AN ABSTRACT OF THE THESIS OF

David Ezra Nelson for the degree of Master of Science in Geology presented on March 19, 1985

Title: Geology of the Fishhawk Falls - Jewell Area, Clatsop County, Northwest Oregon

Abstract approved: Redacted for privacy

Dr. Alan R. Niem, Thesis advisor

The study area is located on the NW flank of the northern Oregon Coast Range. Seven Tertiary formations compose the bedrock units: the Tillamook Volcanics, the Cowlitz, Keasey and Pittsburg Bluff formations, Oswald West mudstone (informal), Astoria Formation (Silver Point member), and Grande Ronde (Depoe Bay) Basalt of the Columbia River Group.

Major element geochemistry, petrology, and radiometric ages of volcanic rocks near Green Mountain suggest that this is an upthrown tectonic block of middle to upper Eocene Tillamook Volcanics. This outlier is composed of subaerial basaltic andesite flows and epiclastic debris flows which are intruded by complexes of basaltic andesite dikes. The volcanics typically contain 58-62% SiO_2 and reflect a rugged stratovolcano or mid-ocean island that rose above sea level. Radiometric dates from the uppermost part of the upper Tillamook Volcanics in and near this study area are from 37.1 $\pm$ 0.4 m.y. (late middle Eocene) to 42.4 $\pm$ 0.5 m.y. (early late Eocene). Preliminary paleomagnetic investigation of three sites in the Tillamook Volcanics and overlying Cougar Mountain intrusions indicates that

48.4 ± 26° of clockwise rotation has occurred since the late middle Eocene.

The middle to upper Eocene (Narizian) Cowlitz Formation overlies the Tillamook Volcanics w th angular unconformity in the study area. The Cowlitz is an onlapping marine sequence of basaltic and arkosic sandstone and deep-marine turbidite sandstone overlain by a regressive sequence of arkosic sandstone. Four lithofacies are considered informal members of the 465-m-thick Cowlitz Formation. These are: a basal fluvial-littoral basaltic andesite conglomerate (Tc_1), a lower shallow-marine sandstone composed of intrabasinal basaltic sandstone and extrabasinal micaceous arkosic sandstone and mudstone (Tc_2), a thin turbidite sandstone and siltstone unit (Tc_3), and an upper shallow-marine arkosic sandstone (Tc_4). The lower sandstones are volcanic arenites derived locally from the Tillamook Volcanics. They are interbedded with micaceous plagi clase-bearing arkosic sandstone redistributed from the Cowlitz delta of southwestern Washington via longshore drift. The friable arkosic upper sandstone member may be correlative to the "Clark and Wilson" reservoir sandstone in the Mist gas field.

The Cowlitz Formation is overlain by the 1,640-2,050-m-thick upper Narizian to Refugian Keasey Formation. Three mappable lithofacies of the Keasey are defined as informal members based on lithology and biostratigraphy. The tuffaceous Jewell mudstone forms the lower member of the Keasey Formation. It contains foram and coccolith assemblages that correlate to the *Valvulineria tumeyensis* Zone of California of Donnelly (1976). The middle member is the Vesper Church member which is late Refugian in age. This well-bedded to laminated graded sandstone and mudstone unit was deposited in ested slope channels by turbidites as micaceous arkosic Cowlitz sands and muds were redistributed offshore. The thick-bedded, structureless tuffaceous upper mudstone member is upper Refugian and contains Foraminifera equivalent to the *Uvigerina vicksburgensis* Zone of California. Foraminifera paleoecology suggests that the three members were deposited in upper bathyal depths.

The upper Eocene to Oligocene (upper Refugian to Zemorrian) 200-500-m-thick Pittsburg Bluff Formation disconformably overlies the Keasey Formation. The thick-bedded tuffaceous to arkosic Pittsburg Bluff sandstones were deposited in a shallow-marine inner to middle shelf environment. Local uplift and/or eustatic sea level fall (corresponding to the end of cycle TE3 of Vail and Hardenbol, 1979) combined to cause a late Eocene marine regression and disconformity at the base of the Pittsburg Bluff Formation.

The mollusc-rich bioturbated Pittsburg Bluff sandstone and the overlying tuffaceous Oswald West deep-marine mudstone are, in part, coeval facies that represent inner to middle shelf sands and an adjacent deep-water outer shelf-upper slope depositional environment, respectively. An Oligocene marine transgression corresponding to Vail and Hardenbol's cycle TO1 eventually caused onlap of Oswald West slope muds over inner shelf Pittsburg Bluff sands. The Oswald West is Oligocene (Zemorrian) in age in the thesis area but is as young as lower Miocene (Saucesian) in western Clatsop County. The deep-marine lower Miocene to middle Miocene Silver Point mudstone and the turbidite sandstones of the Astoria Formation overlie the Oswald West mudstones with minor unconformity.

The sedimentary strata of the thesis area were intruded by several dikes and sills of middle Miocene tholeiitic basalt. Principal among the intrusions are three extensive dikes (Beneke, Fishhawk Falls, and Northrup Creek) composed of low-MgO-high-TiO_2 and low-MgO-low-TiO_2 basalt. These subparallel NE-trending dikes are 10 to 20 km long and are geochemically and magnetically correlative to low-MgO-high-TiO_2 and low-MgO-low-TiO_2 subaerial flows of the Grande Ronde Basalt that are exposed 6.5 km NE of the thesis area near Nicolai Mountain and Porter Ridge. This correlation supports the hypothesis of Beeson and others (1979) that these intrusions were formed by "invasive" flows of Columbia River Basalt. The dikes and flows represent the R2 and N2 magnetozones. Paleomagnetic results and detailed mapping along the three major dikes indicate that the dikes are cut into many small blocks by NE-trending dextral and NW-trending sinistral faults. Oblique slip along these faults may have rotated these small blocks clockwise from the expected middle Miocene declination. One such fault-bounded block in Beneke quarry has been rotated 11° clockwise relative to other blocks in the quarry.

The area has apparently undergone four periods of structural deformation. Late Eocene deformation produced normal faults and a highly faulted anticline in the Cowlitz, Keasey and Pittsburg Bluff formations. Uplift of the Oregon Coast Range commenced during the Oligocene. NW-SE extension in the middle Miocene permitted intrusion of the NE-trending dikes, perhaps along pre-existing faults or joints. Post-middle Miocene N-S compression produced a conjugate shear couplet of dextral NW-trending and sinistral NE-trending oblique-slip faults and associated E-W thrust faults. These may compose a 20-km-wide zone of distributed shear between the Oregon Coast Range tectonic block and the smaller tectonic blocks of SW Washington (Wells, 1981). These post-middle Miocene faults may be related to wrench tectonics and NW-trending dextral slip faults observed on the Columbia Plateau. They may have formed sympathetically to regional right-lateral wrenching of the North American plate by oblique subduction of the Juan de Fuca plate and/or extensional opening of the Basin and Range province (Magill and others, 1982).

The north-central and eastern parts of the study area hold the greatest potential for natural gas accumulation in the permeable upper Cowlitz sandstones (Tc_4) that may be correlative to the "Clark and Wilson" sand. Mapping of the limited outcrops of this potential reservoir suggests that the unit may pinch out to the west. It is overlain by Keasey mudstones that could form cap rock. A highly faulted NW-trending antiform in the subsurface, postulated from surface mapping, represents the best structural trap in the area if the reservoir sands are not breached by faulting.

GEOLOGY OF THE FISHHAWK FALLS - JEWELL AREA, CLATSOP COUNTY, NORTHWEST OREGON

by

David Ezra Nelson

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Frontispiece: Aerial view looking southwest across the Fishhawk Falls - Jewell area. The quarry in the foreground is the Beneke Quarry located on the Beneke dike trend which forms three hillocks in the foreground, middle ground (Boiler Ridge) and background (Flagpole Ridge). The peak on the far right is Saddle Mountain. The highlands in the background are Humbug and Sugarloaf Mountains, Kidders Butte and Onion Peak, all Miocene submarine basalt volcanos.

GEOLOGY OF THE FISHHAWK FALLS - JEWELL AREA, CLATSOP COUNTY, NORTHWEST OREGON

INTRODUCTION

Purpose of Investigation

The purposes of this thesis study are:

1. to produce a geologic map of the Fishhawk Falls - Jewell area (scale 1:31,680) and to determine the structural and stratigraphic relations of the Tertiary sedimentary and volcanic rock units;
2. to describe the facies and interpret the depositional environments, paleocurrent dispersal patterns, geometries and provenances of the gas-producing middle to upper Eocene Cowlitz Formation, the overlying upper Eocene to lower Miocene Keasey, Pittsburg Bluff and Oswald West formations;
3. to determine the origin of middle Miocene basalt dikes that occur in the thesis area;
4. to measure the paleomagnetic directions and evaluate the possibility of tectonic rotation and origin of the upper Eocene Tillamook Volcanics in this area. The significance of this rotation relative to other Coast Range paleomagnetic studies is considered;
5. to estimate the petroleum source rock and reservoir potential of sedimentary rocks in the thesis area using surface mapping, subsurface correlations, and laboratory analyses of total organic carbon, porosity and permeability.

Location and Accessibility

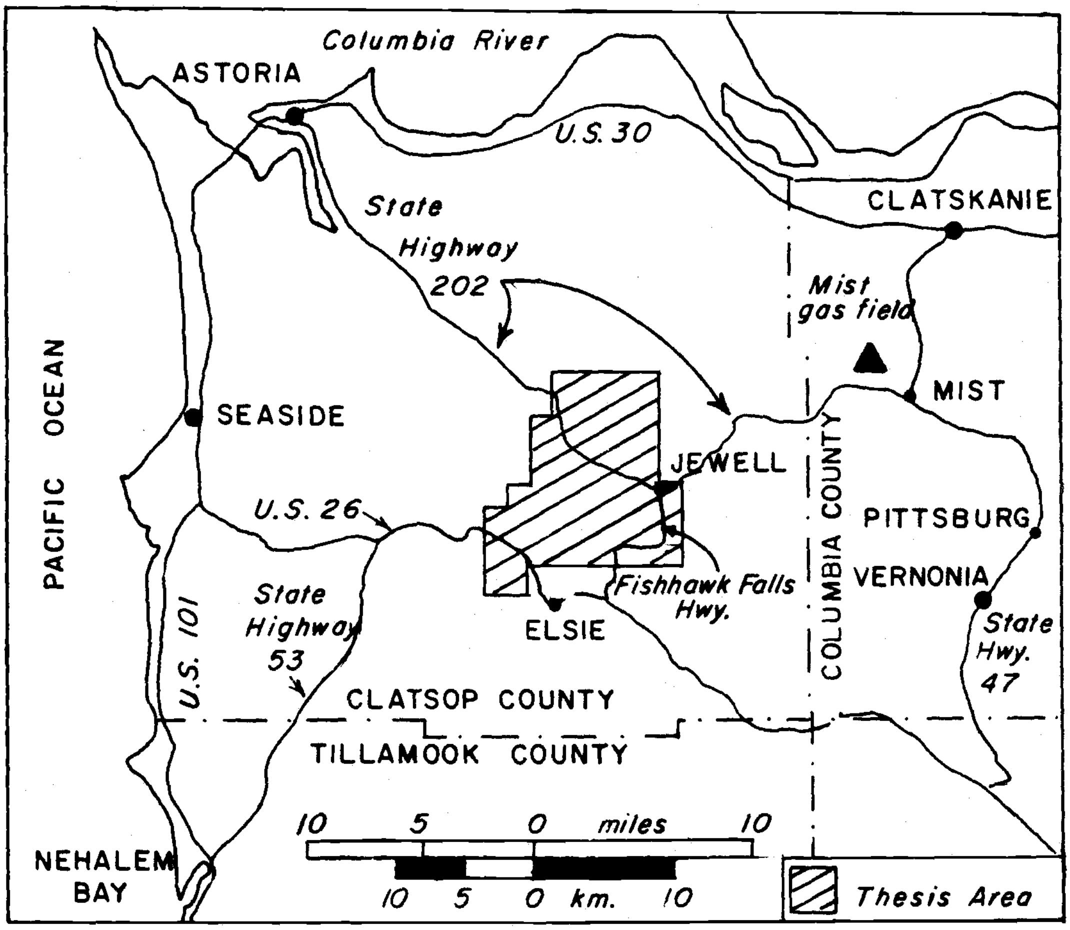
The thesis area is located in Clatsop County approximately 72 km west of Portland and 40 km southeast of Astoria, Oregon (Fig. 1). The 168 square kilometer area is included on parts of four 15-minute U. S. Geological Survey maps (Birkenfeld, Cathlamet, Saddle Mountain, and Svensen Quadrangles). It lies between latitudes 45° 53' and 46° 00' N. and longitudes 123° 29' and 123° 40' W.

Access is provided by U. S. Highway 26, which crosses the southwest part; State Highway 202, which crosses the middle part; and the Fishhawk Falls Highway in the southeast part of the area (Fig. 1). In addition, numerous gravel logging roads, maintained by Crown Zellerbach and the Oregon Department of Forestry, provide access to the interior of the study area. The best outcrops are exposed on these logging roads and in the Nehalem River.

Geographic Features

Prominent topographic features include Flagpole and Boiler Ridges. These ridges transect the thesis area from southwest to northeast, and appear as a lineament on aerial photographs (scale 1:62,500) and Landsat I satellite imagery (Fig. 2).

The maximum relief of the area is approximately 530 meters. The southward-flowing Nehalem River forms a base level of 120 meters in the southwest part of the area.



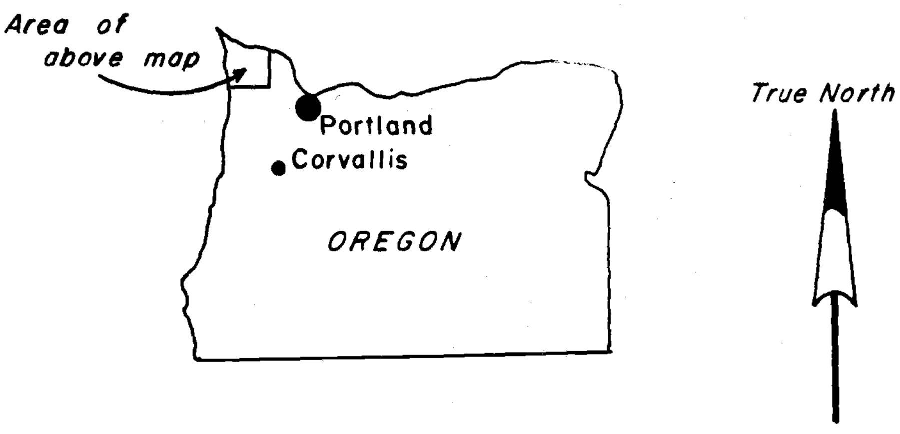


Figure 1. Index map showing location of the thesis area.

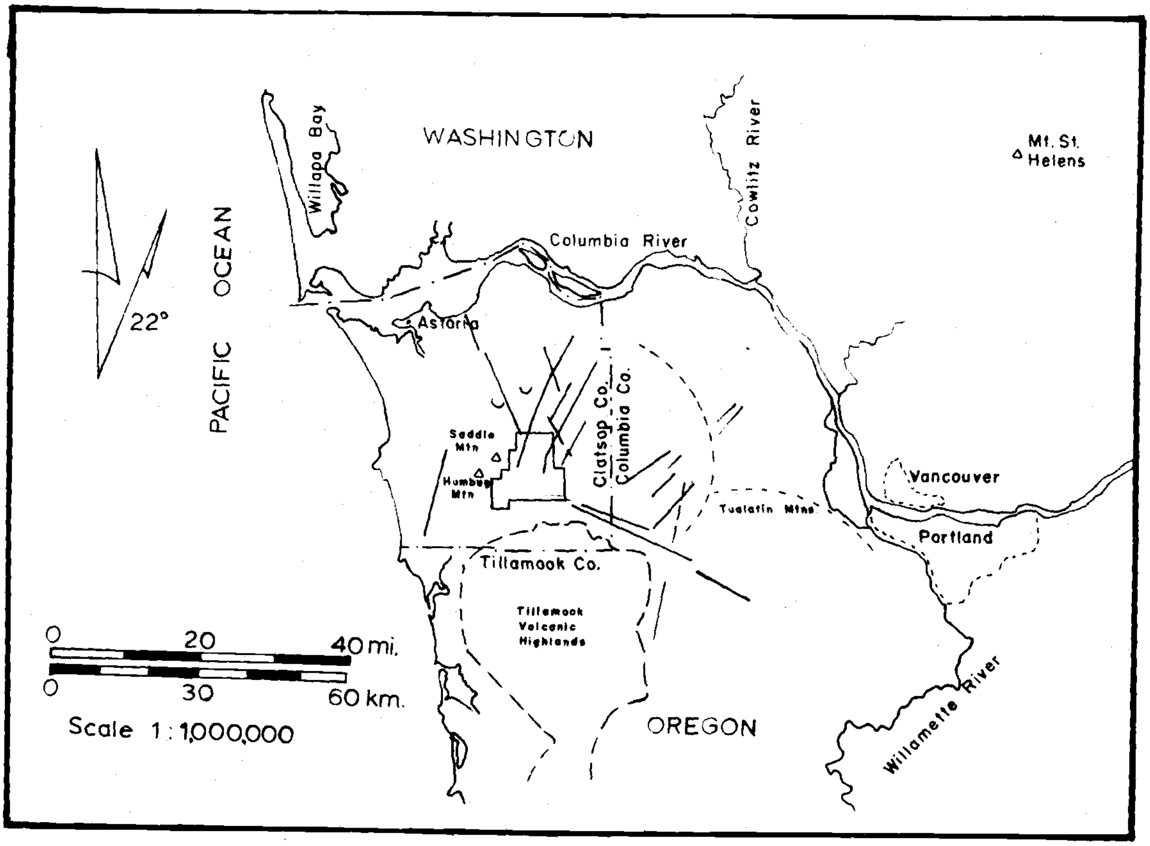


Figure 2. Lineaments in northwest Oregon traced from Landsat I imagery (1:1,000,000). The northeast trending lineaments nearest the thesis area reflect the Beneke, Fishhawk Falls and Northrup dikes (middle Miocene basalt).

The highest elevation is a 650 meter-high ridge, in the northwest part which forms a topographic divide between the northwest-flowing Klaskanine River and the Nehalem River drainage basin (Plate I). Walker Creek, Fishhawk Creek, Little Fishhawk Creek, Buster Creek, Hamilton Creek, and Humbug Creek are tributaries of the upper Nehalem River.

The communities of Jewell, Vinemaple and Elsie occur in the thesis area. Other cultural and natural features include the Lee Wooden County Park; the scenic, cascading Fishhawk Falls; and the Jewell Meadows Wildlife Refuge. The refuge incorporates 1,200 acres of public and private contractual land and it contains large herds of Roosevelt elk (Fig. 3) and other wildlife which are best seen during early mornings and late afternoons.

Methods of Investigation

Field Procedures. Field work was completed during the spring and summer of 1981. Daily field work consisted of geologic mapping and sampling of sedimentary and igneous rock units. Field geology was recorded on topographic base maps having a scale of 1:31,680 (2 inches = 1 mile). Low-altitude (scale 1:12,000) and high-altitude (1:62,300) aerial photographs and an altimeter were used as aids to field mapping.

Figure 3. Roosevelt elk (Alces americana) graze in the Jewell Meadows Wildlife Refuge within the heart of the thesis area.

An outcrop map was prepared and updated each day during the mapping. A geologic map was constructed showing the distribution of 16 different lithologies without assignment to formations. The geologic map of the thesis area (Plate I) is the synthesis of several preliminary maps.

Measurement of representative stratigraphic sections were made using a chain and Brunton compass, or Jacobs staff and Abney level. Clastic rock units were described using standard grain size charts, the Geological Society of America "Rock Color Chart", and the stratification and cross-stratification terminology of McKee and Weir (1953). Other sedimentary structures were described following the Bouma classification (1962). Basaltic rocks were described by color, by phenocryst content, and size (e.g., phyric or microphyric), and by the intrusive contact. Geochemistry and magnetic polarity of basaltic rocks were later determined in the laboratory for further classification.

Sedimentary rock samples were collected for heavy mineral analysis, petrography, source rock maturation, porosity and permeability, molluscan fossils, (foraminifers, diatoms, and coccoliths) and trace fossils. Samples of middle Miocene Grande Ronde Basalt and upper Eocene Tillamook Volcanics were collected for major oxide chemistry, petrography and determination of paleomagnetic polarity.

Paleomagnetic core samples were collected using a water cooled diamond drill at 22 selected outcrops (see further discussion of sampling method in Appendix XVI). Nineteen sites in middle Miocene basalt dikes and sills and three roadcut and quarry sites in upper Eocene Tillamook Volcanics were sampled. Of these, five sample sites of middle Miocene intrusive basalt and two sites of the upper Eocene Tillamook Volcanics occur in the thesis area. The other sites occur in the Buster Creek - Nehalem Valley thesis area (Olbinski, 1984) and the Elk Mountain - Porter Ridge thesis area (Goalen, in prep.). Orientations of core samples were measured using a Brunton compass and a sun compass, when possible. Dr. Shaul Levi, O. S. U. School of Oceanography, directed the drilling operations. Drs. Alan Niem and Robert Bentley assisted in the drilling operations.

A proton precession magnetometer was used on traverses to locate the middle Miocene basalt dikes not exposed on the forested surface. Basalt bodies in the subsurface can be interpreted where strong magnetic gradients are observed (See Appendix XI). Surface float of basalt is also common, suggesting the presence of an igneous body. These magnetic anomalies are valuable in locating dikes where no float is present.

Laboratory Procedures. Laboratory work included:

1. disaggregation of samples for microfossil recovery (Appendix I);

2. heavy mineral analysis and provenance study by separation using a funnel separatory method and

tetrabromoethane, and point count of thin sections and grain mounts (Appendix VIII);

3. modal analysis and petrography of basalt and sandstone thin sections;

4. porosity, permeability and source rock maturation (performed by Amoco Production Company) (Appendix XIV);

5. major oxide chemistry of selected basalt samples (Appendix VIII);

6. determination of magnetic polarity and remanent magnetism using fluxgate and spinner magnetometers (Appendix VII and XV).

Mudstone samples were disaggregated using the method described in Appendix I. Samples of Foraminifera from these disaggregated samples were sent to Dr. Kristin McDougall of the U. S. Geological Survey, Menlo Park, California, for identification, age determination and paleoecological information. Coccoliths recovered from disaggregated samples were identified by Dr. David Burky of the U. S. Geological Survey, La Jolla, California. Diatom samples were identified by Mr. Jack Baldauf, U. S. Geological Survey, Menlo Park, California. Molluscan fossils were identified by Dr. Ellen Moore of the U. S. Geological Survey, Menlo Park, California. Representative trace fossil specimens were identified by Dr. C. Kent Chamberlain of Valero Producing Company, Denver, Colorado.

Sandstone samples were impregnated with an epoxy resin and thin sections were cut from the resulting billets. Modal analyses of these samples were made by point count and the rocks classified following Williams, Turner, and Gilbert (1954) and Folk (1980). Tectonic associations were interpreted following Folk (1980) and Dickinson (1982).

Chemical analyses of 11 major oxides were performed by Dr. Peter Hooper and technicians at the Washington State University X-ray Fluorescence Facility using the international basalt standard. In order to compare the Miocene basalt chemical analyses with other Columbia River basalts, the results of analyses of the Miocene basalt samples were recalculated to the Columbia River Basalt Standard using a correction factor derived by Goalen (in prep.).

Chemical classification of igneous rocks follow the methods of MacDonald and Katsura (1964), Snavely and others (1973), and Pearce and others (1977). Modal analyses of 11 samples were completed using the petrographic microscope. Compositions and igneous rock textures were classified following Williams and others (1954) and Nockolds, Knox and Chinner (1978).

Determination of normal or reverse magnetic polarity of oriented samples of middle Miocene basalt was determined using a fluxgate magnetometer. The procedures of Doell and Cox (1964) were followed.

Paleomagnetic directions of core samples from 22 selected sites were determined by the writer in the magnetics laboratory in the O. S. U. School of Oceanography, under the direction of Dr. Shaul Levi. Natural remanent magnetization (NRM) was measured using a Schonstedt DSM-1 spinner magnetometer. Demagnetization levels were determined for selected pilot samples by stepwise alternating field demagnetization (AFD). Following these initial steps, the remainder of the samples were "cleaned" using the preselected AFD levels determined during the pilot runs in order to obtain directional stability of the paleomagnetic directions. Paleomagnetic directions were determined with the spinner magnetometer that was linked to a computer. Statistical analyses of the data were also performed by the computer (Appendix XV).

Porosity, permeability and source rock maturation of selected rocks were analyzed by Amoco Production Company's Petroservices Group in Tulsa, Oklahoma through the courtesy of Terry Mitchell, of Amoco, Denver, Colorado.

Previous Work

Dana (1849) was the first geologist to examine the geology of northwest Oregon. He accompanied the Wilkes Exploring Expedition of 1838-1842. Condon (1880, in Washburne, 1914) named the Astoria "shale" near Astoria, Oregon. He dated the Astoria "shale" as Oligocene and Miocene based on molluscan fossils. Diller (1896) described "Eocene basic volcanic rocks along the Nehalelm River, in southern Clatsop County", 6.5 km south of the thesis area. Washburne (1914), in an oil and gas reconnaissance investigation of northwest Oregon, traversed the thesis area and recognized exposures of Astoria "shale" at several localities along Little Fishhawk Creek. He mentions no fossils that confirm this stratigraphic assignment, however. Washburne (1914) also noted that a locality near the mouth of Buster Creek in the thesis area (Plate I) was where Diller (1896) collected Eocene or Oligocene molluscan fossils. Washburne described the structure of the Jewell area as a series of gentle northeast-trending anticlines and syclines with flank dips of 2° to 15°. Washburne found residues of "dead" oil and investigated a number of reported gas seeps in Tertiary sedimentary rocks of northwest Oregon.

