AN ABSTRACT OF THE THESIS OF

JAMES STEVEN OLBINSKI for the degree of MASTER OF SCIENCE in GEOLOGY presented on April 22, 1983

Title: GEOLOGY OF THE BUSTER CREEK-NEHALEM VALLEY AREA, CLATSOP COUNTY, NORTHWEST OREGON

Abstract approved: Alan R. Niem

Alan R. Niem

Six Tertiary rock units are exposed in the Buster Creek-Nehalem Valley area. They are, from oldest to youngest: upper Eocene Tillamook Volcanics; upper Eocene Cowlitz Formation; upper Eocene Keasey Formation; upper Eocene Vesper Church formation (informal); upper Eocene to Oligocene Pittsburg Bluff Formation; and middle Miocene Depoe Bay Basalt.

The Tillamook Volcanics is composed of basaltic andesite subaerial flows (SiO_2 54.19% to 55.67%) and volcanic debris flows. The platy jointed subaerial flows are generally porphyritic with a pilotaxitic groundmass; a few aphyric flows with well defined flow banding are present. Highly vesicular flow tops typically show alteration of ilmenite to leucoxene producing a diagnostic bleached white appearance. Debris flows are comprised of very poorly sorted, angular, volcanic and minor sedimentary rock clasts in a mud matrix. Commonly this lithology is intruded by porphyritic and vesicular dikes. Major oxides of the Tillamook basaltic andesites suggest that these volcanic rocks may have erupted in an oceanic island "spreading center" environment.

The Cowlitz Formation unconformably overlies the Tillamook Volcanics in the study area. This formation is divided into five

informal members: a basal basaltic andesite conglomerate; a unit of interbedded micaceous arkose, volcanic lithic arenite and mudstone; a thick structureless mudstone; rhythmically laminated turbidite sandstone and siltstone; and a thick upper arkosic sandstone. The basal conglomerate represents a fluvial braided stream to high energy marine shoreline environment. The finer grained middle members indicate a deepening up sequence. The upper sandstone member is a micaceous, well-sorted, hummocky bedded, porous, very friable sandstone deposited in a high energy storm-dominated shelf to nearshore environment. The upper sandstone member of the Cowlitz Formation ("Clark and Wilson sand" of the Mist gas field) is the current target of active drilling in adjacent areas by several petroleum companies. This upper sandstone and lower arkosic sandstones represent favorable targets in contact with organic-rich, but immature, source rocks in potential fault bounded structural highs and erosional pinchouts in the northern part of the study area.

The Narizian to Refugian Keasey Formation is represented by the Jewell member (informal), in the study area. The Jewell member, a well-bedded to laminated, tuffaceous, indurated mudstone, unconformably overlies the more extensively faulted Cowlitz Formation. Upper slope water depths of 200-600 m are indicated by foraminiferal and molluscan assemblages.

A lithologically distinct and mappable turbidite unit crops out in the study area and is informally named in this thesis the Vesper Church formation. The Vesper Church formation represents west- to northwest-trending turbidite-filled "sea gullies" deposited at bathyal depths (1,000-1,500 m) on the lower slope. Thin-bedded channelized turbidites with Bouma c, d and e sequences and local thick amalgamated sandstones characterize this unit.

The upper Eocene (Refugian) Pittsburg Bluff Formation conformably overlies the Vesper Church formation. Molluscan assemblages from the basal part of this formation indicate water depths of 20-200 m; thus, a significant shallowing episode between the Vesper Church and Pittsburg Bluff formations is indicated. Thick, bioturbated, glauconitic to fine-grained tuffaceous sandstone and sandy mudstone suggest an inner to middle (possibly outer) continental shelf depositional environment for the Pittsburg Bluff strata.

Following a period of high-angle northeast trending faulting, two middle Miocene Depoe Bay Basalt dikes intruded the sedimentary formations exposed in the area. The reversely polarized Northrup Creek dike can be traced over 8.5 km and has a paleomagnetic declination of 170° and a steep inclination of -74°, possibly a result of secular variation of the geomagnetic pole during cooling of the dike through its Cuire temperature (Nelson, 1983). These aphanitic to sparsely micro-porhyritic tholeiitic basalts are chemically identical to the Grande Ronde Basalt of the Columbia Plateau. A recent hypothesis by Beeson _et al_. (1979) suggests that all Miocene coastal basalts represent the distal ends of subaerial Columbia River basalts which reached the Miocene shoreline and intruded or "invaded" soft marine sediments. The reversed stratigraphic order of high and low MgO Depoe Bay (Grande Ronde) basaltic sills intruding Keasey and Cowlitz strata, as much as 1600 m below the surface in the petroleum exploration well Quintana Watzek 30-1

Watzek 30-1 in this study area, illustrates a complicating factor in the emplacement mechanism if these are "invasive" intrusions.

In late middle Miocene the northern Oregon Coast Range anticline was formed, possibly in response to a period of underthrusting (Snavely et al., 1980b). Contemporaneously, a second set of left-lateral and right-lateral conjugate faults (N55°E and N55°W) cut the middle Miocene basalt dikes. This faulting may be related to north-south compression and clockwise rotation of western Oregon and southwest Washington associated with the oblique subduction of the Juan De Fuca Plate beneath the North American Plate as suggested by Magill et al. (1981) and Coe and Wells (1982).

Geology of the Buster Creek-Nehalem Valley Area, Clatsop County, Northwest Oregon

by

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Dr. Alan R. Niem, my thesis advisor, has made a tremendous impression on my mind. He has directed me towards a high standard of quality and thoroughness of study which I hope to maintain in all my future work.

Behind the scenes, but ever present with support, love, and spiritual encouragement is my wife, SuChong. She far exceeds the influence of any other person in my life except my Lord. I have earned only half a Masters Degree at Oregon State University, she has earned the other half.

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INTRODUCTION

Purpose of Investigation

Over the last ten years geology graduate students at Oregon State University, under the direction of Dr. Alan Niem, have been systematically mapping and describing the Tertiary strata of northwest Oregon. This study is a continuation of that effort. In the past, the geology of the Buster Creek-Nehalem Valley area in southeast Clatsop County has been mapped only on a reconnaissance scale as undifferentiated upper Eocene through Oligocene sedimentary strata, Eocene volcanics and Miocene intrusives (e.g., Warren et al., 1945; Peck et al., 1961; Newton & Van Atta, 1972)

The purposes of this study are: 1) to construct a detailed geologic map of the Buster Creek-Nehalem Valley area (scale 1:31,680); 2) to determine the vertical and lateral stratigraphic relations within the upper Eocene Cowlitz Formation and adjacent volcanic and sedimentary formations; 3) to better correlate these units with the formalized stratigraphy of northern Oregon; 4) to interpret the environments of deposition, ages, and provenances for each of the sedimentary units in the area; 5) to interpret the structural and geological history of the area; and 6) to evaluate the economic resources of the area, in particular the hydrocarbon potential of the sedimentary units.

Two major geologic conclusions were developed during the course of this investigation. First, a turbidite unit described by previous workers as either lower Pittsburg Bluff or Keasey represents a mappable rock unit of formational status herein called the Vesper Church formation. Second, upper Cowlitz sandstones which are the reservoir rocks in the Mist gas field can be subdivided into two sandstone units, based on heavy mineral assemblages, which pinch out to the west. These findings about the Cowlitz Formation have important implications for petroleum exploration in Clatsop County.

Location and Accessibility

The 152.8 square km (59 square mile) study area in east-central Clatsop County, Oregon is approximately 88.5 km (55 miles) northwest of Portland and 27.4 km (17 miles) southeast of Astoria (Figure 1). No towns or hamlets are located in the area, but the Nehalem River valley is occupied by many small farms. The small hamlet of Jewell is located 0.5 km west of where the Nehalem River flows out of the west-central part of the study area.

The Nehalem River bisects the area from northeast to southwest. The area is bordered on the east by the Clatsop-Columbia county line. Elevations range from 146 m where the Nehalem River exits the area, to 710 m on the face of Green Mountain in the southernmost part of the area.

Accessibility is good. The Nehalem Highway (State Route 202) bisects the area as it follows the Nehalem River and provides ready access to the numerous logging roads in the area. Many logging roads have been recently improved for the current timber harvest. The improved, or new, logging roads provide good fresh exposures,

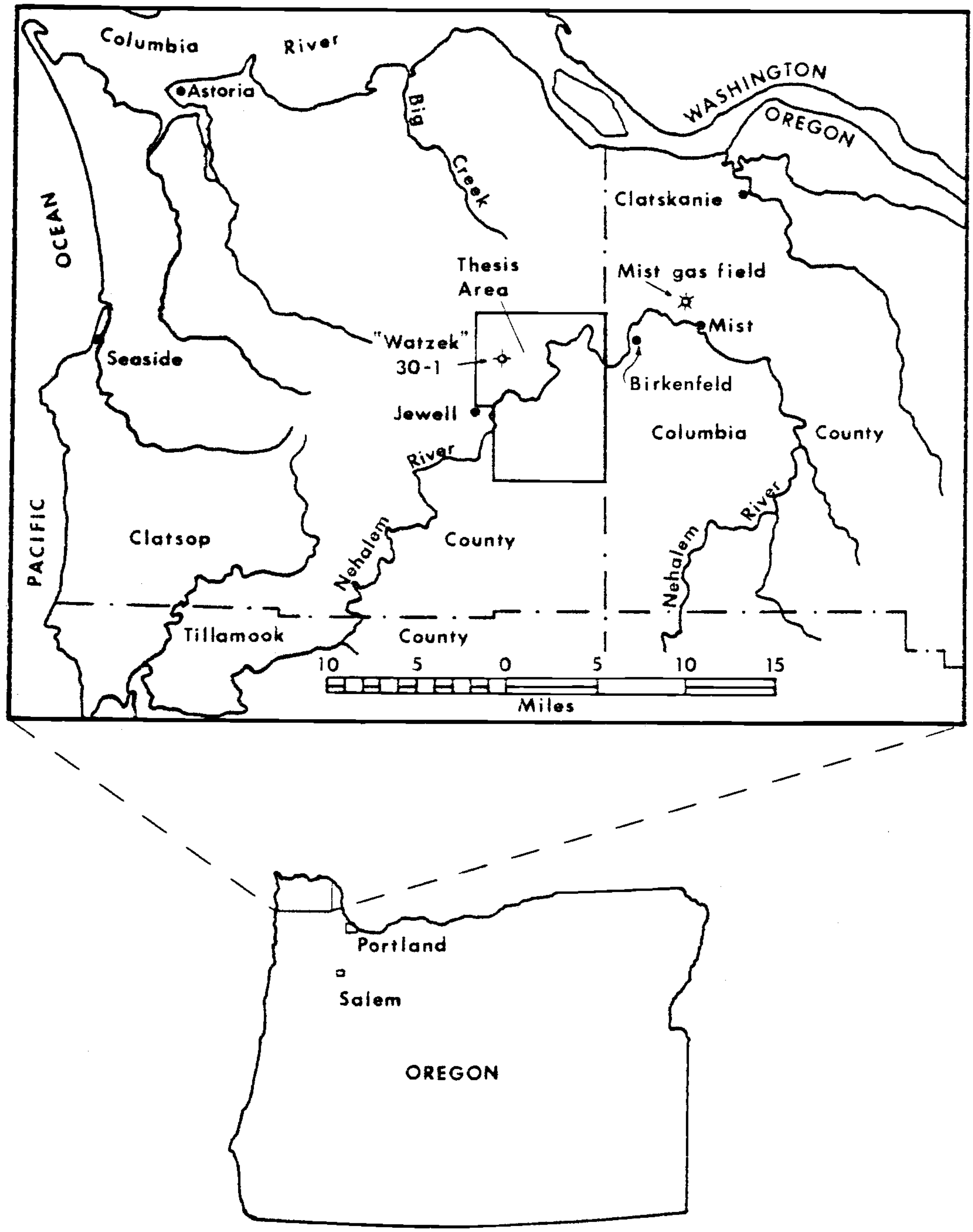

Figure 1. Index map showing the location of the thesis area.

but the best outcrops are in the banks of the Nehalem River. Access to these river outcrops was by rubber raft (wait for low water in late summer or early fall and be careful of hidden snags).

A small part of land along Beneke Creek is owned by the Oregon State Game Commission; permission to enter was obtained from the personnel at the Jewell Elk Refuge north of Jewell, Oregon. Longview Fibre Company owns timberland in the northwestern and southeastern parts of the study area. The largest timberland holder in the area is the State of Oregon Forestry Department.

Previous Work

The first published study on the Tertiary strata of the Pacific Northwest was by Conrad and Dana in 1849 (Moore, 1963). Dana described the lithology and structure of the "Tertiary Formation" in the city of Astoria. Another early geological reconnaissance of northwest Oregon, often cited as the earliest work, was accomplished by Diller (1896). Diller described dark shales containing abundant volcanic material exposed in cliffs cut by Rock Creek located 3.7 to 6.2 km west of Vernonia and 1 km to the southeast of the study area. These sedimentary rocks were described and named the Keasey Formation by Schenck (1927). Crinoids in the Keasey Formation near Mist have been described by Moore and Vokes (1953).

The small town of Pittsburg is the type locality for the Pittsburg Bluff Formation described and named by Hertlein and Crickmay (1925) in Columbia County. The town of Pittsburg is a well-known molluscan fossil locality along the Nehalem River approximately 3 km north of Vernonia and just north of the junction of

Highways 47 and 202 (Moore, 1976). Warren and Norbisrath (1946) published a paper formalizing and describing the Tertiary stratigraphy of the upper Nehalem River Basin. Their oil and gas investigation and reconnaissance map that preceded it (Warren et al., 1945) included the present study area. They mapped and described the Eocene Tillamook Volcanics, and the Cowlitz, Keasey and Pittsburg Bluff formations, placing particular emphasis on molluscan fauna correlations. Deacon (1953), in his Master's thesis, re-examined the Cowlitz and Keasey formations in Columbia County and redefined these units solely on the basis of lithology. He used the informal names "Rocky Point formation" for the Cowlitz Formation and "Nehalem formation" for the lower member (Warren and Norbisrath, 1946) of the Keasey Formation. Deacon contended that Warren and Norbisrath (1946) had based their correlations of Cowlitz strata primarily upon molluscan fauna and had missed significant lithologic differences between the northwest Oregon rock units and the type section of the Cowlitz Formation in southwest Washington. Deacon's thesis was located in parts of the Keasey, Timber and Vernonia 15' quadrangles of Columbia County, Oregon.

Wells and Peck (1961) mapped the Tillamook volcanic series and Cowlitz, Keasey and Pittsburg Bluff formations as well as an 8 km long middle Miocene mafic dike in the thesis area on the geologic map of Oregon west of the 121st meridian. Van Atta (1971) studied the stratigraphic relations between five formations in southern Columbia County and northern Washington County. He used petrographic analysis to determine the provenance of the sandstone units. Emphasis also was placed on physical data such as sedimentary structures in order to determine environments of deposition. The latest work that included the study area was completed by Newton and Van Atta (1976). In their study of natural gas potential and underground storage in the upper Nehalem Basin, they provided brief stratigraphic descriptions, structural and geologic history interpretations, and petrographic analyses of Pittsburg Bluff and Cowlitz sandstones.

Methods of Investigation

Field Methods

Three months were spent in the field from the end of June through the end of September, 1981. Subsequent three day trips were made in October, 1981 and March 1982. Mapping was accomplished using Oregon State Department of Forestry aerial photographs at a scale of 1:12,000 and 1:63,360 and a U.S. Geological topographic map at a scale of 1:31,680 (2 inches = 1 mile). High-altitude U-2 infrared imagery helped in locating large-scale lineations which were field checked to prove or disprove the existence of faults. The final map was constructed from the Birkenfeld (1955), Cathlamet (1953), Saddle Mountain (1955), and Svensen (1955) U.S. Geological Survey 15' quadrangle maps enlarged to the scale of 1:31,680 (2 inches = 1 mile).

One stratigraphic section of the Cowlitz Formation (Appendix 1) was measured using the indirect method of Secrist (1941, in Regan, 1973). This method geometrically corrects to true thickness the apparent thicknesses obtained from dipping strata. Two stratigraphic sections of the Vesper Church formation were constructed using a

Jacob's staff and Abney level (Appendices 2 & 3). The Geological Society of America Rock-color Chart (1970) and Wentworth's size classification (Pettijohn et al., 1973) were used in field descriptions of the rock units. Reineck and Singh's (1980) classification of sedimentary structures was followed to help define paleoenvironments. Field terminology of Miocene basalt units was based on the work of Snavely et al. (1973).

Approximately 250 rock samples were collected in the field. Later, key samples were selected for laboratory analysis. Sample locations appear on Plate I and in Appendices 10, 11, 12 & 13. One sample locality of Miocene basalt was drilled for paleomagnetic study. These core samples were oriented using a sun compass and a Brunton compass.

Laboratory Analysis

Laboratory analyses included preparation of molluscan and microfossils for identification, petrography, sieve analysis, hydrocarbon maturation and porosity determinations, and whole rock chemical and paleomagnetic analyses of basalts. Tetrabromoethane (sp. gr. 2.95) was used to separate 3.0-3.5 and 3.5-4.0 phi-size heavy minerals from the light minerals. Fifteen heavy mineral grain mounts of the 3.5-4.0 phi-size fraction, were made using Petropoxy 154 for the mounting medium. These grain mounts were point counted using a petrographic microscope and mechanical stage (Table 2). The average number of heavy minerals counted was approximately 700 per grain mount.

Twenty-six sandstone and fourteen basalt thin sections were studied. Modal analyses were made for 16 sandstone (an average of 450 points were counted) and 11 basalt samples (Appendix 12). Sandstone classifications are from Folk (1974). Basalt classifications are those of Williams et al. (1954).

Whole-rock, major element analyses of 16 basalt samples were obtained from Dr. Peter Hooper of Washington State University (Appendices 13 & 14). Unaltered samples were first selected and then broken to obtain chips without a weathered rind. Three grams of sample were weighed out and then placed in an ultra-sonic cleaner for 30 minutes to dislodge any dirt or dust picked up during the chipping process. Clean chips were then shipped to Dr. Hooper. Samples were prepared at W.S.U. and run against five U.S.G.S. international standards (G-2; GSP-1; AGV-1; BCR-1; PCC-1) using the procedure set by Hooper et al. (1976). All samples were analyzed on an X-ray fluorescence spectrometer. Data obtained were plotted on silica-variation diagrams to assist in field identification of petrologic types.

Remanent magnetic polarity was determined for 11 oriented basalt samples. A fluxgate magnetometer was used following the methods of Doell and Cox (1964).

Several traverses were made using a proton precession magnetometer to define shallow subsurface Miocene intrusives (Appendix 16). In addition, faults involving the Cowlitz Formation and Tillamook Volcanics have juxtaposed sedimentary strata against volcanic rocks. Such occurrences could be detected by the magnetometer if offsets on a fault were large or near the surface. Each traverse was treated as a separate study and no effort was made to reduce all the data using a single base station.

Fresh outcrop mudstone and sandstone samples were sent to Mr. Terry Mitchell of Amoco Production Company, Denver, for determination of percent total organic carbon, hydrocarbon maturation, porosity and permeability, and vitrinite reflectance (Appendix 15).

Molluscan assemblages collected from each of the prominent lithologic units were sent to Dr. Ellen J. Moore of the U. S. Geological Survey. Two methods were used in concentrating foraminifera from mudstones. These methods are described in Appendix 4. Mounted foraminifera assemblages were sent to Dr. Weldon W. Rau of the Washington State Department of Natural Resources and Dr. Kristin McDougall of the U. S. Geological Survey. Smear slides of nannofossils were made using the procedure outlined in Appendix 5. Smear slides containing diatoms were sent to Dr. John Barron and Mr. Jack Baldauf of the U.S. Geological Survey. Smear slides containing coccoliths were sent to Dr. Richard Poore and Dr. David Bukry of the U.S. Geological Survey. Trace fossils collected during the study were sent to Dr. C. Kent Chamberlain of Valero Producing Company, Denver, Colorado.

REGIONAL STRATIGRAPHY

The Cenozoic rocks of northwest Oregon are exposed along the broad northward plunging Coast Range anticline (Warren and Norbisrath, 1946; Niem and Van Atta, 1973). Upper Eocene and younger sedimentary rocks dip away from the central axis of the northern Coast Range. Smaller northwest- and northeast-trending open folds flanking the large anticline prompted Snavely and Wagner (1964) to use the term anticlinorium in describing this large structure. Seven thousand meters of Cenozoic sedimentary and volcanic rocks have accumulated in the central Oregon Coast Range and adjacent inner continental shelf of Oregon (Snavely et al., 1980). More than 3000 m of Tertiary marine rocks underlie Columbia County, Oregon (Newton and Van Atta, 1976). The core of the Coast Range structure is comprised of early to late Eocene Tillamook Volcanics and Siletz River Volcanics (Baldwin, 1976; Snavely et al., 1980b). The stratigraphy of Oregon and southwest Washington is summarized in Figure 2. Periodic underthrusting and extension along the boundary of the Farallon and North American plates has apparently controlled the structure of western Oregon. Formation of the north-plunging anticline probably occurred during a major episode of underthrusting in late middle Miocene (Baldwin, 1976; Snavely et al., 1980). All folds in the Coast Range are cut by northeast- and northwest-trending normal and reverse faults (Snavely and Wagner, 1964; Niem and Van Atta, 1973.)

The Siletz River Volcanics and the northern Oregon lower Tillamook Volcanics form the basement rocks of western Oregon. Tholeiitic pillow basalt flows and breccias similar in composition

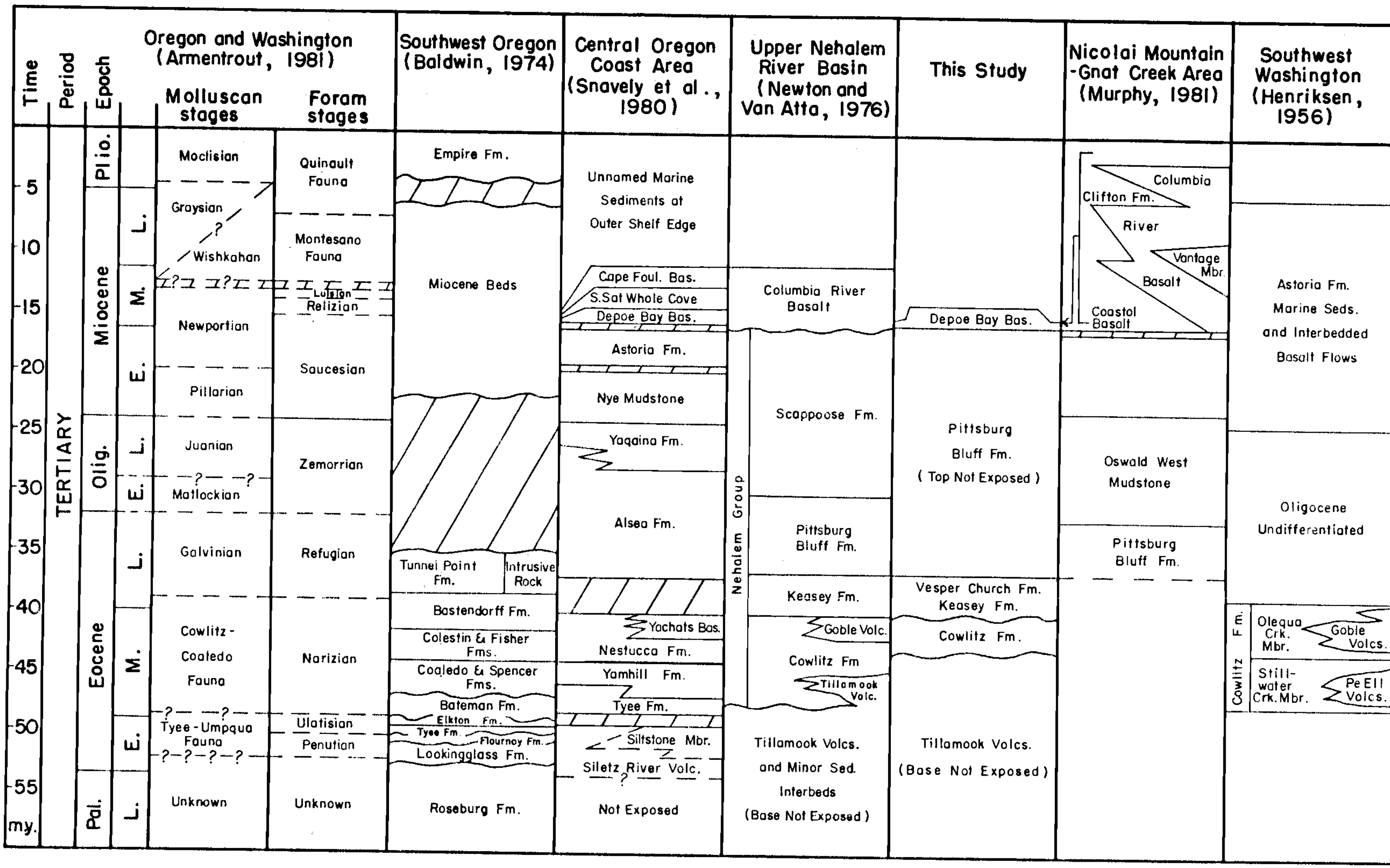

Figure 2: Correlation of Tertiary Coast Range stratigraphy for Oregon and southwest Washington.

to ocean ridge basalt in the lower parts of these formations grade up into breccias, lapilli tuff, and pillow structures of alkalic basalt. The upper parts are interstratified with basaltic sandstone, siltstone and conglomerate (Snavely *et al.*, 1980). Snavely and MacLeod (1977) interpret the upper parts of these formations as having erupted from oceanic islands and seamounts on oceanic ridge basalt.

Magill *et al.* (1981) gave a "best minimum age" estimate of 46 m.y. for the "upper" unit of the Tillamook Volcanics. In the same paper they showed there was 46° ± 13° of clockwise rotation recorded in the Tillamook Volcanics. This rotation is believed to have occurred in two different tectonic phases. The first phase took place during the Eocene, between 50 and 40 m.y.b.p. Rotation about a southern pivot point north of the Klamath Mountains resulted from the Tillamook Volcanics being caught between two subduction zones. This rotation ended with the accretion of the Oregon Coast Range (fragmented part of the Farallon plate) to North America. The second phase of rotation occurred between 20 m.y.b.p.. and the present. The Cascade Mountains and the Oregon Coast Range, as one coherent block, rotated clockwise resulting from extension in the Basin and Range Province.

Recently, new K-Ar radiometric dates, 36.7 ± 0.4 and 37.3 ± 0.5 m.y., were calculated for upper Tillamook Volcanics in the Tillamook Highlands by Kristine McElwee (1983, personal communication). These dates are younger than those given by Magill *et al.* (1981) and suggest that the Eocene volcanic rocks on Green Mountain (36.7 ± 0.4

m.y., Kristine McElwee, 1982, personal communication) are Tillamook Volcanics rather than Goble Volcanics as mapped by Newton (Newton and Van Atta, 1976).

The Goble Volcanics which are interstratified with the Cowlitz Formation in southwest Washington are composed of subaerial basaltic flows and flow breccia with a composite thickness of less than 300 m (Henriksen, 1956). In the type area north of Portland near the town of Goble, Oregon, these basaltic flows and pyroclastic rocks have a total thickness of more than 1,525 m (Wilkinson et al., 1946). In contrast, Warren and Norbisrath (1946) considered the Cowlitz strata in northwest Oregon to unconformably overlie the older Tillamook Volcanics. In the present study, evidence for such an unconformity between the Cowlitz Formation and Tillamook Volcanics has been found (see Descriptive Geology--Tillamook Volcanics).

The oldest sedimentary formation in the northern Coast Range is the middle to late Eocene Cowlitz Formation. The biostratigraphic nomenclature of Armentrout (1981) followed in this study (Figure 3) places the Cowlitz Formation (Narizian) in the middle Eocene. Traditionally, Narizian strata have been listed as late Eocene. Three hundred meters of tuffaceous mudstone, siltstone and arkosic sandstone, with a basal basaltic conglomerate, comprise this unit (Van Atta, 1971; Niem and Van Atta, 1973). Dale Timmons (1981) of Portland State University wrote an M.S. thesis on the Cowlitz Formation in Columbia County, Oregon. He found the Cowlitz strata represented nearshore, wave-dominated sedimentary environments. In the study area, five distinct members are distinguished and represent marine strata deposited first in a deepening upward sequence

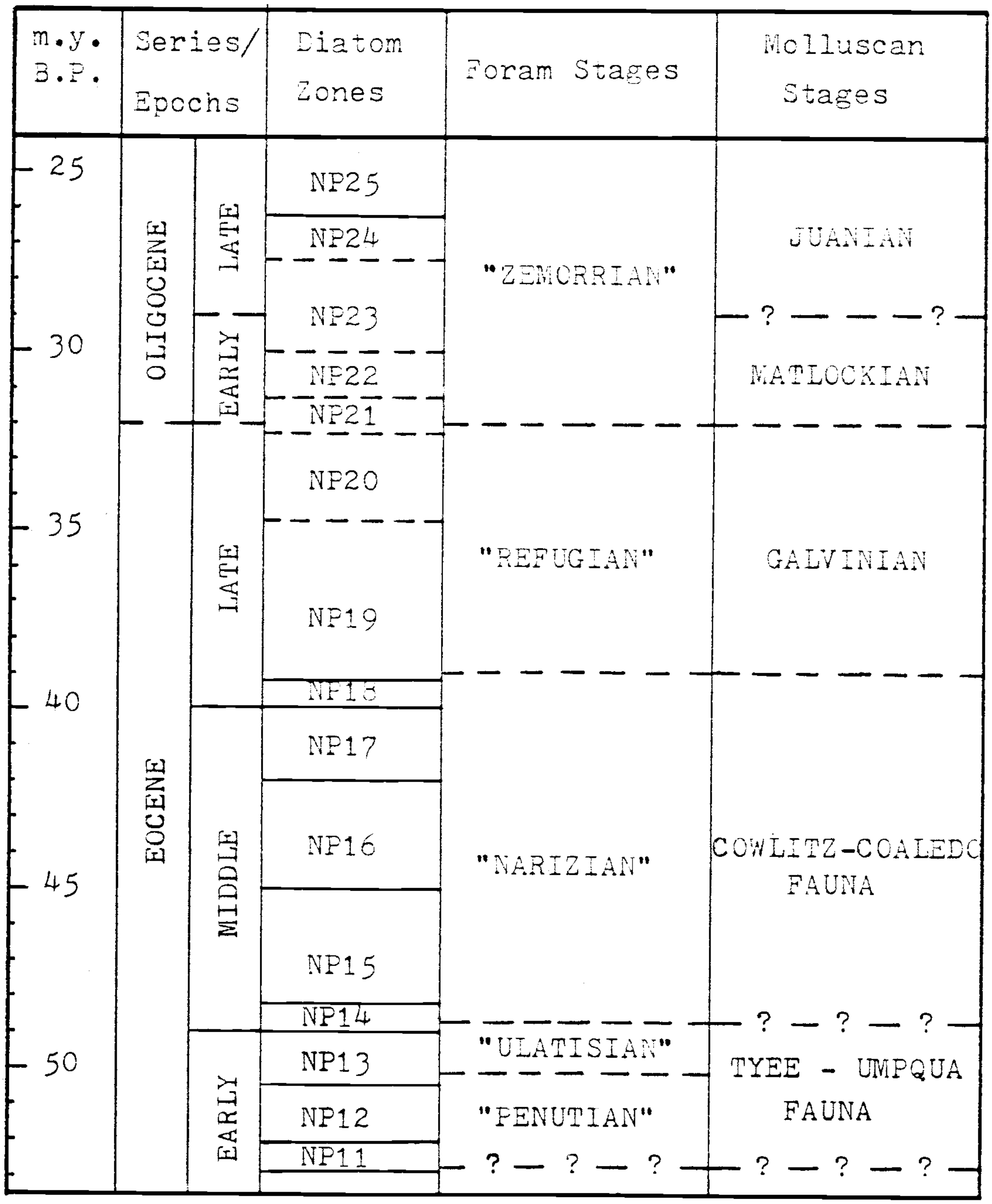

Figure 3: Correlation chart of biostratigraphic units (from Armentrout, 1981).

followed by a shallowing upward sequence (see Descriptive Geology--Cowlitz Formation). The Cowlitz Formation correlates with the Nestucca and Spencer formations in the central Coast Range and Willamette Valley of Oregon (Snavely and Wagner, 1964, Figure 2). The 1979 discovery of commercial quantities of natural gas from a Cowlitz sandstone reservoir in Columbia County near Mist, Oregon, has prompted recent drilling activity in northwest Oregon including the present study area (Newton, 1979; Olmstead, 1981; Olmstead, 1982). In southwest Washington, the type Cowlitz Formation has a maximum total thickness of 3,500 m and is divided into four members; the basaltic Pe Ell Volcanics Member, the deep marine Stillwater Creek Member, the coal-bearing arkosic sandstone of the Olequa Creek Member and the basaltic Goble Volcanics Member (Henriksen, 1956; Wells, 1981).

The tuffaceous siltstone of upper Eocene Keasey Formation unconformably overlies the Cowlitz Formation in northwest Oregon. Van Atta (1971) divided the Keasey Formation in Columbia County into three members based on lithologic differences. Van Atta (1971) estimated a total thickness of 500 m for the Keasey Formation. At least 326 m of lower Keasey strata are penetrated by the Quintana "Watzek" 30-1 well recently drilled in the study area (Plate III).

In the study area a striking change of lithology occurs. The middle member of the Keasey Formation (cf. Van Atta, 1971) is not present. Instead a thick (1,158 m) rock unit comprised of micaceous thin-bedded arkosic turbidite sandstone and mudstone and rare channelized thick amalgamated sandstone is present. This rock unit, mapped in this study as a separate formation, is named informally the Vesper Church formation.

The Pittsburg Bluff Formation conformably overlies the Vesper Church formation. A significant amount of uplift occurred at the end of Keasey time so that, at the inception of Pittsburg Bluff sedimentation, inner to middle shelf sands and muds were deposited. Thick beds of glauconitic, bioturbated, muddy, tuffaceous sandstone typify the lower part of the Pittsburg Bluff Formation in the study area. An upper mudstone unit of the Pittsburg Bluff Formation indicates gradual subsidence during deposition of Pittsburg Bluff sediments (this study, and Murphy, 1981). The Lincoln Creek Formation of southwest Washington correlates in part with the Refugian age Pittsburg Bluff Formation (Figure 2).

Outside the study area the late Oligocene to early middle Miocene Scappoose Formation disconformably overlies the Pittsburg Bluff Formation (Niem and Van Atta, 1973; Murphy, 1981; Kelty, 1981). The fossiliferous, micaceous arkosic sandstones and subordinate tuffaceous mudstones and basaltic conglomerates which comprise this formation are deltaic in origin (Van Atta, 1971; Kelty, 1981). The Scappoose Formation correlates in part with the Nye Mudstone and Yaquina Formation of the west-central Coast Range and the deep water Oswald West mudstone of the northern Oregon coast (Niem and Van Atta, 1973). Kelty (1981) recently extended the range of the Scappoose Formation to the middle Miocene on the basis of middle Miocene Columbia River basalt clasts discovered in a Scappoose conglomerate.

The lower to middle Miocene Astoria Formation is exposed along the Oregon Coast from Astoria to Newport (Cooper, 1981). Five facies recognized within the Astoria Formation include fluvial and deltaic sandstones, deep water turbidite sandstones and hemipelagic mudstones, deep water channelized sandstones and beach to shelf sandstones (Nelson, 1978). The Astoria Formation is approximately 610 m thick at Newport, Oregon (Snavely et al., 1969) whereas in southwest Washington, across the Columbia River from Astoria, the formation is estimated to be 1,370 m thick (Wolfe and McKee, 1972).

During the middle Miocene several flows of the Columbia River Basalt Group reached the paleoshoreline near Westport, Oregon where thick piles of pillow basalts were formed in the Nicolai Mountain area (Murphy, 1981). Comagmatic middle Miocene Depoe Bay and Cape Foulweather basalts simultaneously intruded the unconsolidated Miocene and Oligocene sediments along the Oregon Coast forming peperites, submarine basaltic breccias and pillow lavas, dikes and sills (Snavely et al., 1973; Beeson et al., 1979). These Coastal basalts are geochemically and chronologically identical in all respects to the correlative Columbia River basalts of the Yakima and Late Yakima Basalt Subgroup. The similarities of the Miocene Coastal basalts to the Yakima Basalt flows have prompted a new hypothesis of "invasive" intrusion by Beeson et al. (1979). The invasive hypothesis explains the similarities in geochemistry and chronology as indicating the Coastal basalts are in fact Columbia River basalts. The term "invasive" is used to describe the way in which the Coastal basalt sills and dikes were formed. That is, the Columbia River basalts, upon reaching the Miocene shoreline, ponded up and then intruded down into unconsolidated sediments under their own hydrostatic pressure.

Pliocene and Pleistocene deposits of the ancestral Columbia River are scattered terrace outcrops that unconformably overlie older Tertiary rocks. The lower Pliocene Troutdale Formation is the most notable terrace unit which crops out as quartzite gravels and sands on both sides of the Columbia River from Portland to Astoria, Oregon (Lowry and Baldwin, 1952; Schlicker et al., 1972).

BIOSTRATIGRAPHIC NOMENCLATURE

The revision of biostratigraphic zones with respect to the world-wide Cenozoic geologic time scale constructed by Armentrout (1981) is used in this study (Figure 3). Radiometric age dates were used by Armentrout to tie the calcareous nannoplankton zones of Bukry (1981), foraminiferal stages of McDougall (1980), and molluscan stages of Armentrout (1975), and Addicott (1976) to the world-wide geologic time scale. The major changes made by Armentrout (1981) are: 1) the Ulatisian is now early to middle Eocene instead of middle Eocene; 2) the Narizian was moved down to middle Eocene from late Eocene; 3) the Refugian, formerly in early Oligocene-late Eocene, is now totally in late Eocene and; 4) the Zemorrian, previously limited to late Oligocene, now occupies the entire Oligocene. These adjustments change significantly the traditional (pre-1980) literature age of units in the study area such as the Cowlitz Formation (from late Eocene to middle Eocene).

DESCRIPTIVE GEOLOGY

Tillamook Volcanics

Nomenclature and Distribution

The name Tillamook Volcanics is used for a series of upper Eocene subaerial basalt flows, dikes, pyroclastics and volcanic debris flows (Plate I). The Tillamook Volcanics crop out on Green Mountain in the south part of the study area. Warren et al. (1945) mapped the volcanic rocks on Green Mountain first (in the present study area) as Tillamook volcanic series. Wells and Peck (1961) included Green Mountain units as undifferentiated upper Eocene volcanics separate from the Tillamook Volcanics on the State geologic map of western Oregon. Van Atta (1971) used petrographic and lithologic characteristics and stratigraphic position (e.g., interbedded with Cowlitz strata) to correlate these late Eocene volcanics in Columbia County to the type Goble Volcanics near Goble, Oregon. Newton and Van Atta (1976) mapped the rocks on Green Mountain as Goble Volcanics, a separate formation from the "older" Tillamook Volcanics to the south.

The volcanic rocks on Green Mountain are named Tillamook Volcanics in this study. This choice of terms is based on earliest historical usage, on identical K-Ar age dates, and on the unconformable contact between the Cowlitz Formation and Tillamook Volcanics. In addition, mapping to the south (Mumford and Safley, 1983, personal communication) shows that the volcanics on Green Mountain represent an isolated NW-trending block of Tillamook Volcanics separated from the type upper Tillamook by a downdropped

NW-trending graben containing Cowlitz strata similar to those found in this study area.

Lithology

The Tillamook Volcanics in the study area can be divided into two main lithologies: 1) a lower unit (Ttv_1) of subaerial basaltic andesite flows, dikes, pyroclastics and minor sedimentary interbeds, and 2) an upper unit (Ttv_2) of volcanic debris flows, dikes and subordinate subaerial basaltic andesite flows. The lower unit (Ttv_1) is composed of thick, gently northward dipping (7° to 20°) flows (up to 6 m thick) with basal flow breccias (0.6 m) and vesicular flow tops (0.9 m). One autobrecciated top was also found at outcrop 822-14 (ne sw se sec. 29-T5N-R6W). The center parts of flows commonly display platy cooling joints reflecting a pilotaxitic flow texture. The bottom flow breccias are highly fractured with some fractures extending upward into the platy jointed interval. Some vesicles are found in the bottom flow breccias. The platy jointed intervals of flows are composed of dense glomeroporphyritic dark gray (N3)[1] to grayish black (N2) basaltic andesite. Flow banding occurs in a few flows on Green Mountain as light and dark subplanar bands produced by relative abundances of micro-granular ilmenite in the platy jointed interval. The upper vesicular tops are commonly altered to white (N9) or very light gray (N8). This is the result of thorough hydrothermal or groundwater alteration of groundmass ilmenite to leucoxene, as seen in thin section. These

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[1]G.S.A. Rock-color Chart (1970)

flows display such subaerial features as vesicular tops and bottoms, and baked paleosols (Figure 4). There is a paucity of basalt pillow structures. Paleosols are usually developed on thin (0.6 m) interbeds of basaltic pyroclastics composed of tuff or volcanic debris flows. The few pyroclastic interbeds are composed of angular, coarse-grained basaltic andesite clasts, leucoxene-altered basaltic clasts, and plagioclase crystals in a mud matrix. A few of these interbeds have been reworked to form epiclastic sediments as evidenced by scour-and-fill structures and cross bedding.

Fracturing caused by faulting is very abundant in the Tillamook Volcanics subaerial flows. Quarries on Green Mountain (s s s sw 25-T5N-R6W; s s se se 27-T5N-R6W; sw sw sw sw 27-T5N-R6W) display subaerial flows which in places are highly fractured by faulting, but no dominant fracture pattern was determined. Each quarry displays a different fracture orientation.

The upper unit of Tillamook Volcanics (Ttv_2) is composed of volcanic debris flows with a few associated basaltic andesite dikes and subaerial flows. The volcanic debris flows are heterogeneous mixtures of angular palagonitized scoria, volcanic sandstone, claystone, and vesicular and porphyritic basaltic andesite clasts in a mud and silt matrix. Clast sizes range from pebble through boulder size (up to 3 m in length). No bedding or grading was found in these sediments, but one amalgamated outcrop (822-7) is 6 meters thick. The subaerial basaltic andesite flows associated with these sediments (820-11 & 93-11) commonly contain bulbous load casts at the base indicating flowage over loosely consolidated, water-saturated, possibly thixotropic material.

Figure 4: Blocky subaerial flow of Tillamook Volcanics overlying a baked paleosol (moderate red, 5 R 4/6). Notebook and rock hammer at top of paleosol (Oc 821-3, sec. 27-T5N-R6W).

The relative positions of the two units which comprise the Tillamook Volcanics in the study area are based on the types of contacts with the Cowlitz Formation. In exposures (93-11) where subaerial basalt flows of the lower unit (Ttv_1) are closely associated with sedimentary rocks of the Cowlitz Formation, evidence for faulting contact occurs. Whereas the contact between the Cowlitz Formation (basal volcanic conglomerate) and the volcanic debris flows of the Tillamook Volcanics (Ttv_2) is an angular unconformity. It is hypothesized that the subaerial basaltic andesite flows (Ttv_1) built up, forming steep topography. The upper unit (Ttv_2), comprised of volcanic debris flows and associated rare subaerial basaltic andesite flows, later in-filled topographic lows.

A fluxgate magnetometer was used to determine magnetic polarities of four samples from the Tillamook Volcanics in the study area. Three of the samples are from the lower unit of the Tillamook Volcanics. Sample 95-7 (see Appendix 11 for locations) has normal polarity. Samples 821-1 and 824-6 have reverse polarities. Sample 820-7 is from a subaerial flow in the upper unit of the Tillamook Volcanics and has reverse polarity. Nelson (1983, personal communication) did a preliminary paleomagnetic study of the upper part of the Tillamook Volcanics. From three sites he calculated 48.4° ± 20.8° of clockwise rotation with an inclination of 57.7°. One of the sites is normal polarity, the other two are reverse.

Petrography

Tillamook Volcanics in the Green Mountain area are represented by a variety of igneous textures. Three different petrographic flow textures can be distinguished in thin section analysis. In outcrop, highly vesicular subaerial basaltic andesite flows and associated dikes are characteristically altered to a very light gray (N8) color. In addition to these, other igneous rocks (location 95-6) are amygdaloidal basalt breccia, very similar in appearance to scoriaceous ejecta and may represent a cinder cone deposit. All flows and intrusives are characterized by a glomeroporphyritic texture of subhedral to euhedral phenocrysts of plagioclase, augite, ilmenite and altered pseudomorphs of euhedral olivine. The phenocrysts are scattered in a felted to pilotaxitic groundmass of plagioclase microlites, ilmenite and augite.

