse quartz, chert, phyllosilicates, and non-volcanic rock fragments. The chert count may include a few microgranular felsic rock fragments.

Twinning allows nearly all of the feldspar to be identified as plagioclase, but some orthoclase was undoubtedly missed due to the absence of stain. Most of the plagioclase grains are medium-sand sized broken euhedra, and probably represent relatively unabraded cleavage fragments and tephra. These grains are predictably most abundant in medium- to fine-grained volcanic sandstone; coarser samples are more

lithic.

Volcanic rock fragments display a pilotaxitic, felty or microgranular texture with occasional large plagioclase and augite phenocrysts. Plagioclase in lithic fragments (phenocrysts and microlites), and framework plagioclase were checked for anorthite content in the course of point counting. Twenty determinations were made, using the Michel-Levy method. The distribution of data suggests a bimodal plagioclase population, clustered around An_{20} (oligoclase), and An_{40} (andesine). In addition, three samples of pebbly very coarse-grained volcanic sandstone to pebble conglomerate were examined in thin section. The most common pebble types, in decreasing abundance, were pilotaxitic andesite, microgranular andesite, and felty-textured andesite. These observations, and the cited anorthite contents, indicate an andesitic provenance for sandstones of the Ohanapecosh Formation in the field area.

COMPARATIVE MINERALOGY OF THE CHAMBERS CREEK BEDS AND CORRELATIVE ARKOSIC SANDSTONE UNITS

Systematic mineralogic comparison of sandstone units has been shown to be a very useful technique in basin analysis (e.g. Graham and others, 1976). In order to better understand the provenance and depositional setting of the Chambers Creek beds, I compared detailed published modal data from the correlative middle to upper Eocene Roslyn, Chumstick, and Renton Formations (Figure 19) and the Eocene to lower Oligocene(?) Naches Formation of Washington (Frizzell, 1979a), and the middle to upper Eocene Cowlitz and Spencer Formations of northwest Oregon (Jackson, 1983; Al-Azzaby, 1980). Limited modal data was obtained for the middle to

Figure 19. Outcrop area of middle to late Eocene arkosic sandstone units referred to in text: CC, Chambers Creek beds; COW, Cowlitz Formation; CH, Chumstick Formation; NA, Naches Formation; RN, Renton Formation; RO, Roslyn Formation; S, Spiketon Formation; SK, Skookumchuck Formation; SP, Spencer Formation. Reference points: B, Bellingham; E, Eugene; O, Olympia; S, Seattle; Y, Yakima. Outcrop area of lower Tertiary rocks is stippled. May include some younger units in coastal areas.

upper Eocene Spiketon and Skookumchuck Formations of western Washington (Buckovic, 1974; and unpublished reports). The time-correlation of these units is shown in Figure 33 (p. 96).

Mean values were calculated for each formation for each of the following grain types:

Qm: monocrystalline quartz

Qp: polycrystalline quartz plus chert

Q: total quartz (Qm + Qp)

P: plagioclase feldspar

K: potassium feldspar

F: total feldspar (P + K)

Lv: volcanic plus metavolcanic rock fragments

Ls: sedimentary plus metasedimentary rock fragments

Lu: unidentified rock fragments*

L: Lv + Ls

Lt: Lv + Ls + Qp

Dickinson (1970) and Dickinson and Suczek (1979) suggest that these parameters may be combined to form ratios that can highlight subtle differences in provenance. These authors' ternary and secondary ratios (Figures 20 and 21) are used to compare and contrast the composition of the Chambers Creek beds with correlative arkosic sandstone units. Table III lists mean values for the grain types given above. These data are evaluated in terms of provenance in Chapter X.

* Lu is included in calculation of QFL and QmFLt, but is not included in calculation of Lv/L.

Figure 20. Composition of the Chambers Creek beds and correlative arkosic sandstone units; CC, Chambers Creek beds; COW, Cowlitz Formation; CH, Chumstick Formation; NA, Naches Formation; RN, Renton Formation; RO, Roslyn Formation; S, Spiketon Formation; SK, Skookumchuck Formation; SP, Spencer Formation; components identified on page 61.

Figure 21. Ratio of polycrystalline quartz to total quartz (Qp/Q), plagioclase to total feldspar (P/F), and volcanic lithic fragments to total lithic fragments (Lv/L) for Chambers Creek beds and correlative arkosic sandstone units, identified on preceding figure. Bars show 80% confidence interval for data. Data and references given in Table III, page following.

TABLE III

MEAN COMPOSITION OF CORRELATIVE MIDDLE TO LATE EOCENE ARKOSIC SANDSTONE UNITS

unit	n	Qm	Qp	pc	kf	Lv	Ls	Lu	reference	remarks
Spencer Fm.	12	30+16	5+2	35+11	22+11	6+6	<1	1+1	Al-Azzaby, 1980	upper member
Cowlitz Fm.	10	36+6	2+2	31+6	25+4	3+3	2+2	1+1	Jackson, 1983	
Skookumchuck	10	Q = 37+11	19+8	13+7	24+21				unpub. data	
Chambers Crk.	14	55+7	4+3	17+7	12+7	1+3	5+3	6+3	this report	excludes KTR-102
Renton Fm.	6	30+5	13+6	29+13	15+8	9+8	3+4		Frizzell, 1979a	
Naches Fm.	16	33+11	15+12	42+8	3+5	5+5	2+1		"	excludes 2 samples (Frizzell, p.51)
Roslyn Fm.	15	30+8	18+12	36+12	7+5	7+5	3+3		"	
Chumstick Fm.	40	27+10	14+13	40+15	8+6	11+21	1+1		"	

Stated range is 80% confidence interval, assuming t (small sample) distribution.

A comparison of QFL ratios for correlative arkosic sandstone units (Figure 20a) reveals a generally low content of lithic fragments, and a variable ratio of quartz to feldspar. The most evident differences here are the more quartzose nature of the Chambers Creek beds and Spiketon Formation ($Q \sim 60$), the relatively feldspathic nature of the Cowlitz and Spencer Formations ($Q \sim 40$)*, and the high lithic count of the Skookumchuck Formation. All are classified as arkose or lithic arkose (Folk, 1974).

Ratios sensitive to the type of quartz, feldspar, and lithic fragments present (Figure 21) highlight the differences between the Chambers Creek beds and correlative units. The ratio of polycrystalline quartz to total quartz is significantly lower in the Chambers Creek beds, Cowlitz and Spencer Formations than in the other units. This difference is due both to the unusually high content of monocrystalline quartz in the Chambers Creek beds ($Q_m \sim 55$), and the fact that the more northerly Chumstick, Naches, Renton, and Roslyn Formations have three times as much polycrystalline quartz as do the more southerly Cowlitz, Spencer, and Chambers Creek units (Table III). Frizzell suggests a possible overestimation of polycrystalline relative to monocrystalline quartz (1979a, p. 79) but this would only account for a small part of this difference.

The relatively low ratio of plagioclase feldspar to total feldspar (P/F) in the Chambers Creek beds is shared by the Cowlitz, Spencer, Skookumchuck, and possibly the Renton Formation. The Cowlitz and Spencer,

* However, Van Atta (written comm., 1983) reports that the Cowlitz Formation in Columbia County, north of Jackson's study area, is notably less feldspathic ($F < Q$).

however, are notably more feldspathic than the Chambers Creek beds (Figure 20a), and exceed this unit in the percentage of both feldspars (Table III).

The virtual absence of volcanic rock fragments in the typical Chambers Creek sandstone sets it well apart from the other units shown (Lv/L ratio, Figure 21). If many unidentifiable rock fragments (Lu, Table III) are volcanic, this count is too low.

Low percentages of plagioclase feldspar and polycrystalline quartz in the Chambers Creek beds correspond to regional trends, discussed below. The low count of volcanic rock fragments is unique, and results either from failure to identify many volcanic grains, or relative isolation of the Chambers Creek beds from active Eocene volcanic centers. The slightly elevated Ls count could indicate a minor sediment contribution from the Jurassic Russell Ranch Formation, presently exposed about 15 km to the east-northeast (directly "up current", Chapter VII).

A regional comparison suggests that middle to upper Eocene arkosic sandstones of south-central and southwest Washington and northwest Oregon fall into two compositionally distinct, geographically separated groups. The Chumstick, Roslyn, and Naches Formations of south-central Washington (Figure 19) contain a significant amount of coarsely polycrystalline quartz ($Qp/Q \sim 0.30$), and are relatively low in potassium feldspar ($P/F \sim 0.85$). By comparison, arkoses of the more southerly Chambers Creek beds and Skookumchuck Formations (southwest Washington), and of the Cowlitz and Spencer Formations (northwest Oregon), all contain very little polycrystalline quartz ($Qp/Q \sim 0.05$), but notable amounts of potassium feldspar ($P/F \sim 0.60$). The Renton Formation, located between these

two groups, contains elevated amounts of both polycrystalline quartz and K-feldspar. The significance of these trends is discussed in Chapter X.

DIAGENESIS

A diagenetic study was not one of the intended products of this project. However, for completeness, I include the following: 1) my own pedestrian observations made in the course of thin section study, 2) diagenesis and maturation data generously released by Amoco for several samples I provided.

Sandstone Diagenesis

The most common interstitial authigenic minerals I observed in thin section were high birefringence clay minerals, sparry calcite, chlorite, and zeolites. Illite, chlorite, and mixed layer illite/smectite were the most abundant clay minerals that Amoco identified by x-ray.

I observed a strong negative correlation between sparry, poikilotopic calcite cement and compaction in the Chambers Creek arkosic sandstones. Clay and zeolite cemented arkosic sandstones usually showed evidence of extreme compaction, including folded and crinkled mica, fractured feldspar, and fractured to shattered quartz. By comparison, arkoses cemented with sparry calcite did not show grain fracturing, and showed only slight deformation of micas. This is evidence, I believe, for localized calcite cementation prior to deep burial. However, poikilotopic calcite locally fills fractures in some grains, perhaps indicating that some of the calcite did not assume its present crystallographic form until after burial.

Most thin sections show evidence of replacement of framework grains

by secondary minerals. Jagged grain outlines surrounded by sparry calcite indicate local replacement of framework, and the absence of a silt fraction suggests replacement of detrital matrix. Small flakes of sericite replacing feldspars is a very common relationship. Hematite locally replaces biotite, especially adjacent to fractures, but the presence of many unaltered biotite grains suggests generally low post-burial permeability.

Five porosity values reported by Amoco range from 5.5 to 14.1 percent, permeability ranges from 1.4 to 7.6 mD. These very low values are probably representative, and are due to extreme compaction, and abundant secondary minerals. Most porosity is secondary, resulting from partial or complete dissolution of framework grains, and by fracturing.

Maturation

Thermal maturity of the rocks in the study area was assessed by vitrinite reflectance of four coal samples from the Chambers Creek beds. Average values ranged from 1.35 to 2.49 %RO with a mean of 1.94 %RO.

Solid organic matter trapped in sediments undergoes biochemical diagenetic changes, followed by progressive chemical and physical changes (catagenesis) as it is subject to geothermal heat following burial (Bostick, 1979). The extent of catagenesis is a function of both temperature and time, but can be assessed directly by several laboratory techniques, including measuring the reflectance of polished surfaces of vitrinite, the major constituent of most coals.

The relationship between vitrinite reflectance values (%RO), and paleotemperature will differ for each basin, depending upon burial and heat flow conditions. However, since oil and gas are generated within

a fairly narrow range of reflectance values, the technique is useful for basin evaluation. The mean of reflectance values reported for the Chambers Creek beds is well above the range of values considered favorable for oil and gas generation; therefore, these rocks are "overmature". Late catagenic methane would be the only hydrocarbon capable of being generated at this point (Bostick, 1979, Table 3).

What was the heat source for this thermal metamorphism? The most apparent source would be the abundant basaltic to andesitic sills intruding the section. Most of these are 3 to 6 meters thick, and they locally make up 10 to 20 percent of the section. However, Bostick (1979, Figure 21) compiles data which indicates that the thermal effects of dikes and sills only extend into enclosing sediments for a distance equal to about 60% of the thickness of the intrusion.

Walsh and Phillips (1983) demonstrate that coal rank (as determined from fixed carbon and BTU values) in Eocene rocks on the western and eastern flanks of the Washington Cascade Range bears little relation to stratigraphic position or structural trends, but instead shows a systematic increase toward the axis of the mountains. They propose that catagenesis in these rocks bears little relation to burial depth or structural control, but depends on proximity to a region-wide thermal aureole created by Eocene to Miocene plutonism associated with Cascade volcanism.

Reflectance values from four coal samples from the Chambers Creek beds are fairly uniform, and the lowest value is from the stratigraphically lowest sample, the reverse of what would be expected if there was a direct relationship between paleotemperature and burial depth. Based upon this limited data, it would appear that the rocks of the Johnson

Creek - Chambers Creek area were affected by an area-wide thermal episode.

CHAPTER V

PETROLOGY OF INTRUSIVE ROCKS

The stratigraphic sequence in the Johnson Creek - Chambers Creek area is intruded by a large volume of greenish-gray to grayish-black, phyric to aphyric, dense to sparsely vesicular basalt, basaltic andesite, andesite, and diorite. Petrographic and geochemical data are summarized here; structural relations are described in Chapter IX.