Warren and others (1945) mapped undifferentiated Tertiary sedimentary rocks and basaltic rocks in the thesis area at a scale of 1:143,000 as part of a reconnaissance investigation of the oil and gas potential in northwest Oregon. Wells and Peck (1961) compiled a geologic map of Oregon west of the 121st. meridian (1:500,000 scale). They mapped the two Miocene basalt dikes, Eocene volcanics and Cowlitz Formation, but did not differentiate the younger Eocene and Oligocene strata.

Beaulieu (1973) published a regional study and geologic map of the potential geologic hazards of eastern Tillamook and Clatsop counties. Part of his study included the thesis area. He suggested that mass movement and flash foods may be significant environmental hazards. Earthquakes may be important hazards insofar as they may trigger down slope movement of unstable ground. The accompanying geologic map of eastern Clatsop County in Beaulieu's report showed upthrown late Eocene volcanics, along an E-W trending fault, against undifferentiated Oligocene - Eocene mudstones.

Since 1973, Dr. Alan R. Niem and more than 15 Oregon State University graduate students under his guidance have undertaken projects of detailed geologic mapping and sedimentological and stratigraphic studies in Clatsop and Tillamook counties, northwest Oregon. Several shallow marine, deltaic and turbidite lithofacies have been defined and assigned informal member status in the Astoria Formation. Penoyer (1977) completed a study of Saddle and Humbug Mountains on the western border of the thesis area. Other M. S. theses, in progress or completed, surround the Fishhawk Falls - Jewell theses area (Jeff Goalen, Carolyn Peterson, Jim Olbinski, Dan Mumford, Phillip Rarey and Eugene Safley). In addition, graduate students working under the direction of Dr. Robert O. Van Atta and Tom Benson of Portland State University are studying the stratigraphy, sedimentology and structure of the Eocene and Oligocene units in nearby Columbia County.

A U. S. G. S. open file regional geologic compilation map of the western half of the Vancouver map sheet (scale 1:125,000) by Wells and others (1983) includes the thesis area.

Renewed interest in Clatsop and Columbia Counties has recently occurred because of the discovery of commercial quantities of natural gas on a northwest trending anticline near the town of Mist, Oregon, 20 km east of the thesis area (Newton, 1978; Olmstead,, 1982; Fig. 1).

REGIONAL STRATIGRAPHY

The Fishhawk Falls - Jewell area is located near the axis of the northward-plunging Oregon Coast Range "anticlinorium" described by Niem and Van Atta (1973). Numerous high-angle normal and reverse faults which trend northeast and northwest are superimposed upon this regional structure (Snavely and Wagner, 1964; Baldwin, 1981). Low amplitude, broad, gentle, northwest- to southeast-trending folds with flank dips typically 10° to 20° also occur in the area (Newton and Van Atta, 1976). The thesis area is located on the western flank of the northern Oregon Coast Range gravity high (Bromery and Snavely, 1964). This gravity high reflects the northern continuation of the Tillamook Volcanics basement rocks within the core of the anticline.

Ten volcanic and sedimentary formations form the bedrock units of the northern Oregon Coast Range. From the oldest to youngest these are: Tillamook Volcanics, Goble Volcanics, Cowlitz Formation, Keasey Formation, Pittsburg Bluff Formation, Scappoose Formation, Oswald West mudstone, Astoria Formation, and the Columbia River Basalt Group and its coastal equivalents (e.g., Depoe Bay and Cape Foulweather basalts).

The Siletz River and Tillamook Volcanics (2,700 to 4,200 m thick) form the basement rocks of the Oregon

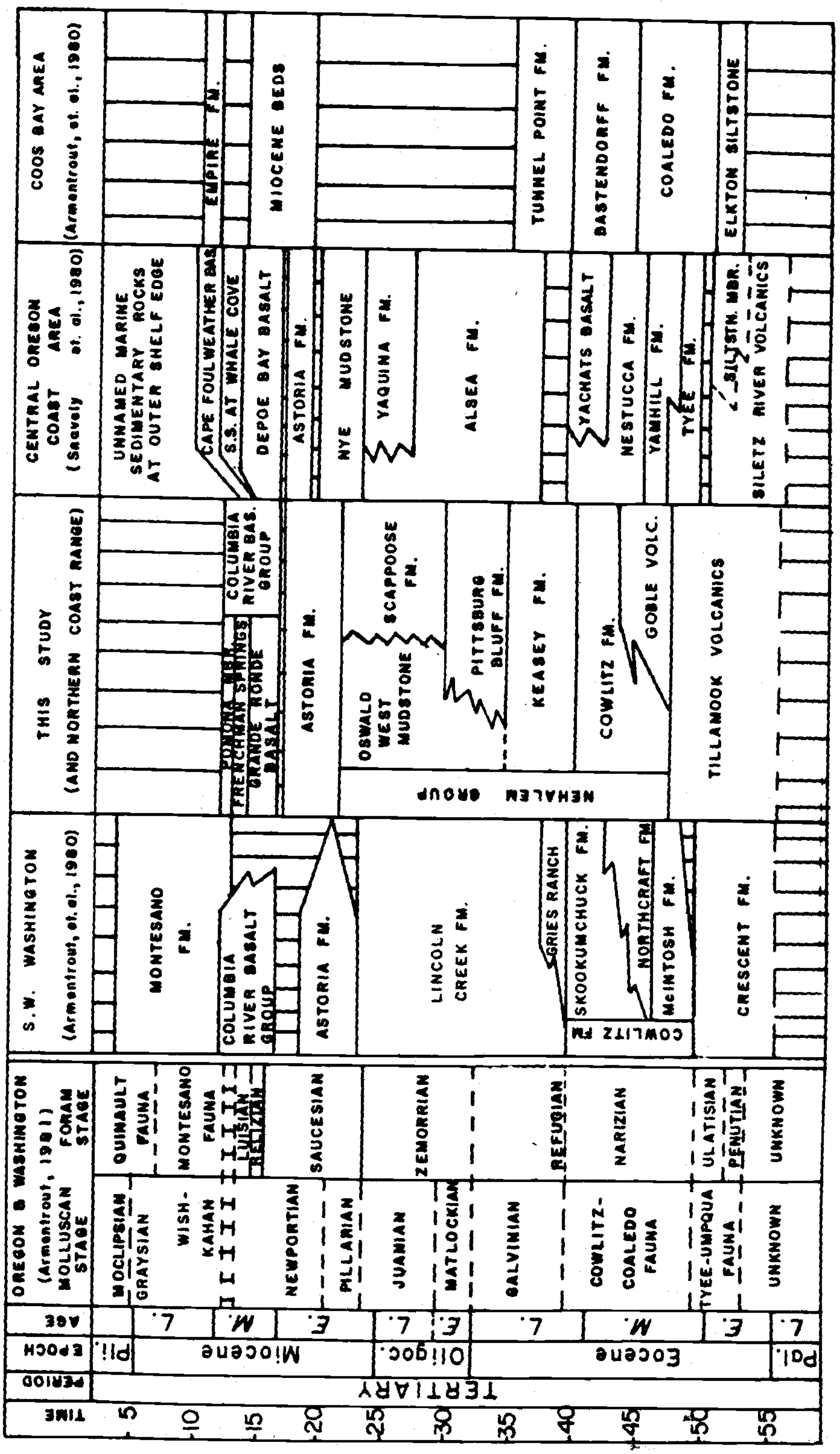


Figure 4. Stratigraphic correlation chart of Tertiary rock-stratigraphic and biostratigraphic units in western Oregon and southwest Washington.

Coast Range and crop out within the core of the range (Fig. 4). These lower to middle Eocene formations consist of tholeiitic and alkalic basalts having similar geochemistry to mid-oceanic basalts (Snavely and others, 1980). Kulm and Fowler (1976) postulated that these formations may represent a detached part of the Farallon oceanic plate (e.g., a volcanic archipelago or the Coast Range seamount province of Dickinson (1976) obducted onto the North American continental plate). Duncan (1982) suggests that these volcanic rocks formed over a hot spot. Recent workers (Kulm and Fowler, 1976; Snavely and others, 1980) suggest the episodic underthrusting of the converging Farallon plate beneath the North American plate in western Oregon and Washington caused repeated uplift and high-angle faulting of the Coast Range during the Tertiary. Much of the upper part of the Tillamook Volcanics consists of basaltic andesite and volcanic debris flows (Olbinski, 1983; Jackson, 1983) developed on underlying basaltic submarine breccias, pillow lavas and dikes 45 m.y. ago (Magill and others, 1981; Wells and others, 1983).

Regional uplift formed an angular unconformity between the lower to middle Eocene Tillamook Volcanics and the overlying middle to upper Eocene Cowlitz Formation. A basal basaltic conglomerate characterizes the lower Cowlitz Formation (Olbinski, 1983; Jackson, 1983). Middle Eocene underthrusting may also have initiated rotation of the Coast

Range following a westward shift of the subduction zone (Dickinson, 1976; Magill and Cox, 1981).

The upper Eocene Goble Volcanics consist of 60 to 1,500 m of alkalic and tholeiitic subaerial basalt flows, pillow lavas, flow breccias and minor interbedded basaltic conglomerates, mudstones and sandstones. The unit was named by Wilkinson and others (1946) for exposures near Goble, Oregon, on the Columbia River in Columbia County. Whole rock radiometric dates reported for the Goble Volcanics range from 45 ± 1.4 to 32.2 ± 0.3 m.y. (Beck and Burr, 1979); thus, spanning late middle Eocene to the end of Eocene time.

The Goble Volcanics intertongue with the upper part of the 300-m-thick middle to upper Eocene Cowlitz Formation near the type section along the Cowlitz River in southwest Washington (Henriksen, 1956). There, the Cowlitz Formation consists of micaceous and arkosic marine sandstone, siltstone and claystone. Thick sub-bituminous coal beds also occur in non-marine parts of the type Cowlitz Formation (Yett, 1979; Armentrout and others, 1980).

The 400-m-thick Cowlitz Formation in northwest Oregon is described as a littoral to sublittoral marine deposit by Niem and Van Atta (1973) and Newton and Van Atta (1976). A recent study of the Cowlitz Formation in the northern Oregon Coast Range suggests that the unit was deposited in a forearc basin associated with orogenic arc volcanic rocks of the Goble Volcanics (Timmons, 1981). Small scale channels, high-angle planar cross-bedding and trace fossils indicate that the depositional environment of the Cowlitz Formation was a high energy, wave-dominated, shallow marine environment (Olbinski, 1983; Timmons, 1981). However, McKeel (1979) interpreted age-diagnostic benthic foraminiferal assemblages from the Texaco Clark and Wilson #6-1 well in Columbia County (21 km east of the thesis area) as a regressive sequence from open marine bathyal to neritic conditions for the upper Cowlitz Formation of northwest Oregon. Bruer (1980) suggested that the Cowlitz sandstone in the subsurface in the Mist field may have formed in a deep marine gorge similar to the present Strait of Juan de Fuca, between the Olympic Mountains and south Vancouver Island.

The 600-m-thick upper Eocene Keasey Formation unconformably overlies the Cowlitz Formation in northwest Oregon and contains three members. These are: a basal thin pebbly volcanic sandstone and conglomerate; a thick middle member of structureless, fossiliferous, tuffaceous mudstone; and an upper thin sequence of interbedded siltstone and fine-grained sandstone (Niem and Van Atta, 1973). Benthic Foraminifera in the type section of the Keasey Formation indicate deposition in water depths of 200 to 300 m (McDougall, 1980). Rare free-swimming Tertiary crinoids also occur in the upper Keasey Formation in bluff-forming outcrops along the Nehalem River near Mist, Oregon (Vokes and Moore, 1953). The Keasey Formation is correlative to the Bastendorff and Tunnel Point Formations of the central Oregon Coast area and may be, in part, correlative to the lower Lincoln Creek Formation in southwest Washington (Fig. 4).

The 260-m-thick upper Eocene to Oligocene Pittsburg Bluff Formation disconformably overlies the Keasey Formation. Warren and Norbisrath (1946) and Van Atta (1971) divided the Pittsburg Bluff Formation into two units. The lower unit consists of massive to thin-bedded, bioturbated, arkosic, tuffaceous sandstone and siltstone. The upper unit is composed of basaltic conglomerate, cross-bedded sandstone and thin coal lenses (Niem and Van Atta, 1973). Shallow marine, estuarine and deltaic sedimentary depositional environments are represented by the Pittsburg Bluff Formation (Van Atta, 1971). The Pittsburg Bluff is correlative to the upper part of the Lincoln Creek Formation in southwest Washington and to parts of the Alsea Formation of the central Oregon Coast (Moore, 1976; Fig. 4).

A disconformity separates the overlying Scappoose Formation from the Pittsburg Bluff Formation. The Scappoose Formation consists of 450 m of carbonaceous micaceous arkose and tuffaceous mudstone with basalt and polymict conglomerate (Niem and Van Atta, 1973). A deltaic depositional environment is interpreted for the unit by Van Atta (1971). Warren and Norbisrath (1946) defined the upper Oligocene to lower Miocene Scappoose Formation in the northeast Oregon Coast Range and correlated the unit to the

Sooke Formation of Vancouver Island on paleontological basis. The Scappoose Formation is also correlated to the Lincoln Creek Formation of southwest Washington and to parts of the Alsea Formation, Yaquina Formation and Nye Mudstone of the central Oregon Coast Range (Fig. 4). Cressy (1974) suggested that the sandstone-rich Scappoose Formation is equivalent to Oswald West mudstones of the northwest Oregon Coast Range.

Kelty (1981) and Van Atta and Kelty (1982) show that coarse-grained fluvial basaltic conglomerate and arkoses of the Scappoose Formation fill channels eroded into the underlying Pittsburg Bluff Formation. In places, the Scappoose rests directly on strata of the Keasey Formation. Basalt clasts in the conglomerate in the Scappoose channels have a Columbia River Basalt Group (Grande Ronde) chemistry (Kelty, 1981). This implies that the upper part of the Scappoose Formation as mapped by Warren and others (1945) and Wells and Peck (1961) is interbedded with, and younger than, the middle Miocene Grande Ronde Basalt of the Columbia River Basalt Group. In light of this information, revision of the stratigraphic nomenclature may be required to define the age of the Scappoose Formation.

The 550-m-thick Oswald West mudstone crops out only in the northwest part of the Oregon Coast Range. This unit was informally named for sea cliff exposures at Oswald West State Park (Cressy, 1974) where distinctive trace fossils and foraminiferal assemblages indicating a bathyal depositional environment occur. The thick, tuffaceous, bioturbated mudstone unit was divided into three parts by Neel (1976) and Penoyer (1977). Warren and others (1945) originally measured a section at the type section of the Oswald West mudstone and referred the rocks to the Blakeley Stage. Using fossil evidence, Penoyer (1977) suggested that the lower part of the Oswald West mudstone is correlative to the Keasey Formation; that the middle part is equivalent in age to the shallow marine and deltaic Pittsburg Bluff Formation; and that the upper part of the Oswald West is equivalent in age to the deltaic Scappoose Formation of the northwest Oregon Coast Range. Penoyer (1977) mapped the deep-marine Oswald West mudstone adjacent to the western boundary of the Fishhawk Falls - Jewell thesis area. This unit apparently grades laterally into the shallow marine Pittsburg Bluff Formation. Sandstones that crop out in the map area (Plate I) have yielded a probable upper Oligocene molluscan fossil assemblage that is equivalent to the upper part of the Lincoln Creek Formation (E. J. Moore, pers. comm., 1982).

The lower to middle Miocene Astoria Formation crops out in three marine embayments (the Newport, Tillamook, and Astoria areas) in the western part of the Oregon Coast Range (Cooper, 1981). Several informal mappable members, reflecting a variety of lithologic and depositional facies, have been defined. These units include: the Angora Peak sandstone, a deltaic facies (Cressy, 1974); the Big Creek sandstone, a shallow marine unit (Coryell, 1978; Cooper, 1980); the Silver Point member, a deep-water mudstone with rhythmically bedded turbidite sandstone in its lower part (Smith, 1975); and the Pipeline member, a submarine sandstone channel or canyon head deposit (Nelson, 1978). Only the Silver Point member occurs in the study area (Plate I).

Two middle Miocene coastal basalt units have been differentiated in the western Oregon Coast Range (Snavely and others, 1973). These are the aphanitic Depoe Bay and sparsely porphyritic Cape Foulweather Basalts. These basalts form headlands and prominent topographic highs composed largely of submarine breccia and pillow lavas and related intrusives. Snavely and others (1973) interpreted these coastal basalts to be correlative on petrological, chemical and age bases to the Yakima and late-Yakima types of the Columbia River Group of Waters (1961). In a revision of the stratigraphic nomenclature of the Columbia River Basalt by Swanson and others (1979), the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt of the Columbia River Basalt Group are the petrologic correlatives of the coastal Depoe Bay and Cape Foulweather Basalts, respectively, of Snavely and others (1973) (Fig. 4). Beeson and others (1979) suggested that the Depoe Bay and Cape Foulweather Basalts may be the submarine extension of invasive flows of the Grande Ronde and Frenchman Springs

Basalts, respectively, which flowed down an ancestral Columbia River valley to the sea.

Biostratigraphic and Chronostratigraphic Nomenclature

The biostratigraphic framework used in this thesis follows that of Armentrout (1981) and Bukry (1981) (Fig. 5). Calcareous nannofossil, benthic and planktonic foraminiferal and molluscan biochronologies are tied in part to the worldwide geologic time scale. The coccolith zones and subzones of Bukry (1981) and Martini (1971) are tied by Armentrout to the revised chronostratigraphic chart for Oregon and Washington.

Some Paleogene units have been shifted on the geologic time scale in the revision of Tertiary chronostratigraphic units by Armentrout (1981). The Eocene/Oligocene boundary (Refugian/Zemorrian) for Oregon rocks is near 32 m.y.B.P. This is younger than the accepted European boundary for the Eocene/Oligocene which is placed at 37 m.y.B.P. (Hardenbol and Berggren, 1978) (Fig. 5). The "Narizian"/"Refugian" boundary in Oregon is placed at 39 m.y.B.P. on the new

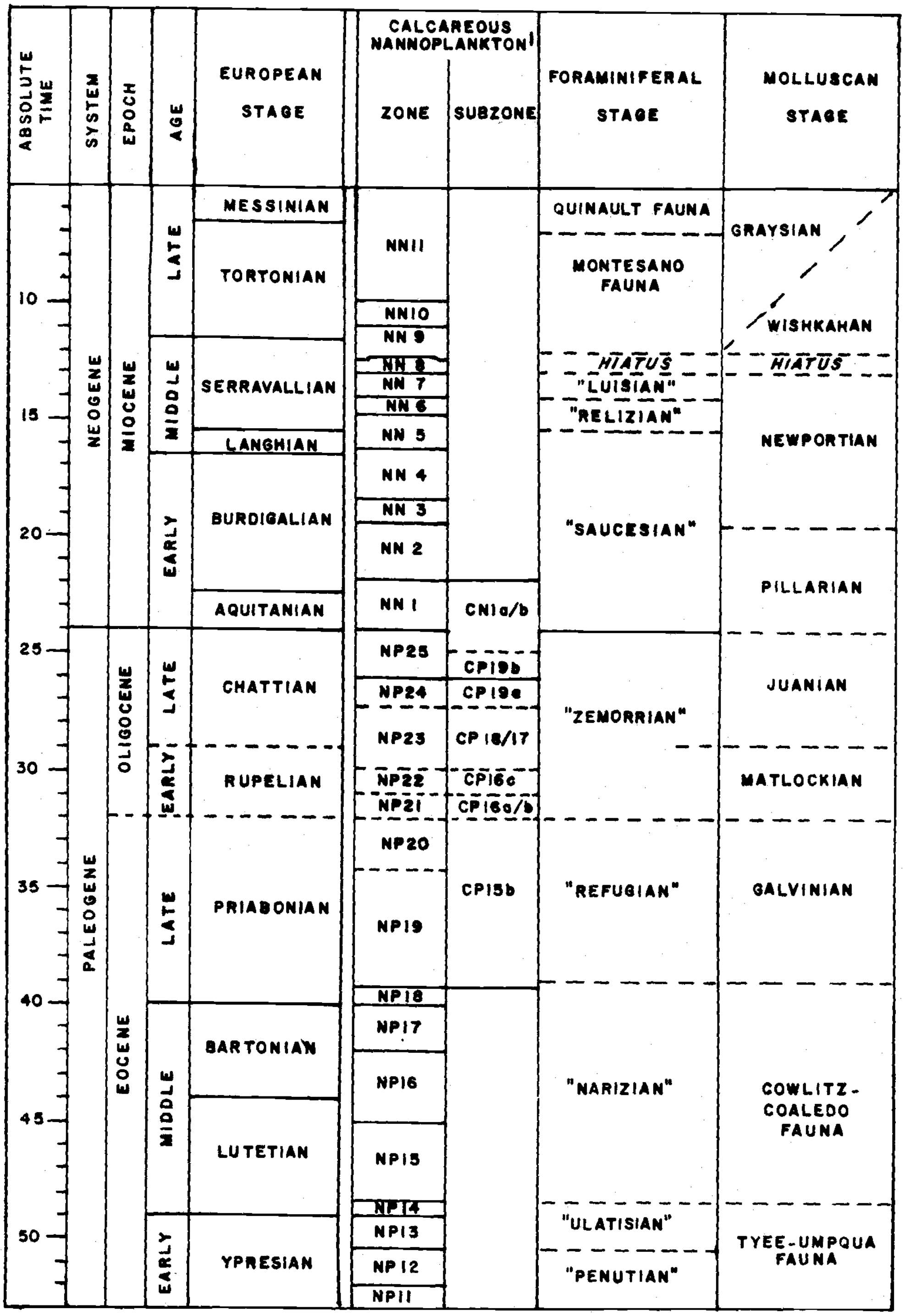


Figure 5. Stratigraphic correlation chart of some Tertiary biostratigraphic units in western Oregon and southwest Washington (after Armentrout, 1981, and Bukry, 1981).

scale. The Narizian Pacific Coast provincial Foraminiferal Stage has been shifted on the geologic time scale to the middle Eocene. The Refugian Foraminiferal Stage was formerly referred to as early Oligocene (Snavely and others, 1969), but is now considered entirely upper Eocene. The Zemorrian Stage, which was formerly late Oligocene, is now considered entirely Oligocene.

DESCRIPTIVE GEOLOGY OF THE THESIS AREA

Tillamook Volcanics

Nomenclature

The name, Tillamook Volcanics, was first proposed by Warren and others (1945) and Warren and Norbisrath (1946) for the Eocene basalts that form the Tillamook highlands of the Oregon Coast Range. They also mapped an outlier of Eocene volcanic rocks on Green Mountain north of the Tillamook highlands as Tillamook Volcanics. Part of this outlier is within the study area (Plate I). Culver (1919) and earlier workers also recognized these volcanic rocks as Eocene and noted differences from the suprajacent Columbia River Basalt of Miocene age.

Later, Wells and Peck (1961) labeled this outlier of Eocene volcanic rock on Green Mountain as Goble Volcanics, differentiating this outlier as a younger unit than the main mass of Tillamook Volcanics to the south.

Van Atta (1971) and Newton and Van Atta (1976) mapped a part of the Tillamook Volcanics as Goble Volcanics in nearby Columbia County, Oregon. Van Atta referred to volcanic flows and intrusive rocks associated with Cowlitz strata as the Goble Volcanics member of the Cowlitz Formation. He apparently followed the reasoning of Henriksen (1956) in assigning a lower stratigraphic rank to these rocks because they are not as thick as the type Tillamook Volcanics and are enclosed within a predominantly marine sedimentary rock section Newton and Van Atta (1976, p. 11) believed that the Goble Volcanics of Green Mountain, located southeast of the study area, are overlain and interbedded with the lower Cowlitz sedimentary rocks.

In this study, the Eocene volcanic rocks and associated sedimentary rocks in the southeast part of the map area (Plate I) are referred to the Tillamook Volcanics. This is based on: 1. historical usage, 2. similar lithology of the rocks found in this study area to those originally described in the upper part of the Tillamook Volcanics, 3. K/Ar radiometric dates of basalt flows similar to those obtained from the upper part of the Tillamook Volcanics (Magill and others, 1981; Olbinski, 1983; Mumford and Safley, pers. comm., 1983), and 4. similar major element chemistry of both volcanic piles (Jackson, 1983).

In addition, detailed mapping to the south of our study area indicates that Tillamook Volcanics exposed on Green Mountain and in the study area are part of an uplifted block separated on the south from the main mass of Tillamook Volcanics by a graben composed of the Cowlitz Formation. The mapping also shows that the type Tillamook Volcanics can be mapped almost continuously from the Tillamook highlands to the Green Mountain and Jewell areas.

Distribution

The Tillamook Volcanics (Ttv) crop out in a 2.5 square mile area in sec. 25 and 26, T5N, R7W, and are repeated by a small thrust fault in sec. 23 (S1/2) and 24 (SW1/4) of the same township (Plate I). The rocks are best exposed in the east and west Buster Creek quarries (sec. 25), on the banks of Buster Creek, along the Fishhawk Falls Highway, and in the Nehalem River where the river lows southward through a gorge formed by the weathering-resistant Tillamook volcanic rocks.

The Tillamook Volcanics mapped in this area are part of the larger topographic high composed of Tillamook Volcanics that form an outlier near Green Mountain between Jewell and Elsie.

Tillamook volcanic rocks tend to be resistant to weathering and erosion relative to the fine-grained clastic sedimentary rocks of adjacent formations. As a result, the volcanics form topographic ridges deeply dissected by narrow stream valleys. Broader alluvium-filled valleys and meandering creeks tend to form on the less resistant younger sedimentary rocks and in structural lows and down-faulted blocks.

Lithology

In the thesis area, the Tillamook Volcanics consist predominantly of epiclastic volcanic breccias and minor subaerial flows with a few minor volcanic sandstone interbeds. Some vesicular and scoriaceous basaltic rocks also occur. Basalt and andesite dikes and sills intrude the epiclastic volcanic breccia in the east and west Buster Creek quarries (localities 265 and 268). These relations are well exposed where the resistant intrusive is excavated for crushed road aggregate. The Tillamook Volcanics are unconformably overlain by the middle to upper Eocene Cowlitz Formation.