The first flow type (outcrops 822-11 and 822-12) is distinct from the other petrologic types by a prominent bimodal size distribution of phenocrysts. One group of plagioclase phenocrysts has a maximum length of 2.2 mm while the plagioclase phenocrysts in the second size group average 0.6 mm long. Other distinguishing characteristics include: abundant oscillatory zoned phenocrysts and microlites with cores of labradorite (An_{62}) and rims of andesine (An_{48}). Resorption voids are not present in the plagioclase phenocrysts. Augite phenocrysts always occur with plagioclase as glomerocrysts. Albite twinned plagioclase phenocrysts from this flow type range in composition from andesine (An_{40}-An_{48}) to labradorite (An_{59}-An_{64}). Randomly oriented, intersertal, microlites of plagioclase have compositions of labradorite (An_{63}-An_{69}). In flows and dikes total plagioclase abundance is close to 80% of the total rock. Phenocrysts comprise 10% to 20% of flow type I with plagioclase ranging in abundance from 8% to 18%; ilmenite and augite phenocrysts range from 1% to 3% and olivine is less than 1%. Plagioclase microlites form 62% to 70% of the groundmass. Ilmenite grains in the groundmass comprise 10% of the flow while groundmass augite and olivine abundances are each 5%.

The second petrographically distinct basaltic andesite flow type (II) displays a very characteristic light and dark flow banded texture common in andesitic to basaltic andesite volcanic rocks. The difference in shade in the bands is a result of variable relative density of ilmenite grains in the groundmass. The plagioclase phenocrysts contain resorption voids commonly filled with green-brown smectite clays (possibly an alteration product of glass). Although not distinctive, oscillatory zoned plagioclase phenocrysts are present (Figure 5). An autobrecciated basaltic andesite of flow type II is located at outcrop 822-15 (Plate I). Some of the breccia clasts display in thin section a hyalopilitic texture. A smectite clay matrix of devitrified glass surrounds the volcanic clasts and secondary sparry calcite fills the remaining larger void spaces. Flow type II consists of labradorite (An_{55}) and andesine (An_{41}-An_{58}) phenocrysts and labradorite (An_{54}-An_{60}) microlites. Plagioclase phenocryst size distribution in the flow type II is different than flow type I in that type II has a unimodal size distribution with the long crystal axes up to 4 mm long and an average length of 1.5 mm. Plagioclase abundances range from 55% to 85% of the total rock. This wide variation is dependent upon the

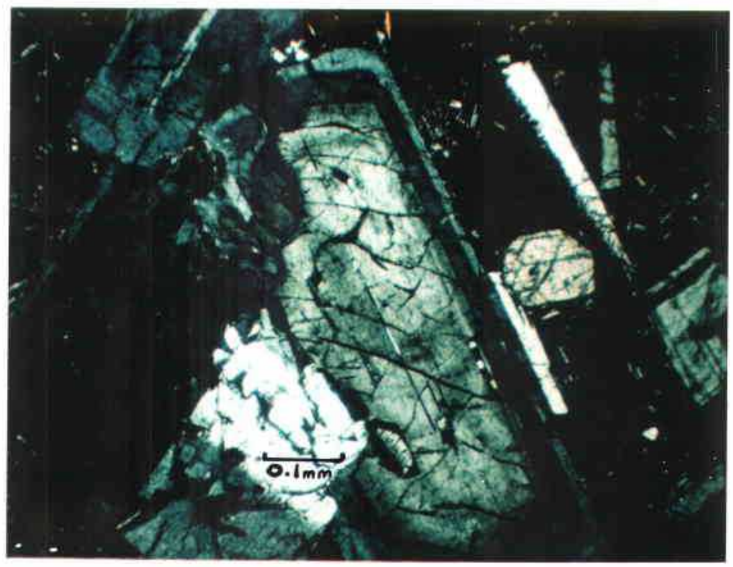


Figure 5: Photomicrograph of porphyritic Tillamook Volcanic sample. Note glomerocryst of oscillatory zoned labradorite, An_{65} (labradorite) in center and An_{48} (andesine) in the rim. Crossed nicols. Sample 822-14 #11.

flow banding and which part of the flow (light or dark band) was examined. This pilotaxitic flow texture appears to be reflected in the characteristic platy jointing of the unit in outcrop which parallels the microlite alignment. Phenocrysts comprise 10% to 15% of flow type II with plagioclase the most abundant mineral at 10% of the total rock. Ilmenite, augite and olivine abundances range from 1% to 2%. The groundmass forms approximately 90% of the flow with the following constituent abundances: plagioclase microlites 35-85%, augite 10-20%, magnetite-ilmenite 4-35% and olivine 1-5%.

The third petrographically distinct flow type (III) has an unusually high silica content (locality 824-2, Plate I) which differentiates this flow type from other more mafic lavas on Green Mountain. Distinguishing optical characteristics include: 1) smaller plagioclase phenocrysts, 1.5 mm long maximum and 0.5 mm long average, 2) augite as individual phenocrysts, 3) a lack of oscillatory zoned plagioclase, and 4) the lack of labradorite phenocrysts or microlites. Plagioclase phenocrysts range in composition from An_{40} to An_{48}, entirely andesine. The groundmass consists predominantly of plagioclase microlites of andesine (An_{40}). Phenocrysts abundances are: plagioclase 3%, ilmenite 1%, augite 2% and altered olivine (to iddingsite) 1%. Groundmass abundances, from point counts, are plagioclase 85%, magnetite-ilmenite 6%, olivine 2% and augite less than 1%.

Alteration. Alteration of Tillamook Volcanics is typically noted in vesicular flows and in dikes. The principal deuteric alteration product is leucoxene after opaque ilmenite. Ilmenite is so abundant (up to 10% of the groundmass) and finely disseminated in some flows that complete alteration of ilmenite to leucoxene (typically white in reflected light) results in basaltic andesite with a very light buff colored appearance in outcrop. Flows at outcrop localities 86-MSIV and 93-7 are examples showing this intense alteration. These basaltic andesites are glomeroporphyritic. They consist of euhedral to subhedral phenocrysts of labradorite (An_{56}-An_{61}), leucoxene (after ilmenite) and partially smectite-replaced pyroxene (augite?) scattered in a pilotaxitic groundmass of andesine and leucoxene. Some vesicles show partial radial infilling by secondary fibrous zeolites (Figure 6).

A few amygdaloidal basaltic andesite flows (e.g., 95-6) have a grayish red (5 R 4/2) color with white amygdules in outcrop. The vesicle-filling amygdules are composed of radiating fibrous zeolites. The red color is a result of very thorough oxidation of the iron-bearing minerals to hematite. This basalt was collected from a breccia through which percolating ground water provided an oxidizing environment for hematite alteration. These rocks may represent the oxidized top of a subaerial basaltic andesite flow with labradorite (An_{54}) phenocrysts which was later brecciated by movement on the Green Mountain thrust fault (Figure 37). An alternative interpretation would be that these rocks represent scoriaceous ejecta of cinder cone origin.

Volcaniclastic Rocks. Volcaniclastic rocks from below the Cowlitz/Tillamook unconformity (e.g., outcrop locality 93-5) are highly weathered but clearly indicate a volcanic origin related to contemporaneous explosive Tillamook volcanism. These volcaniclastic strata are very poorly sorted, with angular rock fragments of

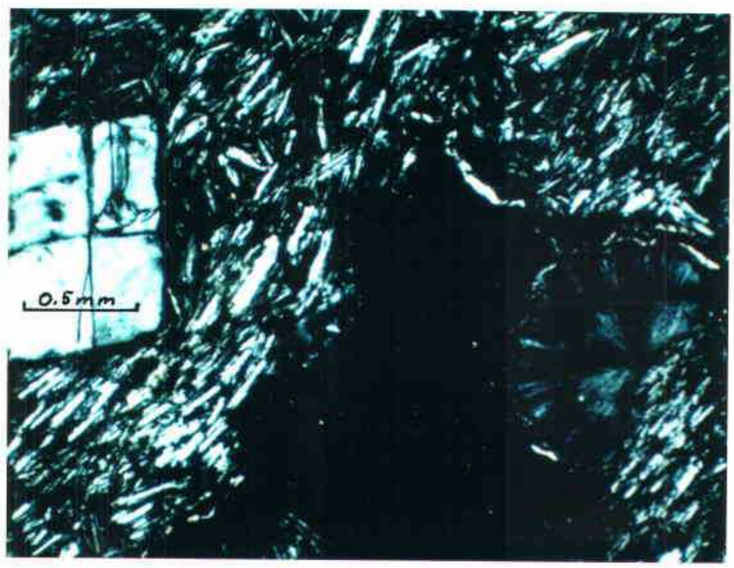


Figure 6: Photomicrograph of sample from vesicular top of Tillamook Volcanics subaerial flow. Note phenocryst of labradorite in a pilotaxitic plagioclase groundmass. Spherical zeolite precipitated along the edge of the large dark vesicle in center of field. Crossed nicols. Sample 93-7 #8.

basaltic andesite in abundant diagenetically altered clay and silt matrix. With 99% of the constituents being volcanic rock fragments, the rock is classified as a volcanic arenite following Folk's sandstone classification (Folk, 1974). Two varieties of volcanic rock fragments are found: 1) amygdaloidal glassy basaltic scoria, and 2) fragments of porphyritic basaltic andesite lava containing subhedral phenocrysts of plagioclase in an altered groundmass. The matrix and a large part of the volcanic rock fragments have been altered to palagonite and smectite clays forming a reddish hematite. The high degree of textural and compositional immaturity suggests a fluvial environment associated with rapid burial or an eroded basaltic cinder cone related to near-by explosive shallow submarine or subaerial volcanism. The author supports the latter origin since these rocks were collected near vesicular dikes which are thought to have provided the lava for explosive submarine eruptions. Rapidly quenched, the volcanic rock fragments would be composed predominantly of altered basaltic glass, scoria and angular brecciated lava clasts. The glass was later altered to form a greenish smectite clay and yellow brown palagonite matrix which subsequently hematized through weathering processes. Similar altered amygdaloidal basalt scoria fragments form the majority of submarine volcaniclastic sands around submarine volcanic highs in Miocene strata off the Southern California continental borderland (Gretchen _et al._, 1981).

Geochemistry

Major oxide analyses[1] of 5 Tillamook Volcanic flows in the study area show a moderate variation of geochemistries (Appendix 13). Although only two basic geochemical groups can be distinguished from these data, the spread in SiO_2 values (54.2 to 64.8%) based on the classification scheme by Taylor (1978) indicates that volcanic compositions in the Tillamook Volcanics range from basaltic andesite to dacite. Samples of the Tillamook Volcanics from the study area do not plot in the Calc-alkaline series of Taylor (1979), but lie between the Alkaline series and Tholeiitic series (Figure 7). When these samples are plotted silica (SiO_2) versus sodium (Na_2O) plus potassium (K_2O) (Figure 8) they fall solidly within the alkaline field of MacDonald and Katsura (1964). One flow (824-2) from section 27-T5N-R6W has a very high SiO_2 value of 64.77% and a relatively low CaO value of 2.72%. High silica and low calcium contents, coupled with intermediate plagioclase (andesine, An = 40 to 48) suggest that this flow is a dacite. However, it lacks quartz, hornblende and oligoclase found in most dacites (Jackson, 1970) and may be an altered andesite. Most samples of Tillamook subaerial flows range between basaltic andesite and andesite in composition (SiO_2 = 54 to 56%, Al_2O_3 = 16.6 to 17.1%).

Silica variation diagrams distinguish Tillamook Volcanics from Depoe Bay Basalt (Figure 35a-g). The Tillamook Volcanics generally

[1]Major oxide analyses done by W.S.U. Chemical Analytical Facility under the direction of Dr. Peter Hooper using the International Basalt Standard.

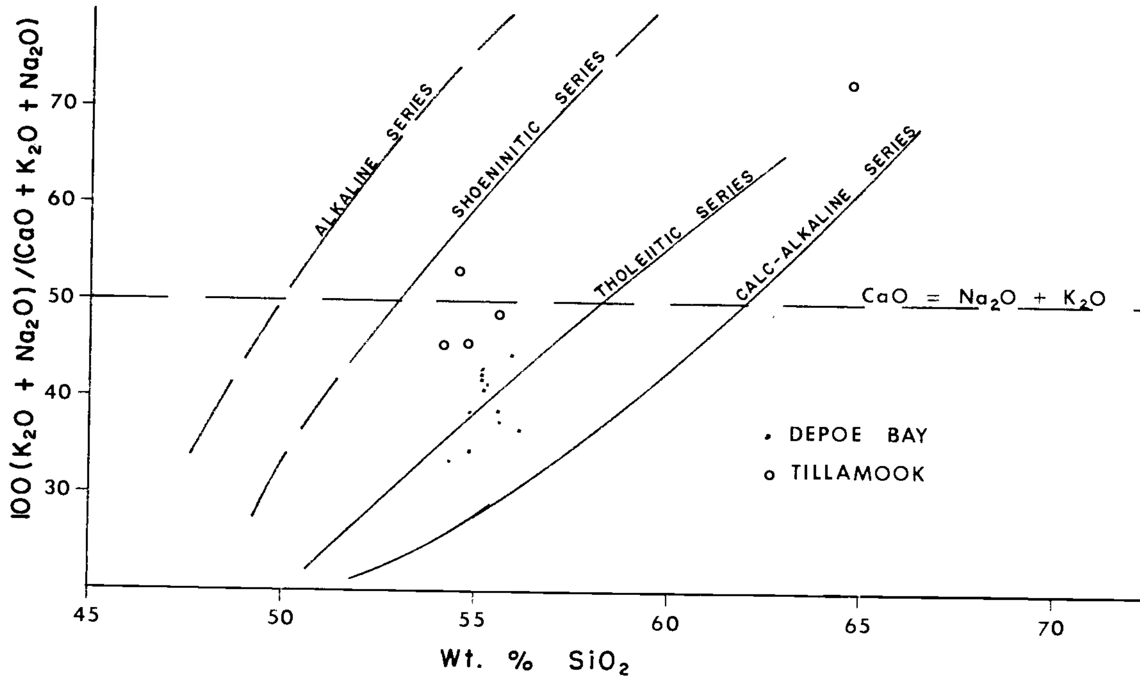


Figure 7: Tillamook Volcanics and Depoe Bay Basalt cross-plot (after Taylor, 1979).

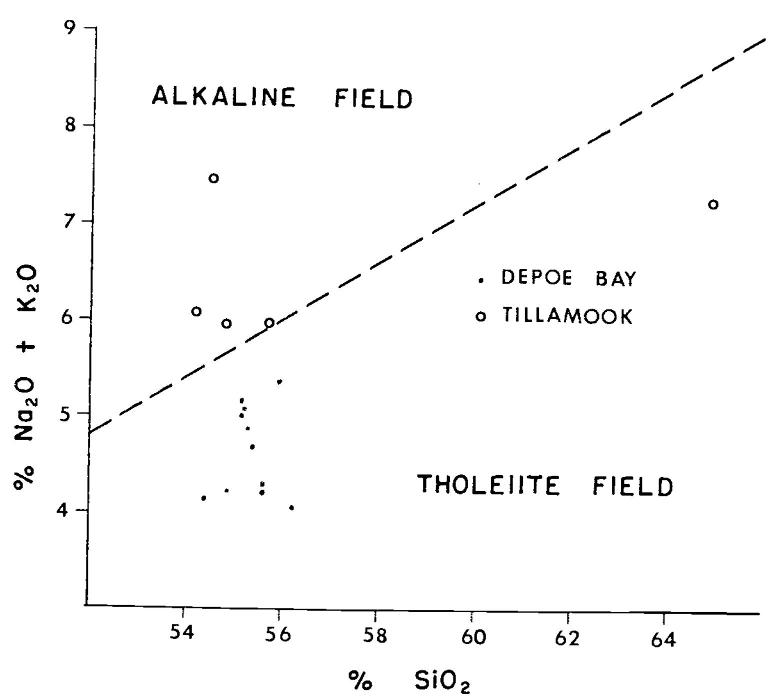


Figure 8: Tillamook Volcanics and Depoe Bay Basalt cross-plot (modified from MacDonald and Katsura, 1964).

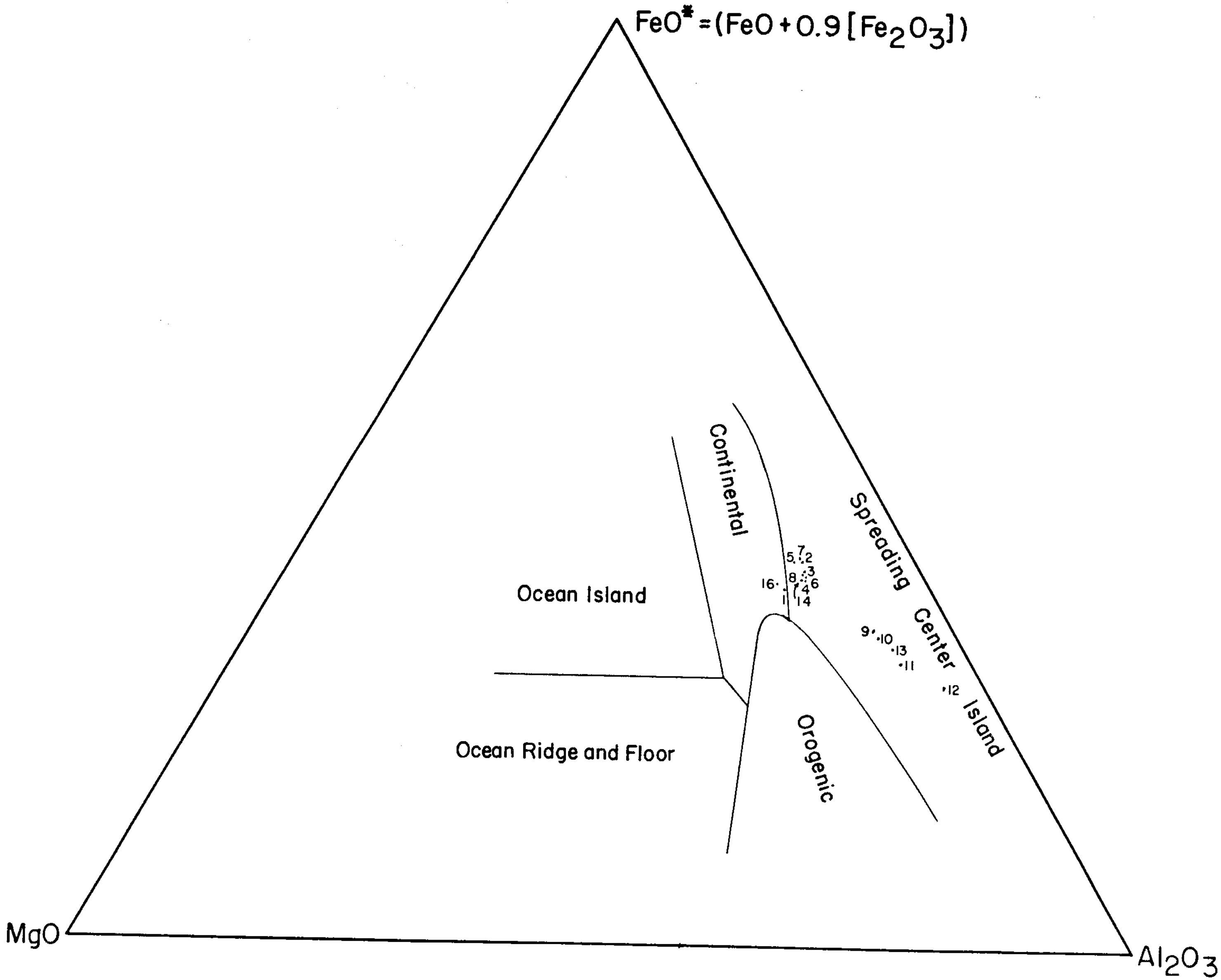
have lower total iron and MgO percentages and higher Na_2O and Al_2O_3 contents than the Depoe Bay Basalt in the study area. Similar proportions of CaO, TiO_2 and K_2O occur for these two igneous units.

When chemical data from the Tillamook Volcanics are plotted on a MgO-FeO-Al_2O_3 Pearce discriminant diagram (Figure 9), the low amount of MgO in these volcanic rocks is obvious. When compared with Cenozoic discriminant boundaries suggested by Pearce et al. (1977), these basaltic andesites plot well within the "spreading center island" field (e.g., similar to Iceland's subaerial basalts on a spreading ridge). Results from plotting Tillamook Volcanics data, from the study area, on this ternary diagram are not conclusive since this diagram was developed for Calc-alkaline series rocks not alkaline. But, a similar magmatic origin has been independently suggested by Magill et al. (1981) and by Duncan (1983, in press) for the late Eocene volcanics of the Oregon and Washington Coast Ranges.

Contact Relations

The lower contact of the Tillamook Volcanics is not exposed in the study area. The upper contact of the Tillamook Volcanics with the overlying Cowlitz Formation is an angular unconformity. This is based on the basal conglomerate member of the Cowlitz Formation (Tc_1) directly overlying Tillamook Volcanics and containing basaltic andesite clasts similar in lithology to the Goble Volcanics. This relationship is inferred from outcrops in the study area (823-5 and 823-6) along Stanley Creek Road on Green Mountain

Figure 9: MgO-FeO^*-Al_2O_3 diagram showing Cenozoic discriminant boundaries, after Pearce et al., (1977). Plot numbers 1 through 8 are Depoe Bay basalts. Plot numbers 9 through 13 are Tillamook volcanics.


FeO* = (FeO + 0.9 [Fe2O3])
MgO
Al2O3
Continental
Spreading Center Island
Ocean Island
Ocean Ridge and Floor
Orogenic

(e e sw sec. 28-T5N-R6W). This unconformable contact is well exposed in the Buster Creek quarry in section 25-T5N-R7W (Nelson, 1982, personal communication). Warren and Norbisrath (1946) also noted the unconformable aspect of this contact.

Age and Correlation

The Tillamook Volcanics represent the oldest rock unit in the study area. Kristine McElwee of Oregon State University, School of Oceanography (1982, unpublished data) has recently obtained two K-Ar age dates from Tillamook volcanic rocks which crop out on Green Mountain. Rocks in Buster Creek quarry (section 25-T5N-R7W) yield an age of 32.4 ± .5 m.y. This sample was from a basaltic andesite dike intruding the upper volcanic debris unit of the Tillamook Volcanics (Nelson, 1982, personal communication). A subaerial basaltic andesite flow exposed in a large active quarry on top of Green Mountain, immediately south of the study area (n n nw ne sec. 34-T5N-R6W), yielded an age date of 36.4 ± .4 m.y. This same outcrop (821-1) has reverse polarity as discussed previously. More recent data collected by Kristine McElwee, Dan Mumford and Eugene Safely (1983, personal communication) to the south of the study area gave radiometric dates of 37.5 ± 0.5 m.y. in the southern part of Green Mountain area and 36.7 ± 0.4 m.y. in the northernmost Tillimook Highlands along the Nehalem River.

These K-Ar age dates suggest that the subaerial flows of Green Mountain are part of the upper Tillamook Volcanics which are also basaltic andesite subaerial flows (Snavely, et al., 1970). Norbisrath et al. (1946) were correct in calling the volcanic flows on Green Mountain (in this study area) Tillamook Volcanics and not Goble Volcanics as Newton and Van Atta (1976) later concluded. Indeed, further mapping to the south of the study area (Niem, Mumford and Safley, 1983, personal communication) indicate the "lower" Cowlitz strata of Newton and Van Atta (1976) are instead grabens containing a very similar Cowlitz stratigraphic sequence as found exposed in this study area. Mumford and Rarey (1983, personal communication) recently concluded the upper most part of the Tillamook Volcanics in the northern part of the Tillamook Highlands consist of two units. The first unit is comprised of subaerial basaltic andesite flows and minor volcanoclastic interbeds. This first unit is overlain by sedimentary marine interbeds and a second volcanic unit of pillow basalts and breccias which they have informally named the Cougar Mountain volcanics. These two volcanic units may correspond respectively to my Ttv_1 subaerial flows and overlying Ttv_2 volcanic debris flows and intrusives.

The radiometric age dates calculated by Kristine McElwee for Eocene volcanic flow and dikes in Clatsop County, Oregon indicate a conflict exists with Armentrout's (1981) biostratigraphic zones and time scale (Figure 3). Further discussion of this problem is found in the Age and Correlation section of the Cowlitz Formation.

Cowlitz Formation

Nomenclature and Distribution

The name Cowlitz Formation (Tc) is used for the upper Eocene sedimentary rocks which crop out in the southern part of the study area and overlie the Tillamook volcanics (Plate I). Weaver (1912) first proposed the name Cowlitz Formation for Eocene marine strata exposed along the Cowlitz River east of Vader, Washington. Weaver (1937) later expanded the definition of the Cowlitz Formation to include the upper Eocene sedimentary rocks exposed along Olequa Creek between Winlock, Washington and the Cowlitz River. Henriksen (1956) has written the most detailed description of the Cowlitz Formation. In his report, he divided the Cowlitz Formation (1,645 m thick) into four members: 1) Stillwater Creek Member; 2) Pe Ell Volcanics Member; 3) Olequa Creek Member; and 4) Goble Volcanics Member. The term "Goble volcanics series" was originally proposed by Warren _et al_. (1945) for a thick sequence of mafic pyroclastics, basalt flows and minor amounts of sedimentary rocks exposed near the town of Goble, Oregon. Upper Eocene strata in northwest Oregon were first named Cowlitz strata by Warren and Norbisrath (1946) based on correlations of molluscan fauna with the type Cowlitz Formation in Washington. Warren and Norbisrath (1946) divided the Oregon Cowlitz Formation into four members: 1) a basal basalt conglomerate; 2) a lower shale member; 3) a sandstone member; and 4) an upper shale member.

In northwest Oregon, Deacon (1953) considered the rocks identified as Cowlitz strata (Warren and Norbisrath, 1946) to be lithologically distinct from the type Cowlitz Formation. He proposed the informal term "Rocky Point formation" for these strata. Van Atta (1971) completed a very detailed lithologic study of Cowlitz rocks in Columbia County, Oregon. He found that the similarities between the type Cowlitz and Oregon Cowlitz formations far exceeded the differences and thus accepted the usage of the term Cowlitz Formation introduced into the Oregon Coast Range by Warren and Norbisrath (1946). Van Atta thought facies relations were such that the basal conglomerate and lower siltstone member of Warren and Norbisrath (1946) should be included as one lithologic unit.

In this study, the Cowlitz Formation is divided into five mappable members: 1) a basal basaltic andesite conglomerate (Tc_1); 2) a unit of interbedded micaceous arkoses, volcanic lithic arenites and mudstones (Tc_2); 3) a thick structureless mudstone (Tc_3); 4) rhythmically laminated turbidite sandstone and siltstone (Tc_4); and 5) an upper arkosic sandstone (Tc_5). The upper Cowlitz shale member of Warren and Norbisrath (1946) is included in the Jewell member (informal) of the Keasey Formation in this study (see Descriptive Geology--Keasey Formation).

Faulted Cowlitz strata crop out in a narrow band (approximately 1.25 km wide) in the southern part of the study area just north of, and including, the north flank of Green Mountain (Plate I). Cowlitz arkosic sandstones appear to pinch out to the west 0.15 km northwest of Vinemaple, Oregon (Nelson, 1982, personal communication). To the east the thick arkosic sandstones of the Cowlitz Formation crop out along the banks of Rock Creek south of Keasey Station and in the Nehalem River near Rocky Point south of Vernonia (Timmons, 1981).

Lithology and Sedimentary Structures

The Cowlitz Formation in the study area, measuring at least 620 meters thick in the Quintana Watzek well 30-1 (sec. 30-T6N-R6W), can be divided into five main lithologies. The basal conglomerate (Tc_1) crops out only on the northwest flank of Green Mountain (Plate I). The second unit is an interbedded sandstone/mudstone unit (Tc_2) which grades upward to the third unit, a foraminiferal mudstone (Tc_3). The fourth mappable unit, a rhythmically laminated turbidite (Tc_4), occurs only in the western half of the study area (Plate I). The upper arkosic sandstone unit (Tc_5) occurs across the width of the study area but thickens significantly to the east.

Basal Conglomerate Unit. The basal conglomerate, approximately 45 meters thick in outcrop, is composed of thick, amalgamated beds of boulder- to pebble-size basaltic clasts in a poorly sorted sand matrix. In the Quintana Watzek 30-1 (Plate III) this unit is interpreted to be at least 49 meters thick and was the unit reached at total depth. Rounding increases with a decrease in clast size. Clasts are in framework support. At some localities (820-8 & 820-9) the conglomerate shows an increase in sorting and rounding up section. The conglomerate is typically composed of 25% volcanic sand and silt matrix, 75% pebble- and cobble-size clasts, and 25% boulder-size clasts. Generally the clast compositions are less than 1% sandstone or mudstone, 20% scoriaceous basalt, 30% vesicular basaltic andesite (very light gray, N8) and 50% dense dark gray (N3) porphyritic basaltic andesite. Lenticular beds (10 cm to 3.0 m thick) of volcanic sandstone are commonly found interbedded within the boulder conglomerate. In some cases pebble-size clasts of basalt and mudstone form crude horizontal stratification in the sandstones. The better sorted volcanic sandstones have planar laminations. Mudstone beds of variable thickness (average--25 cm) locally overlie some sandstone beds. Sandstones and mudstones commonly display gradational basal contacts and sharp, erosional upper contacts with the surrounding conglomerate (Figure 10). Fossils are rare, but the pelecypod LIMA (LIMA?) sp. and the brachiopod TEREBRATALIA? sp. (Moore, 1982, written communication) were found in a sandstone bed within the conglomerate member (outcrop 820-3). "LIMA (LIMA) lives at depths between 10 and 110 meters," (ibid.). The conglomerate outside the study area varies in thickness from 3 m to greater than 60 m (Warren and Norbisrath, 1946). The basal conglomerate unit (Tc_1) in the study area appears to thin markedly to the east, but this may be the result of the conglomerate being cut out by the Green Mountain fault. This conglomerate unit is mapped to the west of the study area where it has a maximum thickness of 60 meters and pinches out laterally (Nelson, 1983).

Sandstone/Mudstone Unit. The second unit of the Cowlitz Formation is poorly exposed in the study area, but is 210 meters thick in the Quintana Watzek 30-1 (Plate III). This unit (Tc_2) is best described as interbedded coarse-grained basaltic arenite, medium- to fine-grained arkose, mudstone and claystone. The coarse-grained basaltic andesite arenites are thick-bedded (.6 m) to structureless. Locally, these beds are very fossiliferous (810-14, 813-2 & 823-4). The pelecypod Nuculanid? and gastropods SCAPHANDER sp. and "HEMIPLEUROTOMA?" sp. (Moore, 1982, written communication)

Figure 10: Lower conglomerate member of the Cowlitz Formation (Tc_1). Notebook lies on a 25 cm thick mudstone bed. A coarse-grained, planar laminated, volcanic lithic sandstone lies under the mudstone and yellow notebook. The mudstone is overlain by a basaltic andesite boulder conglomerate. Joseph Olbinski is sitting to the right of a 1 m diameter sandstone boulder. Outcrop locality 823-5 along Stanley Creek Road, sec. 28-T5N-R6W e e ne sw.

were collected at these localities. One excellent exposure (86-1) along Buster Creek logging road displays the interbedded form of the sandstone/mudstone member (Tc_2). The 60 m long outcrop contains a basal coarse-grained bedded sandstone (1.5 m thick), with spheroidal weathering and white weathered calcareous concretions underlying a foram bearing laminated, tuffaceous siltstone (approximately 1.2 m thick). Overlying the siltstone is a laminated, very fine-grained, arkosic sandstone (2 m thick) with rare foreset laminations. Above the arkosic sandstone, is a coarse-grained basaltic sandstone 3 m thick. Abundant medium-grained arkosic sandstone lenses (.3 m wide, 5 to 7.5 cm thick) occur in the upper basaltic sandstone. Large (1.3 cm diameter) tubular burrows infilled with coarse-grained basaltic sand from the overlying bed are common in the lenses of arkosic sandstone. The contact between the basaltic sandstone and the underlying arkosic sandstone is gradational over a very thin (10 cm) interval. This sandstone/mudstone unit correlates with the lower sandstone member of the Cowlitz Formation in the Fishhawk Falls-Jewell area (Nelson, 1983).

Mudstone Unit. This structureless, bioturbated, foram bearing (aglutinated forms, McDougall, 1982, written communication) mudstone (Tc_3) occurs across the width of the study area (Plates I & II). Pelecypod SACCELLA? sp. and gastropod SCAPHANDER? sp. (Moore, 1982, written communication) occur locally (outcrops 95-3 & 95-6). SCAPHANDER lives at water depths of 20 to 5200 meters with water temperature most likely being the controlling factor. SACCELLA lives at depths of 5 to 1090 meters but is most common in water depths ranging from 20 to 80 meters (Moore, 1982, written communication).

This unit thickens to the east and to the north, in the Quintana Watzek 30-1 (Plate III), the mudstone unit is 244 meters thick.

Turbidite Unit. The Cowlitz Formation in the study area has a thin (approximately 15 m thick) distinct mappable turbidite unit (Tc_4). This unit is characterized by laminated rhythmically interbedded, graded arkosic sandstones and mudstones. Abundant mica and finely comminuted plant debris are concentrated along the lamination planes. This unit (Tc_4) is similar to the turbidite Vesper Church formation (Tvc) (informal) in the study area (Plate I). This turbidite unit of the Cowlitz Formation (Tc_4) is localized in the western part of the study area and grades into the underlying mudstone unit (Tc_3) toward the east (Plates I & II).

Upper Sandstone Unit. The upper sandstone member of the Cowlitz Formation (Tc_5) is well exposed in the east and west parts of the study area (Plate I). Two separate arkosic sandstone units can be distinguished in this member based upon a very distinctive heavy mineral assemblage (see Petrography). For brevity these sandstone units are herein described as "zircon-rich" (Tc_5, Plate II only) and an overlying "epidote-rich" sandstone (Tc_{5b}, Plate II only). The zircon-rich sandstones crop out in the western part of the study area whereas the epidote rich sandstones crop out in the eastern part.

The zircon-rich arkosic sandstones are fine-grained, friable, very micaceous and are bioturbated to planar laminated. Finely comminuted plant debris and mica form the laminations. Glauconite is present locally (outcrop localities 87-4 & 87-5) but overall it is very rare in the upper sandstone member. Bioturbation is common, totally destroying any primary sedimentary structures. Although bioturbation is abundant, fossils (e.g., mollusk) are rare. When preserved, the only sedimentary structures noted are planar laminations and rare unidirectional ripple laminations. At the best exposures planar laminations have low angle (5°-10°) truncation surfaces. One 30 m long outcrop in particular (727-4, Figures 11, 12 & 13) displays well preserved repetitive sequences of planar- to low angle cross-laminations grading upward into unidirectional ripple cross-laminations reflecting a decreasing flow regime. These sequences found in the study area are similar to hummocky cross-stratification described by Dott and Bourgeois (1982). Each ripple laminated bed yields slightly different current directions, S70°W to N45°W, with the average being N77°W (nearly east to west). The upper contact of the ripple laminated beds are sharp and erosional with overlying low-angle cross-laminated sandstones. Each planar to ripple cross-laminated sequence contains slight graded bedding. The planar- to low-angle cross-laminated interval displays repeated grading upward from medium- to fine-grained sandstone. The overlying ripple cross-laminated intervals are fine-grained silty sandstone. One normal fault (2 cm offset) truncated by a scour surface within the low angle cross-laminated interval (Figure 14) attests to soft sediment deformation during rapid deposition. Very few burrows are present implying rapid sediment deposition. Those found were cylindrical (.5 cm diameter), perpendicular to low angle cross-laminations (escape(?) burrows) and parallel to bedding in the ripple laminated interval (feeding(?) burrows). Although rare at

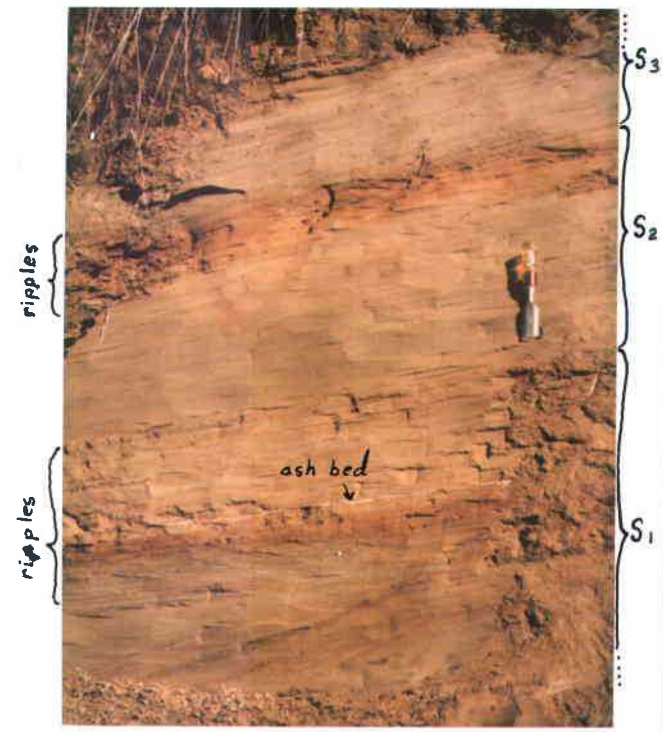


Figure 11: Outcrop of upper arkosic sandstone member (zircon-rich) of the Cowlitz Formation (Tc_5). Note repeated sequences of sandstone sedimentary structures. Lower most bed has liesegang banding (iron precipitation). Each sedimentary sequence (S) begins with a truncated base followed by parallel laminated sandstone scoured and filled by cross-laminated sandstone grading upward into unidirectional ripple laminations. Note thin white ash bed in lower rippled interval. One inch chisel for scale (OC 727-4, sec. 18-T5N-R6W).

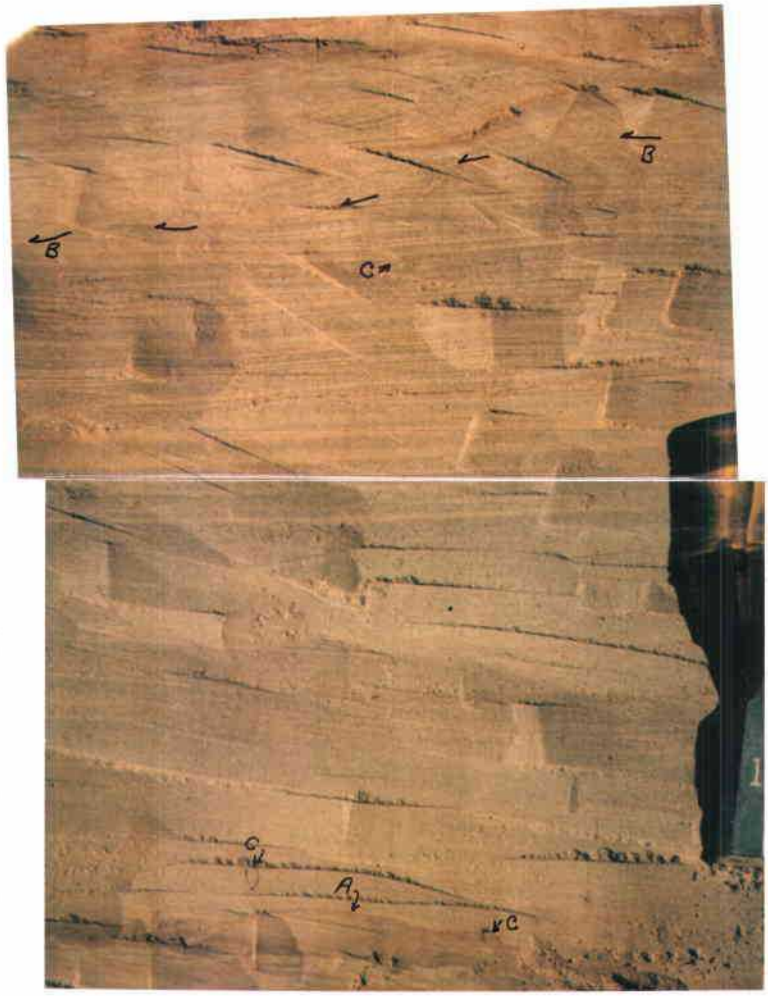


Figure 12: Composite photograph of upper arkosic sandstone member (zircon-rich) of the Cowlitz Formation (Tc_5). Disregard scrapes made by the chisel. Note the basal scoured surface (A) overlain by planar laminated interval (25 cm thick). Planar laminated interval is scoured out (B) and infilled by ripple- and cross-laminated sandstone. This sequence is topped by a unidirectional ripple laminated interval not seen in this photograph (see Figure DC). A few vertical to subvertical burrows are present (C). One inch chisel for scale (OC 727-4, sec. 18-T5N-R6W).

Figure 13: Close-up of unidirectional ripple (arrow) laminated interval in upper "zircon-rich" sandstone member of the Cowlitz Formation (Tc_5). Current directions from this bed are N50°W and N40°W. One inch wide chisel for scale (OC 727-4, sec. 18-T5N-R6W).

Figure 14: Planar cross-laminated Cowlitz sandstone (Tc_5). Note soft sediment faults (A) and lower parallel laminations truncated by low-angle scour surface (B) and overlain by undeformed planar laminations. One inch chisel for scale (OC 727-4, sec. 18-T5N-R6W).

this outcrop, burrows are slightly more abundant in the ripple laminated interval.

The beds of epidote-rich sandstone (Tc_{5b}) of the upper sandstone member (Tc_5) are best exposed in section 24-T5N-R6W (Plate I). This very fine- to medium-grained sandstone is always micaceous (coarse flakes) and very friable. Rare calcarious concretions occur in this unit. The most prominent sedimentary structures are planar laminations where intense bioturbation (also common) has not destroyed them. Less common sedimentary structures include: ripple laminations; low-relief channels; mudstone rip-up clasts in channels; and rare 30 cm thick cross-beds. One fossil hash bed (molluscan molds, outcrop 825-5) overlies a mudstone bed with the mudstone forming flame structures which penetrate the overlying fossil-rich sandstone bed. At one locality (outcrop 93-20), complete deciduous leaf imprints (unidentified, Moore, 1982, written communication) are found in the plane of the laminations.

Localities where the very top of the upper sandstone member is exposed show a relatively thin unit of laminated, rhythmically interbedded, graded, fine-grained sandstone and siltstone. This thin unit was not mapped separately but, overlies both the zircon-rich and epidote-rich sandstones of the upper member. This same unit, interpreted as a turbidite sequence, occurs at 4900 feet in the Quintana "Watzek" 30-1 well (Plate III).

Petrography

Modal analyses were performed on eight thin sections and nine heavy mineral grain mounts of Cowlitz sandstones (Tables 1 & 2).

FORMATION & SAMPLE NO. / MINERAL SPECIES	PITTSBURG BLUFF	VESPER CHURCH				KEASEY		COWLITZ								
	713-14 #13	78-5 #10	81-10 #4	83-14 #5	917-12 #3	717-5 #5	728-7 #3	85-WR #5	88-14 #8	813-1 #1	813-4 #4	93-5 #6	924-8 #3	QW-4980	QW-6550	A-3150
QUARTZ																
Monocrystolline	18.0	36.0	50.1	56.3	57.0	21.0	46.4	38.4	3.0	17.7	48.8	.3	42.7	46.1	37.6	66.4
Pollycrystolline	1.5	3.6	6.3	4.5	5.6	3.6	6.1	4.7	.5	6.6	4.7	-	4.7	5.8	4.5	8.3
Chert	.2	.4	.7	.2	.2	.7	-	.8	-	1.2	.4	-	.7	.3	.9	.7
PLAGIOCLASE	3.9	7.5	5.9	5.5	10.1	1.6	4.6	5.6	1.8	5.1	3.1	.4	8.0	6.7	19.7	7.2
ORTHOCLASE	3.3	7.2	6.6	9.8	5.9	5.3	6.8	10.1	-	2.7	12.1	-	8.2	12.2	8.6	3.5
MICROCLINE	.1	.4	.2	.6	-	.1	.2	.3	-	.3	.2	-	.5	.2	.5	1.3
ROCK FRAGMENTS																
Volconic	1.3	4.0	1.0	-	1.8	1.3	.3	1.7	73.3	8.1	1.1	64.3	.2	.3	1.4	.2
Plutonic	-	-	1.2	1.8	1.8	.9	1.2	.8	-	-	.9	-	1.2	.7	.5	1.1
Sedimentory	1.7	6.9	-	7.3	4.7	2.4	4.6	1.7	-	1.7	1.6	-	4.4	2.7	.8	3.1
AMPHIBOLES	2.5	.1	2.6	-	-	.6	1.2	-	.3	3.6	.2	-	.2	-	.5	-
AUGITE	-	-	2.6	-	.9	-	.2	-	-	1.0	1.6	-	.3	-	-	-
MICAS																
Muscovite	1.0	1.7	2.4	4.9	2.5	1.2	2.6	3.2	.2	.9	2.2	-	3.1	.9	1.2	1.3
Biotite	.2	.6	2.4	1.8	1.4	-	5.0	2.7	-	-	10.8	-	6.3	.7	1.1	.6
Chloritic oltered groins	.7	1.5	.7	1.4	-	1.3	.8	-	-	.3	.4	-	2.4	1.4	1.7	.4
GLASS SHARDS	1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BASALTIC SCORIA	-	-	-	-	-	-	-	-	-	15.6	-	-	-	-	-	-
GLAUCONITE	2.6	-	-	-	-	-	-	-	-	.3	-	-	-	-	-	-
MATRIX	60%	10%	15%	1%	1%	45%	10%	15%	1%	15%	10%	15%	15%	2%	1%	1%
CEMENT	2%	20%	2%	5%	7%	15%	10%	15%	20%	20%	2%	20%	2%	20%	20%	5%

Table 1: Modal analysis of sandstone samples from the Buster Creek-Nehalem Valley Area.