Most intrusions in the field area are tabular, sheet-like sills. Initially, it was believed that many of these features were lava flows, hence the detailed data collection. As these features are now known to post-date deposition of the stratigraphic sequence, the following discussion is incidental to sedimentologic considerations, but is included as a part of the first study of the stratigraphy of this area. Readers of sedimentary persuasion are urged to skip ahead to Chapter VII.

Composition and Mineralogy

Twenty whole-rock samples were analyzed for eleven major oxides by x-ray fluorescence (XRF) by Dr. Peter Hooper and associates at Washington State University. These analyses are reported in Table IV; sample localities are shown on Plate II (back pocket). A comparison of petrographic characteristics with chemical data reveals that two distinct types of intrusions are present.

Phyric basalt forms sills and less common dikes throughout the map area. Seven analyzed samples ranged from about 48.5 to about 50.5 per-

TABLE IV

WHOLE ROCK CHEMICAL ANALYSES, JOHNSON CREEK - CHAMBERS CREEK AREA

<u>Intrusive Rocks</u>	<u>SiO₂</u>	<u>Al₂O₃</u>	<u>TiO₂</u>	<u>Fe₂O₃</u>	<u>FeO</u>	<u>MnO</u>	<u>CaO</u>	<u>MgO</u>	<u>K₂O</u>	<u>Na₂O</u>	<u>P₂O₅</u>	<u>total</u>
BT10	63.30	15.12	0.72	4.46	5.11	0.20	4.99	0.62	1.29	3.94	0.25	100.00
BT15	63.13	15.02	0.72	4.57	5.24	0.21	4.66	0.62	0.76	4.63	0.23	99.99
DCR102	48.55	22.69	0.90	4.37	5.00	0.17	10.36	3.62	1.00	3.23	0.12	100.01
EMM109	49.26	22.66	1.12	4.43	5.08	0.19	10.67	3.42	0.05	2.99	0.13	100.00
EMM114	50.27	19.47	1.21	5.56	6.37	0.20	9.78	4.06	0.05	2.91	0.14	100.02
EMM147	55.83	17.29	1.25	4.04	4.63	0.14	8.05	4.05	0.88	3.63	0.21	100.00
HG100	54.90	17.29	1.83	4.67	5.35	0.16	7.74	3.29	0.87	3.57	0.33	100.00
HG130	51.40	15.73	1.86	6.21	7.12	0.25	9.80	4.61	0.05	2.77	0.20	100.00
JC203	51.18	17.61	1.48	4.33	4.96	0.22	10.34	6.69	0.02	2.95	0.22	100.00
JC251	55.13	16.38	1.58	5.24	6.01	0.20	7.41	3.07	1.30	3.30	0.37	99.99
JC4002	49.78	22.64	0.85	3.84	4.40	0.13	11.63	3.80	0.04	2.79	0.09	99.99
JOR104	63.66	15.34	0.70	4.25	4.86	0.20	5.37	0.54	1.03	3.81	0.22	100.00
KTR309	51.31	18.10	1.54	4.81	5.51	0.17	8.80	5.12	0.89	3.54	0.22	100.01
KTR404	52.87	19.67	1.35	4.45	5.10	0.15	8.42	3.11	1.01	3.66	0.20	99.99
KTT8	48.87	23.48	0.74	3.77	4.32	0.13	11.17	3.98	0.21	3.26	0.08	100.01
MCR191	56.12	16.66	1.51	4.95	5.67	0.20	5.95	2.82	1.56	4.19	0.38	100.01
MFJ011	49.52	22.16	0.98	4.37	5.01	0.17	10.09	4.28	0.26	3.11	0.12	99.98
MFJ4012	62.17	14.86	1.29	5.05	5.78	0.20	4.25	1.54	0.34	4.34	0.19	100.01
MFJ417	58.43	15.13	1.28	5.82	6.67	0.23	5.62	1.25	1.44	3.59	0.54	100.00
MWR104	49.88	19.71	1.25	5.04	5.77	0.18	10.82	4.34	0.05	2.82	0.15	100.01

High Cascade
Rocks

HG104	60.13	17.42	0.97	3.04	3.48	0.10	5.87	3.27	1.53	3.90	0.28	99.99
JOR102	67.11	15.87	0.66	2.03	2.33	0.07	3.56	1.53	2.82	3.87	0.14	99.99

cent silica. These rocks have a medium-gray to grayish-black groundmass with 25 to 70 percent plagioclase phenocrysts, and were identified in the field as phyrlic basalt and andesite. Five of the analyzed samples were examined in thin section, and are composed of An_{44} to An_{70} phenocrysts in a groundmass of 40 to 75 percent plagioclase (An_{36-59}), sparse to 25 percent granular to ophitic augite, sparse to 30 percent magnetite, and locally abundant fine-grained alteration minerals.

Several small stocks, and numerous sills and dikes of aphyric andesite crop out along the crest of the Johnson Creek anticline (Plate I, back pocket). Five analyzed samples ranged from about 58.5 to 63.5 percent silica, and showed an unusually low concentration of MgO (0.54 to 1.54 percent). These rocks have color indices similar to the more mafic group, and were identified in the field as basalt and andesite. In thin section, these five samples were found to be composed of 75 to 80 percent slightly pilotaxitic andesine (An_{39-44}), sparse augite and magnetite and rare hypersthene and quartz. Two samples were glomeroporphyritic. This second, andesitic chemical group is therefore less phyrlic, more pilotaxitic, and has a higher plagioclase/pyroxene ratio than the basalts.

Field names referred to here highlight the lack of correspondence between color index and silica content. Medium-gray to greenish-gray intrusions were found in thin section to be substantially more altered than dark gray rocks. Abundant fine-grained secondary minerals and hematite(?) replacing magnetite are responsible for the lighter hues.

Eight analyzed samples are chemically and petrographically intermediate between the two groups. These range from 51 to 56 percent SiO_2

(basalt to basaltic andesite), and were identified in the field as aphyric to phyrlic basalt and andesite, and diorite. Thin sections of five samples revealed 10 to 60 percent labradorite (An_{55-64}) and rare augite phenocrysts in a groundmass of 50 to 80 percent plagioclase (An_{47-52}), about 5 to 25 percent augite granules, and about 5 to 10 percent magnetite.

The cited relationship between field occurrence, mineralogy, texture, and silica content does not in itself establish a cogenetic relationship for intrusions of a particular group. Additional chemical study, particularly trace element geochemistry, is required for petrogenetic inferences to be made. However, the unusually low MgO concentration in the five most silicic intrusions, and their apparent geographic restriction, suggests these may represent a cogenetic group.

No statement can be made about a genetic relationship between the more mafic and the more silicic groups of intrusions. Variation diagrams (Figure 22) show a large amount of scatter, probably due in part to the mobility of major elements (Garcia, 1978) during a region-wide low-grade metamorphic episode (Fiske, 1963, and Walsh and Phillips, 1983). Additional scatter is due to the analysis of phyrlic samples (circled), which appear to show enrichment in Al and dilution of Mg concentration by included calcic plagioclase phenocrysts.

Petrologic Type

The Western Cascade Group of the southern Washington and Oregon Cascade Ranges is divisible into two broad stratigraphic intervals. The lower Western Cascade Group of Washington (Hammond, 1980), and volcanic rocks of the early Western Cascade episode of Oregon (Priest and others,

Figure 22. Variation diagrams of major oxides versus silica, analyzed intrusive rocks. Numbers by data points are abbreviated sample numbers from Table IV. Circled areas show clustered data from pyritic samples.

1983) consist of generally andesitic lahars, ignimbrites, lava flows, and volcanic sediments, with distinctive, iron-rich, mostly basaltic andesite lavas in its upper portion. Early Western Cascade rocks show generally calc-alkaline major element chemistries, but the basaltic andesite lavas are tholeiitic.

A shift to more silicic magmatism about 17 to 20 million years ago is reflected by the generally andesitic to dacitic-rhyodacitic lavas and volcanoclastic rocks of the middle and upper Western Cascade Groups in Washington, and the volcanic rocks of the late Western Cascade episode in Oregon. Basalt and basaltic andesite are also present, but rarely match the composition of the iron-rich tholeiites of the early Western Cascade episode (Priest and others, 1983, p. 11). Rocks of the late Western Cascade episode are therefore almost exclusively calc-alkaline.

Field relations and major oxide geochemistry (Figures 23 and 24) suggest that analyzed basalt to basaltic andesite intrusions in the Johnson Creek - Chambers Creek area may be related to lower Western Cascade Group tholeiitic volcanism. Comparisons of AFM and $(\text{FeO}^*/\text{MgO})/\text{SiO}_2$ ratios (Figures 23 and 24) for published analyses of Western Cascade Group rocks reveal the contrast between calc-alkaline upper Western Cascade Group rocks, and analyzed tholeiitic samples from the lower Western Cascade Group. Samples from the field area correspond closely to the latter group, except for the five low MgO andesitic samples shown, which form a field of their own.

Structural relations (see p. 105), and the presence of an aphanitic groundmass in all examined intrusions, suggest that intrusive bodies in the Johnson Creek - Chambers Creek area were emplaced at relatively shal-

Figure 23. AFM diagram for analyzed intrusive rocks, Johnson Creek - Chambers Creek area. Closed triangles: aphyric, low MgO andesite; open triangles: phyric to aphyric basalt to andesite. Diagram from Irvine and Baragar, 1971.

Figure 24. Plot of FeO^*/MgO versus silica, analyzed intrusive rocks, Johnson Creek - Chambers Creek area. Closed triangles: aphyric, low MgO andesite; open triangles: phyric to aphyric basalt to andesite. Diagram after Miyashiro, 1974.

low depths. I suggest that these hypabyssal intrusions (except for the low MgO rocks) may have been related to tholeiitic volcanism in the latter part of the early Western Cascade volcanic episode.

Low magnesium andesitic intrusions in the field area form a distinct textural, mineralogic, and chemical group. Intrusions of this type only crop out near the crest of the Johnson Creek anticline, and a dike of this intrusive type cross-cuts the Middle Fork reverse fault (Plate I). These factors suggest that these intrusions were emplaced following deformation of the Chambers Creek/lower Ohanapecosh sequence, perhaps considerably after the early Western Cascade volcanic episode.

CHAPTER VI

PETROLOGY OF HIGH CASCADE ROCKS

Plio-Pleistocene High Cascade pyroxene andesite lava flows locally lap over the Paleogene strata along the eastern edge of the map area. Vent locations, flow directions, and the areal extent of these flows are shown by Swanson and Clayton (1983). These units are easily recognized by their fresh, unaltered appearance, purplish-gray color, and distinctive 2 to 10 cm, subrounded to angular, sugary-textured cognate inclusions.

A columnar-jointed hornblende-pyroxene dacite porphyry forms a prominent flat-topped mesa north of Jordan Creek. D.A Swanson (pers. comm., 1982) interprets this feature as an erosionally isolated intracanyon flow.

Composition and Mineralogy

A sample of pyroxene andesite and one of dacite porphyry were analyzed by x-ray fluorescence. These analyses are included in Table IV (p. 72); sample localities are given on Plate II (in back pocket).

In thin section, the analyzed pyroxene andesite (sample HG-104) consists of ~85% pilotaxitic calcic andesine microlites ($\sim \text{An}_{49}$), and scattered small (~ 0.3 mm) augite granules and hypersthene euhedra. About ten percent of the volume is made up of ~2 mm glomeroporphyritic clots of andesine, augite, magnetite, and opaque secondary minerals. The analyzed dacite porphyry (sample JOR-102) is seriate porphyritic, hyalopilitic, and is composed of ~40% andesine ($\sim \text{An}_{38}$), ranging from ~3 mm

rounded to embayed oscillatory-zoned megacrysts to ~ 0.3 mm euhedral microlites, $\sim 7\%$ subhedral to euhedral hypersthene microphenocrysts (~ 0.5 mm average), and scattered very small augite and magnetite granules and pigeonite euhedra in a glassy groundmass. A few altered megacrysts of oxyhornblende(?) and augite are present, along with many small (~ 1 mm), and a few large (~ 5 mm) cognate inclusions of plagioclase microlites, altered hornblende(?) and brown glass.

Petrologic Type

Pliocene to Holocene High Cascades volcanism has been characterized by voluminous outpourings of tholeiitic olivine basalt and basaltic andesite, and eruption of lesser volumes of generally calc-alkaline andesite and dacite. Chemical analyses of an andesitic suite from Mt. Hood published by Wise (1969) were used by Irvine and Baragar (Figure 2, 1971) to help define the compositional range of AFM values characteristic of calc-alkaline rocks. The two analyzed High Cascade samples from the field area lie within the range of Mt. Hood values shown on Figure 25. Similarly, Miyashiro (1974) defined calc-alkaline and tholeiitic fields for $(\text{FeO}^*/\text{MgO})/\text{SiO}_2$ ratios by comparing suites of known affinity. The analyzed samples fall well within the calc-alkaline field on this type of plot (Figure 26). Field and chemical evidence therefore indicate that these are undeformed, unaltered, calc-alkaline, andesitic-dacitic High Cascade rocks.