Volcanic breccias. The volcanic breccias are best exposed in the Nehalem River (SE corner, sec. 23, T5N, R7W) and in the Buster Creek quarries (sec. 25, T5N, R7W). These rocks consist of poorly sorted, angular, boulder- and cobble-sized volcanic clasts supported in a volcaniclastic sandstone matrix (Fig. 6). The breccias are unstratified and poorly indurated, and the clasts have variable degrees of angularity, roundness and lithology, all suggesting that these are debris flow deposits. The clasts consist of porphyritic plagioclase-augite andesite, palagonitized scoria, volcanic sandstone and vesicular and porphyritic basaltic andesite. The matrix is composed of lapilli, coarse ash and volcaniclastic sandstone.

Figure 6. Volcanic breccia of the upper Tillamook Volcanics (Ttv). Locality 268 near Buster Creek. (Hammer is 29 cm long.)

The breccias are a light olive gray (5 Y 6/1) to greenish gray (5 GY 6/1). Red paleosols are developed at the tops of some debris flows suggesting subaerial exposure. A moderate blue green (5 BG 4/6) mineral in the matrix of some rocks is probably celadonite, possibly a low-temperature hydrothermal alteration product resulting from a younger Tillamook Volcanics intrusive, or from present day weathering. In the Buster Creek quarry exposures (localities 265, 268), calcite veins and veinlets fill fractures in the volcanic breccia and occur as cement in the matrix.

Basaltic andesite flows. Vesicular subaerial lava flows are lithologically distinct from the epiclastic volcanic breccias. There are two types of basaltic andesite flows in the thesis area, porphyritic and aphyric. The porphyritic flows contain lathlike plagioclase phenocrysts and are light olive gray (5 Y 5/2). Vesicles are lined with shiny brownish-black altered glass (chlorophaeite); some are filled with zeolites or chalcedonic silica.

Although the lithostratigraphic sequence within the Tillamook Volcanics in the Buster Creek vicinity is not well exposed, Olbinski (1983) noted that in the adjacent Green Mountain area subaerial flows are most abundant underlying the volcaniclastic breccias and dikes. The Tillamook Volcanics in this study area are dominantly dikes and epiclastic debris flows and appear to correlate well with the upper unit of the Tillamook Volcanics of Olbinski (Ttv_2; 1983).

<u>Petrography of flows</u>. A thin section (sample 265B) of an aphyric vesicular basalt flow consists of an intergrowth of plagioclase (50-55%), augite (25%), leucoxene and magnetite (5%), and chlorophaeite (10-15%). The latter is an orange-brown isotropic alteration product in the matrix and in vesicles.

Plagioclase microlites form euhedral and subhedral lathlike crystals with albite and pericline twins. Oscillatory zoned plagioclase was not observed. The microlites have an Anorthite content of 50-56% (labradorite), based on the measurement of extinction angles of a-normal sections. Augite occurs as smaller subhedral grains interstitial to plagioclase.

Chlorophaeite occurs in the groundmass as botyroidal spherulites in some vesicles, and the spherulites are commonly birefringent. Chlorophaeite also occurs in the groundmass as an alteration product of volcanic glass. Ilmenite appears to be entirely altered to leucoxene.

Volcanic textures of the aphyric vesicular flows are a hyalocrystalline and microcrystalline groundmass set in a hypidiomorphic-granular framework of feldspar and pyroxene. The abundant feldspar microlites in the groundmass display a pilotaxitic to intersertal texture. Chlorophaeite and brown basaltic glass fill the interstices between the feldspar microlites and augite.

The porphyritic vesicular basalt flow (sample 211-3) consists of phenocrysts of plagioclase and augite set in a groundmass of plagioclase microlites, augite, volcanic glass, chlorophaeite and celadonite. The composition of plagioclase phenocrysts averages An_{75} (bytownite). The composition of plagioclase in the groundmass was not petrographically determined.

Petrographic textures of the porphyritic flow include a microcrystalline groundmass displaying a pilotaxitic alignment of plagioclase microlites. Plagioclase and augite phenocrysts are hypidiomorphic-porphyritic. The groundmass is sub-ophitic, suggesting that the plagioclase crystallized prior to augite.

Lithology and Petrography of intrusive rocks. The intrusive rocks in the Buster Creek area (localities GV1, 265, 269) are largely an anastomosing system of finger-like dikes and apophyses that intrude epiclastic volcanic breccia (Fig. 7). The intrusives are massive, black, aphyric basaltic rocks. The irregular basalt mass has an apparent horizontal thickness of 50 m. but coalesces and thickens toward the base of the exposure. Columnar jointing is well developed in some of the intrusive bodies.

There are petrographic and geochemical differences between the intrusives in the two Buster Creek quarries. The intrusive complex in the west Buster Creek quarry (paleomagnetic sample site GV1, sec. 25, T5N, R7W) is andesitic in composition (62.3% SiO_2) and contains an

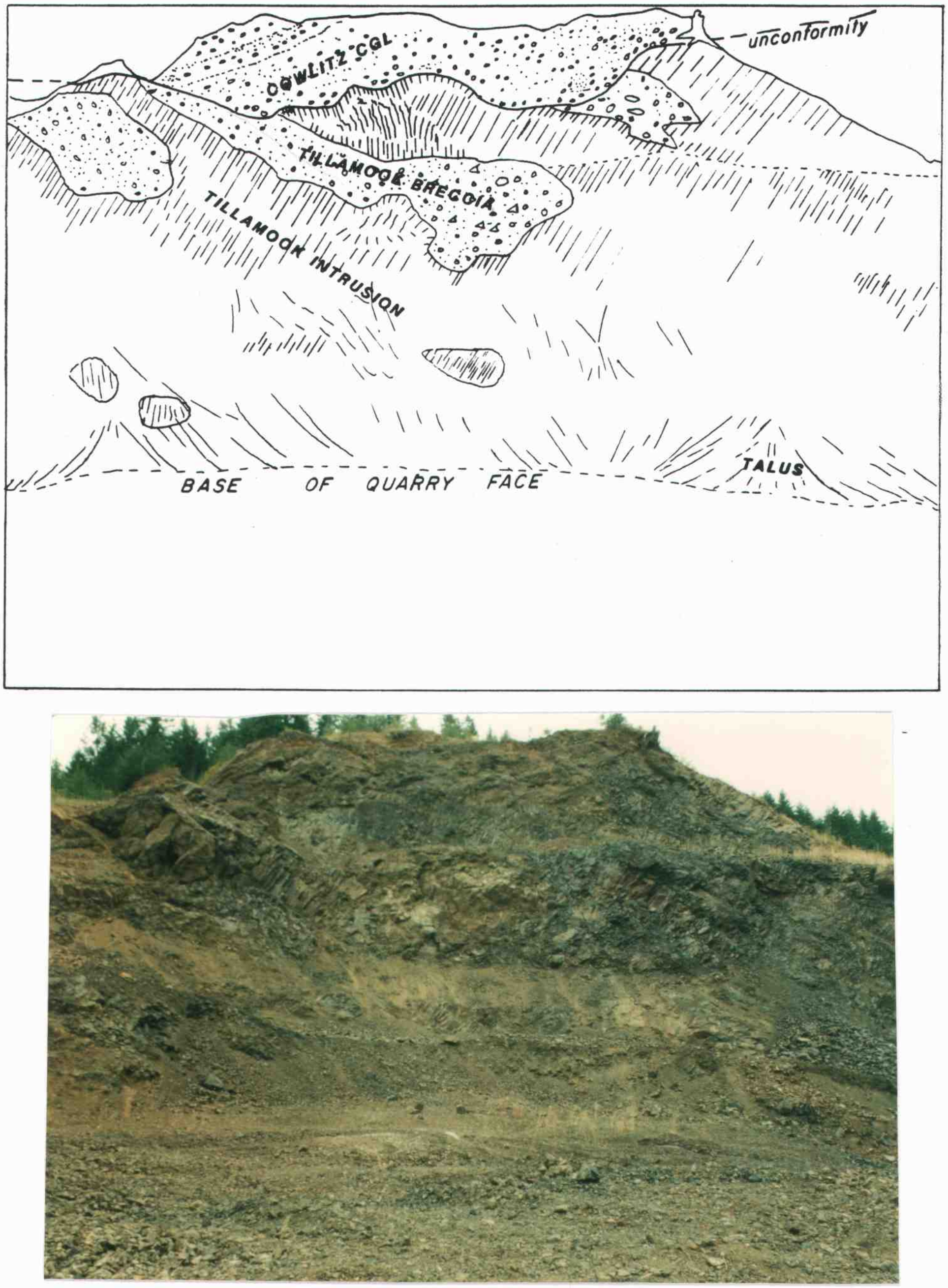


Figure 7. Photograph and line drawing of the west Buster Creek quarry. The inclined columnar jointed andesitic Tillamook Volcanics intrusion into volcanic breccia is truncated by angular unconformity of overlying Cowlitz basalt conglomerate. (Face of quarry is 35 m high.)

intergrowth of Carlsbad and Albite twinned plagioclase, augite, magnetite and chlorophaeite. The average An-content is An_{32}, which is andesine. Sparry calcite and chlorophaeite occur as irregular vesicle and veinlet fillings. The groundmass is fine-grained phaneritic and composed of sub-ophitic augite and plagioclase microlites that surround a hypidiomorphic-porphyritic framework of plagioclase. These petrographic observations suggest that this rock is an andesite.

Below the quarries and within the bed of Buster Creek, a massive aphyric intrusive basaltic rock is exposed (locality 269) that is macroscopically similar to the intrusive system in the west quarry above. As the hand specimens are similar, it is probable that these igneous rocks are part of the same dike system. However, the petrographic textures are quite different.

The intrusive rock collected from the creek bed consists of fresh plagioclase, clinopyroxene (augite?), magnetite, and glass. The composition of plagioclase phenocrysts ranges from An_7 to An_{12}, which seems to silicic for the overall mineralogy of the rock. This determination is questionable because perfect orientations of laths having uniform illumination were few. All of the minerals in the groundmass are cryptocrystalline. Lathlike plagioclase crystals in the groundmass are acicular. The matrix also contains pyroxene, glass and crystallites of an opaque mineral, probably magnetite.

The intrusive rock exposed in the creek bed is probably related to the dikes exposed in the quarry above the creek. The petrographic differences are probably textural differences that were imparted to the rock during cooling. The intrusive exposed in the creek bed may have cooled more rapidly than the intrusives in the quarry as indicated by the fine acicular microlites in the groundmass of the intrusive.

In the east Buster Creek quarry, another dike is exposed that is 25-30 m thick. The intrusive rock is massive, black and rarely phyric. The dike intrudes epiclastic volcanic breccias and has irregularly shaped contacts. The jointing pattern is also irregular, unlike the well-developed columnar joint sets of the adjacent dike complex in the west quarry.

The rock is composed of 56.9% SiO_2, making it a basaltic andesite. From a petrographic analysis, the rock is determined to consist of 70-80% euhedral to subhedral plagioclase microlites in the groundmass, with augite, magnetite and chlorophaeite comprising the remainder. Plagioclase compositions from two phenocrysts average sodic oligoclase (An_{12}). Augite occurs as sub-ophitic grains interstitial to plagioclase in the groundmass. One augite phenocryst was also observed in thin section. The groundmass is hypocrystalline and microcrystalline. Porphyritic plagioclase crystals are hypidiomorphic and pilotaxitic.

Geochemistry of the Tillamook Volcanics

Geochemical analyses for 11 major oxides from four samples of the Tillamook Volcanics were performed (see Appendix VI). Sample GV1, from the west Buster Creek quarry, and sample GV2, from the Fishhawk Falls Highway, are intrusive rocks. Sample GV3, from Lukarilla Road in sec. 4, T4N, R7W, and sample 265, from the east Buster Creek quarry, are flows. One bleached volcanic clast was collected and analyzed from the Cowlitz conglomerate in the west Buster Creek quarry.

The compositional range of all samples is from 56.9 to 62.6% SiO_2, 15.57 to 16.65% A1203, 7.34 to 9.61% total iron, and 4.38 to 7.92% total alkalis. These rocks thus range from basaltic andesite to andesite. The one sample from the Cowlitz conglomerate (sample 268) that directly overlies the Tillamook Volcanics has an anomalous chemistry that suggests that the sample has been highly altered. The anomalous chemistry consists of 70.5% SiO_2, very low total iron, MgO, CaO and MnO (see Appendix VI).

As a group, these rocks can be classified as subalkaline tholeiitic rocks as suggested by the silica versus alkali diagrams (Figs. 8 and 9). A silica variation diagram (Fig. 8) indicates that the broad range of silica content is concomitant with a broad range of other major oxides. The four samples appear scattered on the silica

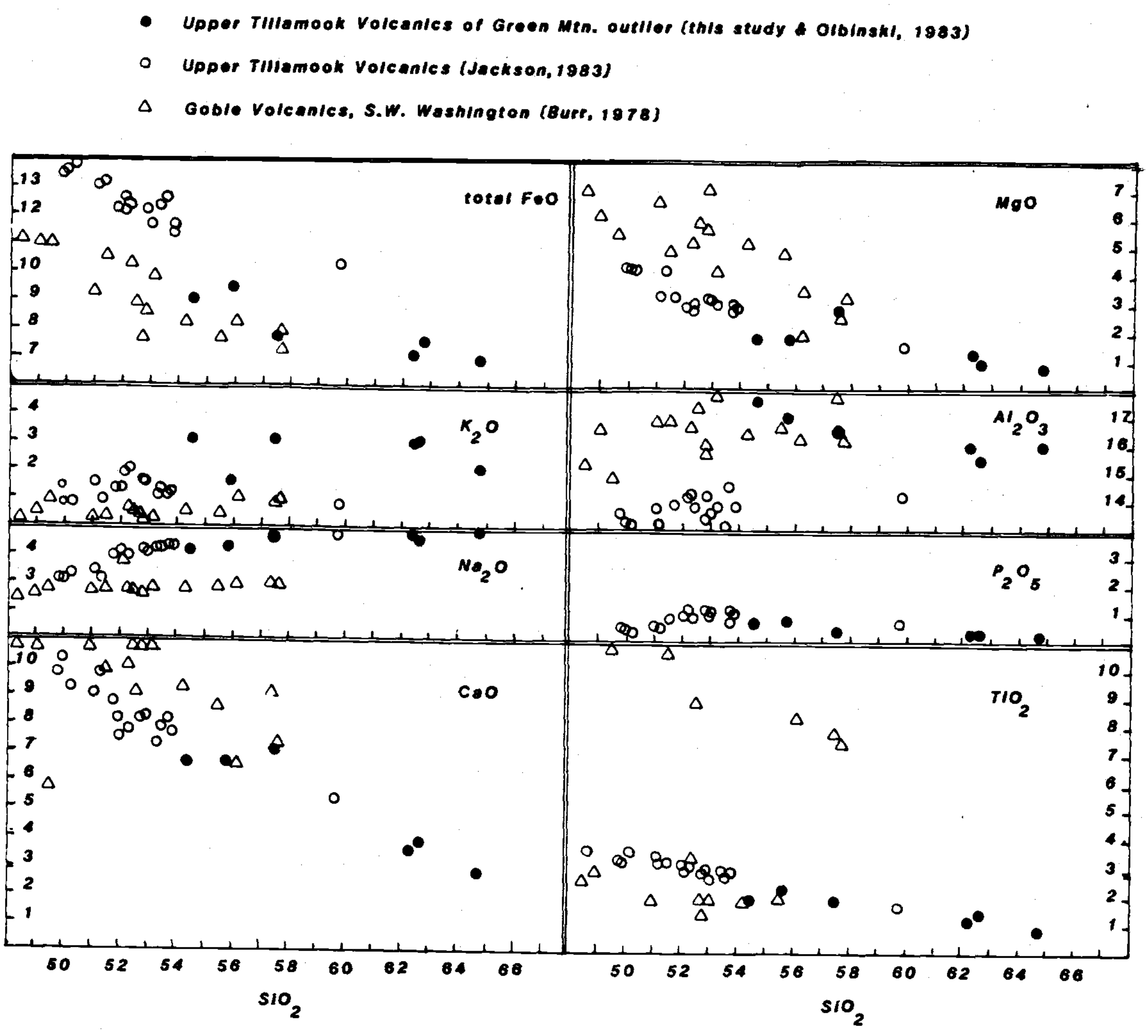


Figure 8. Silica variation diagram of major oxides for upper Tillamook and Goble Volcanics; data from Burr (1978), Jackson (1983), Olbinski (1983) and this study.

versus alkali diagram (Fig. 9) of MacDonald and Katsura (1964), reflecting the broad range of both silica alkalis.

Comparison of these geochemical data with other geochemical work on the Tillamook Volcanics (Fig. 8) shows similar chemical variability of the middle to upper Eocene volcanics (Burr, 1978; Timmons, 1981; Cameron, 1980; Jackson, 1983). Because the section of Tillamook Volcanics that is exposed in the study area is near the uppermost part of the Eocene volcanic pile, it is best to compare these data to other uppermost Tillamook rocks.

The upper part of the Tillamook Volcanics consists of several different rock types suggesting several intrusive and eruptive events during the late Eocene. The Tillamook Volcanics exposed on Green Mountain (Olbinski, 1983) are also basaltic andesite in composition and have a similar range of major element chemistry as those collected in this study area. Jackson (1983) collected and analyzed basaltic andesites from the uppermost part of the Tillamook volcanic pile. He also observed a range of silica, iron and alkali content similar to those reported for this thesis area. He also noted two distinct groupings in his geochemical data, and some samples that did not fit either group. Thus, Jackson (1983) suggested that there may be other unrecognized geochemical groups indicative of separate volcanic events within the upper part of the Tillamook Volcanics.

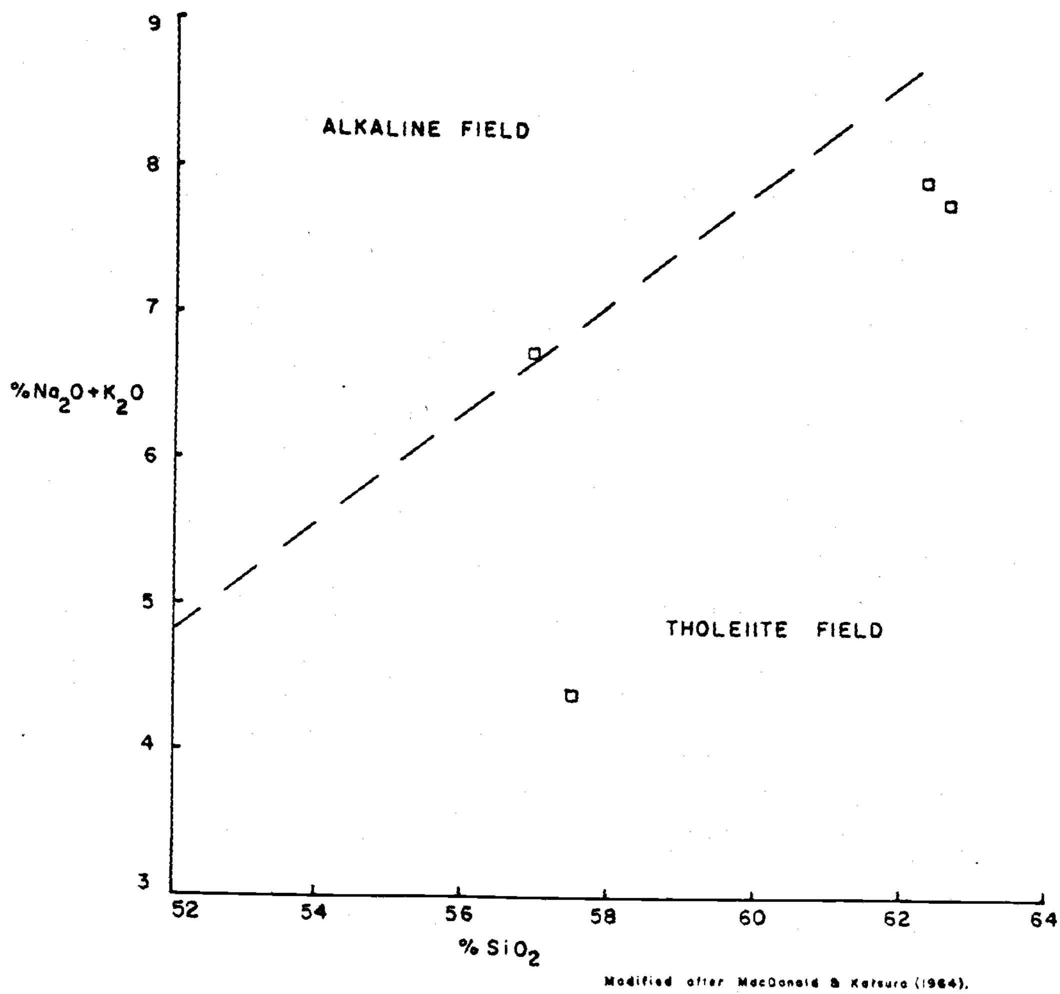


Figure 9. Alkali vs. silica diagram depicting the difference of tholeiitic and alkalic rocks and showing four samples from the upper Tillamook Volcanics in the study area.

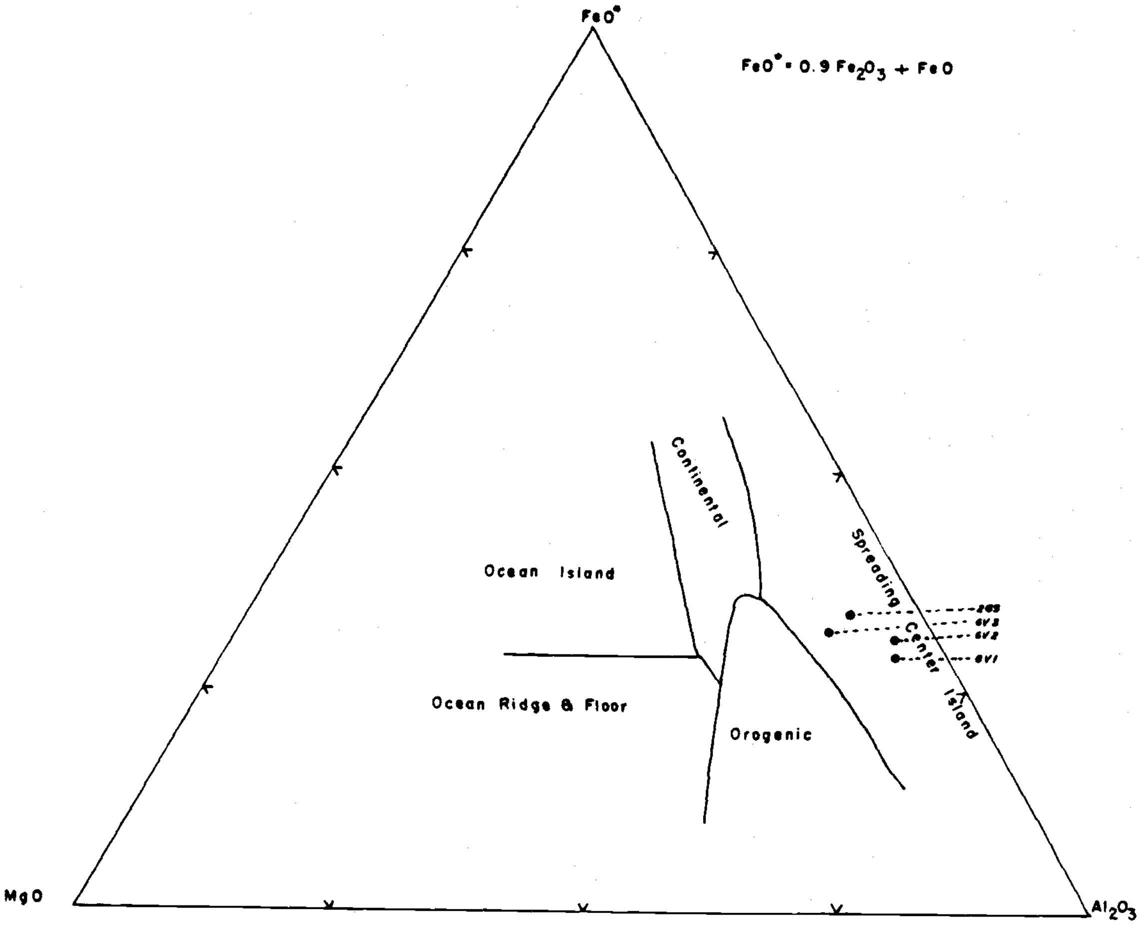


Figure 10. MgO-FeO*-Al_2O_3 geochemical discriminant diagram for Tillamook Volcanics (after Pearce and others, 1977).

Pearce and others (1977) attempted to relate the major oxide chemistry of subalkaline "basaltic andesites" to plate tectonic setting using a geochemical discriminant diagram of MgO-FeO-Al_2O_3 (Fig. 10). The four rocks analyzed from the Tillamook Volcanics in the thesis area fall within the "spreading center island" field. That is, the Tillamook Volcanic flows and intrusives most similar fit a differentiated mid-ocean ridge island, like Iceland. In a study of the Goble Volcanics, Beck and Burr (1979) found that the Goble rocks fall within the "orogenic" field on the MgO-FeO-Al_2O_3 discriminant diagram. This finding is significantly different from the results for four samples of Tillamook Volcanic rocks from the present study. These geochemical data thus suggest that the Tillamook Volcanics near Green Mountain are geochemically different from the Goble Volcanics exposed near the Columbia River.