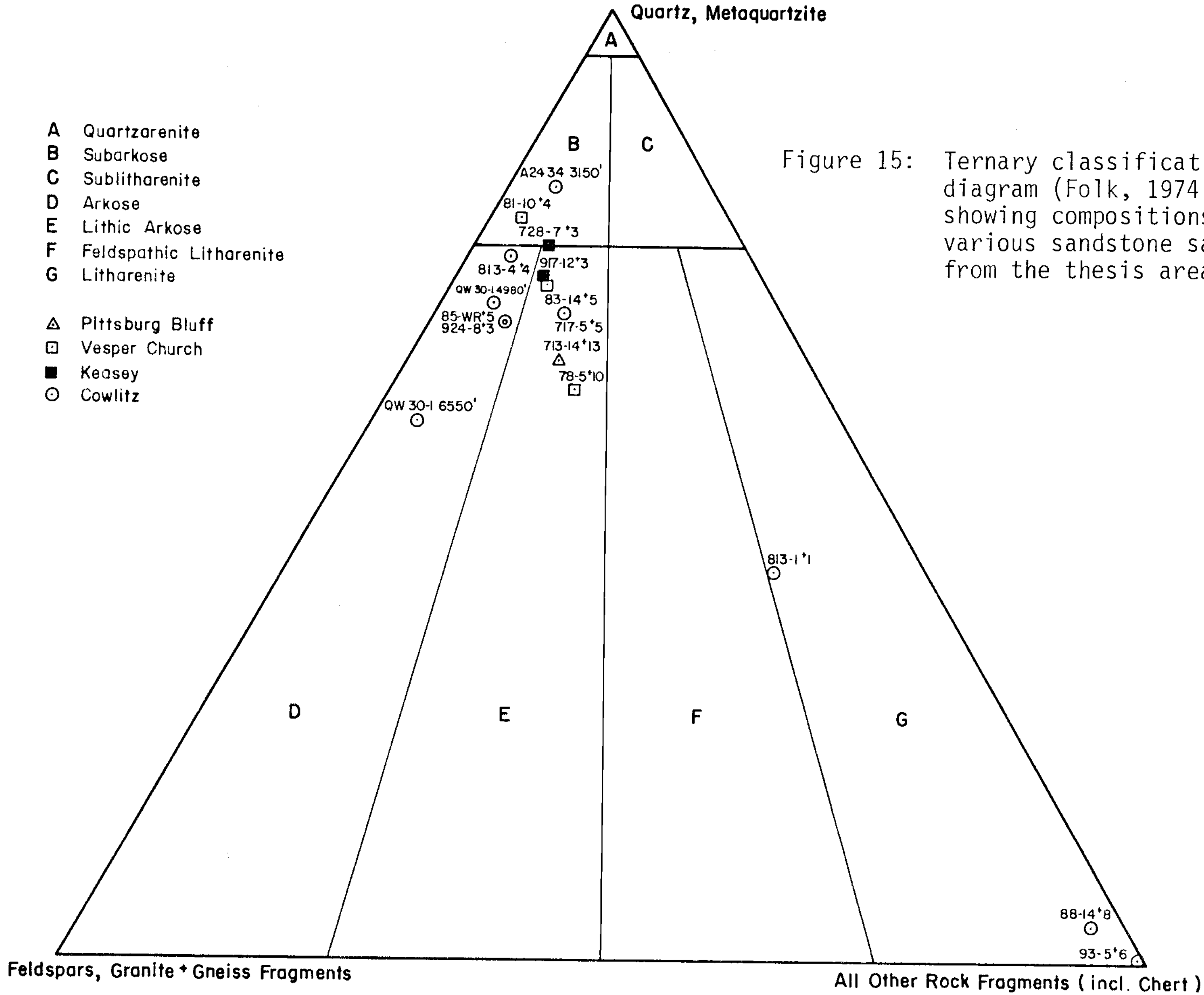


Figure 15: Ternary classification diagram (Folk, 1974) showing compositions of various sandstone samples from the thesis area.

The sandstones of the Cowlitz Formation are volcanic arenites, subarkoses and arkoses, following Folk's 1966 classification (Figure 15). The wide variety of textural and compositional maturity appears to be related to the stratigraphic position of the sandstone. That is, volcanic sandstones were deposited closer to the Cowlitz/Tillamook Volcanics unconformity while arkoses, the more abundant sandstone type, are more prevalent in the upper part of the Cowlitz Formation. This up-section change in sandstone lithologies suggests a changing environment and provenance during Cowlitz deposition.

Two sandstones from the interbedded sandstone/mudstone unit (Tc_2, see Plate I) were studied. Due to a lack of adequate arkosic sandstone outcrops only the volcanic lithic arenites were available for analysis (samples 88-14 #8 and 813-1 #1). Both rocks are classified as basaltic andesitic-arenites. Texturally and compositionally they are immature. Igneous crystalline textures in the angular to subrounded rock fragments include: 1) hyalopilitic (Figure 16), some with dark flow bands, 2) intersertal with plagioclase microlites predominant over iddingsite (deuteric alteration product of olivine), 3) porphyritic with subhedral phenocrysts of albite twinned andesine or labradorite in an opaque hyalopilitic groundmass, 4) porphyritic with a pilotaxitic groundmass of finely crystalline hypidiomorphic plagioclase, 5) dark glassy scoriaceous basalt or basaltic andesite and 6) (found only in sample 813-1) vesicular basaltic (?) glass altered to greenish smectite clay (Figure 18), and partially replaced by calcite.

The lower Cowlitz sandstone from outcrop 88-14 is dominated by basaltic andesite fragments (93%), and contains less than a few percent of quartz and feldspar and 1% clay matrix. The remaining pore space is partially filled with diagenetic, fiberous, birefringent chlorite cement (Figures 16 & 17). Other lower Cowlitz lithic sandstones are also dominated by coarse-grained basaltic andesite rock fragments (36%) but have nearly an equal amount of angular fine-grained, polycrystalline quartz. This texturally immature rock is poorly sorted with 15 to 20% silt and clay matrix suggesting rapid burial. Clasts are predominately angular to rarely subrounded. The most notable component of the constituent grains is abundant vesicular basaltic to basaltic andesite scoria fragments thoroughly devitrified to green smectite clay with spherical vesicles partially infilled with birefringent chlorite (Figure 18). Some of these fragments have been replaced by calcite. Similar Neogene scoriaceous tuff fragments have been described by Grechin _et al_. (1981).

All other Cowlitz sandstones studied petrographically, from the Cowlitz units Tc_2 and Tc_5 (Plate I), are classified as micaceous arkoses to subarkoses (Folk, 1974). A listing of these rock samples includes: 1) an upper Cowlitz sandstone (85-WR #5) from the Cowlitz measured section (Appendix 1); 2) Arkosic sandstones from outcrop localities 813-4 and 924-8, located 3 and 5 miles east of the Cowlitz measured section respectively; 3) Subsurface sandstone samples QW 4980 (Tc_5) and QW 6550 (Tc_2) from the Quintana Watzek 30-1 well at depths of 4,980 and 6,550 feet respectively (Plate 3); and 4) A Cowlitz subarkosic sandstone (A 3150) from 3,150 feet

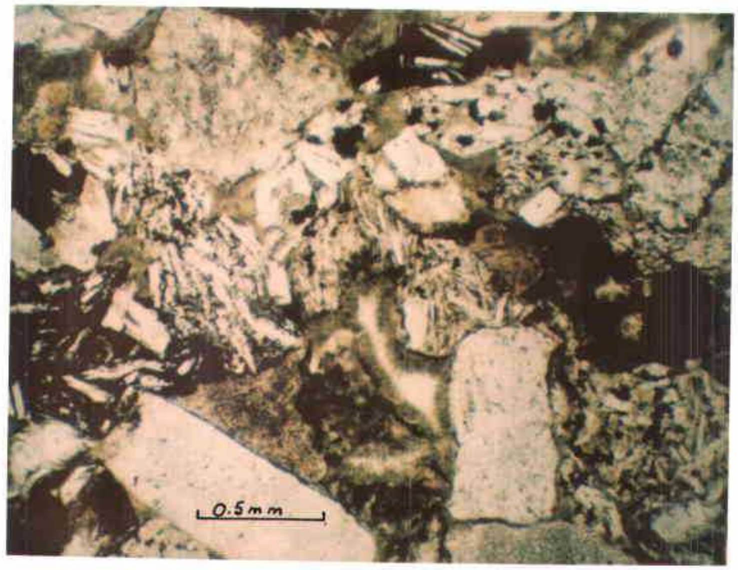


Figure 16: Photomicrograph (plane polarized light) of basaltic-andesitic arenite of Cowlitz Formation (Tc_2). Note abundant volcanic fragments surrounded by chlorite-smectite lined voids. Plane polarized light. Sample 88-14 #8.

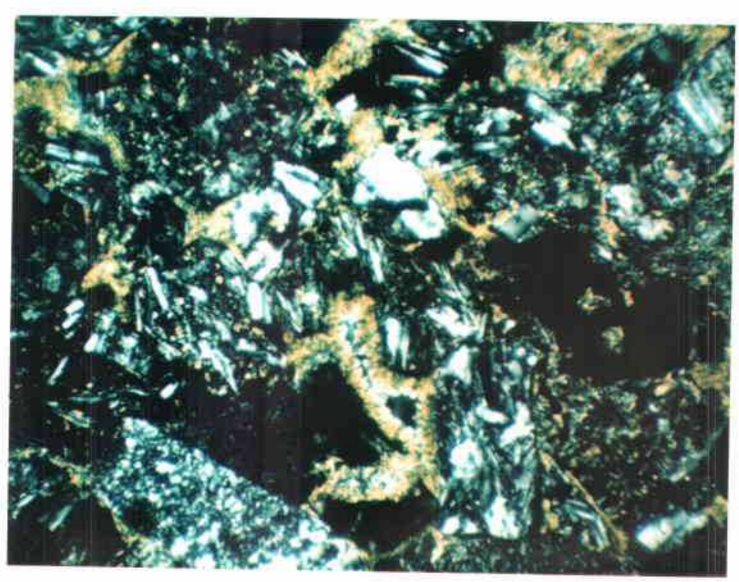


Figure 17: Figure 16 photomicrograph with crossed nicols.

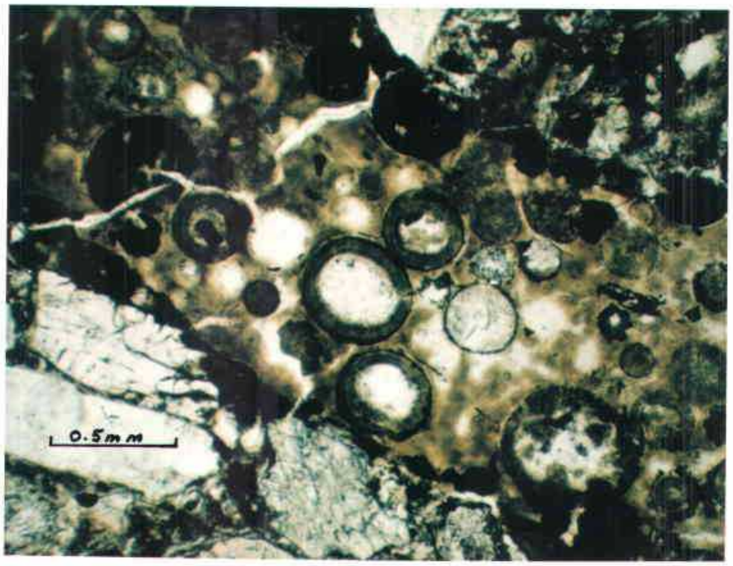


Figure 18: Photomicrograph of basaltic scoria fragment in an arenite from the Cowlitz Formation (Tc_2). Note that the vesicular basalt scoria fragment is altered to green smectite clay. Some spherical vesicles lined with fibrous smectite clays and infilled with zeolites and sparry calcite. Crossed nicols. Sample 813-1 #1.

("Clark and Wilson sand") in the Adams 24-34 well of the Mist gas field. The QW 4980 and A 3150 sandstones are the only rocks of the six having a mature texture (e.g., well sorted, matrix poor), the other four are texturally immature to submature (e.g., poorly sorted, angular and matrix rich). Compositionally, all these rocks are mature.

Framework grains of all the Cowlitz arkosic sandstones have similar mineralogical abundances except sample QW 6550 (Tables 1 and 2). Quartz and feldspar abundances need to be stressed since the interpretation that sandstones in the eastern part of the study area (813-4 and 924-8) are upper Cowlitz sandstones (Tc_5) is based upon both mapping patterns (see Descriptive Geology--Cowlitz and Plate I) and petrographic analysis. The one sandstone (QW 6550) known to be from lower Cowlitz strata (Tc_2) deviates from all other Cowlitz sandstone in relative mineralogical abundances. A lower quartz abundance (57%) and a plagioclase to K-feldspar ratio of 7:3 distinguishes this sandstone, a plagioclase arkose, from the upper Cowlitz sandstones (K-feldspar arkoses). The other upper Cowlitz sandstones (Tc_5) yielded an average quartz abundance of 72% and a plagioclase to K-Feldspar ratio of 3:5. The upper Cowlitz sandstones (Tc_5) in this study are classified as K-feldspar arkoses or subarkoses (Figure 15). This mineralogical change in these six arkosic sandstones may indicate a progressive upward increase in K-feldspar and quartz content throughout the Cowlitz Formation in the study area. The sandstones in the eastern part of the study area, (outcrops 813-4 and 924-8) mineralogically correlate very well with all other upper Cowlitz arkoses (Tc_5).

Porosities determined in thin section, of sandstones from the eastern part of the study area, are as high as 2%. It is more likely that upper Cowlitz sandstones (Tc_5) have much higher porosities since most of the samples collected were poorly cemented and were totally disaggregated during transport from the field. Subsurface samples QW 4980, OW 6550 and A 3150 have carbonate cement filling the pore spaces. It is most probable that more porous and poorly cemented subsurface sandstones were disaggregated by the drilling process. Samples QW 6550 and A 3150 displayed quartz grains with secondary silica overgrowth rims, an indication that older sedimentary rocks comprised a portion of the Cowlitz provenance.

Heavy Minerals. Heavy minerals (greater than 2.95 sp. gr.) vary from less than 1% to 5% of the arkosic Cowlitz sandstones (Table 2). Two arkosic sandstones from the Quintana Watzek 30-1 well (QW 4980 and QW 6550) were studied along with the surface sandstones (localities 727-5, 85-WR, 813-4, 813-10 and 825-7) and the gas producing "Clark and Wilson sand" (A 3150) from the Adams 24-34 well in the Mist gas field. Common heavy minerals occurring in these sandstones are, in decreasing abundance: epidote, zircon, garnet, altered chloritic grains, muscovite, biotite, rutile, green-brown tourmaline, apatite, kyanite and pyrite. Abundant pyrite in all samples indicate that these rocks were in a reducing diagenetic environment.

Based on heavy mineral assemblages, two distinct upper Cowlitz sandstones (Tc_5) can be differentiated. Epidote, zircon, garnet and rutile form the characteristic Cowlitz heavy mineral assemblage

FORMATION & SAMPLE NO. / MINERAL SPECIES	PITTSBURG BLUFF		VESPER CHURCH				COWLITZ								
	713-14 #13	724-6 #3	78-1 #2	79-3 #2	725-16 #5	81-10 #4	727-5 #6	85-WR #5	813-4 #4	813-10 #7	825-7 #3	825-7 #4	QW-4980	A-3150	QW-6550
AMPHIBOLES															
Hornblende															
Green	62.0%	4.9%	.0%	.5%	.0%	49.5%	.0%	.4%	.0%	.0%	1.6%	6.2%	1.5%	1.2%	.0%
Brown	4.6	.9			.7	2.1	.2		.1		.1	.6		.3	
Lamprobolite	1.7				.2%	.4%	.2%								
Actinolite					.2										
Tremolite	3.2	.4			.4	2.1					.6	1.3	.5		
PYROXENES															
Hypersthene															
Augite			1.1	1.5											
MICAS															
Biotite	.1	5.3	37.0	13.5	2.0	.4		4.1	.7	8.4	1.4	.7	2.0	.9	16.3
Muscovite	.3			.5	4.2		.8			1.8	.9	.7	16.3	.6	7.9
Chloritic matter		17.3	42.0	9.0	12.8	1.7	1.7	6.7	.9	4.8	1.7	1.5	23.0	4.0	15.2
EPIDOTE															
Undifferentiated	4.8	4.0	1.1	5.5	5.5	24.9	8.7	6.0	85.5	69.9	87.3	76.4	8.2	77.1	40.4
Clinozoisite	.3			1.0		.6			.1		.9	1.3		.3	1.7
ZIRCON															
Colorless	7.4	9.3	1.7	9.0	9.5	4.6	57.2	23.9	2.3	1.4	.7	4.7	15.8	3.4	3.4
Pink	.7				1.1		3.7	2.2	.1	.2					
TOURMALINE															
Blue															
Brown-green	.9	7.1	1.1	8.0	2.4	1.7	2.1	13.8	1.6	1.6	.6	.2	2.6	.3	2.8
GARNET															
Colorless	5.8	12.9	9.0	11.0	21.9	.9	8.1	26.9	2.2	3.7	.6	1.5	19.4	8.3	8.4
Pink	1.7				4.2	.2		.7					3.6	.6	.6
KYANITE		2.2	.6	3.5	1.1	.8	3.9	.4		.5		.2			.6
STAUROLITE	.4					.6	.2	.4							
SILLIMANITE					.9		.4								
MONAZITE		.4	.6		2.0	3.2	2.7	.4							1.7
RUTILE	.6	.9			.4	.2	8.1	8.2	1.3	2.1	.4	.4	3.6	.6	
SPHENE				8.5											
APATITE	5.1	32.0	5.6	27.5	28.5	4.4	.4	1.1	4.6	4.3	2.6	2.1		.6	
OPAQUES															
Magnetite															
Hematite															
Leucoxene															
Pyrite															

Table 2: Heavy mineral percentages (excluding opaques) of selected samples from the Buster Creek-Nehalem Valley area.

in the arkosic sandstones. Upper Cowlitz sandstone near the Clatsop/ Columbia County border and "Clark and Wilson sands" of the Mist gas field (in the Adams 24-34, Figure 39), differ significantly in the relative abundances of these constituents from upper arkosic sandstone found in the western part of the study area, (which includes the upper Cowlitz measured section (Appendix I), and the QW 4980 sample (Plate 3)). The "Clark and Wilson sand" from the Mist gas field contains a very high percentage of epidote (77%), relatively low percentage of zircon (3%), a moderate percentage of garnet (9%) and a low percentage of rutile (1%) (Figures 19 and 20). This heavy mineral assemblage correlates very well with upper Cowlitz sandstones (Tc_5) which crop out northeast of Green Mountain (813-4, 813-10, & 825-7) and with the sandstone (QW 6550) from 6,550 feet in the Watzek 30-1 well. All are upper Cowlitz sandstones except for QW 6550 which is an epidote rich sandstone from the lower Cowlitz Formation (Tc_2). These sandstones, with the exception of QW 6550, are thus thought to be outcrops of the gas producing "C & W sand" at Mist. The upper Cowlitz sandstone (QW 4980) from 4,980 feet in the Watzek 30-1 has a much lower percentage of epidote (8%), a much higher percentage of rounded zircon crystals (16%), garnet (23%) and rutile (4%) (see Table 2). This assemblage (Figure 21) is nearly duplicated in arkosic Cowlitz sandstones of unit (Tc_5) (727-5 and 85-WR) which crop out in the southwestern part of the study area and thus is, in part, the basis for correlating the surface sandstones with the Cowlitz sandstones in the subsurface (Plate II). From this initial study it is believed that heavy mineral assemblages should

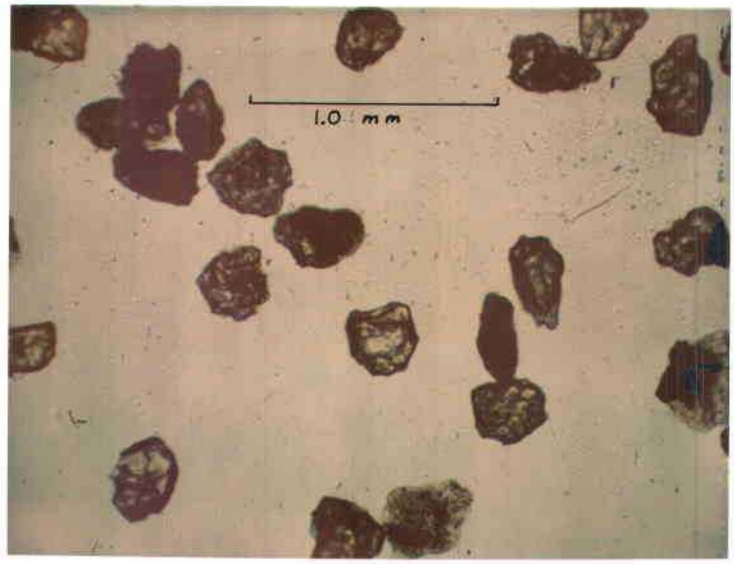


Figure 19: Photomicrograph of heavy mineral assemblage from "epidote-rich" upper Cowlitz sandstone member (Tc_5). Note typical "broken-glass" appearance of pistachio green epidote grains which comprises 90% of the grains in the slide. Plane polarized light. Sample 825-7 #3.

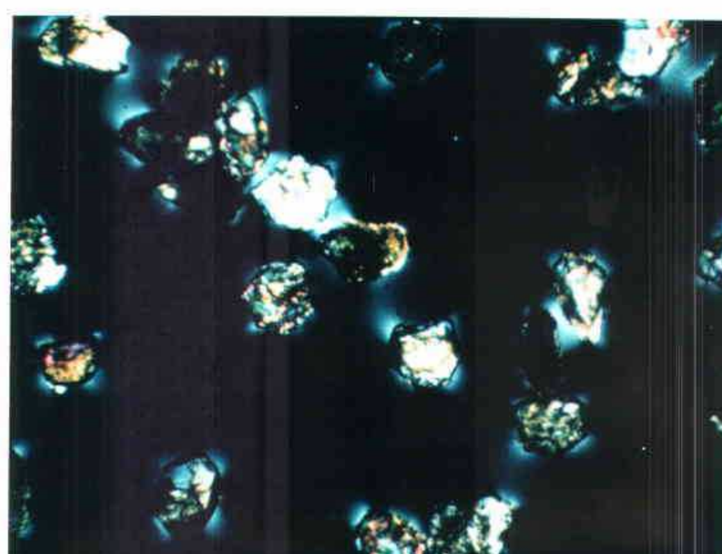


Figure 20: Figure 19 photomicrograph with crossed nicols.

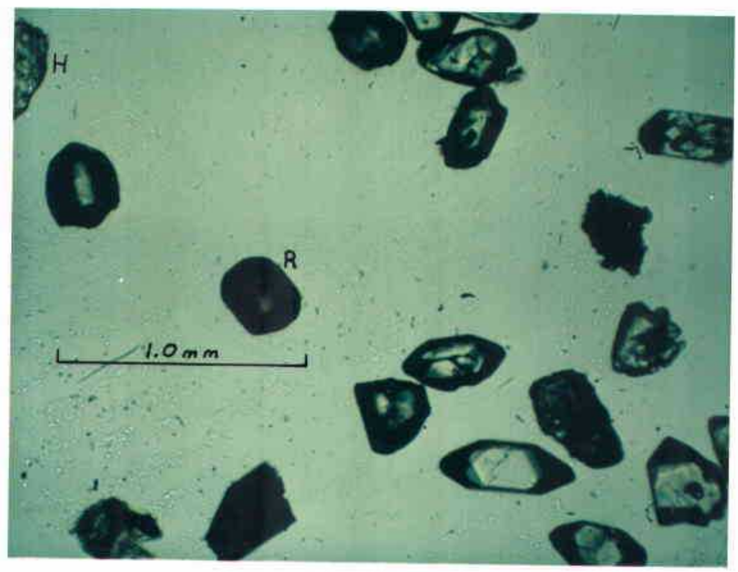


Figure 21: Photomicrograph of "zircon-rich" heavy mineral assemblage from the upper Cowlitz sandstone member (Tc_5). Note the very high relief of the doubly terminated euhedral zircon grains, the red rutile near the center of the photo and the hornblende in the upper left corner. Plane polarized light. Sample 727-5 #6.

be used along with other data to help correlate and show the facies distribution of Cowlitz sandstone in the subsurface.

Provenance

In a vertical stratigraphic sense, the Cowlitz sandstones show a progressive change in provenance away from a volcanic highland toward a plutonic and metamorphic terrain. The lithic arenites at the base of the Cowlitz section (unit Tc_2) have volcanic rock fragments with textures identical to those occurring in basaltic andesite flows and intrusions of Tillamook Volcanics. The high degree of rounding and sorting in some samples (e.g., 88-14) could be an indication of a beach environment near an exposed Tillamook Volcanic highland. The occurrence of coarse-grained, very angular, scoriaceous devitrified glass (813-1) being more abundant than fine-grained subrounded stable quartz suggests a short episode of renewed explosive volcanic activity above the Cowlitz/Tillamook unconformity. In describing volcanic textures Williams *et al.* (1954, p. 39) wrote:

> varieties composed entirely of glass are formed chiefly in the quickly chilled borders of shallow intrusions, in the crusts of flows, and in *lavas cooled rapidly by discharge into the water* or under ice [underlining is mine].

These are highly vesiculated scoriaceous glass fragments with no microlites or phenocrysts suggesting a nearby eruptive source in relatively shallow water, less than 500 meters (McBirney, 1963; Grechin *et al.*, 1981). This is a consequence of the high confining pressure of sea water preventing vesiculation of lava at greater depths.

Metamorphic, acid plutonic and subordinate volcanic sources are indicated for all upper Cowlitz sandstones (Tc_5) by major mineral constituents and heavy mineral assemblages. A granitic or granodioritic source is supported by the presence of oligoclase, microcline, orthoclase, euhedral zircon, polycrystalline quartz, very coarse-grained muscovite and biotite flakes and blue green hornblende. A high rank metamorphic source such as schist or gneiss is strongly indicated by the presence of kyanite, epidote, green brown tourmaline, garnet, rutile and clinozoisite. A Tillamook andesitic or basaltic andesitic source is substantiated by oscillatory zoned plagioclase, apatite, volcanic rock fragments augite, hornblende and andesine (An_{32}-An_{37}) to oligoclase (An_{25}-An_{28}) plagioclase grains. Snavely and Wagner (1963, p. 11-14) and Van Atta (1971, p. 183-184) inferred a volcanic source to the south (e.g., Goble or Tillamook volcanics). Scarce paleocurrent directions (Figure 23) in upper ripple laminated Cowlitz sandstones (Tc_5) indicate these arkoses were derived from the east and the south. Drainage of the Cretaceous and Jurrassic Idaho and Wallowa batholiths by an ancestral Columbia River, first suggested by Van Atta (1971), is the most likely means of providing plutonic igneous and metamorphic micaceous arkosic sandstone to the Cowlitz Formation.

Contact Relations

The lower contact of the Cowlitz Formation is not exposed in the study area. The presence of subaerial basaltic andesite flows on Green Mountain and the basal conglomerate member of the Cowlitz Formation clearly imply an unconformable contact between the

Tillamook Volcanics and the overlying Cowlitz Formation. This unconformity is well exposed in the Buster Creek quarry in section 25-T5N-R6W, 1.5 km to the west (Nelson, 1982, personal communication). Warren and Norbisrath (1946) pointed out that the basal conglomerate in the Northern Oregon Coast Range rests on top of the volcanic flows and breccia with an irregular unconformable contact.

Based on mapping of a thin turbidite unit which caps the upper sandstone member (Tc_5), and the presence of two mineralogically distinct sandstones which directly underlie this turbidite facies, an angular unconformity is postulated for the contact between the Cowlitz Formation and overlying Keasey Formation (Figure 22). The total thickness of the upper sandstone member of the Cowlitz Formation, though not measured in the east part of the study area, appears to thin toward the west. At the Wage Road measured section (Appendix 1), the upper sandstone member is represented by 91 m of sandstone. This thinning to the west and the lack of upper epidote-rich arkosic sandstones (Tc_{5b}) in the west indicate an angular truncation of the Cowlitz Formation by the overlying Keasey Formation. The presence of the thin (approximately 20 m in the "Watzek" 30-1) turbidite unit at the top of the Cowlitz section immediately overlain by a deep marine mudstone unit (Jewell member of the Keasey Formation) indicates the unconformity was due to a submarine erosional event where a change in the slope provided the opportunity for turbidity currents to remove the unconsolidated shallow marine arkosic sands of the upper Cowlitz Formation. Sediment bypassing was prominent since only a thin (20 m) turbidite unit was deposited prior to deposition of the Jewell member of the

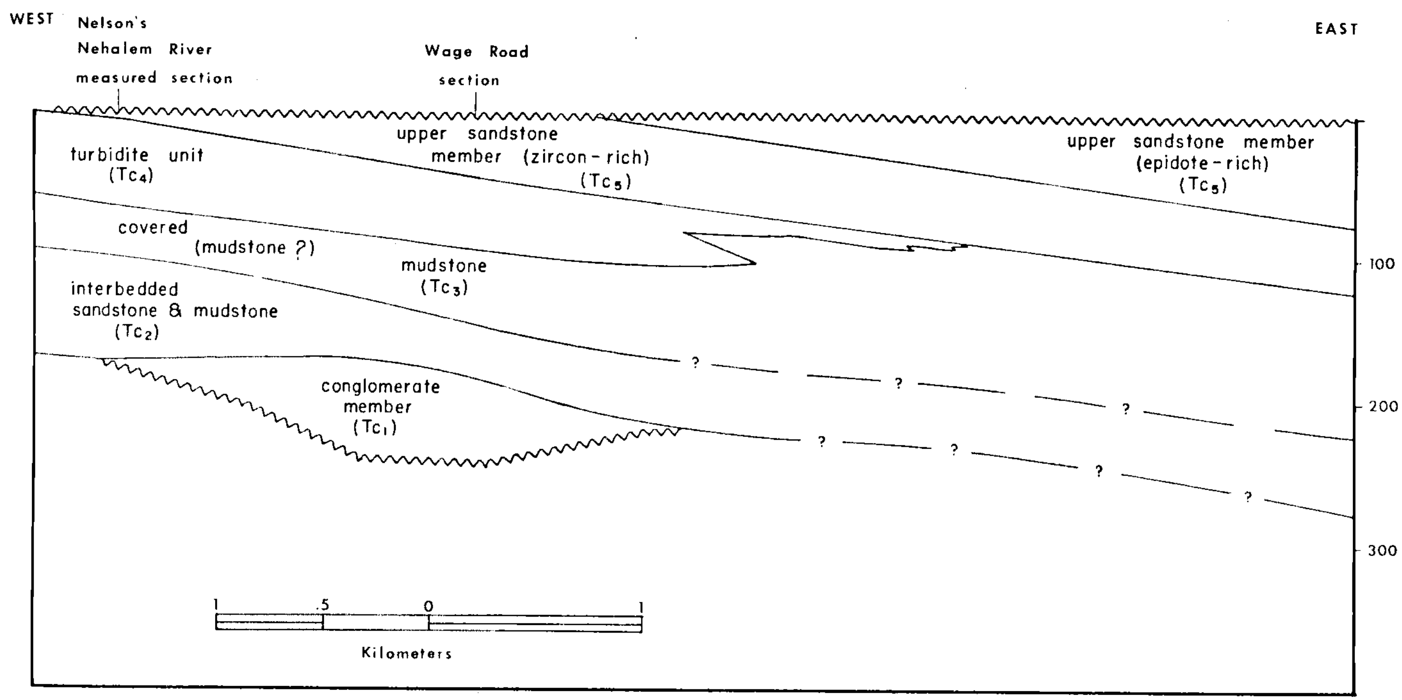


Figure 22: Schematic reconstructed cross-section of the Cowlitz Formation across the thesis study area and eastern part of the Fishhawk Falls - Jewell area of Nelson (1982, personal communication). Reconstructed to the time immediately prior to deposition of Keasey Formation (Jewell member).

Keasey Formation. Van Atta (1971) and Niem and Van Atta (1973) noted that there is a significant change in attitude, 45° to 90° in the Northern Oregon Coast Range, between the Cowlitz sandstone member and upper mudstone member (Jewell member of the Keasey Formation this study), which also supports an angular unconformable contact between the two formations.

Age and Correlation

The Cowlitz Formation in the study area represents an Eocene transgressive sequence of sedimentation. Weaver (1916) correlated the type late Eocene Cowlitz Formation to the late Eocene Tejon Formation of California. Beck (1943) correlated the type Cowlitz Formation with the upper 275 m of the Tejon Formation and the Coaledo Formation of Coos Bay, Oregon. Warren and Norbisrath (1946) named the upper Eocene sandstone strata of northwest Oregon (which includes this study area) the Cowlitz Formation based on correlative molluscan assemblages with the type Cowlitz Formation in southwest Washington. This unit in Clatsop and Columbia counties, Oregon has been subsequently referred to as the Cowlitz Formation by Wells and Peck, 1961; Van Atta, 1971; Niem and Van Atta, 1973; and Newton and Van Atta, 1976.

The Cowlitz Formation in Washington encompasses the Narizian foraminiferal stage of middle to upper Eocene which is currently thought to range from approximately 48.5 to 39 m.y. or middle to late Eocene (Armentrout, 1981, and, Figure 3). Newton and Van Atta (1976) reported Narizian age microfauna in strata mapped as Cowlitz in the study area (Plate I). No diagnostic molluscan or microfauna in the Cowlitz were discovered in this study. Calcareous nannofossils from the Quintana Watzek 30-1 (Appendix 9 and Plate III) only gave ages of middle to late Eocene and the Narizian/ Refugian boundary was not defined. McDougall's (1975) work on the microfauna of the type section of the overlying Keasey Formation in northern Oregon shows that the Keasey is in part Refugian and in part Narizian. Thus, the Cowlitz Formation in the study area which underlies the nearby type Keasey Formation, must not be younger than the Narizian stage.

As mentioned earlier, in the Age and Correlation section of the Tillamook Volcanics, recently acquired K-Ar age dates from the Goble Volcanics are in conflict with Armentrout's (1981) newly revised biostratigraphic zones and time scale for the Pacific Northwest. These recent radiometric dates require the Eocene strata, traditionally mapped as Cowlitz in Northwest Oregon, to fall in the Refugian foramineferal stage (late Eocene, Figure 3). But, the Cowlitz Formation in Northwest Oregon is clearly in the Narizian foramineferal stage, and thus the K-Ar ages do not agree with Armentrout's (1981) radiometric age range of this Paleogene chronostratigraphic unit. Perhaps the radiometric dates indicate that the benthonic Narizian foraminiferal assemblages that characterize these zones are facies controlled and may extend into the late Eocene-early Oligocene. In which case the age range of the Narizian would have to be revised on Armentrout's 1981 time scale. McDougall (1975) pointed out the occurrence of time-transgressive facies controlled Narizian fauna in the overlying Keasey Formation. Alternatively, the absolute age range of the Narizian on Armentrout's scale may be in error and it extends to 32 million years before present. The solution to this problem is beyond the scope of this study, but further radiometric and stratigraphic investigation is needed.

Depositional Environment

The Cowlitz Formation in the study area represents a transgressive sequence of subaerial alluvial valley fill and marginal marine gravels at the base to overlying high energy shelf sands and slope turbidites at the top. This interpretation of depositional environments is supported by lithology, sedimentary structures, trace fossils and molluscan fossils.

The basal member of the Cowlitz Formation (Tc_1) is composed of thick, structureless, amalgamated boulder to pebble conglomerate beds unconformably overlying Tillamook Volcanics. The size and composition of basaltic andesite clasts reflect the proximity of a rugged terrain of subaerially exposed Tillamook lava flows and dikes. The very poor sorting, subrounded nature of the framework supported clasts and lenticular channels of cut and fill are typical of fluvial braided deposits. Rare sedimentary structures in this member are crude laminations in the lenticular volcanic sandstone interbedded with the conglomerate. Squires (1981) in a comparative study of the Eocene Llajas Formation of Southern California and modern depositional environments, describes sedimentological features in the Llajas conglomerates that are similar to features in the basal Cowlitz volcanic conglomerate unit (Tc_1). Specifically, the conglomerates are poorly sorted, unstratified and ungraded, implying rapid deposition from bed load. Rare sandstone beds are lenticular and interbedded with the conglomerate, having gradational lower contacts and abrupt erosional upper contacts. The only sedimentary structure reported, other than the narrow (1 m wide) lenticular channels, were laminations in the well sorted sandstones. Squires suggests that the better sorted laminated sandstones were deposited as sheetflood deposits on an alluvial fan. The Llajas conglomerates have a range of thickness from 20 to 35 m. The Cowlitz conglomerates have a variable thickness from 3 to 60 m (Warren and Norbisrath, 1946). The overall stratigraphy of thick, structureless, poorly sorted, interbedded lenses of sandstone and conglomerate are typical of modern braided stream channel deposits on alluvial fans (Squires, 1981). Alternatively, since the Eocene was a time of tropical climate in Oregon (Baldwin, 1981), it is unlikely that semi-arid alluvial fans could have formed here. More likely, braided stream gravels were deposited in steep valley fills around the uplifted and dissected Tillamook Volcanic highlands.

Rare TEREBRATALIA sp. brachiopods and pelecypods (LIMA (LIMA) sp.) (Moore, 1983, written communication) occur locally in interbedded basaltic sandstone of the conglomerate member. Van Atta (1971) reported oyster fossils in the basal Cowlitz volcanic conglomerate in the Rocky Point quarry. Overall, fossils are rare in the basal Cowlitz conglomerate, a feature also noted by Warren and Norbisrath (1946). The presence of these fossils imply the braided streams flowed into a high energy marine environment surrounded by volcanic sea cliffs and headlands.

An interpretation of the depositional environment for the middle three members of the Cowlitz Formation (Tc_2, Tc_3, and

Tc_4) is difficult to make because these members are so poorly exposed. However, rare forest laminations, tubular burrows and the molluscan fossils SCAPHANDER sp., "HEMIPLEUROTOMA?", and Nuculanid, and foraminiferal fauna prove that these clastic sediments are of marine origin, 20 to 1000 meters deep (Moore, 1982, written communication). The shallow marine facies of interbedded coarse-grained volcanic arenites, medium- to fine-grained arkoses and mudstones (Tc_2) exposed in the west part of the study area grades upward to a thick, structureless, bioturbated, foraminiferal mudstone exposed in the east. In the Quintana "Watzek" 30-1 well, the 800' of the mudstone unit (Tc_3) (Plate III) is predominantly mudstone in contrast to a sandier sublittoral facies exposed along the Nehalem River south of Jewell, Oregon (Nelson, 1983). This suggests that during the deposition of the Cowlitz mudstone unit (Tc_3) a deeper water environment was located to the east and north where wave base and storm energy did not affect the deposition of these fine-grained bioturbated hemipelagic sediments. The turbidite unit (Tc_4) which is not found in the eastern part of the study area may be a localized turbidite channel cut into the underlying mudstone (Tc_3).

The upper Cowlitz sandstone member, including both the zircon-rich and epidote-rich sandstones (Tc_{5a} and $_{5b}$, differentiated on Plate II only), represents a high energy sublittoral to shoreface environment. This interpretation is based on open marine molluscan fauna, trace fossils, authigenic mineral constituents, and textural and mineralogical maturity of the sandstones and sedimentary structures.

The dominant sedimentary structures in modern sublittoral storm or inner shelf deposits are parallel laminations (Johnson, 1980). Commonly associated with the parallel laminations are low-angle (5-8°) cross-stratification (hummocky bedding-Kulm et al., 1975; Dott and Bourgeois, 1982), cross-laminations, upward transitions from parallel- to cross-lamination, grading and some load structures. This association of sedimentary structures occurs in the upper sandstone member of the Cowlitz Formation (727-4, Figures 11-14). The outcropping sequence of planar- to low-angle cross-laminations, grading upward into ripple laminations reflect a decreasing flow regime and is similar to turbidite beds displaying Bouma b & c sequences (Johnson, 1980). The lack of hemipelagic mudstone interbeds and the presence of repeated grading within the planar-laminated interval suggests, however, that these sediments are not turbidites, but rather reflect increasing and decreasing energy conditions during a single storm event (Johnson, 1980). The low-angle planar cross-beds with scoured bases (Figures 11, 12 & 14) are remaniscent of hummocky cross-bedding typically formed on storm dominated shelves described by Dott and Bourgeois (1982) for the Eocene Coaledo Formation of the Southwest Oregon Coast. The burrowed ripple laminated interval shows that unidirectional currents were flowing to the west and northwest (Figure 23), possibly from seaward moving rip currents during waning storm conditions. These two differing paleocurrent patterns may reflect varying storm wave generated tractive currents on the shelf. They may also reflect structural deformation from post late Eocene small block rotations

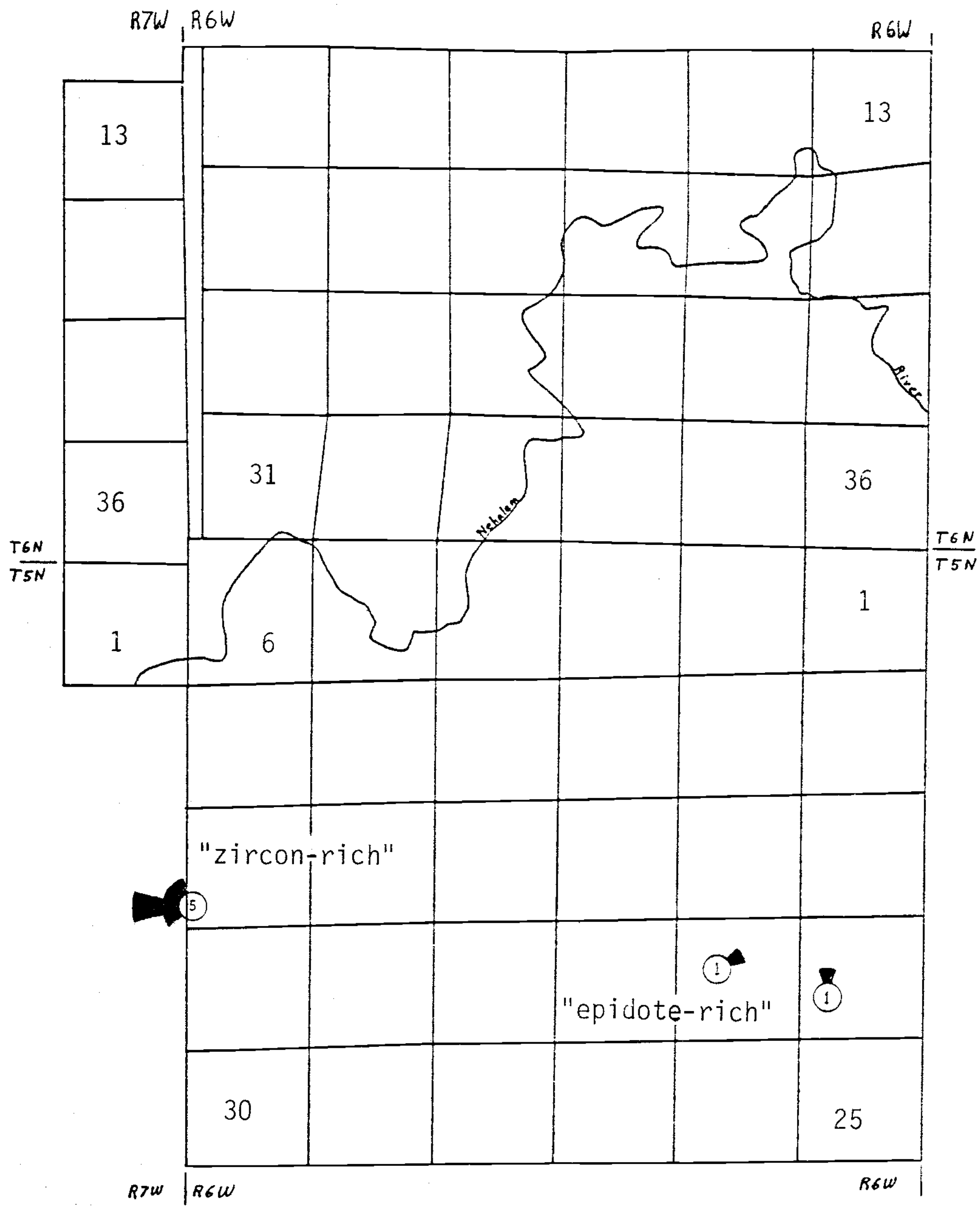


Figure 23 : Rose diagrams of paleocurrent measurements from the Cowlitz Formation (upper sandstone member). Number of measurements with diagrams.

of Cowlitz strata between adjacent strike-slip faults first suggested in paleomagnetic studies by Nelson (1983).

