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Stratigraphic relationships of the Tillamook Volcanics and the Cowlitz Formation in the upper Nehalem River-Wolf Creek area, northwestern Oregon

Michael Keith Jackson
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AN ABSTRACT OF THE THESIS OF Michael Keith Jackson for the Master of Science in Geology presented January 28, 1983.

Title: Stratigraphic Relationships of the Tillamook Volcanics and the Cowlitz Formation in the Upper Nehalem River-Wolf Creek Area, Northwestern Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Robert O. Van Atta, Chairman

Marvin H. Beeson

Richard E. Thoms

The upper Nehalem River-Wolf Creek area is located on the northeastern flank of the Tillamook Highlands in the northern Oregon Coast Range. Three rock stratigraphic units underlie the thesis area, and these units range from late Eocene to Oligocene in age.

The oldest exposed unit is the late Eocene Tillamook Volcanics. It consists of mostly subaerial basalt flows, minor pyroclastic rocks, and basaltic sandstones and conglomerates. Most of the flow

rocks are microphyric with microphenocrysts of plagioclase and, less commonly, pyroxene. Plagioclase and pyroxene phenocrysts occur in some rocks. The basaltic sandstones and conglomerates, which are interbedded with the volcanic flow rocks, contain clasts that were locally derived from the Eocene volcanic center(s) in the Coast Range. These volcanic sedimentary interbeds were probably deposited in subaerial paleochannels, and some units are debris flow deposits. Around the periphery of the mapped volcanic terrane is a fossiliferous conglomerate, which is overlain by marine mudrocks of the Cowlitz Formation.

Samples from the Tillamook Volcanics in the thesis area are varied in major, minor, and trace element geochemical composition. The volcanic flows range from 49.9 to 59.8 percent SiO_2 , and a typical flow rock contains 52.6 percent SiO_2 . The analyzed samples are characterized by high total alkalis, total iron, titania, and phosphate contents. The samples classify predominantly as alkalic basalt. The wide range in geochemical composition, which is characteristic of the rocks in the thesis area, is also typical of volcanic rocks from other late Eocene volcanic centers in the Coast Range. In major element composition, REE patterns, Th-Hf-Ta ratios, and petrographic characteristics, the Tillamook Volcanics in the thesis area are comparable to volcanic rocks in an oceanic island tectonic setting.

Sedimentary rocks of the late Eocene Cowlitz Formation depositionally overlie and flank the Tillamook Volcanics in the thesis area. The Cowlitz Formation is characterized by arkosic, micaceous,

and carbonaceous sandstones, siltstones, and mudstones. Quartz, plagioclase, K-feldspar, and mica are the major detrital components of the sandstones of the Cowlitz Formation, and the detrital composition indicates a continental, metamorphic and/or plutonic provenance. Lithofacies, sedimentary structure, stratification sequences, and fossil paleoecology are interpreted to indicate a storm-influenced or storm-dominated, paleodepositional environment in a nearshore, shallow marine, shelf basin. This basin was located on the Eocene continental margin. The Tillamook Volcanics formed a paleotopographic, volcanic high on the westward side of this basin.

The Cowlitz Formation is unconformably overlain by the Keasey Formation, which is Oligocene in age. The Keasey Formation consists of tuffaceous, fossiliferous siltstones and mudstones that were deposited in a deep, cool water environment.

The upper Nehalem River-Wolf Creek area is structurally deformed by northwest- and northeast-trending faults. The dominant fault trend is N50° to 70°W, and a less prominent trend is N20° to 40°E. The northwest-trending Gales Creek fault is transverse to the southwest part of the thesis area. The style of faulting indicates a pattern of northwest-trending, en echelon faults.

STRATIGRAPHIC RELATIONSHIPS OF THE
TILLAMOOK VOLCANICS AND THE COWLITZ
FORMATION IN THE UPPER NEHALEM
RIVER-WOLF CREEK AREA, NORTHWESTERN
OREGON

by

MICHAEL KEITH JACKSON

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

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Portland State University

1983

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

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INTRODUCTION

PURPOSES OF INVESTIGATION

The Coast Range of northwestern Oregon is underlain by Tertiary submarine and subaerial basaltic lava flows plus marine sedimentary strata that were formed in response to a tectonically active continental margin. Recent discoveries of commercially productive natural gas reservoirs in the Oregon Coast Range have promoted a growing interest in the stratigraphy and structure of these volcanic and sedimentary units. In 1979-1980, four graduate students at Portland State University mapped the sedimentary strata in the vicinity of the Mist Gas Field in Columbia County, which is the location of the initial discovery. This study has been undertaken to extend the geologic mapping in an area immediately to the south of the Mist project area in Washington and Tillamook Counties. The purposes of this thesis are:

- 1) to map and describe the Eocene volcanic rocks and Cowlitz Formation in the upper Nehalem River-Wolf Creek area
- 2) to determine the stratigraphic relations between the Eocene volcanic rocks and sedimentary units of the Cowlitz Formation
- 3) to postulate a paleoenvironment of deposition for the sandstones of the Cowlitz Formation.

LOCATION, GEOGRAPHY, AND ACCESS

The study area is located in the northwestern part of Washington County and the northeastern part of Tillamook County (Figure 1). It lies within E1/2 T3N, R6W and T3N, R5W (excluding the east half

Figure 1. Location map of the thesis area.

of sections 1, 12, 13, 24, 25, and 36, T3N, R5W) and encompasses approximately 125 km².

The Tillamook Highlands, which are underlain by volcanic rocks, form a rugged, mountainous terrain to the west and southwest of this study area. The Nehalem River and its tributaries form the major drainage system in the northern part of the Oregon Coast Range. The headwaters for the Nehalem River originate on Giveout Mountain, which is located in the southwestern part of the map area. It follows a generally easterly course in the west half of the map area, then, a northerly to northeasterly course in the east half of the area. Wolf Creek, Lousignont Creek, and Derby Creek also have headwaters in the west half and follow generally easterly flow directions.

Access to the study area is very good. The area is approximately 65 km northwest of Portland, Oregon, via U. S. Highway 26. This highway approximately delineates the northern boundary of the study area. Gravelled county roads and private logging roads provide access to the core of the area, and these roads are generally passable to year-round travel. A line of the Southern Pacific Railroad parallels the southern boundary of the map area and provides pedestrian access to some key outcrop locations.

Due to the abundant, luxuriant growth of vegetation in the Coast Range, bedrock exposures are limited to roadcuts and railway cuts and to the beds and banks of major streams. Where roadcuts have been exposed for several years, the rock is frequently weathered and bedding attitudes are often affected by slumping. Of

course, the sedimentary rocks, which are poorly indurated, are more adversely affected by weathering than the more resistant outcrops of basalt.

METHODS OF INVESTIGATION

Field work for this thesis was conducted in 1981, during late summer and early fall; thereafter, field work was performed intermittently during the spring, 1982, as weather permitted. This work consisted of geologic mapping at a scale of 1:24,000 and lithologic descriptions of the volcanic and sedimentary rocks. During the execution of the mapping, representative rock samples were collected for laboratory analysis. Attitudes of bedding surfaces and shears were measured with a Brunton compass, and stratigraphic sections were measured with a staff and Brunton compass.

A composite mylar of four U.S.G.S. 7.5 minute topographic quadrangles--Cochran, Timber, Sunset Spring, and Clear Creek--was assembled to provide several copies for field and sketch maps. High altitude aerial photographs, with a scale of 1 inch equals 1 mile, were used for field location and geologic interpretation of tectonic structure. Side Looking Radar Imagery (SLAR), with a scale of 1:250,000, were also analyzed for geologically produced linears. All linears were checked in the field for direct evidence of faulting.

Laboratory work was completed during the winter and spring months, 1982. Thin sections were made of 18 sedimentary and 23 volcanic rocks for petrographic study. The sedimentary rock thin

sections were prepared commercially in the laboratory of R. von Huene, Pasadena, California, while the volcanic rock thin sections were prepared by the author using the facilities at P.S.U. and at Lewis and Clark College.

Nineteen basalt samples were analyzed for major oxide chemistry by x-ray fluorescence at Washington State University by Dr. Peter Hooper. Fifteen of these samples were also analyzed for minor and trace element composition, plus Na and Fe, by Instrumental Neutron Activation Analysis. INAA was executed by the author at P.S.U., and the procedure is discussed in Appendix I.

Paleontological samples were examined for quality of fossil preservation and appropriate stratigraphic location. Then, selected samples were forwarded to professional consultants for identification: Foraminifera were identified by Daniel McKeel, megafossils by Elizabeth Nesbitt and R. E. Thoms, trace fossils by C. Kent Chamberlain, and plant fossils by Howard Schorn. (These consultants are identified in Appendices III, IV, V and VI, respectively.)

PREVIOUS WORK

The geology of the upper Nehalem River basin has been under investigation for almost a century. In the earliest geologic report on the northern Oregon Coast Range, Diller (1896) described the Tertiary sedimentary units that are located along Rock Creek upstream from the community of Vernonia. Subsequent to Diller's study, many paleontologists have reported on the generally well-preserved Tertiary molluscan fauna.

In 1945, Warren, Norbistrath, and Grivetti, U.S.G.S. geologists, published a geologic map of northwestern Oregon in the area north of latitude 45°15' N, as part of a war-related oil and gas exploration project. Until recent years, this map has not been modified and has been the accepted geologic map of the upper Nehalem River basin area. In 1946, Warren and Norbistrath elaborated on the stratigraphy by giving lithologic and paleontologic descriptions of the Tertiary formations. They described three distinct groups of rocks: Tillamook Volcanics, marine sedimentary strata, and Columbia River basalt. The marine strata include the Cowlitz, Keasey, Pittsburg Bluff, and Scappoose Formations.

Deacon (1953) revised the upper Eocene and lower Oligocene stratigraphy in the upper Nehalem River basin. Deacon believed the Cowlitz Formation in Oregon was lithologically dissimilar to the type locality on the Cowlitz River in southwestern Washington. Thus, he proposed the Rocky Point Formation for the Cowlitz Formation and the Nehalem Formation for the lower part of Keasey Formation. This stratigraphic nomenclature has not been accepted by later investigators of the region.

Van Atta (1971) studied the petrology of the sedimentary units in the upper Nehalem River basin. He discussed the petrographic characteristics for each of the Tertiary sedimentary formations and discussed the similarities in lithologies, stratigraphy, and environment of deposition of the Cowlitz Formation in Oregon and Washington.

REGIONAL GEOLOGY

TECTONIC AND DEPOSITIONAL SETTING

The Coast Range of Oregon is underlain by more than 7600 meters of Tertiary volcanic and sedimentary rocks that accumulated in a marginal marine basin (Snively and Wagner, 1964). This marine basin extended from the site of the present Klamath Mountains to the Olympic Peninsula, and it has undergone a complex tectonic and depositional history as a result of relative movement between the North American and Pacific plates (Snively and Wagner, 1963; Snively, MacLeod, and others, 1980).

In the Oregon Coast Range, the oldest rocks exposed are pillow lavas and breccias and interbedded basaltic sandstones and siltstones. These volcanic strata of early and middle Eocene age are referred to the lower unit of the Tillamook Volcanics (Snively and others, 1970), the Siletz River Volcanics (Snively and others, 1968), and the Roseburg Formation (Baldwin, 1974) in the northern, central, and southern parts of the Coast Range, respectively. Correlative units in western Washington are the Crescent Formation and Metchosin Volcanics (Snively and Wagner, 1963). The Siletz River Volcanics have been studied in greatest detail. In the lower part, these volcanic rocks consist of tholeiitic basalts that have a chemical composition similar to oceanic ridge basalt (Snively, MacLeod and others, 1980). Locally, the Siletz River Volcanics

developed into subaerial volcanic piles (i.e. islands) constructed above the oceanic ridge basalts.

By middle Eocene time, this early to middle Eocene oceanic crust, which represents the basement of the Coast Range, had been accreted to the continental margin, and an inferred subduction zone shifted westward from the position of the present Cascade Range to the present inner continental shelf. East of the new zone of underthrusting, a deep marginal basin accumulated over 2000 meters of turbidite sandstone and siltstone of the Tyee, Flourney, and Yamhill Formations in the central and southern Coast Range (Snively, Wagner, and Lander, 1980; Baldwin, 1974, 1981). These formations are middle and early late Eocene in age, and correlative with tuffaceous siltstone and sandstone that are found in the middle unit of the Tillamook Volcanics (Snively and others, 1970).

Snively, Wagner, and Lander (1980) infer that the Oregon Coast Range, at least in the central part, underwent episodes of transform faulting between the North American and Pacific plates in the late middle or early late Eocene, plate convergence in middle late Eocene, and extension in late Eocene through middle Miocene time. These intermittent changes in relative plate motion produced increasingly segmented shallow shelf basins along the continental margin (Baldwin, 1981).

Volcanism continued on the continental margin during late Eocene time with the eruption of mostly subaerial flows from local volcanic centers (Snively and MacLeod, 1974). These volcanic sequences occur in several places in the Oregon Coast Range with

different names. They include the Yachats Basalt and flows at Cascade Head on the central coast and the upper unit of the Tillamook Volcanics and the Goble Volcanics in the northern Coast Range (Snively and others, 1970; Snively and MacLeod, 1974).

GENERAL STRATIGRAPHY OF NORTHERN OREGON COAST RANGE

The rock stratigraphic units of the northern Oregon Coast Range, in the vicinity of the map area for this thesis, have been divided into three distinct groups: the Eocene Tillamook Volcanics, late Eocene to middle Miocene marine sedimentary strata, and middle Miocene Columbia River Basalt Group (Warren and Norbistrath, 1946; Baldwin, 1981). The Tillamook Volcanics are structurally exposed in a large northward plunging anticlinorium, and late Eocene to middle Miocene tuffaceous mudstones and siltstones plus arkosic and volcani-clastic sandstones flank this basaltic, structural highland (Warren and Norbistrath, 1946).

On the basis of reconnaissance mapping, Snively and others (1970) divided the Tillamook Volcanics into three units: 1) a lower unit, which has an unknown thickness, is comprised of basaltic pillow lavas, submarine breccias, and tuffs and interbedded sedimentary rocks, 2) a middle unit, which is 760 meters thick, is comprised of tuffaceous siltstone, sandstone, basaltic tuff, pillow lavas, and breccias, and 3) an upper unit, which is 1500 meters thick, consists of subaerial basalt flows. Respectively, these units are assigned ages of early to middle Eocene, middle and early late Eocene, and late Eocene.

On the northeastern flank of the Tillamook Volcanics, the sedimentary stratigraphic section is composed of the Cowlitz, Keasey, Pittsburg Bluff, and Scappoose Formations. (See Figure 2 for stratigraphic correlations).

The Cowlitz Formation is comprised of more than 300 meters of micaceous arkose and carbonaceous, micaceous siltstones and mudstones (Van Atta, 1971). Warren and Norbistrath (1946) stated that the Cowlitz Formation unconformably overlies the Tillamook Volcanics, while Wilkinson and others (1946) and Van Atta (1971) show the Cowlitz Formation as interfingering with Goble Volcanics. The depositional environment of the Cowlitz Formation has been interpreted as part of a marine strait between volcanic highlands (Bruer, 1980) or as a shallow marine, nearshore basin (Van Atta, 1971). The Cowlitz Formation is late Eocene in age (upper Narizian Foraminiferal Stage of Mallory, 1959). It is correlative with the Coaledo Formation in the southern Oregon Coast Range and the Spencer Formation in the central Coast Range.