Contact Relations

The base of the Tillamook Volcanics is not exposed in the thesis area. Regionally, the several thousand meter thick Tillamook Volcanics overlie the middle Eocene Yamhill mudstone (Wells and others, 1983; Armentrout and others, 1983) and are interbedded with marine sedimentary rocks of the Cowlitz Formation (Wilkinson and others, 1946; Warren and Norbisrath, 1946; Van Atta, 1971). The contact with the overlying Cowlitz Formation is an angular unconformity in the thesis area (Plates I and III). The unconformity truncates epiclastic volcanic breccias and intrusive rocks (Fig. 7). The Tillamook rocks dip approximately 20° southeast whereas the overlying Cowlitz strata dip 20° northward.

Age and Correlation

On the basis of similar K-Ar ages, major and trace element geochemistry, petrology, lithology, stratigraphic position and geographic proximity, the late Eocene volcanics in the uplifted outlier in the Jewell - Green Mountain - Elsie area are assigned to the upper Tillamook Volcanics. This is in agreement with the original mapping of the Tillamook highlands by Warren and others (1945), with the recent compilation geologic map of the western half of the Vancouver Sheet by Wells and others (1983) (Fig. 9), and with Olbinski's (1983) mapping of the Green Mountain area adjacent to this study.

Radiometric dating using whole rock K-Ar analysis of the Tillamook intrusive rock in an abandoned quarry on the Fishhawk Falls Highway (sec. 23, T5N, R7W) yields an age of 42.4 $\pm$ 0.5 m.y. A flow in the Tillamook Volcanics on the south flank of Green Mountain (sec. 34, T5N, R6W) yields a whole rock K-Ar date of 37.1 $\pm$ 0.4 m.y. (Kris McElwee, pers. comm., 1984). This is the youngest reliable date obtained from the upper Tillamook Volcanics so far.

A volcanic rock near the Fishhawk Falls Highway and the Nehalem River (south of the thesis area, sec. 3, T4N, R7W) yields an age of 41.6 ± 0.4 m.y. (Alan Niem, and Kris McElwee, pers. comm., 1984). The U. S. Geological Survey dated this same sample as 40.1 ± 1.2 m.y. (Leda Beth Parker and Parke D. Snavely, written comm. to Alan Niem, 1983).

Other ages of the upper Tillamook Volcanics outlier in the Jewell - Green Mountain - Elsie area are 37.1 ± 0.4 m.y. in the Rock Creek area on the south flank of Green Mountain (NE1/4, SE1/4, sec. 15, T4N, R5W; McElwee, pers. comm., 1984) and 43.5 ± 0.5 m.y. for a flow in the Columbia Quarry (NW1/4, SE1/4, sec. 22, T4N, R5W) near the top Cowlitz contact in Columbia County and 37.2 ± 0.4 m.y. for basaltic lavas in the Rocky Point Quarry (SW1/4, SW1/4, sec. 15, T4N, R5W; Kris McElwee, pers. comm., 1984).

Hence, the K-Ar whole rock dates of the Tillamook Volcanics range from 37.1 ± 0.4 to 43.5 ± 0.5 m.y., a span of 6.4 m.y. This places the uppermost part of the Tillamook Volcanics in the middle to late Eocene on Armentrout's (1981) time scale for the Pacific N.W. (Fig. 5).

The main Tillamook Volcanic pile, three to five km south of the study area, has yielded radiometric dates ranging from 40 to 45 m.y. near the upper part of the unit along the Nehalem River (Mumford and McElwee, pers. comm., 1983). Hence, there is an overlap of several million years between the K-Ar dates of the type Tillamook Volcanics to the south and in this study.

These observations suggest that the two areas are composed of the same volcanic unit. In the past, the late Eocene volcanic outlier of the Jewell - Green Mountain - Elsie area has been mapped as the Goble Volcanics, a younger unit that the Tillamook Volcanics (Wells and others, 1961; Newton and Van Atta, 1976). Beck and Burr (1979) reported that radiometric dating of the Goble Volcanics in southwest Washington yielded the following ages: 32.2 ± 0.3 m.y. and 35.9 ± 0.4 m.y. in the Toutle River area; and, 45.0 ± 1.4 m.y. and 41.4 ± 1.3 m.y. along Coweman Road (south of the Toutle River area). Kris McElwee (pers. comm., 1983) also reports unpublished whole rock K-Ar dates of 42.8 ± 1.2 m.y. for the type area of the Goble Volcanics along the Columbia River south of Longview, Washington and 41.5 ± 0.5 m.y. for the Goble Volcanics in the Willipa Hills, which was mapped by Wells (1981).

The dates of Goble rocks span late middle Eocene to latest Eocene ("Narizian" to "Refugian" Stages) on Armentrout's (1981) time scale (Fig. 5). Hence, the age range of the Goble Volcanics of S.W. Washington overlaps the age range of the upper Tillamook Volcanics of N.W. Oregon and are age correlative rocks. Most of the Goble Volcanics of S.W. Washington are more than 41 m.y. old and would be correlative to the lower Tillamook Volcanics along the Nehalem River which are dated 42.5 ± 0.4 m.y. at two localities: SW1/4, SE1/4, sec. 35, T4N, R8W; and, SW1/4, SE1/4, sec. 23, T5N, R7W.

The upper Tillamook Volcanics can be correlated to several other upper Eocene volcanic sequences that occur in western Oregon and Washington (COSUNA chart, Armentrout and others, 1983). These include: the Yachats Basalt (Snavely and MacLeod, 1974); and the Cascade Head volcanics (Barnes, 1981) along the central Oregon coast; the upper Eocene Unit B basalt in the Grays River area of S.W. Washington (Wolfe and McKee, 1972); the Hatchet Mountain Volcanics in the Toledo - Castle Rock, Washington area (Roberts, 1958); and, the Tukwila Volcanics near Renton and Seattle, Washington (Vine, 1962).

In summary, the upper Eocene volcanic outlier between Jewell and Elsie is correlated to the upper part of the type Tillamook Volcanics four to five km to the south on the basis of similar lithology, stratigraphic position and geochemistry. Both the type Tillamook Volcanics and the middle to late Eocene volcanics of this study area underlie the same facies of middle to late Eocene Cowlitz Formation (Safley, in prep; Mumford, in prep.). Both volcanic units are dominantly composed of subaerial basaltic to basaltic andesite flows, and minor dikes and volcanic breccias. Basaltic andesites, mudflows and intrusives appear to be more developed than other lithologies within this thesis area because only the uppermost part of the Tillamook Volcanics that immediately underlies the Cowlitz - Tillamook unconformity is exposed here.

Major element geochemistry of the two volcanic units also overlap on silica variation diagrams. The trace element chemistry of late Eocene rocks in the Green Mountain outlier and in the main Tillamook Volcanics mass to the south are similar (Jackson, 1983).

Geologic mapping along Highway 26 in southeast Clatsop County (Mumford, Safley, M.S. theses in prep.) has shown that this basalt outlier of Tillamook Volcanics actually consists of several horst-like blocks between a conjugate NE- and NW-trending fault system. The Cowlitz Formation is exposed, in the adjacent graben between the outlier and main Tillamook mass. Scattered fault exposures occur within one km of the Green Mountain outlier. This field evidence also suggests that the middle to late Eocene volcanics of the study area are indeed an uplifted part of the Tillamook Volcanic basement.

Paleomagnetism of the Tillamook Volcanics

Samples for paleomagnetic analysis were collected from three sites in and near the thesis area. The three sites are located and referred to as: 1. the west Buster Creek quarry (site GV1); 2. near the Nehalem River on the Fishhawk Falls Highway (site GV2); and 3. in the Cougar Mountain sills on Lukarilla Road southeast of the study area (site GV3). (See the Site Location Map in Appendix IX.)

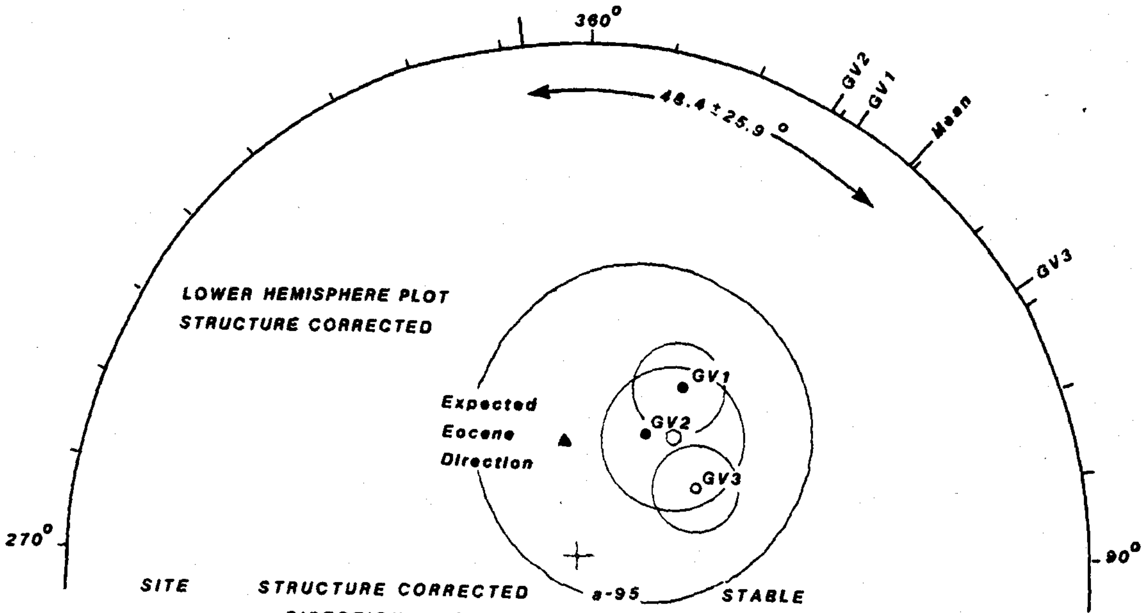
No detailed paleomagnetic investigation of the Tillamook Volcanics in the Green Mountain outlier has been published. Although three sites are insufficient for independent paleomagnetic analysis, the data can be utilized in future studies and is compared with the more extensive paleomagnetic analysis of the upper Tillamook Volcanics by Magill and others (1981).

From the three sites, 21 cores were recovered (7 from each site). All samples were magnetically cleaned using alternating field demagnetization (AFD) in peak fields of 100, 200, 300, 400, and 500 oersted (10-50 milliteslas). The data from each site show that duplicate specimens from each core correlate well (Table I). Some samples were subjected to 400-500 Oe. AFD treatments and the stable primary remanent direction at these levels was found to be parallel to the stable component after 200-300 Oe. treatments. Tilt corrections were determined from attitudes of overlying Cowlitz sedimentary strata (Plate I).

The part of the upper Tillamook Volcanics that was sampled appears to consist of normal and reverse polarity rocks. The Buster Creek quarry site (GV1) and the Nehalem River site (GV2) have reversed polarity; these sites are only 1 km apart. The Sports Acres site (GV3) has normal polarity and is located 5.7 km southwest of the Buster Creek site and 5.9 km from the Nehalem River site. Although only the uppermost part of the upper Tillamook volcanic pile was sampled, the presence of normal and reverse polarities indicate that at least two polarity epochs are represented. Based on whole rock K-Ar radiometric dates and stratigraphic position, the reverse polarity epoch represented by the Buster Creek quarry site (GV1) is the younger event. The age of the andesite dike sampled at this site has not been reliably determined but is probably 42 m.y. like the nearby sample collected at the abandoned Fishhawk Falls Highway quarry (sec. 23, T5N, R7W) which yields a K-Ar date of 42.4 $\pm$ 0.5 m.y. The dike in the Buster Creek quarry intrudes mudflow deposits which are immediately overlain by the Cowlitz - Tillamook unconformity. This unconformity also truncates the sampled dike (Fig. 7).

The Sports Acres site consists of upper Tillamook Volcanics that are believed to be slightly older than the rocks at Buster Creek. The site is south of site GV1 and thus lower in the north-dipping stratigraphic section. Therefore, the normal polarity epoch represented by the Sports Acres site preceded the reversed epoch the Buster Creek rocks.

The Nehalem River site (GV2) occurs in a fault zone and samples collected here were fractured. Several cores shattered during cutting and preparation and could not be used, resulting in an exceptionally high scatter of observed paleomagnetic directions (Fig. 11). It is not known with certainty whether or not the Nehalem River site represents the same reversed paleomagnetic polarity epoch as the Buster Creek site (GV1).



SITE	STRUCTURE CORRECTED DIRECTION (D, I)		a-95	STABLE AFD LEVEL
GV1	32^{o}	-49^{o}	9.7^{o}	400 Oe.
GV2	28.7^{o}	-60.3^{o}	33.1^{o}	400 Oe
GV3	58^{o}	61.8^{o}	9.5^{o}	100 Oe.
MEAN OF SITES	38.5^{o}	57.7^{o}	16.6^{o}	

Figure 11. Upper Tillamook Volcanic paleomagnetic directions for three sites in the study area. These are structure corrected data and are restored to horizontal using an attitude of N85^{o}E, 19^{o}N, which closely fits the present-day orientation of the upper Tillamook Volcanics. The mean of sites is 38.5^{o}, 57.7^{o} (D,I), with an a-95 of 16.6^{o}, indicating clockwise rotation of 48.4 ± 25.9^{o} from the expected Eocene direction (designated by triangle; Irving, 1979). GV1 and GV2 (both reverse polarity) are projected through the origin to the lower hemisphere; GV3 has normal polarity.

The paleomagnetic directions of the three sites (17 core specimens used) is consistent with the hypothesis of clockwise tectonic rotation of this area. The observed clockwise rotation is 48.4°$\pm$25.9°, where the uncertainty in rotation corresponds to a 95% confidence level (alpha-95). The upper Tillamook Volcanics in northern Tillamook County also show clockwise rotation of 46°$\pm$13°, a value which overlaps these three sites in the Green Mountain outlier, and suggests that the rocks are paleomagnetically related (Fig. 11). The rotation expressed by these rocks is unlike that of the Goble Volcanics of S.W. Washington which have undergone considerably less clockwise rotation of 23°$\pm$19° (Wells, 1982; Beck and Burr, 1979).

The observed inclination of the upper Tillamook Volcanics in the Green Mountain outlier, after tectonic tilt correction, is 57.5°. This is not significantly different than the expected value of the middle Tertiary pole of the North American craton (350° declination, 65.4° inclination; Irving, 1979), nor is it different from that observed from the upper Tillamook mass to the south (64°; Magill and others, 1981).

Cowlitz Formation

Nomenclature

The Cowlitz Formation was originally defined by Weaver (1912) as a 200-foot (61 m) section, 2.4 km east of Vader, Lewis County, southwest Washington. This is the "Big Bend" locality on the Cowlitz River just downstream from its confluence with Lacamas Creek. In 1937, Weaver expanded the definition to include 1,310 m of strata along Olequa Creek. Henriksen (1956) expanded the definition of the Cowlitz Formation to include 1,646 m of sedimentary rocks and minor intercalated volcanic rocks overlying the Metchosin Volcanics (middle Eocene). The Metchosin Volcanics are now called the Crescent Formation (lower to middle Eocene) in southwest Washington.

In the Centralia - Chehalis, Washington area, Snavely and others (1951) referred to stratigraphic equivalents of the Cowlitz Formation as the McIntosh, Northcraft and Skookumchuck formations, in ascending stratigraphic order. The Skookumchuck is stratigraphically equivalent to the upper part of the Cowlitz Formation that Weaver (1912, 1937) defined and to the Cowlitz Formation of northwest Oregon. Snavely and others (1951) described the Skookumchuck as a shallow-marine neritic deposit. Buckovic (1979), describing rocks from the same area as these earlier workers, referred to the McIntosh, Northcraft and Skookumchuck formations, collectively, as the "Cowlitz Formation". He correlated this formation to the Puget Group of west-central Washington. The Puget Group contains several formations of the middle to upper Eocene Puget deltaic system. Armentrout (1973) and Yett (1979) wrote definitive papers on the molluscan faunas and microfossils of the type Cowlitz Formation in southwest Washington.

The Cowlitz Formation in northwest Oregon was first mapped by Warren and others (1945). The sedimentary rocks are composed of basal conglomerate, siltstone, mudstone, sandstone and intercalated volcanic materials that unconformably overlie the Tillamook Volcanics. Faunas are correlative to the type Cowlitz Formation of Washington. Warren and Norbisrath (1946) divided the Cowlitz Formation of northwest Oregon into four informal members: a basal conglomerate of variable thickness, a lower shale member, a sandstone member 200 to 300 feet (61 to 91 m) thick, and an upper shale member. These workers estimated the overall thickness of the Cowlitz Formation to be 290 m.

Van Atta (1971), Timmons (1981), Newton and Van Atta (1976), Olbinski (1983) and Jackson (1983) have further described the sandstone petrography, stratigraphy, facies and depositional environments of the Cowlitz Formation of northwest Oregon. Olbinski (1983) recognized and mapped five informal members in the Cowlitz Formation in southeast Clatsop County; these correlate well with the four members recognized in the present study.

Distribution

Warren and Norbisrath (1946) described the Cowlitz strata as occurring in creeks northwest of Green Mountain, in Rock Creek near Keasey, at Rocky Point southwest of Vernonia, and along the Wolf Creek Highway (Sunset Highway, U.S. Highway 26). None of these areas are included in the thesis area, but Warren and others (1945) do show one fossil locality which they considered Cowlitz in the thesis area. This is located near the bridge over the Nehalem River at the common corner of sec. 21, 22, 27, and 28, T5N, R7W (locality FM-20 of Warren and others, 1945). I have included this locality in the lower sandstone member of the Cowlitz Formation ($Tc_{2,3}$; Plate 1).

Within the thesis area, the Cowlitz Formation crops out in the southeast part over approximately 10 square km and a 465-m-thick section (Plate 3) is exposed discontinuously along the Fishhawk Falls Highway three km south of Jewell. Outcrops occur in roadcuts, in ditches and in some places in the Nehalem River bed at summertime low water levels. Strata strike generally east-west and average 15° northward dip (Plate 1).

Four informal members are recognized. The basal conglomerate member (Tc_1) is discontinuously exposed along the Fishhawk Falls Highway in roadcuts and ditches (Plate 3), but good exposures occur in two quarries on the Buster Creek road (NW1/4, sec. 25, T5N, R7W). An angular unconformity between the underlying Tillamook Volcanics and overlying Cowlitz Formation is well-exposed in both quarries (Fig. 7).

The conglomerate members and lower sandstone (Tc_1 and $Tc_{2,3}$) of the Cowlitz Formation are relatively resistant to erosion and form low dissected hills and slopes adjacent to the high elongate ridges cored by volcanic rocks. Where the southward-flowing Nehalem River, in the southeastern part of the map area, cuts through the Cowlitz units, it lacks the broad floodplain that tends to be well-developed where the bedrock is composed of the less-resistant mudstone of the Keasey Formation.

The lower sandstone member ($Tc_{2,3}$) is best exposed along the Nehalem River and in highway cuts between sec. 23 and 24, T5N, R7W (see measured section, Plate 3), in old logging roadcuts, in forest service roadcuts, above the Nehalem River bridge (SE1/4, sec. 22, T5N, R7W), in the Nehalem River in sec. 28, T5N, R7W, and along Buster Creek road (sec. 26, T5N, R7W).

The overlying turbidite member (Tc_3) is well exposed in roadcuts along the Fishhawk Falls Highway, three km south of Jewell (locality 236, sec. 14, T5N, R7W). The overlying arkosic sandstone member (Tc_4) overlies the turbidite member at this same locality.

Lithologies, Structures and Provenance

Conglomerate Member. The basal volcanic conglomerate (Tc_1) consists of rounded to angular boulders and cobbles of basalt, basaltic andesite, andesite and rhyodacite derived from local Tillamook volcanic source areas. The member has a maximum thickness of 60 m and pinches out to the west (Plate 1). The unit thickens to the east in the adjacent thesis area (Olbinski, 1983). The poorly sorted conglomerate reflects a marked period of subaerial and coastal sea cliff erosion of the Tillamook volcanics prior to the dominantly shallow marine shelf deposition of the overlying volcanic and arkosic sandstones and mudstones of that comprise most of the Cowlitz Formation (Plate 3). Marine diatoms collected from interstratified mudstone (locality 446, Coscinodiscus marginatus Ehrenberg) suggest that the conglomerates and sedimentary breccias were deposited at or very near sea level.

The basal conglomerate consists of several thick, structureless, very poorly sorted, epiclastic volcanic boulder-cobble-pebble conglomerate beds and debris flow breccias with minor thin dark gray mudstones and volcanic sandstone interbeds (Appendix XII; Fig. 12). Boulders and cobbles in the conglomerate range in size from 15 x 30 cm (major and minor diameters) to 30 to 90 cm (-7 to -9 phi). These clasts are dominantly (up to 90%) a mixture of gray vesicular to dense plagioclase-porphyritic and aphyric basaltic andesite and basalt. Some subrounded light gray to buff clasts of hydrothermally altered pyritized basalt and rarer light gray to buff rhyodacite clasts are present.

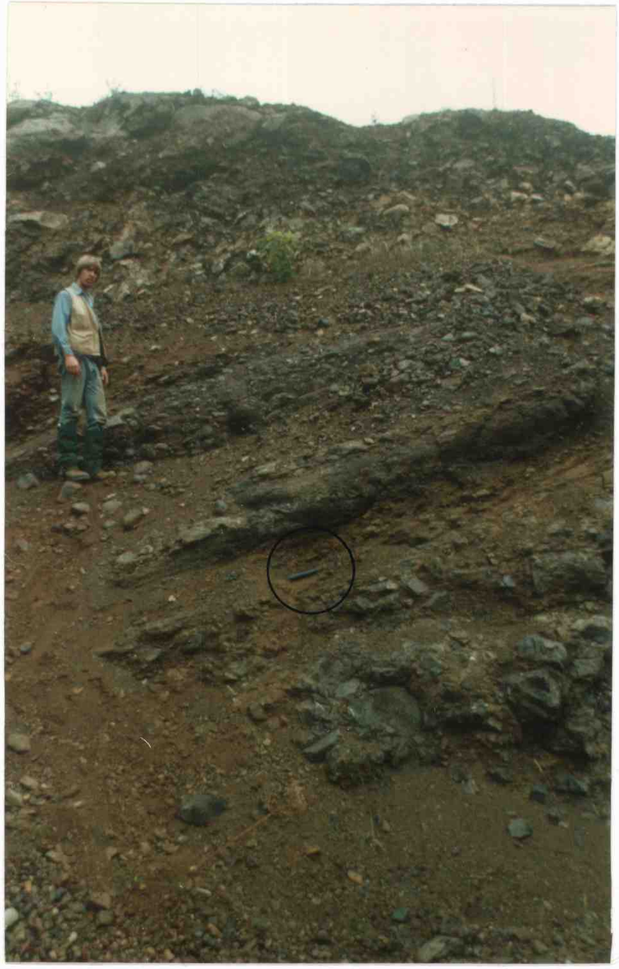


Figure 12. Epiclastic volcanic conglomerates and debris flow breccias of the basal conglomerate member (Tc_1) of the Cowlitz Formation. The conglomerate beds are unstratified and contain smaller subrounded clasts (as at geologist's feet). Debris flow breccias consist of larger angular clasts, are more poorly sorted and are in matrix support (e.g., below hammer, circled). Locality 268, west Buster Creek quarry.

Smaller, less-resistant, amygdaloidal and scoriaceous basaltic andesite clasts are less abundant (up to 10% in some beds) and contain hollow cavities partly filled with quartz crystals (geodes). Clasts in the conglomerate beds are in framework support and are subrounded.

In the debris flow deposits, the breccias are in matrix support and are angular to subangular and generally contains much larger clasts. The matrix consists of coarse grained basaltic volcaniclastic sandstone which is grayish yellow green (5 GY 7/2). Most conglomerates and debris flow breccias are poorly sorted and unstratified and range from one to three meters in thickness (Fig. 12; Appendix XII).

One leucocratic, aphanitic clast (20 x 25 cm) of particular interest was analyzed geochemically (Appendix VI) and petrographically. This rock (sample 268G), from the west Buster Creek quarry, contains 70.5% SiO_2, is depleted in iron and magnesium and is enriched in alumina (16% by weight). It is a peraluminous rhyodacite and is interpreted as a rhyolitic differentiate. Wells and others (1983) show the occurrence of several siliceous masses within the upper Tillamook Volcanics which could have served as a source for this clast.

Petrographic textures of this sample (265G) are a hypidiomorphic-porphyritic feldspar-phyric framework set in a microcrystalline siliceous groundmass. The feldspar microlites have a trachytic alignment. Potassium feldspar (4.36 wt.% K_2O) comprises 85-90% of the groundmass.

Leucoxene was also observed in the groundmass. Overall, the rock is composed of 90% feldspar that appears fresh and unaltered.

Some conglomerate and breccia beds above the Buster Creek quarries contain abundant highly vesicular clasts (up to 50%) which may be derived from Tillamook volcanic flow tops and/or local cinder cones. Olbinski (1983) reported finding similar rock types in the adjacent thesis area.

A few poorly preserved diatom fragments (sample 446) were found in the thin, one to two meters thick, dark gray mudstone interstratified with the conglomerate above the west Buster Creek quarry. These diatoms are *Coscinodiscus marginatus* Ehrenberg 1843. This fossil is not useful for stratigraphic correlation but it is restricted to the marine environment (Jack Baldauf, written comm., 1982).

Lower Sandstone Member. The basal conglomerate (Tc_1) grades upward into a 300-m-thick unit consisting of interbedded volcanic and arkosic micaceous sandstones. I have included within this unit a poorly exposed, and unknown thickness of, mudstone(?) which correlates to a mudstone unit mapped by Olbinski (unit Tc_3, 1983). The poorly exposed mudstone unit may be included in the covered part of the measured section between 800 and 1,100 foot markers (Plate 3). Collectively, then, these two lithofacies are named the lower sandstone member ($Tc_{2,3}$) (Fig. 13).