Fossils are rare in the upper sandstone member. The high mobility of the substrate in the high energy shelf deposits probably prevented faunal colonization, burrowing and broken fossil remains are typically scarce (Johnson, 1980). Only one locality (825-5) in the epidote-rich sandstones (Tc_{5b}) contains abundant molluscan fossils. At this locality, broken and disarticulated fossil molds and internal casts of pelecypods and gastropods are concentrated at the base of a sandstone bed on an erosional surface. Squires (1981), in his investigation of the Eocene Llajas Formation, commonly noted shell hashes in low-relief shelf sand channels which he attributed to storm lag deposits. Sheet-like shell lenses were considered the result of flushing of surge channels in a shallow marine shoreface environment (Brenner and Davies, 1973).

Broad channelized sandstone beds show low-relief scouring with mudstone ripup clasts forming crude parallel laminations in some instances (locality 825-4). Squires (1981) notes this same feature in the shallow marine facies of the Llajas Formation. Johnson (1980) points out that laterally extensive, low-relief erosion surfaces and an absence of deep channelling, are features diagnostic of high-energy shallow marine sandstones.

Only one sandstone bed (30 cm thick) containing planar cross-laminations (10° dip) is found in the study area (outcrop locality 825-7). Although the exposure is very limited, the bed is evidence for tractive sand wave deposition resulting from storm waves or longshore currents in the shallow marine Cowlitz environment.

In review, the basal Cowlitz Formation in the study area represents volcanic alluvial valley fill developed along a rugged coastal Tillamook Volcanic highland which interfingers with a transgressing high-energy storm-dominated marine arkosic shoreline-shelf facies. The upper sandstone member represents a shallowing up sequence from sublittoral to shoreface environments. A change in submarine topography or local uplift to the west caused partial erosion of the upper sandstone member (Tc_5) prior to deposition of the deeper water facies of the overlying Keasey Formation (Figure 22).

Keasey Formation (Jewell Member)

Nomenclature and Distribution

Schenck (1927) first applied the name "Keasey Shale" for dark to medium gray siltstone and structureless tuffaceous gray mudstone. The type locality of the Keasey Formation is in Rock Creek, from the hamlet of Keasey to a point approximately 1.1 km downstream. Weaver (1937) expanded the definition of the Keasey Formation to include younger sedimentary rocks that crop out further downstream from the type locality. Warren and Norbisrath (1946) proposed a three-fold division of the Keasey Formation into: 1) a lower shale member of variable thickness; 2) a middle member of uniform, thick, structureless silty tuffaceous shale with some concretionary beds, 520 meters thick; and 3) an upper member of tuffaceous, stratified, sand and shale 30 to 60 meters thick. The middle member, according to Warren and Norbisrath, is best exposed east of the Nehalem River along the Sunset Highway.

A revision of the Cowlitz and Keasey nomenclature in northwest Oregon was attempted by Deacon (1953). Deacon introduced the term "Rocky Point formation" for parts of the upper Cowlitz Formation including the sandstone member and the upper shale member of Warren and Norbisrath (1946). He also introduced the term "Nehalem formation" for the lower member of the Keasey formation of Warren and Norbisrath (1946). These formation names were never formally proposed and have generally not been accepted by later workers. Van Atta (1971) and McDougall (1975) made very thorough petrologic and detail microfossil studies of the Cowlitz and Keasey formations respectively and suggested few changes in the overall three member division of the Keasey Formation of Warren and Norbisrath (1946).

The major deviation in this study from the stratigraphic terminology of Warren and Norbisrath (1946) and Van Atta (1971) is the "upper shale member" (Warren and Norbisrath, 1946) or upper mudstone member (Van Atta, 1971) of the Cowlitz Formation, herein referred to as the Jewell Member of the Keasey Formation (Tk).

Exposures of the Keasey Formation to the west have a NE-SW trend (Nelson, 1982, personal communication). Peterson (1982, personal communication) has mapped mudstones equivalent to the Keasey cropping out in a part of the Green Mountain-Young's River area. In the study area, the Keasey Formation crops out over a narrow area with an E-W trend. To the east, in Columbia County, the type Keasey exposures occur in a broad bend to the southeast (Van Atta, 1971). This regional arcuate outcrop distribution of Keasey strata is a result of the large Coast Range anticlinal fold the axis of which projects north to south across the study area.

Lithology and Sedimentary Structures

The Keasey Formation in the thesis area, informally called the Jewell member (Tk), is a bedded, well indurated foraminiferal mudstone. The Jewell member is informally named after exposures east, west and northwest of Jewell, Oregon (Nelson, 1982, personal communication). This member is characteristically dark gray (N3) and weathers to very pale orange (10 YR 8/2) or pale yellowish brown (10 YR 6/2). When weathered the indurated well laminated mudstone typically displays shaly partings. Local thin (approximately 1 m thick) glauconitic sandstone beds (83-10) and scattered water-laid tuff beds (83-6) occur throughout the unit. The tuff beds (typically 10 cm thick) are grayish yellow (5 Y 8/4) and display repeated normal grading. Typically, a thin basal lamination of medium-grained sand in a clay matrix rapidly grades upward to a claystone over a one or two lamination thickness (1-2 mm). These tuff beds also show a color gradation from a basal grayish yellow (5 Y 8/4), 5 cm thick, to a dusky yellow (5 Y 6/4) unit 7.5 cm to 10 cm thick. Agglutinated forams and Helminthoida trace fossils are very abundant. Thin laminations are caused by concentrations of agglutinated forams. Mudstone beds (1 cm to 5 cm thick) with light colored (on weathered surface) wispy laminations are the most common sedimentary structures. In the western part of the study area (723-21 and 727-15), very coarse-grained to pebbly basaltic sandstone which locally contains cobble to pebble size mudstone rip-up clasts is interbedded with the well indurated mudstone of the Jewell member. Drill cuttings from the Quintana "Watzek" 30-1 show that rare thin interbeds of coarse-grained arkosic (at 3,600-3,700') and basaltic (at 4,080') sandstone are found throughout this member (Plate III). The total thickness for the Jewell member, as measured from the lithologic log of the Quintana "Watzek" 30-1, is approximately 365 meters (Plate III).

The Jewell member of the Keasey Formation contains few molluscan fossils. At locality 717-5, a coarse-grained basaltic sandstone in the lower part of the Jewell member contained gastopods TURRITELLA sp. and scaphopods DENTALIUM sp. (Moore, 1982, written communication) in great abundance representing a fossil hash. At locality 97-4, the pelecypod Delectopecten sp. was collected from this mudstone unit (Moore, 1982, written communication). Dr. Moore wrote, "a depth of 200 to 600 or so meters can be postulated" for the occurrence of this pelecypod. Although the shell of Delectopecten is thin, fragile and usually flattened when fossilized, the samples from the study area are not flattened or broken, suggesting little compaction and slow sedimentation rates in a low energy depositional environment.

Foraminifera (arenaceous forms) are abundant in the Jewell member but were so weathered that no diagnostic species were recovered in the thesis area. Lower Refugian stage forams in the Jewell member, recovered to the west and southwest of the study area, indicate water depths of 200 to 600 meters or greater (Nelson, 1982, personal communication). A sample from the northwest quarter of section 11-T5N-R7W yielded an age of late Eocene, upper Narizian stage (Niem, 1982, personal communication). The assemblage collected by Dr. Niem and identified by Weldon Rau of Washington State Department of Natural Resources was characteristic of "substantial water depths," possibly middle to lower bathyal.

Petrography

Modal analyses were performed on two thin sections of sandstones (Tk) from the Keasey Formation (Table 1). Both sandstones classify as micaceous arkoses using Folk's (1974) classification scheme. Sandstone samples 715-5 and 728-7 from the Jewell member (Tk) are calcareous concretionary sandstone with abundant molluscan fossils and a sandstone dike respectively. Glauconite, which is locally abundant in the Jewell member is not present in these samples. The most abundant constituents are monocrystalline quartz (68-75%). Plagioclase composition, determined using the Michel-Levy method, (sandstone from outcrop 728-7) ranges from oligoclase to andesine, An_{28}-An_{39}. Plagioclase compositions in sandstone sample 717-5 were obtained using the Carlsbad-albite twin determinative method with results yielding andesine, An_{37}-An_{49}. Potassium feldspar is dominated by weathered orthoclase and minor microcline. Rock fragments in order of decreasing abundance include siltstone clasts, mudstone ripups, volcanic and rare granitic clasts. Amongst the granitic fragments are grains with micrographic intergrowth indicating a high temperature acid plutonic igneous source. The basaltic andesite rock fragments display hyalopilitic and pilotaxitic igneous textures. Pyritized diatoms and pyrite crystals are common constituents. The effect of sediment compaction was slight in the concretionary Keasey sandstone. This is shown by slightly deformed mica flakes. The sandstone dike sample contains abundant distorted and crushed muscovite mica. This may be due to penecontemporaneous deformation of the sandstone by spontaneous liquefaction resulting in formation of the sandstone dike.

Contact Relations

The lower contact of the Keasey formation is seen in only three roadcut localities, 723-3, 813-6 (Plate I) and in the Quintana "Watzek" 30-1 well cuttings (Plate III). Each outcrop shows evidence for an unconformity. The upper contact with the Vesper Church formation is not exposed in the study area, but similar bedding attitudes from closely spaced outcrops (section 1-T5N-R7W, Plate I) suggest a conformable contact.

The base of the Jewell member overlies a thin (approximatley 20 m thick) planar laminated, micaceous, carbonaceous turbidite unit at the top of the Cowlitz Formation. The Jewell member also overlies both the epidote and zircon rich sandstones in the map area suggesting a regional unconformable contact (Plate I, Figure 22). Van Atta (1971) and Niem and Van Atta (1973) described a local change in strike from 45° to 90° between the Cowlitz sandstone member and upper mudstone member (Jewell member of the Keasey Formation--this study). Based on the preceding evidence, the lower contact of the Keasey Formation is unconformable with the Cowlitz Formation.

Age and Correlation

The Keasey Formation is represented, in the study area, by an upper Eocene hemipelagic mudstone unit (Jewell member, Tk). Weaver *et al*. (1944) regarded the "*Uvigerina cocoaensis*" zone of California (upper Refugian) as correlative to the Keasey Formation. McDougall (1975) made the latest and most detailed foraminiferal study of the type Keasey Formation along Rock Creek Road 3.2 km to the southeast, and noted that the Narizian stage is present in the very lowest part of the type section. The Narizian age strata are overlain by 1) a basal Refugian zone followed by 2) strata of lower Refugian state, the *Uvigerina cocoaensis* zone of California and the *Sigmomorphina schencki* zone of Washington. Molluscan assemblages collected in this study area and identified by Dr. Ellen Moore of the U.S.G.S.

(1982, written communication) were "compatible" with a Keasey Formation assignment (Appendix 7).

The Jewell member of the Keasey Formation (this study) fits the description of the "upper shale member" of the Cowlitz Formation of Warren and Norbisrath (1946) and the "upper mudstone member" of the Cowlitz Formation of Van Atta (1971). These previous workers suggested that this mudstone unit be included in the Keasey Formation as a member. That suggestion was followed in this study after considering the evidence for an unconformable contact and lithologic break between the mudstone rich Jewell member and the underlying Cowlitz Formation. On Warren and Norbisrath's 1946 map of the upper Nehalem basin, which includes the study area, the Jewell member was also included in their Keasey formation.

Cushman and Schenck (1928) correlated the Keasey Formation with the Bastendorff Formation near Coos Bay, Oregon. Durham (1944) correlated the Keasey Formation with the Townsend shale of northwest Washington.

Depositional Environment

The Keasey Formation in the study area represents a depositional environment of upper bathyal quiet water, hemipelagic sedimentation. This depositional environment is supported by fossil assemblages, sedimentary structures and overall morphology of Keasey strata.

The Jewell member of the Keasey Formation is composed of well indurated, bedded, planar laminated siltstone and mudstone with a few interbeds of graded tuff. Some planar laminae are composed of current formed concentrations of arenaceous foram fossils. Locally, beds of glauconite formed under slightly reducing conditions were deposited within this unit. Glauconite is now forming on the outer continental shelf and slope of Oregon and Washington under slow sedimentation rates (Kulm *et al.*, 1975) and may reflect a hiatus in sedimentation. Molluscan fauna are sparse but one outcrop (97-4) contained the pelecypod *Delectopecten* sp. which likely represents a water depth of 200 to 600 meters. This typically fragile pelecypod was not flattened or broken, indicating a slow rate of sedimentation in a quiet body of water (Moore, 1982, written communication). No ecologically diagnostic foraminiferal assemblages were obtained from the Jewell member in the study area. To the west in the Fishhawk Falls-Jewell area, forams collected from the Jewell member near the towns of Jewell and Elsie indicate a paleobathymetry of 200-600 meters or deeper for this unit (Nelson, 1982, personal communication).

The rare basaltic sandstones with cobble size mudstone rip-up clasts may represent turbidite or tractive current erosion and deposition of short duration interrupting the normal rain of hemipelagic sediments in the 200-600 meter deep basin.

Vesper Church Formation

Nomenclature and Distribution

The term Vesper Church formation (Tvc) is used for the thickest (approximately 1160 m) most widespread unit of sedimentary rock in the study area (Plate I). This upper Eocene (Refugian) unit covers approximatley 35 square miles of the central part of the study area. This distinct lithologic unit cropos out over a wide area in adjacent Columbia County, to the east of the study area, where it overlaps the thick structureless type Keasey mudstone (Kadri's lower Pittsburg Bluff member, 1982). To the west, the Vesper Church formation crops out in an arcuate pattern (bending to the southwest) and interfingers with and is seperated from the Pittsburg Bluff Formation by the Oswald West mudstone.

In past literature this sedimentary unit has been placed in the Pittsburg Bluff Formation by Warren et al., 1945; Warren and Norbisrath, 1946; and most recently by Kadri, 1982. But, the Vesper Church formation is very unlike the thick, tuffaceous, bioturbated sandstones of the Pittsburg Bluff Formation because it is composed of rhythmically bedded, micaceous, arkosic, turbidite sandstone and laminated siltstone and mudstone. Wells and Peck (1961) and Newton and Van Atta (1976) have mapped this rock unit as the Keasey Formation, but again these turbidite sandstones and hemipelagic mudstones are far different from the thick tuffaceous mudstones of the type Keasey Formation along Rock Creek which Warren et al. (1946) and McDougall (1980) described. Therefore, this turbidite unit should not be called Pittsburg Bluff nor Keasey formation.

I propose the term Vesper Church formation be used to refer to the thick turbidite unit cropping out in the study area. The type section (Appendix 2) is a 21 m (70 ft.) slump scarp located 240 m (.15 mi) north of the Presbyterian church (along State Highway 202) in the abandoned hamlet of Vesper in section 25-T6N-R6W. A second reference section (Appendix 3) is located in section 23-T6N-R6W, 2.25 km west of the Presbyterian church along the Nehalem Highway (202). Both outcrops are fresh and result from frequent landsliding. The Vesper Church formation is stratigraphically above the Keasey Formation (Jewll member this study) and conformally below the Pittsburg Bluff Formation.

Lithology and Sedimentary Structures

The Vesper Church formation is typically composed of rhythmically bedded and laminated sandstone, siltstone and mudstone (Figures 24 and 28). The feldspathic sandstone is light gray (N8), to dark yellowish orange (10 YR 6/6), very fine- to fine-grained, and thin bedded (5-30 cm), with parallel laminations and subordinate climbing ripple laminations (Bouma B, C & D intervals-Figure 24). Carbonaceous material and coarse flakes of mica are ubiquitous and commonly form laminations in the sandstones. The basal contacts of the sandstone beds are sharp with rare (5 mm thick), low-relief scour and load casts. Gradational upper contacts and normal grading are common. Elongate calcareous and dolomitic concretions are prominent in several of the sandstone beds. Flame structures of the interbedded dark gray mudstone very commonly protrude up into overlying sandstone beds (Figure 25). The upper contacts of these

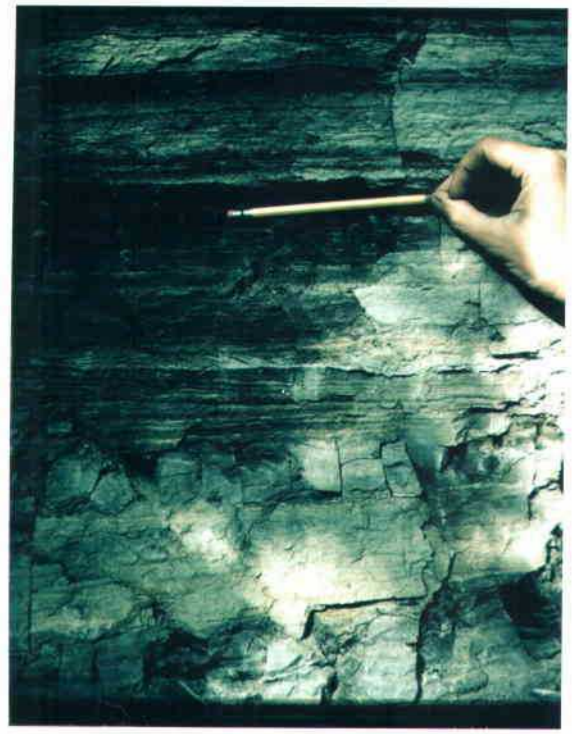


Figure 24: Rhythmically bedded fine-grained sandstone and siltstone, with Bouma c, d & e intervals from the Vesper Church formation (OC 78-1, sec. 21-T6N-R6W).

Figure 25: Typical sedimentary structures of thinly bedded turbidites from the Vesper Church formation. Note rhythmically graded sequence with well developed flame and load structures in the Bouma a and e intervals (←), dark carbonaceous laminae, and small dark and light colored Helminthoidia burrows (b). Sample 96-1 #1.

sandstone beds are gradational with the overlying planar laminated, grayish black (N2) to light olive gray (5 Y 6/1) siltstone and mudstone. Sickle shaped HELMINTHOIDA trace fossils (less than 1 cm long) are locally abundant in the uppermost part of the mudstone beds. Overall, the turbidite sequence of Bouma structures, b, c, and d are preserved in the repetitive sequence of sandstone. Locally, displaced, disarticulated pelecypod and fragmented gastropod fossils are abundant along laminations in sandstone beds (e.g., locality 96-2).

Rare intraformational mudstone pebble conglomerate and thick, channelized sandstone units occur at various stratigraphic levels within the Vesper Church formation. The intraformational pebble conglomerate beds (810-7, 710-2 & 725-4) are composed primarily of rounded mudstone clasts. Clast sizes range from pebble to cobble size. Planar laminations are commonly preserved within the larger clasts. The pebble conglomerates display horizontal bedding but no imbrication. At one locality (710-2), there are two channelized mudstone pebble conglomerates. The lower unit is deformed and truncated by the overlying conglomerate. The lithology is exactly the same in both units implying one continuous sedimentary event involving soft-sediment deformation and channel erosion of muds during deposition.

The large channelized sandstone beds (78-5, 711-6, -9, & -12, 715-4, 725-16 and 81-10) are easily distinguished in the field from rhythmically interbedded sandstone and siltstone. The channelized sandstone (fine to medium-grained arkoses) typically occurs as thick sandstone units (4.5 to 9 meters or greater) totally lacking interbeds of mudstone. Bedding within the sandstone is noted at some outcrops (715-4 & 81-10) and ranges from 10 cm to 0.6 m thick. Well defined planar laminations or amalgamated beds with no apparent sedimentary structures also occur in the channelized sandstone. One locale (78-5, Figures 26 and 27) displays soft-sediment deformation and loading of underlying mudstone and thin bedded sandstone strata. This sequence is overlain by undeformed rhythmically bedded thin sandstone and siltstone. The channel axes trend N45°W. The overall appearance of these sandstone strata suggest a sequence of very rapid, grain flows or fluidized flows or high concentration turbidite deposition (eg. Middleton and Hampton, 1973) of thick sands, possibly a distal channel lobe, on top of thixotropic muds. The underlying sediments were deformed by rapid buildup of overburden pressure from the channel sands which were, in turn, deformed by collapse of the underlying sediments. Deposition of thin-bedded overbank turbidites continued after this sequence of deposition and deformation.

Compositionally, the sandstones from the Vesper Church formation are sedimentary lithic arkoses. The one exception is a large channelized sandstone (81-10) which is a subarkose and is very similar to Cowlitz sandstone mineralogy. Even the heavy mineral assemblage is epidote-rich, similar to the "Clark and Wilson sand" of the Adams 24-34 well in the Mist Gas Field (see Petrography).

A forth lithology found in the Vesper Church formation is widespread and is composed of laminated to bioturbated silty mudstone. This mudstone is not as well indurated as the Jewell member (informal, Tk) of the Keasey Formation. This mudstone unit

Figure 26: Channelized sandstone in the Vesper Church formation (Tvc). Soft sediment deformation occurs both below in the thin bedded mudstone and within the sandstone channel. Notebook 5 X 8 inches for scale (locality 78-5, sec. 22-T6N-R6W).

Figure 27: Close-up of Vesper Church channel sandstone. Note load structure at base of channel and soft sediment synclinal fold overlying notebook. Same outcrop locality as above.

is locally found interstratified with the interbedded, laminated sandstone/siltstone lithology. Due to the interstratified relationship this mudstone lithology was not easily mappable as a separate unit and is included in the Vesper Church formation (Tvc). I have delineated this lithology by using a mudstone symbol on Plates III. The mudstone unit is more prominent to the north and west of the study area. At one locale (91-12), 15 cm thick tuff lenses are interbedded with the silty mudstone. This mudstone lithology becomes thicker, and overlies the turbidite strata, to the west (Nelson, 1983) and may be correlative with the upper member of the Keasey Formation to the east as described by Van Atta (1971) in nearby Columbia County. Coarse glauconite sand is common in this lithology where it underlies the Pittsburg Bluff Formation in the northwestern part of the study area. This is the same area where the Pittsburg Bluff Formation is locally glauconite-rich.

The laminated to structureless mudstone lithology also occurs at the base of the Vesper Church formation in the west central part of the study area. The outcrop pattern of the Vesper Church turbidite strata shows it is wedge shaped, being thicker to the east along the Clatsop/Columbia county line and thinner to the west and north of Jewell, Oregon (Nelson, 1982, personal communication).

Petrography

Four turbidite arkosic sandstones from the Vesper Church formation (78-5, 81-10, 83-14 and 917-12) were studied petrographically. Both monocrystalline and polycrystalline quartz abundances in these rocks are slightly higher than those in the Cowlitz arkoses and markedly higher than the Pittsburg Bluff sandstone analyzed in this study (Table 1) and the Pittsburg Bluff sandstone analyzed by Murphy in the Nicolai Mountain area to the north (1981, p. 244). Plagioclase compositions include both andesine and oligoclase with andesine the most abundant. Oscillatory zoned plagioclase also occurs. Potassium feldspar abundances range from 6% to 13% and are dominated by orthoclase. Potassium feldspar is equal to or commonly more abundant than total plagioclase content (Table 1). Green hornblende is a significant constituent of the channelized amalgamated sandstone. Xenomorphic granular granitic rock fragments with intergrown quartz, plagioclase and muscovite are present. The most abundant rock fragments are siltstone clasts. Abundant carbonized plant debris is found in most sandstones. Sediment compaction was moderate in Vesper Church strata, clearly shown by fractured plagioclase grains and compacted mica flakes. Carbonate staining with Allursaline Red indicated ferrous dolomite cementation was the latest diagenetic feature. This accompanied partial dissolution of quartz and feldspar clasts. Although dolomite cement is locally abundant, it is only a minor constituent of most of the sandstones from the Vesper Church formation. In the field, this dolomite cement forms one- to two-foot thick concretionary sandstones that pass laterally into friable uncemented sandstone beds.

Heavy minerals (greater than 2.95 sp. gr.) comprise from 1% to 9% of four samples from Vesper Church arkosic sandstones. Common heavy minerals include, in order of decreasing abundance: apatite, chloritic altered minerals, garnet, biotite, zircon, epidote, brown tourmaline, monazite, kyanite and pyrite. Pyrite indicates that these sandstones passed through a reducing diagenetic environment after burial and before the present exposure to weathering and oxidation. The thick channelized amalgamated sandstone (locality 81-10) was most striking since it had the same characteristic heavy mineral assemblage (Table 2) as the epidote-rich Cowlitz sandstones. In addition to this, the same rock also has a very large amount of green hornblende (50%) which is similar to the Pittsburg Bluff heavy mineral assemblage.

Provenance

A wide variety of source rocks are suggested for the Vesper Church formation. These include: high- and low-grade metamorphic rocks, acid plutonic rocks, andesitic to basaltic andesite volcanics and sedimentary rocks (e.g., mudstone ripups). The unusual heavy mineral assemblage in Vesper Church turbidite sandstone sample 81-10 is interpreted by the author as suggesting erosion of the underlying upper Cowlitz epidote-rich sandstone. Pittsburg Bluff sandstones do not contain abundant epidote and thus can not be the main source for this epidote-rich Vesper Church sandstone. Overall, both Vesper Church and Cowlitz arkosic sandstones contain abundant coarse flakes of biotite whereas Pittsburg Bluff sandstones are biotite poor (Table 2). But, the relative abundances of epidote (except at Vesper Church sandstone locality 81-10), zircon, brown tourmaline, garnet and apatite are the same for Vesper Church and Pittsburg Bluff sandstones. Thus, it is very likely that most Vesper Church turbidite sandstones are related to Pittsburg Bluff sandstones. Paleocurrent indicators (Figure 29) suggest a variable paleocurrent direction for the Vesper Church turbidites, thus, it can only be postulated that at some locale the Cowlitz Formation was uplifted and eroded providing a source for some of the sandstones in the lower Vesper Church formation. Alternatively, the same metamorphic source for some Vesper Church sandstone existed after Cowlitz time.

Abundant sedimentary rock fragments support erosion of contemporaneously deposited Vesper Church cohesive silt and mud interbeds. The dominance of turbidite sedimentary structures (e.g., Bouma sequences), abundant siltstone clasts and some mudstone clasts suggest that these fragments were ripped up from subjacent mud and silt interbeds of the middle Keasey Formation. Van Atta (1971, p. 186) believes that great volumes of sediment were supplied to the middle Keasey member in Columbia County which commonly displays load deformation structures. He suggests these sediments must have been thixotropic and subject to liquefaction and failing. This presents an ideal situation for initiating debris flows and turbidite currents to supply siltstone and mudstone ripup clasts to the Vesper Church formation further to the west.

An intermediate to high-grade metamorphic source is suggested by the heavy mineral assemblage of biotite, epidote, tourmaline, colorless and pink garnet and kyanite. Oscillatory zoned plagioclase, volcanic rock fragments, green hornblende and andesine and oligoclase grains support an andesitic to basaltic andesite volcanic terrain such as the Tillamook Volcanics or the Western Cascades Little Butte Volcanics (Peck et al., 1964) or the Ohanapecosh Formation (Hammond, 1979). An acid plutonic or granitic source is indicated by oligoclase, microcline and orthoclase, polycrystalline quartz, muscovite, biotite, zircon and monazite. These grains form a mixed igneous and metamorphic provenance and suggest that an ancestral Columbia River drainage system probably supplied the metamorphic and plutonic igneous detritus from eastern Oregon, Washington and Idaho. Rivers from the Western Cascades supplied intermediate volcanic detritus. Much of the type Keasey is tuffaceous mudstone suggesting an erupting Western Cascade source while the Vesper Church formation is not as tuffaceous reflecting a period of influx of more metamorphic and plutonic debris from eastern Oregon, Washington and Idaho.

Contact Relations

Although not conclusive, outcrops of both the Jewell member of the Keasey Formation and Vesper Church formation have an apparently conformable contact along the banks of the Nehalem River in the southeast quarter of section 1-T5N-R7W (Plate I). The exact contact is covered but attitudes of bedding in both members show little deviation from one another.

The upper contact of the Vesper Church formation with the Pittsburg Bluff Formation is best exposed along Beneke Road in section 17-T6N-R6W and is conformable. Similar attitudes of bedding and the presence of interbedded non-turbidite glauconitic to arkosic sandstone and mudstone in the upper Vesper Church and lower Pittsburg Bluff support this conclusion. The same gradational contact is observed in Cow Creek, immediately north of the study area (Goalen, 1982, personal communication).

Age and Correlation

The term Vesper Church formation is applied to this thick turbidite unit based on: 1) stratigraphic position, this unit lies between the Keasey and Pittsburg Bluff formations, and 2) a rock unit lithologically distinct from both the Keasey Formation and Pittsburg Bluff Formation. The Vesper Church formation does not correlate lithologically with the structureless tuffaceous Keasey Formation defined by Warren and Norbisrath (1946) but is instead arkosic. This lithologically distinct, mappable well-bedded turbidite sandstone unit is promoted to a separate formation in this study. The Vesper Church formation is more than 1159 meters thick in the Quintana "Watzek" 30-1 well (Plate 3). The thickness and upper conformable contact indicates that the Vesper Church is laterally equivalent to the structureless tuffaceous middle and upper members of the Keasey Formation of Van Atta (1981) in Columbia County. This facies change in the Keasey Formation was implied by Newton and Van Atta (1976) when they wrote:

> between Green Mountain and Birkenfeld, the lithology changes to siltstone and fine-grained, silty, micaceous sandstone in contrast to the predominantly mudrock facies elsewhere.

Warren and Norbisrath (1946, p. 230) states that these same rocks between Green Mountain and Birkenfeld were Pittsburg Bluff sediments even though molluscan fossil assemblages were not found to substantiate their conclusion. They also included the Vesper Church strata in the Pittsburg Bluff Formation on their 1946 geologic map that included the thesis area. Kelty (1981), Timmons (1981) and Kadri (1983) included Vesper Church turbidite strata, which overlies

Keasey rocks, in their lower Pittsburg Bluff Formation in the Birkenfeld and adjacent quadrangles in western Columbia County. However, on the basis of distinct compositional and lithologic differences between the well bedded, micaceous, deep marine, laminated turbidite strata of the Vesper Church and the thick, structureless bioturbated, tuffaceous, shallow marine Pittsburg Bluff strata, I concluded that this unit should be considered a separate formation. In addition, from the regional mapping of Kelty (1981) and Warren and Norbisrath (1946, figure 2) in Columbia County the thick tuffaceous mudstone of the Type Keasey occurs in places between the Vesper Church and the thick sandstone of the Pittsburg Bluff Formation and thus the Vesper church member strata should not be included as part of the Pittsburg Bluff Formation.

Depositional Environment

Interpretation of the deposition of the Vesper Church formation is modeled after Dott and Bird's (1979) analysis of the deposition of the middle Eocene Elkton Formation south of Coos Bay, Oregon. The Vesper Church formation is predominantly composed of rhythmically interbedded fine-grained, ripple and planar laminated, graded sandstone and planar laminated siltstone. Glauconite is locally present in the upper part of the Vesper Church strata in the northwest part of the study area where the lithology is predominantly laminated to structureless mudstone (Plate I). Molluscan fauna (gastropods CONOMITRA sp., SVETTELLA sp., and PROCERAPEX sp. and pelecypods PORTLANDIA sp. and ACILA (TRUNCACILA) sp.) collected from thin, graded sandstones of the Vesper Church formation indicate water depths of 200-1,000 meters (Moore, 1982, written communication). In contrast, forams from mudstone interbeds of the Vesper Church formation indicate water depths of 1,500-2,000 meters (McDougall, 1982, written communication). This disparity in paleobathymetry supports turbidity current transportation of shallow water molluscan fauna, and crab remains (Appendix 7, 96-2), to much greater depths as indicated by the foram assemblages. The presence of Bouma $T_{bcd\&e}$ sequences rhythmically interbedded with countless similar sequences also supports turbidite deposition.

The most abundant large scale sedimentary feature in the Vesper Church formation are channelized thin turbidite beds (Figure 28). Dott and Bird (1979) described cross-cutting, turbidite filled channels in the middle Eocene Elkton Formation of Coos Bay, Oregon. These channelized turbidites, along with drag associated with faulting and slumping, produce the disparity of opposing strike and dips in the Vesper Church formation in the study area (Plate III). These channels represent the main conduits through which fine-grained sands bypassed the mudstone slope environment of the Type Keasey Formation to the east.

The thick amalgamated sandstone filled channels of the Vesper Church formation display identical sedimentary structures as the thick, sandstone filled channels of the middle Eocene Elkton Formation. On close inspection, some faint parallel laminations are seen. Graded bedding is rare. These sandstones may have been formed by high concentration turbidity current (Middleton and Hampton, 1973), grain or fluidized flows. The Elkton channels are thought "to represent the uppermost elements of submarine fan

Figure 28: Exposure of the Vesper Church (Tvc) turbidite strata. Note large cross-cutting channel in center of photo with similar turbidite fill above and below the channel base. Dolomitic concretion above channel base in center of photo is approximately 0.5 m (2 feet). Outcrop 79-3 along the Nehalem Highway 202, section 23-T6N-R6W.

systems" or sea gullies cut into delta front slope deposits (Dott and Bird, 1979). The thick amalgamated Elkton and Vesper Church channel sandstones would correspond to "proximal" turbidites of Facies B of Mutti and Ricci Lucchi (1972). Contorted mudstone layers below some sandstone channel bases in the Vesper Church formation (outcrop 81-10) verify sudden disturbances and soft sediment loading (Dott and Bird, 1979). Local mudstone channel conglomerates are present in both the Vesper Church and Elkton formations.

The middle Eocene Elkton strata also contain abundant penecontemporaneous deformation features. Similar soft-sediment folds and faults occur in the Vesper Church formation in the Nehalem River bed (918-1, section 22-T6N-R6W) and along Squaw Ridge Road 200 meters off the Nehalem Highway in section 4-T5N-R6W. These deformation features are typical of spontaneous liquefaction and loading of rapidly deposited outer shelf-slope deposits (Dott and Bird, 1979). The main deviation from the Elkton Formation as a depositional model for the Vesper Church formation is paleobathymetry. The Elkton fauna represent water depths of 100 to 200 meters, whereas Vesper Church fauna indicate water depths of 1,500 to 2,000 meters.

Overbank facies and interchannel facies are represented by thin beds of turbidite sandstone and siltstone with Bouma T_{cde} or T_{de} sequences (Normark, 1978). This type deposit is the most common variety in the Vesper Church strata and is described in detail in Measured section (see Appendices 2 & 3). The Vesper Church measured section shows two thinning and fining-upward sequences each representing a gradual abandonment of a channel. This section would correspond to the middle fan sub-association of Mutti and Ricci

Lucchi (1978) with Unit 3 representing a lenticular sand body of Facies B. However, many other submarine fan facies such as thick coarse-grained inner and 1000's of feet of thin bedded outer fan facies of Mutti and Ricci Lucchi are missing from the Vesper Church member. Thus, the classical deep sea fan model of Mutti and Walker (1973) is not likely. The association of Vesper church turbidite strata with the thick structureless tuffaceous Keasey Formation to the east (Van Atta, 1971) suggest a series of canyon head or sea gullies cut into the outer slope as the environment most likely for the Vesper Church formation.

The Vesper Church formation (turbidite facies) is apparently confined between the Refugian slope, tuffaceous mudstone of the Type Keasey (McDougall, 1975) to the east and equivalent thick, structure-less, tuffaceous siltstone and sandstone of the Oswald West mudstone to the west (Tolson, 1976; M. Nelson, 1978; Coryell, 1978 and Penoyer, 1977). However it may be more widespread than previously recognized, a similar Refugian age thin-bedded turbidite sandstone and mudstone sequence occurs in the Lincoln Creek Formation in Gray's River area on the north side of the Columbia River (Wolf and McKee, 1972). In addition, the Vesper Church formation is also lithologically identical to the lower member of the Keasey Formation in nearby Columbia County described by Van Atta (1971).

> Primary structures in the siltstones of the lowermost beds of the Keasey Formation...include cross-lamination, ripple lamination and occasional flame-structure in thin mudstone interbeds.

He also made special note of one 16-foot thick outcrop of matrix free, well-sorted, poorly indurated, laminated, arkosic silty sandstone. This thick unit of sandstone is identical to thick, channel sandstones in the Vesper Church formation.

Orientations of channel axes are difficult to obtain in the study area, but one channel axis trending N45°W was measured (outcrop 78-5). Outcrops 711-6 through 711-12 also indicate a N-NW trend of a channel. Paleocurrent indicators display no consistent orientation between outcrops (Figure 29), possibly indicating that channels with different directions could be in-filling the basin from several sources. Conversely, the paleocurrent directions measured from ripple laminations in the thin-bedded turbidites may be indicating the direction of overbank flow out of a main turbidite channel.

These paleocurrent readings have not been corrected for post late Eocene regional rotation nor small block tectonic rotations between adjacent strike-slip faults. Paleomagnetic studies of the Eocene Tillamook Volcanics and middle Miocene Depoe Bay (Grand Ronde) dikes in the area by Nelson (1983) shows 39.7° and 48° ± 21° of post Miocene and late Eocene clockwise rotation respectively. Thus, the anamolous paleocurrent directions (Figure 29) in the Vesper Church formation could also be reflecting post late Eocene clockwise tectonic rotation between adjacent small blocks.

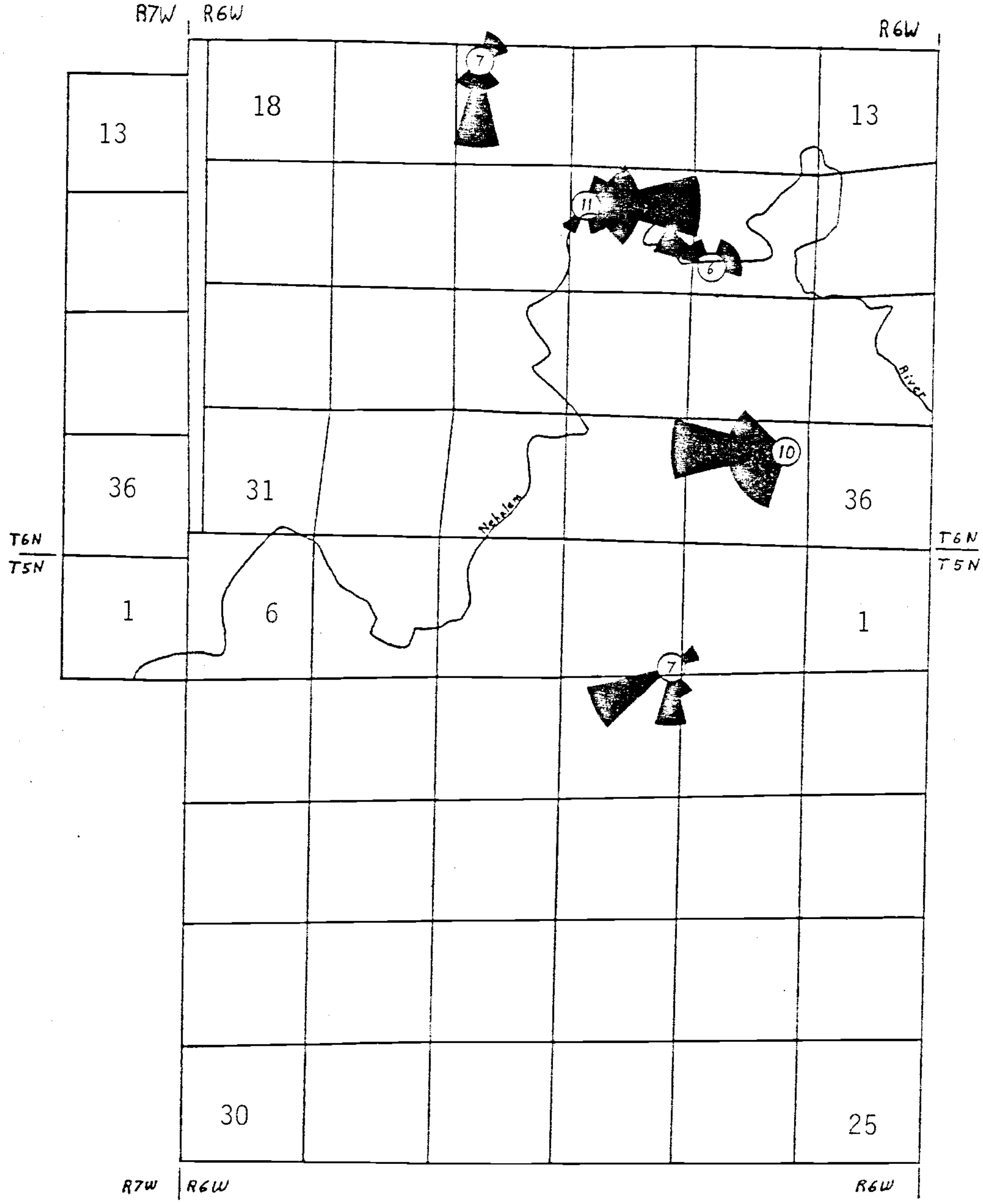


Figure 29: Rose diagrams of paleocurrent measurements from the Vesper Church formation. Number of measurements with diagrams. Paleocurrent vectors are corrected for tectonic tilt but not for post Eocene clockwise rotation based on paleomagnetic studies of Eocene Goble Volcanics and middle Miocene Depoe Bay basalt dikes in the area (Nelson, 1983).

Pittsburg Bluff Formation

Nomenclature and Distribution

The name Pittsburg Bluff Formation (Tpb) is used for a thick sequence of upper Eocene (Refugian) tuffaceous sandstone beds exposed in the extreme northwest and northeast parts of the study area (Plate I). The term "Pittsburg Bluffs" was first used by Hertlein and Crickmay (1925) for lower Oligocene strata of Oregon. Schenck (1927) described sedimentary rocks overlying the "Keasey Shale" and called them the "Pittsburg Bluff sandstone." Weaver (1937) formally proposed that the term "Pittsburg Bluff Formation" be used for naming the entire "middle Oligocene" sequence of sedimentary rocks in Columbia County, Oregon. He suggested the type area of the formation be between the towns of Pittsburg and Mist along the Nehalem River. Warren et al. (1945) divided the formation into two members and estimated a total thickness of 260 meters along the Clark and Wilson logging railroad in Columbia County.

Exposures of the Pittsburg Bluff Formation form an arc around the northward plunging Coast Range anticline (Wells and Peck 1961). Exposures as far as five miles west of Jewell, along Little Fishhawk Creek, and on Tidewater Summit have been recently mapped by Nelson (1982 personal communication). In the study area, the distribution of exposures and the attitudes of bedding, reflect the northward plunge of the broad Coast Range anticline (Plate I). To the east of the study area, Pittsburg Bluff exposures occur north and east of Mist, Oregon, bending around to the south and cropping out along the

Nehalem River. Near the town of Vernonia, Pittsburg Bluff strata crop out in Pebble Creek.

Lithology and Sedimentary Structures

The Pittsburg Bluff Formation in the study area can be divided into two main lithologies. The lower member is predominantly a fine-grained fossiliferous sandstone (Tpb_1 on Plate I). The best exposures of this member (Tpb_1) are located along Walker Road in the west half of section 13-T6N-R7W and along a new unnamed logging road in sections 13 and 14-T6N-R6W (Plate I). The upper member (Tpb_2) is a silty mudstone which crops out only in section 13-T6N-R7W. The thickness of the Pittsburg Bluff strata in the study area is approximately 275 meters (Plate II).

Lower Member. The lower member (informal) contains a characteristic light olive gray (5 Y 5/2), glauconitic, sandy siltstone at the base. This basal glauconitic unit has a variable thickness from 0.6 meters (71-9) to 1.5 meters (71-11). At one locality (71-9) this lower glauconitic siltstone overlies a very coarse-grained sandstone (grit) bed. Wavy laminations and bedding occur in the lowest part of the Pittsburg Bluff. The overlying sandstone which comprise the remaining part of the lower member form the bulk of Pittsburg Bluff rocks exposed in the study area. This lithology is medium bluish gray (5 B 5/1), tuffaceous sandstone which weathers to light olive gray (5 Y 6/1). This sandstone unit is fine- to medium-grained, very poorly sorted, texturally and compositionally immature (see Petrography). The sandstone is moderately indurated with hematite cement and has a blocky weathering pattern. Extensive bioturbation has destroyed most primary sedimentary structures. Higher in this member are some interbeds (7.5 meters) of laminated light buff altered tuff. In the lower part are a few interbeds (0.5 to 0.9 m thick) of mudstone (713-16, 730-7 & 730-8). Throughout the lower member and especially to the west where it is best exposed, glauconite-rich sandstone units, greater than 9 meters thick, are interstratified with non-glauconitic tuffaceous-feldspathic sandstone beds.