Figure 25. AFM diagram for analyzed High Cascade rocks, Johnson Creek - Chambers Creek area. Diagram from Irvine and Baragar, 1971.

Figure 26. Plot of FeO*/MgO versus silica, analyzed High Cascade rocks, Johnson Creek - Chambers Creek area. Diagram after Miyashiro, 1974.

CHAPTER VII

PALEOCURRENTS

CHAPTER SUMMARY

Cross bedding and current ripples in the Chambers Creek beds and Ohanapecosh Formation in the Johnson Creek - Chambers Creek area indicate generally westward to southwestward paleoflow. Lineations in these two units are roughly parallel, indicating that, in this vicinity, no major change in paleodrainage direction accompanied the volcanism responsible for the Ohanapecosh lithologies.

Symmetrical ripples in the two units are generally oriented normal to this paleoflow pattern. Paleocurrent lineations show no consistent variation along depositional strike. In addition, there appears to be no relation between lineations and present day structure, suggesting the Johnson Creek anticline was not active during deposition of the rocks in the field area.

METHODS

The orientations of primary sedimentary structures were recorded to allow paleocurrents to be inferred. Data was recorded for features whose orientation could be estimated within $\pm 5^\circ$. Either the apparent bearing of the feature, or its rake, was recorded, along with local strike and dip.

Tectonic dip in the study area generally exceeds 25° , so tilt

corrections were applied to all field data with a standard equal area net. Southeast of the latitude of Butte Top Quarry (BT in Figure 32, p. 92), the Johnson Creek anticline forms a broad dome, with plunge not exceeding 15° . A single rotation of bedding about strike was sufficient to restore lineations in this area to within three degrees of their original bearing (Potter and Pettijohn, 1977, p. 374). To the northwest of Butte Top, the axial pitch steepens to 20° to 30° . Lineations in this area therefore required a two-fold rotation: first, rotation of bedding about the fold axis, then, rotation of bedding to horizontal through the plunge angle (Ragan, 1973, p. 100-101).

The distribution of corrected bearings is shown in a series of rose diagrams (Figures 27 through 30). Vector means were calculated from the ungrouped data by the following equation, given by Pincus (1956, p. 536):

$$\tan \bar{\alpha} = \frac{\sum_{i=1}^n \sin \alpha_i}{\sum_{i=1}^n \cos \alpha_i} \quad (\alpha = 1, 2, \dots, n)$$

where α = bearing
 $\bar{\alpha}$ = vector mean

In practice, the vector and arithmetic means differed by only one to two degrees for the data presented here. The arithmetic standard deviation is reported.

The area of each class interval on the rose diagrams is proportional to the percentage of readings represented. The sample size should be kept in mind; isolated class intervals are generally due to only one or two readings.

Paleocurrent localities were assigned to either the Chambers Creek beds or Ohanapecosh Formation on the basis of stratigraphic position,

not lithology. Some Ohanapecosh paleocurrents were actually taken on meter-scale interbeds of arkosic sandstone. These are referred to in the following section.

DISCUSSION

Paleocurrent data from cross bedding and current ripples are shown together (Figure 27) due to their genetic relationship.

The vector mean and greatest class interval for the Chambers Creek beds are somewhat more southerly than the median value. This difference is because six of the seven readings in this class interval (210° - 240°) were taken on a single ~50 meter thick channel sandstone that shows a strongly unimodal current distribution (Road 21 measured section, Figure 9). This sampling bias was due to the relatively good exposure of this unit. Chambers Creek paleocurrents, therefore, show a generally west to southwesterly trend.

Cross bedding and current ripples in the Ohanapecosh Formation in the study area generally parallel those in the underlying Chambers Creek beds. The apparently non-Gaussian distribution is due to the small sample size. Three of the bearings shown are from three to five meter thick arkosic intercalations within the volcanoclastic Ohanapecosh sequence. As these bearings lie close to the mean value of the volcanic sandstones, it seems reasonable to group them. Several meters of well-exposed coarse volcanic sandstone at one station (MMR-107, Plate II) shows a nearly southerly trend; otherwise, westward trends predominate. The Ohanapecosh vector mean is slightly more westerly than that of the Chambers Creek beds. However, the data presented here are insufficient to argue

Figure 27a. Chambers Creek beds

Figure 27b. Ohanapecosh Fm.

Figure 27c. Combines both units

Figure 27. Orientation of cross bedding and current ripples, Johnson Creek - Chambers Creek area. Class interval equals 30 degrees.

for a shift in depositional patterns.

Channel axes (Figure 28) generally parallel cross bedding trends, while oriented small woody fragments (Figure 29) show scattered lineations.

Most symmetrical ripple sets in the two formations (Figure 30) lie in the second and fourth quadrants, generally perpendicular to the southwesterly trend of current lineations. Two well-exposed symmetrical sets in the Ohanapecosh Formation are an exception, and trend almost due east-west (Figure 31).

The symmetrical ripple mean in the study area indicates predominantly northeast-southwest oscillatory wave motion during the time of deposition of the mapped sequence. This may be due to the predominance of paleowind vectors in the northeast and/or southwest quadrants, or a northwest-southeast trending paleoshoreline, or both. The lack of evidence of marine influence suggests the data should only be interpreted as an indication of paleowind patterns.

Figure 32 shows the distribution of paleocurrent lineations in the field area. The data obtained show no consistent vertical or lateral variation. In addition, there does not seem to be a relationship between paleocurrent trends and the present day structure. There appears to be a parallelism between paleocurrent lineations and dip direction on the western limb of the Johnson Creek anticline. However, note that lineations on the northern "nose" of this structure, in the northwest portion of the map area, do not swing to the north, but closely follow the generally westerly trend. Lineation data from the poorly exposed eastern limb of the Johnson Creek structure is regrettably lacking, and

Fig. 28 Channel axes

Fig. 29 Oriented wood

Fig. 30a
Chambers Creek beds

Fig. 30b
Ohanapecosh Fm.

Fig. 30c
Combines both units

Figure 30. Orientation of symmetrical ripples. Class interval equals 20 degrees.

Figure 31. Relatively large-scale symmetrical ripples in Ohana-pecosh Formation medium-grained volcanic arenite, station EMM-200. Ripples are oriented east-west.

Figure 32. Distribution of paleocurrent lineations, Johnson Creek - Chambers Creek area. See following page for key.

Tpa	High Cascades pyroxene andesite
Thpd	High Cascades hornblende-pyroxene dacite
	angular unconformity
To	Ohanapecosh Formation
Tcc	Chambers Creek beds
BT	Butte Top quarry, referred to in text
	contact, located approximately (solid where observed)
	fault, located approximately (solid where observed)
	reverse fault, teeth on hanging wall
	lineation: possible fault
	0-30 degrees
	30-60 degrees
	60-90 degrees
	attitude inferred from air photo
	horizontal bedding, or nearly so
	direction of movement (cross-bedding, current ripples)
	line of movement: current <u>parallel</u> to symbol
(channel axes, oriented wood)
	line of movement: current <u>perpendicular</u> to symbol
(wave ripples)

Most paleocurrent symbols show outcrop means. Some symbols moved slightly to avoid overlap.

would more definitely establish the relationship between paleocurrents and structure.

The apparent lack of a consistent relationship between paleocurrent vectors and structure suggests the Johnson Creek anticline was not active at the time the rocks in the field area were being deposited. Additional evidence is discussed in Chapter IX.

CHAPTER VIII

AGE AND CORRELATION

CHAPTER SUMMARY

The mapped stratigraphic sequence in the field area, including the Chambers Creek beds and the lowermost ~700 meters of the Ohanapecosh Formation, most probably ranges in age from late middle Eocene to late upper Eocene. Age assignment is based upon the occurrence of a floral form near the base of the section that is restricted to the lower Puget Group (late? middle Eocene), and correlation of the base of the Ohanapecosh Formation with a region-wide onset of tuffaceous sedimentation that coincides with foraminiferal and molluscan stage boundaries. Palynologic and radiometric data from the field area are inconclusive.

AGE OF THE MAPPED SEQUENCE

The age of the sedimentary sequence in the Johnson Creek - Chambers Creek area is not very well constrained. A fission-track dated zircon separate from a vitric tuff layer ~600 meters below the top of the Chambers Creek beds (unit 8, Figure 4) yielded an apparent age of 35.9 ± 0.7 million years (m.y.) before present (see Appendix B). This is considerably younger than the faunally and radiometrically established middle to upper Eocene age for other units in the same stratigraphic position (Figure 33), and suggests that zircon in this sample has been thermally reset (J.A. Vance, pers. comm., 1983).

Figure 33. Chronostratigraphic correlation chart. Dashed vertical line between columns indicates lithostratigraphic equivalence; solid line indicates uncertain lithostratigraphic relationship. References for local columns are: 1, Al-Azzaby, 1980; 2, Armen-trout and others, 1983; 3, Buckovic, 1974; 4, Gard, 1968; 5, Mullineaux, 1970; 6, Rau, 1981; 7, Snavelly and others, 1958; 8, Tabor and others, 1984; 9, Vine, 1969; 10, Wells, 1981; 11, this report. Full citations are given in the bibliography.

The area-wide thermal episode (p. 69) probably responsible for fission-track annealing of zircon has also destroyed pollen that might have originally been present. Seven coal and mudstone samples examined by Kent Van Zandt of Amoco were barren due to heating past preservation temperatures. An eighth sample yielded a badly burnt and oxidized fungal spore assemblage "possibly characteristic of the Eocene", but containing no age-diagnostic forms (T. Hemler, written comm., 1984).

A floral collection examined by Dr. Stewart Lowther of the University of Puget Sound provides some age control. A tuffaceous mudstone bed in the stratigraphically lowest portion of the Chambers Creek beds (Station HG-121, Plate II) yielded a floral assemblage including the tree fern Cyathea inequilateralis (Hollick) Wolfe (Wolfe, 1977, p. 53). This form is restricted to the lower portion of the Puget Group in the Green River Gorge section (King County, Washington), where it ranges from Wolfe's Franklinian through lower Ravenian floral zones (Lowther, pers. comm., 1984). Wolfe (1981, p. 45) correlates this range with a late lower to late middle Eocene faunal age, but Turner and others (1983) report radiometric ages that suggest the lower part of the Green River Gorge section is no older than the latter two-thirds of the middle Eocene. On the basis of this identification, I suggest that the lowest exposed portion of the Chambers Creek beds is approximately late middle Eocene in age.

It is more difficult to assign an age to the upper portion of the mapped sequence. Dr. Lowther stated that the wide-ranging genera Platanus (sycamore), and Laurace (laurel) were present in several samples from the upper portion of the Chambers Creek beds, but these could

not be assigned to a species.

On the basis of stratigraphic position, I tentatively correlate the upper portion of the mapped sequence with the upper Puget Group and lower Ohanapecosh Formation in the western foothills of the Cascades (Pierce and King Counties, Washington, Figure 33). Gard (1968) and Buckovic (1974) describe the conformable contact of the Spiketon Formation with the base of the Ohanapecosh Formation in the Pierce County foothills. Similarities of lithology, stratification style, and paleocurrents indicate this sequence is lithostratigraphically equivalent to the upper portion of the sequence in the field area.

The lithostratigraphic boundary between arkosic and volcanic sediments exposed within the Spiketon/Ohanapecosh and Chambers Creek/Ohanapecosh sequences has been found to be generally time-synchronous on a regional scale. Throughout southwest Washington and northwest Oregon, a close correspondence has been found between the top of Rau's (1958) Bulimina schencki - Plectofrondicularia cf. P. jenkinsi benthic foraminiferal Zone, Mallory's Narizian/Refugian stage boundary, and the rock-stratigraphic boundary between arkosic and Ohanapecosh-derived volcanic sediments. In the marine stratigraphic sections shown on Figure 33 (Yamhill and Columbia Counties, Oregon, and south Willapa Hills and Centralia area, Washington), arkosic sequences with Narizian foraminiferal assemblages (Nestucca, Spencer, Cowlitz, and Skookumchuck Formations), and local volcanic highs that interfinger with Narizian-age sediments (Goble Volcanics), are conformably to locally disconformably overlain by tuffaceous siltstone and sandstone with Refugian foraminiferal and Galvinian molluscan assemblages. Volcanic rocks interbedded with

Narizian age strata have yielded consistent potassium-argon dates throughout the region, and indicate an age of about 39 m.y. for the Narizian/Refugian boundary (Armentrout, 1981, p. 140, annotation 5). Armentrout and others (1983) place both the Narizian/Refugian boundary, and the contact between arkosic and tuffaceous marine units, at about 40.5 m.y. Turner and others (1983) propose an absolute age of about 42 to 41 million years for the upper portion of the nonmarine, arkosic Puget Group.

Thus, throughout southwest Washington and northwest Oregon, deposition of marine and continental arkosic sediments was superceded by deposition of volcanic sediments about 42 to 39 million years ago. I suggest that the conformable contact between the Chambers Creek beds and the Ohanapecosh Formation in the Johnson Creek - Chambers Creek area corresponds to that time frame.