The lower sandstone member apparently undergoes a facies change toward the southwest part of Columbia County

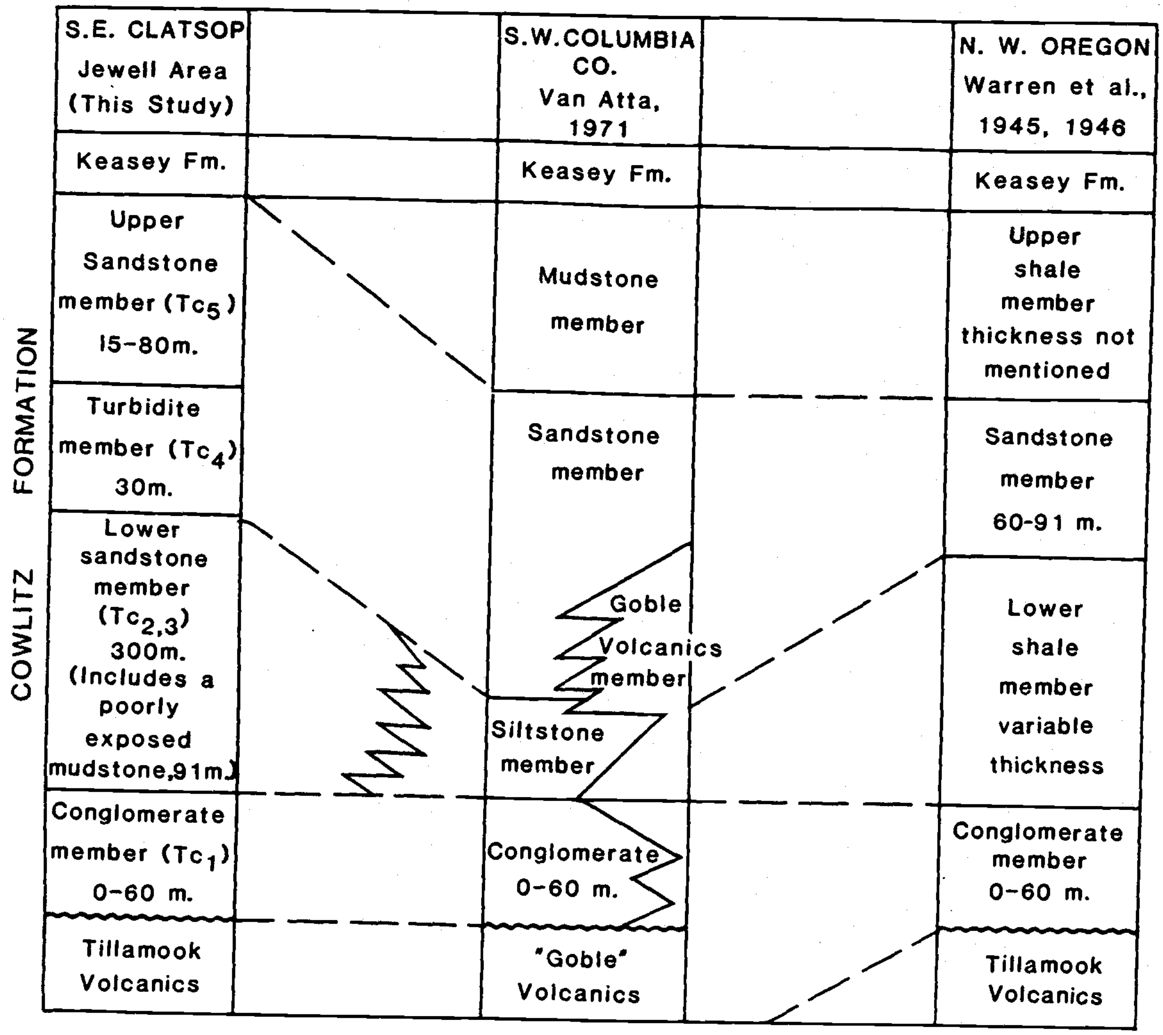


Figure 13. Correlation of the informal members of the Cowlitz Formation as used in this thesis to those of previous workers.

and correlates to the siltstone member of Van Atta (1971) (Fig. 13).

Fossils are scarce in the lower sandstone member. One Dentalium sp. was recovered from the middle part of the measured section (locality 435) and the trace fossil Planolites, a sub-vertical burrow, was found at the same locality.

Lithology of the Lower Sandstone. The lower 135 m (450 ft.) of the lower sandstone member ($Tc_{2,3}$) consists of well-indurated, coarse grained, thick bedded, volcanic sandstone and subordinate micaceous lithic arkosic sandstone. In the upper part of the measured section along Fishhawk Falls Highway, thinner micaceous arkosic fine grained sandstone and mudstone are interbedded with the subordinate coarse grained volcanic-arkosic sandstone (Plate 3).

The sandstones classify as volcanic-arenites and volcanic-plagioclase arkoses (Fig. 14). They are composed almost exclusively of basaltic andesite and andesite fragments with pilotaxitic flow texture of plagioclase microlites in an opaque glassy groundmass. They are compositionally and texturally similar to the underlying Tillamook Volcanics from which they were probably derived. Other grains include plagioclase (labradorite?), augite (?) and magnetite in a pore-filling sparry calcite matrix.

In outcrop, the volcanic sandstones are thin bedded to thick bedded and medium to coarse grained. The

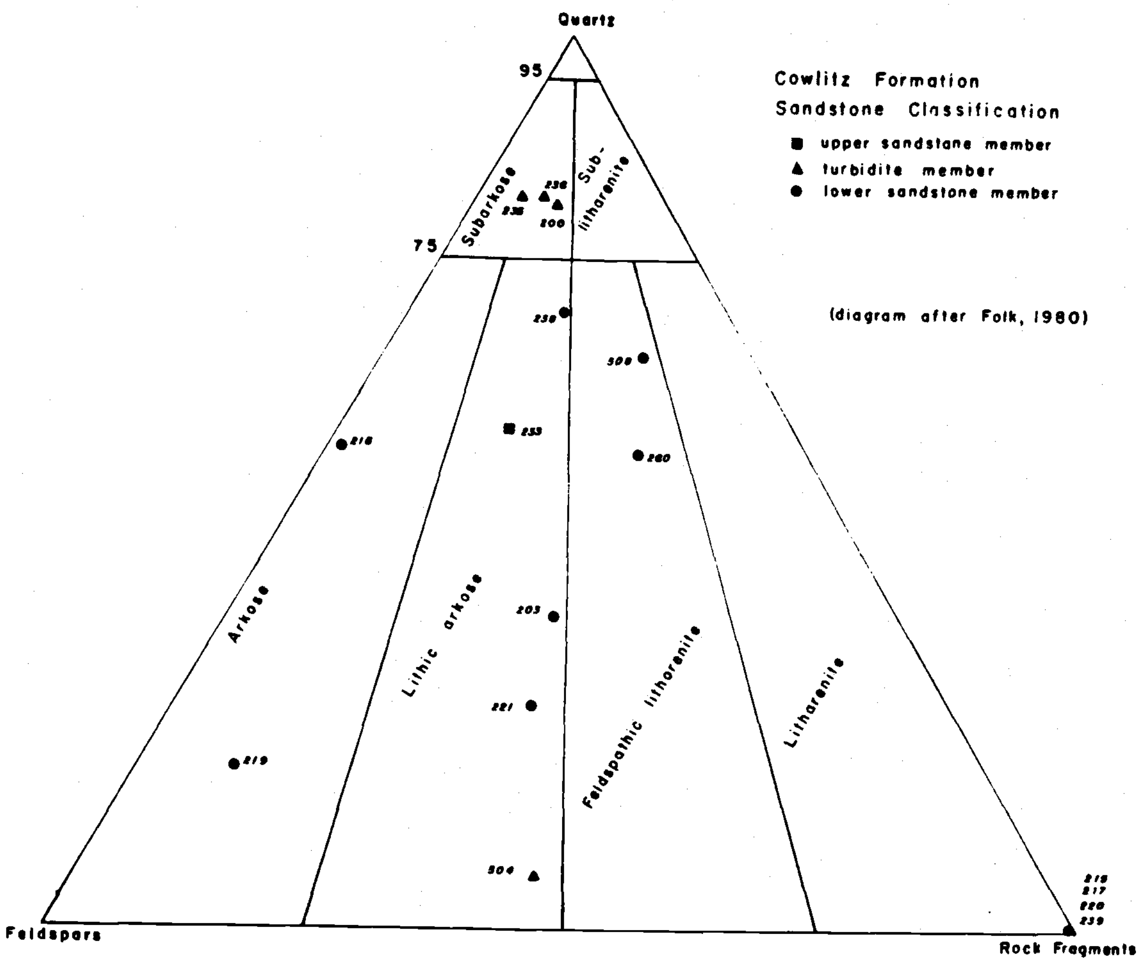


Figure 14. Cowlitz sandstone classification diagram

well-indurated volcanic sandstones are tightly cemented by calcite, clay(?) and iron oxides. Commonly, concentrations of comminuted carbonaceous debris occur on bedding planes. Fresh exposures are greenish olive gray (5 Y 3/2) but weather to light olive gray (5 Y 5/2) and moderate brown (5 YR 4/4). The detrital grains are angular to subrounded and moderately to poorly sorted (Fig. 15). The sandstones are texturally and compositionally immature (Folk, 1980), suggesting rapid deposition and burial after derivation from a high rugged relief area.

Arkoses and lithic arkoses are micaceous, containing both biotite and muscovite in a 4:1 ratio. The mica and carbonized wood fragments define bedding planes in some parallel laminated sandstones. Mica shows crenulation due to compaction during burial.

In thin section, biotite shows various stages of chemical weathering. Loss of iron is evident from the formation of "green biotite" and limonite. Muscovite, however, is relatively unaltered.

Arkosic sandstones are loosely consolidated and poorly cemented. Minor iron oxide and diagenetic clay rims around detrital grains act as a weak cementing agent. Such cements commonly form at shallow burial depths and low geothermal gradients in fore-arc regions (Galloway, 1974). Two blue-dyed epoxy-impregnated thin sections have 7 to 12% (point counted) intergranular porosity (Fig. 16). Evidence

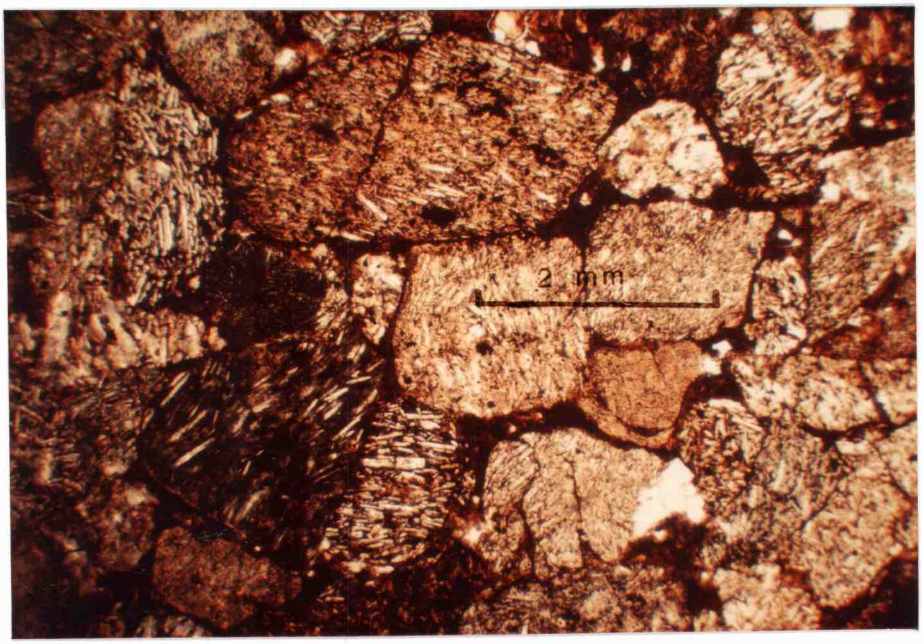


Figure 15. Photomicrograph of volcanic-arenite from the lower sandstone member ($Tc_{2,3}$) of the Cowlitz Formation. The framework clasts of the sandstone are very coarse sand to granules, are poorly sorted and subrounded. Note the pilotaxitic flow texture of the andesitic to basaltic andesite rock fragments that are predominant in this slide. Locality 215, 28x, plane light.

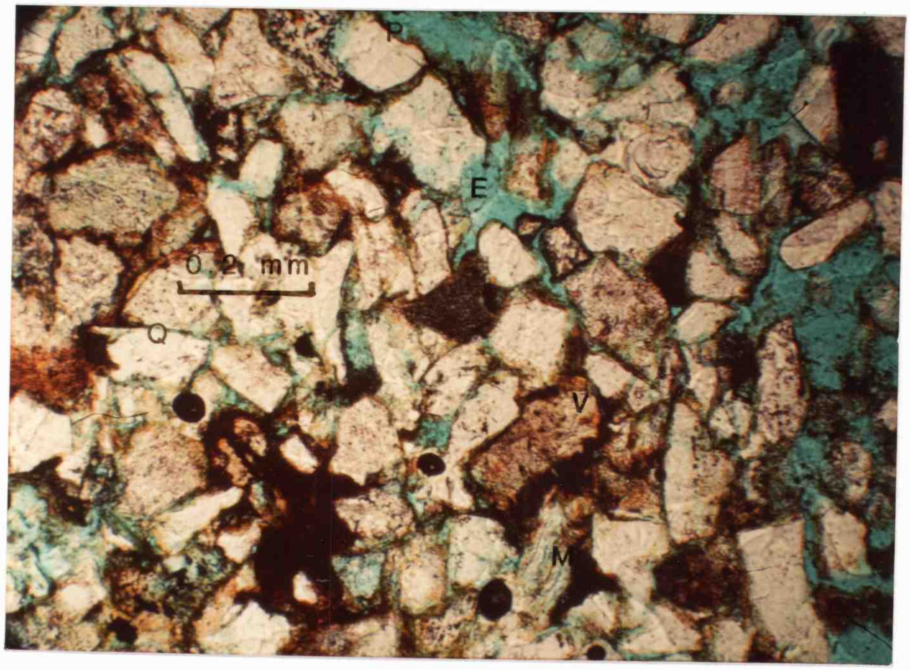


Figure 16. Photomicrograph of lithic arkose (volcanic-plagioclase arkose) from the lower sandstone member ($Tc_{2,3}$) of the Cowlitz Formation. Blue dyed epoxy medium demonstrates intergranular porosity (10%). Note plagioclase (P), quartz (Q), volcanic rock fragments (V), epidote (E) and mica (M) grains with abundant clay rim cements (opaque material around framework grains). Locality 203, 80x, plane light.

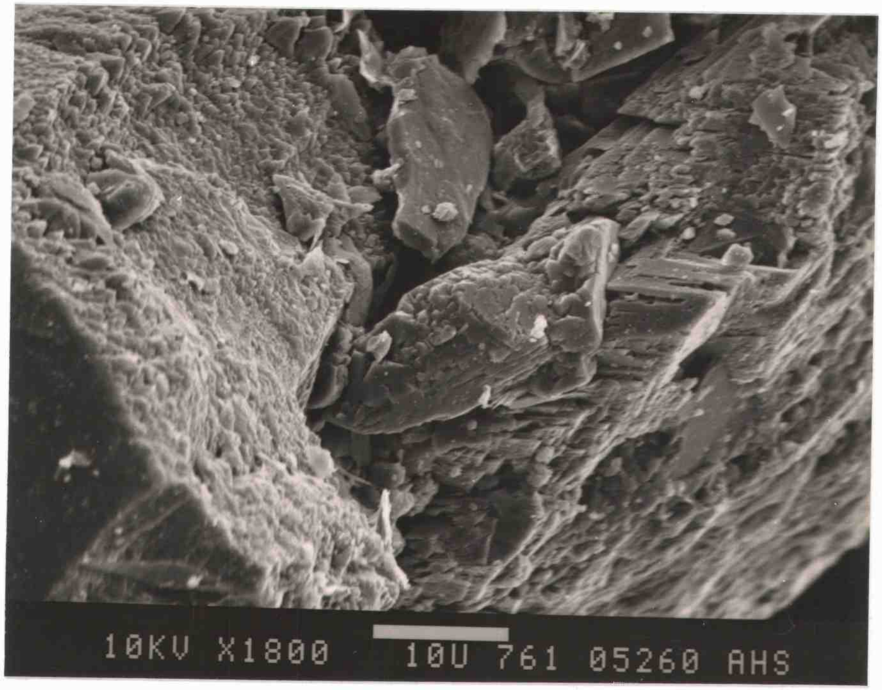


Figure 17. Scanning electron photomicrograph of detrital feldspar grain from arkose in lower sandstone member ($Tc_{2,3}$) of the Cowlitz Formation. Note corrosion along cleavage planes of the feldspar suggestive of diagenesis and secondary porosity development. Bar scale is 10 microns, magnification 1800x.

for secondary porosity development is minor and consists of some solution of feldspars along cleavage planes (Fig. 17).

Lithic arkoses and arkoses are moderately to well sorted and contain subangular to rounded framework grains. Compositional maturity is quite varied, ranging from submature to mature depending on the admixture of volcanic rock fragments. These sandstones are generally texturally mature which reflects prolonged winnowing of detrital clays and sorting by waves and currents (Folk, 1980).

In thin section, the arkoses consist of monocrystalline quartz (5-25%), polycrystalline quartz (4-15%), plagioclase (5-35%), potash feldspar (<5%), mica (3-35%), volcanic rock fragments (1-5%) (probably basaltic andesite and andesite) and minor plutonic rock fragments (<5%). Minor amounts (<1-2%) of glauconite, chlorite and zircon were also observed. Carbonate (probably calcite) is a common pore-filling cement.

A mixed local intermediate volcanic and distant metamorphic-siliceous plutonic provenance is suggested from petrographic and heavy mineral studies. The abundance of intermediate volcanic rock fragments and subangular plagioclase in the volcanic arenites indicate a basaltic to intermediate volcanic source terrain. These sandstones, like the basal basaltic conglomerate member (Tc_1), probably were derived from nearby Tillamook Volcanics highland areas. However, the abundance of potash feldspar with plagioclase, muscovite and biotite in the arkoses suggest that more distant granitic and metamorphic sources also supplied detritus.

Possible source areas include the Jurassic and Cretaceous plutonic rocks of the Idaho Batholith and the Precambrian metamorphic rocks of northeast Washington in the Okanogan highlands. Van Atta (1971) reached a similar conclusion for the Cowlitz arkoses in Columbia County.

Heavy minerals give further confirmation of a metamorphic source for the Cowlitz arkoses. Grain mounts of four arkosic arenite samples (203, 219, 238, 432) from different stratigraphic levels in the lower sandstone member (see measured section, Plate 3) yield an assemblage of heavy minerals rich in epidote (31-41%), garnet (1.5-12%), apatite (4-15%) and less abundant kyanite and rutile. All of these are derived from crystalline metamorphic rocks (Milner, 1940).

Epidote is most abundant and occurs in greenschist-grade and contact metamorphic rocks associated with hydrothermally altered calcareous country rocks. It is not clear what particular rocks in the Cowlitz drainage basin may have contributed the abundance of epidote observed. It seems out of proportion with the diverse nature of the metamorphic and siliceous plutonic source terrains. Alternatively, the abundance of epidote may reflect the selective removal of other less-stable heavy minerals by diagenetic processes.

The Cowlitz arkosic sandstones are interpreted to have been redistributed by longshore and other marine currents around the adjacent Tillamook volcanic highlands and surrounding apron of basaltic gravel and sands thus creating a mixed sediment source for this lower sandstone member. The lack of siliceous pyroclastic clasts (e.g., pumice, shards) suggests that the western Cascades of Oregon were not developed at this period of Cowlitz deposition.

Turbidite Member. The 30-m-thick turbidite member (Tc_4) overlies the lower sandstone member ($Tc_{2,3}$) (Plate 3; Fig. 13). The nature of the contact between the turbidite member and the underlying sandstone unit is not known as it is not exposed. I correlate the turbidite member with the sandstone members described by Warren and Norbisrath (1946) and Van Atta (1971) (Fig. 13). It also correlates directly with the turbidite unit (Tc_4) of the Cowlitz Formation in the adjacent thesis area (Olbinski, 1983).

Farther east, an outcrop in Rock Creek, 0.8 km south of the village of Keasey in Columbia County, is virtually identical in lithology, sedimentary structures and stratigraphic position to the turbidite member (Tc_4). This sandstone sequence occurs immediately below the unconformable Cowlitz - Keasey contact.

This unit consists of alternating 5- to 15-cm-thick beds of laminated micaceous mudstone and fine grained micaceous, subarkosic sandstone (Fig. 18). Mudstone beds contain abundant Helminthoida trace fossil burrows. The

Figure 18. Photograph of the turbidite member (Tc_4) of the Cowlitz Formation. Note the light colored thin sandstone turbidite beds that are separated by darker gray siltstone and mudstone interbeds. A 2-m-thick Miocene (Grande Ronde) basalt sill (arrow) intrudes the sedimentary rocks. Locality 236, on Fishhawk Falls Highway, 3 km south of Jewell.

beds are dusky brown (5 YR 2/2) in color. Sandstone interbeds have sharp basal contacts with the underlying mudstone, gradational upper contacts and contain Bouma T_{abc} and T_{de} sequences. Bouma T_{de} layers are very thin, commonly less than 1 mm thick. Individual sandstone beds display graded bedding, parallel laminations and micro-cross-laminations. A single unidirectional paleocurrent measurement of cross-laminations in a sandstone bed is oriented N 5° W (locality 236).

Elongate calcareous concretionary ledges occur discontinuously in certain sandstone beds. Thin sections of the concretionary layers reveal that sparry pore-filling calcite cement is displacively precipitated causing detrital framework constituents to be wedged apart. Some volcanic rock fragments are entirely replaced by the sparry calcite.

The subarkosic sandstones plot in a cluster on Folk's (1980) sandstone classification chart (Fig 14). Quartz comprises 30 to 40% of the clastic constituents, whereas feldspar makes up 6 to 11%. Monocrystalline and polycrystalline quartz are present, but monocrystalline types predominate. Plagioclase is much more abundant than potassium feldspar. Coarse biotite and flakes of muscovite, in a 3:1 ratio, form 5 to 10% of the framework constituents. The sandstones are typically very fine grained, well sorted, subrounded, texturally and compositionally mature.

Grain size, graded bedding, Bouma T_{abc} and T_{de} sequences and Helminthoida burrows suggest that turbidity currents were operative in the deposition of these subarkosic sandstones in a bathyal or slope environment. No age-diagnostic fossils were recovered from the turbidite member.

A mixed intermediate volcanic and siliceous plutonic provenance is indicated by the andesite rock fragments, coarse grained biotite, K-feldspar, and monocrystalline and polycrystalline quartz. Intermediate volcanic and granitic plutonic rock fragments are rare, yet indicate that volcanic and plutonic terrains were being denuded and supplying fine grained detritus to the sedimentary basin (Fig. 19).

Plagioclase compositions of andesine suggest that the volcanic terrain was more intermediate than mafic. Possible volcanic sources include the Colestin Formation and possibly the Little Butte Volcanics of the western Oregon Cascades and the Tillamook Volcanics. The plutonic and high grade metamorphic detrital grains are probably sourced from crystalline basement rocks exposed in northeast Washington, eastern Oregon, western Idaho and British Columbia.

One grain mount was made of the subarkose from the turbidite member (sample 243). The heavy mineral assemblage in this sample is rich in epidote (23%), apatite (26%), zircon (15%) and garnet (13%). Zircon and apatite may be derived from a silicic plutonic source. Epidote may be weathered from the contact metamorphic aureole associated with igneous intrusion in calcareous country rocks or from greenschist-grade mafic rocks. Garnet is probably derived

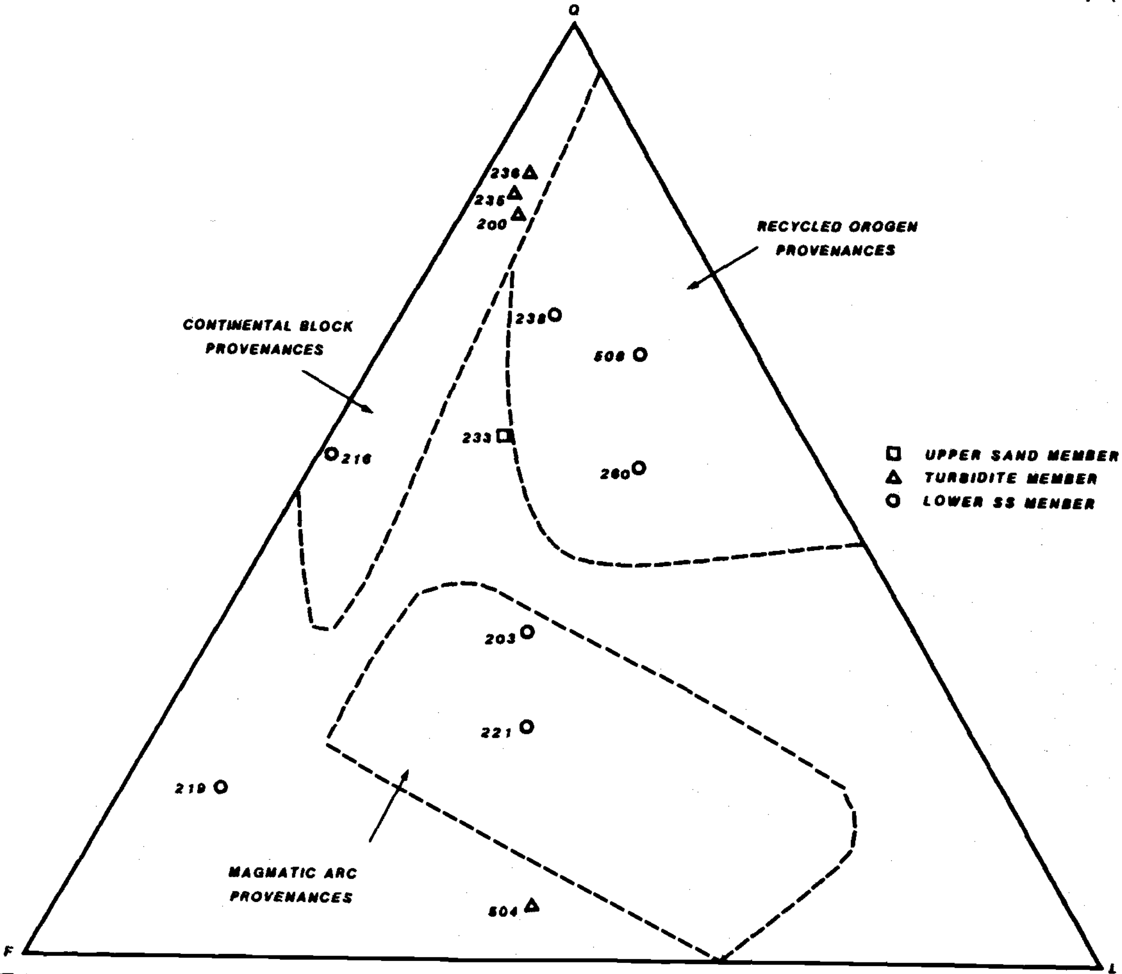


Figure 19. Triangular QFL provenance classification diagram (after Dickinson and Suczek, 1978) indicates mixed source areas for Cowlitz sandstones. The original provenance fields of the mean framework modes of selected sandstone suites were determined by Dickinson and Suczek (1978). These data suggest that Cowlitz turbidite sandstones (Tc_4) were derived from denuded continental block materials. The scatter of arkosic sandstone samples from the lower sandstone member ($Tc_{2,3}$) suggests a mixed influence of all three provenances.

from crystalline metamorphic rocks, or less commonly, from silicic plutonic rocks (Milner, 1940).