In rare exposures where bioturbation has not destroyed primary sedimentary structures, the principal structures are thick bedding (25 cm to 0.9 m) and planar laminations (Figure 30). The best exposed outcrops of interbedded mudstone and sandstone (730-7 & 730-8) show a repetitive sequence of sedimentation (Figure 31). The basal contacts of the mudstone beds (0.9 m thick) above the sandstone are sharp. The lower 0.6 meters of the mudstone is thin-bedded (10 cm) becoming more Molluscan fossiliferous toward the top of the bed. The upper contact of the mudstone bed with the overlying sandstone is gradational. The overlying sandstone is extensively bioturbated at its base and is thin-bedded (25 cm thick) toward the top. No concretionary lenses, which are common elsewhere in the Pittsburg Bluff Formation, were found in the study area.

The lower member of the Pittsburg Bluff Formation contains the largest number of molluscan fossils of any of the formations cropping out in the area. Typically the mollusks are articulated and in some places appear to be in growth position. Among the identified molluscan fossils, collected in the study area, are pelecypods PITAR (PITAR) sp., LUCINOMA sp., LITORHADIA WASHINGTONENSIS and

Figure 30: Outcrop of thick-bedded Pittsburg Bluff fossiliferous sandstone. Note high-angle fault downdropped to the northwest. Notebook (5 X 8 inches) for scale (OC 713-7, sec. 13-T6N-R7W).

Figure 31: Exposure of tuffaceous, moderately indurated, chippy weathered mudstone, interbedded between bioturbated molluscan fossiliferous blocky weathered Pittsburg Bluff sandstone. Outcrop 730-8, sec. 11-T6N-R6W.

NEMOCARDIUM (KEENAEA) sp. and the gastropod PRISCOFUSUS sp. (Moore, 1982, written communication). No diagnostic Foraminifera were collected but this is probably a result of the deeply weathered condition of most roadside exposures.

Upper Member. The upper member (informal) of the Pittsburg Bluff Formation is composed of dark gray (N3) to dark yellowish orange (10 YR 6/6) non-micaceous, structureless, silty mudstone (Tpb_2 on Plate I). This mudstone is moderately indurated. Nondiagnostic arenaceous Foraminifera were recovered in this unit (McDougall and Rau, 1982, personal communication) and two outcrops (713-5 & 713-12) contained small poorly preserved pelecypods. Bedding and other primary sedimentary structures are absent in this unit, but this is more likely caused by the paucity of outcrops in the study area rather than bioturbation.

The contact between the two members was not observed in the study area. But a sharp lithologic change such as Murphy (1981) mentioned is indicated by the lack of sandstone interbeds in the upper member.

Petrography

Modal analyses were performed on one thin section (outcrop locality 713-14) and two heavy mineral grain mounts of Pittsburg Bluff sandstones (Tables 1 & 2). The sandstone is classified as a sedimentary plagioclase arkose (Figure 16 and 32). Compositionally and texturally this rock is immature. The poor sorting, angular to subrounded grains and abundance of clay matrix (60%) suggests little

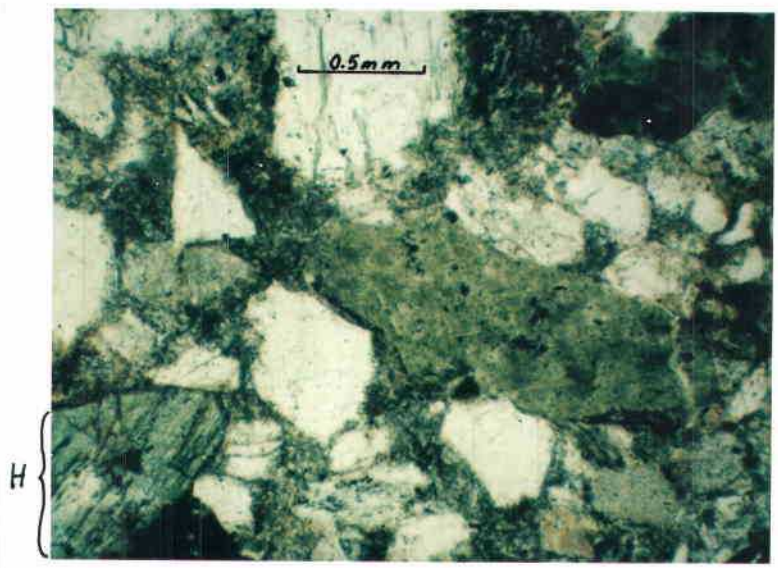


Figure 32: Photomicrograph of a clay matrix-rich lithic arkose from the Pittsburg Bluff Formation. Note crushed glauconite pellet in center of photo and green hornblende (H) clast in the lower left corner. Plane polarized light. Sample 713-14 #13.

reworking by transport processes, although the matrix may be diagenetic, produced by alteration of tuffaceous components.

The quartz fraction (46.3%) consists of monocrystalline and minor polycrystalline strained and unstrained grains (Table I). Polycrystalline quartz grains generally have straight internal crystalline boundaries.

Feldspars (18.3%) include equal proportions of fresh and altered plagioclase ranging from oligoclase to labradorite (An_{15}-An_{58}). These compositions reflect weathering and erosion of metamorphic, acid plutonic rock and andesitic to basaltic volcanic sources. Albite, pericline and Carlsbad twins are common in the plagioclase and some are displaced by microfractures due to minor compaction. Sericitized orthoclase and minor gridiron twinned microcline are the common potassium feldspars.

Volcanic rock fragments are one half as abundant as sedimentary clasts (Table 1). Sedimentary rock fragments are locally derived siltstone and mudstone ripups. Traces of unaltered volcanic glass shards accompany the volcanic rock clasts.

Micas are unevenly divided between chloritic mica and biotite. The chloritic mica is generally larger in size. The micas show some distortion due to compaction and are relatively rare compared to Vesper Church and Cowlitz sandstones. Unlike Vesper Church and Cowlitz sandstones, many of the green chloritic micas are alteration products of volcanic glass (Table 2). Vesper Church and Cowlitz micas tend to be coarse flakes of muscovite or biotite.

Abundant glauconite is present in Pittsburg Bluff sandstones as fecal pellets (7%). These pellets are generally associated with silt- and clay-filled burrows.

Heavy minerals (greater than 2.95 sp. gr.) form 2-6% of the Pittsburg Bluff sandstone. Green hornblende is extremely abundant comprising 62% of the heavy minerals suggesting the importance of an intermediate volcanic or granodioritic source for these sandstones. In contrast epidote- and zircon-rich sandstones are more abundant in the Cowlitz Formation. The total abundance of amphioboles in Pittsburg Bluff sandstones is much greater than in Vesper Church and Cowlitz sandstones (Tables 1 and 2). Other common minerals include: biotite, chloritic micas, epidote, zircon, brown tourmaline, colorless garnet, kyanite, apatite, pyrite and hematite.

The presence of pyrite shows that the rocks were in a reducing diagenetic environment prior to cementation by hematite. Hematite also occurs in large quantities in the heavy mineral suite. Its origin is diagenetic and due to ground water percolating through the porous sandstone producing oxidation of the iron-rich minerals. Diagenetic clay minerals are the other cementing agents.

Provenance

During late Eocene (Refugian) time the shallow marine Pittsburg Bluff strata were derived from an intermediate tuffaceous volcanic and acid plutonic source with a minor metamorphic input. Volcanic fragments and rare lamprobolite along with andesine to labradorite grains indicate a relatively close source where eruptions of basaltic and intermediate volcanism occurred contemporaneously with sediment transport. A relatively short transport distance is supported by the textural and compositional immaturity. Three likely sources for Pittsburg Bluff sandstone include: 1) exposed older (middle Eocene) Goble and Tillamook basaltic andesites as suggested by Van Atta (1971); 2) upper Eocene Little Butte Volcanics and Ohanapecosh Formations of the Western Cascades (Peck et al., 1964, Hammond, 1979) and 3) the middle to upper Eocene lower Clarno Group of central Oregon, as suggested by Murphy (1981). If the Clarno Group was a source for Pittsburg Bluff sands, an ancestral Columbia river drainage system would be required to transport the sediment through the Cascades to the Eocene sea (Murphy, 1981).

Both metamorphic and subordinate plutonic igneous sources are indicated by major mineral constituents and heavy mineral assemblages. A granitic or granodioritic source is supported by the presence of oligoclase, microcline, orthoclase, polycrystalline quartz, relatively rare coarse biotite and hornblende. Euhedral crystals of tourmaline, rutile, garnet, kyanite, staurolite, epidote and clinozoisite indicate a minor high-grade metamorphic source. Murphy (1981) and M. Nelson (1978) suggested a series of metamorphic and silicic igneous terrains which could have acted as source terrains. These include the Eocene and Cretaceous batholiths of northeast Washington and southeast British Columbia, the Blue Mountains and Wallowa Mountains of eastern Oregon and the Cretaceous Idaho Batholith.

Contact Relations

The lower contact of the Pittsburg Bluff Formation is best exposed in the western part of section 17-T6N-R6W along Beneke Road. As at the type locality, the contact is conformable (Moore, 1976). Attitudes of bedding and the presence of interbedded sandstone and mudstone in upper Vesper Church and lower Pittsburg Bluff sedimentary rocks indicate a gradational contact. The same contact relationship between Pittsburg Bluff and Vesper Church strata is observed in Cow Creek in section 9-T6N-R6W (Goalen, 1982, personal communication). The upper contact is not present since this is the youngest sedimentary unit exposed in the study area.

Age and Correlation

The Pittsburg Bluff Formation is the youngest sedimentary rock unit in the study area. The molluscan fauna represent the Galvinian stage (Armentrout, 1975) which has recently been placed, in its entirety, into the late Eocene (Armentrout, 1981). The molluscan assemblages identified by Dr. Moore (1982, personal communications) "are compatible with that assignment (Pittsburg Bluff Formation) except for location 730-9 which is Keasey" (see Appendix 8). Among the mollusks identified by Dr. Ellen Moore of the U. S. Geological Survey (1982, written communication) is ACILA (TRUNCACILA) NEHALAMENSIS Hanna (outcrop 730-9). Dr. Moore states that this fossil most likely "does not occur in the Pittsburg Bluff Formation but is found in the Keasey Formation." The tuffaceous sandstone this fossil was extracted from, along with stratigraphic position makes it unlikely that sedimentary rocks from this outcrop (730-9) are Keasey strata. The most plausible explanations for this discrepancy are: the sample collections were mixed; identification of the fossil was wrong; or the fossil has a larger age range than previously thought. Further recollection will be necessary to solve this disparity.

The name Pittsburg Bluff Formation is applied to this sandstone/mudstone unit due to similarities in lithology, fossils, age and outcrop pattern which trends into earlier mapped type Pittsburg Bluff strata in Columbia County (Warren and Norbisrath, 1946). The lower member (Tpb_1), as mapped and described in this study, correlates with Murphy's (1981) basal member, Goalen's (1982, personal communication) lower member and the lower member of the Pittsburg Bluff Formation of Warren _et al_. (1945).

The fine-grained upper member (Tpb_2) in the study area lithologically and stratigraphically correlates with the Pittsburg Bluff upper member of Murphy (1981) and Warren _et al_. (1945). All these reports describe this unit as fine-grained tuffaceous mudstone. The theses completed or in progress by Penoyer (1977), M. Nelson (1978), D. Nelson (1983), Goalen (1983) and Peterson (1983) show that the Pittsburg Bluff Formation undergoes a lateral facies change from sandstone to deeper water tuffaceous mudstone and siltstone a few miles to the west. The deep water mudstone and siltstone facies is tentatively correlated to the Oswald West mudstone. The upper member (Tpb_2) of the Pittsburg Bluff (in the study area) may be correlated in part with the Oswald West mudstone.

Schenck (1927) correlated the Pittsburg Bluff Formation with the Tunnel Point Sandstone at Coos Bay and the Eugene Formation of the Willamette Valley. Snavely et al. (1980) correlate the Pittsburg Bluff Formation with the tuffaceous mudstone of the Alsea Formation along the central Oregon coastal area. The Lincoln Creek Formation in southwest Washington is considered coeval with the Pittsburg Bluff Formation by Moore (1976).

Depositional Environment

The Pittsburg Bluff Formation in the study area was deposited in open marine inner to middle and possibly outer continental shelf conditions. This is supported by fossil assemblages, authigenic mineral constituents (glauconite) and sedimentary structures. Murphy (1981) compared the Pittsburg Bluff sediments with modern sediments described by Kulm et al. (1975) along the Oregon continental shelf. This comparison is followed in the present study.

The lower member in the study area is composed of thick beds of fine-grained, tuffaceous, fossiliferous, bioturbated sandstone. Thin laminations are present where bioturbation was less thorough. This member is interpreted to be a sublittoral facies deposited on an inner to outer continental shelf. Mollusks (PITAR (PITAR) sp., NEMOCARDIUM (KEENAEA) sp., THRACIA sp., and LUCINOMA sp.) collected from the area indicate water depths of 20 to 200 meters (Moore, 1982, written communication). The only identifiable trace fossil collected from the Pittsburg Bluff Formation came from this lower member. Teredo borings (Figure 33) found at locality 713-7 are "usually associated with marginal and shallow marine" sequences (Chamberlain, 1982, written communication).

Figure 33: Sand filled Teredo borings within darker carbonized wood in Pittsburg Bluff sandstone. (OC 713-7, sec. 13-T6N-R7W).

Burrowing benthic Pittsburg Bluff fauna clearly destroyed nearly all sedimentary structures, suggesting conditions of slow sedimentation. On the modern middle to outer Oregon continental shelf intensive burrowing by benthic organisms also destroys all primary sedimentary structures, producing a facies of mixed sand and mud. This mixed sand and mud facies may occur anywhere between the mud facies (largely mid-shelf depths) and sand facies (inner shelf, 50-100 m deep) (Kulm et al., 1975). Moore (1976) stated that the majority of mollusks in the Pittsburg Bluff Formation most commonly occur in muddy-sand and sand substrate and "none of the mollusks found in the formation, except the turrids, are considered indicative of deep water."

Glauconitic sandstone forms thick beds (9 m thick at 716-13) within the lower member; in these beds glauconite comprises more than 36% of the rock (see Petrography section). The interbedded glauconite sandstones in the lower member occur predominantly in the northwestern part of the study area. On the modern Oregon outer continental shelf, glauconite is the principal authigenic constituent of the sands. The largest concentrations (as high as 98% of the coarse fraction) occur on the outer edge of the shelf and on topographic highs where sedimentation rates are low and slightly reducing conditions are present (Kulm et al., 1975).

There is a general absence of primary sedimentary structures in modern Oregon inner to outer shelf sediments due to slow sedimentation rates allowing thorough reworking of the stratification by benthic infauna. The same lack of sedimentary structures is noted in Pittsburg Bluff sandstones. Where sedimentary structures are preserved in the rock record, horizontal bedding predominates with thin laminations being a minor component. Those primary structures that do occur on the modern Oregon shelf are found in water depths of 32 to 64 meters (inner shelf) where sedimentation rates are higher and form a more unstable substrata for burrowing infauna. These structures consist of horizontally laminated fine- and medium-grained sand. Current velocities as high as 75 cm/sec. (Kulm et al., 1975) were recorded at a depth of 50 meters on the modern Oregon Continental shelf during storms. These velocities are sufficient to form upper flow regime structures. Horizontal or planar stratification in Oregon shelf sediments is thought to be a result of upper flow regime conditions created by waves during storms (Kulm et al., 1975).

The upper member of the Pittsburg Bluff Formation in the study area has too few exposures to make a complete environmental interpretation. Those encountered are highly weathered. The very fine-grained texture of the upper member does indicate low energy deposition of hemipelagic and terrigeonis mudstones, possibly in deeper outer-shelf or upper-slope water depths.

In summary, the Pittsburg Bluff Formation was deposited in an environment similar to the present inner to outer Oregon continental shelf. Glauconite-rich units in the western part of the study area indicate close proximity to the outer shelf edge or a topographic high with slightly reducing conditions and slow sedimentation rates. Sedimentary structures, when preserved, indicate deposition or reworking of sediments during storms (Kulm et al., 1975). Molluscan fauna and trace fossils indicate shelf water depths between 20 and

200 meters, well within the 200 m maximum depth of interaction between bottom sediments and long-period winter surface waves (Kulm *et al.*, 1975). The upper mudstone member indicates that there was a gradual increase in water depth during deposition of Pittsburg Bluff sediments.

Depoe Bay Basalt

Nomenclature and Distribution

Middle Miocene basalts which crop out in the central Oregon Coast Range at the town of Depoe Bay, Oregon have been named Depoe Bay Basalts by Snavely, Wagner and MacLeod (1973). These tholeiitic basalts (Figure 8) are aphyric and form most of the middle Miocene dikes, sills, submarine pillow basalts and breccias along the northwest Oregon coast (Snavely et al., 1973). The Depoe Bay Basalts are considered to be of local eruptive origin by Snavely and others (1973). Beeson et al. (1979) proposed a second hypothesis as to the origin of the coastal submarine basaltic sills and dikes. This alternative hypothesis is based on identical major chemical composition, trace element composition, isotopic composition, relative stratigraphic position, paleomagnetic polarity and areal distribution of the coastal basalts to the contemporaneous subaerially erupted Columbia River Basalt Group (e.g., Grande Ronde basalt of Eastern Oregon and Washington). Beeson et al. (1979) suggested that the submarine coastal basalts represent the distal ends of the plateau-derived Columbia River Basalts which poured westward through the Columbia River Gorge to the Miocene coastline near Nicolai Mountain (Murphy, 1981). As the basalts entered the sea they formed thick piles of submarine breccias and pillow lavas. Because of the bulk density contrast between the lava and less dense water saturated sediment the basalt flows sunk and invaded the surrounding strata to form dikes and sills. The mechanism for emplacement of these invasive sills and dikes is still not fully understood, but such Columbia River invasive sills and dikes, on a smaller scale, have been noted on the Columbia Plateau by Swanson et al. (1974). Preliminary data on the paleomagnetics, geochemistry and Miocene basalt stratigraphy of Northwest Oregon undertaken by geology graduate students at Oregon State University (Jeff Goalen, Dave Nelson, Carolyn Peterson, Tom Murphy (1981) and myself) tends to support Beeson's et al. (1979) invasive hypothesis.

In this study the term Depoe Bay Basalt is used for middle Miocene basalt dikes that are petrographically and chemically similar to the type Depoe Bay Basalt. Dikes of Depoe Bay Basalt intrude Eocene and Oligocene strata in the study area (Plates I and II). The Depoe Bay Basalt is identical in all respects (e.g., age, geochemistry, petrography and paleomagnetically) to the Grande Ronde Basalt to the Columbia River Basalt Group (Snavely et al., 1973). But, the term Depoe Bay Basalt is used in this study because a formal proposal to change the coastal basalt nomenclature to reflect a Columbia River Basalt source has not been made. As further studies substantiate this invasive hypothesis (e.g., Nelson, 1983 and Goalen, 1983) it is likely that the Depoe Bay dikes in these study areas will be renamed Grande Ronde basalts of the Columbia River Group.

Lithology

The Depoe Bay Basalt crops out as sublinear dikes intruding the Pittsburg Bluff and Vesper Church formations (Plate I). These dikes commonly form steep linear NE trending ridges, but some minor outcrops occur in subdued stream beds. The best exposed of these dikes is the Northrup Creek dike (Tdb_1) which ranges in thickness from 4 to 12 meters, is horizontally columnar jointed, aphyric, reversely magnetized and can be traced 8.5 km across the northwest part of the thesis area and north into the area mapped by Jeff Goalen (1983). The outcrop pattern of the dikes, particularly the Northrup Creek dike, reflects the dominant fault trend (northeast to southwest) in the study area. This suggests that the dikes were emplaced along older fault planes during a period of extension with lease principle stress axis sigma 3 oriented NW to SE. The Northrup Creek dike is in turn offset and repeated by strike-slip faults (Plate I).

In outcrop these basalts are generally medium gray (N5) to dark gray (N3), dense, aphanitic to very sparsely micro-porphyritic. Contacts with adjacent strata are highly variable. Some surrounding late Eocene and Oligocene strata are complexly deformed into vertical broken folds suggesting soft sediment deformation during lateral and/or vertical emplacement of the dikes. Intimately associated with these deformed sedimentary rocks are highly fractured bulbous shaped bodies and apophyses of basalt. These features are best exposed in active quarries along the Northrup Creek dike at localities 71-12 and 723-9. Other contacts between basalt and sedimentary rocks are very sharp, vertical and discordant suggesting brittle deformation and fracturing during dike emplacement. Minor (3 cm wide) bleached white baked margins were observed. Other basalt-sedimentary rock contacts are faulted and the dikes themselves are offset a few meters by many right lateral NW trending and left lateral NE trending faults.

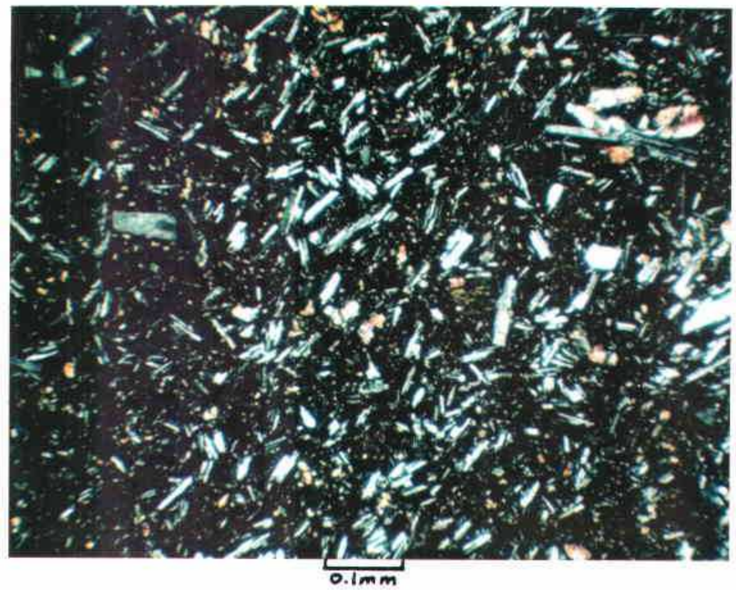
Offsets of dikes were well exposed in quarries. These offsets are due to post middle Miocene movement on northwest-southeast and northeast-southwest trending strike-slip faults with a strong dip slip component. Fault gouge zones with slickensided basalt breccias are 0.1 to 3 m thick. At some localities (southwest quarter of sec. 30-T6N-R6W) where basalt dikes in outcrop appear to end, the basalt bodies continue in the subsurface suggesting that they were intruded from below. Although theoretical modeling (Pfaff, 1981) of the gravity and magnetic data of Depoe Bay dikes in the surrounding area suggest they only extend to a depth of 107 m or are rootless, chemical analysis on intrusives in the Quintana Watzek well 30-1, 0.4 km west of the Northrup Creek dike, suggest this dike was fed from a sill 854 m below the surface (Plates II and III). This is supported by proton precession magnetometer traverses in the eastern half of section 13-T6N-R7W and in the southwestern quarter of section 30-T6N-R6W. Four magnetometer traverses were made perpendicular to the NE-SW trend of the Northrup Creek dike (Appendix 16). Traverse III (sec. 36-T6N-R7W, Plate I) was the only one measured where the basalt dike cropped out (locality 1017-11) and shows a minimum difference of 230 gammas from the surrounding turbidite strata. The shape of the profile (vertical) over the dike agrees with outcrop information that the dike at this location is vertical and trends north-south. Other traverses (I, IV, and IX, Appendix 16) across the Northrup Creek dike trend, where the dike does not crop out, display asymetric profiles near the ridge crest indicating the dike is present in the subsurface. The presence of basalt dikes underlying late Eocene strata suggests that the intrusives were fed from below and not laterally nor from above as invisioned by the invasive hypothesis of Beeson _et al_. (1979).

There were at least two periods of intrusion of Depoe Bay Basalt in the study area. The basalt dike in section 13-T6N-R7W has a higher MgO percentage (4.15%) than any of the other Miocene basalts which crop out in the study area. The basalt dike in section 13 is referred to as the high MgO subtype (Tdb_1, Plate I). The high MgO dike is 8 m thick. The Northrup Creek dike samples consistently gave the same chemistries and are characterized by a high TiO_2 (2.15%) and low MgO (3.3%) subtype (Tdb_2, Plate I). This Low MgO-high TiO_2 dike correlates to the first reverse subaerial flow on Plymptom ridge north of the study area (Goalen, 1983). This difference in the chemistry is found elsewhere in the coastal Depoe Bay Basalts and the Grande Ronde Basalt of the Columbia River Group (Hill, 1975; Anderson, 1978; Beeson and Moran, 1979; and Murphy, 1981). Beeson _et al_. (1979) implied that this reflects at least two separate Grande Ronde Basalt flows. The reverse polarized low MgO-high TiO_2 is the older of the 2 Grande Ronde Basalt chemical types eg. R_2) while the high MgO, normally polarized Grande Ronde Basalt (N_2) is younger.

Magnetic polarities were obtained from seven Depoe Bay Basalt outcrops with the use of a fluxgate magnetometer. One sample (713-7) from the high MgO basalt dike (Tdb_2) yielded a normal polarity. The six other samples along the Northrup Creek dike trend gave inconsistent results between outcrops. Of the six samples half have reverse and half have normal polarity (Plate I). This disparity in magnetic polarities within the same dike trend may be due to secular variation of the earth's geomagnetic field during cooling and or due to subsequent tectonic deformation and differential rotation and tilting of sections of the dikes as evidenced by well exposed faults within the dikes. That is, spinner magnetometer study of 2 sites along the Northrup Creek dike in this area (Northrup Creek quarry) and an area to the north (Goalen, 1983) shows that the reversed polarized Northrup Creek dike has an average declination of 233.4° and a steep inclination of -82.7° with an alpha of 9.1 and precision parameter K equal to 23.9 (Nelson, 1983). If different sections or small blocks of the dike are rotated or tilted differentially by faults (eg. 20-30°) then misleading normal polarities could be recorded with the fluxgate magnetometer. The variable steep inclinations can also be related to different cooling rates through the Currie temperature along different parts of the dike during secular variation of the earth's geomagnetic field.

Petrography

Two petrographically similar but chemically distinct Depoe Bay basalts crop out in the study area (Plate I). The middle Miocene coastal Depoe Bay basalts may alternatively be called Grande Ronde petrologic types based upon their correlation to nearby and similar Columbia Plateau basalt subtypes (see discussion in Basalt Chemistry section). A "high MgO" (4.15%), normally polarized basalt dike is located in the far northwest corner of the thesis area (section 13-T6N-R7W). All other Miocene basalt outcrop samples (7) are from the length of the Northrup Creek dike and were chemically analyzed as "low MgO (3.30%), high TiO (2.14%)" basalts. No significant petrographic differences between the two intrusive basalt types occur except a slightly coarser crystalline texture is noted in the "high MgO" basalt (713-7) (Figure 34). In hand sample both of these basalt chemical types are aphanitic, grayish black (N2) to dark gray (N3) and weather to a grayish red (to R 4/2) color. These basalts are sparsely porphyritic (up to 1%) with microglomero-phenocrysts of labradorite (An_{61}-An_{65}) and augite set in a mottled hyalopilitic groundmass of randomly oriented microlites of labradorite (An_{60}), augite, magnetite, olivine and the basaltic glass tachylyte. The typical abundances of the constituents are: plagioclase 45-50%, augite 20-10%, magnetite 7-5%, and olivine 3%. The microphenocrysts and microglomero-phenocrysts range in size from .7 mm to 1.9 mm long. Light brown sideromelane and dark gray tachylyte forms 25% to 31% of the basalt groundmass. Calcite is a rare replacement product of the groundmass. Other workers who discuss northwest coastal Miocene basalt petrography for the Depoe Bay basalt include Snavely et al. (1973), Tolson (1976), Penoyer (1977), Corell (1978), Murphy (1981), Goalen (1983, in progress), Nelson (1983) and Peterson (1983). Goalen (1983, in progress) correlated the low MgO-high TiO_2 reversely polarized Northrup Creek dike to the nearby subaerial Grande Ronde basalt flow ($LMHT_1$) on Plymptom Ridge which has a similar magnetic polarity, sparsely phyric petrography and geochemistry.



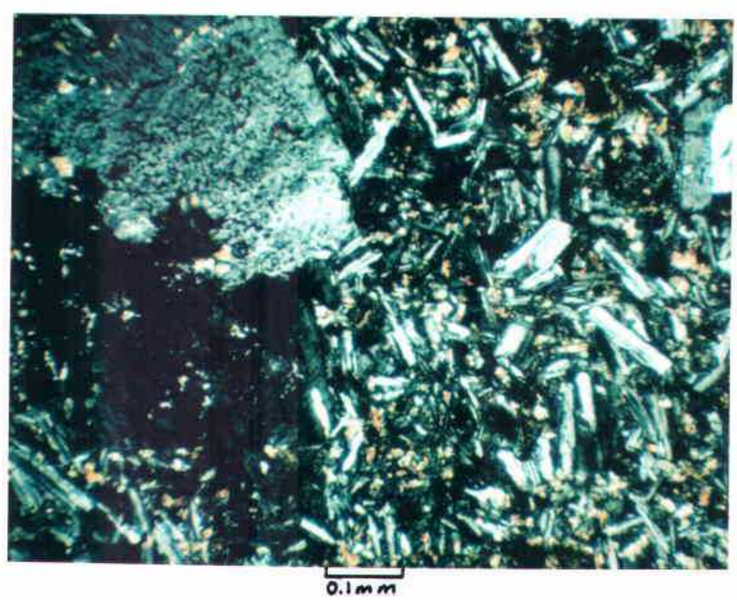


Figure 34: Photomicrographs showing low MgO-high TiO_2 basalt (top) and coarser crystalline high MgO basalt (bottom).

Geochemistry

Analyses for 11 major oxides[1] were made for 8 Depoe Bay dikes in outcrop and 4 intrusives in the Quintana Watzek well 30-1. The Depoe Bay Basalt in the study area has the same SiO_2 content (54 to 56%) and total iron oxides (11.41 to 12.40%) as described for the basalts from the type area and western Oregon and Washington by Snavely et al. (1973). Table 3 compares the average major oxide values from the study area with samples of Depoe Bay and Grande Ronde basalts analyzed by Snavely et al. (1973). Excellent correlation for all the major oxides occur except Al_2O_3. The samples from the study area may be somewhat high in aluminum compared to the Depoe Bay and Grande Ronde samples of Snavely et al. (1973). Silica variation plots (Figure 35 a-g) of the geochemical data from the thesis area shows little change in chemistries along the length of the Northrup Creek dike. This suggests that the Northrup Creek dike is all the same dike even though it is faulted and not continuous in outcrop.

Two geochemical subgroups are distinguished when major oxide data are plotted on a TiO_2/MgO variation diagram (Figure 36). The first group with MgO values of 4.00% or higher, is distinguished from a second group with MgO values of 3.75% or lower and TiO_2 values of 2.1% or greater (eg. Northrup Creek dike trend). This same low MgO versus high MgO chemical division has been noted elsewhere

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[1] Major oxide analysis done by W.S.U. Chemical Analytical Facility under the direction of Dr. Peter Hooper using the International Basalt Standard. Miocene basalt chemistries on Figure 35 are corrected to the Columbia River basalt standard by the methods outlined by Goalen (1983).

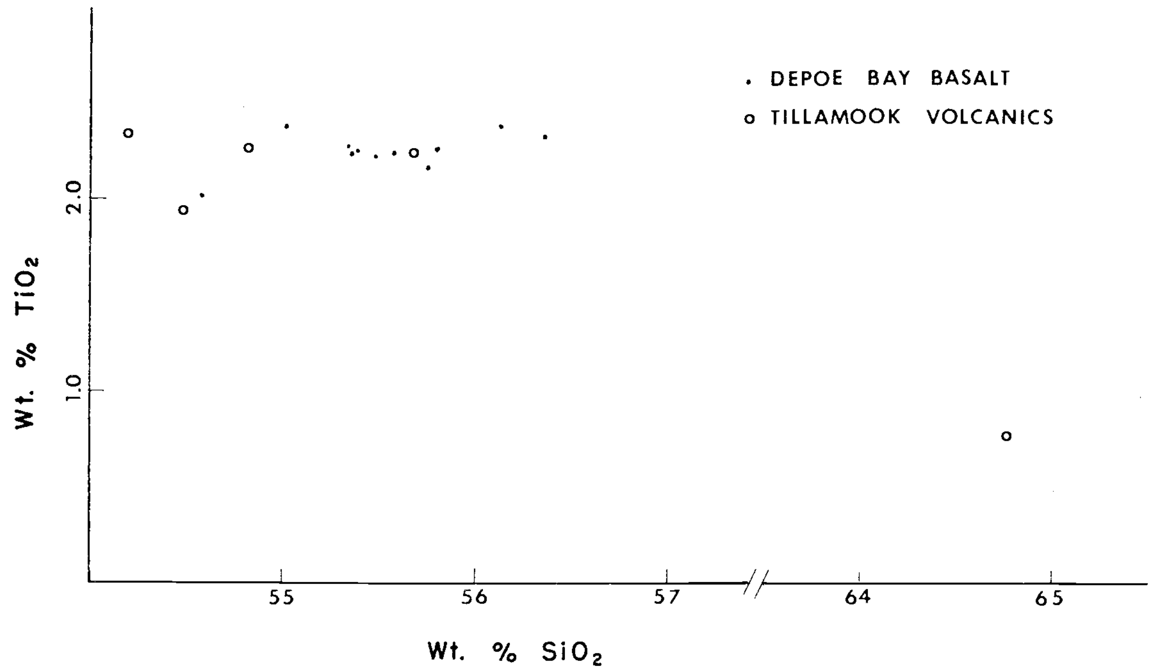


Figure 35a

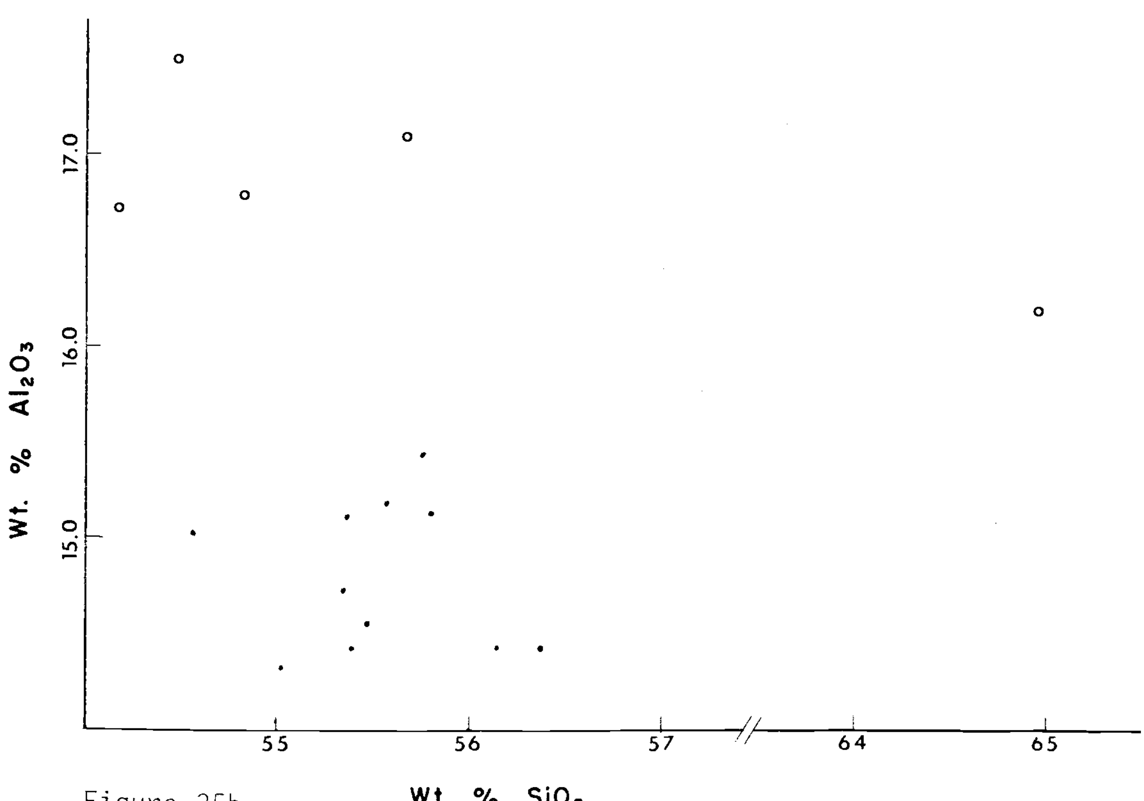


Figure 35b

Silica variation diagrams of Depoe Bay Basalt and Tillamook Volcanics.