In conclusion, the mapped stratigraphic sequence in the Johnson Creek - Chambers Creek area is probably late middle Eocene to late upper Eocene in age, about 45 to 38 million years before present. The correlation of lower Tertiary nonmarine sequences (Naches River, Roslyn, and Leavenworth sections) in Figure 33 is based upon radiometric ages reported by Tabor and others (1984).

CHAPTER IX

STRUCTURAL GEOLOGY

CHAPTER SUMMARY

The northwest-trending Johnson Creek anticline (named here) is the dominant structural feature of the field area. This structure post-dates deposition of the mapped sequence. Two faults, and two inferred faults are shown on Figure 34. The fault plane of a northwest-trending high angle reverse fault (Middle Fork reverse fault, Plate I) and associated drag folding are well exposed in a road cut in the northwest portion of the map area. Near Windy Pass, a five meter wide broken zone is associated with a northeast-trending vertical fault. A northeast-trending lineation between Jordan and Lost Creeks is interpreted as a normal or vertical fault due to the apparent offset of the top of the Chambers Creek beds. A topographic lineament near Hugo Lake trending $\sim N22^{\circ}W$ may be a normal or vertical fault with about 240 meters of stratigraphic throw.

The sequence in the map area is intruded by a large volume of basaltic to andesitic sills, dikes, and stocks. Sills of phyrlic basalt are the most widespread, and are most commonly 3 to 6 meters thick. Planar contacts, and a lack of deformation of the enclosing sediments suggest passive response of the country rock to intrusion. Dikes were only noted in the northern portion of the map area, and intrude fractures along $\sim N55^{\circ}W$ to $\sim N25^{\circ}E$ trends. Small andesite stocks are prominent along

Figure 34. Geologic structure of the Johnson Creek - Chambers Creek area. Key on following page.

KEY TO STRUCTURE MAP

	High Cascades pyroxene andesite
	High Cascades hornblende-pyroxene dacite
	angular unconformity
	Ohanapecosh Fm.
	Chambers Creek beds
	stocks of diorite, andesite, and basalt
	contact, located approximately (solid where observed)
	fault, located approximately (solid where observed)
	reverse fault: teeth on hanging wall
	lineation: possible fault
	0-30 degrees
	30-60 degrees
	60-90 degrees
	attitude inferred from air photo
	horizontal bedding, or nearly so
	sill, with dip
	dike, with dip of joint
	vertical dike

abbreviations: BT: Butte Top Quarry, HL: Hugo Lake, JC: Jordan Creek, LC: Lost Creek, WP: Windy Pass.

the hinge line of the Johnson Creek anticline.

FOLDS

The dominant structural feature of the field area is a faulted, doubly plunging anticline, here named the Johnson Creek anticline. The hinge line of this fold lies in an area of low relief and poor exposure, and was located by study of air photos.

Pi plots of poles to bedding allowed the bearing and plunge of the fold axis to be estimated for three fault bounded areas. Bearings estimated by this method agreed well with those sketched in from air photos.

Dip angles in stratigraphically high intervals exposed along the fold limbs do not shallow, indicating that the Johnson Creek anticline was not an active structure at the time the rocks in the field area were being deposited. This is supported by the lack of a consistent relationship between paleocurrent vectors and structure (Chapter VII).

FAULTS

The northernmost fault shown in Figure 34 is a high angle reverse fault trending $\sim N48^{\circ}W$, and dipping $60^{\circ}E$, and is referred to here as the Middle Fork reverse fault. The fault plane is well exposed in a road cut on USFS Road 2140, about 0.7 miles (~ 1.1 km) beyond (NNW from) the bridge over Johnson Creek. The relative movement (northeast side up) is inferred from associated drag folding. The amount of throw on this fault cannot be determined due to poor constraint of contacts on the hanging wall. The parallelism of this fault to the trace of the Johnson Creek anticline suggests the two may be cogenetic.

Two small (~ 3 meter apparent offset) sub-horizontal thrust faults exposed on Deception Creek Road just northwest of the map area (station DCR-102, Plate II) are significant in that they cross-cut two dikes of phyrlic basalt (including analyzed sample DCR-102, Chapter V). By contrast, the Middle Fork reverse fault is cross-cut by a dike of low MgO andesite (analyzed sample MFJ-401 Z). The relative timing of faulting and intrusion is discussed in Chapter X.

The only other fault observed in outcrop is shown as the southernmost fault in Figure 34. This feature is exposed in a road cut on USFS Road 22 just south of Windy Pass, and consists of a zone about five meters wide of half meter-scale blocks in various orientations. The north edge of this zone is abrupt and vertical, so I believe this is a vertical fault. The fault plane appears to trend $\sim N44^{\circ}E$. Stratigraphic throw is less than 50 meters.

A lineation trending $N25^{\circ}E$ to $N30^{\circ}E$ shows up on high altitude air photos of the northeast portion of the map area. This is interpreted as a vertical or normal fault, southeast side down, due to the apparent offset of the top of the Chambers Creek beds in the area between Jordan and Lost Creeks. The throw is unknown, but a cross-section sketched across the fault (B-B', Plate I) suggests it may be about 90 meters.

A second lineation, trending $\sim N22^{\circ}W$, is shown bisecting the southern portion of the map area near Hugo Lake and is referred to here as the Hugo Lake lineation. This feature is prominent on the topographic map and on SLAR imagery, and is believed to be a normal or vertical fault, east side down, due to the apparent offset of the top of the Chambers Creek beds between the western and eastern limbs of the Johnson

Creek anticline. Stratigraphic throw may exceed 240 meters (see cross-section C-C', Plate I), but poor constraint of the Chambers Creek/Ohanapecosh contact on the eastern limb of the anticline makes this a rough estimate.

STRUCTURE OF INTRUSIVE ROCKS

Intrusive rocks of andesitic to basaltic composition are widespread in the map area. The mineralogy and chemistry of these rocks are discussed in Chapter V; a description of their structure is included here.

Figure 34 shows the distribution of some of the larger sills, stocks, and dikes in the map area. Sills are by far the most widespread, stocks crop out mostly in the axial area of the Johnson Creek anticline, and dikes were only prominently noted in the northernmost portion of the map area.

The sills range in thickness from about 1.5 meters to almost 12 meters; most noted were between 3 and 6 meters. Most are simple, with coarse interiors and chilled to vesicular margins, but some of the larger bodies show internal chilled zones and porphyritic to foliated porphyritic layers toward the margins which imply a more complex history. These multiple sills appear to be compositionally homogeneous; composite and differentiated sills were not noted.

Perhaps the most striking structural feature of these abundant sills is their lack of deformation of the enclosing sediments. Figure 35 shows a 6 meter thick diorite sill intruding mudstone. A distinctive 15 cm thick interbed of volcanic sandstone can be seen about 90 cm below the base of the sill. The parallelism of the sill to the volcanic sand-

Figure 35. Six meter thick diorite sill (Chambers Creek measured section, unit 33) intruding mudstone. Note the concordance of the sill, and its lack of deformation of the underlying rocks. Shovel (to left) rests on top of a 15 cm thick, undeformed, volcanic sandstone interbed.

stone, the planar nature of both the base of the sill and this interbed, and the absence of apophyses of diorite, all suggest passive response of the mudstone to intrusion. This type of field relation is associated with nearly every sill observed, and led me to initially believe that some of these tabular bodies were lava flows. However, the consistently smooth, unbrecciated, unweathered tops of these features indicate an intrusive origin. Passive response of country rock, and aphanitic groundmass indicate these sills were emplaced at relatively shallow (hypabyssal) depths.

Sills are more abundant than Figure 34 implies. In areas of low relief, such as the crest of Mission Ridge (Plate I) and the area west of Chambers Lake, they form the only outcrops. In well exposed areas, sills make up from ten to twenty percent of the thickness of the Chambers Creek beds; and a lesser percentage of the Ohanapecosh sequence.

Small stocks of andesite and phyric basalt are scattered throughout the map area. These range in outcrop area from about 0.02 km^2 to about 0.2 km^2 . Some of the smaller features may be dikes whose trend is obscure. The larger of these features crop out near the hinge line of the Johnson Creek anticline. The most accessible and best exposed stock is at Butte Top Quarry (BT on Figure 34; see Plate II for location). Here, a ~ 20 meter high vertical face exposes four jointed andesite sills separated by thin screens of interbedded arkose and mudstone. The screens disappear as they are traced north, and the cliff face is massive andesite. The sills are lithologically very similar, and an analyzed sill sample chemically matched the massive andesite, interpreted as a stock (samples BT-1S, sill, and BT-10, stock, Table IV, Chapter V). This

exposure represents sills radiating from an andesite stock. The relatively undeformed nature of the country rock is again notable; screens show gentle warping between sills, but their relatively uniform thickness and parallel stratification can be traced across the outcrop. A series of lithologically and chemically similar stocks (including analyzed sample JOR-104) form a ~ 1.2 km long zone trending $\sim N25^{\circ}E$ from Butte Top, apparently cross-cutting the Hugo Lake lineation (previous section). A greenish-gray rock that forms an arcuate intrusion southeast of Butte Top (Tib, Plate I) is texturally very similar to the rocks exposed at the quarry, but is chemically a basalt.

Dikes are relatively scarce in the field area. An andesite dike that is 21 meters wide where it intersects USFS Road 2100-017 (station MCR-191, Plate II), crops out for more than 600 meters along a $N30^{\circ}W$ trend. Farther north, a three meter thick altered andesite dike trending $\sim N55^{\circ}W$ $61^{\circ}S$ (station MFJ-401Z) cross-cuts the Middle Fork reverse fault (Plate I).

A $N8^{\circ}W$ trending 90 cm thick porphyritic basalt dike on the Middle Fork of Johnson Creek (station MJF-011), two northeast-trending ~ 125 cm thick porphyritic basalt dikes on Deception Creek Road (stations DCR-102, 103), and two $\sim N25^{\circ}E$ trending 25 and 90 cm thick andesite dikes on Angry Mountain Road all intrude sharp, subvertical joints in volcaniclastic country rock, without apophyses. The sharpness of these fractures suggests relatively passive response to intrusion.

CHAPTER X

CONCLUSIONS

ENVIRONMENTS OF DEPOSITION - CHAMBERS CREEK BEDS

Summary

Four lithofacies are recognized in the Chambers Creek beds. These are interrelated within a model of alluvial plain to delta plain sedimentation.

Ten to nineteen meter thick coarsening-upward sequences (lithofacies A,B intervals) represent infilling of interdistributary lakes or lagoons. An associated fine-grained facies (lithofacies C) represents thinly interlayered to flaser bedded sandstone and mudstone from these quiet water environments. Thick intervals of relatively coarse-grained, cross bedded lithic arkose (lithofacies D) represent sedimentation in and adjacent to fluvial or deltaic distributary channels.

Lithofacies A,B Intervals

Where well exposed, lithofacies A mudstone and lithofacies B very fine-grained arkose to lithic arkose frequently form 10 to 19 meter thick coarsening-upward intervals (Figure 6, p. 23). These lithofacies are interpreted in light of these coarsening-upward intervals, as this allows a more specific environmental reconstruction to be made.

Lithofacies A,B coarsening-upward intervals represent probable nonmarine regressive sequences (Chapter III). Thick channel sandstones

(lithofacies D) are found intercalated with, and laterally adjacent to, these A,B intervals. This suggests that lithofacies A,B regressive intervals represent shoaling in lakes or lagoons adjacent to large distributaries.

Coleman and Prior (1982, p. 147) describe modern regressive lake fill sequences from fresh water interdistributary lakes in the upper delta plain. These lakes are usually shallow (less than 15 meters), and are characterized by quiet water deposition, reducing conditions, and abundant burrowing organisms. Compaction and subsidence enlarge and deepen these lakes, unless infilled by a diverted distributary. This produces a progradational "lacustrine delta-fill deposit" (Figure 36) consisting of dark gray to black, commonly intensely bioturbated organic-rich clay, grading upward into laminated silt and clay, small-ripple bedded fine sandstone, and coarser sandstone with large-scale cross beds. Note that sequences lateral to the depositional axis (logs 2, 4, and 5 in Figure 36) coarsen upward, but like lithofacies A,B intervals (Figure 6) are mud dominated, and are not overlain by a coarse-grained sandstone member. This suggests that lithofacies A,B intervals could represent a relatively distal lacustrine delta-fill facies.

Elliott (1974, 1978) suggests that the type of sedimentation in interdistributary quiet-water environments depends upon the height and proximity of adjacent distributary-bearing alluvial ridges. Areas close to distributaries are infilled by coarse overbank sands and crevasse splays; more isolated areas receive only suspended fine overbank mud and silt, and sediment funneled down crevasse channels.

Figure 36. Summary of characteristics of lacustrine delta-fill deposits (Coleman and Prior, 1982, Figure 6).