Upper Sandstone Member. The zircon-rich upper sandstone member (Tc_5) is correlated to parts of the sandstone members of Warren and Norbisrath (1946) and Van Atta (1971) (Fig. 13). This member lacks preserved fossils and is exposed in weathered outcrops in the thesis area making exact correlations difficult. The unit is best exposed in the measured section along the Fishhawk Falls Highway three km south of Jewell where it is at least 15 m thick and the top contact is covered (Plate 3). A 40-m-thick section of sandstones that are petrographically and stratigraphically similar to the upper sandstone member (Tc_5) occurs in the southeast part of the Nehalem Valley - Buster Creek area (Olbinski, 1983). Overlying the zircon-rich sandstones are 80 m of epidote-rich sandstones (Olbinski, 1983, p.65). The upper sandstone member is tentatively correlated to the 230-m-thick "Clark and Wilson" sand that is present in the subsurface in the Mist, Oregon area (Mr. Larry O'Connor, pers. comm., 1982). The upper sandstone member (Tc_5) appears to thin or is truncated to the west by the overlying Jewell member of the Keasey Formation (Plate 1).

In outcrop, the upper sandstone member is massive, poorly consolidated and weathered. Fresh exposures display low-angle cross-stratification and parallel stratification.

Petrographically, the rock classifies as a lithic arkose (Folk, 1980) (sample 233, Fig. 14). It is medium grained, moderately sorted and is composed dominantly of subangular to subrounded monocrystalline and polycrystalline quartz and albite-twinned plagioclase. The abundance of monocrystalline quartz exceeds that of polycrystalline quartz by 2:1 and plagioclase is more abundant than K-spar by a 9:1 ratio. The matrix consists of chloritic clay and abundant yellowish-red limonite cement. The sandstone is friable and poorly cemented by limonite. Much of the limonite is probably due to surface weathering and oxidation of biotite and volcanic rock fragments which has significantly reduced primary porosity. The rock is texturally immature and compositionally submature; however, the textural immaturity (e.g., clay matrix) may be due to the degree of weathering and diagenesis.

A mixture of sources is indicated by thin section and grain mount studies. Mudstone fragments comprise 4% of the framework fragments, suggesting penecontemporaneous erosion of earlier-deposited Cowlitz mudstone. Metamorphic and intermediate volcanic rock fragments also comprise a minor proportion (4%) of the rock.

The heavy mineral assemblage (sample 233) is rich in euhedral zircon (34%), apatite (18%), tourmaline (6%) and garnet (20%). Zircon, apatite and tourmaline are indicative of a silicic plutonic provenance (Milner, 1940). Garnet may be derived from either a crystalline metamorphic area or, less commonly, from silicic plutonic rocks and contact metasomatic aureoles.

The upper sandstone member (Tc_5) contains a zircon-rich heavy mineral assemblage which correlates with the zircon-rich arkosic sands (Tc_5) of Olbinski (1983) (e.g., the Waage Road section 11 km to the east) and with the zircon-rich arkosic sands in the Quintana "Watzek" #30-1 well 6.5 km to the north. The plagioclase, K-spar, monocrystalline and polycrystalline quartz, muscovite and biotite all suggest a distant eastern plutonic source of granitic and high grade metamorphic (e.g., gneiss) rocks for the upper sandstone member of the Cowlitz Formation.

Contact Relations

The basal conglomerate (Tc_1) of the Cowlitz Formation overlies the Tillamook Volcanics with angular discordance. This relationship is well exposed in two basalt quarries on the Buster Creek road (N1/2, sec. 25, T5N, R7W; Fig. 12). The angular unconformity truncates basaltic andesite feeder dike systems that intrude Tillamook volcanic breccias. The erosional surface is uneven (Fig. 12). The beds of volcanic breccia dip 30° to 40° southeast. The overlying Cowlitz conglomeratic sandstone dips 20° to 30° northward. It is possible that the intrusion of the dike system may have tilted the Tillamook breccias slightly, and therefore attitudes taken from the quarry do not represent regional dip of the Tillamook section.

The angular unconformity is also inferred at a locality along the Fishhawk Falls Highway (SE1/4, SW1/4, sec. 23, T5N, R7W, north of road). It is interpreted that this area is far enough removed from the Buster Creek intrusive center that these Tillamook beds are not deformed by igneous intrusion. Here, two subaerial flows of the Tillamook Volcanics are separated by a sandstone interbed. The beds strike N 80° W and dip 35° S. The overlying Cowlitz strata dip northward in the area (Plate 1), and are poorly exposed on the hill above this locality.

Conformity is assumed between each member of the Cowlitz Formation previously described. The strike and dips between units are very similar (e.g., Plates I and III). The locations and positions of these contacts are inferred due to cover in many places and are drawn on the map with some geologic license (Plate 1). Local disconformity between units of the Cowlitz Formation is possible.

The contact between the Cowlitz Formation and the overlying Keasey Formation is not exposed anywhere in the thesis area due to the thick vegetative and soil cover. There is indirect evidence of disconformity and seismic evidence of angular unconformity. The upper sandstone member (Tc_5) of the Cowlitz Formation appears to thin to the west in east-to-west transects from the Clatsop - Columbia county line to the Jewell area. The thickness changes from an estimated 200 meters near the county line to 15 meters on the Fishhawk Falls Highway three km south of Jewell (Plate 3). If this is due to erosion of the upper sandstone unit prior to deposition of the Keasey Formation, then a hiatus of deposition occurred between Cowlitz and Keasey time and a disconformity separates to the two formations. Olbinski (1983) also interpreted an unconformity between the two units in the Buster Creek - Green Mountain area to the east of this study.

Seismic reflection surveys have been made through the thesis area and in the Mist gas field to the east. I have learned that the seismic records also indicate an angular unconformity between the Cowlitz and Keasey Formations (Larry O'Connor, Mike Navolio, Tenneco; John Girgis, Diamond Shamrock, pers. comm., 1981).

Age and Correlation

Exposures at the "Big Bend" of the Cowlitz River, Weaver's (1912) type locality of the Cowlitz Formation in southwest Washington, were correlated to the Tejon formation of California by Arnold (1906). Molluscan fossils of the Cowlitz Formation were studied by Weaver (1912), Van Winkle (1918), Armentrout (1973) and Nesbitt (in Armentrout and others, 1980). Foraminiferal studies were made by Hanna and Hanna (1924), Beck (1943), Rau (1958), Yett (1979) and McDougall and Jefferis (in Armentrout and others, 1980).

All faunas indicate a late Eocene age (upper Narizian Stage) for the type Cowlitz Formation.

Henriksen (1956, p.58) reported that the Olequa Creek Member of the type Cowlitz Formation should be assigned to Laiming's (1943) upper Eocene A-1 (*Plectofrondicularia jenkinsi* Zone). He considered the Olequa Creek Member to be stratigraphically equivalent to the Skookumchuck Formation of central western Washington. Henriksen correlated the underlying Stillwater Creek Member of the type Cowlitz Formation to Laiming's A-2 foraminiferal Zone, which is middle Eocene. He considered the McIntosh Formation of Washington a stratigraphic equivalent of the Stillwater Creek Member. Some subsequent workers have maintained this correlation (Rau, 1958; Yett, 1979) (Fig. 4). Wells (1981) restricted the definition of the Cowlitz Formation in the Willapa Hills to the Olequa Creek Member and remapped the Stillwater Creek Member as part of the McIntosh Formation.

In Oregon, Warren and Norbisrath (1946, p.225) considered the Cowlitz Formation to be close in age (late Narizian) to the beds of the type section on the Cowlitz River. The major difference noted in the microfaunas from the two areas was the presence of *Plectofrondicularia packardi* Cushman and Schenck in the Oregon Cowlitz Formation. This foraminifera species does not occur in the Washington section, suggesting to Weaver that a difference of facies or age may exist.

Additional refinement of the Cowlitz stratigraphy in Oregon and Washington by regional mapping and whole rock K-Ar dating of volcanic rocks suggests that the Cowlitz is late middle to late Eocene in age. Mapping by Wells (1981) in the Willapa Hills shows that the type Cowlitz Formation (Olequa Creek and Stillwater Creek Members) underlies the Goble Volcanics which have been recently radiometric dated by the K-Ar method at 41.5 ± 0.5 m.y. (McElwee, pers. comm. from A. R. Niem, 1984) and 32-39 m.y. (Wells, 1981). The range of Goble deposition in southwest Washington overlaps the age of the Tillamook Volcanics in this thesis study area and in northern Tillamook County.

Megafossils and foraminferal assemblages from the Cowlitz Formation in nearby Columbia County, Oregon, yield a late Narizian age (Norbisrath and others, 1944; Newton and Van Atta, 1976; Jackson, 1983). No age-diagnostic fossils were found in the Cowlitz Formation in the thesis area during this study. However, Warren and others (1945) reported a Cowlitz-age molluscan and foraminifera locality (FM-20 in the lower sandstone member (Tc_2), see Plate 1) near the Nehalem River and Fishhawk Falls Highway in the SW1/4, sec. 22, T5N, R7W. Molluscs in this collection include:

<u>Nucula</u> n. sp.
<u>Nuculana</u> cf. <u>N. vaderensis</u> (Dickerson)
<u>Pholadomya</u> n. sp.
<u>Hemipleurotoma pulchra</u> (Dickerson)
<u>Cyclammina natlandi</u> Beck
<u>C. pacifica</u> Beck

Epistomina eocenica Cushman & Hanna
Marginulina saundersi (Hanna & Hanna)

Correlation of the Cowlitz Formation in the thesis area to the Cowlitz mapped in northwest Oregon by Warren and others (1945) is made by continuous mapping into the adjacent areas, by similarity of lithologic units (or members) within the Cowlitz, and by their stratigraphic position above the older Tillamook Volcanics and below the younger lower Refugian Keasey Formation.

The Cowlitz Formation in Oregon is lithologically different from the Cowlitz in Washington. The former contains a basal volcanic conglomerate and no obvious coal beds, suggesting different depositional facies for each unit. Deacon (1953) also noted these differences and suggested that the Cowlitz Formation in Columbia County be named a separate formation (e.g., Rocky Point formation). But I suggest retaining the name Cowlitz Formation for Narizian sandstones and mudstones overlying the Tillamook Volcanics in Oregon because the usage is deeply ingrained in the literature since the original descriptions by Warren and Norbisrath (1946).

Regionally, the Cowlitz Formation is correlated to other Narizian formations of western Oregon. These include: the Nestucca Formation of the central Oregon Coast Range (Snavely and others, 1980); the Spencer Formation and the upper part of the Yamhill Formation of the northeast Coast Range (Schlicker and Deacon, 1963; Al Azzaby, 1980); and, the Coaledo and Bastendorff Formations of the southern Coast Range (Baldwin, 1981; Armentrout and others, 1980).

The revision of chronostratigraphic units in Oregon and Washington by Armentrout (1981) places the Narizian in the middle Eocene and lowest upper Eocene (Figs. 4 and 5). This affects other formations assigned to the Narizian as well. As this is a very recent revision, some time is needed to see if it is accepted or requires further modification by workers studying the Paleogene of Oregon and Washington.

Radiometric dating and biostratigraphic problems. There is a 7 m.y. discrepancy between the 31.7 $\pm$ 0.5 m.y. K-Ar date of the youngest upper Tillamook intrusions in the study area and the absolute age correlated to the Narizian foram stage on Armentrout's time scale. The top of the Narizian Stage is approximately 39 m.y.b.p. according to this time scale (Fig 20).

The young radiometric date of 31.7 $\pm$ 0.5 m.y.b.p. is probably not be correct. Potential ^{40}Ar loss, potassium enrichment, or presence of nonradiogenic argon in crystalline phases could yield a date that is too young. Lost radiogenic ^{40}Ar could be diffused from the mineral lattice by chemical weathering and alteration from fluid in the amorphous volcanic glass (devitrification) and formation of secondary minerals may result in K enrichment. Radiometric dating of other nearby Tillamook basaltic andesites (by K. McElwee) from the top of the Tillamook volcanic pile has yielded older dates of 42 to 37 m.y.

(McElwee, pers. comm., 1984). (See Age and Correlation of the Tillamook Volcanics, p. 44.)

Depositional Environments

A transgressive open marine depositional environment is interpreted for much of the Cowlitz Formation in the thesis area. Sediments deposited in the marine environments vary from alluvial basaltic gravels and debris flow sediments (Tc_1) to marginal shallow marine sands and muds ($Tc_{2,3}$) to deeper marine shelf and slope turbidites (Tc_4) near the top of the section, and possibly followed by short-lived regressive (or progradational) shelf sand (Tc_5). Scarce marine fossils occur in the formation (*Dentalium* sp. and the trace fossil *Planolites*).

The depositional environments are interpreted from sedimentary structures, lithologies and facies relationships. Textural maturity of a sediment is also an indicator of the energy of the final depositional environment (Folk, 1980). Sediment maturity is influenced by the tectonic setting of the depositional basin. Folk's (1980) guidelines for interpreting the depositional environment and relief from textural maturity parameters are used in the interpretation of the Cowlitz depositional environment.

Depositional environment of the conglomerate member (Tc_1). Abundant subrounded clasts, poor sorting, lack of stratification and the lenticular nature (0-60 m) of the basal conglomerate suggest that the depositional environment was a humid coastal alluvial fan or river mouth. The thin basal conglomerate contains one-meter-diameter angular clasts of basaltic andesite derived from the subaerial Tillamook volcanics and intrusives which directly underlie the conglomerate (e.g., see Fig. 7). The size, compositions and angularity of the clasts indicate that the clasts were not transported far and were derived from a rugged, high relief source terrain. The subrounded clasts of mixed compositions in framework support suggest fluvial transport, perhaps by a braided stream. The subangular clasts in some breccia beds are in matrix support and were probably deposited by debris flows which are common in alluvial fan sequences (Rust, 1979). Interbedded graded basaltic sandstone beds may reflect overbank deposits or sand bars between stream gravels and debris flows.

The thinness of the basal conglomerate (0-60 m) suggests that the alluvial fan was small, perhaps at the mouth of short high-gradient streams which drained a dissected volcanic highland. Marine diatoms in the interbedded mudstones in the basal Cowlitz (Tc_1) at the Buster Creek quarry suggest that the alluvial fan or braided river mouth deposit prograded into the adjacent shallow marine environment.

A surf zone probably existed nearby. This is supported by the occurrence of nearby shoreface deposits of rounded conglomerate and well sorted basaltic sandstone and the proximity of the overlying shallow marine facies represented by the lower sandstone member in this study area (see Plates I and III). Van Atta (1971), Rarey and Mumford (pers. comm., 1983) report broken oysters, barnacles and mytilus mussel shells in the basal conglomerate (Tc_1) to the south and east of the study area. These disarticulated intertidal fossils indicate that the basal conglomerate and sandstone were deposited along a high energy nearshore marine terrace adjacent to volcanic seacliffs much like the basaltic headlands and beach gravels along the Oregon coast today. The topography of this marine shoreline may have been very steep, deepening quickly from the strandline to inner shelf depths in a very short distance. A similar origin is envisioned by Timmons (1981) and Olbinski (1983) for the origin of the basal Cowlitz conglomerate in adjacent areas .

I envision small coastal alluvial fans and braided stream mouth deposits which accumulated near sea level. The fans and braided streams would have cut into the nearby steep and dissected topography of the Green Mountain - Tillamook Volcanic highlands (probably islands). As a result of degradation of the highland and a marine transgression which followed, a gradual facies change occurred from subaerial coastal fan-river mouth gravel deposits to a high energy shallow-marine shelf sand environment forming the overlying lower sandstone member (Tc_2) and bordering the Green Mountain volcanic island high.

Depositional environment of the lower sandstone member ($\underline{Tc}_{2,3}$). The lower sandstone member consists of texturally mature lithic arenites and micaceous arkoses. As in the basal conglomerate, the abundance of granule to coarse grained basaltic andesite rock fragments in the volcanic sandstone in the lower part of the lower sandstone member implies a local subaerial source.

Short steep-gradient streams as well as volcanic sea cliffs supplied coarse grained epiclastic volcanic detritus directly to the marine shoreline. Strong wave, tidal and longshore currents abraded and redistributed this coarse grained detritus in the littoral zone. The fine grain size, a high degree of roundness, the moderate sorting and lack of matrix in thin sections (e.g., see Fig. 15) of the the lithic arenites support the hypothesis that strong currents and wave action were capable of winnowing silt and clay material and of breaking down the larger clasts into fine sand size detritus.

A neritic sublittoral depositional environment is inferred for the fine grain basaltic sandstone and micaceous arkose and mudstone in the upper part of the lower sandstone member (Plate 3). Norbisrath and others (1945) collected shallow marine molluscs in this unit at locality FM-20 in the study area. The fine grained micaceous arkosic sandstones interbedded with the coarse grained arenites in the upper part of the lower sandstone member are texturally submature to mature.

The two sediment compositions reflect two different sources. The mineralogy and texture of the clean arkosic sandstones suggest longer transport and final deposition in a lower energy environment than the underlying coarser grained basaltic sandstone and conglomerate. Because of its hydrodynamic behavior in fluid, mica will not settle in a high energy wave environment but will settle out on a lower energy shelf. The provenance of these K-spar, mica and epidote rich sandstones is a very distant plutonic and metamorphic source (e.g., the Idaho Batholith).

The fine grained arkosic sandstones, which are interbedded with mudstone, were probably transported into the sublittoral inner shelf depositional environment around the subdued Tillamook volcanic islands from a river mouth to the east by longshore drift or sediment plumes off the river mouth. Kulm and others (1975) reported that fine grained sands are carried onto the present inner continental shelf by the Columbia River plume and by high amplitude storm waves. These modern inner shelf sands are fine grained, sorted and laminated with carbonaceous debris like the arkosic sandstones of the lower sandstone member ($Tc_{2,3}$).

The Cowlitz arkosic sands were probably deposited by the Cowlitz delta to the north of the thesis area in southwest Washington where there are coal beds in the type section (Henriksen, 1956). Green Mountain (southeast of the thesis area) and the Tillamook highlands (southwest of the thesis area) may have formed subdued topographic highs bordering the Cowlitz sea and contributed volcanic detritus to the lower sandstone member ($Tc_{2,3}$). Strandline and nearshore volcanic gravels and coarse grained sandstone grade to deeper marine mudstone to the southeast and southwest of the thesis area (Mumford, Safley, and Rarey, pers. comm., 1983).

Depositional environment of the turbidite member (Tc_4). A turbidity current origin is interpreted for the sandstones of this member based upon the graded bedding, Bouma sequences T_{ac} and T_{de}, sharp bottom and gradational upper contacts, and even-bedded alternating mudstones and sandstones. These features are attributed to low density distal turbidites by Middleton and Hampton (1973) and by Walker and Mutti (1973). The *Helminthoida*-burrowed mudstones between turbidites indicate slow hemipelagic sedimentation rates between the turbidites (Howard, 1978). *Helminthoida* is most common in offshore to bathyal environments (Chamberlain, 1978).

The 30-m-thick unit is thin relative to typical turbidite fan sequences and lacks associated upper and middle fan facies (Mutti and Ricci Lucci, 1978). The thin turbidite unit is sandwiched between the arkosic shallow water shelf units, Tc_2 and Tc_5 (Plate 3).

Two models are possible for the deposition of this lithofacies. The turbidites may signify increasing water depth followed by a regressive event within the Cowlitz section. This water depth change might have been caused by either a transgressive sea or gradual basin subsidence due to tectonism (or a combination of the two). The result of the change in depth may have been that shelf and nearshore arkosic sand (Tc_2) was redistributed down-slope by low-density turbidity currents moving across the continental shelf.

Dott and Bird (1979) described a similar thin channelized sequence of thin-bedded turbidites (Elkton Formation) which were funneled down "sea gullies" from the upper Eocene Coaledo delta front sands in the Coos Basin, southern Oregon Coast Range. Similar small-scale channelized turbidites were noted in the lateral equivalent of this turbidite member (Tc_4) in the Cowlitz Formation in Rock Creek (13 km to the east near Keasey) on a field reconnaissance. Perhaps the turbidite member formed in sea gullies cut into the slope off the main Cowlitz delta to the northeast (i.e., the type Cowlitz in southwest Washington).

The second model requires no significant change in water depth due to eustacy or basin subsidence. C. H. Nelson (1982) discussed thin storm-generated graded sand layers between mud layers on the Yukon delta - Bering shelf. He demonstrated that rhythmically bedded graded sand sequences on epicontinental shelves can be the result of storm-surge processes that affect the sediment-laden shelf. Seaward sand transport has been observed by the ebb flow of wind driven storm currents. Nelson (1982) showed that graded sand sequences formed by these storm-surge currents can mimic the classical Bouma T_{a-e} structures commonly associated with deeper marine turbidite deposits on continental slopes.

The primary sedimentary structures in the turbidite member are compatible with the sequences that Nelson (1982) described as storm-generated graded sand layers. The Cowlitz basin in northwest Oregon may have been a sediment-laden system off the main Cowlitz delta centered in the type area.

Walker (1979) and Dott and Bourgeois (1981, 1982) also picture thin-bedded "turbidites" and muds forming below storm wave base seaward from and associated with storm deposited hummocky cross-bedded shelf sandstones. Olbinski (1983) and Jackson (1983) report storm induced hummocky bedding in the thick- and thin-bedded shelf arkosic sandstones in the Cowlitz Formation in adjacent areas, suggesting that the turbidites may be associated with the density entrained storm surge currents that created the hummocky bedding (Fig. 20).

Depositional environment of the upper sandstone member (Tc_5). The sandstones of the upper member (Tc_5) of the Cowlitz Formation are micaceous and zircon-rich. These friable rocks are generally poorly exposed and lack abundant primary sedimentary structures and fossils that may be definitive of a specific depositional environment. However, the unit is thick bedded and, in places, displays parallel

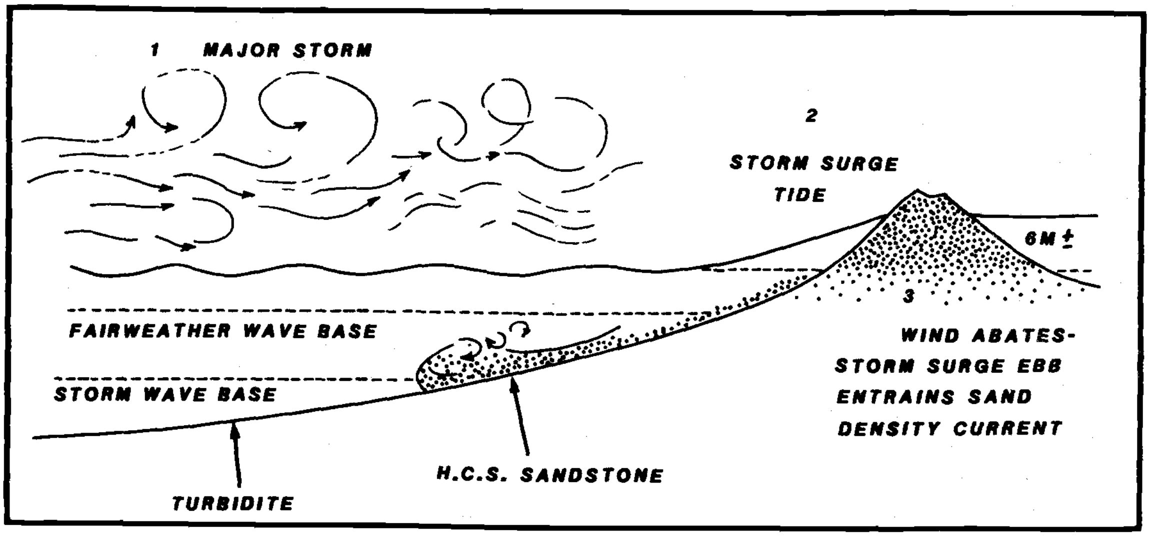


Figure 20. Conceptual diagram of major storm and storm surge currents (tides) on a sediment-laden shelf (after Walker, 1979). When storm winds abate, a seaward-flowing density current is generated forming hummocky cross-stratified sandstone and turbidite deposits above and below storm wave base, respectively.

stratification and low-angle cross-stratification suggesting a tractive current shallow marine origin. The present inner shelf sands of the Oregon continental shelf are also parallel laminated (Kulm and others, 1975).