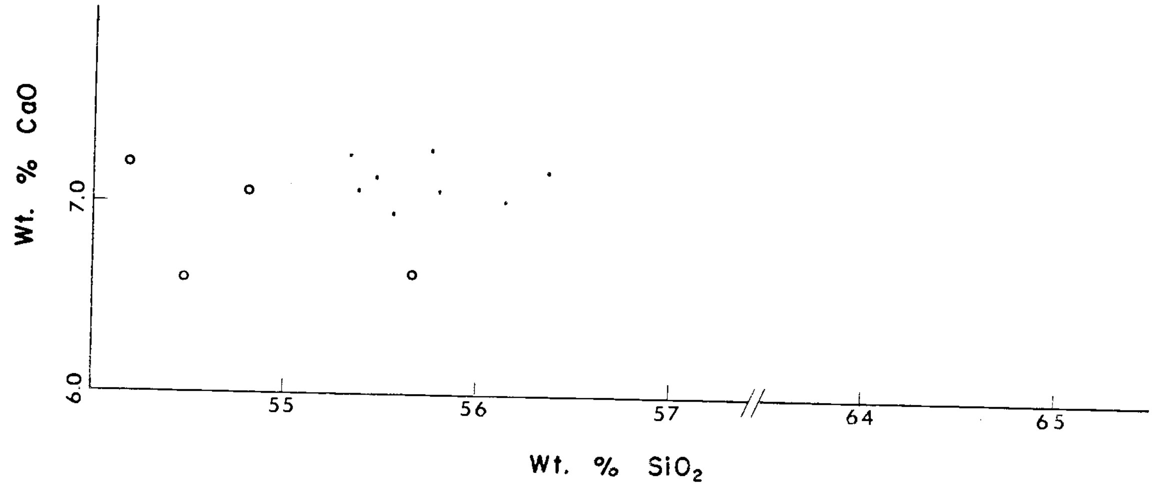


Figure 35c

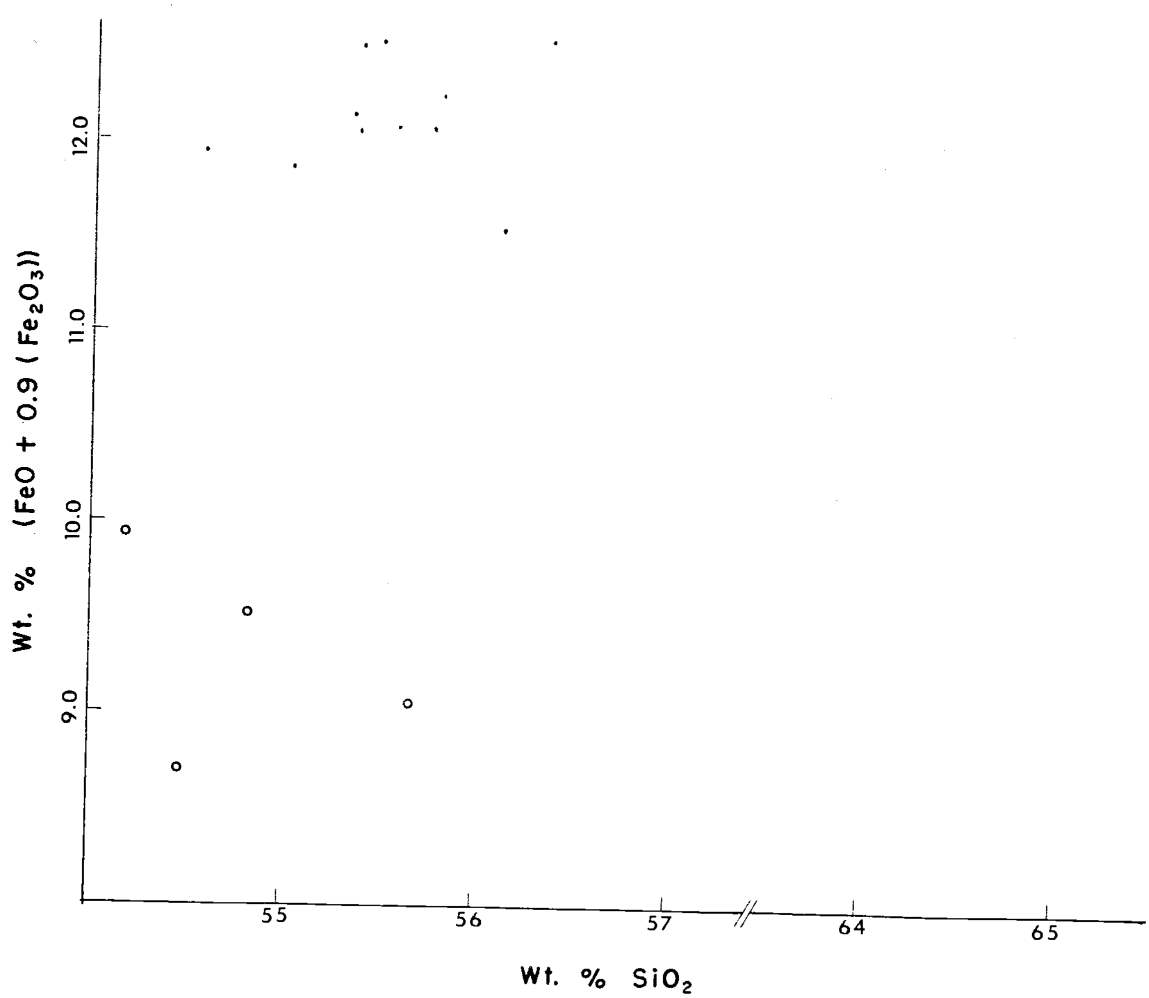


Figure 35d

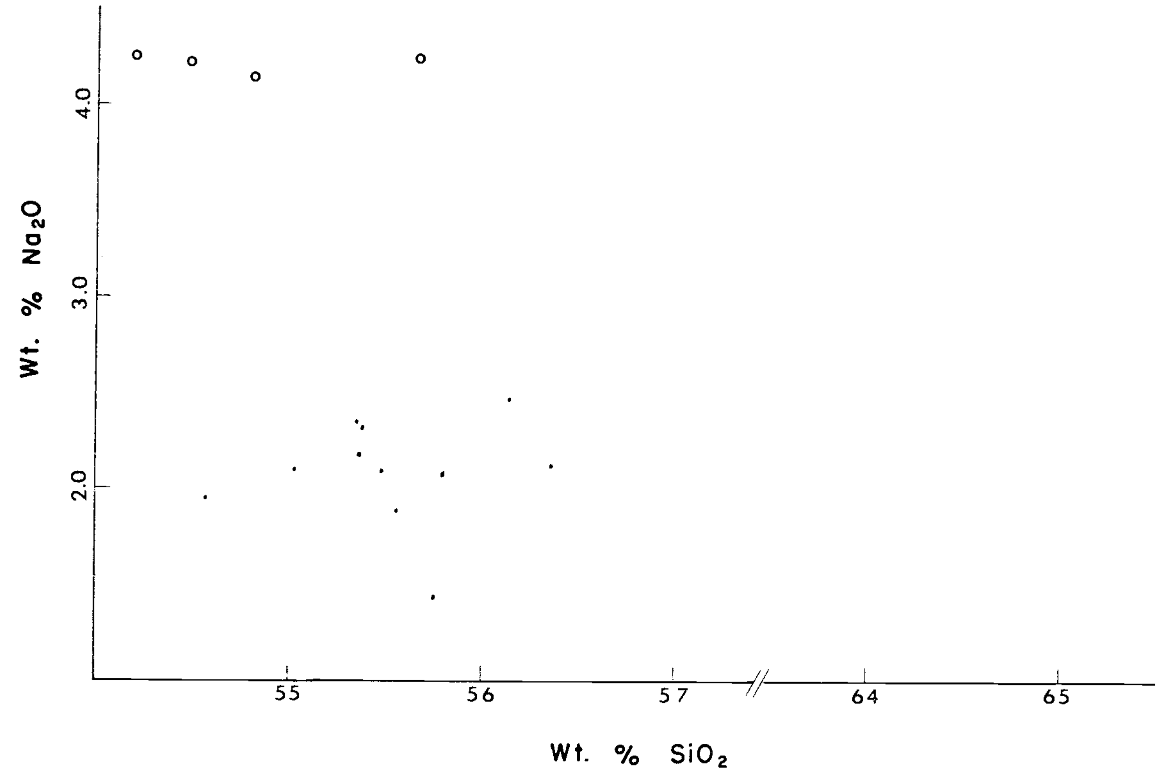


Figure 35e

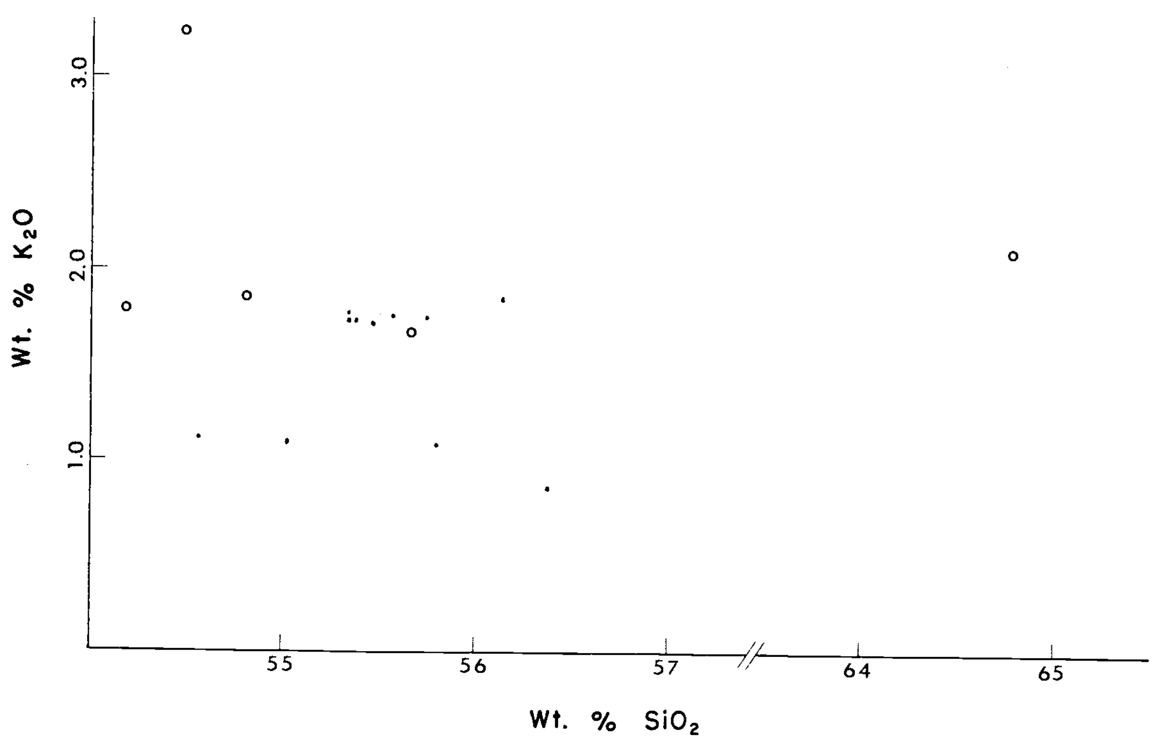


Figure 35f

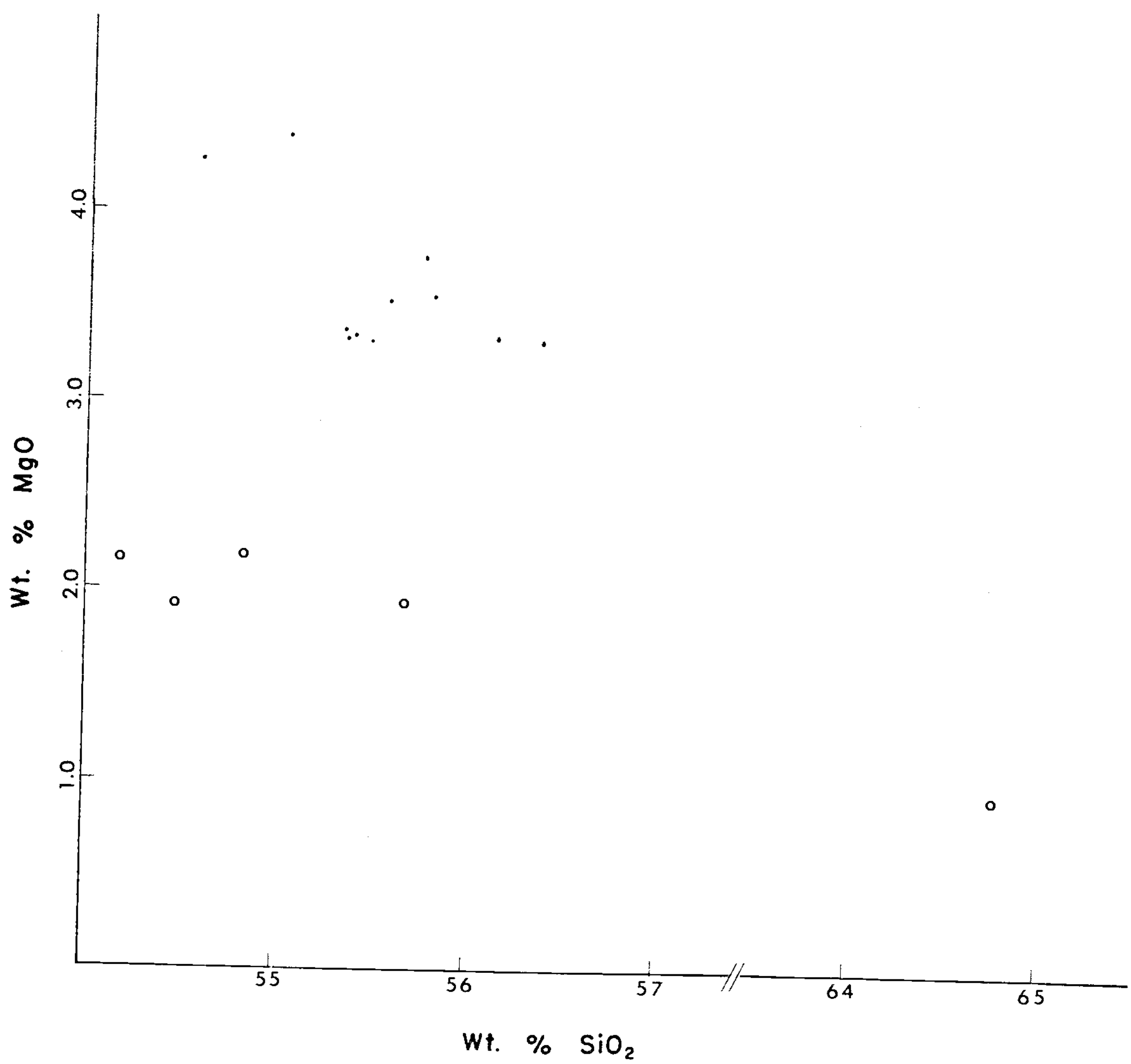


Figure 35g

within Depoe Bay and Grande Ronde basalts in western Oregon by Hill (1975), Anderson (1978), Beeson and Moran (1979), and Murphy (1981). This suggests that there has been at least two intrusive episodes of Grande Ronde Basalt in the thesis area. In the Columbia River Basalt Group, the high MgO, Grande Ronde type N_2 basalt is younger than low MgO Grande Ronde reversely polarized flows.

In the study area, four different basalt intrusives were encountered in the Quintana "Watzek" 30-1 well. Samples were collected at depths of 2,820', 3,540', 4,560' through 4,650', and 5,250' (Plate III). These basalts intrude upper Eocene Keasey and Cowlitz strata (Plate II). Each basalt unit has a different geochemistry. A high MgO Depoe Bay or Grande Ronde basalt was penetrated at a depth of 5,250'. There is good geochemical correlation (Figure 36, data points 1 and 16) between this intrusive and the high MgO dike in section 13-T6N-R7W. This intrusive at 5,250' had only a slight response on the deep induction well log (Plate III) and results from the sill being very thin, less than 10'. In addition, a 30' thick (Plate III) low MgO-high TiO_2 Depoe Bay basalt occurs at a depth of 2,820' which has the same chemistry as the Northrup Creek dike. This sill may have fed the dike at the surface (see Plate II). A 50' thick (Plate III) basalt sill (?) at the intermediate depth of 3,540' between the previously mentioned two intrusives has a third distinctive chemistry of low MgO-low TiO_2 (Goalen, 1982, personal communication). This basalt intrusive (data point 17, Figure 36) is lower in MgO (3.77%) than the dike (MgO = 4.28%) in section 13-T6N-R7W, yet lower in TiO_2 (2.17%) than the Northrup Creek dike (TiO_2 = 2.24 to 2.34%). Thus, this basalt

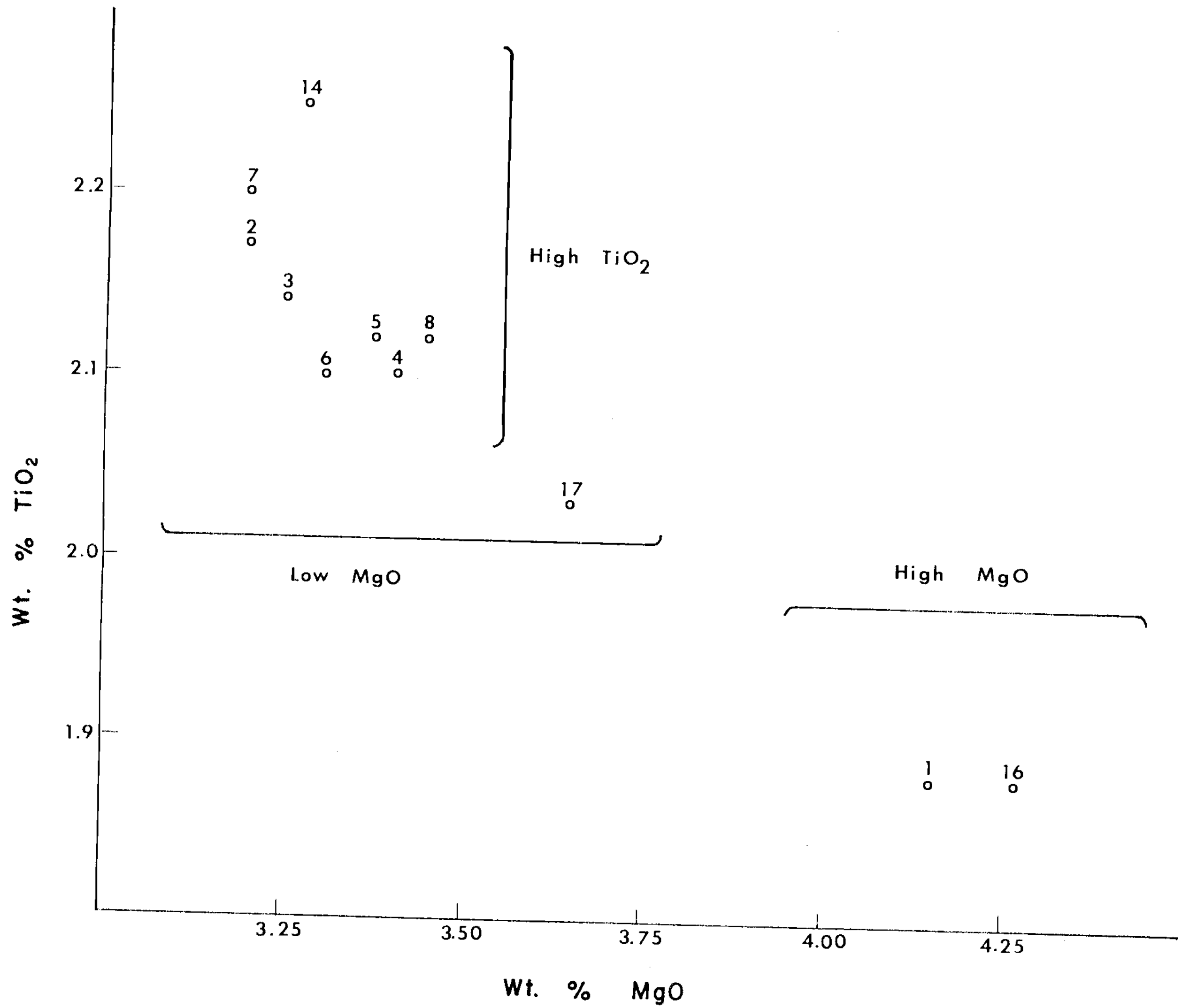


Figure 36: MgO versus TiO_2 cross-plot of middle Miocene Depoe Bay Basalt intrusives in the study area.

chemistry is referred to as low MgO-low TiO_2. Admittedly, one data point is not definitive and basalts of this chemistry do not crop out in the study area yet, Depoe Bay or Grande Ronde basalts with this distinctive chemistry crop out to the west and north of the study area as both sills and subaerial flows (Goalen, 1982; Nelson, 1982; and Peterson, 1982, personal communication). When plotted on the ternary diagram of Pearce (1977, Figure 9), the Depoe Bay basalt cluster very near the "Continental-Spreading Center Island" discriminant boundary.

Field mapping, geomagnetic declinations and inclinations and major element basalt chemistries of the Northrup Creek dike (this study and Goalen, 1983) suggest this low MgO-high TiO_2 phyric reversely polarized dike may be fed invasively by a nearby chemically and geomagnetically similar subaerial to submarine pillow Grande Ronde Basalt flow on Porter Ridge (second R_2 flow $LMHT_1$, Plympton Creek section, Jeff Goalen, 1982, personal communication). This would support Beeson's et al. (1979) hypothesis of the origin of the coastal Miocene basalts as seaward extensions of Columbia River basalt flows. Chemical data from outcrops in the study area and well cuttings from the Quintana Watzek 30-1 prove these basalts are likely to be sills at depth. However, a problem is indicated from the basalt chemistries of the Quintana Watzek 30-1. That is, a mechanism is unknown for subaerial Columbia River basalt to invade down 2,820' (860 m) to 5,250' (1.6 km) below the surface and also the sills are out of stratigraphic order from the Grande Ronde subaerial flows cropping out nearby. For example, the reversely polarized high TiO_2-low MgO Grande Ronde subaerial flow (R_2) underlies the normally polarized low MgO-low TiO_2 Grande Ronde flow (N_2) which is in turn below the high MgO Grande Ronde flow in the Nicolai Mountain-Porter Ridge area 8 miles to the north of this study area (Murphy, 1981 and Goalen, 1983). In the "Watzek" 30-1, the intrusive Grande Ronde-Depoe Bay petrologic equivalents are in inverse order. The younger high MgO sill is at 5,250', below the low MgO-low TiO_2 basalt at 3,540' and the presumably older low MgO-high TiO_2 sill lies on top at 2,820'. This reverse order of intrusion and the eastward dip (from seismic, Nelson, 1983) of the sills in the Quintana Watzek 30-1 would argue for a local coastal intrusive origin for the Depoe Bay basalts. But, on a larger scale field and laboratory data are tending to produce overwhelming support for the invasive Columbia River Plateau origin for these Miocene "intrusives" (Niem, Goalen and Nelson, 1983, personal communication). However, an explanation of the mechanism for "younger" Grande Ronde sills invading 1.6 km down through, around and below "older" Grande Ronde sills as encountered in the "Watzek" 30-1 is necessary for the invasive hypothesis of Beeson _et al_. (1979) to be valid.

A 200' thick micro-grabbroic sill in the "Watzek" 30-1 encountered at a depth of 4560' displays a fourth distinctive basalt chemistry (Appendix 14). This sill is between the high MgO and low MgO-low TiO_2 Depoe Bay sills and has a chemistry more like the Goble Volcanics (Appendix 13) than the Depoe Bay basalts. But, high contents of aluminum (19.69%) and sodium (4.39%) and low amounts of titanium (1.05%), iron (6.8%) and potassium (0.86%) suggest that this basaltic sill has been hydrothermally altered. Only a small chip of this basalt was thin sectioned; thus, accurate analysis of alteration products was severely limited. The MgO content of this basalt (3.26%) could indicate that this rock is a low MgO Depoe Bay Basalt rather than a Goble intrusive, but evidence of extensive hydrothermal alteration affecting the major oxide analysis precludes definitive correlation of this unit to the igneous rock units in the area.

Age

Pottassium-argon age dates of Depoe Bay basalts have been reported by Snavely et al. (1973) as middle Miocene. A Depoe Bay Basalt sill from Mount Hebo in the Central Oregon Coast Range yield an age of 16 ± 0.65 m.y. Basalts from Cape Meares have been dated as 14.5 ± 1.0 m.y. and 15.2 ± 0.6 m.y., while Depoe Bay Basalt near Ecola State Park was dated at 14 ± 2.7 m.y. (Turner, 1970). Niem and Cressy (1973) dated basalts on Neahkahnie Mountain and Tillamook Head areas as 15.5 m.y. The Northrup Creek dike has not been radiometrically dated but based on similar chemistries to Columbia River Grande Ronde basalts it should be middle Miocene. It is certainly post latest Eocene (Refugian) since it intrudes the Pittsburg Bluff Formation.

Table 3. Average chemical compositions (percent total weight) of Depoe Bay and Grande Ronde basalts.

	Average this study (int. std)	Corr. factor[1]	Average this study (bas. std)[2]	Average Depoe Bay[3]	Average Gr. Ronde[3]
Number of analyses	11		11	7	18
SiO_2	55.35	+0.18	55.53	55.7	55.0
Al_2O_3	14.27	+0.54	14.81	14.0	14.2
ΣFeO	12.00	+0.14	12.14	12.1	11.5
MgO	3.50	+0.13	3.63	3.6	4.2
CaO	7.06	+0.29	7.35	7.1	7.9
Na_2O	3.16	-1.07	2.09	3.3	3.0
K_2O	1.48	+0.02	1.50	1.4	1.3
TiO_2	2.09	+0.14	2.23	2.0	2.0
P_2O_5	0.36	-0.05	0.31	0.38	0.37
MnO	0.19	+0.01	0.20	0.21	0.21

[1] Correction factors determined by Jeff Goalen (1983).

[2] Values for basalt standard were calculated by adding correction factor to the international standard values in Appendix 13.

[3] From Snavely *et al.*, 1973.

Quaternary Deposits

Quaternary deposits in the study area are fluvial in origin. Quaternary alluvium (Qal) occurs along the Nehalem River and along all major low gradient streams (e.g., Walker Creek) in the study area (Plate I). A higher stream terrace (6 m) of older alluvium (Qal_1, Plate I) occurs in the western half of section 25-T6N-R6W. The terrace is marked by a linear contact (1.2 km long) with adjacent lower lying alluvium (Qal_2, Plate 1). The northwest-southeast linear trend might indicate that faulting and/or river entrenchment is still active in the study area. The best exposures of alluvial deposits (Qal_2) were observed along the Nehalem River bed (nw n n sec. 25-T6N-R6W) and are 1.5 m thick. There the alluvium is composed of rounded, poorly sorted sedimentary rock cobbles and pebbles displaying imbrication in a feldspathic sand matrix. Cobble and pebble deposits are interbedded and channelized into, subordinate coarse-grained arkosic sands displaying trough cross-bedding. Point bars along the Nehalem River are capped by muds.

STRUCTURE

Plate Tectonic Setting

Recent studies of the central Oregon continental margin by Snavely, Wagner and Lander (1980b), along with paleomagnetic studies in the Oregon Western Cascades by Magill and Cox (1981), the Tillamook Volcanics of the Northern Oregon Coast Range by Magill, Cox and Duncan (1981), and in southwest Washington by Magill, Wells, Simpson and Cox (1982), show that the Tertiary tectonic histroy of western Oregon and Washington involved periodic subduction and differential clockwise rotation of the northeastward moving Farallon oceanic Plate under the westward moving North American Continental Plate. The Oregon Coast Range, from the Klamath Mountains to the Columbia River, is thought to have acted as a coherent rotating block with a rotational pivot point in the Klamath Mountains during and after late Eocene accretion to the North American Plate. Rotations of 75° have been suggested based on paleomagnetic study of the Middle Eocene Siletz River Volcanics and of 46° ± 13° for the late Eocene upper Tillamook Volcanics (Magill et al., 1981). Gravity data display smooth, low-frequency wavelengths indicating a deep, elongate regionally continuous Oregon Coast Range block. In contrast, gravity anomalies in western Washington are high-frequency with sharp gradients indicative of shallow and smaller independent crustal tectonic blocks (Magill and Cox, 1980). The late Eocene Goble Volcanics in southwest Washington show rotations of only 25° ± 13° (Beck and Burr, 1979). Thus, a major structural break or discontinuity may occur along the Columbia River between the Oregon

Coast Range block and the smaller tectonic blocks in southwest Washington which show much less tectonic rotations (Magill et al., 1982).

Magill and Cox (1981), Magill et al. (1981) and Coe and Wells (1982), have recently proposed a two-phase rotation model of the Oregon Coast Range oceanic block. The first phase occurred during late middle Eocene time and produced 48° of clockwise rotation of the upper Tillamook Volcanics. At this time the proto-Coast Range was a seamount province of the spreading Farallon Plate which was in the process of being accreted obliquely to the North American Continental Plate. The late middle Eocene pivot point occurred in the Klamath Mountains and the subduction zone lay beneath the present Cascades. The second phase occurred approximately 15 to 20 my B.P. (Miocene) after late Eocene accretion of the Coast Range to the North American Plate. During this second phase the Western Cascades, Oregon and southwest Washington Coast ranges and Klamath Mountains rotated 15° to 27° clockwise as one coherent structural block (Magill et al., 1981). The pivot point is hypothesized to have been located in southwest Washington (Magill et al., 1982). Unlike the first phase where rotation was related primarily to oblique subduction, the second phase of clockwise rotation, according to Magill et al. (1981) may have been the result of Cenozoic Basin and Range differential extension in post middle Miocene time. Alternatively the last 25° of late Miocene clockwise rotation may be related to fault bounded blocks undergoing Riedel strike slip shear along transcurrent faults as a result of northward oblique subduction of the Farallon Plate (Coe and Wells, 1982).

Interpretations of offshore multichannel seismic reflection records in conjunction with detailed onshore geologic mapping of the central Oregon Coast Range indicates episodic late Eocene and middle Miocene periods of compression related to rapid plate convergence and extension of Cenozoic strata along the Oregon Coast Range during periods of slow plate convergence (Snavely *et al.*, 1980). Extensional periods are indicated by the occurrence of Goble-Yachats alkalic volcanism, and Oligocene dikes and sills and middle Miocene Coastal basalts (Snavely *et al.*, 1980).

Regional Structure

The largest structural feature of northwestern Oregon is the Coast Range "northward-plunging anticlinorium" (Snavely and Wagner, 1964 and Niem and Van Atta, 1973). The regional anticlinal structure of the northern Oregon Coast Range may reflect the compressional regime produced by the convergence of the Farallon Plate beneath the North American plate. Regionally late Eocene and younger strata dip to the west, north and east away from the central axis of this large north-south anticlinal fold (Snavely and Wagner, 1964, Niem and Van Atta, 1973). Smaller folds trend northeastward in the central part of the Coast Range whereas folds generally trend northwest near the present study area (Wells and Peck, 1961; Snavely and Wagner, 1964; Newton and Van Atta, 1976; Nelson, 1983, and Peterson, 1983). Numerous younger northeast and northwest trending high-angle faults truncate the Cenozoic strata of the Coast Range (Snavely and Wagner, 1974; Newton and Van Atta, 1976; Murphy, 1981; Goalen, 1983; Nelson, 1983; and Peterson, 1983). A similar conjugate NW and NE fault pattern has been recognized in southwest Washington by Wells (1981).

Local Structure

The study area is situated on the northward plunging nose of the northern Oregon Coast Range anticlinorium (Snavely and Wagner, 1964). Overall, attitudes of bedding and rock units reflect the plunge of this fold. That is, most units dip to the north (Plate II). However, many strikes and dips do not conform to this regional structure but are chaotic due to drag by extensive faulting and/or slumping. Some anomolus dips and strikes may also be in part controlled by original deposition processes such as channel cut-and-fill sedimentary structures as in the Vesper Church formation (Tvc). The large northward plunge of the northern Coast Range anticline from south to north through the center of the study area is best delineated by the outcrop pattern of the different formations in the study area, especially the Pittsburg Bluff Formation which dips to the northeast and northwest in the northern part of the study area (Plate I). The axis of the regional north-south fold would run through sections 15 and 16-T6N-R6W.

The structure of the study area is dominated by northeast and subordinate northwest trending high-angle faults. Other subordinate high-angle faults trend north-south and east-west. In the southern part of the study area, low-angle east-west trending thrust faults indicate that different tectonic stresses may have been active during and soon after the formation of the Cowlitz strata and Tillamook Volcanics. Only minor folding was noted in the study area. This is in contrast to the reconnaissance mapping of Newton in Newton and Van Atta (1976) which on the basis of few strikes and dips showed northwest trending fold axes in the area and no faults. The high-angle faults display two distinct periods of faulting, the second set of faults having cut through and displaced middle Miocene Depoe Bay Basalts which were entruded along earlier formed high-angle faults. Commonly, these faults appear as lineations on ERTS imagery and high altitude U-2 infrared photos. Where field evidence is lacking, photo lineations were not mapped as faults but are mapped seperately (Plate I). Many of the faults mapped in the study area are subjective and can not be seen in the field due to heavy forest cover, but are based upon aerial photo lineations, anomalous juxtaposition of sedimentary strata and volcanic units and opposing sets of chaotic strikes and dips. Many of the high-angle conjugate faults display apparent normal and reverse offsets (e.g., Section 16 Fault, Figure 37, and Plate I) based on outcrop patterns of rock units and juxtaposition of dipping strata. However, where the fault traces are exposed in outcrop, particularly in basalt quarries, NW right-lateral and NE left-lateral slickensides with some dip-slip component are evident. These two fault trends probably represent conjugate sets of strike-slip faults with some normal and reverse component.

The winding east-west fault trace (Green Mountain fault, Figure 37) mapped along the north face of Green Mountain (Plate I) is interpreted as a thrust fault. Evidence for this conclusion includes: 1) where exposed, the Cowlitz strata and subaerial Tillamook basaltic andesite flows (Tgv_1) on Green Mountain are everywhere in

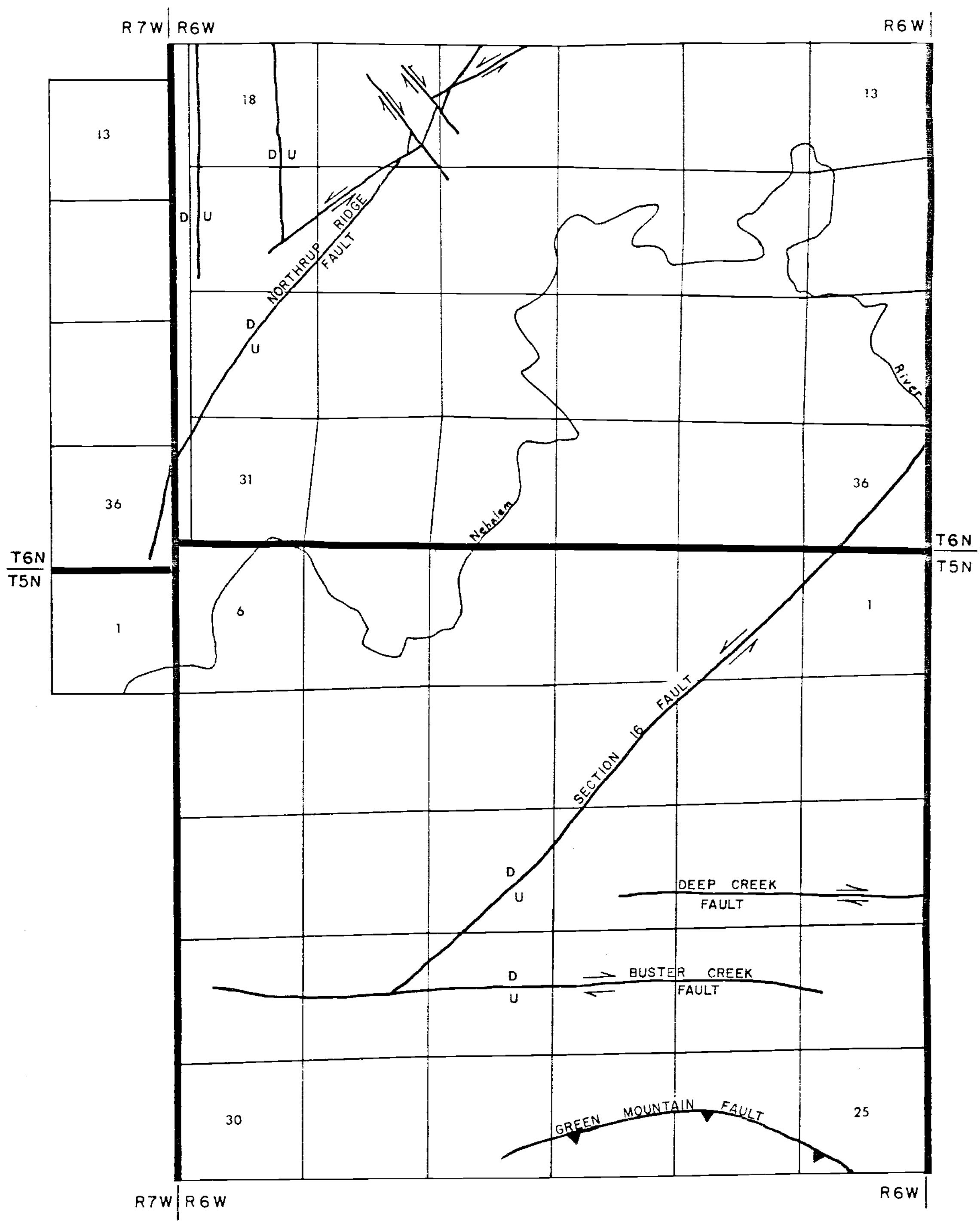


Figure 37: Major structural features in the Buster Creek-Nehalem Valley area.

fault contact; the faulting is characterized by high-angle, buff white altered shears in subaerial flows and the adjacent lithified basaltic conglomerates of the basal Cowlitz (Tc_1); 2) the fault contact between these formations follows topography and thus indicates low-angle faulting, 3) the relative sense of throw on the faults is down to the north based on stratigraphic position; and 4) no low-angle normal faults (indicative of extension) are observed elsewhere in the study area nor in any of the surrounding study areas (Goalen, 1982; Nelson, 1982; Peterson, 1982, personal communication). On the contrary, conjugate high angle, NW and NE trending strike-slip faults with normal and reverse components are prominent with rare folds (indicative of compression) according to these workers. Nelson, (1983) has mapped a thrust fault to the west of the study area. At one outcrop along Deep Creek logging road (95-6, 26-T5N-R46W) a coarse-grained basaltic sandstone bed (15 cm thick) in the mudstone member (Tc_3) of the Cowlitz Formation stands vertical with abundantly sheared, brecciated, and faulted Tillamook Volcanics subaerial flows lying structurally higher and in close proximity to the sandstone bed. The attitude of this bed is most likely due to drag along the Green Mountain fault. The lack of any extensional tectonic features coupled with the presence of a well supported low-angle fault to the west (Nelson, 1983) indicates to the writer that the Green Mountain fault is a thrust fault. A possible continuation of this east-west thrust fault, offset by younger northwest trending faults, occurs in the southwest most part of the study area and continues 6.5 km to the west to control the east-west orientation of the Nehalem River (Nehalem River Fault, Nelson, 1983). The sense of thrusting of this fault, however, is to the north.

A small east-west thrust fault with little stratigraphic throw also is exposed in the Vesper Church (turbidite) member (Tk_2) of the Keasey Formation in the Nehalem River banks (Figure 38, and Plate I, sections 22 and 23-T6N-R6W). It may control the east-west orientation of the river in this area.

Few folds were noted in the study area. A broad apparent northeast trending, highly faulted anticline involving both Cowlitz and Keasey strata (Tc_2 thru Tvc) occurs along Walker Creek 1.6 km to the northwest of Green Mountain (sections 16, 17, 18, 19 and 20-T5N-R6W, Plate I). A smaller more subdued, east-west anticline is cut by right-lateral northwest trending strike-slip faults folds in Cowlitz strata (Tc_3 and Tc_5, Tc_4 not present) on the northeast flank of Green Mountain (sections 25 and 26-T5N-R6W, Plate I). The presence of these folds are indicated by opposing bedding attitudes and outcrop patterns of Cowlitz and Keasey strata. Several other smaller NW and NE trending symmetrical anticlinal and synclinal folds are based on opposing dips in the Keasey and Cowlitz strata and may be related to drag along faults (see fold axes on Plate I, sections 23, 29, 32 and 34-T6N-R6W and sections 23 and 28-T5N-R6W).

Other east-west fault trends (Buster Creek and Deep Creek faults, Figure 37) occur in Keasey and Cowlitz strata along Buster Creek and north of Buster Camp (Plate I). The longest is the Buster Creek Fault which offsets Cowlitz subunits. The sense of relative movement along these faults is unclear, but one shear plane, along

Figure 38: Exposure of thrust fault (facing west) in rhythmically bedded Vesper Church turbidite strata. Thrust is at base of five-foot oar. (OC 917-10, se¼ sec. 22-T6N-R6W). Nehalem River cut-bank.

the Deep Creek Fault just outside of the study area (s sw sw section 18 T5N-R5W, Columbia County), in Keasey strata has horizontal slickensides which suggest right-lateral movement with no dip-slip component. The Deep Creek Fault extends eastward into Columbia County where it is mapped by Moin Kadri (1982). These faults are easily seen as lineaments in high-altitude U-2 infrared photos.

The prominent northeast fault pattern is best developed in the Vesper Church and Pittsburg Bluff formations in the central and northern parts of the study area (Plate I). Relatively straight N45°E lineaments are prominent on high altitude photos. These lineaments were then field checked. In several cases (locations 99-1 through 99-9, section 1-T5N-R6W ne, Plate I) the lineaments coincided with brecciated sedimentary rocks, anomalously high dips (e.g., 84° overturned, location 72-15, Plate I) and chaotic bedding attitudes due to fault drag, small-scale high-angle normal faults and juxtaposition of different stratigraphic units striking or dipping into one another across a photolineament. Near some of these faults, drag tends to align strike of bedding parallel to the strike of the fault plane (Plate I). These data strongly suggest that the relatively straight N45°E photolineaments are surface expressions of closely spaced high-angle faults cutting the sedimentary rocks. Not all anomalous dips and strikes necessarily reflect faults; some may be due to undetected slumping or sedimentary channeling. But where several sets of similar strikes and dips over a wide area cross drainages and hills and then strike or dip into another grouping of strike and dips (e.g., sections 26 and 35-T6N-R6W, Plate I) faulting is likely.

In contrast, the N45°E photolineaments are not as well developed in the older Tillamook Volcanics and Cowlitz strata in the southern part of the study area (Plate I). This may be due to more pronounced older (middle Eocene) east-west and north-west trending faulting in these strata masking a younger (post Refugian pre-middle Miocene) NE trending fault pattern. Another possibility is that the east-west right-lateral strike-slip faults are the conjugate shears to the pre-middle Miocene N45°E left-lateral strike-slip faults and that the northeast trending faults (e.g., Section 16 Fault, Figure 37) but up to the east-west Buster Creek fault and simply do not extend further south. One series of northeast trending lineaments were noted in photos of section 29-T5N-R6W, but field checks produced no data to support a fault (see photolineation symbol on Plate I). Relative offset, in these N45°E trending faults, of down to the northwest was determined by juxtaposition of formations in sections 15 and 16-T5N-R6W. Offsets noted along smaller, synthetic NE faults appear to mimic the larger structures.

A post late middle Miocene period of deformation produced N55°E and N55°W high-angle conjugate shear faults with left- and right-lateral offset respectively. These faults truncate and offset the middle Miocene Northrup Creek dike (Depoe Bay Basalt) which intruded along the older (post Refugian pre-middle Miocene) N45°E fault pattern (Northrup Ridge fault, Figure 37). The sense of throw of the faults was determined by relative offset of the near vertical dikes and by subhorizontal (30° dip) slickensides. The best exposures of these faults and gouge zones are located in quarries along the Northrup Creek dike in sections 16 and 17-T6N-R6W. This same conjugate set of strike slip faults is well exposed to the west in the Fishhawk Falls-Jewell area where the Beneke and Fishhawk Falls dikes are offset by many closely spaced faults (Nelson, 1983). These conjugate sets of faults also occur in the Porter Ridge-Elk Mountain area (Goalen, 1983), in the Green Mountain-Youngs River area (Peterson, 1983) and in the Willapa Hills area of southwest Washington (Wells, 1981) and may be more pervasive through the study area. Magill et al. (1982) and Coe and Wells (1982) suggest these conjugate sets of NW trending right-lateral and NE trending left-lateral faults (Riedel shears) and subordinate east-west thrusts may reflect a late Miocene north-south component of compression related to the oblique subduction of the Farallon Oceanic Plate beneath the North American Continental Plate and the Basin and Range extension in southeast Oregon and subsequent clockwise rotation of the Oregon and Washington Coast ranges.

A less understood north-south fault pattern subordinate to all other fault trends occurs in the north-western most part of the study area (sections 18 and 19-T6N-R6W). Poorly defined photo-lineaments and outcrop patterns support the existence of these faults. The sense of throw on these faults is down to the west and may be high angle normal faults.

GEOLOGIC HISTORY

Regional Geologic History

The Oregon Coast Range and adjacent inner continental shelf is comprised of more than 7,000 m of Cenozoic sedimentary and volcanic rocks deposited on a thickened lower and middle Eocene oceanic crust (Snavely et al., 1980b). These rocks reflect several periods of compression and tension related to subduction events. According to Magill's et al. (1981) hypothesis, prior to middle Eocene time the oceanic Farallon Plate (includes the Roseburg, Siletz River and lower Tillamook volcanics) was being subducted beneath the North American Continental Plate. The subduction zone lay either under or east of the present Cascade Range. Magill et al. (1981) have suggested that the Farallon oceanic plate with seamounts was too buoyant to be subducted and "clogged" this eastern subduction zone. By middle Eocene time, another subduction zone is believed to have formed to the west near the present outer Oregon continental shelf and slope. The basaltic crust of the Oregon Coast Range has been interpreted as a "micro-plate" or piece of trapped Farallon Plate caught between the two subduction zones. This micro-plate rotated clockwise during subduction and the trapped oceanic crust formed a linear trough or forearc basin in which the middle Eocene Tyee and Flournoy turbidites were deposited (Magill et al., 1981; and Snavely et al., 1980) It was in this forearc basin that much of the sedimentary strata of the study area were subsequently deposited.

In early late Eocene time, as the Oregon Coast Range "micro-plate" was accreted to the North American Plate (Snavely et al.

1980b), rejuvenation of older Eocene eruptive centers (subaerial seamounts), which include the Goble Volcanics and upper Tillamook Volcanics, occurred. Regional uplift which accompanied this period of convergence produced a regional angular unconformity at the base of upper Eocene strata (Snavely and MacLeod, 1977). By approximately 20 my B.P. the Coast Range was fully accreted to the North American Plate (Magill et al., 1981).

The Western Cascade Range is the Tertiary magmatic arc corresponding to the subduction zone along the base of the present continental shelf (Kulm and Fowler, 1974; Niem, 1976; and Snavely et al., 1980).

Local Geologic History

The Tillamook Volcanics are the oldest rocks in the study area. Preliminary paleomagnetic data suggest that these volcanics have undergone at least 48° of clockwise rotation (Nelson, 1983). Subaerial basaltic andesite flows, dikes and volcanic debris flows comprising this formation reflect a deeply dissected volcanic edifice. These volcanics and volcaniclastics are truncated by an angular unconformity. K-Ar age dates of 36.4 ± 0.4 m.y. and 32.4 ± 0.5 m.y. for the uppermost Tillamook flows and dikes (McElwee, 1982, personal communication) show that this unconformity may correspond to the regional late Eocene (Narizian) angular unconformity of Snavely and MacLeod (1977).

After uplift of the upper Eocene Tillamook Volcanics, steep gradient streams eroded cliffs of Tillamook subaerial flows, dikes and debris flows. Coastal fluvial basalt conglomerates and sands of the overlying Cowlitz Formation were deposited on this surface. The coarse basaltic andesite fluvial sediments spilled out into a high energy shallow marine environment where shelf sands were interbedded with the poorly sorted basaltic andesite conglomerates. Deeper marine mollusk-bearing mudstone, graded turbidites and finer grained hummocky bedded micaceous arkosic sandstone higher in the Cowlitz section suggests a gradual marine trangression. This transgression may be correlative to Vail and Hardenbol's (1979) TE2.2 transgressive cycle in the late middle Eocene. The micaceous arkosic composition of the upper Cowlitz sandstones indicate introduction of sediment from a different, more silicic source (eg. granitic and metamorphic rocks of eastern Oregon and Washington, British Columbia and Idaho via an ancestral Columbia River system) that gradually replaced the local basaltic andesite source. The uppermost sandstone member (Tc_5) of the Cowlitz Formation represents high-energy inner shelf sedimentation that shallowed upward into a nearshore environment; thus, reflecting a minor regression or sediment progradation. Later subsidence and/or a change in shelf configuration resulted in marine turbidity current deposition at the end of Cowlitz deposition.

An angular unconformity between the Cowlitz and overlying Keasey is suggested by truncation of the uppermost Cowlitz sandstone member (Tc_5) by the overlying Keasey mudstones (this study) and by discordant bedding attitudes between Cowlitz and the overlying Keasey formations further to the east (Van Atta, 1971; Niem and Van Atta, 1973; and Niem and Van Atta, 1976). The unconformity may have been produced by slight tectonic warping and submarine erosion before subsidence and deposition of deep water Keasey mudstones (Jewell member).

North-south compressional forces followed Cowlitz sedimentation prior to turbidite deposition of the Vesper Church formation. The evidence for this is an east-west trending thrust fault on Green Mountain and east-west strike-slip faults (Buster Creek and Deep Creek) 1 km north of Green Mountain which cut Tillamook Volcanics and Cowlitz and Keasey strata but do not cut the younger Vesper Church formation in the area. Only minor east-west thrust faults occur in the Vesper Church formation.

Near the end of Narizian time, quiet water deposition initiated Keasey sedimentation. The foraminiferal bearing bedded mudstone and glauconitic sandstone of the Jewell member of the Keasey Formation were deposited on the continental shelf and slope as hemipelagic muds in quiet water 200-600 m deep. Similar glaconite sands are now found on the outer Oregon continental shelf and slope (Kulm et al., 1977). Rare turbidity currents transported coarse-grained basaltic sands into this predominantly low energy environment. A few interbedded graded ash beds indicate that the ancestrial western Cascade volcanic arc was beginning to contribute tuffaceous sediment to the forearc basin. Continued subsidence, in Refugian time, followed deposition of the Jewell member of the Keasey Formation.

Deeper marine (1500-2000 m) turbidite deposits of the Vesper Church formation were laid down in sea gullies following deposition of the quiet water mudstone in the underlying Keasey Formation. Repeated channeling truncated underlying thin-bedded turbidites and deposited similar thin, rhythmically bedded turbidite sequences in the channel at slight angular discordance to the walls of the channels. Some channels were filled with thick, amalgamated, structureless fine-grained micaceous sands with rare mudstone ripups that may have formed by grain or fluidized flows combined with turbidity transport. This turbidite facies is similar to the middle Eocene Elkton siltstone of the Coos Bay area that Dott and Bird (1979) described as "Sea Gullies" or slope channel fills off the prograding main Coaledo (late Eocene) deltaic shelf facies. A similar origin may be represented by these Vesper turbidite facies with the overlying Pittsburg Bluff sandstone being the deltaic-shallow marine facies. The lack of any medium- to coarse-grained sediments in the Vesper Church formation indicates that only fine-grained sands and hemipelagic muds (middle member of the Keasey Formation of Van Atta, 1971) were available to this depositional system. Heavy minerals, sandstone petrography, palecurrent orientations, channel axes, and outcrop pattern suggest a west to north-west progradation of the channelized Vesper turbidites from uplifted micaceous Cowlitz-like sandstone sources to the east and southeast (e.g., perhaps around Green Mountain).

Rapid uplift followed deposition of the Vesper Church formation in the study area. Bathyal water depths of 1,500-2,000 m are indicated in the upper part of the Vesper Church formation based on foraminiferal assemblages whereas molluscan fauna in the overlying sandy lower part of the Pittsburg Bluff Formation (Tp_1) indicate water depths of 20-200 m (Moore, 1982, written communication). However, no evidence for a disconformable contact between these two formations occurs in the study area. Alternatively, the abrupt change in water depths may correlate to the global regression at the end of the late Eocene TE3 cycle of Vail and Hardenbol (1979).