Figure 37 shows Elliott's model of bay-fill sedimentation, whereby overbank sedimentation is superceded by crevasse-channeled sedimentation as the alluvial ridge aggrades. A vertical section distal to the breached distributary would, like A,B intervals, show overbank mud and silt gradationally overlain by sand conveyed down crevasse channels. These crevasse channels are capable of diverting the entire flow of the main distributary (Figure 37), thus making this model analogous to the lacustrine delta-fill model already discussed. The lack of typical crevasse-splay sandstones (sharp base, fines upward) in lithofacies A,B intervals suggests their deposition relatively distal to the distributary channels of Figure 37.

Areas subject to active subsidence can produce a considerable thickness of stacked regressive sequences. In the well-documented West Bay and Cubits Gap bay-fill sequences of the modern Mississippi delta, crevasse breach, bay fill, marsh formation, and marine innundation took place in a span of only 100 to 150 years (Coleman and Prior, 1982, p. 150).

Sequences remarkably like lithofacies A,B intervals have been described by McBride and others (1975) from the Late Cretaceous to Paleocene Difunta Group of northeastern Mexico (Figure 38). These are interpreted as regressive sequences from fresh to brackish water deltaic lakes. A comparison of these rocks with regressive sequences in the field area reveals several important factors. Similarities include a basal mudstone grading upward into small-ripple bedded very fine-grained sandstone with roots and burrows, the stacking of regressive sequences (to 100 m thick), and sharp or gradational upper and lower contacts. The lithofacies A,B cycles, however, show much better preservation of plant material, are

Figure 37. Model of interdistributary bay sedimentation; for clarity, only considers a single distributary and a single breach (Elliott, 1974, Figure 4).

Figure 38. Sketch of cycle interpreted as lake-fill deposits, typical of delta plain deposits of Difunta Group red-bed units. (Mc Bride and others, 1975, Figure 16).

grayer (Difunta cycles are redbeds), show much less intense bioturbation and rooting, have smoother tops, and are much thicker than the Difunta lithosomes.

McBride and others attribute the near absence of plant debris in the Difunta beds to its rapid decomposition prior to burial in well-drained swamp conditions. Evidences of subaerial exposure such as uneven bedding surfaces on top of the cycles and rare dessication cracks are also cited as evidence of well-drained conditions.

Abundant well-preserved plant material in lithofacies B very fine-grained arkose indicates low Eh depositional conditions (Blatt and others, 1972, p. 392). Poorly-drained conditions account for the high organic content, smooth tops, rarity of roots, and lack of dessication cracks and evaporites in the lithofacies A,B intervals. A high water table after burial and/or low post-burial permeability is required to prevent the diagenetic reddening common in the Difunta and other nonmarine sequences.

Lithofacies A,B intervals differ from both the Difunta beds and modern lake-fill and bay-fill sequences of the Mississippi delta in their apparent lack of bioturbated mudstone, the relative thickness of their cycles, and the apparent rarity of emergence.

X-ray radiography of lithofacies A mudstone is necessary to determine if bioturbation is indeed absent. Low faunal density would be expected if sediment fall-out from suspension was fairly continuous.

The thickness of the depositional cycles and the rarity of emergence could both be due to rapid subsidence. If compactional subsidence was augmented by tectonic subsidence, many regressional cycles would

never become emergent.

Lithofacies C

Stacked composite sets, comprised of couplets of thinly inter-layered mud and sand and flaser- to lenticular-bedded very fine-grained sand characterize lithofacies C. Individual laminations indicate small fluctuations in energy (waves, intermittent currents), the two bedding types suggest larger scale fluctuations in sand supply (discharge cycles or progradational cycles), and the stacking of composite sets indicates repetition of depositional conditions.

Both thinly interlayered sand/mud and flaser to lenticular bedded sand have been reported from tidal and delta front environments (Reineck and Singh, 1980, p. 112-118 and 123-125). Both of these environments are characterized by variable energy, a fluctuating supply of sand, and long term sedimentologic cycles (lunar, annual, or progradational). However, the stacking of composite sets shown by lithofacies C, and the absence of reactivation surfaces, requires an environment with a high preservation potential. The delta front or prodelta of a lacustrine delta, or a subtidal environment, would meet these requirements.

Lithofacies D

Lithic arkose with meter-scale coarse to medium-grained planar cross sets (bars?), and half meter-scale medium- to fine-grained planar and trough cross sets (megaripples?) that fine and thin upward into ten to twenty centimeter thick fine- to very fine-grained cross sets characterizes lithofacies D. Mud and gravel are notably absent. Unimodal paleocurrents, a large sand body that is elongate parallel to paleoflow,

a laterally extensive scour, many reactivation surfaces, large scale planar and epsilon cross bedding, fining-upward intervals, and a scour-generated intraformational recumbent fold all indicate an origin in a fluvial or deltaic channel environment.

Inference of channel pattern (e.g. braided, meandering) from lithofacies requires considerable caution. Jackson (1978) has pointed out that many of the lithologic and stratigraphic criteria widely accepted as diagnostic of a particular channel pattern are widespread in Holocene streams of varied channel types. The few criteria cited by Jackson as fairly diagnostic of channel form are absent in the limited exposure of lithofacies D, so the available data are considered.

The sandstone body exposed along Road 21 shows a unimodal paleo-current pattern in a 290 meter longitudinal section. Foreset bedding measurements were taken on 30 to 50 centimeter thick planar and trough cross beds, inferred to represent cross-channel megaripples in a straight reach of a straight, meandering, or sandy braided stream. Reactivation surfaces, a laterally extensive scour, and a low width/depth ratio ($\sim 50-120$) suggest a relatively confined channel. The relatively low width/depth ratio makes a braided channel form unlikely.

Unit 23 of the Chambers Creek measured section is a 17 meter thick, medium- to very fine-grained, upward-fining interval. Fining-upward sequences, especially those with epsilon cross-stratification (ECS) like unit 23, have been widely interpreted as deposits of point bars of meandering streams since the studies of Allen (e.g. 1970). However, ECS and fining-upward cycles can form in any stream where channels shift laterally, and have been reported from braided stream

environments (Reineck and Singh, p. 308-309). Fining-upward cycles from braided rivers shown by Miall (1977), however, are less than 7 meters thick, suggesting that much thicker cycles, such as unit 23, represent instead the deposits of a laterally confined, non-braided channel.

Lithofacies D therefore appears to represent sedimentation in non-braided, laterally confined channels.

Depositional Setting of the Chambers Creek Beds

The interstratification of the four described lithofacies suggests their origin within a single depositional setting. The major requirements are long-lived (non-ephemeral) lakes or lagoons, and laterally confined distributary channels. These two environments are found in close proximity in the alluvial plain and delta plain of large rivers.

Deposition of relatively coarse-grained sand (lithofacies D, Figure 39) was restricted to major distributaries, where it formed cross-channel and point bars. Lateral confinement of the channel by well-developed levees resulted in relatively narrow sand bodies with unimodal paleocurrents. Flooding resulted in extensive channel scour, and spill over of sediment-laden flood waters into adjacent lacustrine or lagoonal environments via well-established crevasse channels. This process formed regressive lacustrine delta-fill sequences (lithofacies A,B intervals), and related delta-front or prodelta facies (lithofacies C).

Sedimentation was affected by relatively rapid basin subsidence. In the Chambers Creek measured section, four of the five exposed regressive cycles are incomplete; the top of only one cycle shows clear evidence of emergence (a rooted, irregular surface). This suggests that flood

basin subsidence generally kept pace with the sedimentation rate.

The thickness and apparent lateral confinement of the channel facies (lithofacies D) also imply rapid subsidence. Avulsion, or channel switching, only occurs when a distributary aggrades above the level of the surrounding flood basins (Figure 37). If subsidence keeps pace with aggradation, sediments will sink below base level relatively rapidly, avulsion will occur less often, and thick sand bodies will form within the relatively confined channels (Johnson, 1984a, p. 387).

ENVIRONMENTS OF DEPOSITION - OHANAPECOSH FORMATION

Summary

In the Johnson Creek - Chambers Creek area, three lithofacies are recognized in the lower ~ 700 meters of the Ohanapecosh Formation. Cross-bedded medium- to very coarse-grained volcanic arenite (lithofacies P) represents sand deposition in and adjacent to paleochannels. Thick, very poorly sorted, generally massive beds of volcanic diamictite (lithofacies Q) represent lahars. Volcanic mudrocks with intercalated massive to graded beds of medium- to very coarse-grained volcanic arenite and pebbly diamictite (lithofacies R) represent open lacustrine/lagoonal mud and silt sedimentation with periodic density flows. A thick sequence of tabular units of graded and massive lapilli-tuff and tuff (Angry Mountain Road sequence) represents pyroclastic flow and pyroclastic fall deposition.

Lithofacies P

Abundant cross bedding indicates the medium- to very coarse-grained volcanic arenite of lithofacies P was deposited by tractive currents of

varying strength in relatively shallow water. Unimodal paleocurrents, epsilon cross stratification, and sharp basal contacts with associated volcanic siltstones all suggest deposition in or adjacent to fluvial or deltaic paleochannels.

Lithofacies Q

Lithofacies Q consists of 3 to 23 meter thick beds of volcanic diamictite. These intervals are interpreted as deposits of lahars, water-mobilized mass flows that initiate on the slopes of a volcano, but readily travel tens of kilometers down fluvial drainages into adjacent lowlands. Abundant subrounded to rounded andesite clasts indicate incorporation of channel detritus during flowage.

In the middle portion of the North Cispus measured section (Figure 12, p. 39), lithofacies Q volcanic diamictite is interstratified with 2.5 to 12.5 meter thick beds of medium- to fine-grained arkosic sandstone similar in composition to sandstones of the underlying Chambers Creek beds. The paleocurrents, stratification style, and composition of these arenaceous interbeds suggest they are the products of sedimentation in and adjacent to a major paleochannel draining crystalline areas to the east.

Lower-order tributaries could have funneled lahars from adjacent volcanic highlands into the main trunk stream (Figure 40, p. 129). Rapid deceleration due to reduced gradient would result in subaqueous lahar deposition. The resulting subaqueous channel-fill and debris fan deposits (Lipman and Mullineaux, 1981, p. 714) constitute the thickest parts of the laharc deposit, and would also have the highest potential for preservation in the geologic record.

Subaqueous lahar deposits would be winnowed by current action and diluted with river-borne sediment, possibly yielding a layer of polymict orthoconglomerate like those overlying two lithofacies Q lahar units. Subsidence and aggradation would cause this interval to be overlain by fluvial sands. Repeated lahar deposition could yield a sequence like the one in the middle portion of the North Cispus section. A similar sequence occurs in the Pliocene Ellensburg Formation of central Washington. Here, distal lahars are interstratified with cross-bedded volcanic sandstone containing numerous reworked laharic clasts (Schminke, 1967).

Elsewhere in its outcrop belt, lithofacies Q is intercalated with medium- to very coarse-grained, cross-bedded to parallel-bedded, current-deposited volcanic arenite and associated volcanic siltstone (lithofacies P).

Lithofacies Q therefore represents the products of laharic deposition in paleochannels draining both relatively proximal volcanic areas, and more distant crystalline areas. These depositional sites were probably located in lowlands many tens of kilometers from the volcanic source or sources of the lahars.

Interpretation of Lithologies in North Cispus Measured Section.

Intercalated volcanic diamictite of laharic origin and arkosic sandstone form an ~158 meter thick stratigraphic interval in the North Cispus section (Figure 12, p. 39). This forms the middle portion of a ~211 meter thick sequence of diamictite, conglomerate, and very coarse- to medium-grained volcanic to arkosic arenite (units 9 through 26), inferred to represent bed load sedimentation with periodic incursion of lahars.

This coarse-grained interval is underlain by at least 30 meters of

argillaceous to carbonaceous mudstone with subordinate 5 to 15 cm thick, sharply bounded, normally graded interbeds of medium-grained volcanic arenite. This lowermost interval is interpreted as an open lacustrine/lagoonal facies. The base of a cobble orthoconglomerate (unit 9) is interpreted as the initiation of a major distributary across the lake or lagoon-filled basin. Deposition of volcanic and arkosic arenite in the new channel was periodically disrupted by incursion of lahars from tributaries draining adjacent volcanic highlands.

The lahar/arenite lithosome (units 11 through 24) is overlain by 21 meters of subequal, meter-scale, lensoid intercalations of horizontally-bedded pebbly medium-grained arkose, and massive to horizontally-bedded polymict pebble orthoconglomerate (unit 25). Grain size and stratification style are intermediate between Miall's suggested model sequences for proximal ("Scott type") and distal ("Donjek type") gravelly rivers (Miall, 1977). Discontinuous bedding, including lensoid beds, pebble stringers in sandstone, and sand stringers in conglomerate all suggest deposition in a shallow, gravelly, and probably braided, river.

Twenty three meters of overlying graded to massive-appearing coarse- to medium-grained pebbly arkose (unit 26) becomes less pebbly upward, reflecting waning currents at the top of this ~211 meter thick channel-generated sequence.

In summary, the ~158 meter thick sequence of intercalated lahars and arkosic channel sandstones within the North Cispus measured section represents a lahar-dominated interval of sedimentation within a fluvial sequence. The base of the fluvial sequence is exposed, and indicates initiation of the paleochannel across a pre-existing lake or lagoon.