Although coarser grained, the sand is compositionally related to the fossiliferous micaceous arkoses in the lower sandstone member ($Tc_{2,3}$). Therefore, deposition probably took place in a similar inner shelf, shallow marine environment with longshore currents. Olbinski (1983) noted gastropod and disarticulated pelecypod molds, mudstone rip-up clasts, hummocky bedding, ripple micro-cross-laminations and trough cross-bedding in correlative upper arkosic sandstones (Tc_5). These primary sedimentary depositional structures indicate high energy storm dominated shelf conditions. Perhaps the upper sandstone member of the Cowlitz Formation reflects a shallowing-up sequence, or a more shoreward depositional facies, that prograded in time over the underlying storm-generated turbidites (Tc_4).

Keasey Formation

Nomenclature

The "Keasey shale" was originally defined by Schenck (1927b). The type section was described as dark gray fossiliferous and well-stratified sandy shales 1.1 km north of the hamlet of Keasey, Oregon. The type section is exposed along Rock Creek, which is a tributary to the Nehalem River east of the thesis area. Weaver (1937) calculated the thickness of the Keasey Formation as 366 m in the Rock Creek area.

Warren and Norbisrath (1946) redefined the Keasey Formation to include three members and extended the section beyond Schenck's original description. The lower member, which includes the type section of Schenck (1927), consists of a dark gray shale with variable thickness. In some localities away from the type section, these workers encountered difficulty distinguishing this unit from lithologically similar underlying Cowlitz mudstones. Warren and Norbisrath (1946, p. 225) discussed the problems of discerning this lower shale member where it is either poorly exposed, missing, or replaced by a rock of slightly different lithology.

The middle member is a light gray, unstratified, tuffaceous siltstone with resistant calcareous concretionary beds. This fossiliferous member is approximately 518 m thick near the Sunset Tunnel on U. S. Highway 26, where it is best exposed in the Sunset light rock quarry (Niem and Van Atta, 1973). It is also moderately well exposed along Rock Creek and in the banks of the Nehalem River in Columbia County.

The upper member of the Keasey Formation consists of fossiliferous claystone, tuffaceous siltstone and thin tuff beds. It is 30 to 60 m thick. Warren and Norbisrath (1946) indicated that this three-fold lithofacies division of the Keasey Formation is justified by concomitant changes in faunas of each facies. The estimated total thickness of the Keasey Formation is 700 m.

Van Atta's (1971) stratigraphic and petrologic investigation of the Keasey Formation essentially followed the division that Warren and Norbisrath (1946) used. Kadri (1982) presented a more recent study of the lithology and depositional environments of the Keasey in Columbia County.

The Keasey Formation has been extensively studied for its well preserved fossil assemblages. Weaver (1942) published a treatise on molluscan fossils that included species from the Keasey. Schenck (1927b) studied the foraminifers recovered from the type section. Correlation of the Keasey to the Refugian Provincial Foraminiferal Stage of California was made by Schenck and Kleinpell (1936, in McDougall, 1975). McDougall (1975, 1980) recently studied the paleoecology and biostratigraphy of microfaunas from the type section of the Keasey Formation and studied other surface sections and well samples.

McDougall has considered the relation of the Keasey Formation to other biostratigraphically correlative formations in California, Oregon and Washington (McDougall, 1980). She concluded that part of the benthic Foraminifera in the Keasey are facies controlled and that much of the Keasey was deposited in outer shelf and upper slope environments.

Usage of the term Keasey Formation as a faunal stage has caused confusion of the definition. The name has been applied in the Pacific N.W. both in lithostratigraphic and time-stratigraphic senses (McDougall, 1975). Within the outcrop area of the Keasey Formation (Columbia and Clatsop counties), the lithologic description of the members is variable due to facies changes. The lack of continuous exposure makes intraformational stratigraphic correlation difficult in detailed study. Warren and Norbisrath (1946) indicated that without fossils the Keasey Formation west of the Nehalem River basin could not be distinguished from the claystones of the Cowlitz Formation.

Deacon (1953, p. 18) proposed the "Nehalem formation" for exposures within the type section of the Keasey in Rock Creek. The formation was proposed for heterogeneous strata between the lithologically distinct Cowlitz Formation (which Deacon called "Rocky Point formation") and the overlying Keasey Formation. Deacon's Keasey Formation included only the middle member, as defined by Warren and Norbisrath (1946). He did not work with the upper member of the Keasey Formation. The "Nehalem formation" of Deacon (1953) corresponds to the "lower dark shale member" of Warren and Norbisrath (1946).

In this thesis, the Keasey Formation consists of three informal members that are defined by lithology and age-diagnostic foraminiferal assemblages. Identifiable coccoliths that could be used in an age-diagnostic sense were not recovered from the study area. Most description of lithology are similar to those of Warren and Norbisrath (1946) and Van Atta (1971); however, the relative stratigraphic position of the lithofacies is different (Fig. 21). The informal members proposed here are mappable facies of the formation.

The lower member is informally called the Jewell member, and consists of thin bedded to laminated mudstone that contains ledge-forming calcareous beds (Fig. 22). This is lithologically similar to the lower member described by Warren and Norbisrath (1946). The laminated, thin bedded unit may be, in part, a facies and age equivalent of the more massive thick bedded bioturbated middle member of the type Keasey of Warren and Norbisrath (1946) (Fig. 21).

The Vesper Church member (middle member) consists of laminated dark gray siltstone with well bedded micaceous arkosic to subarkosic very fine grained graded sandstone. This facies does not have a correlative member in Warren and

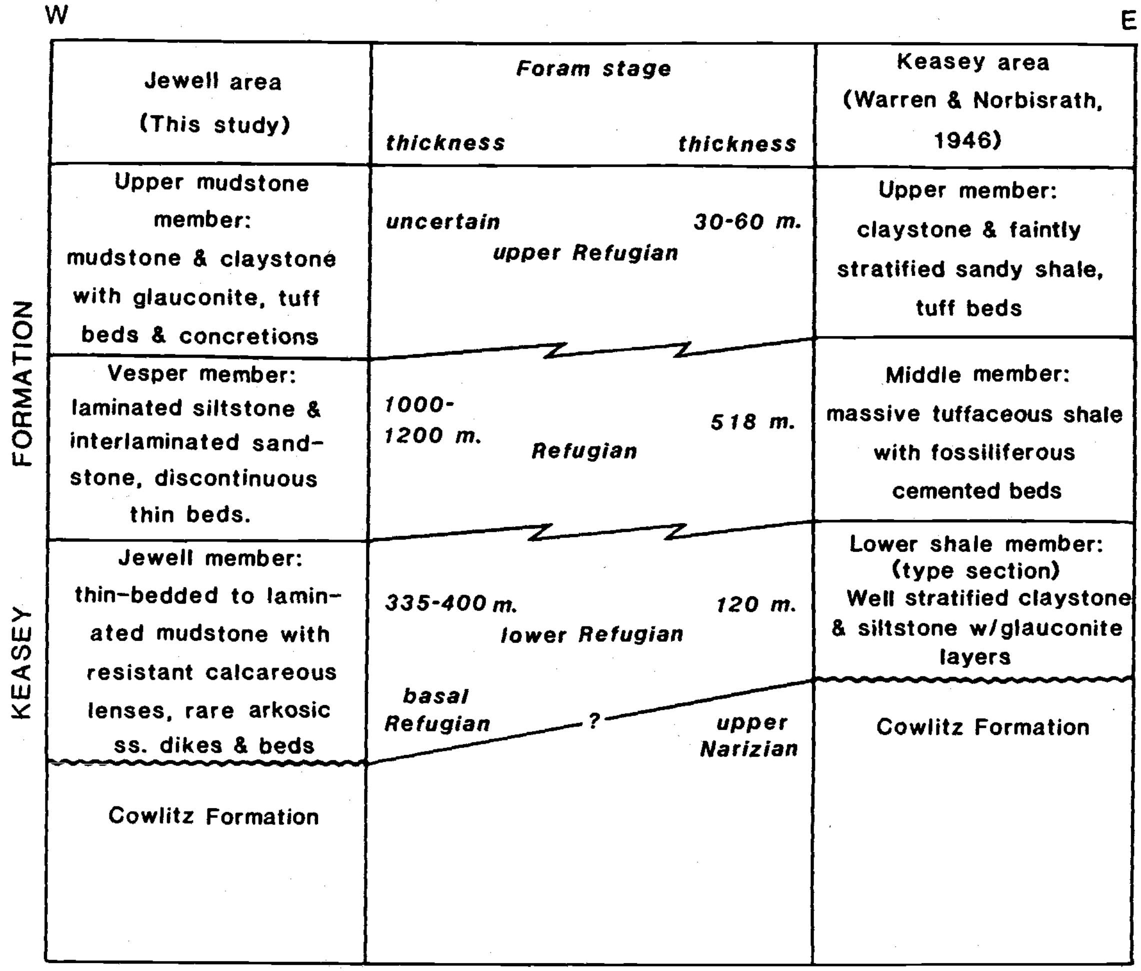


Figure 21. Correlation of the informal members of the Keasey Formation used in this thesis to those used by Warren and Norbisrath (1946) in the NE Oregon Coast Range.

Norbisrath's division of the Keasey Formation but is believed to be a lateral facies of the middle member (Fig. 21). It appears from their descriptions and sketch map that they considered this facies to be the lower part of the Pittsburg Bluff Formation (Warren and Norbisrath, 1946, p. 230). For both lithologic and chronostratigraphic reasons stated in the following section, it is unlikely that this unit should be included in the Pittsburg Bluff Formation. It best fits as a facies of the Keasey Formation. Olbinski (1983) thought that the Vesper Church member is so different from the type Keasey and Pittsburg Bluff Formations described by Warren and Norbisrath (1946) that he proposed it as a new informal formation.

The upper member consists of massive dark gray mudstone and claystone. It has foram abundant assemblages and glauconite and contains distinctive thin white tuff beds. This member is correlative to the upper member of Warren and Norbisrath (1946) (Fig. 21).

Distribution

The Keasey Formation crops out over 60 km^2 in a broad band trending northeast-southwest through the middle part of the thesis area. The formation ranges in thickness from 1,450 to 2,100 m, based on surface mapping and the Quintana well. The outcrop pattern follows that of the underlying Cowlitz Formation. Numerous strike-slip, oblique-slip and vertical normal faults have offset the members of the Keasey

Formation (Jewell, Vesper Church and upper mudstone members). The outcrop belt wraps around the N.W. side of the northward-plunging axis of the Coast Range anticlinorium and gravity high. To the east in Columbia and Washington counties, the strike of the Keasey Formation changes to northwest-southeast and north-south, where the unit crops out on the east flank of the regional structure.

The mudstones of the Keasey Formation weather quickly and form low, stream-dissected hills. Areas underlain by the Keasey mudstone are prone to landslides and mudflows (as on Plate I). U. S. Highway 26 is constantly repaired in order to keep up with the rate of erosion. Furthermore, the removal of the toes of landslides and mudflows near highways and residences can destablize the hillslope, prompting further sliding.

The upper Nehalem River has formed broad floodplains in areas underlain by Keasey mudstone (Q_{al} on Plate I). The river meanders through this broad valley. At springtime high water levels, the cutbanks are rapidly eroded by floods. Roadways constructed near these undercut banks often require repair. The Red Bluff Road (south-center part of map area, NW1/4, sec. 24, T5N, R7W) formerly connected the communities of Jewell and Elsie, but the Nehalem River undercut the road years ago, and it has never been reconstructed.

Lithologies, Structures, and Provenance

Jewell member. The Jewell member forms the lower 335 to 400 m of the Keasey Formation in the thesis area (Tk_1, Plate I). It is herein informally named for roadcut exposures that occur 1.5 km west of Jewell along the Nehalem River Highway (State Route 202) and along the Beneke Creek Road near its intersection with State Route 202 (S1/2, sec. 2, N1/2, sec. 11, T5N, R7W). Other exposures also occur along cutbanks of Humbug Creek and roadcuts near Elsie in the southern part of the study area (sec. 5 & 6, T4N, R7W). This member correlates with the lower and middle members of the Keasey Formation as defined by Warren and Norbisrath (1946) (Fig. 21).

The unit consists of thin, well bedded to laminated, foram-rich, tuffaceous mudstone. It is olive gray (5Y4/1) to grayish black (N2) when fresh and weathers to grayish brown (5YR3/2) and greenish gray (5GY6/1) (Fig. 22). The strata commonly display a shaly parting. Small chips of weathered mudstone accumulate in talus piles at the base of outcrops (Fig. 22). Light buff, calcareous concretionary tuff beds and lenses occur in the unit and form resistant ledges 5 to 10 cm thick. Clastic sandstone dikes, though rare, seem unique to this member of the Keasey Formation. These clastic dikes can be seen in the type area along the Beneke Creek Road and in roadcuts above Humbug Creek near

Figure 22. Typical exposure of the Jewell member (Tk_1) of the Keasey Formation. Locality 89 on East Humbug Road, SE1/4, sec. 13, T5N, R8W. The purple foxglove (Digitalus purpurea) in lower left approximately 1 meter tall; the hammer is 28 cm.

Elsie (NW1/4, sec. 5, T4N, R7W). Clastic dikes have not been observed in the Cowlitz Formation nor in other members of the Keasey Formation, but occur elsewhere in northwest Oregon in the upper Eocene to lower Miocene Oswald West mudstone (Cressy, 1974; Penoyer, 1977). The sandstone in the dikes is arkosic and micaceous and is similar in appearance and composition to the thick bedded upper sandstone member of the Cowlitz Formation.

The Jewell member contains abundant foraminifers that indicate a late Eocene or early Refugian age that is equivalent to the California *Valvulineria tumeyensis* Zone of Donnelly (1976). Representative forams collected from the member are:

Bathysiphon eocenica Cushman and Hanna
Cibicides elmaensis Rau
Cyclammina pacifica Beck
Dentalina dusenburyi Beck
Gyroidina orbicularis
Hoeglundina eocenica (Cushman and Hanna)
Valvulineria tumeyensis Cushman and Simonson

McDougall (1982, written communication).

Vesper Church member. The Vesper Church member (Tk_2) is the middle member of the Keasey Formation in the thesis area. In the Nehalem Valley - Buster Creek area to the east, the same unit has been mapped as the Vesper Church formation (Olbinski, 1983). The unit lenses or pinches out into the tuffaceous Keasey mudstone (Tk_1) in the southwestern part of the thesis area. The estimated thickness is 1,000 to 1,200 m from outcrop and well information (e.g., Quintana "Watzek" #30-1). This informal member was named by Olbinski (1983) for roadcut and landslide scarp exposures near the Vesper Church, approximately 0.25 km north of the Nehalem River Highway in sec. 25, T6N, R6W. This locality is close to the Clatsop-Columbia county line.

Warren and Norbisrath (1946), Van Atta (1971), and most recently Kadri (1982) described this member as a lower unit of the Pittsburg Bluff Formation rather than as a member of the Keasey. However, the Vesper Church is distinctly dissimilar to the type Pittsburg Bluff Formation. It is composed of rhythmically bedded micaceous arkosic turbidites and mudstones, and the unit is both underlain and overlain by typical Keasey strata (i.e., the Jewell member and upper Keasey mudstone) (Plate I). It is not associated with the Pittsburg Bluff Formation because it contains late Narizian to early Refugian forams and equivalent coccolith assemblages. The younger type Pittsburg Bluff contains late Refugian to early Zemorrian forams and equivalent age coccoliths.

The Vesper Church is missing in the type section of the Keasey Formation on Rock Creek, however. Probably the facies represented by this member had local distribution and was not deposited in the area of the type section (Fig. 21). Although Olbinski (1983) called the Vesper Church a separate formation, it is considered by the author to be part of the

Keasey Formation since the unit occurs between two other mappable Keasey members.

The Vesper Church member consists of a well bedded sequence of thinly laminated micaceous carbonaceous siltstone and very fine to fine grained arkosic micaceous sandstone (Figs. 23 & 24). The alternating very thin to thin, even beds of sandstone and siltstone give this facies a distinct thin-bedded to laminated character (Fig. 23) compared to the Jewell member and overlying massive tuffaceous mudstone member. Siltstone beds range from 1 to 5 cm thick. Sandstone beds are 0.1 to 10 cm thick and are laterally persistent. Coarse flakes of mica are abundant on bedding surfaces and define bedding in the thin sandstone beds. Abundant comminuted carbonized plant twigs and leaves also occur on bedding planes. The finely laminated siltstone is dark gray (N3) to black (N1) where fresh, and weathers rapidly to yellowish gray (5Y7/2) and dusky yellow (5Y6/4). Sandstone beds are light gray (N7). In deeply weathered outcrops, the sandstone laminations are indistinct. Small pyrite (weathers to earthy hematite) concretions are common in siltstone beds, and resistant calcareous lenses occur in sandstone beds.

In some outcrops (e.g., localities 38, 96, Plate I), the sandstone beds are thicker, measuring 10 to 15 cm and have sharp upper and lower contacts. These commonly display ripple cross-laminations and parallel lamination (Fig. 24).

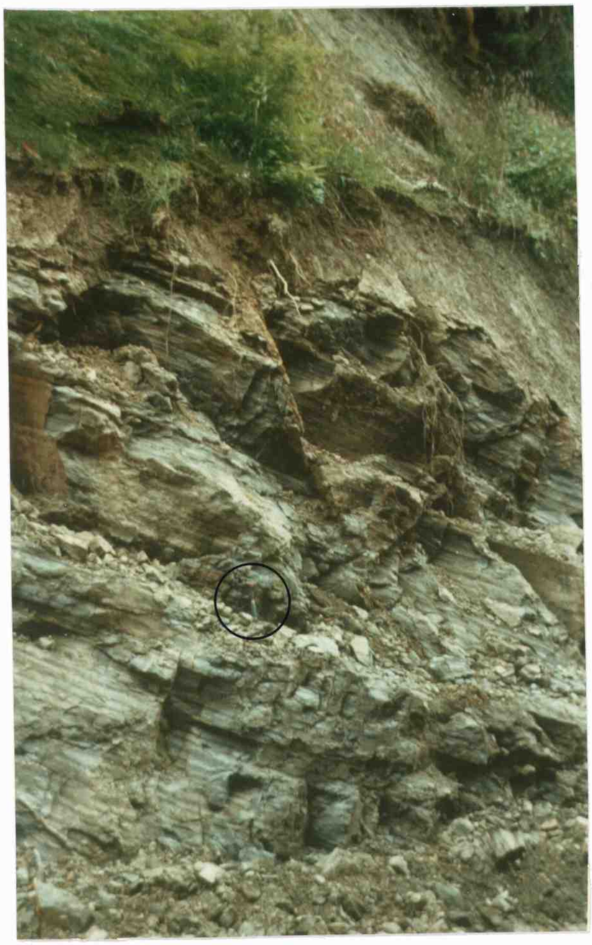


Figure 23. Sequence of alternating thin siltstone (dark gray) and fine-grained micaceous arkosic sandstone (light gray) beds of the Vesper Church member of the Keasey Formation. Locality 251 on Pope Ridge logging road, NW1/4, sec. 21, T5N, R7W. Note hammer (0.3 m) for scale.

Figure 24. Light gray sandstone beds in the Vesper Church member of the Keasey Formation have ripple laminations and planar beds (T_{c-d}). These normally-graded 10- to 15-cm-thick beds are separated by very thin darker gray mudstone (T_e). Locality 38 on logging road near Flagpole Ridge. (Hammer is 28 cm long.)

Bouma sequences T_{abc} and T_{bcd} occur in some of these normally-graded turbidite sandstones. Thirty to 60 foot wide nested channels also occur in the unit along logging roads in sec 26, T5N, R8W (see Plate I). Channels are exposed along the Nehalem River Highway in the adjacent thesis area (Olbinski, 1983). The channels truncate the thin bedded strata and are filled with thin bedded sandstone and siltstone of similar lithology.

Benthic foraminifers, mollusks, and trace fossils have been recovered from the Vesper Church member. The foram Lenticulina inornata (d'Orbigny) indicates water depths not less than 50 m, the upper limit of this species (McDougall, 1982, pers. comm.). This species could be transported to greater depth. Foraminiferal assemblages from the Vesper Church member in the adjacent thesis area suggest deposition in water depths ranging from 1,000 to 1,500 m (Olbinski, 1983). Mollusks include the pelecypod Propeamusium sp. and an unidentified nuculanid which are not age-diagnostic (Ellen Moore, written comm., 1982). The nuculanid burrowers are commonly in growth position in siltstone beds, and the burrows are filled with arkosic sandstone. Trace fossil ichnogenera Helminthoida and Planolites are typically found in the siltstone above graded sandstone beds in this member (Fig. 25).

Petrographically, the thin bedded sandstones are feldspathic litharenites (Folk, 1980) or feldspathic wackes

Figure 25. Helminthoida trace fossils in the interbedded siltstone from the Vesper Church member of the Keasey Formation (locality 188).

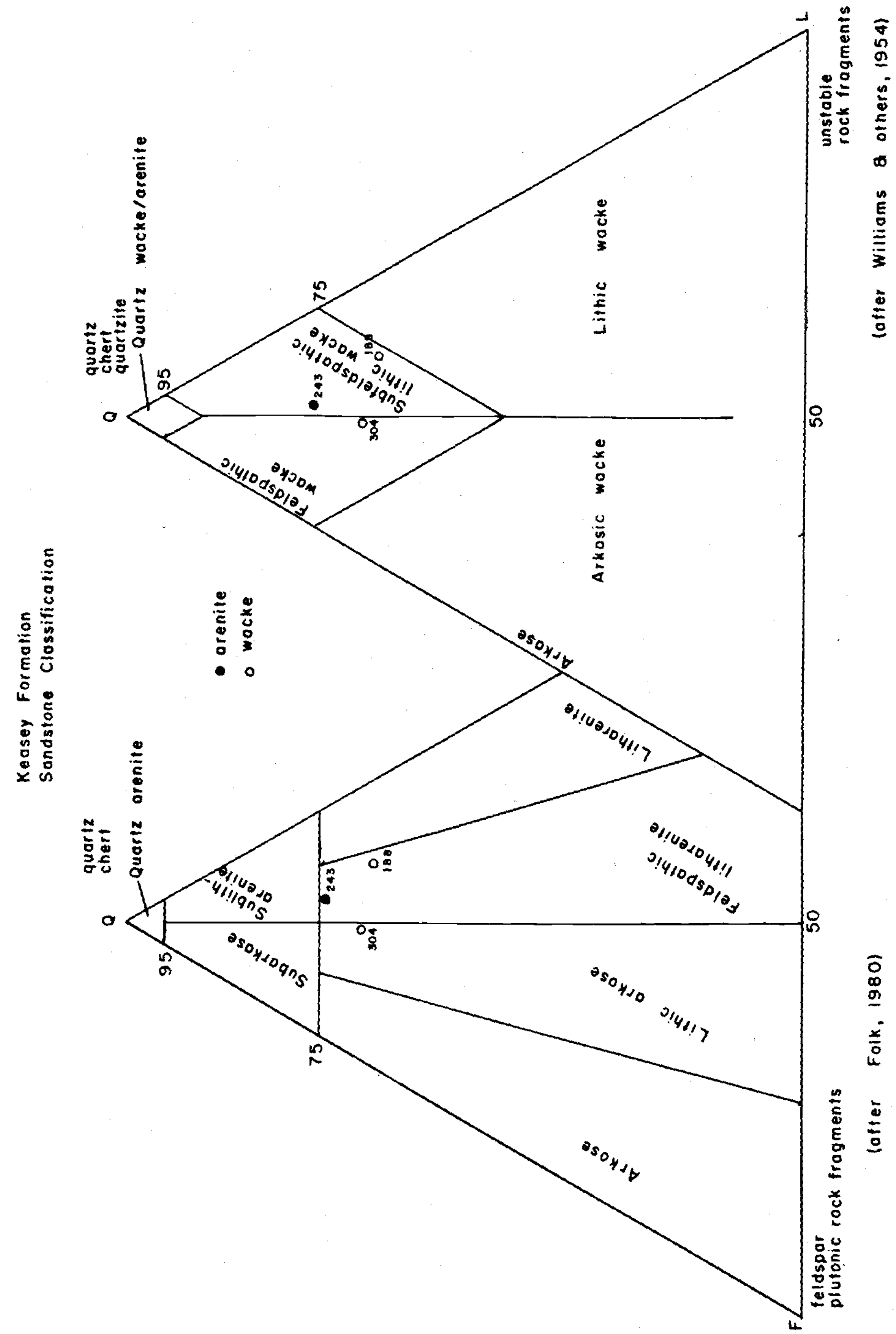


Figure 26. Classification of sandstones of the Vesper Church member of the Keasey Formation.

(Williams and others, 1954) (Fig. 26). Two thin sections of very fine to fine grained sandstone were examined (samples 188, 304). The sandstone consists of quartz (35 to 50%), albite twinned plagioclase (5 to 8%), orthoclase (1 to 3%), muscovite and biotite (3 to 20%), and rock fragments (11 to 16%). Accessory framework clasts include chlorite, glauconite, opaque iron oxides and carbonaceous plant fragments. The matrix composes 3 to 20% of the rock (by volume). The framework grains are moderately sorted and subrounded to subangular. Textural maturity is low (submature) indicating low to moderate energy in the depositional environment. Compositional maturity is submature to mature due to the varying abundance of rock fragments. Rock fragments include metamorphic, volcanic, sedimentary, and rare plutonic and chert clasts.

Grain mounts of heavy minerals from three samples (38, 243, 304) were examined to determine provenance. The heavy mineral assemblage (listed in Appendix VIII) is rich in apatite (13 to 34%) and biotite (9 to 44%); garnet, epidote and tourmaline are also present but are less abundant. The heavy minerals and framework mineralogy and rock fragments indicate a mixed provenance. The K-feldspar, coarse biotite flakes, apatite, garnet, epidote and quartz indicate that distant siliceous plutonic and metamorphic sources contributed detritus to the sandstones, probably via an ancestral Columbia River drainage system. The andesitic to basaltic lava fragments could have been derived from the

Figure 27. Typical exposure of the upper mudstone member (Tk_3) of the Keasey Formation. White tuff bed is approximately 5 cm thick. Sample localities 155, 488 and 505 are near this location (SE1/4, SW1/4, sec. 6, T5N, R7W) in Little Fishhawk Creek (Plate I).