Pittsburg Bluff tuffaceous sandstones were deposited in a shallow water continental shelf environment. Molluscan and trace fossil assemblages, sedimentary structures and glauconitic sandstone indicate that deposition of Pittsburg Bluff strata occurred in an open marine inner to middle (and possibly outer) continental shelf. Similar fine-grained laminated to bioturbated feldspathic and glauconitic sands are now forming on the present Oregon inner to outer continental shelf (Kulm et al., 1979). The highly tuffaceous character of the Pittsburg Bluff Formation and the volcanic heavy mineral assemblage reflects intense western Cascade calc-alkaline volcanism at this time.

Following deposition of the upper Eocene (Refugian) Pittsburg Bluff Formation, a series of N45°E trending high-angle normal and subordinate reverse faults were formed, most likely the result of alternating periods of compression and relaxation between the Farallon and North American plates. Oligocene (Zemorrian) and early Miocene (Saucesian) deposition are not represented by strata in the thesis area, but further to the west, this was a time of deep marine slope deposition followed by deltaic progradation and turbidite deposition of the Astoria Formation (Cressy, 1974 and Cooper, 1981).

In middle Miocene time, a reversely polarized, low MgO-high TiO_2 Depoe Bay basaltic dike intruded the sedimentary rocks in the study area along previously formed N45°E fault planes. These tholeiitic intrusive basalts are thought to have formed during a period of extension in the Oregon Coast Range from local magmatic sources (Snavely *et al.*, 1973). Beeson *et al.* (1979) recently proposed an alternative hypothesis that the submarine basalts and intrusives of the middle Miocene Depoe Bay, Cape Foulweather and basalts of Pack Sack Lookout are the distal ends of plateau derived Columbia River Basalt subaerial flows (e.g., Grande Ronde, Frenchman Springs and Pomona basalts) which reached the middle Miocene coast-line near Nicolai Mountain (Murphy, 1981) and invaded loosely consolidated thixotropic Oligocene and Miocene marine sediments. The high TiO_2-low MgO, reverse polarized Northrup Creek dike of this study area can be traced northward to within a few kilometers of chemically and paleomagnetically similar subaerial flows of Grande Ronde basalt (Goalen, 1983 and Nelson, 1983) supporting this invasive hypothesis. However, the intrusive Depoe Bay Basalts penetrated at depths of 2,820', 3,540' and 5,250' in the Quintana "Watzek" 30-1 well in the study area are in inverse stratigraphic order to the subaerial Grande Ronde sequence recognized on Nicolai Mountain by Murphy (1981) and on Porter Ridge by Goalen (1983) (eg. high MgO to low MgO-high TiO_2 to low MgO-low TiO_2 going up section respectively). Although the subsurface data do not disprove the hypothesis of Beeson *et al.* (1979), they do point out the difficulties in working out the mechanical problem of emplacing (in inversed order) different "invasive" sills to depths of 5250' in late Eocene Cowlitz strata from subaerial flows only 15 km to the north of this study area.

Following intrusion and solidification of the Depoe Bay Basalt dike, the stress system adjusted slightly to a more north-south compression and conjugate faulting occurred along fault planes of slightly different orientation. The conjugate faults offset the Depoe Bay Northrup Creek dike and show right-lateral displacement on N55°W trending faults and left-lateral displacement on N55°E trending faults in the northwest part of the study area. This may reflect north-south compression related to oblique subduction of the Juan De Fuca Plate beneath the North American Plate or the effect of Basin and Range extension and the clockwise rotation of the Oregon Coast Range since the late middle Miocene (Magill et al., 1981).

Uplift of the Oregon Coast Range in the late middle Miocene and formation of the Northern Oregon Coast Range anticlinorium are related to another period of underthrusting of the Juan De Fuca Plate beneath the North American Plate (Snavely et al., 1980). This was followed by entrenchment of the Nehalem River and deposition of its terrace deposits (Qal) in the study area.

ECONOMIC GEOLOGY

Crushed Rock

Presently, the only economically exploited geologic resource in the thesis area is the production of crushed rock from the middle Miocene Depoe Bay Basalt dikes and middle Eocene Tillamook Volcanic subaerial flows (see quarry symbols on Plate I). The largest of these quarries is on the Northrup ridge in section 17-T6N-R6W ne se. Crushed rock is used in the construction of logging roads as gravel road base and as riprap to shore up the base of hillsides susceptible to landsliding. In order for the production of crushed rock to be economical, quarries must be located within 12 km of the market area (Beaulieu, 1973). The Oregon State Forestry Department is actively building new logging roads in Clatsop County, Oregon and currently represents the only user of crushed rock in the study area.

Hydrocarbon Potential

Northwest Oregon and the adjacent continental shelf has been intermittently drilled and tested for commercial quantities of oil and gas for the past 40 years. In 1946 Texaco, Inc. (then Texas Company) drilled two dry wells in Columbia County, Oregon. Although no commercial quantities of hydrocarbons were encountered, shows of gas and oil were tested in upper "Clark and Wilson sands" (C & W) of the middle Eocene Cowlitz Formations at depths of 3,241' to 3,302'. Deeper, water saturated Tillamook "sands" were also penetrated (Newton and Van Atta, 1976). The upper "sands" received their name from the Texaco "Clark and Wilson" 6-1 well in section 19-T6N-R4W of

Columbia County, Oregon. The "Clark and Wilson sands" correlate to the upper arkosic sandstone member of the Cowlitz Formation (Tc_5, Plate I, this study and the upper sandstone member of Van Atta, 1971). Permeabilities ranging from 135 to 1,302 millidarcies and porosities ranging from 25 to 32% were measured from "Clark and Wilson sands", fully substantiating the presence of an excellent reservoir rock (Bruer, 1980). Sandstones below volcanic flows, breccias and tuffs, in the "Clark and Wilson" 6-1 well below 4,400' displayed fair permeability and porosity by flowing saltwater in formation tests (Newton and Van Atta, 1976). Tillamook Volcanics were encountered at 8,355' in the well.

In 1976, Newton and Van Atta published their study of prospects for commercial natural gas production and underground gas storage for northwest Oregon. They hypothesized a reservoir of upper Cowlitz sandstone could be expected along the Mist anticline in Columbia County, some 9 km northeast of this study area. In 1977, a second period of drilling by Diamond Shamrock Corp., Reichold Energy Corp. and Northwest Natural gas commenced along the Mist anticline with the "Columbia County" #1 in section 11-T6N-R5W resulting in a dryhole. In 1979, the "Columbia County" #1 was reentered and directionally redrilled up structure and flowed commercial quantities of gas from the Cowlitz C & W sands at 1,700 Mcf/day (Bruer, 1980). The cap rock is the Keasey mudstone. The reentry of the Columbia County #1 was the first commercial discovery of gas ever found in Oregon (Newton, 1979). Analysis of the gas from the Mist field indicates a thermogenic, rather than a biogenic origin from a mature basin (Bruer, 1980). Possible depositional centers deep enough for this level of maturation are the 10,000' deep Astoria Basin, 22 km to the west and the 20,000' deep Tualatin Basin, 22 km to the southeast of the Mist gas field (Bruer, 1980).

The upper Cowlitz reservoir rocks ("C & W sands") of the Mist gas field crop out in the southern part of the study area (Tc_5, Plate I). This correlation is based on mapping pattern and two distinctive heavy mineral assemblages in the upper sandstone unit (Tc_5) of the Cowlitz Formation (see Descriptive Geology-Cowlitz). Plate II, cross-section B-B' depicts the stratigraphic relation between the two upper Cowlitz sandstones (Tc_5 and Tc_{5e}) in the study area. The upper most epidote-rich sandstone (Tc_{5e}, broken out as a separate unit on Plate II only) is interpreted to be eroded off since it does not crop out in the west part of the study area nor is it encountered in the Quintana Watzek 30-1 (cross-section A-A", Plate II). Only the zircon-rich upper Cowlitz sandstone (Tc_5, Plate II) occurs in the Quintana Watzek 30-1. The upper most Cowlitz "C & W sands" in the Mist gas field (e.g., Adams 24-34 well) correlate very well (ie. identical heavy mineral assemblages) with the upper Cowlitz epidote-rich sandstone in the southeastern part of the study area (Figure 39). The depositional environment interpreted from data obtained from the outcropping Cowlitz sandstones is a widespread high-energy shelf to near-shore environment where clean, moderately well sorted, micaceous arkosic sands, derived predominantly from a plutonic/metamorphic provenance, were deposited. Timmons (1981) has mapped the Cowlitz Formation to the east and southeast of the study area in Columbia County. He describes similar sedimentary structures, to those in this study, in

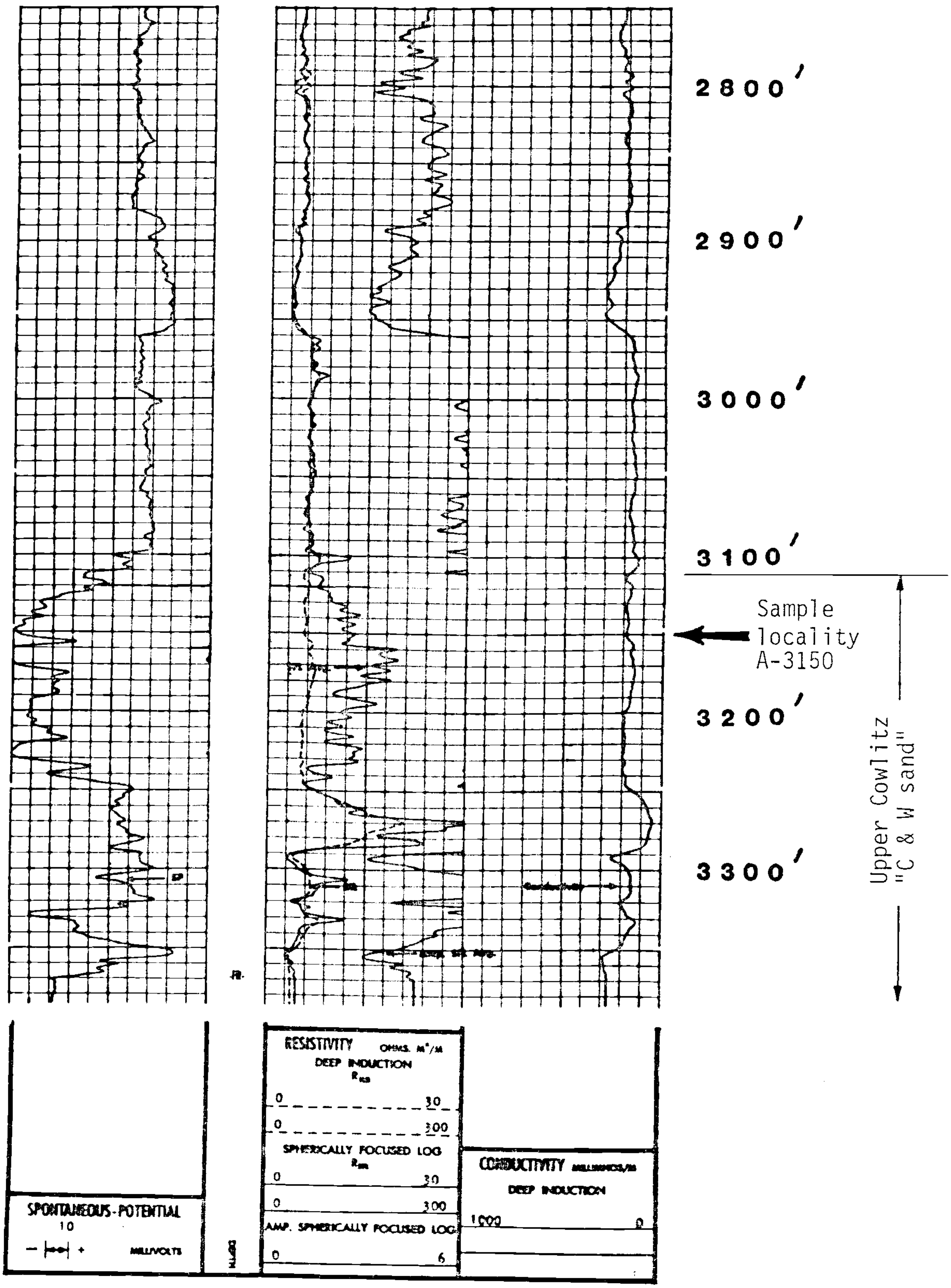


Figure 39: Well log from the Adams 24-34 in the Mist gas field. Sample A-3150, upper Cowlitz "C & W sand", is a subarkose with the same epidote-rich heavy mineral assemblage found in arkosic sandstones (Tc_5) cropping out in the southeast part of the study area.

the upper Cowlitz sandstone of Columbia County and also interprets them to represent a near-shore wave-dominated environment of deposition. The high textural maturity and mineralogically stable constituents indicate that good porosity and permeability will occur wherever this clean, friable, well sorted sandstone unit is encountered. The upper sandstone member of the Cowlitz Formation is capped in the study area by several tens of meters of well-indurated lower mudstone of the Keasey Formation (Jewell member, Plates I & II). Lower Cowlitz clean arkosic sandstones interbedded with mudstone and volcanic lithic arenite (Tc_3) occur in the Quintana Watzek 30-1 (Plate III) and in outcrop (Nelson, 1983). The occurence of these sandstones provide the potential for multiple reservoirs in a single structure. With the presence of reservoir, cap and source rock (Mist gas field) known to be in the area, only a trapping mechanism is needed for gas accumulation.

The highly faulted Mist anticline (Bruer, 1980) is one model for future exploration. But evidence for such an anticlinal structure in this thesis area does not occur as indicated by my geologic mapping. An alternative structural trap more likely to occur in the study area, based on surface mapping, would be the fault bounded horst or half-graben. Recent reflection seismic data recorded in the study area (Diamond Shamrock Corp.) during the years 1981 and 1982 have indeed indicated subsurface structures (up-thrown fault blocks, John Girgis, Diamond Shamrock Corp., 1983, personal communication). One such structure is currently being drilled by Diamond Shamrock Corporation in section 19-T6N-R6W (see Plate I).

Another possible trapping mechanism should be considered. The lack of upper "epidote rich" Cowlitz sandstone (Tc_5, equivalent to the "C & W" in the subsurface at Mist) to the west, both in outcrop and in the Quintana "Watzek" 30-1 (Plate III), indicate that an erosional pinchout to the west with an overlying cap rock of Keasey mudstone (Jewell member, Tk, Plate I) can be anticipated. A combination of structural and erosional unconformity trap may thus be a viable exploration model in the northern half of the study area where the Cowlitz Formation has not been breached.

Older east-west structural features, such as the Green Mountain thrust fault in the Tillamook and Cowlitz units, are unconformably covered by less deformed Keasey mudstone. It is probable that faults and associated drag folds favorable to gas accumulation in the subsurface in the northern part of the study area are also covered by younger strata having a different deformational style (e.g., N45°W faults) than that mapped in the Vesper Church strata on the surface.

Thick turbidite sandstone channels encased in the impermeable mudstones and thin turbidites of the Vesper Church formation may be encountered in future drilling in the area. In outcrop (e.g., 81-10, Plate I), these arkosic sandstones are as friable (porous and permeable) as the gas producing upper sandstones (Tc_5) of the Cowlitz Formation. These 15 m thick channelized sandstones will be more difficult to locate in the subsurface and may have limited volume but present an ideal reservoir for a stratigraphic trap model with adjacent mudstone as source and cap rock.

Two mudstone samples (83-14 and 96-2, Appendix 15) from the Vesper Church formation were analyzed for potential source rock by Amoco Petroleum Company (Terry F. Mitchell, 1982, written communication). These samples had total organic carbon (TOC) percentages of 1.3% and 2.3%, and vitrinite reflectances (VR) of 0.46% and 0.44%. These vitrinite reflectance values indicate that the mudstones in the study area are above the "oil window" of Dow (1977, Figure 40). In addition, although these rocks had good to very good generation ratings for gas, both were pre-generation or thermally immature source rocks and thus only biogenic methane can be expected from them. Results from the tests by Amoco may be erroneous or misleading since extensive deep weathering of exposed outcrops in the moist northwest Oregon climate probably reduced both the quantity and quality of organic matter resulting in an underestimation of petroleum generating abilities. If the source rock analyses of the organic rich mudstones of the Vesper Church formation are misleading and sufficient burial for thermal maturation occurred, the channelized sandstones would have all the necessary features of a productive reservoir. In the thesis area, much of the Vesper Church formation is breached by erosion but further to the north it is overlain by younger Pittsburg Bluff, Eocene to Oligocene Oswald West mudstone and the Astoria Formation (Goalen, 1983, in progress).

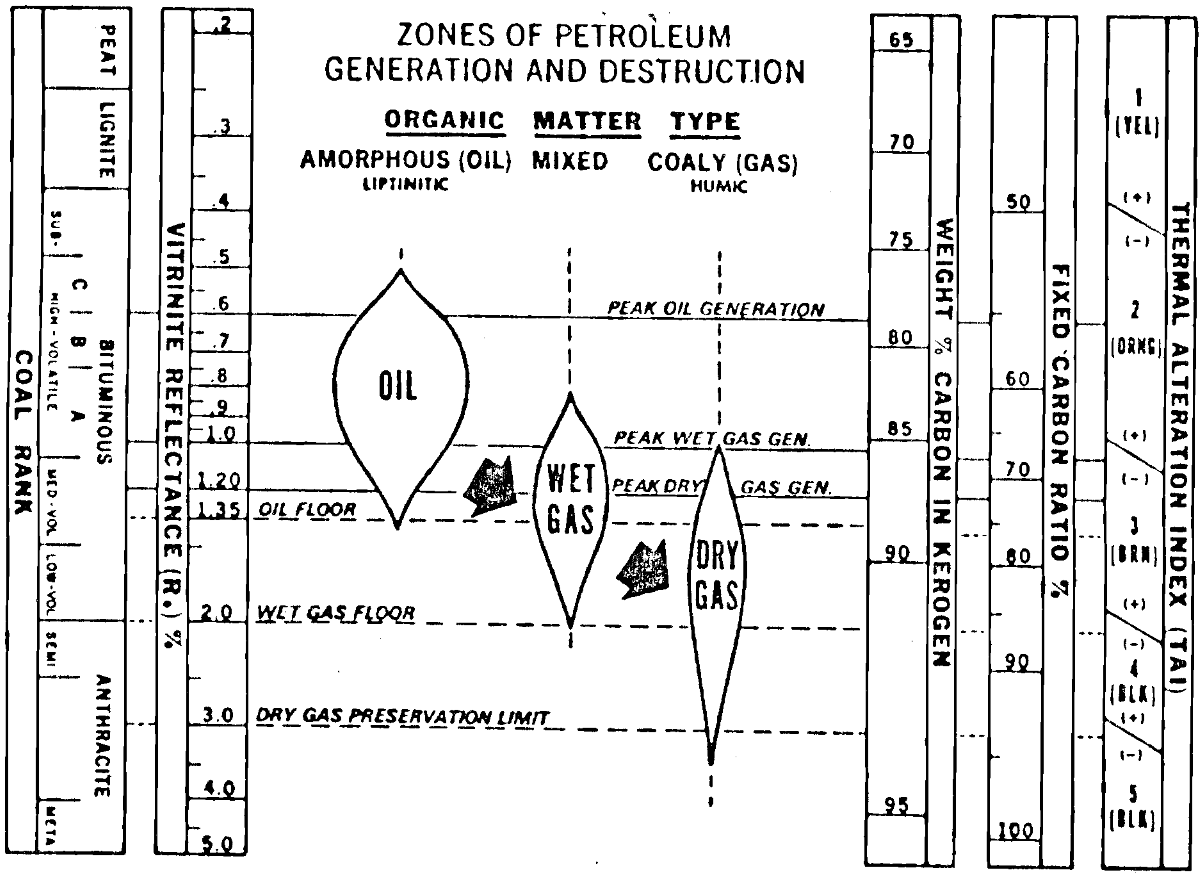


Figure 40: Correlation of the coal rank scale with various maturation indices and the zones of petroleum generation and destruction (Dow, 1977).

REFERENCES CITED

Addicott, W. O., 1976, Neogene molluscan stages of Oregon and Washington, in Wornardt, W. W. (ed.), Symposium on the Neogene of the Pacific Coast: Soc. Econ. Paleontologists and Mineralogists, Pac. Sec., San Francisco, Calif., April, p. 95-115.

Anderson, J. L., 1978, The stratigraphy and structure of the Columbia River Basalt in the Clackamas River drainage: unpub. M.S. thesis, Portland State University, Portland, 136 p.

Armentrout, J. M., 1975, Molluscan biostratigraphy of the Lincoln Creek Formation, southwest Washington: in Weaver, D. E., ed., Future energy horizons of the Pacific coast; Paleogene symposium and selected technical papers: Annual meeting of the Pacific Sections, Amer. Assoc. Pet. Geol., Soc. Econ. Paleont. and Min., Soc., Econ. Geol., Long Beach, Calif., April, p. 14-18.

____________________, 1981, Correlation and ages of Cenozoic chronostratigraphic units in Oregon and Washington: Geol. Soc. Am. Special Paper 184, p. 137-148.

Baldwin, E. M., 1974, Eocene stratigraphy of southwestern Oregon: State of Oregon, Department of Geology and Mineral Industries, Bull. 83, 40 p.

____________________, 1981, Geology of Oregon, Revised Edition: Kendall/Hunt Publishing Co., Dubuque, Iowa, 170 p.

Baldwin, E. M., Brown, J. E. Gair and Pease, M. H., Jr., 1955, Geology of the Sheridan and McMinnville quadrangles, Oregon: U.S. Geol. Survey Oil and Gas Inv. Map OM - 155.

Beaulieu, J. D., 1973, Environmental geology of inland Tillamook and Clatsop Counties, Oregon: Oregon Dept. Geology and Mineral Industries Bull. 79, 65 p., 43 figs., 4 tables, 14 maps.

Beck, M. E., Jr., 1976, Discordant paleomagnetic pole positions as evidence of regional shear in the western Cordillera of North America: Amer. Jour. Sci., v. 276, p. 694-712.

Beck, M. E., Jr., and Burr C. D., 1979, Paleomagnetism and tectonic significance of the Goble Volcanic Series, southwestern Washington: Geology, v. 7, p. 175-179.

Beck, M. E., Jr. and Plumley, P. W., 1980, Paleomagnetism of intrusive rocks in the Coast Range of Oregon: Microplate rotations in middle Tertiary time: Geology, v. 8, p. 573-577.

Beck, R. S., 1943, Eocene Foraminifera from Cowlitz River, Lewis County, Washington: Jour. Paleontology, v. 17, no. 6, p. 584-614.

Beeson, M. H. and Moran, M. R., 1979, Columbia River Basalt Group stratigraphy in western Oregon: Oregon Geology, v. 41, no. 1, p. 11-14.

Beeson, M. H., Perttu, R. and Perttu, J., 1979, The origin of the Miocene basalts of coastal Oregon and Washington: An alternative hypothesis: Oregon Geology, v. 41, no. 10, p. 159-166.

Brenner, R. L., and Davies, D. K., 1973, Storm-generated coquinoid sandstone: genesis of high-energy coquinoid sandstone from the Upper Jurassic of Wyoming and Montana: Geol. Soc. Am. Bull., v. 84, p. 1685-1698.

Bromery, R. W. and Snavely, P. D., Jr., 1964, Geologic interpretation of reconnaissance gravity and aeromagnetic surveys in northwestern Oregon: U.S. Geol. Surv. Bull. 1181-N, p. n1-n13.

Bruer, W. G., 1980, Mist gas field, Columbia County, Oregon: Technical Program Reprints, Pac. Sec. Am. Assoc. Pet. Geol., Soc. Econ. Geol., Fifty-fifth Annual Meeting, 10 p.

Bukry, David, 1981, Pacific Coast coccolith stratigraphy between Point Conception and Cabo Corrientes, Deep Sea Drilling Project, Leg 63, in Yeats, R. S., Hag, B. U., and others, eds.: Initial Reports, Deep Sea Drilling Project, Leg 63, U. S. Government Printing Office, Washington D.C., p. 445-472.

Burr, C. D., 1978, Paleomagnetism and tectonic significance of the Goble Volcanics of southern Washington: unpub. M.S. thesis, Western Washington University, Bellingham, 66 p.

Chamberlain, C. K., 1982, Paleontologist, Valero Producing Company, written communication, January 28.

Cooper, M. D., 1981, Sedimentation stratigraphy, and facies variation within the early to middle Miocene Astoria Formation in Oregon: unpub. Ph.D. thesis, Oregon State Univ., Corvallis, 443 p.

Coryell, G. F., 1978, Stratigraphy, sedimentation, and petrology of the Tertiary rocks in the Bear Creek - Wickiup Mountain - Big Creek area, Clatsop County, Oregon: unpub. M.S. thesis, Oregon State Univ., Corvallis, 178 p.

Cressy, F. B., Jr., 1974, Stratigraphy and sedimentation of the Neahkahnie Mountain-Angora Peak area, Tillamook and Clatsop Counties, Oregon: unpub. M.S. thesis, Oregon State Univ., Corvallis, 148 p.

Cushman, J. A., and Schenck, H. G., 1928, Two Foraminiferal faunules from Oregon Tertiary: Univ. Calif. Pub. in Geol. Sci., v. 17, no. 9, p. 305-324.

Deacon, R. J., 1953, A revision of upper Eocene and lower Oligocene stratigraphic units in the upper Nehalem River basin, northwest Oregon: unpub. M.S. thesis, Oregon State Univ., Corvallis, 84 p.

Dickinson, W. R., 1982, Compositions of sandstones in circum-pacific subduction complexes and fore-arc basins: Am. Assoc. Pet. Geol. Bull., v. 66, no. 2, p. 121-137.

Dickinson, W. R. and Seely, D. R., 1979, Structure and stratigraphy of forearc regions: Am. Assoc. Pet. Geol. Bull., v. 63, no. 1, p. 2-31.

Dickinson, W. R., and Suczek, C. A., 1979, Plate tectonics and sandstone compositions: Am. Assoc. Pet. Geol. Bull., v. 63, no. 12, p. 2164-2182.

Diller, J. S., 1896, Geological Reconnaissance in northwestern Oregon: U.S. Geol. Survey 17th Ann. Report, p. 441-520.

Doell, R. R., and Cox, Allan, 1964, Determination of the magnetic polarity of rock samples in the field: U.S. Geol. Survey Prof. Paper 450-D., p. 105-108.

Dott, R. H., Jr. and Bird, K. J., 1979, Sand transport through channels across an Eocene shelf and slope in southwestern Oregon, U.S.A.: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. no. 27, pp. 327-342.

Dott, R. H., Jr. and Bourgeois, Joanne, 1982, Hummocky stratification: significance of its variable bedding sequences: Geol. Soc. of Am. Bull., v. 93, no. 8, p. 663-680.

Dow, W. G., 1977, Petroleum source beds on continental slopes and rises, in Mcfarlan, E., Drake, C. L. and Pittman, L. S., eds., Geology of Continental Margins: A.A.P.G. Continuing Education Course Note Series #5, Washington, D.C., p. D1-D37.

Durham, J. W., 1944, Megafaunal zones of the Oligocene of northwestern Washington: Calif. Univ. Dept. Geol. Sci. Bul., v. 27, no 5, p. 101-212.

Folk, R. L., 1974, Petrology of sedimentary rocks, Austin, Texas, Hemphill Pub. Co., 182 p.

Galloway, W. E., 1974, Deposition and diagenetic alteration of sandstone in northeast Pacific arc-related basins: Implications for graywacke genesis: Geol. Soc. Am. Bull., v. 85, p. 379-390.

Goalen, J. S., 1983, The Geology of the Elk Mountain-Porter Ridge area Clatsop County, northwest Oregon: unpub. M.S. thesis in progress, Oregon State Univ., Corvallis.

Grechin, V. I., Niem, A. R., Mahood, R. O., Alexandrova, V. A., and Sakharov, B. A., 1981, Neogene tuffs, ashes and volcanic breccias from offshore California and Baja California, Deep Sea Drilling Project Leg 63: Sedimentation and Diagenesis: in, Yeats, R. S., Haq, B. U., et al.: Initial Reports of the Deep Sea Drilling Project, v. 63, Washington, Gov't Printing Office, p. 631-657.

Hammond, P. E., 1979, A tectonic model for evolution of the Cascade Range, in Armentrout, J. M., Cole, M. R., and TerBest, Harry, Jr., eds., Cenozoic Paleogeography of the western United States, Pacific Coast Paleogeography Symposium 3: Pacific Section SEPM, p. 219-237.

Hardenbol, J., and Berggren, W. A., 1978, A new Paleogene numerical time scale, in Cohee, G. V., and others, eds., Contributions to the Geologic Time Scale: Am. Assoc. Petrol. Geol. Studies in Geology, no. 6, p. 213-234.

Henriksen, D. A., 1956, Eocene stratigraphy of the lower Cowlitz River-eastern Willapa Hills area, southwestern Washington: Wash. Div. Mines and Geol. Bull., no. 43, 122 p.

Hertlein, L. G., and Crickmay, C. H., 1925, A summary of the nomenclature and stratigraphy of the marine Tertiary of Oregon and Washington: Amer. Philos. Soc. Proc., v. 63, p. 224-282.

Hill, D. W., 1975, Chemical composition of Oregon and Washington coastal basalts: unpub. M.S. thesis, Oregon State Univ., Corvallis, 99 p.

Hooper, P. R., 1982, Professor, Department of Geology, Washington State University, Pullman, Washington, written comm., February 15.

Hooper, P. R. Reidel, S. P., Brown, J. C., Bush, J. H. Holden, G. S., Kleck, W. D., Robinette, M., Sundstrom, C. E., and Taylor, T. L., 1976, Major element analyses of Columbia River basalt, part I: Pullman, Basalt Research Group, Wash. State Univ., open-file report.

Jackson, K. C., 1970, Textbook of lithology: McGraw-Hill Book Co., New York, 552 p.

Johnson, H. D., 1980, Shallow Siliclastic Seas: in Reading, H. G. (ed.): Sed. Environmental Facies, Elsevier, New York, p. 207-258.

Kadri, M. M., 1982, Structure and influence of the Tillamook uplift on the stratigraphy of the Mist area, Oregon: unpub. M.S. thesis, Portland State University, Portland, 102 p.

Kulm, L. D. and Fowler, G. A., 1974, Oregon continental margin structure and stratigraphy: a test of the imbricate thrust model, in Burk, C. A., and Drake, C. L., eds., The geology of continental margins: Springer-Verlag, New York, p. 261-283.

Kulm, L. D., Roush, R. C., Harlett, J. C., Neudeck R. H., Chambers, D. M., and Runge, E. J., 1975, Oregon continental shelf sedimentation: interrelationships of facies distribution and sedimentary processes; Jour. Geology, v. 83, no. 2, p. 145-175.

Kulm, L. D. and Scheidegger, K. F., 1979, Quaternary sedimentation on the tectonically active Oregon continental slope: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. no. 27, p. 247-263.

Leckie, D. A., and Walker, R. G., 1982, Storm- and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval outcrop equivalents of deep basin gas trap in Western Canada: Am. Assoc. Pet. Geol. Bull., v. 66, no. 2, p. 138-157.

Livingston, V. E. Jr., 1966, Geology and mineral resources of the Kelso-Cathlamet area, Cowlitz and Wahkiakum Counties, Washington: State of Wash., Div. Mines and Geol. Bull. no. 54, 110 p.

Lohmar, J. M., May, J. A., Boyer, J. E., and Warme, J. E., 1979, Shelf edge deposits of the San Diego embayment, in Abbott, P. L., ed., Eocene depositional systems, San Diego: SEPM Pacific Section, Field guidebook, Los Angeles, California, p. 15-34.

Lovell, J. P. B., 1969, Tyee Formation: undeformed turbidites and their lateral equivalents: Mineralogy and Paleogeography, Geol. Soc. Am. Bull., v. 80, p. 9-22.

Lowry, W. D., and Baldwin, E. W., 1952, Late Cenozoic geology of the lower Columbia River valley, Oregon and Washington: Geol. Soc. Am. Bull., v. 63, p. 1-24.

MacDonald, G. A., and Katsura, T., 1964, Chemical classification of Hawaiian lavas: Jour. Petrology, v. 5, p. 82-133.

Magill, J. R., Wells, R. E., Simpson, R. W., and Cox, A. V., 1982, Post-12 m.y. rotation of southwest Washington: Jour. of Geophys. Res., v. 87, p. 3761-3776.

Magill, James and Cox, Allan, 1980a, Tectonic implications and paleomagnetic evidence for post Oligocene rotation of the Oregon Cascades: EOS (Trans. Amer. Geophys. Union), v. 62, p. 948.

__________________, 1980b, Tectonic rotation of the Oregon western Cascades: State of Oreon Dept. Geol. Min. Ind., Spec. Pap. 10, 67 p.

__________________, 1981, Post-Oligocene tectonic rotation of the Oregon western Cascade Range and the Klamath Mountains: Geology, v. 9, p. 127-131.

Magill, James, Cox, Allan, and Duncan, Robert, 1981, Tillamook Volcanic Series: Further evidence for tectonic rotation of the Oregon Coast Range: Jour. Geophys. Res., v. 86, no. B4, p. 2953-2970.

McBirney, A. R., 1963, Factors governing the nature of submarine volcanism: Bull. Volc., v. 26, p. 455-469.

McDougall, Kristin, 1975, The microfauna of the type section of the Keasey Formation of northwestern Oregon: D. W. Weaver, G. R. Hornaday, and A. Tipton (eds): Paleogene Symp. and selected Tech. Pap. Ann. Meet. Pac. Sec. AAPG, SEM, SEG, Long Beach, Calif., April, p. 343-359.

__________________, 1980, Paleoecological evaluation of late Eocene biostratigraphic zonations of the Pacific coast of North America: Jour. Paleo., Paleont. Mono. no. 2, 36 p., 29 plates.

__________________, 1982, Paleontologist, U.S. Geol. Survey, written comm., March 24.

McElwee, Kristine, 1982, Graduate Student, School of Oceanography, Oregon State Univ. Personal communication.

Middleton, G. V. and Hampton, M. A., 1973, Sediment gravity flows: mechanics of flow and deposition, in Middleton, G. V. and Bouma, A. H., eds., Turbidites and deep water sedimentation: SEPM short course, Anaheim, California, p. 1-38.

Moore, E. J., 1963, Miocene marine mollusks from Astoria Formation in Oregon: U.S. Geol. Survey Prof. Paper 419, p.109.

__________________, 1976, Oligocene marine mollusks from the Pittsburg Bluff Formation in Oregon: U.S. Geol. Surv. Prof. Paper 922, 66 p., 17 plates.

Moore, E. J., and Fleming, Daniel, 1982, Paleontologists, U.S.G.S., written comm., February 24, 1982.

Moore, R. C., and Vokes, H. E., 1953, Lower Tertiary crinoids from northwestern Oregon: U.S. Geol. Survey Prof. Paper 233-E, p. 113-148.

Murphy, T. M., 1981, Geology of the Nicolai Mountain-Gnat Creek area, Caltsop County, northwest Oregon: unpub. M.S. thesis, Oregon State Univ., Corvallis, 355 p., 3 plates.

Murphy, T. M., and Niem, A. R., 1982, Tectonic and paleoenvironmental significance and magnetic-geochemical stratigraphy of the Columbia River Basalt at the middle Miocene shoreline, northwestern Oregon Coast Range: EOS (Trnas., Am. Geophys. Union), v. 63, no. 8, p. 163.

Mutti, E., and Ricci Lucchi, F., 1978, Turbidites of the northern Apennines: Introduction to facies analysis: Int. Geol. Rev. Reprint, v. 20, no. 2, p. 125-166.

Nelson, D. E., 1983, Geology of the Fishhawk Falls-Jewell area, Clatsop County, northwest Oregon: unpub. M.S. thesis in progress, Oregon State Univ., Corvallis.

Nelson, M. P., 1978, Tertiary stratigraphy and sedimenatation in the Youngs River-Lewis and Clark River area, Clatsop County, northwestern Oregon: unpub. M.S. thesis, Oregon State Univ., Corvallis, 242 p.

Newton, V. C., Jr. and Van Atta, R. O., 1976, Prospects for natural gas production and underground storage of pipe-line gas in the upper Nehalem River Basin Columbia-Clatsop Counties, Oregon: State Ore. Dept. Geol. Min. Ind., Oil and Gas Invest. 5, 56 p., 1 map.

Newton, V. C., 1979, Oregon's first gas wells completed, Oregon Geology, vol. 41, no. 6, p. 87-90.

Niem, A. R. and Cressy, F. B., Jr., 1973, K-Ar dates from the Neahkahnie Mountain and Tillamook Head areas of the northwestern Oregon coast: Isochron/West, v. 7, no. 3, p. 13-15.

Niem, A. R., and Van Atta, R. O., 1973, Cenozoic stratigraphy of northwestern Oregon and adjacent southwestern Washington: in Beaulieu, J. D., (ed.), Geologic field trips in northern Oregon and southern Washington: Ore. Dept. Geol. Min. Ind. Bull. 77, pp. 75-132.

Normark, W. R., 1978, Fan valleys, channels and depositional lobes on modern submarine fans: Characteristics for recognition of sandy turbidite environments: Am. Assoc. Pet. Geol. Bull., v. 62, p. 912-931.

Olmstead, D. L., 1981, Oil and gas exploration and development in Oregon, 1980, Oregon Geology, vol. 43, no. 3, p. 27-32, 38.

Olmstead, D. L., 1982, Oil and gas exploration and development in Oregon, 1981, Oregon Geology, vol. 44, no. 3, p. 27-31.

Pearce, T. H., Gorman, B. E. and Brikett, T. C., 1977, The relationship between major element chemistry and tectonic environment of basic and intermediate volcanic rocks: Earth and Plan. Sci. Let., v. 36, p. 121-132.

Peck, D. L., Griggs, A. B., Schlicker, H. G., Wells, F. G., and Dole, H. M., 1964, Geology of the central and northern parts of the Western Cascade Range in Oregon: U.S. Geol. Survey Prof. Paper 449, 56 p.

Penoyer, P. E., 1977, Geology of the Saddle and Humbug Mountain area, Clatsop County, northwestern Oregon: unpub. M.S. thesis, Oregon State. Univ., Corvallis, 232 p.

Peterson, C. P., 1983, Geology of the Green Mountain-Young's River area, Clatsop County, northwest Oregon: unpub. M.S. thesis in progress, Oregon State Univ., Corvallis.

Pettijohn, F. J., Potter, P. E., and Siever, Raymond, 1973, Sand and sandstone: Springer-Verlag, 618 p.

Pfaff, V. J., 1981, Geophysical and geochemical analyses of selected Miocene coastal basalt features, Clatsop County, Oregon: unpub. M.S. thesis, Portland State University, Portland, 150 p.

Poore, Richard, 1982, Paleontologist, U.S. Geol. Survey, written comm., March 24.

Ragan, B. M., 1973, Structural Geology, an introduction to geometrical techniques, second edition: John Wiley & Sons, 208 p.

Rau, W. W., 1981, Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework - an overview: Geol. Soc. Am. Spec. Pap. 184, p. 67-84.

Reineck, H. E., and Singh, I. B., 1980, Depositional sedimentary environments: with reference to terrigenous clastics: Springer-Verlag, 549 p.

Rock-color Chart Committee, 1970, Rock-color chart: Boulder, Colorado, Geol. Soc. Am.

Schenck, H. G., 1927, Marine Oligocene of Oregon: Univ. Calif. Dept. Geol. Sci. Bull., v. 16, p. 449-460.

Schlicker, H. G., Deacon, R. J., Beaulieu, J. D., and Olcott, G. W., 1972, Environmental geology of the coastal region of Tillamook and Clatsop Counties, Oregon: Ore. Dept. Geol. Min. Ind. Bull. 74, 164 p.

Simpson, R. W. and Cox, Allan, 1977, Paleomagnetic evidence for tectonic rotation fo the Oregon Coast Range: Geol. v. 5, p. 585-589.

Snavely, P. D., Jr. and MacLeod, N. S., 1974, Yachats basalt-an upper Eocene differentiated volcanic sequence in the Oregon Coast Range: Jour. Res. U.S. Geol. Survey, v. 2, no. 4, p. 395-403.

Snavely, P. D. Jr., and MacLeod, N. S., 1977, Evolution of the Eocene continental margin of western Oregon and Washington: Geol. Soc. Am., Abs. Prog. Ann. Meet., Seattle, p. 1183.

Snavely, P. D., Jr., MacLeod, N. S., and Rau, W. W., 1969, Geology of the Newport area, Oregon: The Ore Bin, v. 31, no. 2 and 3, p. 25-71.

Snavely, P. D. , Jr., MacLeod, N. S., and Rau, W. W., 1970, Summary of the Tillamook area, northern Oregon Coast Range: U.S. Geol. Survey Prof. Paper 650-A, p. A47.

Snavely, P. D., Jr., MacLeod, N. S., and Wagner, H. C., 1973, Miocene tholeiitic basalts of coastal Oregon and Washington and their relations to coeval basalts of the Columbia Plateau: Geol. Soc. Am., v. 84, p. 387-424.

Snavely, P. D., Jr. and Wagner, H. C., 1963, Tertiary geologic history of western Oregon and Washington: Wash. Div. Mines and Geol. Rept. Inv. No. 22, 25 p.

________________________, 1964, Geologic sketch of northwestern Oregon: U.S. Geol. Surv. Bull. 1181-M, pp. M1-M17.

Snavely, P. D., Jr. and Wagner, H. C., 1980, Generalized isopach map of Tertiary sedimentary rocks, western Oregon and Washington and adjacent continental margin: U.S. Geol. Survey Open-File Report 80-889, 2 p.

Snavely, P. D., Jr., Wagner, H. C., and Lander, D. L., 1980a, Geologic cross section of the central Oregon continental margin: Geol. Soc. Am. Map and Chart Ser., MC-28j.

________________________________, 1980b, Interpretation of the Cenozoic geologic history, central Oregon continental margin: Cross-section summary: Geol. Soc. Am. Bull., Part I, v. 91, p. 143-146.

Squires, R. L., 1981, A transitional alluvial to marine sequence: The Eocene Llajas Formation, southern California: Jour. Sed. Pet., v. 51, no. 3, pp. 923-938.

Taylor, E. M., 1978, Geology of Southwest Broken Top; Dogami, Sp. Pub.

Taylor, E. M., 1979, Volcanology G554 classnotes, Oregon State University.

Timmons, D. M., 1981, Stratigraphy, lithofacies and depositional environment of the Cowlitz Formation, T. 4 and 5 N., R. 5 W. northwest Oregon: unpub. M.S. thesis, Portland State Univ., Portland, 89 p.

Tolson, P. M., 1976, Geology of the Seaside-Young's River Falls area, Clatsop County: unpub. M.S. thesis Oregon State Univ., Corvallis, 191 p.

Vail, P. R. and Hardenbol, Jan, 1979, Sea level changes during the Tertiary: Oceanus, v. 22, no. 3, p. 71-74.

Vail, P. F., and Hardenbol, Jan, 1979, Sea-level changes during the Tertiary: Oceanus, v. 22, no. 3, p. 71-79.

Van Atta, R. O., 1971, Sedimentary petrology of some Tertiary formations, upper Nehalem River Basin, Oregon: Ph.D. thesis, Oregon State Univ., Corvallis, 245 p.

Warren, W. C., Norbisrath, Hans, and Grivetti, R. M., 1945, Geology of northwestern Oregon west of the Willamette River and north of latitude 45° 15': U.S. Geol. Survey Oil and Gas Invest. Prelim. Map 42.

Warren, W. C., and Norbisrath, Hans, 1946, Stratigraphy of upper Nehalem River Basin, northwestern Oregon: Am. Assoc. Pet. Geol. Bull., v. 30, no. 2, pp. 213-237.

Weaver, C. E., 1912, A preliminary report on the Tertiary paleontology of western Washington: Wash. Geol. Surv. Bull., no. 15, 80 p.

____________________,1916, The Tertiary formations of western Washington: Wash. Geol. Surv. Bull., no. 13, 159 p.

____________________, 1937, Tertiary Stratigraphy of Western Washington and Northwestern Oregon: Wash. Univ. Pub. Geol., v. 4.

Weaver, C. E., and others, 1944, Correlation of the marine Cenozoic formations of western North America: Geol. Soc. Am. Bull., v. 55, p. 569-598.

Wells, F. G., and Peck D. L., 1961, Geologic map of Oregon west of the 121st meridian: U.S. Geol. Survey Misc. Geol. Invest., Map I-325, scale 1:500,000.