Lithofacies R

One to five meter thick silty/muddy couplets exposed in the Middle Fork measured section (Figure 14, p. 43) represent the alternation of open lacustrine or lagoonal mud sedimentation with periods of very fine-grained sand and silt deposition. Parallel lamination, grading, outsized clasts, and the absence of traction features such as cross bedding suggest the deposition of sandy to silty layers from suspension, possibly by density currents.

Massive to normally graded sandy mudstone is a common lithology in facies R. Its distinctive fabric consists of angular plagioclase grains, andesitic rock fragments, and sparse non-volcanic grains (quartz, chert, muscovite) embedded in a muddy matrix. These beds formed either by grains settling individually from suspension, or more likely, from rapidly deposited, mud-rich density flows.

Prominent intercalations of medium- to very coarse-grained volcanic arenite display many features characteristic of grain-flow deposits. Weak to absent stratification, uniformity of grain size (lack of grading), outsized clasts, sharp contacts, rapid pinching out, and irregular load-deformed bases were all described by Stauffer (1967) from inferred grain-flow deposits in southern California. Grain flows differ from turbidites in that their relatively high concentration of dispersed solids causes the dynamics of movement to be dominated by grain collisions rather than by turbulence. These collisions set up dispersive stresses which tend to keep grains from sorting due to mass differences, resulting in the characteristic lack of grading.

Two beds of polymict granule to pebble diamictite display the

features cited for grain flows, except they fine upward into pebbly arkose. This suggests an intermediate type of flow, possibly a slightly turbulent grain flow which allowed many of the entrained clasts to settle towards the base, or a grain flow with an upper turbulent layer (Cas, 1979, p. 39).

Interpretation of Lithologies in the Middle Fork Measured Section.

Lithofacies R, including coarse-grained intercalations, comprises a ~145 meter thick interval in the Middle Fork section (Figure 14, p. 43). It is sharply overlain by 3.5 meters of fine- to medium-grained arkosic sandstone that is similar in composition to sandstones of the Chambers Creek beds, which is in turn sharply overlain by 3.5 meters of typical lithofacies R mudstone with thin sandy mudstone intercalations.

In the field, the presence of an interbed of cross-bedded arkosic sandstone, surrounded by volcanoclastic mudrocks ~ 250 meters above the top of the Chambers Creek beds, is somewhat startling. This occurrence suggests that distributary channels transporting arkosic sand were laterally adjacent to lacustrine or lagoonal environments where fine-grained tuffaceous sediments and density flow deposits were accumulating. This relationship is plausible if well-developed levees generally kept channel-borne sediment out of adjacent lacustrine/lagoonal environments. By this model, the observed arkosic intercalation could represent an overbank or crevasse-splay deposit.

Facies R mudstone and sandy mudstone overlying the arkosic sandstone interbed is intercalated with a superjacent eight meter thick bed of fine- to medium-grained massive to graded volcanic arenite. These lithologies indicate a return to normal quiet water sedimentation,

followed by an increasing proportion of sandy density flows, possibly due to shoaling.

Interpretation of a Possible Lateral Equivalent. The stratigraphic sequence exposed at milepost 10.65 of USFS Road 21, 0.5 km southwest along strike from the Middle Fork section, probably represents marginal sedimentation in the same, or a similar, lake or lagoon as the one in which the Middle Fork open lacustrine rocks accumulated. A direct correlation is not suggested, due to uncertain structure in this area.

Two to three meter thick sharply bounded beds of medium- to coarse-grained, massive-appearing volcanic arenite with pebble lenses and cut-and-fill may represent subaerial lacustrine bars (Fouch and Dean, 1982, p. 96-97); more likely they are stacked grain-flow deposits. Intercalated 2 to 5 meter thick beds of massive to laminated siltstone with complete, large leaf fossils suggests relatively near-shore deposition, due to the problem of transporting intact leaves.

The dominance of suspension-deposited and probable density-flow-deposited sediments in both this exposure and in the Middle Fork measured section suggests sediment dispersal by hyperpycnal flow. Muddy inflow from nearby highlands could readily generate density currents upon encountering less dense lake or lagoon water.

Angry Mountain Road Sequence

The angularity of lithic and pumiceous lapilli in exposed lapilli-tuff units suggests much of this material is juvenile and accessory pyroclastic ejecta; therefore, these units are probably of pyroclastic origin.

A thick lapilli-tuff unit with a normally graded base (station AMR-

101, Plate II) is believed to be a pyroclastic flow deposit because of fairly good sorting, normal grading, and angularity of lapilli. This unit is much better sorted, and contains a much higher proportion of angular clasts than lithofacies Q diamictite units (inferred to represent lahars).

Very well sorted, massive to weakly graded lapilli-tuff units with highly angular pumice and lithic fragments (station AMR-103, Plate II), represent either pyroclastic flow or pyroclastic fall units. These units are unusually thick (about 0.5 - 2.0 m) for air-fall, but the angularity of pumice is atypical for pyroclastic flows.

A thin interval of green volcanic mudstone with accretionary lapilli underlies the inferred pyroclastic flow described above (station AMR-101). The presence of accretionary lapilli indicates this bed originated as volcanic air-fall in a subaerial or shallow subaqueous environment.

Thin intercalations of cross-bedded volcanic sandstone (station AMR-104), and the presence of accretionary lapilli-bearing mudstone, indicate that much of the sequence exposed along Road 2120 probably originated in a subaerial, or shallow subaqueous environment. The tabular nature of the units implies an environment of low relief, possibly a poorly-drained area adjacent to an active volcano.

PALEOGEOGRAPHY

Stratigraphic relations in the Johnson Creek - Chambers Creek area allow two local time intervals, each characterized by a distinct depositional regime, to be recognized.

Chambers Creek/Middle Fork Time

Figure 40 shows a schematic representation of lateral relations at the time of deposition of the rocks exposed in the Chambers Creek, Road 21, and Middle Fork measured sections. These sections are inferred to be roughly time-equivalent (Figure 3, p. 14).

Arkosic channel-fill and point-bar sequences (lithofacies D) represent the deposits of a major distributary (or distributaries) draining crystalline terranes to the east. Rocks from the Road 21 section to the Middle Fork section, 10.3 km to the north, show evidence of a nearby arkosic sediment-bearing distributary, but it is not known if one distributary swept back and forth across a floodplain, or several parallel channels existed. The lithologic uniformity of the arkosic Chambers Creek beds implies that all distributaries funneled sediment derived from a common source, or sources. Field relations suggest a channel (or channels) confined by well-developed levees. Flooding would result in extensive channel scour, and spill over of sediment-laden flood water into adjacent lakes and/or lagoons via well-established crevasse channels, forming lithofacies A,B regressive sequences, and associated lacustrine delta facies (lithofacies C).

Volcanic-lacustrine/lagoonal sequences (lithofacies R, Figure 40) locally formed adjacent to arkose-bearing major distributaries, but were isolated from them by well-developed levees, except when crevassing occurred during large floods. Sedimentation in these quiet water environments was dominated by mud and silt fall-out and sandy density flows, suggesting a hyperpycnal regime. Laterally adjacent sequences of medium- to very coarse-grained cross-bedded volcanic arenite (lithofacies P)

Figure 40. Schematic paleogeography: Chambers Creek - Middle Fork time; lithofacies A, B, C, associated lacustrine/lagoonal facies; lithofacies D, arkosic channel sequences; lithofacies P, volcaniclastic channel sequences; lithofacies R, volcaniclastic lacustrine/lagoonal sequences; Tcc, Chambers Creek beds; To, Ohanapecosh Formation. See text for discussion.

represent sedimentation in energetic westward-flowing rivers draining local volcanic highlands.

North Cispus/Elk Ridge Time

The depositional regime suggested by Ohanapecosh strata exposed in the North Cispus-Elk Ridge area is shown in Figure 41. The generalizations of this diagram are: 1) numerous arkosic sediment- and volcanic arenite-bearing channels probably existed, and 2) the location of the source(s) of the lahars is not known.

Distal lahars (lithofacies Q) are intercalated with channel-deposited arkosic sandstone in the North Cispus measured section, and with volcanic arenite on Elk Ridge, ~6 km to the south along structural strike. These lahars originated in active volcanic highlands, and traveled kilometers to tens of kilometers down tributaries to floodplain rivers, to form channel-fills and/or debris fans.

Westerly paleocurrents in both volcanic and arkosic sandstones in the lower part of the Ohanapecosh Formation, but minor mixing of sediments, suggests the existence of parallel, levee-bounded drainages bearing local (volcanic) and distal (arkosic) sediments, as Buckovic (1979) has suggested. Uncommon intercalated fine-grained intervals indicate the presence of local lacustrine or lagoonal environments.

GEOLOGIC HISTORY

Figure 42 summarizes the sequence of geologic events inferred for the mapped section. Deposition of the arkosic Chambers Creek beds was superceded by a regime in which arkosic and volcanoclastic sediments accumulated simultaneously in laterally adjacent environments (Figure 40).

Figure 41. Schematic paleogeography: North Cispus - Elk Ridge time; lithofacies P, volcaniclastic channel sequences; lithofacies Q, lahars, shown intercalated with arkosic and volcaniclastic channel sandstone units; lithofacies R, volcaniclastic lacustrine/lagoon sequences. See text for discussion.

Figure 42. Inferred sequence of geologic events, Johnson Creek - Chambers Creek area.

Volcanic sedimentation eventually became dominant, with deposition of arkosic sediments restricted to well-established, antecedent paleochannels (Figure 41). The transition to volcanic-dominated sedimentation probably occurred about 40 million years before present (Chapter VIII).

The composition of Ohanapecosh Formation volcanic sandstones in the field area indicates they were derived from erosion of andesitic volcanic highlands. The texture and composition of Ohanapecosh rocks higher in the section was examined by reconnaissance, and indicates volcanic processes (e.g. air-fall, ash-flow) became dominant over normal sedimentation processes as time progressed.

The type area of the Ohanapecosh Formation in Mount Rainier National Park contains lava flow - mudflow complexes of tholeiitic basaltic andesite to andesite in its upper portion (Fiske and others, 1963; Garcia, 1978). Abundant sills and dikes of tholeiitic basalt to basaltic andesite in the field area may be correlative with this volcanic episode.

The northwest-trending Johnson Creek anticline post-dates deposition of the mapped sequence. Reverse faulting, possibly related to the same tectonic episode, post-dates at least some tholeiitic intrusions, and pre-dates emplacement of low MgO andesitic intrusions.

Either during or after the emplacement of these andesitic intrusions, the sequence in the field area was uplifted and deeply eroded during region-wide uplift of the Western Cascade Group. Much of this orogenic episode occurred after the extrusion of the Grande Ronde Yakima Basalts (~ 16 mybp) and before the earliest (~ 4 mybp) High Cascade lavas (Hammond, pers. comm., 1984), therefore was late Miocene to Pliocene in

age. In the field area, Plio-Pleistocene High Cascade lavas flowed down deep ancestral and modern valleys cut into the older rocks.

REGIONAL SIGNIFICANCE OF STUDY

Provenance of the Chambers Creek Beds and Correlative Units

The composition of the Chambers Creek beds implies a diverse provenance dominated by crystalline rocks. The best way to evaluate the provenance of this unit is to compare its composition with correlative middle to late Eocene arkosic sandstone units in the region.

Dickinson (1970) and Dickinson and Suczek (1979) suggest that framework grain parameters (Q_m , Q_p , etc., Chapter IV) may be combined to form secondary and ternary ratios that can characterize sandstone suites from different plate tectonic settings. These authors compiled petrographic data from 88 suites of modern and ancient sandstones, constructed ternary plots like the ones shown (Figure 43), and contended that the compositional fields defined by these samples of known provenance were sufficiently distinct that such diagrams could be used to determine the provenance of a suite of sandstone samples.

The three general provenance types defined by Dickinson and Suczek are: continental block, with sediment derived from platform successions, shield areas, and uplifted crystalline basement; magmatic arc, with sediment derived from both undissected volcanic arcs and their dissected plutonic roots; and recycled orogen, with active erosion of uplifted sedimentary and low-grade metamorphic rocks along collision orogens, uplifted subduction complexes, and foreland fold-thrust belts.

The composition of the arkosic sandstones compared here places

Figure 43. Composition of the Chambers Creek beds and correlative arkosic sandstone units, shown with provenance types of Dickinson and Suczek (1979). See text for discussion. Units shown are CC, Chambers Creek beds; COW, Cowlitz Formation; CH, Chumstick Formation; NA, Naches Formation; RN, Renton Formation; RO, Roslyn Formation; S, Spiketon Formation; SK, Skookumchuck Formation; and SP, Spencer Formation. Components of ternary plots are identified on p. 61.

them near the merger of Dickinson and Suczek's continental block and magmatic arc fields (Figure 43). The feldspathic end of the continental block field is defined by sandstones derived from uplifted blocks of coarse-grained basement, with short transport distance and rapid sedimentation favoring preservation of feldspars. Magmatic arc sandstones low in lithic clasts reflect derivation from plutonic rocks exposed by erosional dissection of volcanic arcs. These arc-related plutons and batholiths may be texturally and mineralogically similar to uplifted plutonic and high grade metamorphic basement, thus the merger of the two fields. On the basis of these two diagrams, then, the dominant provenance of the arkosic units compared is inferred to be a plutonic and/or a high-grade metamorphic source or sources. A plot of QpLvLs (Dickinson and Suczek, 1979, Figure 3) is not constructed for these rocks due to their low lithic count.