The Keasey Formation is comprised of more than 700 meters of tuffaceous mudstones and siltstones that were deposited at bathyal depths on the outer shelf or upper slope (McDougall, 1975; Baldwin, 1981). The Keasey Formation is assigned an early Oligocene age (Refugian Stage). It is correlative with the Bastendorf Formation in the southern Oregon Coast Range, part of the Alsea Formation in the central coast, and the lower part of the Lincoln Creek Formation in southwest Washington (Niem and Van Atta, 1973).

Series	West Coast Foraminifera Stages	Southern Oregon Coast Range (Snaveley, MacLeod and others, 1980)	Central Coast Oregon (Snaveley and others, 1976a, b, and c)	Upper Nehalem River basin, N. W. Oregon (Van Atta, in prep)	Upper Nehalem River-Wolf Creek area, N. W. Oregon (This report)	Southwestern Washington (Wells, 1981)
Miocene	Saucesian		Miocene basalts (CRBG)	Columbia River Basalt Group	Columbia River Basalt Group	Columbia River Basalt Group
		Astoria Formation	Scappoose Fm.	Scappoose Fm. (Astoria Fm.?)	Astoria Formation
Oligocene	Zemorrian		Nye Mudstone
		Yaquina Formation		Pittsburg Bluff Formation	Lincoln Creek Formation
Eocene	Refugian		Alsea Formation	Keasey Formation	Keasey Formation	
		Bastendorf Formation				
	Narizian	Coaledo Formation	Yachats Basalt Nestucca Formation	Goble Volcanics Cowlitz Formation	Cowlitz Formation Tillamook Volcanics	Skamokawa Creek Sandstone Goble Volcanics Cowlitz Formation

Figure 2. Correlation Chart for Coast Ranges in Oregon and southwestern Washington.

The Pittsburg Bluff and Scappoose Formations are composed of arkosic sedimentary rocks that were deposited in a shallow marine basin and as part of a deltaic environment, respectively. Neither of these two formations nor the Columbia River Basalt Group are exposed in the study area.

TILLAMOOK VOLCANICS

The volcanic rocks in the upper Nehalem River-Wolf Creek area are assigned to the upper unit of the Tillamook Volcanics. However, the volcanic rocks in the thesis area will be referred to as the upper Nehalem River-Wolf Creek volcanics, when they are compared to other upper Eocene volcanic rocks in the northern part of the Oregon Coast Range.

The Tillamook Volcanics are restricted to the western half of the map area, except for one outcrop of a basalt flow overlain by basaltic sandstone in NW1/4 sec. 2, T3N, R5W. The volcanic rocks form topographic highs with fairly steep slopes, since the poorly indurated Tertiary sedimentary strata are easily eroded away from the volcanic terrane.

LITHOLOGY

The Tillamook Volcanics in the study area consist chiefly of subaerial basalt and basaltic andesite flows. Chemically, some flows classify as andesites, but this distinction is not apparent in the field. Therefore, the flows are collectively referred to as basalts. Submarine breccias and pillow lavas were not observed in the thesis area.

In fresh, unweathered hand samples, the basalts are dark to medium gray, very fine-grained to aphanitic, and microphyric to sparsely phytic. The microphenocrysts and phenocrysts are

plagioclase and, less commonly, pyroxene. Occasionally, bladelike, euhedral plagioclase phenocrysts are up to 2 cm in length. Upon weathering, a thick rind of tan to orange colored clays develops over the basalt. In south-facing outcrops and especially along shear zones, the basalt may become "bleached" to a light gray color which imparts a resemblance to a fine-grained sedimentary rock.

The subaerial basalt flows range in thickness from 5 to 10 meters. The base of a typical flow unit is brecciated and rubbly, and it is overlain by dense, jointed basalt. Irregular, blocky jointing is most common, although crude columnar jointing is present in some outcrops. Tectonic shearing accentuates the jointing and fracturing in the rock. The upper part of a typical flow is vesicular and is oxidized to reddish and/or greenish colors. The vesicular zones are commonly amygdaloidal with zeolites and calcite. Also, shear planes are commonly lined with calcite, zeolites, pyrite and silica.

Typical exposures of the basalt flows can be observed along Highway 26, in the vicinity of Lousignont Creek and Hawkins Pit, and in the southwest part in the map area in tributary streams to the Nehalem River. The best exposure is adjacent to the Southern Pacific (SP) Railroad track in the vicinity of Reliance Creek (N1/2 sec. 35, T3N, R6W). At least four different flows are exposed in four discontinuous outcrops. Chemical analyses on these flows are given in Tables III and IV (p. 35-37, samples MJ-11-18-2, 11-28-1, 11-28-2, and 11-20-1). The lower part of each flow is rubbly while the upper part is amygdaloidal and vesicular (Figure 3). A reddish

Figure 3. Typical appearance of subaerial basalt flows in the Tillamook Volcanics. The flows display crude columnar jointing, rubbly base, and oxidized basal contacts. Top of lower flow is amygdaloidal and vesicular. In photograph, upper flow is sample MJ-11-18-2; lower flow, MJ-11-28-2. Hammer (at contact) is 33 cm in length. (SP Railroad track, SW $\frac{1}{4}$ SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 26, T3N, R6W.)

clay zone separates the individual flows, which are approximately 5 to 8 meters thick. The basalt is irregularly jointed which is made more pronounced in places by vertical shear zones. The shears are up to one meter wide and have a N40° to 70°W orientation.

On the east side of Reliance Creek, a greenish, poorly sorted, pebbly coarse-grained basaltic sandstone overlies the upper flow unit. On the west side of Reliance Creek, in the second and third outcrops, an agglutinate is exposed as the lowest unit. The upper part of the agglutinate has a rubbly, clastic-like texture, but the lower part of the unit is massive. The agglutinate contains large euhedral pyroxene crystals that are up to 0.5 cm in length. These phenocrysts are set in an aphanitic groundmass. Furthermore, in the third outcrop, a meter-wide basaltic dike cuts the agglutinate and has a N50°W trend. The agglutinate and dike suggest proximity to a vent.

Pyroclastic rocks form a minor part of the Tillamook Volcanics in the study area. They are principally subaerial lithic-crystal-vitric tuffs and lapilli tuffs, that contain plagioclase, pyroxene (augite), and basaltic lithic fragments. The groundmass is palagonite, which imparts a buff-brown color to the weathered rock. Individual pyroclastic units are generally thinner than basalt flow units.

Basaltic cobble to boulder conglomerates and pebbly to cobbly sandstones are interbedded with the subaerial basalt flows and pyroclastic rocks (Figures 4, 5 and 6). These volcanic sedimentary interbeds consist of subangular to subrounded, poorly sorted clasts

PROFILE	THICKNESS (METERS)	UNIT	DESCRIPTION
	20 m	VI	Weathered, cobble to boulder basaltic conglomerate; subangular to subrounded, poorly sorted, clast- to matrix-supported clasts; unstratified; boulders up to 2 m in diameter; sharp lower contact
	1 m	V	Greenish, pebbly basaltic sandstone; poorly sorted, unstratified, ungraded
	10 m	IV	Dark gray, phyric basalt; plagioclase and pyroxene phenocrysts; rubbly base, crudely columnar, amygdaloidal
	8 m	III	Greenish, pebbly to cobbly basaltic sandstone/conglomerate; horizontally stratified; sharp contacts
	9 m	II	Weathered, brown, lithic-crystal-vitric lapilli tuff; plagioclase and pyroxene phenocrysts; basalt lithic fragments; well-indurated at top, variable thickness; slickensides
	18 m	I	Weathered, cobble to boulder basaltic conglomerate; subrounded to rounded, poorly sorted, clast- to matrix-supported clasts; crude lenses of pebbly sandstone; ungraded

Figure 4. Unnamed creek section in the Tillamook Volcanics (approximately $\frac{1}{2}$ km northwest of the confluence with the Nehalem River, NE $\frac{1}{4}$ sec. 25, T3N, R6W).

Figure 5. Hawkins Pit section in the Tillamook Volcanics (NE $\frac{1}{4}$ sec. 19, T3N, R5W). Contact with the Cowlitz Formation is shown in the figure.

VI--Weathered, yellowish brown, mudstone (Cowlitz Formation).

V--Weathered, pebble basaltic conglomerate; poorly sorted, uneven lower contact with basalt, upper contact gradational into mudstone.

IV--Dark gray, microphyric basalt; plagioclase microphenocrysts; blocky jointing; numerous vertical shear zones.

III--Weathered, cobble to boulder basaltic conglomerate; subangular to subrounded, poorly sorted clasts with clast- support to matrix-support; crudely stratified layers; boulders up to 2 m; sharp lower contact.

II--Weathered, greenish, pebbly to cobbly basaltic sandstone; poorly sorted, unstratified; base not exposed.

I--Dark gray, microphyric basalt (2 flows); plagioclase microphenocrysts; blocky jointing, vesicular; overlies cobble to boulder conglomerate (not shown in figure).

Scale (approximate)--Horizontal, 1 cm = 15 m; Vertical, 1 cm = 3.3 m.

A.

Lapilli
tuff

Conglom-
erate
(3 units)

B.

Basalt

Horizon-
tally
stratified
sandstone/
conglom-
erate

Lapilli
tuff
(and
talus)

Figure 6. A. Basaltic conglomerate exposed in the unnamed creek section (unit I), with lapilli tuff (unit II) partially covered at the top of the photograph. B. Light brown, lapilli tuff (unit II), horizontally stratified, basaltic sandstone and conglomerate (unit III), and basalt (unit IV) exposed in the unnamed creek section. Note the dark gray, indurated upper part of the lapilli tuff. (NE¼ sec. 25, T3N, R6W.)

of aphyric to phyrlic basalt, vesicular basalt and pyroclastic rocks that are locally derived from Eocene volcanic rocks in the Coast Range. Boulders are up to 2-3 meters in diameter in the coarser grained conglomerates. Using the descriptive features of conglomerate (Figure 7), as discussed by Harms and others (1975), clasts in these volcanic sedimentary interbeds are either matrix-supported or partly framework-supported and lack a preferred orientation (Figure 8). Stratification ranges from non-existent to crude, discontinuous layers to horizontal stratification (Figures 6 and 8). Cross-bedding was not observed. Marine fossils are not present.

These basaltic conglomerates and sandstones that are interbedded with subaerial volcanic rocks probably represent subaerial, paleochannel deposits. The coarseness and poor sorting of the clasts plus the absence of well-developed framework-support and cross-bedding indicate a high energy, rapid transport of volcanic debris. The sedimentary interbeds that have matrix-supported clasts and do not display stratification, grading, or clast orientation are probably debris flow deposits (Figure 9). Mudflows are included within this category (Harms and others, 1975).

Adjacent to the SP Railroad track (SW1/4 sec. 25, T3N, R6W), approximately 30 meters of interstratified cobble to boulder basaltic conglomerates and pebbly to cobbly basaltic sandstones are overlain by very poorly stratified basaltic pebbly sandstones and pebble conglomerates. Fossil leaves of Equisetum (horsetail), Lastera (fern), and Platanophyllum (sycamore-like plant) were identified by H. Schorn (1982, written communication) from specimens that were

1. SORTING SIZE DISTRIBUTION

CLAST SUPPORTED
BIMODAL
MATRIX WELL SORTED

CLAST SUPPORTED
POLYMODAL
MATRIX POORLY SORTED

MATRIX SUPPORTED
POLYMODAL

2. FABRIC

a (p) a (i)

a (t) b (i)

UNORDERED FABRIC

3. STRATIFICATION

HORIZONTAL

INCLINED

UNSTRATIFIED

4. GRADING

NORMAL

INVERSE

UNGRADED

Figure 7. Primary sedimentary structures of conglomerate (from Harms and others, 1975).

Figure 8. Cobble to boulder basaltic conglomerate in the Hawkins Pit section (unit III) that displays poor sorting, a crude lens (at level of notebook), and crude clast-support. Notebook is 19 cm in length. (NE $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 19, T3N, R5W.)

Figure 9. Interpretation of conglomerate deposits (from Harms and others, 1975).

collected from this outcrop. Warren and Norbistrath (1946, p. 223) refer to this outcrop as being approximately 200 feet of basal conglomerate of the Cowlitz Formation.

Around the periphery of the mapped volcanic terrane, poorly sorted, basaltic conglomerates crop out that contain a marine megafauna and/or are overlain by marine mudrocks. This conglomerate lithofacies is not interbedded with basalt flows; instead, it depositionally overlies volcanic rocks. In the vicinity of Hawkins Pit and Lousignont Creek, a pebbly basaltic conglomerate overlies an irregular surface of basalt flows and grades upward to a weathered mudrock. In a small quarry on Wolf Creek Road (SW1/4 SE1/4 sec. 6, T3N, R5W), a fossiliferous pebble conglomerate overlies an eroded basalt flow and contains molds of Terebratala and ?Hemithyris (Nesbitt, 1982, written communication; sample M-8-25-1, Appendix IV). Up section from the conglomerate in the Wolf Creek Road quarry locality, a marine mudrock contains foraminifera specimens that are assigned to the upper Narizian stage (McKeel, 1982, written communication, sample F-8-25-10, Appendix III). Along Highway 26 to the west of Sunset Camp (E-W center line sec. 2, T3N, R6W), a fossiliferous, crudely stratified basaltic conglomerate depositionally overlies a basalt flow in an apparent wedge-shaped deposit and contains sheared basalt clasts that are up to 1.5 meters in diameter. This conglomerate lithofacies which is locally fossiliferous and/or overlain by marine mudrocks probably represents volcanic debris being shed into a marine basin surrounding an emergent, volcanic high.

PETROGRAPHY

Twenty-one basalt, two pyroclastic and four volcanic sedimentary rock samples were examined in thin section. Seven basalt and three volcanic sedimentary rock thin sections were selected for point count analysis. Point counts were performed after careful preliminary study of all slides. Five hundred points per slide were counted at $2/3$ mm intervals in rows that were spaced $1\frac{1}{3}$ mm apart (50 points per row, 10 rows).

Basalts and Pyroclastic Rocks

Petrographically, the volcanic flow rocks in the upper Nehalem River-Wolf Creek area range in composition from basalt to basaltic andesite. Point count results are given in Table I. Most samples are microphyric to sparsely phytic or glomeroporphyritic. Phenocrysts are generally less than 5 mm in length, and microphenocrysts are less than 3 mm in length but distinct from the groundmass. Phenocrysts and microphenocrysts are predominantly plagioclase, although pyroxene is common and a few magnetite-ilmenite crystals are present as microphenocrysts. Figure 10 is a photomicrograph of a basalt sample.

The plagioclase microphenocrysts and phenocrysts are lath-shaped, tabular crystals that are euhedral to subhedral in outline although some phenocrysts are corroded along their edges. Compositionally, the plagioclase classifies as labradorite (An_{55} to An_{65}). When normal zoning is present, the rims have a more sodic composition (An_{45} to An_{50}) than the cores (An_{55} to An_{65}). Oscillatory zoning is not as prevalent as normal zoning; reverse zoning is not observed.