Wells, R. E., 1981, Geologic map of the eastern Willapa Hills, Cowlitz, Lewis, Pacific and Wahkiakum Counties, Washington: U.S. Geol. Survey Open file Report 81-674, scale 1:62,500.

Wilkinson, W. D., Lowry, W. D. and Baldwin, E. M. 1946, Geology of the St. Helens quadrangle, Oregon: Oregon Dept. Geol. Min. Ind. Bull. 31, 39 p.

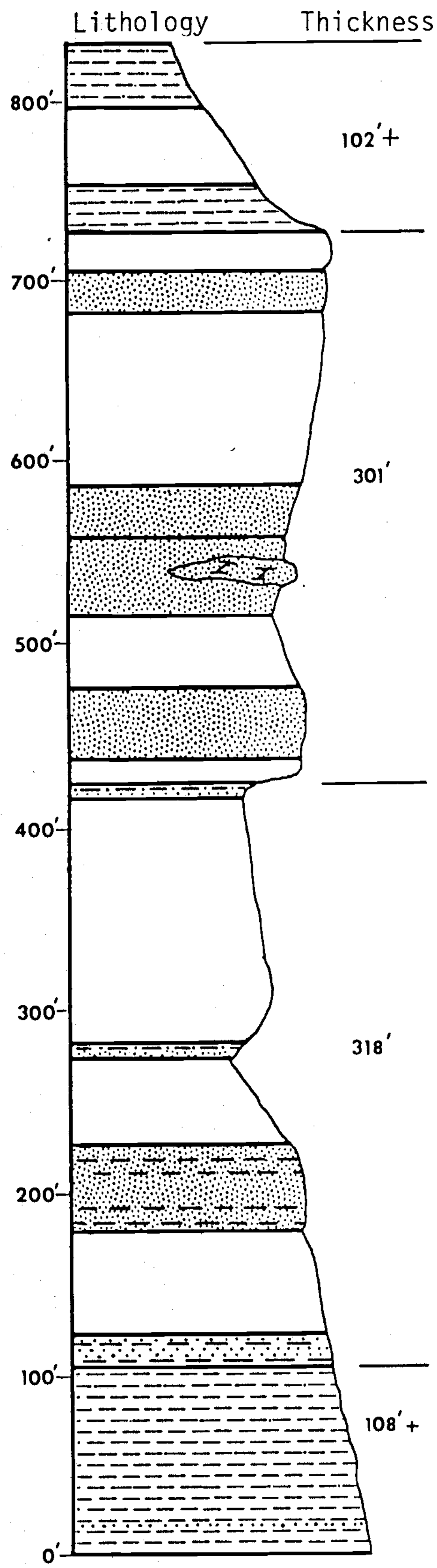
Williams, Howell, Turner, F. J., and Gilbert, C. M., 1954, Petrography: An introduction to the study of rocks in thin sections: W. H. Freeman and Company, 406 p.

Wolfe, E. W., and McKee, E. H., 1968, Geology of the Grays River quadrangle, Wahkiakum and Pacific Counties, Washington: Wash. Div. Mines Geol., Map GM-4, scale 1:62,500.

________________________, 1972, Sedimentary and Igneous rocks of the Grays River Quadrangle: Wash. Geol. Surv. Bull. no. 1335, 70 p.

Yett, J. R., 1979, Eocene foraminifera from the Olequa Creek member of the Cowlitz Formation, southwestern Washington: unpub. M.S. thesis, University of Washington, Seattle, 110 p.

APPENDICES



Description

Medium gray, structureless, slightly silty mudstone.

Light olive gray, structureless, (f. gr.) micaceous silty mudstone.

Dark yellowish orange, thinly laminated with wavy laminations, (med. gr.) v. micaceous, v. c. gr. sandstone. Bioturbated, burrows filled with structureless clean feldspathic sandstone.

Thinly laminated, (med. gr.) micaceous, v. abundant carbonized plant debris along bedding planes, med. gr. feldspathic sandstone.

Dark yellowish orange, structureless, (med. gr.) micaceous, f. to med. gr. sandstone with 4 ft. calcareous concretionary lens. Biotrubated.

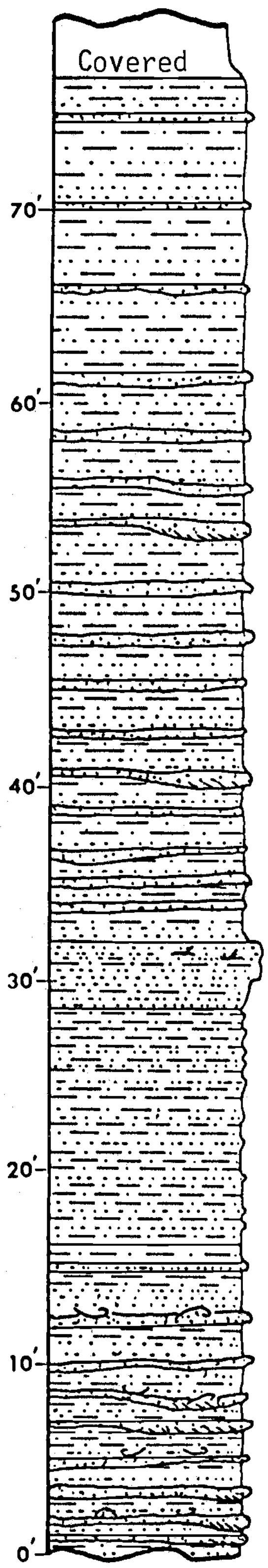
Light olive gray, feldspathic, med. gr. sandstone v. friable.

Pale yellowish orange to dark yellowish orange, thinly laminated, (v.f. gr.) micaceous, v.f. gr. sandstone. Interbedded with light olive gray mudstone to muddy siltstone. Some thin beds of med. gr. feldspathic arkose and lithic arenite.

Foram fossiliferous, small pelecypods, some brown carbonized plant debris, slightly silty in places, dark yellowish orange to pale yellowish orange mudstone. Near base some thinly laminated v.f. gr. sandstone and siltstone.

APPENDIX 1:

Measured section of incomplete Cowlitz Formation, along Wage Road sec. 18-T5N-R6W.



Unit 4

Sandstone/siltstone interbeds: Arkosic sandstone beds: light gray (N7), weathers to dark yellowish orange (10 YR 6/6); fine grained; moderately sorted; planar and some cross-laminations; a few dark gray siltstone laminations; very fossiliferous with crushed and broken pelecypod, gastropod and crab fragments; no bioturbation features; abundant small scale scour-and-fill structures and low relief channeling of sandstone beds into underlying strata; bed thickness ranges from 2 inches to 1 foot with 6 inch beds the most prominent; sandstone beds more common in lower 30 feet.
Siltstone beds: grayish black (N2), weathers to light olive gray (5 Y 6/1); very faintly laminated; slightly fossiliferous; abundant Helminthoida burrows; with very thin laminations of light gray (N7) fine-grained sandstone; a few concretionary beds 1/2 inch thick; bed thickness ranges from 4 inches to 1.5 feet with 6 inch beds most prominent.

Unit 3

Sandstone: Arkosic, micaceous, light gray (N7), weathers to dark yellowish orange (10 YR 6/6); fine-grained; planar laminations; lower 1.5 feet is friable, upper 2 feet is dolomite cemented.

Unit 2

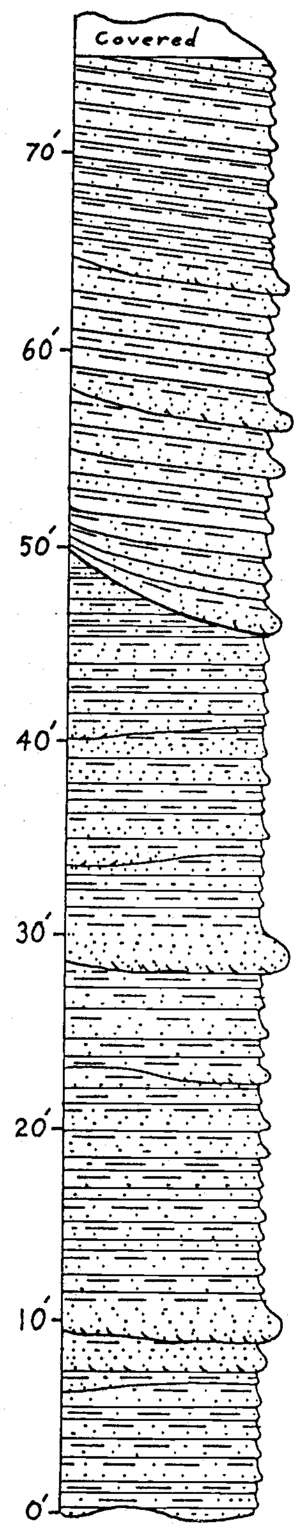
Siltstone: grayish black (N2), weathers to light olive gray (5 Y 6/1); very faintly laminated; slightly fossiliferous; abundant Helminthoida burrows; with thin laminations of light gray (N7) fine-grained sandstones; 1/2 inch concretionary beds every 5 to 8 inches, more abundant than in unit 1.

Unit 1

Sandstone/siltstone (1:1) interbeds: same lithology as unit 4.

APPENDIX 2:

Type Vesper Church formation measured section, 1/4 mile north of the Presbyterian church along Highway 202 in abandoned town of Vesper (sec. 25-T6N-R6W). Outcrop is an eighty foot landslide scarp.



Sandstone/siltstone interbeds: thin; rhythmically bedded; laminated; light gray (N8); fine-grained arkosic sandstone and brownish black (5 YR 2/1) mudstone; micaceous, with large channels (15 to 25 feet) of the same lithology cutting underlying strata producing bedding discordance; carbonaceous material form some laminations in the sandstone; very-fine sandstone laminations in the mudstone; calcareous concretionary sandstone lenses are not laterally extensive, when weathered they show good sedimentary structures; Bouma sequences C, D and E are most common, in thicker sandstone beds Bouma sequences B, C, D and E are seen with C showing convolute and climbing ripple laminations; individual sandstone beds have sharp basal contacts and gradational upper contacts with overlying mudstone bed; mudstone beds have abundant Helminthoida burrows; overall sandstone/siltstone ratio is 1:1.

APPENDIX 3:

Vesper Church reference measured section, 4.25 miles west of the Clatsop/Columbia County line on south side of Highway 202 (sec. 23-T6N-R6W).

APPENDIX 4

Foraminifera Concentration Methods

Method One

1) Dissolve mudstone sample using 1/3 H_2O_2 (Peroxide 30% concentrate) per 2/3 H_2O in beaker on warm hot plate approximately 30 minutes.

2) Wet sieve dissolved sample using 4 phi, 2.5 phi and 1 phi sieves. Most forams are concentrated on the 4 phi sieve.

3) Hand pick forams from the different size fractions under a binocular microscope.

Method Two (The better of the two methods, particularly for samples which will not break down using method one).

1) Place 75-100 grams of sample in a beaker and oven and let dry overnight at 90°C.

2) Cover the sample with Kerosene and let stand for 4 or 5 hours.

3) Decant kerosene carefully, cover with hot water and add 1/2 tablespoon Na_2CO_3.

4) Place beaker with sample on an asbestos pad and heat to just boiling for 3 hours. Do not boil violently.

5) Wet sieve dissolved sample using 4 phi, 2.5 phi and 1 phi sieves. Add small amount of detergent to help wash off kerosene.

6) Hand pick forams from the different size fractions under a binocular microscope.

APPENDIX 5

Smear Slide Preparation

A method described by Dr. John Barron, U.S. Geological Survey, Menlo Park, CA. Preparation time is approximately five minutes per slide. The mounting medium is Piccolyte, manufactured by Wards.

1) Grind up a piece, fingernail size, of the mudstone or siltstone sample with a mortar and pestle, use water to aid grinding. Don't be concerned about breaking microfossils.

2) Use an eye dropper to stir up the water/sample mixture and then allow the large particles to settle out (approximately 15 seconds).

3) Draw up some of the suspended sediment with an eye dropper, and paint a glass cover slip with it. Allow the cover slip to dry on a hot plate. If the coating is too thin, the slide should be repainted.

4) Add a small dab, about the size of a dried split pea, of piccolyte mounting medium on a glass slide, and place the coated cover slip on top. Place this on a hot plate (approximately 400°F). The piccolyte will bubble violently. The volatiles will escape via the edge of the slide. When ½ the bubbles are large (7 mm), place the slide on a cool surface, and position the cover slide with a stick.

This procedure will produce a thin slide of diatom size material concentrated near the objective (50x) when placed under a petrographic microscope. The most diagnostic diatoms are quite small. Larger, broken diatoms are generally not age diagnostic.

APPENDIX 6

Fossil checklist for the Cowlitz Formation

Sample number:	82-3	85-WR#1	810-14	813-2	820-3	825-5	95-6
Brachiopods and mollusks identified by Dr. Ellen Moore, U.S.G.S. (1982)							
Brachiopods							
Terebratalia? sp.	-	-	-	-	X	-	-
Gastropods:							
"Hemipleurotoma?" sp. cf. "H." pulchra (Dickerson)	-	-	-	X	-	-	-
Scaphander sp.	-	-	X	?	-	-	?
Pelecypods:							
Lima (Lima?) sp.	-	-	-	-	X	-	-
Nuculanid?	-	-	X	X	-	-	-
Saccella? sp.	-	-	-	-	-	-	X
Foraminifera identified by Kristin McDougall, U.S.G.S. (1982)							
Bathysiphon eocenica	X	X	-	-	-	-	-
Cyclammina pacifica	X	X	-	-	-	-	-
Cyclammina samanica	X	-	-	-	-	-	-
Fursenkoina bramletti (Galloway and Morrey)	-	X	-	-	-	-	-
Trace fossils identified by Ken Chamberlain, Valero Producing Company, (1982)							
Planolites?	-	-	-	-	-	X	-
Thalassinoids?	-	-	-	-	-	X	-

APPENDIX 7

Fossil checklist for the Keasey and Vesper Church formations

Sample number:	72-5	73-5	73-11	717-5	725-1	725-18	728-12	81-11	83-6	83-10	83-14	96-2	97-4	917-2	924-1	QW-90	QW2910
Mollusks, scaphopods, crabs and crinoids identified by E. Moore (1982)																	
Gastropods:																	
Conomitra? sp.	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–
Naticid (unidentified)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–
Procerapex? sp. cf. P. bentsonae	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–
Svettella? sp.	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–
Turritella sp. cf. T. uvasana washingtoniana Weaver and Palmer	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–
Pelecypods:																	
Acila (Truncacila) sp. cf. A. (T.) nehalamensis Hanna	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–	–
Delectopecten sp.	?	–	–	–	–	?	–	–	–	–	–	–	X	–	–	–	–
Mytilid?	–	–	–	–	–	–	–	–	–	–	–	–	–	–	X	–	–
Portlandia sp.	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–
Scaphopod:																	
Dentalium sp. cf. D. stramineum	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–	–
Crab remains	–	–	–	–	–	–	–	–	–	–	–	X	–	–	–	–	–
Crinoids:																	
Isocrinus? sp.	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–	–	–
unidentified	–	–	–	–	–	–	X	–	–	–	–	–	–	–	–	–	–

Appendix 7 (continued)

Sample number:	72-5	73-5	73-11	717-5	725-1	725-18	728-12	81-11	83-6	83-10	83-14	96-2	97-4	917-2	924-1	QW-90	QW2910
Foraminifera and radiolarians identified by K. McDougall (1982)																	
Anomalina californiensis	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Bolivina kleinpelli	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-
Bolivina pisciformis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Budashevaella multicameratus (Voloshinova)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Cassidulina galvinensis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Cyclammina pacifica	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-
Darbellya sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Dorothia sp. A. of McDougall	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Globobulerina pacifica	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Globocassidulina globosa	-	-	-	-	-	-	-	-	-	-	-	X	-	X	-	-	-
Gyroidina soldanii	-	-	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-
Lenticulina crassa (d'Orbigny)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Nodosaria longiscata	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Nodosaria pyrula	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Oridorsalis umbonatus (Reuss)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Plectofrondicularia packardi	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Praeglobobulimina pupoides (d'Orbigny)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Quinqueloculina imperialis	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Stiloctomella adolphina (d'Orbigny)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Uvigerina atwilli	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Radiolarians	-	-	-	-	-	-	-	-	-	X	-	-	-	X	X	-	-

Appendix 7 (continued)

Sample number:	72-5	73-5	73-11	717-5	725-1	725-18	728-12	81-11	83-6	83-10	83-14	96-2	97-4	917-2	924-1	QW-90	QW2910
Trace fossils identified by K. Chamberlain (1982)																	
Helminthoida	-	-	-	-	-	-	X	-	-	-	-	X	-	-	-	-	-
Tomaculum	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yokoia kattoi	-	-	X	-	-	-	-	-	-	-	-	X	-	-	-	-	-

APPENDIX 8

Fossil checklist for the Pittsburg Bluff Formation

Sample number:	713-4	713-6	713-7	713-11	713-12	713-16	716-3	716-9	730-6	730-7	730-9	1017-2
Mollusks												
identified by E. Moore (1982)												
Gastropods:												
Eosiphonalia? sp.	-	-	-	-	-	-	X	-	-	-	-	-
Perse pittsburgensis Durham	-	-	-	-	-	-	-	-	-	-	-	X
Perse? sp.	-	-	-	-	-	-	-	X	-	-	-	-
Priscofusus? sp.	-	-	-	-	-	-	-	-	-	X	-	-
Pelecypods:												
Acila (Truncacila) nehalamensis Hanna	-	-	-	-	-	-	-	-	-	-	X	-
Cardiid unidentified	-	-	-	-	-	-	-	-	-	X	-	-
Cardiid?	X	-	-	-	-	-	-	-	-	-	-	-
Clinocardium? sp.	-	-	-	-	-	-	-	-	-	-	-	X
Litorhadia washingtonensis (Weaver)	-	-	-	-	-	X	-	-	-	X	-	-
Litorhadia? sp.	-	-	-	-	-	-	-	-	-	-	-	X
Lucinoma sp. cf. *L. columbiana* (Clark and Arnold)	-	-	-	X	-	-	-	-	-	-	-	-
Lucinoma? sp.	-	-	-	-	-	-	-	-	X	-	-	-
Nemocardium (Keenaea)? sp. cf. *N. (K.) lorenzanum* (Arnold)	-	-	-	-	-	-	-	-	X	-	-	-
Pitar (Pitar)? sp. cf. *P. (P.) dalli* (Weaver)	-	X	X	-	-	-	-	-	-	-	-	-
Pitar? sp.	-	-	-	X	-	-	-	-	-	-	-	-
Thracia sp. cf. *T. (T.) condoni* Dall	-	-	-	-	-	-	-	-	-	X	-	-

Appendix 8 (continued)

Sample number:	713-4	713-6	713-7	713-11	713-12	713-16	716-3	716-9	730-6	730-7	730-9	1017-2
Barnacles (unidentified)	-	-	-	-	-	-	-	-	-	-	-	X
Foraminifera identified by K. McDougall (1982)												
Cyclammina pacifica	-	-	-	-	X	-	-	-	-	-	-	-
Trace fossils identified by K. Chamberlain (1982)												
Toredo	-	-	X	-	-	-	-	-	-	-	-	-

APPENDIX 9

Checklist of calcareous nannofossils from the study area and Quintana Watzek 30-1 well.

Sample number:	79-3	96-2	QW-90	QW-1200	QW-1290	QW-3870	QW-4020	QW-4140	QW-4290	QW-4830	QW-5310	QW-6420	QW-6630	QW-6930
Braarudosphaera Bigelowi	-	X	-	-	-	X	-	X	-	X	X	X	-	X
Coccolithus Formosus	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Coccolithus Pelagicus	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Dictyococcites Bisectus	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Dictyococcites Daviesi	-	-	-	-	-	-	X	X	X	X	X	X	-	X
Discoaster sp.	-	-	-	-	-	-	X	-	-	-	-	-	-	-
Helicosphaera Compacta	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Isthmolithus Recurvus	-	X	-	-	-	-	-	-	-	-	X	-	X	-
Pemma Basquense	-	-	-	-	-	-	X	-	-	-	-	-	-	-
Reticulofenestra Bisecta	-	-	-	-	-	-	X	-	-	-	-	-	-	-
Reticulofenestra Callida	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Reticulofenestra Reticulata	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Reticulofenestra Scrippsae	-	-	-	-	-	-	X	X	X	-	X	X	-	X
Rhabdosphaera sp.	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Sphenolithus	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Transversopontis sp. cf. T. Obliquipons	X	-	X	X	X	-	-	-	-	-	-	-	-	-

APPENDIX 10

Fossil Sample Locations
(also shown on Plate I)

Sample no.	Map Unit	Location sec.	T. N.	R. W.	1/4 sec.
72-5	Vesper Ch. (Tvc)	26	6	6	c
73-5	" " "	34	6	6	e1/4 e1/2 sw
73-11	" " "	27	6	6	s1/2 se
78-1	" " "	21	6	6	ne ne ne se
79-3	" " "	23	6	6	w1/3 sw
713-4	Pitts. Bluff (Tpb_1)	13	6	7	n1/2 n1/2 n1/2 ne
713-6	" " "	13	6	7	nw1/4 nw
713-7	" " "	13	6	7	nw nw nw
713-11	" " "	13	6	7	w1/2 w1/2
713-12	" " (Tpb_2)	13	6	7	nw sw
713-16	" " (Tpb_1)	24	6	7	n1/2 ne nw
716-3	" " "	19	6	6	n1/2
716-9	" " "	18	6	6	nw
717-5	Keasey (Tk)	18	5	6	w w w w
725-1	" "	1	5	7	n n sw sw
725-18	Vesper Ch. (Tvc)	36	6	7	n e e
728-12	" " "	5	5	6	se se se se
730-6	Pitts. Bluff (Tpb_1)	13	6	6	nw
730-7	" " "	14	6	6	ne ne ne ne
730-9	" " "	14	6	6	ne ne ne ne
81-11	Keasey (Tk)	14	5	6	w1/4 sw

Appendix 10 -- continued

Sample no.	Map Unit	Location sec.	T. N.	R. W.	1/4 sec.
82-3	Cowlitz (Tc_4)	18	5	6	sw sw se se
83-6	Keasey (Tk)	15	5	6	nw se ne
83-10	" "	15	5	6	e e ne sw
83-14	Vesper Ch. (Tvc)	16	5	6	s se ne
85-WR	Cowlitz (Tc_3)	18	5	6	sw se se se
810-14	" (Tc_2)	22	5	6	n sw
813-2	" "	22	5	6	nw ne nw se
820-3	" (Tc_1)	30	5	6	nw nw
825-5	" (Tc_5)	24	5	6	se nw
96-2	Vesper Ch. (Tvc)	25	6	6	n n n ne
97-4	Keasey (Tk)	18	5	6	n e e e
917-2	Vesper Ch. (Tvc)	13	6	6	w w sw sw
924-1	" " "	13	5	6	e ne
1017-2	Pitts. Bluff (Tpb_1)	18	6	6	se ne ne ne

APPENDIX 11

Sample Localities Mentioned in Text
(also shown on Plate I)

Sample no.	Map Unit	Location sec.	T. N.	R. W.	1/4 sec.
71-9	Pitts. Bluff (Tpb_1)	17	6	6	wl/2 sw
71-11	" " "	17	6	6	e e e
78-5	Vesper Ch. (Tvc)	22	6	6	se nw ne
710-2	" " "	4	5	6	el/2 el/2 ne se
711-6	" " "	32	6	6	ne sw
713-5	Pitts. Bluff (Tpb_2)	13	6	7	w nl/2 nl/2
713-7	" " (Tpb_1)	13	6	7	nw nw nw
713-12	" " (Tpb_2)	13	6	7	nw sw
713-16	" " (Tpb_1)	24	6	7	nl/2 ne nw
715-4	Vesper Ch. (Tvc)	3	5	6	sw sw
715-13	Pitts. Bluff (Tpb_1)	19	6	6	nw sw
723-3	Vesper Ch. (Tvc)	21	6	6	ne sw sw
725-4	" " "	1	5	7	se ne
725-5	" " "	1	5	7	se ne nw
725-16	" " "	36	6	7	s ne
727-4	Cowlitz (Tc_5)	18	5	6	nw sw sw
728-7	Keasey (Tk)	17	5	6	ne nw ne
730-7	Pitts. Bluff (Tpb_1)	14	6	6	ne ne ne ne
730-8	" " "	11	6	6	sl/2 sl/2 se
730-9	" " "	14	6	6	n n n n
81-10	Keasey (Tk)	14	5	6	w ne ne

Appendix 11 -- continued

Sample no.	Map Unit	Location sec.	T. N.	R. W.	1/4 sec.
83-6	Keasey (Tk)	15	5	6	nw se ne
83-10	" "	15	5	6	e e ne sw
86-1	Cowlitz (Tc_2)	19	5	6	sw sw sw sw
87-4	" (Tc_5)	17	5	6	c sw
87-5	" "	17	5	6	c sw
88-14	" (Tc_2)	21	5	6	ne sw
810-7	Keasey (Tk)	13	5	6	s s ne ne
810-14	Cowlitz (Tc_2)	22	5	6	n sw
813-1	" "	22	5	6	nw sw
813-2	" "	22	5	6	nw ne nw se
813-6	" (Tc_5)	23	5	6	c
820-8	" (Tc_1)	30	5	6	n n n sw
820-9	" "	30	5	6	ne ne ne sw
820-11	Tillamook Vol. (Ttv_1)	30	5	6	se
822-11	" " "	29	5	6	e nw
822-12	" " "	29	5	6	sw ne se ne
824-2	" " "	27	5	6	s s se se
825-5	Cowlitz (Tc_5)	24	5	6	se nw
825-7	" "	24	5	6	w1/4
91-12	Vesper Ch. (Tvc)	24	6	6	nw nw nw
93-5	Tillamook Vol. (Ttv_2)	28	5	6	e e se
93-11	Cowlitz (Tc_3)	27	5	6	s s ne
95-3	" "	27	5	6	n n n w

Appendix 11 -- continued

Sample no.	Map Unit	Location sec.	T. N.	R. W.	1/4 sec.
95-6	Tillamook Vol. (Ttv_1)	26	5	6	e se
97-4	Keasey (Tk_1)	18	5	6	n e e e
917-12	Vesper Ch. (Tvc)	22	6	6	nw se
918-1	" " "	22	6	6	e1/3
924-8	Cowlitz (Tc_5)	18 (Columbia Co.)	5	5	sw sw sw sw

APPENDIX 12

Heavy Mineral (H) and Thin Section (T) Sample Locations (also shown on Plate I)

Sample no.	Map Unit			Location sec.	T. N.	R. W.	1/4 sec.
78-5	Vesper Ch.	T		22	6	6	se nw ne
713-14	Pitts. Bluff	T	H	13	6	7	sw
717-5	Keasey	T		18	5	6	s nw nw nw
724-6	Pitts. Bluff		H	20	6	6	sw nw
725-16	Vesper Ch.		H	36	6	7	s ne
728-7	Keasey	T		17	5	6	ne nw ne
81-10	Keasey	T	H	14	5	6	w ne ne
83-14	Vesper Ch.	T		16	5	6	s se ne
85-WR	Cowlitz	T	H	18	5	6	sw se se se
88-14	Cowlitz	T		21	5	6	ne sw
813-1	Cowlitz	T		22	5	6	nw sw
813-4	Cowlitz	T	H	22	5	6	s ne se ne
813-10	Cowlitz		H	24	5	6	n1/4
825-7	Cowlitz		H	24	5	6	w1/4
93-5	Cowlitz	T		28	5	6	e e se
917-12	Vesper Ch.	T		22	6	6	nw se
A-3150	Cowlitz	T	H	3150' from KB in Adams 24-34 well in Mist gas field, Columbia County (sec. 34-T7N-R5W).			
QW-4980	Cowlitz	T	H	Samples from 4980' and 6550' respectively in the Quintana Watzek 30-1 well (sec. 30-T6N-R6W).			
QW-6550	Cowlitz	T	H				

Appendix 12 -- continued

Sample no.	Map Unit		Location			1/4 sec.
			sec.	T. N.	R. W.	
628-2	Depoe Bay	T	36	6	6	e e ne ne
71-1	" "	T	16	6	6	ne nw nw
713-7	" "	T	13	6	7	nw nw nw
723-9	" "	T	20	6	6	n1/2 n1/2 n1/2
822-11	Tillamook Vol.	T	29	5	6	e nw
822-12	" "	T	29	5	6	sw ne se ne
822-14	" "	T	29	5	6	s se
822-15	" "	T	29	5	6	e1/4 se
824-2	" "	T	27	5	6	s s se se
93-7	" "	T	27	5	6	n nw sw
95-6	" "	T	26	5	6	e se
95-7	" "	T	25	5	6	s s s sw
1017-1	Depoe Bay	T	36	6	7	se se se

APPENDIX 13

Major Oxide Values[1] for Basalts in the Buster Creek-Nehalem Valley Area

Plot No.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total %
1	54.40	14.47	1.88	5.77	6.61	0.19	8.06	4.15	1.10	3.04	0.34	100.01
2	55.30	14.03	2.17	6.06	6.95	0.18	6.85	3.19	1.71	3.17	0.39	100
3	55.16	14.19	2.14	5.87	6.72	0.18	6.97	3.25	1.75	3.40	0.37	100
4	55.40	14.66	2.10	5.84	6.69	0.19	6.67	3.40	1.73	2.95	0.36	99.99
5	55.21	13.89	2.12	6.04	6.92	0.18	6.80	3.37	1.71	3.38	0.37	99.99
6	55.19	14.57	2.10	5.82	6.67	0.18	6.80	3.30	1.74	3.26	0.37	100
7	56.19	13.89	2.20	6.06	6.94	0.18	6.90	3.19	0.84	3.20	0.39	99.98
8	55.62	14.58	2.12	5.91	6.76	0.18	6.79	3.44	1.07	3.16	0.36	99.99
9	54.19	16.72	2.34	4.85	5.55	0.18	7.20	2.18	1.70	4.25	0.77	99.93
10	54.81	16.80	2.27	4.65	5.32	0.18	7.06	2.19	1.85	4.13	0.75	100.01
11	54.48	17.60	1.93	4.25	4.87	0.19	6.60	1.91	3.24	4.21	0.72	100
12	64.77	16.20	0.79	3.29	3.77	0.12	2.72	0.93	2.10	5.12	0.18	99.99
13	55.67	17.10	2.25	4.43	5.07	0.19	6.64	1.92	1.68	4.26	0.78	99.99

Appendix 13 -- continued

Plot No.	Outcrop No.	Field Location		Formation	
1	713-7	13-6N-7W	nw nw nw	Depoe Bay dike High MgO	
2	628-2	36-6N-6W	se ne ne		
3	71-1	16-6N-6W	ne nw nw		
4	716-17	30-6N-7W	n1/8 w		Northrup Creek dike
5	716-19	31-6N-6W	nw	Depoe Bay dikes Low MgO, high TiO_2	
6	723-9	20-6N-6W	n1/2 n1/2 n1/2		
7	726-8	36-6N-7W	e e e e		
8	1017-1	36-6N-7W	se se s s		
9	822-11	29-5N-6W	e nw		
10	822-12	29-5N-6W	sw ne se ne		
11	822-14	29-5N-6W	s se	Tillamook Volcanics (flows)	
12	824-2	27-5N-6W	s s se se		
13	95-7	25-5N-6W	s s s sw		

[1] Analyses by Dr. Peter Hooper, Washington State University Dept. of Geology, using international basalt standard.

APPENDIX 14

Major Oxide Values[1] for Basalts from the Quintana "Watzek" 30-1 well, located in section 30-T6N-R6W.

Plot No.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total %
14	55.96	13.90	2.25	5.58	6.39	0.18	6.72	3.27	1.83	3.55	0.37	100
15	54.83	19.69	1.05	3.32	3.81	0.11	8.45	3.26	0.86	4.39	0.22	99.99
16	54.84	13.78	1.88	5.73	6.56	0.21	8.15	4.27	1.08	3.17	0.33	100
17	55.57	14.90	2.03	2.00	10.13	0.19	7.00	3.64	1.73	2.49	0.32	100

Plot No.	Depth from KB (in feet)	Formation
14	2820	Depoe Bay "Low MgO-high TiO_2"
15	4560	Micro Gabbro highly altered
16	5250	Depoe Bay "High MgO"
17[2]	3540	Depoe Bay "Low MgO-low TiO_2"

[1]Analyses by Dr. Peter Hooper, Washington State University Dept. of Geology, using international basalt standard.

[2]This sample from Coalen (1982, unpublished data).

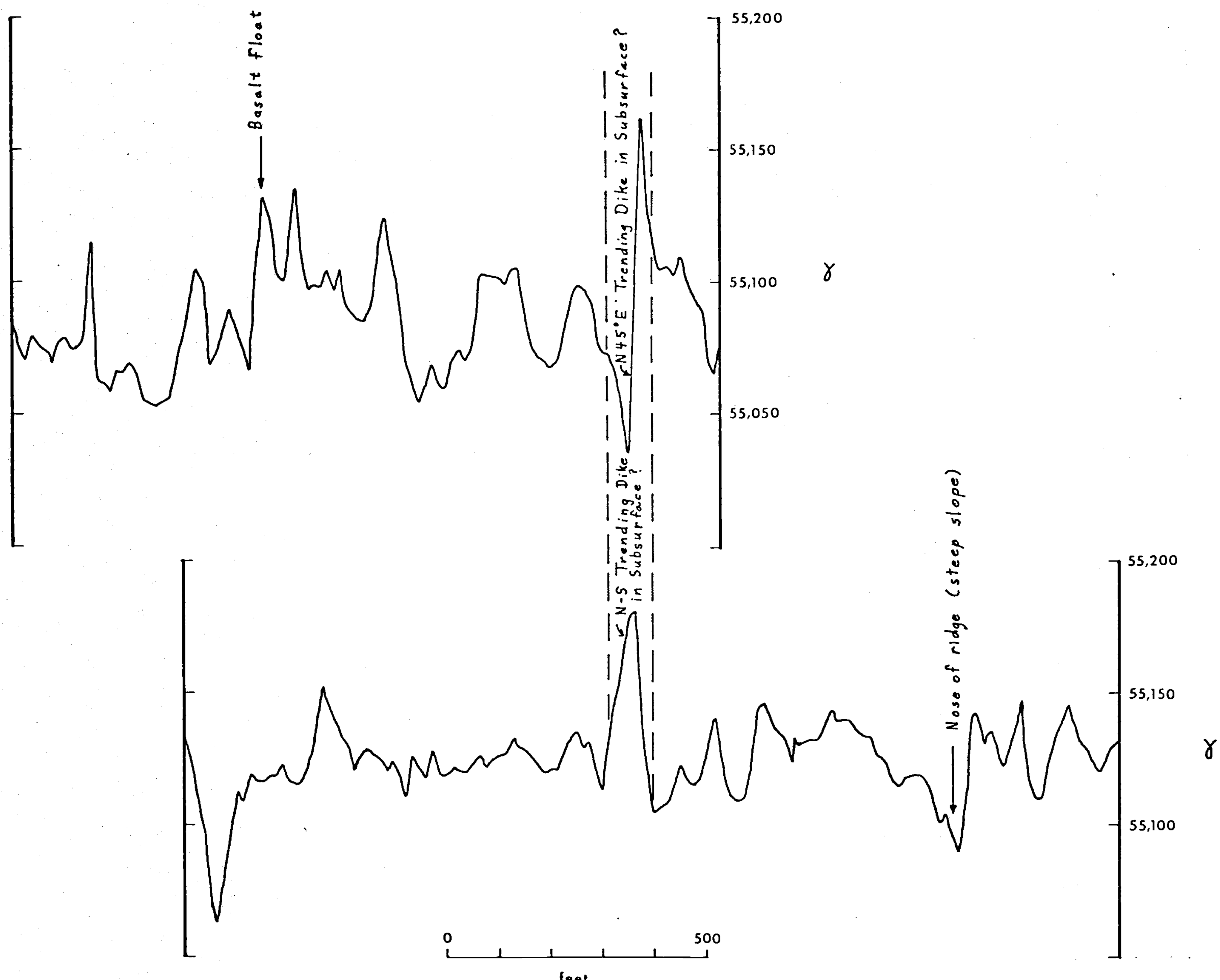
APPENDIX 15: Source Rock Analyses[1]

Sample Number	% TOC	V.R. % RO	Visual Kerogen Type	Kerogen Type Oil/Gas	Generation Rating	Stage of Diagenesis	Formation
83-14-5	1.3	0.46	Structured	Gas	Good	Pre-generation	Vesper Church formation
96-2-2	2.3	0.44	Structured	Gas	Very good	Pre-generation	Vesper Church formation

Sample	Location
83-14-5	s se ne S16-T6N-R6W
96-2-2	n n n ne S25-T6N-R6W

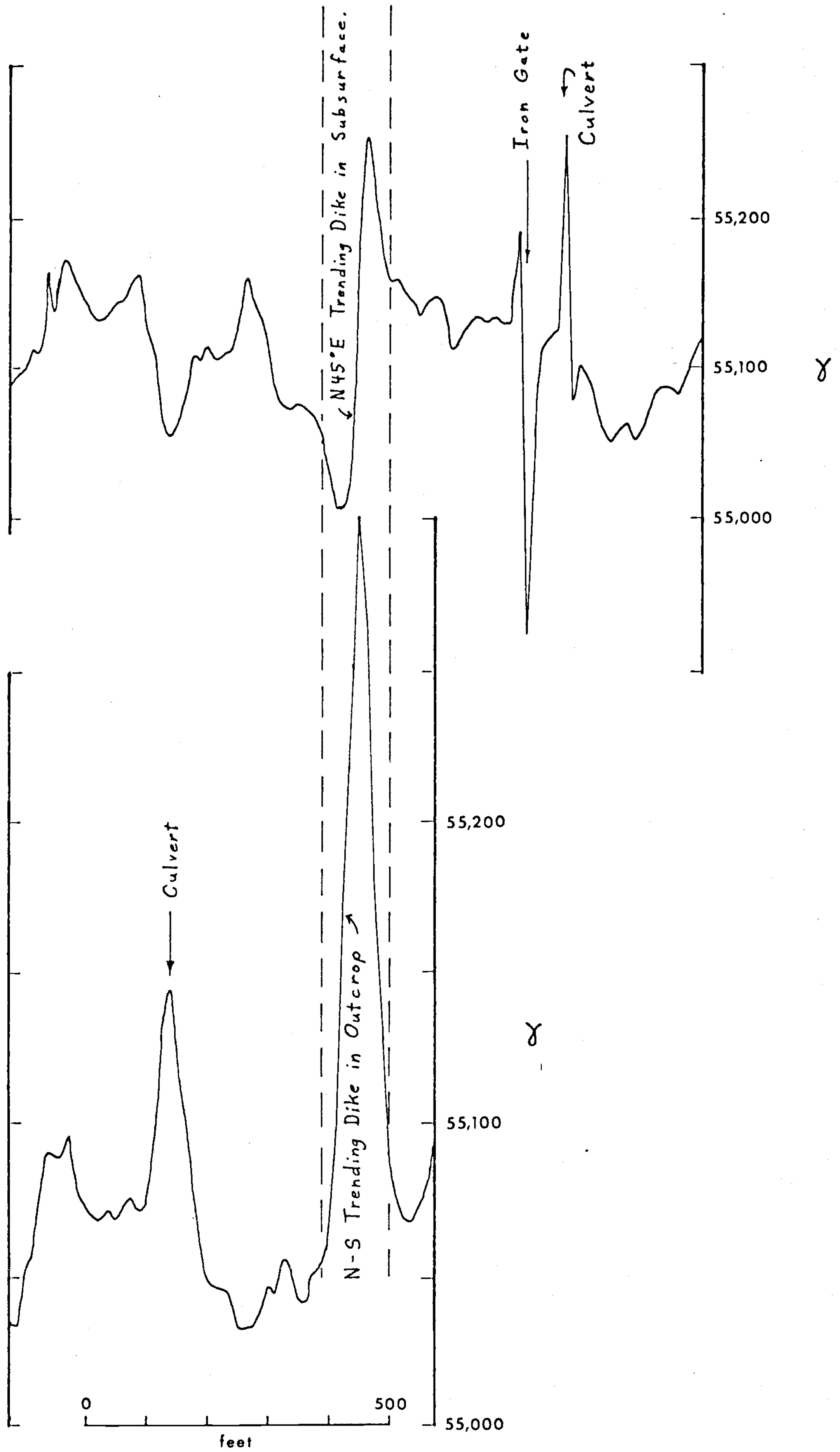
Two additional samples from the Cowlitz Formation were submitted for porosity and permeability analysis but disintegrated during sample preparation. These sandstones were very friable and in hand examination appeared to have excellent porosity and permeability.

[1] Source rock and reservoir rock analyses were made by Amoco Production Company, Denver, (Terry E. Mitchell, 1982, written communication).



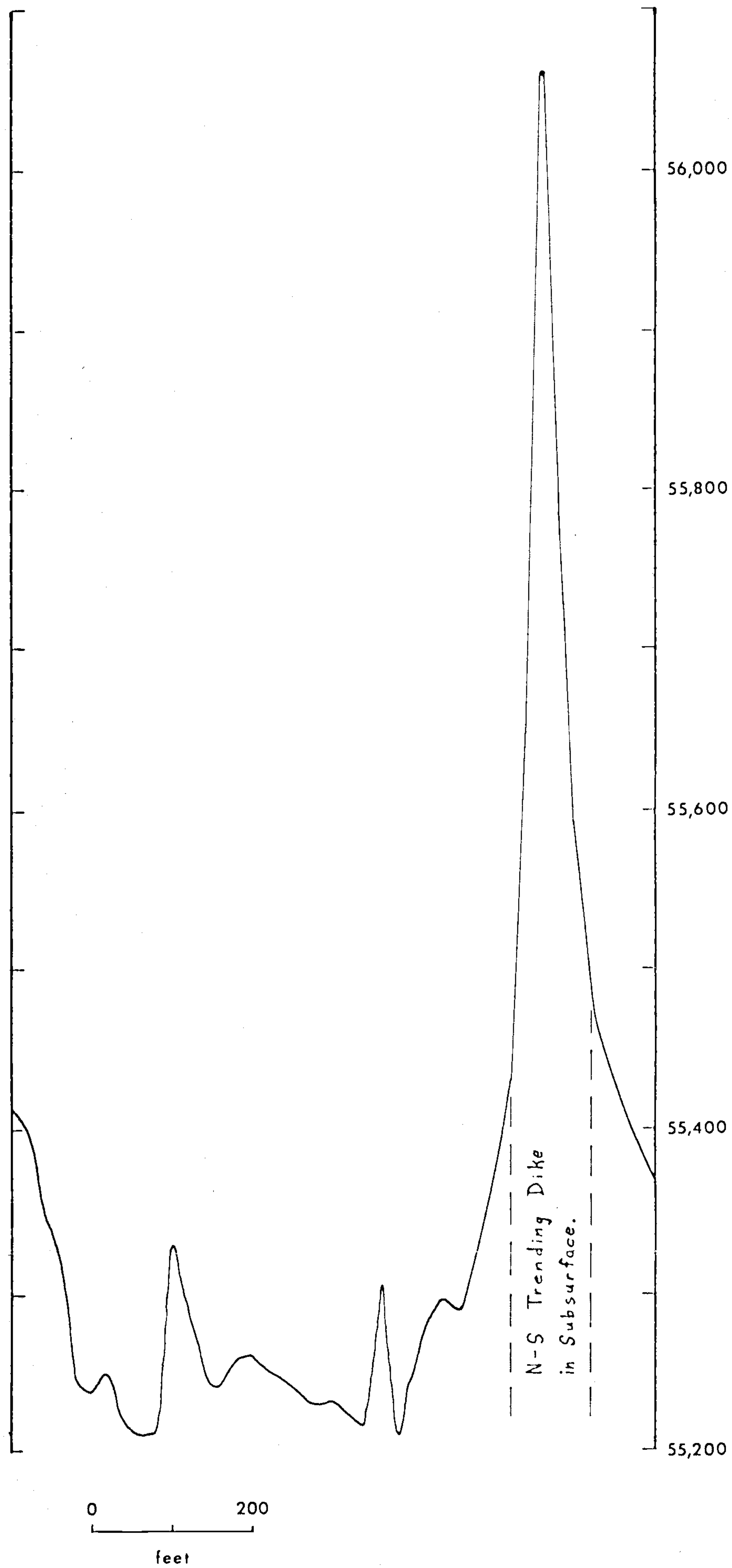
APPENDIX 16:

Magnetometer traverses. Traverse IX (top) is located in e nw sec. 1-T5N-R7W. Traverse I (bottom) is located in ne sw sec. 1-T5N-R7W.



Appendix 16 -- continued

Magnetometer traverses III and IV across Northrup Creek dike. Traverse IV (top) is in sw sec. 30-T6N-R6W. Traverse III (bottom) is in s s se sec. 36-T6N-R7W.



Appendix 16 -- continued

East to west magnetometer traverse number 5 in nw sw sec. 13-T6N-R7W.