A comparison of detailed modal data for these seven units (plus limited data for two additional units) in Chapter IV revealed that two compositionally distinct, geographically separated groups can be distinguished. The Chumstick, Roslyn, and Naches Formations (Figure 19, p. 60) contain a significant amount of coarsely polycrystalline quartz ($Qp/Q \sim 0.30$, and are relatively low in potassium feldspar ($P/F \sim 0.85$). By contrast, the Chambers Creek beds, and the Skookumchuck, Cowlitz, and Spencer Formations all contain very little polycrystalline quartz ($Qp/Q \sim 0.05$) but notable amounts of K-feldspar ($P/F \sim 0.60$). The Renton Formation, located between the two groups, contains elevated amounts of both polycrystalline quartz and K-feldspar (Table III, p. 64).

Sedimentologic and mineralogic factors are cited by Johnson (in

press) against a local (North Cascades) provenance for the Eocene arkoses of central and western Washington. Johnson cites radiometric data indicating rapid uplift of the high-grade metamorphic Omineca crystalline belt and related rocks in northeastern Washington and southern British Columbia in a time frame encompassing the Eocene, and proposes it as a likely provenance. This is consistent with presently available paleocurrent data (Figure 44).

I suggest that a second, more southerly, more potassic, and possibly coarser-grained provenance was a major contributor of sediment to the more southerly arkosic sandstones. One possible source could have been early Tertiary epizonal plutons of biotite granite to biotite alkali granite in the Idaho batholith (Hyndman and Williams, 1977). It is also possible that the southern extension of the Omineca belt (now covered by the Miocene Columbia River basalts) is more potassic than the more northerly, exposed portion. The compositional contrast between these two sandstone groups will hopefully stimulate additional studies.

Interpretation of Observed Regional Trends in Sandstone Composition

In middle to late Eocene time, much of south-central and southwestern Washington between longitudes 120° and 122° was probably a low-lying, westward-draining alluvial plain. Marine facies to the west indicate the shoreline corresponded approximately to the eastern margin of the present day Puget-Centralia-Kelso lowland.

The compositional trends discussed in the previous section suggest at least two major crystalline sources for the middle to late Eocene arkosic sediments compared here. Available paleocurrent data (Figure 44) and the compositional trends discussed suggest the paleodrainage pattern

Figure 44. Paleocurrent vector means for Chambers Creek beds and correlative units (data presently available): CC, Chambers Creek beds, $\bar{x}=248^\circ$ (this report); CH, Chumstick Formation, $\bar{x}=233^\circ$ (Buza, 1979); RO, Roslyn Formation, $\bar{x}=246^\circ$ (Walker, 1980); S, Spiketon Formation, $\bar{x} \sim 275^\circ$ (Buckovic, 1974). Outcrop area of lower Tertiary units is stippled. May include some younger units in coastal areas. Reference points: B, Bellingham; E, Eugene; O, Olympia; P, Portland; Y, Yakima.

shown in Figure 45. Note that the compositionally hybrid Renton Formation could have been derived by down-basin mixing of sediments from multiple sources.

Alternatively, the observed trends in sandstone composition could be a result of tectonic juxtaposition of once widely-separated arkosic sandstone units. Widespread Eocene dextral faulting has been hypothesized by Ewing (1980) and Johnson (1984b). If dextral faults are dominantly northwest-trending, as are the dextral boundary faults of the Chiwaukum Graben (Gresens, 1982b), Eocene arkosic sandstones of western Washington and northwest Oregon can be restored to more southeasterly positions. This would make both the observed compositional contrasts, and the unusual composition of the Renton Formation, easier to explain.

Relation of the Chambers Creek Beds to the Rimrock Lake Inlier

The western edge of the pre-Tertiary Rimrock Lake inlier (Figure 2, p. 10) is presently exposed only about 15 km east-northeast of the outcrop belt of the Chambers Creek beds (directly "up-current"). However, lithic grain and plagioclase counts in the Chambers Creek beds that are not significantly higher than in correlative units (Chapter IV) indicate the lack of a detectable contribution of sediment from the mostly argillaceous, and plagioclase-rich plutonic and metamorphic rocks, of the Rimrock Lake inlier. This indicates that this basement block did not form a major highland "upstream" from the Chambers Creek beds at the time of their deposition (middle to late Eocene). Clayton (1983, p. 23) provides additional evidence, describing fresh, relatively unaltered Eocene arkose depositionally overlying more than a meter of clay-rich paleosol developed upon the Indian Creek crystalline complex. This

Figure 45. Paleodrainage pattern suggested from sandstone compositional trends and paleocurrents if northwest translation of arkosic sandstone units west of about longitude 121° is not considered. Outcrop area of lower Tertiary units is stippled; may include some younger units in coastal areas. Reference points: B, Bellingham; E, Eugene; O, Olympia; P, Portland; S, Seattle; Y, Yakima.

suggests passive onlap of Eocene sediments over basement hills of low relief.

The marked thickening of the Eocene section between the Rimrock Lake area, where it is absent to about 750 meters thick (Clayton, 1983), and the Johnson Creek - Chambers Creek area, where it is at least 1150 meters thick, is problematic. Sedimentologic evidence in this report indicates deposition of the Chambers Creek beds under conditions of rapid basin subsidence. By contrast, the generally thin arkosic section that locally mantles the Rimrock Lake inlier suggests much slower subsidence and/or local erosion of arkose following localized uplift.

I suggest that either down-to-the-west dip-slip or strike-slip movement in a north- to northwest-trending zone paralleling the Cortright Creek fault (Figure 2) during the time of deposition of the Chambers Creek beds could readily account for the rapid westward thickening of these sediments. A northwest-trending graben or pull-apart basin could then have existed in the Johnson Creek - Chambers Creek area, permitting the rapid basin subsidence implied by the stratigraphy.

A strike-slip interpretation is more consistent with low relief upon the Rimrock Lake block during the time of active Eocene faulting. However, vigorous, throughgoing antecedent streams could have maintained their northeast-to-southwest course across a slowly rising Rimrock Lake horst. This explanation is appealing because it does not require a shift from strike-slip offsets to vertical displacements to account for post-Ohanapecosh doming of strata surrounding the Rimrock Lake inlier.

CHAPTER XI

SUMMARY

Over 1150 m of middle to late Eocene nonmarine arkose, lithic arkose, mudstone, and siltstone, referred to here as the Chambers Creek beds, is interstratified with, and overlain by over 1600 m of late Eocene-Oligocene(?) andesitic volcanoclastic and subordinate volcanic rocks assigned to the Ohanapecosh Formation, in a dissected structural high in the southern Washington Cascade Range ~ 18 km south-southwest of the town of Packwood.

Four lithofacies are distinguished in the Chambers Creek beds. Mudstone forms 4 to 17 m thick intervals that are massive except for thin, tabular intercalations of lapilli-tuff, tuff, and coal (lithofacies A). Ripple- to parallel-laminated very fine-grained arkose to lithic arkose is commonly burrowed or bioturbated, and contains less common wave ripples and root scars (lithofacies B). These two facies commonly form 10 to 19 meter thick, mudstone-dominated coarsening-upward intervals, interpreted as lacustrine or lagoonal regressive sequences. An associated rhythmically bedded fine-grained interval (lithofacies C) may represent a lacustrine delta facies.

Lateral to, and intercalated with these facies are thick, relatively coarse-grained sand bodies (lithofacies D), characterized by meter-scale medium- to coarse-grained planar cross sets, and half-meter-scale medium- to fine-grained planar and trough cross sets that grade

upward into thinner, fine- to very fine-grained sets. Unimodal paleocurrents, sand body elongation parallel to paleoflow, a laterally extensive scour, many reactivation surfaces, large-scale planar and epsilon cross stratification, and fining-upward intervals indicate origin of lithofacies D in a nonmarine channel environment.

The intercalation of regressive and channel facies implies a common depositional setting. The former probably originated by infilling of lakes or lagoons adjacent to major distributaries. The latter represents deposition in and adjacent to these paleochannels. The thickness of the regressive cycles, their rarity of emergence, and the low width/depth ratio of the channels suggest rapid basin subsidence.

Paleocurrents and sandstone mineralogy indicate derivation of the arkosic Chambers Creek beds from easterly, crystalline sources, probably plutonic and high-grade metamorphic rocks in Idaho and eastern Washington. The apparent lack of lithic grains derived from the pre-Tertiary Rimrock lake inlier, ~15 km "up-current", indicates this basement block did not form a major highland adjacent to the Chambers Creek beds at the time of their deposition.

The lowermost ~700 meters of the Ohanapecosh Formation, studied in detail, is dominated by volcanic arenite, mudrocks, and diamictite. Medium- to very coarse-grained feldspathic to lithic subquartzose volcanic arenite (lithofacies P) most commonly forms half meter- to 1.5 meter-thick cross-bedded, graded, and less common massive beds which overlie finer-grained units with sharp basal contacts. These volcanic sandstones formed in and adjacent to paleochannels.

Volcanic diamictite assigned to lithofacies Q forms 3 to 23 meter

thick massive to weakly graded intervals. Most units are lithic lapillituffs, composed of very poorly sorted subangular to rounded andesitic lapilli and pebbles ($\sim 3\text{-}5$ cm), and scattered andesitic blocks and cobbles ($\sim 8\text{-}50$ cm) in an abundant, well-indurated, crystal-lithic matrix. These diamictic beds are interpreted as lahars, and are interstratified with thinner, cross-bedded, volcanic and arkosic sandstone units, indicating laharc deposition in westward-flowing paleodrainages.

Volcanic mudrocks assigned to lithofacies R form an ~ 145 meter thick interval in the northern portion of the map area consisting of 1 to 5 meter thick, fining-upward, silty/muddy couplets. The coarser half of these intervals consists of either massive sandy mudstone, or thinly parallel-laminated, graded, or massive very fine-grained volcanic arenite. The absence of traction-related features such as cross-bedding suggests deposition of these lithologies from suspension. Uncommon intercalations of medium- to very coarse-grained massive volcanic arenite and massive to graded pebbly diamictite are probable grain-flow deposits. Lithofacies R therefore represents deposition of dominantly fine-grained volcanic sediments in a long-lived lake or lagoon, with infrequent deposition of coarse sandy and pebbly material, probably in the form of grain flows.

Ohanapecosh volcanoclastic sediments were derived from the erosion of andesitic volcanic highlands. These distal volcanic facies were deposited in westward-flowing paleodrainages and associated quiet-water environments. Intercalations of arkosic sandstone occur up to ~ 650 m above the base of the Ohanapecosh Formation, indicating the persistence of vigorous, interior-draining streams well into the time of Ohanapecosh deposition.

The Chambers Creek/Ohanapecosh sequence is folded into a northwest-trending, northwest-plunging faulted anticline (referred to here as the Johnson Creek anticline). Dip angles in stratigraphically high intervals do not shallow, and there is no consistent relationship between paleo-current vectors and tectonic dip. These factors indicate the Johnson Creek anticline was not active at the time the mapped sequence was being deposited.

Abundant pre(?) - and post-tectonic sills, dikes, and stocks of basaltic to andesitic composition intrude the Paleogene sequence. All intrusions examined displayed an aphanitic groundmass, indicating relatively shallow emplacement. Most analyzed samples of intrusive basalt are tholeiitic in composition, are believed to pre-date deformation, and may be related to later Ohanapecosh tholeiitic volcanism. Andesite forms stocks and dikes that locally cross-cut a reverse fault, share an unusual (low MgO) chemical composition, and may represent a cogenetic, post-tectonic, intrusive group.

Intrusive and deformational events were followed by late(?) Miocene-Pliocene uplift and deep erosional dissection of the Johnson Creek anticline. Plio-Pleistocene High Cascade lavas of calc-alkaline pyroxene andesite and hornblende-pyroxene dacite lap over the older rocks and locally fill ancestral and modern valleys.

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APPENDIX A

POINT COUNT DATA

Categories used in point counts:¹

quartz

- Qm: monocrystalline quartz: undulose or non-undulose extinction; some grains fractured.
- fQpa: foliated polycrystalline quartz aggregate: polycrystalline quartz with sutured to straight crystal boundaries, elongate to equant crystals, and oriented fabric.
- eQpa: equidimensional polycrystalline quartz aggregate: polycrystalline quartz with sutured to straight crystal boundaries, equant crystals, and non-oriented fabric.
- chert: microcrystalline, microgranular, or chalcedonic silica aggregates; if fine grained "dust" exceeds 50%, classified as sedimentary rock fragment.

feldspar

- pc: plagioclase feldspar: often altered or replaced by sericite, calcite, albite, zeolites, or clay minerals.
- kf: potassium feldspar: alteration similar to plagioclase; distinguished by sodium cobaltinitrite stain.

rock fragments

- GRF: microgranitic rock fragment: composed of quartz, feldspar, and mica; non-oriented fabric.²
- SRF: sedimentary rock fragment: composed of mineral and lithic grains in matrix; tally may include a few fine-grained metamorphic rock fragments.
- fMRF: foliated metamorphic rock fragment: composed of quartz and mica; planar oriented fabric.
- eMRF: equidimensional metamorphic rock fragment: composed of quartz and mica; non-oriented fabric.
- fVRF: felsitic volcanic rock fragment: siliceous, fine-grained, microgranular; feldspar laths in a microcrystalline

groundmass of quartz, feldspar, and devitrified siliceous glass.

mVRF: microlitic volcanic rock fragment: microlites and phenocrysts of plagioclase feldspar in a subordinate ferromagnesian groundmass; trachytic to felted texture; intermediate to mafic composition.