TABLE I

MODAL COMPOSITION OF SELECTED BASALTS FROM THE TILLAMOOK VOLCANICS

	11-28-1	11-28-2	10-10-2	10-4-1	10-4-5	11-20-2	11-21-1
<u>Phenocrysts and</u> <u>Microphenocrysts</u>							
Plagioclase	10.2	8.0	0.8	4.0	3.5	5.0	15.8
Ol(?) Altered	0.8	-	-	-	-	-	-
CPX	3.6	2.0	0.6	-	-	0.2	0.6
Mag-Ilm	-	-	2.0	-	-	-	0.2
<u>Groundmass</u>							
Plagioclase	37.8	42.2	52.5	51.0	52.1	51.0	47.4
CPX	32.2	28.6	38.6	26.0	28.2	26.8	26.2
Mag-Ilm	12.6	12.6	3.2	11.2	11.8	13.0	8.2
Clays, undiff.	-	2.0	-	-	0.6	0.4	-

1 mm

Figure 10. Photomicrograph of a typical Tillamook Volcanics basalt under crossed nicols. Microphenocrysts of plagioclase and augite with a glomeroporphyritic texture. The intergranular groundmass is composed of plagioclase, pyroxene, opaques, and glass/clays. Note the large, dark brown glass(?), which is altered to clay in the center and in the upper left quarter of the photograph. (Sample MJ-11-28-2.)

Twinning is very common with both Albite and combined Albite-Carlsbad types, while Pericline twinning is very rare. Inclusions, especially of devitrified volcanic glass, are frequently seen in the phenocrysts.

The pyroxene microphenocrysts and phenocrysts are generally colorless to pale green and have inclined extinction, a moderate $2V_z$ ($\approx 50^\circ$ - 60°), weak pleochroism (if any), and first-order to low second-order birefringence. Thus, the pyroxene is mostly augite. A few pyroxene phenocrysts with a $2V_z \approx 25^\circ$ - 30° and inclined extinction are pigeonite. Orthopyroxene was not observed in any thin sections. The pyroxene phenocrysts usually have a subhedral, equant or stubby shape, and they occur as single phenocrysts or are commonly glomeroporphyritic with plagioclase. Both zoning and twinning are seen in some pyroxene crystals.

Questionable altered olivine phenocrysts are seen in a few thin sections, most notably sample MJ-11-28-1. These doubtful phenocrysts have a subhedral to anhedral outline and are replaced by smectitic clays which in turn are stained by the orange-brown color of iron oxides. Since a relict crystal structure is not identifiable, these "phenocrysts" are probably volcanic glass.

The fine-grained groundmass consists of plagioclase, pyroxene, magnetite-ilmenite, glass (or its alteration products) and minor apatite. The groundmass texture is intergranular and commonly pilotaxitic. Plagioclase in the groundmass forms about 38 to 53 percent of the rock, and pyroxene about 26 to 32 percent. The groundmass pyroxene is predominantly augite with minor pigeonite,

and it is usually anhedral or granular in outline. The plagioclase is mostly subhedral laths of calcic andesine and labradorite (An_{45} to An_{55}). Both Albite and combined Albite-Carlsbad twinning and both oscillatory and normal zoning are observed in the larger crystals of the groundmass. Opaques are an ubiquitous component of the groundmass and form 8 to 13 percent of the rock, except for sample MJ-10-10-2. A few opaque grains are probably pyrite since they reflect light, but magnetite-ilmenite is predominant. Smectitic clays, which have an orange-brown iron oxide stain, enclose relict, devitrified volcanic glass and are interstitial among the minerals in the groundmass. Clays form about 1 to 7 percent of the rock.

Sample MJ-10-10-2 is petrographically distinct from the other basalt samples. It has a subophitic texture instead of an intergranular one, is less phyrlic, and has a coarser grained groundmass than the other samples.

Two pyroclastic rocks were examined in thin section. The two samples are lithic-crystal-vitric lapilli tuffs. Plagioclase and pyroxene phenocrysts plus basaltic lithic fragments are set in a brown, palagonitic groundmass. The plagioclase is composed of labradorite (An_{50} to An_{60}) that displays normal zoning. The plagioclase phenocrysts are commonly embayed, although an euhedral to subhedral outline is usually preserved. The pyroxene phenocrysts are mostly augite and less commonly pigeonite, and both are less common than plagioclase. The lithic fragments consist of phyrlic to aphyric basalt and glassy tuff fragments, that are angular to subangular in

outline. Phenocrysts and lithic fragments are up to 5 mm in length in thin section. The palagonitic matrix contains glass shards and plagioclase crystals.

Volcanic Sedimentary Rocks

Four thin sections were made of representative samples of the pebbly volcanic sandstone. Point count data on three samples is given in Table II. The clasts in these volcanic sedimentary rocks are volcanic rock fragments (VRF), plagioclase, and pyroxene (Figure 11). VRF's are predominantly phyric to aphyric basalt. Glassy pyroclastic fragments are also present as clasts. The VRF's are mineralogically and texturally similar to the basalt flows in the study area: Plagioclase phenocrysts in the clasts are compositionally labradorite (An_{55} to An_{60}) and the basalt clasts have an intergranular, microphyric to sparsely phyric texture. The VRF's are subangular to subrounded with diameters up to 4 mm in thin section. Plagioclase and pyroxene are minor detrital constituents that compose 7 to 18 percent of the samples, and these crystals range from 0.2 to 1.5 mm in length. The plagioclase clasts, again, are compositionally labradorite (An_{50} to An_{60}), display Albite and combined Albite-Carlsbad twinning, and are normally zoned (when present). The pyroxene is augite. The clasts are matrix-supported in a matrix of fine-grained VRF's, plagioclase, clay, and a minor amount of carbonate cement. The matrix forms 13 to 23 percent of the rock.

TABLE II

MODAL COMPOSITION OF SELECTED VOLCANIC
SEDIMENTARY ROCKS FROM THE TILLAMOOK VOLCANICS

	<u>11-27-1</u>	<u>10-3-2</u>	<u>2-20-1</u>
Plagioclase	6.6	6.6	17.4
VRF	74.6	64.0	65.0
Pyroxene	1.6	0.6	1.0
SRF	-	-	-
Matrix	17.2	23.3	12.6
Mag-Ilm	-	0.6	-
Quartz	-	-	3.2
Undiff	-	4.9	0.6

1 mm

Figure 11. Photomicrograph of a pebbly to cobbly basaltic sandstone interbedded in the Tillamook Volcanics under plane polarized light. Clasts in the photograph are plagioclase (clear) and microphyric basalt with plagioclase microphenocrysts. Pyroxene occurs in the rock, but it is not seen in the photograph. The matrix is composed of clay. (Sample MJ-11-27-1.)

Petrographically, these four volcanic sedimentary rock samples classify as volcanic litharenites and feldspathic litharenites in McBride's (1963) classification (Figure 12). The similarities in composition of the clasts in these four samples to the Tillamook Volcanics in the study area indicate that the volcanic sedimentary rocks were locally derived from source rocks in the Coast Range. The only significant petrographic distinction among the samples is the presence of quartz in sample MJ-2-20-1. However, vug-filling quartz is occasionally seen in the basalt flows in both hand samples and thin section.

GEOCHEMISTRY

Nineteen basalt samples from the upper Nehalem River-Wolf Creek area were analyzed for major element chemistry. The results are listed in Table III. The first 16 samples are flow rocks, and the last 3 samples are clasts from cobble to boulder conglomerates. Fifteen of the flow rocks were additionally analyzed for Na, Fe, and minor and trace element geochemical composition (Table IV). The locality for each sample is given in Appendix II and is shown on Plate I.

Chemical Composition

The rocks are varied in chemical composition, as seen in Tables III and IV. The flows range in composition from 49.9 to 59.8 percent SiO_2 , which represents a range from basalt to andesite. The average composition for the samples is 52.6 percent SiO_2 , which classifies as a basaltic andesite. Two of the clasts, samples

Figure 12. Classification of the volcanic sedimentary rocks interbedded with the Tillamook Volcanics (after McBride, 1963). Q= quartz, C= chert, F= feldspar, RF= rock fragments.

TABLE III

MAJOR OXIDE ANALYSES OF VOLCANIC ROCKS FROM THE TILLAMOOK VOLCANICS*

	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	FeO	MnO	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅
8-21-5	51.03	13.87	3.49	6.11	7.00	0.32	9.10	3.34	1.62	3.52	0.61
11-20-2	53.87	13.91	2.85	5.43	6.22	0.27	7.67	3.01	1.32	4.38	1.06
11-20-3	51.60	13.98	3.33	5.76	6.59	0.41	8.83	3.28	1.40	4.04	0.78
9-4-3	53.34	13.97	2.59	5.79	6.63	0.34	7.45	3.11	1.26	4.30	1.22
11-21-1	53.72	14.62	2.65	5.32	6.10	0.20	8.21	2.85	1.32	4.31	0.69
11-21-5	53.49	13.10	2.91	5.93	6.79	0.23	7.94	3.02	1.41	4.03	1.15
11-21-6	52.85	13.27	2.90	5.74	6.58	0.21	8.22	3.31	1.60	4.13	1.17
10-4-1	52.21	14.29	2.73	5.85	6.70	0.26	8.16	2.87	1.40	4.27	1.25
10-4-5	53.04	13.71	3.01	5.48	6.28	0.20	8.31	3.25	1.56	4.13	1.03
10-8-4	52.37	13.81	3.03	5.80	6.64	0.16	7.83	3.16	2.18	4.04	0.96
9-17-3	52.11	14.33	3.14	5.93	6.80	0.16	7.56	3.05	1.91	4.01	1.01
10-17-1	59.75	14.27	1.64	4.85	5.56	0.21	5.45	1.61	0.98	5.02	0.66
11-18-2	50.25	12.81	3.55	6.83	7.82	0.24	9.34	4.36	0.99	3.30	0.49
11-28-1	50.09	13.38	3.32	6.33	7.25	0.24	10.45	4.33	0.89	3.21	0.50
11-28-2	51.27	13.05	3.29	6.15	7.05	0.24	9.83	4.34	1.04	3.23	0.52
11-20-1	49.92	13.59	3.31	6.29	7.21	0.22	9.88	4.37	1.51	3.18	0.51
8-21-2**	64.03	15.77	1.02	3.39	3.88	0.18	4.06	0.88	1.04	5.45	0.30
9-29-7**	62.19	14.91	1.08	4.13	4.73	0.20	4.75	1.19	1.28	5.19	0.34
11-27-2**	54.24	13.85	3.13	5.38	6.16	0.25	8.40	2.75	1.19	4.04	0.61

* All analyses in weight percent

** Conglomerate clast

TABLE IV

Na, Fe AND MINOR AND TRACE ELEMENT ANALYSES OF
VOLCANIC ROCKS FROM THE TILLAMOOK VOLCANICS

	Na	Sc	Fe	Co	Sr	Zr	Ba	La	Ce
8-21-5	3.02 ± .02	25.53 ± .08	12.56 ± .07	39.4 ± .5	340 ± 110	--	350 ± 110	35.2 ± .7	82 ± 3
11-20-2	4.39 ± .03	21.23 ± .11	13.57 ± .12	26.9 ± .6	490 ± 180	--	540 ± 170	55.2 ± 1.3	145 ± 5
11-20-3	3.60 ± .02	21.09 ± .07	11.54 ± .08	29.1 ± .4	500 ± 150	--	350 ± 110	40.3 ± .8	96 ± 3
11-21-1	3.59 ± .02	17.53 ± .06	10.58 ± .07	27.2 ± .4	420 ± 120	58 ± 17	330 ± 100	38.4 ± .8	88 ± 3
11-21-5	3.65 ± .02	18.47 ± .06	11.67 ± .07	25.6 ± .4	340 ± 110	87 ± 19	370 ± 110	46.5 ± .9	111 ± 3
11-21-6	4.00 ± .02	20.34 ± .08	12.86 ± .09	30.2 ± .5	--	100 ± 20	440 ± 130	48.0 ± 1.0	120 ± 4
10-4-1	3.75 ± .02	16.00 ± .07	12.00 ± .08	24.5 ± .4	450 ± 130	78 ± 19	500 ± 130	52.3 ± 1.0	124 ± 4
10-4-5	3.48 ± .01	17.68 ± .05	11.81 ± .07	26.2 ± .4	480 ± 140	--	310 ± 90	42.7 ± .8	102 ± 3
10-8-4	3.50 ± .01	17.50 ± .05	11.16 ± .07	21.8 ± .3	380 ± 110	71 ± 17	400 ± 110	43.8 ± .9	102 ± 3
9-17-3	3.43 ± .01	18.34 ± .06	11.72 ± .08	22.9 ± .4	400 ± 130	75 ± 19	400 ± 110	46.8 ± .9	112 ± 3
10-17-1	4.58 ± .02	13.76 ± .06	9.41 ± .06	9.6 ± .2	330 ± 100	90 ± 18	450 ± 120	53.6 ± 1.0	125 ± 4
11-18-2	2.70 ± .01	26.10 ± .08	14.00 ± .08	59.2 ± .6	280 ± 100	80 ± 20	210 ± 80	29.4 ± .6	69 ± 2
11-28-1	2.71 ± .01	27.03 ± .09	13.03 ± .08	52.6 ± .6	390 ± 120	70 ± 20	300 ± 100	30.3 ± .7	70 ± 2
11-28-2	2.85 ± .01	25.17 ± .08	12.69 ± .09	43.8 ± .6	340 ± 120	--	240 ± 90	31.1 ± .7	71 ± 2
11-20-1	2.81 ± .01	25.40 ± .08	12.68 ± .07	46.0 ± .5	340 ± 110	--	230 ± 80	30.7 ± .7	74 ± 2
W-1*	2.15 ± .01	35.10 ± .05	11.09 ± .05	47.0 ± .4	200 ± 60	--	160 ± 80	9.8 ± .2	23 ± 9
Archo-1*	3.14 ± .01	27.15 ± .06	14.26 ± .06	30.7 ± .3	1700 ± 400	105 ± 19	1700 ± 400	40.9 ± .7	96 ± 3

* = Standard

TABLE IV (Cont'd)

Na, Fe AND MINOR AND TRACE ELEMENT ANALYSES OF
VOLCANIC ROCKS FROM THE TILLAMOOK VOLCANICS

	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ta	Th
8-21-5	35 ± 12	10.08 ± .11	3.03 ± .06	1.36 ± .14	3.5 ± .5	0.61 ± .13	6.9 ± .4	2.6 ± .4	4.7 ± .2
11-20-2	70 ± 20	18.08 ± .19	5.15 ± .10	2.30 ± .20	4.7 ± .8	0.72 ± .16	9.9 ± .6	3.3 ± .5	6.5 ± .4
11-20-3	51 ± 17	11.59 ± .12	3.48 ± .06	1.44 ± .13	3.9 ± .5	0.63 ± .11	7.4 ± .4	2.9 ± .4	4.8 ± .2
11-21-1	30 ± 11	10.52 ± .11	3.16 ± .06	1.44 ± .12	3.7 ± .5	0.54 ± .12	6.9 ± .4	2.9 ± .4	4.49 ± .19
11-21-5	--	13.67 ± .13	3.91 ± .07	1.85 ± .15	3.8 ± .5	0.66 ± .13	7.7 ± .4	3.0 ± .4	5.5 ± .2
11-21-6	60 ± 20	15.27 ± .15	4.39 ± .08	2.00 ± .16	4.4 ± .7	0.67 ± .12	8.4 ± .5	3.3 ± .5	5.1 ± .3
10-4-1	50 ± 16	14.90 ± .15	4.28 ± .08	1.94 ± .15	4.4 ± .6	0.70 ± .15	8.5 ± .4	3.6 ± .5	6.0 ± .2
10-4-5	--	12.55 ± .13	3.72 ± .06	1.65 ± .13	3.9 ± .5	0.64 ± .13	7.6 ± .4	3.2 ± .4	4.7 ± .2
10-8-4	--	12.60 ± .13	3.69 ± .06	1.65 ± .13	4.1 ± .6	0.60 ± .13	7.6 ± .4	2.9 ± .4	4.9 ± .2
9-17-3	--	14.01 ± .13	4.20 ± .07	2.04 ± .16	4.7 ± .7	0.76 ± .12	4.8 ± .2	2.9 ± .4	5.0 ± .2
10-17-1	--	13.97 ± .13	4.27 ± .08	1.93 ± .15	4.8 ± .6	0.73 ± .16	10.4 ± .5	3.4 ± .5	7.4 ± .2
11-18-2	28 ± 11	8.77 ± .09	2.67 ± .05	1.22 ± .12	3.1 ± .4	0.45 ± .11	5.9 ± .3	2.3 ± .3	3.3 ± .2
11-28-1	29 ± 12	8.39 ± .09	2.61 ± .05	1.10 ± .11	2.7 ± .4	0.47 ± .09	5.7 ± .3	2.3 ± .3	3.7 ± .2
11-28-2	44 ± 15	9.02 ± .10	2.67 ± .05	1.16 ± .11	2.3 ± .4	0.40 ± .08	6.3 ± .4	2.5 ± .3	3.6 ± .2
11-20-1	28 ± 11	8.71 ± .09	2.71 ± .05	1.20 ± .11	2.5 ± .4	0.48 ± .10	6.1 ± .4	2.3 ± .3	3.8 ± .2
W-1*	20 ± 6	3.60 ± .04	1.11 ± .02	0.65 ± .06	2.1 ± .3	0.35 ± .07	2.67 ± .17	0.5 ± .09	2.36 ± .13
Archo-1*	--	10.67 ± .10	4.26 ± .07	4.26 ± .07	4.8 ± .5	0.90 ± .14	11.1 ± .5	1.04 ± .15	7.34 ± .19

* = Standard

MJ-8-21-2 and 9-29-7, are more silicic than the flow rocks with values of 64.0 and 62.2 percent SiO_2 , respectively, while the third clast, MJ-11-27-2, has a SiO_2 content similar to the flows.

The analyzed flow rock samples from this study area are characterized by high total alkalis, titania, phosphate, and total iron. Both Na_2O and K_2O are markedly high, and total alkalis average about 5.5 percent. Since alkali feldspar is not a component of the rocks, the K_2O and some Na_2O probably occur within the interstitial volcanic glass. The relatively high P_2O_5 is reflected by apatite in the groundmass; the high TiO_2 and total iron, by the abundance of magnetite-ilmenite in the groundmass.

On the silica versus total alkali diagram of MacDonald and Katsura (1964), the upper Nehalem River-Wolf Creek volcanic rocks plot largely in the field for alkalic basalt (Figure 13). One sample plots in the tholeiitic field, whereas several samples are close to the boundary between alkalic and tholeiitic basalts.

Two geochemical groups for the samples can be delineated by major and minor element variation diagrams (Figures 14-19). The diagrams involving only major elements have some internal variability and inconsistencies, and the two groups are not tightly defined in geochemical values. Co and Sc are the most effective elements for differentiating the two groups. Nevertheless, samples MJ-11-20-2, 11-20-3, 11-21-1, 11-21-5, 11-21-6, 10-4-1, 10-4-5, 10-8-4, 9-17-3, and 9-4-3 are characterized by relatively high P_2O_5 and low TiO_2 , MgO , Co, and Sc in comparison to the second group.

Figure 13. Plot of total alkalis versus silica of volcanic rocks from the Tillamook Volcanics in the thesis area (after MacDonald and Katsura, 1964).

Figure 14. Plot of TiO_2 versus P_2O_5 of volcanic rocks from the Tillamook Volcanics in the thesis area. Groups I and II explained in the text.

Figure 15. Plot of TiO₂ versus MgO of volcanic rocks from the Tillamook Volcanics in the thesis area.

Figure 17. Plot of Sc versus MgO of volcanic rocks from the Tillamook Volcanics in the thesis area.

Figure 18. Plot of Co versus MgO of volcanic rocks from the Tillamook Volcanics in the thesis area.

Figure 19. Plot of Co versus Sc of volcanic rocks from the Tillamook Volcanics in the thesis area.

This first group will be informally referred to as group I. Samples of group I were collected from outcrops in the vicinity of Lousignont Creek and Highway 26. Clast sample MJ-11-27-2 is apparently part of group I, also. Informal group II is comprised of samples MJ-11-18-2, 11-28-1, 11-28-2, and 11-20-1, and group II is marked by relatively low P_2O_5 and high TiO_2 , MgO , Co , and Sc in comparison to group I. Samples of groups II were collected from flows in outcrops that are adjacent to the SP Railroad track in N1/2 sec. 35, T3N, R6W.

Among P_2O_5 , MgO , and TiO_2 , P_2O_5 is the least effective for discriminating these two geochemical groups. Samples MJ-11-20-3 and 11-21-1 have P_2O_5 contents which are intermediate in value between groups I and II, as seen in plots of P_2O_5 versus MgO and TiO_2 . However, in variation diagrams with the other elements, these samples consistently plot with group I as expected, since these samples were collected from outcrops in the vicinity of Highway 26.

Two flow rock samples (MJ-10-17-1 and 8-21-5) and two clast samples (MJ-8-21-2 and 9-29-7) are chemically distinct from groups I and II. Extensive weathering is not evident in hand sample or in thin section and is probably not an explanation for the chemical differences between these samples and groups I and II. An alternative explanation to weathering as a cause for the chemical variability is that these samples represent additional, yet undefined, chemical groups in the upper part of the Tillamook Volcanics. In other words, the upper part of the Tillamook Volcanics may be chemically varied with possibly several geochemical groups.

Age dates in the vicinity of the study area indicate that the upper part of the Tillamook Volcanics may encompass a period of approximately 8 m.y. A basalt flow at a quarry on Wolf Creek Road (SW1/4 SE1/4 sec. 6, T3N, R5W) has a reported K-Ar date 38.2 ± 1.9 m.y. (Van Atta, 1982, personal communication). This flow is geochemically and stratigraphically similar to sample MJ-11-21-6, which was collected from the upper flow in a fault to the south of a gravel shed on Highway 26 (NW1/4 sec. 6, T3N, R5W. (See WC sample of Timmons, 1981, for comparison.) Magill and others (1981) report K-Ar dates of 46 m.y. for subaerial flows in the upper part of the Tillamook Volcanics in the North Fork of the Wilson River drainage, which is approximately 5 km to the southwest of the study area. These two age dates agree well with the regional anticlinorium structure of the northern Oregon Coast Range, i.e., younger volcanic rocks northward and eastward of the central part of the Tillamook Highlands. In accordance with this regional structure and these two age dates, the flows of group I may be younger than the flows of group II. Thus, the geochemical difference between the two groups may represent basalt flows that were erupted from different vents and/or at different times. The flows in the study area that are chemically distinct from groups I and II may represent other vents or eruptive periods. In the field, a stratigraphic break between these different flows is not evident.

Regional Applications in the Northern Oregon Coast Range

The volcanic rocks from within the study area are compared geochemically to volcanic rocks from other upper Eocene centers in the northern Coast Range of Oregon. Chemical analyses on volcanic rocks from other upper Eocene volcanic centers are not very abundant in the available literature. Cameron (1980) analyzed 8 basalts from the Cedar Butte area¹. Timmons (1981) reports analyses on 10 samples which were collected in the vicinity of Rocky Point, Quartz Creek, and Wolf Creek Road quarry. Burr (1978) analyzed 2 samples from near Goble, Oregon. Snively and MacLeod (1974) provide analyses on 5 basaltic flows from the Yachats Basalt on the central part of the Oregon Coast, and Kelty (1981) analyzed 10 samples from the middle Miocene Columbia River Basalt Group (CRBG) in the Mist project area. Trace element data is not available for comparison, and P₂O₅ values are not reported by Burr (1978).

Discrete chemical groupings of the samples from Cedar Butte, Rocky Point, Quartz Creek, and upper Nehalem River-Wolf Creek areas are not easily distinguishable on the basis of major element geochemistry (Figures 20-22). As seen in the variation diagrams, the samples from each of these areas are varied in their geochemistry.

¹Cameron does not assign the Cedar Butte volcanics to a stratigraphic position in the Eocene. However, the 900 meters of sub-aerial basalt that he reports should stratigraphically correlate with the 1500 meters that Snively and others (1970) report for the upper unit of the Tillamook Volcanics. The upper part of the Tillamook Volcanics are considered to be late Eocene in age.

Figure 20. Plot of K₂O versus CaO of upper Eocene volcanic rocks and Columbia River Basalt Group from the Oregon Coast Range. Symbols: ● = upper Nehalem River-Wolf Creek area (this report); Δ = Rocky Point and Quartz Creek areas (Timmons, 1981); □ = Cedar Butte area (Cameron, 1980); ○ = Goble, Oregon, area (Burr, 1978); * = Yachats Basalt (Snively and MacLeod, 1974); o = Columbia River Basalt Group (Kelty, 1981).

Figure 21. Plot of TiO₂ versus P₂O₅ of upper Eocene volcanic rocks and Columbia River Basalt Group from the Oregon Coast Range. Symbols explained in Figure 20.

Figure 22. Plot of TiO₂ versus MgO of upper Eocene volcanic rocks and Columbia River Basalt Group from the Oregon Coast Range. Symbols explained in Figure 20.

The Wolf Creek sample (WC) of Timmons consistently plots with the samples that compose group I of the upper Nehalem River-Wolf Creek rocks. It is stratigraphically and geochemically identical to sample MJ-11-21-6, thus, these two samples probably represent the same flow unit. Otherwise, the samples from Rocky Point, Quartz Creek, and Cedar Butte are widely scattered in their geochemistry. They do not show particular affinity for group I nor group II as defined by the samples from this study area. Neither, do these samples display unique geochemical affinities of their own, especially when compared to the tight clustering of data points for the samples of Grand Ronde Basalt of the CRBG. Similarly, the Yachats Basalt is also widely variable in chemical composition.

Timmons (1981) attempted to geochemically distinguish Tillamook Volcanics from Goble Volcanics by referring the samples from the Cedar Butte area to Tillamook Volcanics and the samples from the Rocky Point and Quartz Creek areas to Goble Volcanics. However, based on the geochemical data presently available, a geochemical distinction between the upper part of the Tillamook Volcanics and the Goble Volcanics does not seem reasonable at this time. The rocks from the Cedar Butte area generally are lower in P_2O_5 and higher in MgO than the samples from other upper Eocene centers. However, only three of the Cedar Butte samples are flow units and these three samples are not tightly grouped geochemically. Three of the other samples from the Cedar Butte area are from a diabase, and Cameron (p. 73) states that the diabase "gives confused, conflicting results". Of the two remaining samples from the

Cedar Butte area, one sample is a dike and the other sample is altered (19 percent MgO). This MgO-enriched sample is not considered. Interestingly, the two samples from Goble Volcanics near Goble, Oregon, show closer geochemical affinity to the Cedar Butte samples than to the Rocky Point or upper Nehalem River-Wolf Creek samples as seen in the plots of TiO_2 versus MgO and K_2O versus CaO.

To geochemically define the Cedar Butte samples as Tillamook Volcanics and the Rocky Point and Quartz Creek samples as Goble Volcanics seems erroneously misleading and simplistic with the data currently available. As seen with the data from this study area, geochemical subdivision of the basalts may be possible, but a geochemical distinction between Tillamook Volcanics (upper part) and Goble Volcanics is not well-defined at this time. Also, a geochemical distinction among flows in the upper Nehalem River-Wolf Creek, Rocky Point, Quartz Creek, and Cedar Butte areas does not seem necessary, since all of these flows are similar in the following attributes. The flows from each area consist of chiefly subaerial basalt to basaltic andesite flows, are varied in geochemical composition, and are late Eocene in age. Additional mapping, geochemical sampling, and age dating is necessary to substantiate or disprove this evidence for overall similarity in these volcanic rocks.

TECTONIC SETTING

In comparison to modern volcanic provinces, particularly as discussed by Carmichael and others (1976, p. 373-563), the volcanic

rocks in the study area are comparable stratigraphically, petrographically, and geochemically, to volcanic rock series of oceanic islands, such as the Galapagos Islands and Iceland. The lavas of these oceanic island settings are typified by Icelandites, which are iron-rich, aluminum-poor andesites.

In comparison to the upper Nehalem River-Wolf Creek volcanic rocks, the Galapagos volcanoes are composed almost entirely of basaltic lavas and pyroclastic rocks, which range from basalt to dacite in chemical composition. The study area volcanic rocks classify mostly as alkalic basalts (Figure 13), while the Galapagos volcanic rocks classify as tholeiitic and alkalic basalts. Both the study area and Galapagos rocks are characterized by high TiO_2 , P_2O_5 , total iron, and total alkalis. Petrographically, the upper Nehalem River-Wolf Creek volcanic rocks are characterized by plagioclase being the most abundant phenocryst, augite being predominant over pigeonite, the absence of orthopyroxene, and olivine being a minor constituent (if present). In comparison to the thesis area rocks, the Galapagos tholeiites have minor olivine and augite is predominant over other pyroxenes. Also, in comparison, the Galapagos Icelandites have abundant plagioclase phenocrysts, two pyroxenes (augite and pigeonite), and an absence of olivine. The upper Nehalem River-Wolf Creek basaltic rocks with intermediate SiO_2 contents could be considered Icelandites.

The major element geochemistry of volcanic rocks from the thesis area compares closely to the average chemical composition for alkali basalt. Average chemical compositions for calc-alkali

basalt, ocean-floor tholeiite, oceanic tholeiite, and alkali basalt (from Nockolds and others, 1978), in addition to an average composition for the 16 flows from this study area are listed in Table V. The rocks from the study area do not display similar characteristics to ocean-floor tholeiite nor to calc-alkali basalt. The ocean-floor tholeiite is marked by much lower K_2O , TiO_2 , and P_2O_5 than the rocks from the upper Nehalem River-Wolf Creek area; ocean-floor basalts are characteristically low in these elements (Carmichael and others, 1976). The calc-alkali basalt is chemically different from the study area rocks with higher Al_2O_3 and lower TiO_2 , P_2O_5 , and total iron. The oceanic tholeiite average shows more similarities to the flow rocks from the study area, but the tholeiite still has lower P_2O_5 and alkalis and somewhat lower TiO_2 . The alkali basalt displays the closest similarity in alkalis, TiO_2 , and P_2O_5 to the rocks from the study area; but the alkali basalt average has lower SiO_2 and higher MgO .