URF: unknown rock fragment: highly altered rock fragment of unknown affinity.

other framework grains

bt: biotite: altered and "bleached" grains may not exhibit pleochroism.

musc: muscovite

chl: chlorite

u-phyl: unidentified phyllosilicate minerals.

py: pyriboles: pyroxenes and amphiboles.

miscell: miscellaneous framework grains: (+) indicates that a single grain was included in point count. No symbol indicates that a species was present, but not counted.

unk: unknown: framework grain that is unidentifiable due to extensive replacement by authigenic minerals; does not include authigenic minerals in pores or matrix.

interstitial constituents

mat: matrix: protomatrix of Dickinson (1970).

car: carbonaceous material

cc: sparry calcite cement

auth: other authigenic minerals: includes clay minerals, chlorite, and zeolites; epimatrix, orthomatrix, and phyllosilicate cement of Dickinson (1970).

footnotes:

1) Categories modified from Frizzell (1979a, p. 104-106).

2) If visible diameter of grain under cross-hair exceeded 0.0625 mm, point assigned to respective mineral; otherwise assigned to felsitic volcanic rock fragments (Dickinson, 1970).

Point count data - arkosic sandstones

(left column: points counted; right column: percentage)

sample number	EMN-111	EMN-203	HG-144	JC-400U	JC-400Y	JOR-107G	KTR-23	KTR-40A
points counted	712	651	700	649	665	652	605	649
% of total points								
mat	10 1	39 6	12 2	9 1	10 2	17 3	5 1	31 5
car			2					
cc	228 32		148 21	97 15	20 3	7 1		
auth		11 2	16 2	3	31 5	9 1	16 3	48 7
% of framework								
bt	20 4	18 3	5 1	1	11 2	8 1	11 2	9 2
msc	14 3	11 2	8 2	8 2	7 1	3	5 1	16 3
chl			2					1
u-phyll	2		8 2	3 1	5 1		5 1	13 2
py			1					
miscell								
unk	24 5	25 4	27 5	7 1	10 2	6 1	5 1	30 5
% of Q+F+L								
Qm	240 58	239 44	237 50	257 49	313 55	326 54	276 50	253 51
fQpa	1	6 1	4 1	4 1		7 1	1	2
eQpa	12 3	12 2	14 3	8 2	9 2	12 2	8 1	14 3
chert	5 1	1	6 1	18 3	14 2	10 2	5 1	2
pc	49 12	120 22	105 22	101 19	96 17	99 16	129 23	127 25
kf	32 8	110 20	35 7	65 12	64 11	48 8	68 12	38 8
GRF							(2)	
SRP	33 8	15 3	23 5	25 5	27 5	15 2	15 3	26 5
fHRF	4 1	9 2	8 2	1	2	4 1	4 1	3 1
eHRF	2		4 1				1	1
fVRF		1					2	
mVRF		5 1		1	1	62 10	4 1	
URF	36 9	29 5	35 8	41 8	45 8	19 3	43 8	34 7

Point count data - arkosic sandstones

(left column: points counted; right column: percentage)

sample number points counted	KTR-102 648	KTR-115 678	MCR-187L 652	MCR-187P 651	MFJ-401P 483	MWR-201 649	MWR-202 656
% of total points							
mat	37 6	46 7	13 2	47 7	5 1	40 6	8 1
car	5 1	8 1	2	14 2		2	
cc						1	38 6
auth	49 8	53 8	52 8	42 6	217 45	55 8	26 4
% of framework							
bt	4 1	40 7	5 1	16 3	21 8	8 1	21 4
musc	7 1	19 3	13 2	6 1	6 2	10 2	15 3
chl	1	2	2	11 2		4 1	
u-phyl	7 1	36 6	36 6	21 4	11 4	12 2	
py	3 1	2		1			
miscell	ct, zir	gg			spinel+		chl
unk	18 3	26 5	27 5	9 2	18 7	41 7	8 1
% of Q+F+L							
Qm	386 75	290 65	287 57	299 62	115 56	280 59	307 57
fQpa		1	2	1	1	3 1	7 1
eQpa	18 3	10 2	7 1	5 1	6 3	18 4	18 3
chert		1	1			1	23 4
pc	66 13	58 13	59 12	41 9	22 11	99 21	81 15
kf	35 7	42 9	96 19	115 24	18 9	40 8	39 7
GRF		(2)	(2)	(4)		(2)	
SRF	3 1	10 2	15 3	4 1	11 5	10 2	16 3
fMRF		2	7 1	3 1	10 5	3 1	2
eMRF	1	6 1	3 1	5 1	3 1	2	
fVRF					1		2
mVRF		1					
URF	8 2	23 5	23 5	7 1	17 8	18 4	45 8

Point count data - volcanic sandstones

(left column: points counted;
right column: percentage)

sample number: points counted	EHM-200A 452	JC-250B 454	KTR-40G 459	MCR-187W 450	MWR-103 468
% of total points					
mat	5 1	21 5		4 1	
car					
cc					
auth	36 8	44 10	66 14	41 9	44 9
% of framework					
bt		1		1	
musc			1		
chl					
u-phyl					1
py	1	2 1	2 1		
miscell	kf	kf, GRP, fQpa		fMRP	
unk	32 8	56 14	34 7	45 11	55 12
% of Q+F+L					
Qm	7 2	23 7	2 1	11 3	8 2
fQpa	5 1			1	2 1
eQpa		2 1		2 1	3 1
chert	2 1	10 3	4 1	11 3	
feldspar	89 24	188 57	60 17	168 47	168 46
GRF	(1)	(1)		(2)	
SRP	2 1	10 3	1	6 2	3 1
fMRP		1			
eMRP				1	
fVRF					
mVRF	226 60	62 19	262 74	119 34	120 33
URF	46 12	33 10	27 8	38 11	64 17

APPENDIX B

TECHNICAL DATA FOR AGE DATE

Sample Description

Sample CT-12 was collected from a ~17 cm thick, tabular bed of orange-weathering clay, located ~3.9 m above the base of a ~7.7 m thick, massive, dark gray mudstone unit. The sampled bed is the upper of two closely-spaced clay beds of subequal thickness. The mudstone comprises unit 5 of the Chambers Creek measured section (this report), and crops out in a road cut on the northwest side of U.S. Forest Service Road 22, ~0.65 mi (~1.05 km) southwest of its intersection with Forest Service Road 21. This locality is at latitude 46°26'11" N, longitude 121°32'50" W, in the SW⁴, NW⁴, SE⁴, sec. 15, T 11 N, R 10 E, Lewis County, Washington. The sample was collected on 10-23-82 by Warren Winters.

A bulk sample was collected which represents the entire thickness of the clay bed. The presence of euhedral crystals, including zircon, in the heavy mineral fraction, the absence of detrital grains, and the occurrence as a tabular layer in a mudstone indicate this clay bed is an altered tuff.

Sample Preparation

(Prepared and analyzed by Geoff Clayton, University of Washington).

Sample was crushed, washed, and sieved. The 100 to 170 mesh fraction yielded <150 cc of material. The heavy mineral fraction was separated with tetrabromoethane, and cleaned with a hand magnet, Franz magnetic separator, and aqua regia. This yielded less than 1 gram of

heavies, with over 300 zircons, and no apatite. Pyrite was abundant, and some zircons were slightly magnetic.

The zircons were mounted on two teflon disks; the one which took a better polish was the only one counted. Zircon was etched for 15 hours, mica was etched for 23 minutes.

Analytical data

CASCADE TRANSECT. BEAR HUNTER (CT-12)

NUMBER OF GRAINS = 6.

NEUTRON FLUX (NEUT./CM**2) = .11400E+16

SIZE OF THE UNIT AREA USED FOR COUNTING (CM**2) = .84640E-04

NO.	FOSSIL TRACKS	AREA	DENSITY (TRX/CM**2)	INDUCED TRACKS	AREA	DENSITY (TRX/CM**2)	TRACK DENSITY RATIO (F/I*2)	AGE (MA)
1	79.	31.	.3011E+05	98.	31.	.3735E+05	.4031	27.434
2	150.	48.	.3692E+05	158.	48.	.3889E+05	.4747	32.296
3	153.	56.	.3228E+05	159.	56.	.3355E+05	.4811	32.734
4	174.	68.	.3023E+05	179.	68.	.3110E+05	.4860	33.066
5	196.	69.	.3356E+05	195.	69.	.3339E+05	.5026	34.188
6	110.	43.	.3022E+05	100.	43.	.2748E+05	.5500	37.406

TOTAL	862.	315.	.3233E+05	889.	315.	.3334E+05	.4848	32.984

*** STATISTICS FOR MEAN AGE ***

THE FOLLOWING VALUES ASSUME A 2.10 (X) RELATIVE ERROR FOR THE NEUTRON FLUX DOSE.

CORRELATION COEFFICIENT (R) = .97443

POISSON STD. ERROR (MA) = .735

RELATIVE POISSON STD. ERROR (X) = 2.230

*** BEST-FIT LINE FOR INDUCED VS. FOSSIL TRACKS

USES THE EIGENVECTOR TECHNIQUE AND MINIMIZES FOR ERRORS IN BOTH VARIABLES (INDUCED AND FOSSIL TRACKS).

GOODNESS OF FIT (X) = 98.724846

COEFF. OF BEST-FIT LINE:

INTERCEPT ON THE FOSSIL-TRACKS AXIS (INDUCED TRACKS = 0) = -12.6950

SLOPE OF LINE (TF/TI) = 1.0553

TRACK RATIO FROM BEST-FIT LINE (TF/TI*2) = .5277

AGE OF THIS TRACK RATIO (MA) = 33.8902

CASCADE TRANSECT. BEAR HUNTER (CT-12)

APPENDIX C

LOCATIONS OF MEASURED SECTIONS

(see Plate II for general locations)

Chambers Creek Measured Section:

base is located at an orange paint spot on a poorly exposed brownish-gray lithic arkose; on U.S. Forest Service (USFS) Road 22, 0.60 miles (~0.97 km) SW of its intersection with USFS Road 21; elevation ~ 4000 ft (~1220 m).

top is located at the top of a 1.35 m thick yellowish-gray weathering unit consisting of 1.05 m of andesite-chert pebble orthoconglomerate grading upward into 30 cm of very coarse lithic subquartzose volcanic arenite (unit 40-G); a few meters above this interval a medium bluish gray, fine-grained andesite intrusion forms a prominent vertical road cut; on USFS Road 22, 1.20 mi (~1.93 km) SW of its intersection with USFS Road 21; elevation ~4200 ft (~1280 m).

Road 21 Measured Section:

base is located at the lowest exposure of a massive-appearing, yellowish-brown weathering lithic arkose; 0.67 mi (~1.08 km) S of milepost 15, USFS Road 21; elevation ~3390 ft (~1034 m).

top is located at the highest exposure of a sill of phyric basalt (2.5 m is exposed), on USFS Road 21, 0.85 mi (~1.37 km) S of milepost 15, elevation ~ 3340 ft (~1018 m).

North Cispus Measured Section:

base is located at the base of a prominent black mudstone, ~ 8 m thick, that is overlain by a reddish-weathering phyric basalt sill; 0.95 mi (~1.53 km) E of St. John Creek on USFS Road 22; elevation ~ 3750 ft (~1143 m).

top is located at the top of a light olive gray-weathering lapillituff, ~ 5.5 m thick, that overlies a prominent 1 m thick coaly bed; 0.65 mi (~1.05 km) E of St John Creek on USFS Road 22, locality is also 0.05 mi E of milepost 13; elevation ~ 3670 ft (~1119 m).

Middle Fork Measured Section:

base is located at the base of a massive, brown-weathering mudstone, 78 cm thick, which overlies a greenish coarse-grained sill; on USFS Road 2140, 0.50 mi (~ 0.80 km) beyond (north-northwest from) the bridge over Johnson Creek; elevation ~ 2875 ft (~ 877 m).

top is located at the top of a 3.4 m thick light olive gray litho-feldspathic subquartzose volcanic arenite that forms a prominent ledge that can be traced above the roadcut into the forest; the exposed top of this unit forms the foot wall of the Middle Fork reverse fault (exposed in road cut); on USFS road 2140, 0.70 mi (~ 1.13 km) beyond (north-northwest from) the bridge over Johnson Creek; elevation ~ 2970 ft (~ 905 m).