In Figure 23, the rare earth element (REE) patterns of the upper Nehalem River-Wolf Creek volcanic rocks are compared to the REE patterns of volcanic rocks from Iceland (alkalic basalt), Hawaii (tholeiitic basalt), Tofua Island (island arc basaltic ande- site), a DSDP ocean ridge site (ocean-floor basalt) and Columbia River Plateau (tholeiitic flood basalt). These REE data are from Kay and Hubbard (1978). The REE values are normalized by using the chondrite average of Nakamura (1974). The basaltic rocks from the upper Nehalem River-Wolf Creek area show a La/Yb ratio which is greater than the La/Yb ratio of the chondrite; thus, the study area rocks

TABLE V

AVERAGE CHEMICAL COMPOSITION OF VOLCANIC ROCKS FROM DIFFERENT TECTONIC SETTINGS
(FROM NOCKOLDS AND OTHERS, 1978) COMPARED TO AN AVERAGE OF THE FLOW ROCKS IN THESIS AREA.

	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	FeO	MnO	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅
Oc.Thol.	51.30	14.20	2.05	2.91	9.14	0.18	10.52	6.40	0.83	2.25	0.23
Oc.Floor	50.30	15.75	1.41	1.75	8.11	0.19	11.43	8.03	0.19	2.72	0.13
Alkali	46.40	15.09	2.55	2.71	9.05	0.17	10.87	9.09	0.89	2.79	0.38
Calc-Alk	51.46	18.66	0.88	2.92	5.83	0.15	10.33	5.97	0.74	2.94	0.12
Thesis Area Flow Rocks	52.68	14.62	9.96	6.03	6.65	0.24	8.29	4.75	1.46	4.00	0.86

Figure 23. Plot of chondrite-normalized REE values of volcanic rocks from the Tillamook Volcanics in the thesis area compared to volcanic rocks from different tectonic settings. Symbols: Stippled area represents 15 samples of the Tillamook Volcanics; ☆, Iceland (alkalic basalt); ■, Hawaii (oceanic tholeiite); ☆, Tofua Island (island arc); ●, Deep Sea Drilling Project (ocean-floor basalt); ○, Columbia River Basalt Group (continental flood basalt).

are enriched in the light rare earth elements (LREE). This pattern is similar to the La/Yb ratio seen for the lava from Iceland, although there is an absolute difference in REE abundances. This enrichment in LREE is typical of alkali basalts (Kay and Hubbard, 1978). Similarly, the Hawaiian lava displays a minor LREE enrichment pattern. In contrast, ocean-floor basalt and calc-alkali basaltic andesite are depleted in LREE.

Wood and others (1979) have distinguished basalts from different tectomagmatic settings by using a ternary plot of Th, Hf, and Ta (Figure 24). The rocks from the upper Nehalem River-Wolf Creek area plot uniformly in field B for anomalous type mid-ocean ridge basalt (MORB), except for two samples that plot in field C. Field C represents basalts generated in within-plate settings. The anomalous MORB is distinguished from normal MORB (which includes ocean-floor basalt) by enrichment in LREE and other incompatible elements and by association with ridge segments that have positive heat flow anomalies (i.e. hot spots), such as Iceland (Wood and others, 1979). The within-plate type is characterized by a lower enrichment in LREE and other incompatible elements and can be generated in either oceanic or continental plate settings. Examples of within-plate basalts in an oceanic setting include Hawaii and the Emperor Seamounts.

Thus, the major, minor, and trace element geochemistry of the upper Nehalem River-Wolf Creek volcanic rocks are geochemically comparable to volcanic rocks of oceanic islands that are associated with mid-oceanic ridges. Furthermore, the stratigraphy, petrography, and geochemistry seem to compare closely with modern oceanic islands

Figure 24. Th-Hf-Ta plot with fields of magma from different tectonic settings in outline (from Wood and others, 1979). Field A represents normal MORB; field B, anomalous MORB; field C, within plate basalt; and field D, destructive plate magmas.

like Iceland or the Galapagos Islands. The thesis area volcanic rocks are dissimilar from volcanic rocks that are associated with other tectomagmatic settings, such as magmatic arcs and continental rifts.

AGE AND CORRELATION

The volcanic rocks of the upper Nehalem River-Wolf Creek area are assigned to the upper part of the Tillamook Volcanics with an age of late Eocene. They are predominantly subaerial basalt flows which correlate with the 1500 meters of subaerial volcanics that Snively and others (1970) reported for the upper part of the Tillamook Volcanics. They are overlain by the sedimentary rocks of the Cowlitz Formation.

Regionally, several volcanic sequences correlate with the upper part of the Tillamook Volcanics in this study area. As first reported by Snively and MacLeod (1974), they include the Yachats Basalt, the basalt at Cascade Head, and Goble Volcanics in southwestern Washington. Each of these sequences is composed largely of subaerial flows and represents local upper Eocene volcanic centers (Snively and MacLeod, 1974). Locally, the stratigraphic relationships of the volcanic rocks to the upper Eocene sedimentary formations vary: On the central Oregon Coast, the Yachats Basalt is underlain and overlain by the Nestucca Formation; in southwestern Washington, the Goble Volcanics overlie the Cowlitz Formation (Wells, 1981); and in the study area, the Tillamook Volcanics underlie the Cowlitz Formation.

COWLITZ FORMATION

LITHOFACIES AND STRATIGRAPHY

The Cowlitz Formation in the thesis area consists of three general lithofacies:

- 1) mudrock lithofacies--homogeneous, thinly to thickly bedded carbonaceous, micaceous siltstones and mudstones
- 2) heterolithic lithofacies--carbonaceous, micaceous, arkosic silty sandstones with interstratified carbonaceous, micaceous silty mudstones
- 3) sandstone lithofacies--thickly bedded, micaceous, arkosic, very fine- to medium-grained sandstones.

Use of these lithofacies terms is adapted from Reading (1978, p. 223). The sedimentary rocks of the Cowlitz Formation are characteristically arkosic, micaceous, and carbonaceous in composition.

Mica consists of fine- to very coarse-grained flakes of muscovite and biotite that are up to 5 mm in diameter. The plant detritus is finely comminuted to coarse-grained, and woody fragments are occasionally up to 2 cm in length. Fossil leaf impressions are also found in the finer grained lithofacies. Both mica and carbonaceous debris are found subparallel to parallel to primary sedimentary structures. In the sandstone lithofacies, mica and carbonaceous material are generally less abundant than in the finer grained heterolithic and mudrock lithofacies.

The lower part of the Cowlitz Formation in the thesis area is exposed in the upper parts of the Nehalem River and Wolf Creek. The lower part of the Cowlitz Formation typically consists of thinly to thickly bedded mudstones and siltstones that are dark gray in color,

micaceous, and carbonaceous. In weathered outcrops, these mudrocks are light yellowish-brown in color, are greasy and soft, possess a chip-like texture, and occasionally display a faint stratification. Calcareous concretions are rare to common in occurrence and often contain either carbonized plant fragments or broken molluscan shells. Arkosic silty sandstone interbeds that are up to 10 cm in thickness are occasionally present, and less commonly, a few, thin, light-colored claystone units are interbedded with the mudrocks.

Megafofossils in this mudrock lithofacies are generally not abundant and are rendered unidentifiable by weathering and leaching of outcrops. Foraminifera are fairly abundant, though, and a sample checklist is given in Appendix III. The only common trace fossils are Chondrites and Helminthoidea (Chamberlain, 1982, written communication, Appendix V).

The mudstones and siltstones of the lower part of the Cowlitz Formation are overlain by silty sandstones with interstratified mudstones (heterolithic lithofacies) and very fine- to medium-grained sandstones (sandstone lithofacies) that crop out west of Timber in the Nehalem River and along the SP Railroad track, west of Sunset Camp in Wolf Creek, and south of Sunset Camp in the Nehalem River. Typical stratigraphic relations are shown in three measured sections (Figures 25, 26, and 27). The Timber and Wolf Creek sections are in the uppermost part of the Cowlitz Formation, since these two sections are overlain by mudrocks of the Keasey Formation. Mudrocks of the Cowlitz Formation are not exposed in the Timber section due to displacement by a fault, whereas the Wolf Creek section is in fault

PROFILE	THICK- NESS (METERS)	UNIT	DESCRIPTION
11 m	V	Medium gray, arkosic sandy siltstone; fossiliferous, micaceous, and bioturbated
35 m		Covered interval
14 m	IV	Medium gray, arkosic sandy siltstone; glauconitic, fossiliferous, carbonaceous, micaceous, and bioturbated; thin section (MJ-11-3-6) <u>Dentalium</u> , <u>Brisaster</u> (M-11-3-1)
8 m	III	Medium gray, silty very fine-grained, arkosic sandstone with interstratified dark gray mudstone; carbonaceous micaceous; parallel laminations, HCS <u>Rosselia-Cylindrichnus</u> , <u>Thalassinoides</u> (T-11-3-5); T. S. (MJ-11-3-5)
16 m	II	Light brown, fine-grained arkosic sandstone; friable, micaceous; low angle trough cross-laminations, parallel laminations, ripple cross-laminations; rare burrows; mudstone interbed (4 cm thick); thin section MJ-11-3-4)
5 m	I	Medium gray, silty very fine-grained arkosic sandstone with interstratified dark gray mudstone; carbonaceous, micaceous; vertical/subvertical burrows

Figure 25. Timber section in the Cowlitz Formation (SP Railroad track, SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 28, T3N, R5W).

PROFILE	THICK- NESS (METERS)	UNIT	DESCRIPTION
	6 m	V	Medium gray, arkosic sandy siltstone; carbonaceous, micaceous, mottled, bioturbated; <u>Pitar</u> (M-11-10-1)
	6 m	IV	Light brown, arkosic sandstone; friable micaceous; trough cross-laminations
	1 m	III	Medium gray mudstone with interbedded arkosic sandstone; no forams (F-11-10-1)
	20 m	II	Light brown, fine-grained, arkosic sandstone; friable, micaceous; trough cross-laminated to massive; no burrows; mudstone interbed (5 cm thick); thin section (MJ-11-10-5)
	60 m		Covered interval
	16 m	I	Medium gray, silty very fine-grained arkosic sandstone with interstratified dark gray mudstone; parallel laminations, low angle trough cross-laminations, HCS; vertical/subvertical burrows Arkosic sheet sandstones Thin sections (MJ- 9-30-2 & 9-30-4) Forams (F-9-30-2)

Figure 26. Reeher Park section in the Cowlitz Formation (Unit I in the Nehalem River; Units II-V on the SP Railroad track; NW $\frac{1}{4}$ NW $\frac{1}{4}$ and SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 32, T3N, R5W).

PROFILE	THICKNESS (METERS)	UNIT	DESCRIPTION
	15	XII	Dark gray, mudstone and siltstone; sparsely tuffaceous, finely micaceous, fossiliferous; calcareous concretions; Megafossils assigned to Keasey Formation (M-9-14-1)
	5		Covered interval; Cowlitz-Keasey contact
	7	XI	Light gray, silty very fine-grained, arkosic sandstones with interstratified mudstones; carbonaceous, micaceous
	20		Covered interval
	10	X	Light gray, silty very fine-grained, arkosic sandstones with interstratified mudstones; carbonaceous, micaceous; parallel laminations, low angle trough cross-laminations, HCS; shell concentrates, vertical/subvertical burrows thin section (MJ-9-13-4)
	4		Covered interval
	10	IX	Light gray, silty arkosic sandstone with interstratified mudstone
	30		Covered interval
	2	VIII	Light gray, arkosic silty sandstone with interstratified mudstone
	5		Covered interval
	14	VII	Light gray, silty arkosic sandstone with interstratified mudstone; carbonaceous, micaceous, parallel laminations, low angle trough cross-laminations; vertical/subvertical burrows
	25		Covered interval
	5	VI	Dark gray silty mudstone; carbonaceous, micaceous
			Covered interval
	8	V	Dark gray silty mudstone; carbonaceous, micaceous
	2		Covered interval
	10	IV	Dark gray silty mudstone; carbonaceous, micaceous
	2	III	Medium gray, fine-grained arkosic sandstone; carbonaceous, micaceous; trough cross-laminations, channel fill; thin section (MJ-9-11-3)
	8	II	Light gray, arkosic sandy siltstone; carbonaceous, micaceous; parallel laminations; 5 arkosic sandstone channels
	5		Covered interval (fault)
	5+ m	I	Dark gray silty mudstones; carbonaceous, micaceous

Figure 27. Wolf Creek section in the Cowlitz Formation. Contact with the Keasey Formation is shown in the figure. (In Wolf Creek, SE $\frac{1}{4}$ NW $\frac{1}{4}$, SW $\frac{1}{4}$ NE $\frac{1}{4}$, SE $\frac{1}{4}$ NE $\frac{1}{4}$ and NE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 5, T3N, R5W.)

contact with mudrocks of the lower part of the Cowlitz Formation. The Reeher Park section gradationally overlies mudrocks of the lower part of the Cowlitz Formation, thus, it may be stratigraphically lower in the formation than the other two sections.

The typical heterolithic lithofacies consists of discontinuously interstratified silty mudstones and silty sandstones that range in thickness from thin lamina (<1 mm) to discontinuous beds that are up to 10 cm thick. The silty mudstones are dark gray in color, carbonaceous, micaceous, burrowed, and thinly laminated. The silty sandstones are light gray in color, carbonaceous, micaceous, and arkosic in composition. Primary sedimentary structures displayed by the silty sandstones include even parallel lamination (Figure 28), truncated wave ripple cross-lamination, and starved ripple cross-lamination. Lateral continuity of the silty sandstone strata is disrupted by vertical to subvertical burrows (Figure 28). The truncated ripple cross-laminated silty sandstone strata are up to 5 cm in thickness by 40 cm in length, have an undulating geometry, and are enclosed in mudstone drapes (Figure 29). This style of cross-stratification is similar to hummocky cross-stratification as described by Harms and others (1975). Mica and carbonized plant detritus in thin lamina give the rock a streaky appearance.

Interbedded with the discontinuously interstratified silty sandstones and mudstones are laterally persistent, silty to very fine-grained sandstones that range from 5 cm to 175 cm in thickness (Figure 30). These sandstones have very sharp, erosive bases with very minor relief (<2 cm generally), plus shell fragments and

Figure 28. Parallel-laminated, silty arkosic sandstone with interstratified mudstone exposed in the Timber section (unit III). Burrows are identified as Rosselia-Cylindrichnus. Ruler is 15 cm in length. (SP Railroad track, SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 28, T3N, R5W.)

Figure 29. In the center of the photograph is an example of hummocky cross-stratification in a silty arkosic sandstone, that is exposed in the Timber section (unit III). (SP Railroad track, SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 28, T3N, R5W.)

Figure 30. Laterally persistent, sheet sandstone exposed in the Reeher Park section (unit I). Offset is less than 1 meter. Hammer is 33 cm in length. (NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 32, T3N, R5W.)

mudstone clasts are concentrated near the base of some units. Primary sedimentary structure consists of even parallel lamination or parallel lamination with low angle cross-lamination at the top of individual strata. The upper contacts between sandstone and overlying mudstone are sometimes gradational and burrowed. These silty sandstones are interpreted to represent storm-produced sheet sandstones (Reading, 1978; Goldring and Bridges, 1973).

Bioturbation is common in the heterolithic lithofacies. In the Timber section, the subvertical/vertical burrows are identified as Rosselia and/or Cylindrichnus and ?Thalassinoides by Chamberlain (1982, written communication, Appendix V). Similar burrows are found in the Reeher Park and Wolf Creek sections, and in other isolated outcrop localities. Bioturbation may almost completely obliterate any primary sedimentary structure and stratification and produce a mottled-appearing sandy siltstone (Unit IV and V, Figure 25; Unit V, Figure 26). Fossils of Brisaster and Pitar were identified from these extensively bioturbated strata.

The sandstone lithofacies typically consists of very fine- to medium-grained micaceous, arkosic sandstone that forms units up to 20 meters in thickness (Figures 26 and 31). Primary sedimentary structures include trough cross-lamination, parallel lamination, and ripple cross-lamination. In the Reeher Park section (Unit II and IV, Figure 26), trough cross-lamina are steeply dipping at a 30°-40° angle and indicate variable directions of paleocurrent transport (Figure 32). In most sandstones, though, low angle (<10°) trough cross-laminations are more prevalent than steep trough sets

Figure 31. Cross-stratified, arkosic sandstone with interbedded mudstone and fossiliferous, bioturbated sandy siltstone that is exposed in the Reeher Park section (units II-V). (SP Railroad track, SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 32, T3N, R5W.)

Figure 32. Trough cross-laminations exposed in the Reeher Park section (unit II). Note the bidirectionality of paleocurrent at level of hammer. A third paleocurrent direction is less obvious above the hammer. Hammer is 33 cm in length. Vertical groove marks are due to scraping to expose the sedimentary structures.

(Figure 33). The sandstones are friable and poorly indurated with a clay cement, thus, weathering and slumping promote a massive-appearing outcrop. Micaceous, carbonaceous mudstone that are thinly laminated are usually interbedded with the sandstones (Unit II, Figure 25; Unit III, Figure 26). Burrows and fossil shells are rarely observed, and signs of subaerial emergence, e.g., rootlets, are not present in outcrop.

In the Wolf Creek section (Figure 27), small, low-relief, sandstone channels are scoured into strata of parallel to low angle trough cross-laminated silty sandstones, and the channels are up to 2 meters in thickness. Width of the channels is not determinable. The channel-fill sandstones are trough cross-laminated to massive and are arkosic, micaceous, carbonaceous and concretionary in composition.

PETROGRAPHY

Thirteen sedimentary rock samples of the Cowlitz Formation were studied in thin section; modal analyses were performed on ten of these samples (Table VI). Five hundred points were counted per slide in 10 rows with 50 points per row. The reader is referred to Van Atta (1971) for a detailed discussion of the petrography of the Cowlitz Formation.

The samples studied in thin section for this study range from silty very fine-grained sandstones to fine-grained sandstones, that were collected from the heterolithic and sandstone lithofacies. These rocks are composed of moderately sorted, angular to subangular

Figure 33. Low angle trough cross-laminations exposed in the Timber section (unit II). Ruler is 15 cm in length. (SP Railroad track, SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 28, T3N, R5W.)

TABLE VI

MODAL COMPOSITION OF SELECTED SANDSTONES OF THE COMLITZ FORMATION

	9-11-3	9-13-4	9-23-5	9-24-1	9-30-2	9-30-4	11-3-4	11-3-5	11-3-6	11-10-5
Qm	30.6	22.7	22.6	20.8	29.0	29.0	26.4	25.0	29.2	30.8
Qp	1.2	1.0	0.2	1.0	0.2	2.0	1.0	0.2	3.0	4.2
Chert	0.4	-	-	-	0.2	-	-	0.2	0.8	1.0
Plag	20.4	21.5	27.0	24.0	16.8	21.6	26.6	19.2	24.4	28.2
K-spar	19.2	12.6	17.3	19.8	20.6	19.4	18.4	16.4	20.4	18.2
VRP	-	5.9	1.6	3.6	1.2	2.0	4.2	1.4	3.0	2.4
SRP	0.4	1.8	-	-	0.4	1.4	0.6	1.2	1.0	2.4
MRP	0.2	0.2	0.2	0.2	-	0.6	0.6	0.4	0.8	1.2
IRP	-	-	-	-	-	0.2	-	-	0.8	1.4
URP	-	0.4	1.8	2.0	0.8	0.6	-	0.4	0.8	0.6
Mica	13.4	13.8	12.6	10.0	10.8	7.4	3.6	12.4	5.4	3.6
Carbon debris	4.0	2.6	1.0	4.1	4.0	0.2	5.6	4.6	0.2	0.6
Hb	0.6	-	0.6	0.5	0.6	1.8	1.2	0.4	1.0	1.2
Pyx	0.8	0.6	2.6	1.2	2.6	1.8	2.4	2.0	1.8	1.2
Opaque	0.2	-	-	1.0	0.8	1.2	0.6	0.4	0.4	-
Glauc.	<0.1	-	<0.1	-	-	<0.1	-	-	<0.1	-
Other	0.4	0.2	0.4	0.6	0.8	2.0	1.0	0.8	2.0	0.8
Matrix	2.8	2.6	4.5	4.8	3.0	3.2	3.2	5.0	-	-
Unident	5.4	14.0	6.0	6.4	8.2	5.6	8.6	5.0	5.0	2.2
Recalculated framework modes (after Dickinson and Suczek, 1979):										
Qm	44.8	34.3	30.3	29.1	41.9	37.8	33.9	38.8	34.7	34.1
Qp	2.1	1.5	0.3	1.4	0.3	2.6	1.3	0.3	3.6	4.6
Chert	0.7	-	-	-	0.3	-	-	0.3	1.0	1.1
P	26.2	32.5	38.8	33.7	24.3	28.1	34.2	29.8	29.0	31.2
K	24.8	19.1	25.3	27.7	29.8	25.3	23.7	25.5	24.2	20.1
L	0.7	12.6	5.3	8.1	3.3	6.3	6.9	5.3	7.6	8.9

grains and have less than 5% matrix (Figure 34). Thus, these rocks are texturally submature (Folk, 1980), which is also reported by Van Atta (1971). On the classification diagram for sandstones of McBride (1963), the rocks classify as arkoses except for one sample which is a lithic arkose (Figure 35). Feldspar, quartz, and mica are the dominant clastic constituents of these sandstones and range from 34 to 46%, 21 to 36% and 4 to 14% of the rock volume, respectively.

Plagioclase is the dominant feldspar, although K-feldspar is only slightly less abundant (Table VI). The plagioclase commonly displays Albite twinning, and less commonly, Carlsbad and combined Carlsbad-Albite twins. A few grains of plagioclase are not twinned; Pericline twins are rarely observed. Composition of plagioclase ranges from oligoclase to andesine (An_{20} to An_{42}). K-feldspar in the thin sections is generally orthoclase, although microcline is common.

Quartz is predominantly monocrystalline types with a few inclusions and nonundulose extinction. Polycrystalline quartz and chert are considerably less abundant than monocrystalline quartz (Table VI) and are distinguished by undulatory extinction plus sutured grain boundaries.

Mica is represented by both biotite and muscovite. It is most abundant in the well-laminated, very fine-grained sandstones (and mudrocks that were not examined in thin section). In these well-laminated rocks, mica plus carbonized plant detritus form lamina that are up to 2 mm thick or are delicately cross-laminated. Mica flakes are up to 2 mm in length, and both mica and carbonaceous detritus are subparallel to parallel to the lamination.

—
0.1 mm

Figure 34. Photomicrograph of arkose in the Cowlitz Formation under plane polarized light. Composed of subangular, moderately sorted grains of quartz, plagioclase, and K-feldspar. (Sample MJ-11-10-5.)

Figure 35. Classification of sandstones of the Cowlitz Formation (after McBride, 1963).
 Q= quartz, C= chert, F= feldspar, RF= rock fragment.

Rock fragments are a minor constituent in the sandstones of the Cowlitz Formation. Volcanic rock fragments (VRF) are the most abundant rock fragments; metamorphic rock fragments (MRF), least abundant. VRF's are mostly aphyric but some are microphyric. An compositions of plagioclase in the VRF's were indeterminate. MRF's are mostly phyllites, and sedimentary rock fragments (SRF) include mudstones and siltstones. Plutonic rock fragments (IRF) are rare and usually seen only in the coarser-grained rocks. However, coarse-grained IRF's and MRF's are not an expected component of very fine- to fine-grained sandstones (Folk, 1980). Volcanic glass and pyroclastic rock fragments are not observed in thin section.

Other clastic constituents include amphiboles, pyroxene, epidote group minerals, and opaques. Glauconite is a trace constituent in four samples.

Van Atta (1971) reported VRF's to be more prevalent in some mudrocks than in the sandstones of the Cowlitz Formation on the basis of grain mount sections. The mudrocks classify mostly as arkoses and lithic arkoses, although two samples are feldspathic litharenites and one sample is a litharenite (Van Atta, 1971).

CONTACT RELATIONS

The Tillamook Volcanics are overlain in outcrop by extensively weathered mudrocks which are assigned to the lower part of the Cowlitz Formation. In the upper parts of the Nehalem River and Wolf Creek, carbonaceous, micaceous mudrocks are dipping generally eastward and away from the volcanic terrane. (See Plate I.) Thus, in

the thesis area, the basal portion of the Cowlitz Formation consists of this mudrock section that depositionally overlies and dips away from the upper unit of the Tillamook Volcanics.

Volcanic flows are not observed as being interbedded with sedimentary rocks of the Cowlitz Formation. Along Highway 26, contacts that were interpreted by Van Atta (1971) as demonstrating an interfingering relationship of basalt flows, basaltic conglomerates, and marine siltstones are reinterpreted as fault contacts. However, some volcanic detritus, that was shed off the volcanic terrane, is interbedded with mudstones and siltstones of the Cowlitz Formation.

The upper contact of the Cowlitz Formation with the Keasey Formation is mapped at the uppermost interval of burrowed, micaceous, arkosic strata. This contact is exposed in Wolf Creek to the west of Sunset Camp (Figure 27), in the Nehalem River to the south of Sunset Camp, and in the Nehalem River to the west of Timber. In each locality, burrowed, interstratified silty arkosic sandstones and mudstones are unconformably overlain by thickly bedded, richly fossiliferous mudstones and siltstones. These mudrocks are finely micaceous, sparsely tuffaceous and concretionary. Megafossils that were collected from these mudrocks are assigned to the Keasey Formation (Nesbitt, 1982, written communication, samples M-9-14-1 and 10-1-3, Appendix IV). Up section, mudrocks of the Keasey Formation are increasingly tuffaceous and are not micaceous in composition.

AGE AND CORRELATION

The sedimentary rocks that are mapped as part of the Cowlitz Formation in the study are assigned to the upper Narizian stage of Mallory (1959) on the basis of foraminifera. Megafossils collected from lithofacies of the Cowlitz Formation were not age-diagnostic.

The Cowlitz Formation in the study area correlates with other formations that are assigned an upper Narizian age. These formations include: Cowlitz Formation in the vicinity of Mist, Oregon (Timmons, 1981), Cowlitz Formation in southwestern Washington (Henricksen, 1956; Wells, 1981), Spencer Formation in the east-central part of the Coast Range (Al-Azzaby, 1980; Baldwin, 1981) and Nestucca Formation on the central Oregon coast (Snively and others, 1976a, b, c). The lithofacies in each of these formations are similar to the described lithofacies of the Cowlitz Formation in the study area. The similarities are: parallel-laminated, cross-laminated, and massive, micaceous arkosic sandstones; interbedded micaceous, carbonaceous siltstones and mudstones; and locally interbedded volcanic sandstones. Each of these formations is interpreted to have been deposited in a nearshore marine to brackish water environment.

STRUCTURE

The structure of the northern Oregon Coast Range is dominated by a regional anticlinorium that plunges northward and that is complicated by northwest-, northeast-, and west-trending faults (Snively and Wagner, 1964). The outcrop pattern of the Tertiary strata in the study area reflects this regional structure: The upper unit of the Tillamook Volcanics is flanked by the progressively younger Cowlitz and Keasey Formations to the east. Also, this general eastward dip of the Tertiary strata is complicated by northwest- and northeast-trending faults. However, west-trending faults are not mapped within this study area. (See Plate I.)

Faults in the study area are recognized by:

- 1) juxtaposition of different stratigraphic formations
- 2) lineaments on SLAR, high altitude black and white aerial photographs, and topographic maps
- 3) offset in strata
- 4) shear zones.

Lineaments were mapped from the photographs and SLAR prior to field work, then field checked for direct evidence of tectonic displacements. The volcanic rocks are more competent than the sedimentary rocks, thus shearing is more commonly seen in the volcanic strata, especially in the basalt flows.

The dominant fault trend in the thesis area is approximately N50° to 70°W. A less well-developed fault trend is N20° to 40°E. Examination of strikes and dips reveals that folds, if present, are

probably not prominent in the study area: Changes in dip direction are usually abrupt, which is more likely to indicate faulting rather than folding.

In the southwest part of the map area (Sec. 25, 26, 35, and 36, T3N, R6W), several faults trend approximately N50°W. The drainages of the uppermost part of the Nehalem River and an unnamed tributary creek are fault-controlled; Derby Creek is also probably fault-controlled, but a fault was not observed here. On the SP Railroad track in the vicinity of Reliance Creek (NW1/4 sec. 35, T3N, R6W), basalt flows are cut by vertical shear zones that trend N40° to 70°W, which is parallel to subparallel to the stream drainages in the area. Also, chemical analyses on these flows indicate a lack of stratigraphic continuity of the flows that are adjacent to the railroad track, and this condition is also suggestive of faulting. Maximum observed vertical offset in strata in this area is one to two meters.

On the Geologic Map of Oregon West of the 121st Meridian, the northwest-trending Gales Creek fault is mapped to the southern boundary of this study area (Wells and Peck, 1961). Also, to the northeast in the vicinity of Humbug Mountain, Penoyer (1976) mapped the Humbug Mountain fault that he reported as being colinear to the Gales Creek fault. Thus, the faults in the southwest part of the study area are probably an extension of the Gales Creek fault.

Other northwest-trending faults in the thesis area are approximately parallel to the trend of the Gales Creek fault. These faults include a fault in the Lousignont Creek valley, three faults that are

transverse to Highway 26 in the northwest part of the study area, and a fault in Wolf Creek.

The style of faulting seems to indicate well-developed, en echelon, northwest-trending shear zones. The amount of displacement--vertical and horizontal--is difficult to discern, although the faults that juxtapose different formations probably have considerable throw.

DEPOSITIONAL ENVIRONMENT

The sedimentary rocks of the Cowlitz Formation are interpreted to have been deposited in an open shallow marine and/or restricted open shallow marine shelf environment. The environment of deposition was storm-influenced or storm-dominated, and deposition occurred in the offshore, transition, and shoreface zones on a beach to offshore shelf profile (Figure 36). Environmental interpretations are based collectively on lithofacies, stratification sequences, sedimentary structure, and fossil paleoecology. Any single trait of a sedimentary formation is not diagnostic in determining depositional environments; therefore, each characteristic of a formation must be considered in conjunction with other data (Reading, 1978).

This interpretation of a shallow marine shelf depositional environment is based on the presence of the following features in the Cowlitz Formation:

- 1) open marine to restricted open marine foraminifera
- 2) nearshore, shallow marine trace fossils and megafossils
- 3) extensively bioturbated strata
- 4) interfingering of sandstones and mudrocks in laterally continuous to discontinuous strata
- 5) mudstone drapes over silty sandstone and sandy siltstone strata
- 6) shell concentrates at the base of sandstone beds
- 7) scour and fill structure with low relief and small scale channels
- 8) absence of signs of subaerial emergence (e.g. rootlets)
- 9) abundance of carbonized plant debris
- 10) trace of glauconite in some sandstones

Figure 36. Beach to offshore profile showing relative position of different geomorphic units (from Reineck and Singh, 1980, p. 346).

Reading (1978, p. 229-233) and Reineck and Singh (1980) have inferred the association of these features to indicate a shallow marine depositional environment.

The heterolithic lithofacies of the Cowlitz Formation in the study area is interpreted to have been deposited in a storm-influenced, subtidal transition zone, which was located at or just below fair weather wave base. The discontinuously and variably interstratified silty sandstones and mudstones in this lithofacies indicate "fluctuations in the intensity and periodicity of hydrodynamic conditions and in the supply of sediment" (Reading, 1978, p. 233). Also, subvertical to vertical "escape" traces reflect a periodicity in energy conditions: An infauna living in the lower energy mudstone layers periodically had to burrow through higher energy sandstone strata. Fluctuating conditions in energy and sediment supply are typical of a transition zone that is below or near fair weather wave base (Reineck and Singh, 1980). Storms cause a lowering of the wave base, thus, increasing the energy and increasing the coarseness of the transported sediment into an otherwise low energy environment on a shallow shelf. Storm-generated deposition in the Cowlitz Formation is indicated by hummocky cross-stratification (HCS), sheet sandstones, and shallow channels.

HCS is interpreted to form "by deposition during oscillatory flow produced by large waves" (Harms, and others, 1982, p. 3-31). These large waves are inferred to be produced by episodic storms, since hummocky cross-stratified sandstones are enclosed in lower-energy mudstone strata, cross-laminations are truncated, and zones

of burrowed strata alternate with unburrowed strata. In the stratigraphic record of ancient rocks, HCS strata occur between outer shelf and nearshore facies and are inferred to have formed in water depths that ranged from 0 to 80 m (Dott and Bourgeois, 1982).

The laterally persistent, sheet sandstones are interpreted as being deposited by storm activity. These turbidite-like sandstones, which have erosive bases and occasional shell concentrates, are deposited by storm currents that transport sand from above fair weather wave base in the shoreface zone to below fair weather wave base in the transition zone, and sometimes into the offshore zone. The transitions in sedimentary structure from the parallel- to low angle trough cross-lamination plus the gradational upper contact of sandstone to mudstone in some strata reflects a waning in energy as a storm layer is deposited (Harms and others, 1982; Reading, 1978). Also, burrows in the upper part indicate recolonization of the substrate after a period of storm deposition (Reading, 1978).

These sheet sandstones are very similar to storm sand layers that are found in a high energy, beach to offshore sequence on the modern California coast. These modern sheet sands, as described by Reineck and Singh (1980), are deposited in a transition zone and are characterized by:

- 1) layers that are 10-50 cm in thickness; maximum 190 cm
- 2) shell layers, wood pieces, mudclasts at the base of units
- 3) mostly laminated sand with wave ripples at the top
- 4) frequently burrowed at the top.

In comparison to the inferred sheet sandstones in the Cowlitz Formation, the traits are almost identical.

The extensively bioturbated strata represent periods of slower deposition during lower energy conditions, which allows an infauna to thoroughly "churn" the sediment. However, the presence of some relict primary structure (parallel lamination) and bedding (interbedded mudstone and sandstone) suggest at least minor fluctuating energy conditions during deposition. Extensive bioturbation of sediments is characteristic of shallow marine environments (Reineck and Singh, 1980).

Trace fossils collected from the heterolithic lithofacies--Rosselia-Cylindrichnus, and ?Thalassinoides--indicate a nearshore marine environment and are similar to Echiurus that is found in the German Bay, North Sea (Chamberlain, 1982, written communication). In the Büsum region of the North Sea, Echiurus echiurus and Thalassinoides are found in shelf muds with storm sand layers (Reineck and Singh, 1980, p. 396). Megafossils in the Cowlitz Formation included Pitar which is found in shallow marine or brackish water environments (Nesbitt, 1982, written communication) and Brisaster which is preferentially found in subtidal, shallow marine environments (Thoms, 1982, written communication).

The sandstone lithofacies is abundantly cross-stratified which indicates deposition by currents, but this lithofacies does not have any signs of subaerial emergence during deposition. Thus, currents in the shoreface zone or deeper water are indicated. Current conditions were variable as indicated by the multidirectional paleocurrents and by the diversity in sedimentary structure. The steep foresets in the cross-stratification of units II and IV of the

Reeher Park section are similar to the sedimentary structure that is formed in an upper shoreface environment, as for example, the Gulf of Gaeta, Italy (Reineck and Singh, 1980, p. 387). However, the interbedded mudstone in these sandstones and the fine-grained sediment size implies a lower energy environment than an upper shoreface zone. In the Nordergründe region of the North Sea, mudstones are interbedded with broad, subtidal channel sandstones that are deposited below wave base. But, above wave base, the mudstones are absent (Reineck and Singh, 1980, p. 392). Both the Cowlitz Formation sandstone lithofacies and the Nordergründe subtidal channel sandstones have similar primary stratification; however, bioturbation is more prevalent in the Nordergründe sediments. An alternative interpretation is that the sandstone lithofacies of the Cowlitz Formation was deposited as long-shore bars. The sandstones are moderately well-sorted (Van Atta, 1971) which typifies bars; however, bars usually have planar cross-stratification. This style of stratification is not seen in the rocks of the study area.

The mudrock lithofacies of the Cowlitz Formation in the study area represent lower energy deposition in deeper water conditions than either the heterolithic or sandstone lithofacies. In accordance with the shallow marine shelf interpretation, the mudrock lithofacies was deposited as offshore shelf muds. Deposition would be largely by suspension, and the few thin sandstone interbeds represent transport of coarser-grained detritus by very large storms (Reading, 1978). Trace fossils that are found in the mudrock lithofacies--Helminthoidea and Chondrites--are found in abyssal through

nearshore environments, although these traces may be more common in deeper water muds (Chamberlain, 1982, written communication).

Foraminifera specimens from the heterolithic lithofacies indicate middle neritic or deeper water, and those specimens from the mudrock lithofacies indicate outer neritic to upper bathyal water depths (McKeel, 1982, written communication). As interpreted from the above discussion on sedimentary structures, stratification styles, trace fossils, and megafossils, this author believes that the middle neritic or deeper water interpretation that is based solely on microfossils is too deep. The shallow marine environment extends to a water depth of about 200 meters (Reading, 1978), but the transition zone in modern environments has a maximum depth of about 20 meters (Reineck and Singh, 1980). Thus, the mudrock lithofacies in the Cowlitz Formation could have been deposited in depths greater than 20 meters, but an outer neritic or upper bathyal setting is beyond the limit of a shallow marine environment. However, the microfossils do correctly reflect relative changes in water depth: The mudrock lithofacies is a deeper water facies than the heterolithic and sandstone lithofacies.

PROVENANCE

The basaltic sandstones and conglomerates of the Tillamook Volcanics contain clasts that are mineralogically and texturally similar to the Eocene volcanic flow rocks, and both are interbedded with each other. Composition of plagioclase in the clasts and matrix is labradoritic, which is similar to the plagioclase in the Coast Range basalts. Also, pyroxene is common to both the volcanic sedimentary rocks and flow rocks. None of the clasts appeared to be foreign to a local source in the Coast Range. Thus, the basaltic composition of the sedimentary interbeds of the Tillamook Volcanics and their interbedded relationship with lavas of the Tillamook Volcanics indicate a nearby Eocene source and contemporaneous deposition.

In contrast to the volcanic sedimentary interbeds of the Tillamook Volcanics, the detrital composition of sandstones of the Cowlitz Formation indicates a plutonic and/or metamorphic source area, which is not present in the Oregon Coast Range province. Volcanic rock fragments and pyroxene, which could be locally derived, are only minor constituents of the sandstones. Instead of being volcanic-rich, feldspar, quartz and mica are the major constituents. The arkosic composition indicates a feldspar-rich source rock, which are usually granites and gneisses (Tucker, 1981). Plagioclase in the sandstones is mostly oligoclase and sodic

andesine, while plagioclase that is more calcic in composition and common in the local Eocene basalts was not observed (cf. Van Atta, 1971). Microcrystalline, nonundulose quartz with some inclusions, polycrystalline sutured quartz, microcline and mica further support a plutonic and metamorphic source (Folk, 1980). Micas are most commonly derived from schists and phyllites.

Van Atta (1971) also reported a metamorphic and/or plutonic provenance for the Cowlitz Formation. In addition to this petrographic evidence, trace element geochemistry of sedimentary rocks of the Cowlitz Formation indicates a metamorphic and/or plutonic provenance (Kadri and others, 1983). The Eocene volcanic rocks in the Coast Range probably contributed some volcanic detritus to the depositional basin, but most of the detritus in rocks of the Cowlitz Formation was derived from source areas other than Eocene volcanic centers.

Detrital framework compositions of sandstones are determined by provenance, which is influenced by plate tectonic setting (Dickinson and Suczek, 1979). The sandstones of the Cowlitz Formation in the study area are compared to the provenance types of sandstones, as described by Dickinson and Suczek, in triangular plots of QFL and QmFLt (Figure 37). The sandstones of the Cowlitz Formation plot mostly in the "continental block" field, which has sediment sources on continental platforms or uplifted basement blocks. These sandstones plot toward the F pole which reflects decreasing maturity and stability of the detrital clasts and which is characteristic of

Figure 37. A) Triangular QFL plot of sandstones from the Cowlitz Formation. B) Triangular Q_mFL_t plot of sandstones from the Cowlitz Formation. Both diagrams from Dickinson and Suczek (1979). Symbols: Q is total quartz grains including Q_m (monocrystalline quartz types) and Q_p (polycrystalline quartz types); F is total feldspar; L is unstable lithic fragments; and L_t is total polycrystalline lithic fragments including Q_p .

faulted basement complexes. This quartzo-feldspathic composition suggests high relief and/or rapid erosion of the source rocks.

The "continental block" source corresponds to the indicated metamorphic and/or plutonic provenance. Significantly, the sandstones of the Cowlitz Formation do not plot in the field for "magmatic arc." This latter provenance would imply active subduction and development of a forearc basin in late Eocene time. Detritus from undissected magmatic arcs characteristically has a non-quartzose, feldspathic, and volcanic-lithic composition (Figure 37). The sandstones of the Cowlitz Formation are feldspathic but are too quartzose and non-volcanic to be derived from such a terrane. Dissected arcs, in which cogenetic plutons are exposed, shed sands that are less volcanic and more feldspathic (both feldspars) than undissected arcs, and these sands contain plutonic quartz. The "plutonic arc" field approaches and perhaps merges with the "continental block" field.

An interpretation of the tectonic setting of the Cowlitz Formation depositional basin is perhaps open to question and requires a regional investigation. However, based on limited data, the detrital composition of the sandstones of the Cowlitz Formation does not appear to be characteristic of a forearc basin with active volcanism and penecontemporaneous erosion. Instead, the provenance suggests a continental block, metamorphic and/or plutonic source, with the development of a fluvial system to transport the detritus across the continental margin. Major deltaic complexes that are contemporaneous with the Cowlitz Formation in late Eocene time are the Puget

Group in western Washington (Buckovic, 1979) and the Coaledo Formation in southwestern Oregon (Dott, 1966).

GEOLOGIC HISTORY AND PALEOGEOGRAPHY

Throughout Eocene time, a large marine embayment bordered the continental margin of Oregon and Washington, and it extended from the present-day Klamath Mountains to the Olympic Peninsula (Snavely and Wagner, 1963). Low relief, swampy, alluvial plains were situated on the eastward side of this marine basin, particularly to the northeast in the vicinity of Olympia, Washington. This basin was underlain by fissure, flood-type basalts with oceanic characteristics that were erupted in early and middle Eocene time and that form the basement complex of the Coast Range (Snavely and others, 1968).

By late Eocene time, a nearshore, shallow marine basin on a continental shelf existed in the vicinity of the upper Nehalem River-Wolf Creek area. The earliest record of geologic events in the thesis area is the volcanic rocks that are referred to the upper unit of the Tillamook Volcanics. These chiefly subaerial, alkalic basalt and basaltic andesite lavas formed an emergent, volcanic island on the oceanward side of this shallow marine basin (Figure 38). Coarse-grained basaltic conglomerates and sandstones that are interbedded with the subaerial volcanic flows indicate the existence of paleochannels, and perhaps, considerable paleorelief on the volcanic island. Locally, some volcanic detritus from the volcanic terrane was shed into the marine basin. Fossil leaves that are preserved in the basaltic sedimentary rocks indicate a subtropical

Figure 38. Late Eocene paleogeography of Oregon and Washington: open marine embayment with local volcanic islands, coastline, costal plain, and moderate relief uplands. O= Olympia, P= Portland, E= Eugene, and CB= Coos Bay. (Modified from Dott, 1966, Figure 3.)

paleoclimate with a mean annual temperature of 13°C (Schorn, 1982, written communication).

In late Eocene time, streams flowed westward across a broad, low-lying continental margin (Figure 38). Based on fossil floras, Axelrod (1968) suggested that the elevation of central Oregon and Washington was less than 300 meters and that uplands with elevations greater than 2100 meters existed to the east in eastern Idaho, northeastern Washington, and north-central Nevada. The streams carried mostly micaceous and arkosic sediments that were derived from continental plutonic and/or metamorphic source areas. Deltas and adjacent, swampy plains, developed where the streams entered the marine basin (Dott, 1966; Buckovic, 1979). In the vicinity of the thesis area, carbonaceous, micaceous, and arkosic sedimentary rocks of the Cowlitz Formation were deposited in this nearshore, shallow marine basin. Volcanic detritus was uncommon except near the volcanic islands in the deeper water lithofacies. A model for this basin in late Eocene time is shown in Figure 39.

In Oligocene time, deep, cool waters invaded the upper Nehalem River-Wolf Creek area as a marine transgression occurred on the continental margin. Tuffaceous mudstones and siltstones of the Keasey Formation were deposited in this sea. The tuffaceous composition of these mudrocks indicates a volcanic provenance for the Keasey Formation. Andesitic volcanism along the eastern margin of the continental basin (Snively and Wagner, 1963) was probably the source area for much of the volcanic detritus that is present in the Keasey Formation.

Figure 39. A model for the paleogeographic and stratigraphic relations of the late Eocene Cowlitz Formation and Tillamook Volcanics in the upper Nehalem River-Wolf Creek area. (Modified from Dott, 1966, Figure 16.)

SUMMARY AND CONCLUSIONS

In late Eocene time, subaerial basalt and basaltic andesite lavas and minor basaltic pyroclastic rocks were erupted from volcanic centers in the present-day Tillamook Highlands. In the upper Nehalem River-Wolf Creek area, these volcanic rocks are referred to the upper unit of the Tillamook Volcanics. The Tillamook Volcanics formed a paleotopographic high in an Eocene continental margin basin.

Basaltic pebbly sandstones and basaltic cobble to boulder conglomerates are interbedded with the subaerial volcanic rocks of the Tillamook Volcanics. They were probably deposited in subaerial paleochannels, and some units are probably debris flow deposits. The basaltic composition of the clasts indicates a local provenance from volcanic centers in the Coast Range.

Samples of the volcanic rocks in the upper Nehalem River-Wolf Creek area range geochemically from basalt to andesite and are mostly alkalic in composition. The samples are divided informally into two loosely-defined geochemical groups, although a wide range in values of major, minor, and trace elements is characteristic of all the samples. The significance of these two groups, if any, is uncertain, but it may be related to different eruptive events or eruptions from different vents.

These two geochemical groups, as defined by samples of basalt flows in the thesis area, are not related to Tillamook Volcanics versus Goble Volcanics. Similar to the volcanic flows in the upper Nehalem River-Wolf Creek area, flows at Rocky Point and Quartz Creek and flows at Cedar Butte also display a wide range in geochemical composition. Timmons (1981) referred the former group to the Goble Volcanics and the latter ones to the Tillamook Volcanics. This geochemical distinction seems invalid for the following reasons:

- 1) insufficient number of samples to define regionally applicable, geochemically defined volcanic groups
- 2) absence of well-defined geochemical groups

The flows in the vicinity of the upper Nehalem River-Wolf Creek, Rocky Point, Quartz Creek, and Cedar Butte areas show an overall similarity in the following attributes:

- 1) variability in geochemical composition
- 2) mostly alkalic lavas, although tholeiitic lavas are present
- 3) mostly subaerial volcanic rocks

Speculatively, the flows at Rocky Point may be part of the upper unit of the Tillamook Volcanics. In the thesis area, the extension of the Gales Creek fault is mapped as well-defined, en echelon faults that are colinear with the Gales Creek fault to the southeast and the Humbug Mountain fault to the northwest of the thesis area. On SLAR, prominent, northwest-oriented lineations trend through the thesis area and to the southwest of the Rocky Point area. Thus, the volcanic rocks at Rocky Point may possibly be a detached, fault-bounded block of Tillamook Volcanics.

The geochemistry and petrography of the flows in the upper Nehalem River-Wolf Creek area compare to lavas that are part of subaerial, oceanic islands, such as Iceland and the Galapagos Islands. The similarities are:

- 1) variability in geochemical values
- 2) alkalic and tholeiitic lavas, although alkalic lavas are more prevalent in thesis area
- 3) enrichment in LREE
- 4) similar Th-Hf-Ta ratios

Some low aluminum, iron-rich andesite flows in the thesis area may be considered Icelandites, which are characteristic of oceanic islands. The upper Nehalem River-Wolf Creek volcanic rocks differ from volcanic rocks that are found in a magmatic arc setting.

Snavely and MacLeod (1974) also note the upper Eocene volcanic centers are probably unrelated to a subduction tectonic setting. As these authors explain, the upper Eocene volcanic rocks do not show a systematic variation in K_2O , are more alkalic than the calc-alkalic rocks in the Oregon Cascades, and do not form a linear, "island arc" belt. They infer that the late Eocene volcanism in the Coast Range is related to tensional rifting.

The sedimentary rocks of the Cowlitz Formation were deposited in a nearshore, shallow marine, shelf basin on the continental margin. The depositional environment is concluded to have been storm-influenced or storm-dominated. The Tillamook Volcanics (upper unit) probably represented an emergent, paleotopographic highland on the western margin of the basin, since marine mudrocks of the

Cowlitz Formation depositionally overlies the volcanic rocks around the periphery of the mapped volcanic terrane.

The sedimentary rocks of the Cowlitz Formation were derived mainly from a continental plutonic and/or metamorphic source area. Locally, volcanic-rich mudrock interbeds are found in the Cowlitz Formation. However, most sedimentary rocks of the formation are carbonaceous, micaceous, and arkosic in composition.

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APPENDIX I

INAA TECHNIQUE

Chips of fresh, unweathered basalt were ground to produce a fine powder for x-ray fluorescence analysis by Dr. Peter Hooper at Washington State University. Unused powders of the samples were returned to the author and were used for INAA.

An approximately one gram sample was irradiated for one hour at 235 kw in a "lazy susan" apparatus. The irradiation was executed at Reed College, Portland, Oregon, in a Triga Mark I nuclear reactor.

Detection was made on a high resolution Ge(Li) detector with a Tracor-Northern 4000 terminal in the Earth Sciences Department at Portland State University. The samples were counted for 1000 seconds about 5 to 6 days after irradiation and for 3000 seconds at 4 to 6 weeks after irradiation. Standards were counted for 3000 seconds for the first count; 9000 seconds, second count. Concentrations were calculated by the comparative method by using peak information that was obtained from the Tracor-Northern peak search program.

APPENDIX II

BASALT SAMPLE LOCATIONS*

<u>Sample</u> (all MJ prefix)	<u>Location</u>
8-21-5	Logging road, NW1/4, NW1/4, NE1/4 sec. 10, T3N, R6W
11-20-2	North side of U. S. 26, SW1/4 NW1/4 sec. 2, T3N, R6W
11-20-3	South side of U. S. 26, E-W center line, sec. 2, T3N, R6W
9-4-3	North side of U. S. 26, SE1/4 NE1/4 sec. 2, T3N, R6W
11-21-1	Lowest flow (in Wolf Creek), south of U. S. 26 gravel shed, NW1/4 sec. 6, T3N, R5W
11-21-5	Next to upper flow, south of U. S. 26 gravel shed, NW1/4 sec. 6, T3N, R5W
11-21-6	Upper flow, south of U. S. 26 gravel shed, NW1/4 sec. 6, T3N, R5W
10-4-1	Unit I, Hawkins Pit section, NE1/4 NW1/4 sec. 19, T3N, R5W
10-4-5	Unit IV, Hawkins Pit section, NE1/4 NW1/4 sec. 19, T3N, R5W
10-8-4	Borrow pit, SW1/4 SE1/4 sec. 19, T3N, R5W
9-17-3	Old Lousignont Road, NW1/4 SW1/4 sec. 18, T3N, R5W
10-17-1	Giveout Mountain, NW1/4 NE1/4 sec. 23, T3N, R6W
10-10-2	SP Railroad track, NE1/4 NE1/4 sec. 32, T3N, R5W
11-18-2	SP Railroad track, west of Reliance Creek, upper flow, SW1/4 SE1/4 SW1/4 sec. 26, T3N, R6W
11-28-2	SP Railroad track, west of Reliance Creek, middle unit, SW1/4 SE1/4 SW1/4 sec. 26, T3N, R6W
11-20-1	SP Railroad track, west of Reliance Creek, lower unit, NE1/4 SE1/4 SW1/4 sec. 26, T3N, R6W
11-28-1	SP Railroad track, east of Reliance Creek, upper flow, SW1/4 SE1/4 sec. 26, T3N, R6W
8-21-2**	Logging road, NW1/4 NW1/4 NE1/4 sec. 10, T3N, R6W
9-29-7**	Wheeler Road, SE1/4 NW1/4 sec. 30, T3N, R5W
11-27-2**	SP Railroad track, SE1/4 SW1/4 sec. 25, T3N, R6W

* locations for samples that were point counted and/or analyzed for geochemical composition

** conglomerate clast

APPENDIX III

FORAMINIFERA SAMPLES OF THE COWLITZ FORMATION

MUDROCK LITHOFACIES

F-8-25-10

Location: Wolf Creek Road, SW1/4 NE1/4 sec. 6, T3N, R5W

Age: Upper Narizian

Environment: Outer Neritic to Upper Bathyal

Cassidulina globosa VR*, Caucasina schencki VA, Gyroidina sp. R, Cassidulina margaretae? R, Diatoms (pyritized) A, Plectofrondicularia sp. VR, Arenaceous indeterminate R, Ostracod var. (deep saddle) VR, Bolivina kleinPELLI R, B. oregonensis? (Pyritized) VR

F-9-2-1

Location: U. S. 26, SE1/4 NW1/4 sec. 3, T3N, R6W

Age: Indeterminate

Environment: Marine undifferentiated

Arenaceous indeterminate VR, Diatoms (pyritized) R

F-9-6-1

Location: Wolf Creek, NW1/4 SE1/4 sec. 1, T3N, R6W

Age: Upper Narizian

Environment: Upper Bathyal, Restricted Open Marine

Lenticulina inornata R, Arenaceous indeterminate (crushed) C, Plectofrondicularia gracilis R, P. packardi VR, Bolivina kleinPELLI VR, B. oregonensis C, Gyroidina cf. condoni R, Pseudohastigerina micra VR, Nonion applini R, Bulumina ovata var. VR, Subbotina sp. VR, Caucasina schencki A

F-9-13-1

Location: Wolf Creek, SE1/4 NW1/4 NW1/4 sec. 5, T3N, R5W

Age: Upper Narizian

Environment: Outer Neritic to Upper Bathyal, Restricted Open Marine

Lenticulina inornata RC, Cassidulina margaretae? RC, Ellipsonodosaria sp. R, Plectofrondicularia cf. searsi RC, Nonion applini VR, Angulogerina hannah C, Cibicides natlandi VR, Lenticulina cf. welchi VR, Subbotina sp. VR, Gyroidina sp. (small) R, Bolivina kleinPELLI A, Caucasina schencki A

F-9-30-1

Location: Nehalem River, NE1/4 NE1/4 sec. 31, T3N, R5W

Age: Upper Narizian to Lower Refugian undifferentiated

Environment: Outer Neritic to Upper Bathyal

Lenticulina sp. R, Caucasina schencki R, Nonion planatum VR,
Bolivina kleinpelli R, Cibicides aff. fleischeri VR

HETEROLITHIC LITHOFACIES

F-9-30-2

Location: Nehalem River, NW1/4 NW1/4 sec. 32, T3N, R5W

Age: Upper Ulatisian to Refugian undifferentiated

Environment: Middle Neritic or deeper

Lenticulina sp. R, Caucasina schencki R, Bolivina kleinpelli VR

F-11-3-5

Location: SP Railroad track, SE1/4 NE1/4 sec. 28, T3N, R5W

Age: Indeterminate

Environment: Possibly marginal Marine to Non-Marine.

Barren of marine fossils. Coal/ lignite VA.

SANDSTONE LITHOFACIES

F-11-10-9

Location: SP Railroad track, SW1/4 NW1/4 sec. 32, T3N, R5W

Age: Indeterminate

Environment: Indeterminate

Barren of fossils.

*VR= 1-2 specimens per sample, R= 2-10, C= 11-32, A= 33-100,

VA= 101-320

Identification and interpretation by Daniel McKeel, consultant, Otis,
Oregon.

APPENDIX IV

MEGAFOSSIL SAMPLES OF THE COWLITZ AND KEASEY FORMATIONS

KEASEY FORMATION

M-9-14-1

Location: Wolf Creek, NE1/4 SE1/4 sec. 5, T3N, R5W

Dentalium porteriensis (Weaver)

Polinices (Euspira) ?clementensis Hanna--some juveniles

Comitas (Boreocomitas) sp. indeterminate--poor preservation

Conus sp. ?armentrouti Hickman--poor preservation

Acila shumardi (Dall)

Parasyrinx delicata Hickman--spire only

Pecten (Delectopecten) cf. peckhami (Gabb)

Tellina sp. mold

M-10-1-3

Location: Nehalem River, NW1/4 NE1/4 sec. 32, T3N, R5W

Dentalium porteriensis

Echinophoria dalli Dickerson--evolved from E. trituberculata of
Cowlitz Formation

?Acamptogenotia tessellata--spire only

Whitneyella lincolniensis (Van Winkle)

Polinices (E.) nuciformis Gabb

M-10-15-3

Location: Nehalem River, SW1/4 SW1/4 sec. 22, T3N, R5W

Naticidae indeterminate

M-10-15-5

Location: Nehalem River, SE1/4 SW1/4 sec. 22, T3N, R5W

Procerapex bentsonae (Durham)

Conus armentrouti Hickman

Acila shumardi

M-10-16-1

Location: SP Railroad, SW1/4 SE1/4 sec. 26, T3N, R5W

Dentalium porteriensis

Epitonium (Boreoscala) schencki Durham

Argobuccium jeffersonense (Durham)

?Bonellita sp.

Polinices (E.) clementensis

Tellina sp. cf. T. gibbsenensis Van Winkle

Environment: Deep, cool water, low energy

COWLITZ FORMATION

M-8-25-1

Location: Wolf Creek Road, SW1/4 SE1/4 sec. 6, T3N, R5W

Terebratula oakvillensis?Hemithyris sp.

M-9-23-1

Location: Lousignont Road, NE1/4 NE1/4 sec. 17, T3N, R5W

Tellina sp. indeterminate--T. lincolnensis or new species of the
Cowlitz Formation

M-11-3-1

Location: SP Railroad track, SE1/4 NE1/4 sec. 28, T3N, R5W

Brisaster--preferentially found in subtidal environments

M-11-10-1

Location: SP Railroad track, SW1/4 NW1/4 sec. 32, T3N, R5W

?Pitar sp. indeterminate, new species of Cowlitz Formation?

Shallow marine or brackish water

No specimens diagnostic of the Cowlitz Formation.

Identification and interpretation by Elizabeth Nesbitt, consultant,
Irvine, California, except for sample M-11-3-1 which was identified by R. E. Thoms, Portland State University.

APPENDIX V

TRACE FOSSIL SAMPLES OF THE COWLITZ FORMATION

MUDROCK LITHOFACIES

T-8-25-10

Location: Wolf Creek Road, SW1/4 NE1/4 sec. 6, T3N, R5W
Chondrites

T-9-13-1

Location: Wolf Creek, SE1/4 NW1/4 NW1/4 sec. 5, T3N, R5W
Chondrites

T-9-30-1

Location: Nehalem River, NE1/4 NE1/4 sec. 31, T3N, R5W
Helminthoidea

HETEROLITHIC LITHOFACIES

T-11-3-5

Location: SP Railroad track, SE1/4 NE1/4 sec. 28, T3N, R5W
cf. Rosselia and/or Cylindrichnus, and ?Thalassinoides

Helminthoidea--semi-systematic, subhorizontal, feeding burrow.
Abyssal through nearshore environments. Preferential in deep
water sediments; common in shale parts of turbidites.

Chondrites--branching, three-dimensional feeding burrow. Abyssal
through lagoonal environments.

Rosselia-Cylindrichnus, Thalassinoides--dwelling or feeding burrows.
Similar to Echiurus in the German Bay, North Sea.

Identification and interpretation by C. Kent Chamberlain, Valero
Producing Company, Denver, Colorado.

APPENDIX VI

FOSSIL LEAVES

Sample P-11-26-1

Location: SP Railroad track, NW1/4 SW1/4 SE1/4 sec. 25, T3N, R6W

Equisetum

Lastera

Palm frond

Platanophyllum

Eocene age.

Mean annual temperature greater than 13°C.

Identification and interpretation by Dr. Howard Schorn, Museum of
Paleontology, University of California, Berkeley, California.

APPENDIX VII

SYMBOLS FOR THE SEDIMENTARY MEASURED SECTIONS

LITHOLOGY

Sandstone

Silty sandstone

Sandy siltstone

Siltstone

Mudstone

SEDIMENTARY AND BIOGENIC STRUCTURES

Bioturbation

Burrows

Shells

Parallel lamination

Trough cross-lamination

Low angle trough cross-lamination

Ripple cross-lamination

Hummocky cross-lamination (HCS)

Channel