Tillamook Volcanics or a western Cascade Volcanic series in central Oregon. The rock fragments indicate a diversity of source areas.

Most of the clastic grains in the graded sandstones were probably reworked and redistributed from shallow inner shelf environments to deep-water environments of deposition. Some of the sand may have been recycled from the underlying Cowlitz sandstone which has a similar arkosic and lithic composition.

Upper Mudstone Member. The upper member of the Keasey Formation (Tk_3, Plate I) correlates to the upper member of the type Keasey as used by Warren and Norbisrath (1946) and Van Atta (1971) (Fig. 21). The thickness is variable. An accurate measurement cannot be made because the location of the gradational contact with the underlying Vesper Church member is uncertain. Based on surface mapping, the upper mudstone member varies in thickness across the map area from 305 m in the northeastern part to 450 m in the southwestern part of the area (Plate I). The best exposures are freshly excavated logging roadcuts near Boiler Ridge, especially on Lewis & Clark Main Line, Fishhawk X-Over and Samuelson Main Line in secs. 7, 8, & 18, T5N, R7W.

The strata are dark gray (N3) to black (N1) tuffaceous mudstone and claystone that most commonly weather to a yellowish gray (5Y7/2). Scattered glauconite pellets are found in the freshest exposures. The mudstone and claystone are structureless; therefore, measuring attitudes of bedding is difficult. Thin (5 to 15 cm) white tuff beds in the unit are commonly the only stratigraphic reference planes where strike and dips can be measured accurately (Fig. 27).

Foraminiferal assemblages recovered from this facies indicate that the unit was deposited at upper bathyal water depths of 200 to 500 m (McDougall, written comm., 1982). The diatom, *Braarudosphaera*, was also recovered from this member (Baldauf, written comm., 1982).

Nodular calcite concretions weather out of this unit. These are 5 to 15 cm in diameter and contain megafossil fragments about which calcite has precipitated. A crab carapace (*Zanthropsis*? cf. *Z. vulgaris* Rathbun) was discovered within one of these nodules (Moore, written comm., 1982). The best locality to collect these fossil-bearing concretions is in Little Fishhawk Creek (secs. 6 & 7, T5N, R7W).

Contact Relations

The contact between the Keasey Formation and the underlying Cowlitz Formation has been described in the literature as both conformable and unconformable. Van Atta (1971) explains that strikes of bedding differ by as much as 90° between the Cowlitz and Keasey formations in Columbia County, suggesting a disconformable relationship. Seismic evidence (see Cowlitz Formation Contact Relations section) indicates angular discordance between Cowlitz and Keasey formations.

Attitudes of bedding within the thesis area (e.g., Plate I) are not as discordant as Van Atta (1971) found. The contact between the underlying upper sandstone member of the Cowlitz Formation (Tc_5) and the overlying Jewell member (Tk_1) is not exposed. However, the contact is placed between the outcrops of upper Cowlitz sandstone member and Jewell member mudstone and then is drawn on the geologic map (Plate I) by projection, using average strike and dip of the mudstone strata. I suspect that there is a small angular discordance between the Keasey and Cowlitz formations as other regional mapping also indicated this in Columbia County (Van Atta, 1971; Newton and Van Atta, 1976; Kadri and others, unpublished map, 1980). The locality where the Cowlitz - Keasey contact comes nearest to exposure is in the Nehalem River, south of Jewell (N1/2, sec. 13, T5N, R7W). The contact is concealed by alluvium, thick cover and minor faulting.

Contacts between the three informal members of the Keasey Formation (the Jewell, Vesper Church, and upper mudstone members) are shown as concordant on the map (Plate I) and cross-sections (Plate 2), though in actuality these facies probably interfinger. Therefore, the contacts between lithofacies are schematic. The similarity of strikes and dips between the three members suggests conformable contacts.

The contact with the overlying Pittsburg Bluff Formation is disconformable. This disconformity is suggested by a substantial change in lithologic character (e.g., from mudstone to fine grained sandstone) and in water depth indicated by the fossils. The Pittsburg Bluff Formation was deposited in 20 to 200 meters of water whereas the underlying upper member of the Keasey Formation was deposited in depths as much as 500 m. The best locality to observe the Keasey - Pittsburg Bluff contact is in Little Fishhawk Creek and logging roadcuts in W1/2 sec 6, T5N, R7W.

Warren and Norbisrath (1946) reported a regional unconformity between the Pittsburg Bluff and Keasey. This is also suggested in the regional map pattern. The Pittsburg Bluff overlies the upper mudstone member of the Keasey in the study area but it overlies the Vesper Church member to the east toward the Clatsop - Columbia county line (Olbinski, 1983; Kadri and others, unpublished map, 1980). In the northeast part of Columbia County, the Pittsburg Bluff overlies the thick, massive, tuffaceous mudstone member of the Keasey (as exposed in the type section on Rock Creek) (Wells and others, 1983; Van Atta and others, unpublished map, 1980).

Age and Correlation

Schenck (1927) considered the type Keasey shale to be lower Oligocene. Later, Schenck and Kleinpell (1936) suggested that the formation is late Eocene. Weaver and others (1944) correlated the Keasey Formation to the lower Refugian Foraminiferal Stage and considered the Keasey to be late Eocene to Oligocene.

McDougall (1975) studied the collections of foraminifers from the type section. The basal tuffaceous pebbly sandstone and the first 30 meters of the section are assigned a late Narizian (late Eocene) age. The "basal" Refugian is represented by the next 60 m of strata in the type section (Fig. 21). This part of the section is called basal Refugian because Narizian species are not present and key species belonging to the lower Refugian Uvigerina cocoaensis Zone are absent as well (McDougall, 1975, p. 347-350). The remainder of the type section is poorly exposed but is considered lower Refugian by McDougall (1975).

In the thesis area, forams collected from the Jewell member are equivalent to the lower Refugian Valvulineria tumeyensis Zone of Donnelly (1976) (McDougall, written comm, 1982). Assuming that the California zonal schemes are workable in northwestern Oregon, the V. tumeyensis Zone is lower Refugian and correlates to the time-transgressive modified Sigmomorphina schencki Zone of McDougall (1980). The thick section of massive tuffaceous shale of the type Keasey which Warren and Norbisrath (1946) assigned to the middle member of the Keasey Formation yields lower Refugian foraminifers (McDougall, 1975). Therefore, the biostratigraphic correlation of the Jewell member to the lower shale and middle member of Warren and Norbisrath (1946) seems valid (Fig. 21) (sample locality 302, sec. 11, T5N, R7W).

The best estimate of age will probably come from the combined use of age-diagnostic Foraminifera and calcareous nannofossils. A foram assemblage from the type Jewell member on State Highway 202 indicates a late Narizian age (Rau, pers. comm. to A. R. Niem, 1980) for the Jewell member. Similarly, foram assemblages identified by a consulting paleontologist on the Quintana "Watzek" #30-1 well indicate a Narizian age for the Jewell member (Cressy, 1981, and Bruer, 1983, pers. comm. to A. R. Niem). A coccolith assemblage identified by Laurel Bybell of the U.S.G.S. (written comm., 1982) in the Cowlitz below the Jewell member would be in the coccolith zones NP17 to NP21 (see Fig. 5, p. 24), which equates to the Refugian Stage. Hence, the age of the unit may straddle the upper Narizian - lower Refugian boundary (latest Eocene on Armentrout's geologic time scale for the Pacific NW (1981) (Fig. 5).

The Vesper Church member and upper mudstone member are assigned to the upper Refugian on the basis of Foraminifera (McDougall, written comm., 1982). The one foram species collected from the Vesper Church member in the thesis area is not age-diagnostic.

The diverse assemblage of foraminifers from the upper mudstone member of the Keasey are equivalent to the upper Refugian <u>Uvigerina vicksburgensis</u> Zone of California

(Donnelly, 1976; McDougall, written comm., 1982). The *U. vicksburgensis* Zone is correlative to the modified *Cassidulina galvinensis* Zone (McDougall, 1980, p. 28). In terms of the new time scale proposed by Armentrout (1981), the Keasey Formation represents the upper Eocene Stage (Figs. 4 & 5).

The upper Eocene Keasey Formation is correlative to the Bastendorff and Tunnel Point formations of the Coos Bay, Oregon area. In Washington, the correlative formations are the Lincoln Creek Formation and the Gries Ranch beds.

Depositional Environment

The depositional environment interpreted for the Keasey Formation is a deepening-then-shallowing, bathyal open-marine sequence. Paleobathymetry, as indicated by benthic foraminifers, is the principle tool for this interpretation.

The foraminiferal assemblage collected from the Jewell member suggest deposition in water depths of 200 to 500 m and is equivalent to the upper bathyal biofacies of McDougall (1980) (McDougall, written comm., 1982). This corresponds to the upper slope region of the continental margin.

The trace fossil *Helminthoida*, although not restricted to a specific depositional marine environment (Chamberlain, written comm., 1982) is most common in offshore to bathyal environments.

The tuffaceous character of the Jewell member, unlike the underlying Cowlitz Formation, reflects the input of increasing explosive silicic volcanism in the growing western Cascades. The fine grain size, composition and occurrence of some planktonic coccoliths and some diatoms (Appendix III) suggest that the fine ash settled as hemipelagic muds on the upper continental slope at this time. The lack of extensive bioturbation and occurrence of laminations imply either rapid sedimentation and/or a low oxygen (e.g., dysaerobic to anoxic) environment which was unfavorable for abundant burrowers (Howard, 1978). Such an environment occurs today at the oxygen minimum zone that impinges on the continental slope (Friedman and Sanders, 1978).

The clastic dikes in the Jewell member suggest rapid sediment loading, spontaneous liquefaction, and intrusion of arkosic sand in the overlying sediment as a result of burial and overburden pressure. The source for the arkosic sand is enigmatic, perhaps the underlying Cowlitz arkosic sand in the upper sandstone member (Tc_5) was the source. A more likely source is rare arkosic sand beds in the Jewell member such as the beds observed by Mumford and Rarey (pers. comm., 1983) to the southeast of the study area.

The Vesper Church member was deposited in depths as much as 2,000 meters, which is upper to middle bathyal and represents a deepening of the depositional environment from the Jewell member. This corresponds to the middle to lower continental slope environment. The thin and rhythmically bedded sandstones and siltstones of the Vesper Church member are interpreted to be low-density turbidity current deposits as indicated by the numerous graded beds and Bouma T_{a-c} and T_{b-c} sequences (Middleton and Hampton, 1973). Possibly these sediments are overbank deposits on a small submarine fan. The sedimentary structures and lenticular character of beds correspond to turbidite Facies E or Facies G of Mutti and Ricci Lucchi (1978).

The upper mudstone member records a paleobathymetry of 200 to 500 meters, which is upper bathyal (McDougall, written comm., 1982). Some of the species recovered from this facies are inner and outer neritic faunas that have probably been transported to the deeper marine environment. The oxygen level of the environment was normal indicating that an open connection with the sea occurred during Keasey time. Water temperatures were cool (McDougall, written comm., 1982). The diverse foraminiferal fauna collected from the upper mudstone member of the Keasey Formation in the thesis area are equivalent to the California *Uvigerina vicksburgensis* Zone of Donnelly (1976), which is upper Refugian. The foraminifers include (see also Appendix III):

Allomorphina trigona Reuss
Anomalina californiensis Cushman and Hobson
Bathysiphon eocenica Cushman and Hanna
Bathysiphon sp.
Biloculinella cowlitzensis Beck
Cibicides elmaensis Rau
Cibicides pseudoungerianus evolutus Cushman and Frizzell
Cyclammina pacifica Beck

Dentalina spinosa d'Orbigny
Gaudryina alazaensis Cushman
Globocassidulina globosa
Guttulina irregularis
Gyroidina orbicularis planata
Karreriella washingtonensis Rau
Lagena costata (Williamson)
Lenticulina sp.
Melonis sp. of McDougall 1980
Planulina cf. *P. weullerstorffi*
Quinqueloqulina imperialis Hanna and Hanna

The changes in water depth from Cowlitz through Keasey time can be related to eustatic sea level rise and to basin subsidence. The global cycles of Cenozoic sea level changes record a moderate eustatic rise during the late Eocene (cycle TE3 of Vail and Mitchum, 1979). Continuing basin subsidence during the late Eocene probably accounts for further depth increases of marine facies represented by the Keasey lithofacies.

Each of the three bathyal Keasey lithofacies contains some shallow water benthic forams transported from the neritic zone (McDougall, pers. comm., 1982) by low-density turbid layers or clouds of fine hemipelagic clays and silts and forams stirred up by wave activity on the shelf. Low-density, storm wave generated turbid layers are common on the modern Oregon continental slope during the winter months (Kulm and others, 1975). These depositional processes must have been active throughout Keasey time not just during deposition of the Vesper Church member.

Pittsburg Bluff Formation

Nomenclature

The Pittsburg Bluff Formation is named for exposures of fossiliferous massive sandstone near Pittsburg, Columbia County, Oregon. The type area was designated by Weaver (1937) as the area between Pittsburg and Mist. The type locality occurs in roadcuts near the intersection of State Highways 47 and 202, approximately 1 km northeast of Pittsburg (Moore, 1976). The lower part of the formation is exposed here.

Warren and others (1945) and Warren and Norbisrath (1946) distinguished two informal units in Columbia County. The lower unit is a compact, richly fossiliferous, shallow marine and brackish-water, fine grained sandstone. The upper unit is finer grained, more tuffaceous, and less fossiliferous.

Weaver (1937, 1942) and Warren and others (1946) considered the Pittsburg Bluff Formation to be middle Oligocene. The original assignment to the Oligocene was made by Dall in 1896 from fossil samples collected by Diller from the type locality. Dall's assignment was based on comparison of molluscan genera from Pittsburg to Oligocene genera in Europe (Moore, 1976, p. 23).

Schenck and Kleinpell (1936; in Moore, 1976) believed the Refugian Stage in northern Oregon is represented by the

Keasey and Pittsburg Bluff formations. The type locality of the Pittsburg Bluff contains the *Molopophorus gabbi* Zone (Durham, in Weaver and others, 1944) and the *Acila shumardi* Zone. Schenck and Kleinpell included the *Acila shumardi* Zone in the Refugian. They consider the Refugian Stage to represent the upper Eocene and lower Oligocene European stages (Priabonian and Rupelian, respectively) (Fig. 5).

Distribution

The Pittsburg Bluff Formation (Tpb) crops out with a pattern similar to the Keasey Formation in the Nehalem and Astoria basins. The resistant strata wrap around the northward-plunging anticlinal axis of the Oregon Coast Range. In Columbia County, on the east flank of the Coast Range uplift, the outcrop pattern of the Pittsburg Bluff trends north-south to northwest-southeast. Local folds and faults cause variable strikes and reversals of dip (Newton and Van Atta, 1976; Kadri and others, unpub. map, 1980).

In the northern part of the thesis area, 26 to 39 km west of the type area (and on the west flank of the Coast Range uplift), the Pittsburg Bluff Formation (Tpb) crops out in a narrow northeast-southwest-trending band and dips northwest (Plate I). The homoclinal northwestward dipping unit typically forms ridges or bluffs that stand a few hundred feet above the lower hummocky hills and valleys of the underlying less-resistant Keasey mudstones. Dips of strata are gentle, ranging from 10° to 27° to the northwest. Local reversals and steepening of dip are probably due to faulting (Plates I and II).

The best localities to observe the Pittsburg Bluff Formation in the thesis area are: in logging roadcuts in the upper reaches of the Little Fishhawk Creek valley (N1/2, sec. 1, T5N, R8W and NW1/4, sec. 6, T5N, R7W); near the Nehalem River Highway (State Route 202, NW1/4, NW1/4, sec. 30, T6N, R8W); and in logging roadcuts in the Bull Heifer Creek drainage area (sec. 22, T6N, R7W). Several well-preserved molluscan fossils were recovered from silty fine grained bioturbated sandstone in NE1/4, NW1/4, sec. 22, T6N, R7W.

The Pittsburg Bluff Formation crops out only in the hills having an elevation greater than 230 m. The formation does not crop out in the lower valleys. This suggests that it was once more extensive, probably covering the entire upper Nehalem River valley area. Downcutting and erosion by the Nehalem River and its tributaries has removed much of the formation in the area of the Coast Range anticlinal axis.

Lithologies, Structures, and Provenance

The Pittsburg Bluff Formation consists of tuffaceous, micaceous, arkosic, fine to medium grained silty sandstone which grades into siltstone. Glauconitic sandstone and mudstone are locally abundant and in some exposures comprises more than 50% of the framework constituents (locality 335, SE1/4, SW1/4, sec. 22, T6N, R7W and locality 138 NE1/4, SE1/4, sec. 1, T5N, R8W). Sandstones form resistant structureless bioturbated beds 1 to 3 m thick. Thin tuffaceous mudstone, 0.3 to 1 m thick, is interbedded with the thick bedded sandstones (Fig. 28). Rare grit bids and molluscan fossils occur at the base of some thick sandstone beds. The molluscan fossils, including articulated bivalves, are commonly well-preserved and in growth position, or concentrated on bedding planes as fossil hash. In weathered outcrops, molds are common where the shell has been leached by meteoric waters. Spheroidal calcareous concretions are rare but commonly are concentrated along beds with fossil hash. In addition to rich molluscan, foraminiferal and coccolith faunas, scattered pieces of carbonized wood are preserved. A small crab (Branchioplat? sp. cf. B. washingtoniana Rathbun) was discovered in the sandstone (locality 407, SE1/4, SW1/4, sec. 21, T6N, R7W). A checklist of fossils collected from the Pittsburg Bluff Formation in the thesis area occurs in Appendix IV and fossil localities are shown on the geologic map (Plate I) and listed in Appendix X.

Fresh exposures of the Pittsburg Bluff Formation are rare. The tuffaceous strata are yellowish gray (5Y7/2) to light gray (N7). A spheroidal fracture pattern is common in weathered exposures.

Figure 28. Typical exposure of thick bedded, structureless sandstone of the Pittsburg Bluff Formation. Sandstone is interbedded with thinner, less resistant tuffaceous mudstone (arrow). Locality 118, on Oldy Mainline, SW1/4, sec. 1, T5N, R8W.

Three thin sections of sandstones from the Pittsburg Bluff Formation were examined. One of these (sample 138) is a greensand consisting of glauconite pellets or grains (48%), quartz (12%), reworked sedimentary rock fragments (9%), feldspar (1%), muscovite (1%), and abundant clay matrix (20%). The glauconite grains are well rounded. The very abundant silt-sized angular grains of quartz, feldspar and mica in the clay matrix precludes the chance that currents may have winnowed the bioturbated sediments or that the matrix is diagenetic in origin. Most detrital matrix probably formed by bioturbation and mixing by infauna (e.g., mollusks, crabs, worms, etc.) of better sorted clay, silt and sand layers.

Pittsburg Bluff sandstones typically have greater than 10% matrix and thus are classified as wackes. The framework constituents of two such wackes (from localities 315, 347) include dominantly subangular monocrystalline and polycrystalline quartz (33-49%), biotite (10-15%) and muscovite (3-5%), subrounded volcanic lava fragments (4-15%), plagioclase (5-10%), microcline and orthoclase (2%), glauconite (2%) and opaques (13%). The matrix consists of finely disseminated limonite and fine silt. These sandstones are subarkoses to feldspathic litharenites in Folk's (1980) classification (Fig. 29) or subfeldspathic lithic and feldspathic wackes in Williams and others (1954) classification (Fig. 29).

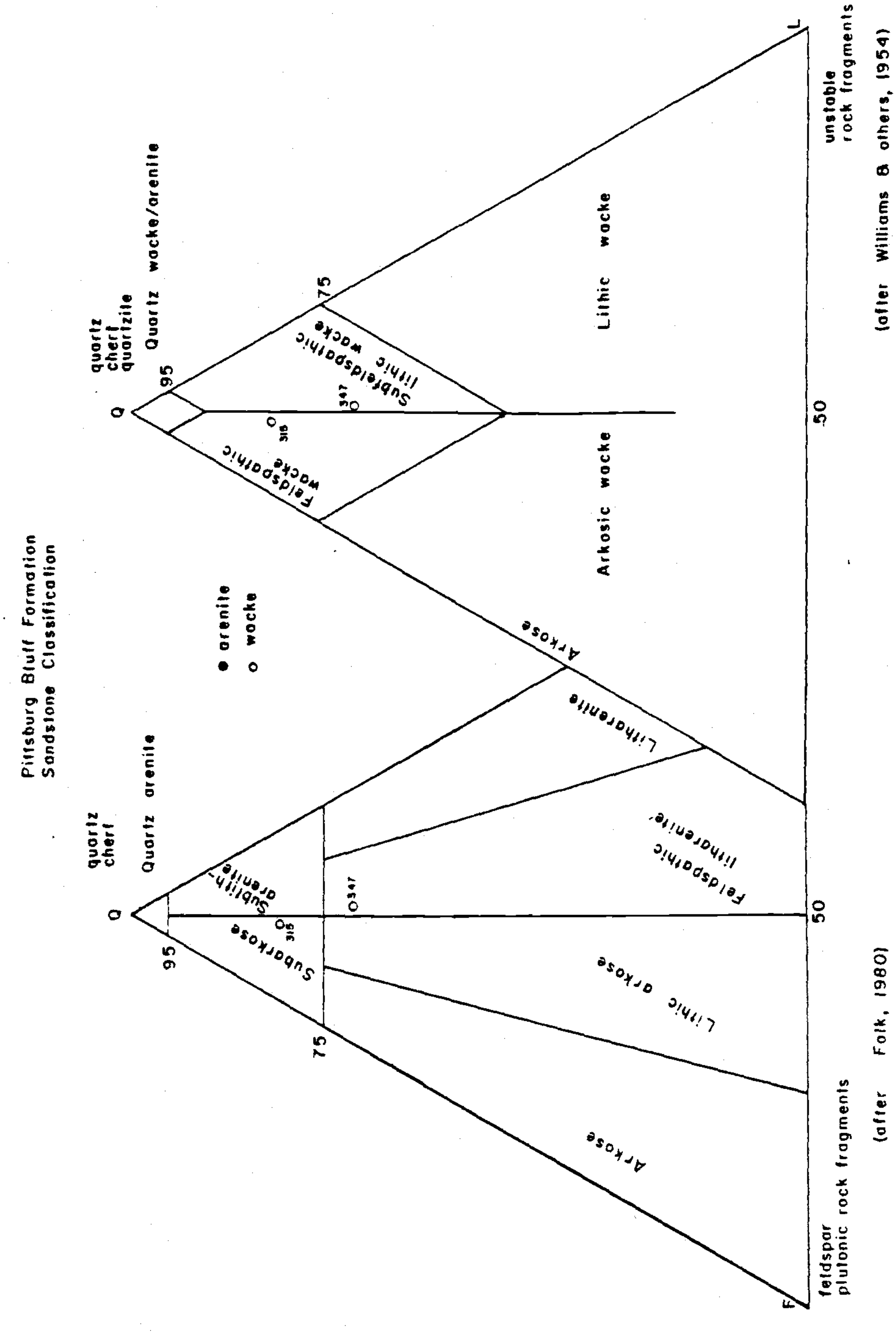


Figure 29. Classification of Pittsburg Bluff sandstones.

Pittsburg Bluff sandstones are texturally immature to submature which suggests low energy conditions and rapid burial and/or bioturbation in the final depositional environment. The abundance of clay-silt matrix strongly affects this parameter and has reduced the permeability of the sand. The compositional maturity of Pittsburg Bluff sandstones is submature to mature due to the abundance of feldspar minerals and low proportion of lithic fragments.

Two grain mounts of heavy minerals in Pittsburg Bluff sandstone were examined (sample localities 315, 347). The heavy mineral assemblage shows a marked difference from sandstones of the Cowlitz and Keasey formations. Green hornblende and basaltic hornblende (lamprobolite) are abundant, comprising 9 to 17% of the heavy mineral fraction (see Appendix VIII). Biotite, apatite, zircon and epidote are also important, as each comprises more than 5% of the heavies. Accessory heavy minerals include kyanite, staurolite, rutile and garnet.

This hornblende-dominated heavy mineral assemblage, along with the tuffaceous character of the Pittsburg Bluff sandstone and mudstone, indicates an influx of intermediate (basaltic andesitic to silicic) volcanic detritus from the coeval eruptive Western Cascades to the forearc Coast Range basin during Pittsburg Bluff time. This contrasts with the sands of upper Eocene Cowlitz and Keasey formations which have a heavy mineral assemblage reflecting a more prominent metamorphic and silicic plutonic provenance. Much of the

Pittsburg Bluff detritus may have been derived from hornblende-bearing pyroclastics and lavas of the upper Eocene to Oligocene Little Butte Volcanics of the Oregon Western Cascades and the Ohanapecosh Formation of the Washington Cascades (Hammond, 1979). Peck and others (1964) described a small percentage of the Little Butte Volcanics as porphyritic hornblende-bearing andesitic lava and pyroclastics. This does not seem to have been the sole or primary source of abundant hornblende. Alternatively, the upper Eocene Clarno andesitic lavas and Oligocene John Day Formation of central Oregon may have been the source of detritus (Oles and Enlows, 1971; Peck, 1964; Robinson, 1975). These units contain more hornblende lavas and pyroclastics than the Oligocene Little Butte Volcanics.

Contact Relations

The contact with the underlying Keasey Formation is disconformable. This relationship is suggested by the abrupt bathymetric and lithologic change from bathyal water depths and deposition of thick tuffaceous mudstone during late Keasey time to neritic depths and deposition thick sandstone during Pittsburg Bluff time. The contact is placed on the geologic map (Plate I) where thick structureless Pittsburg Bluff sandstones comprise 70% of the section.

In addition, a regional unconformity is suggested by mapping. The Pittsburg Bluff Formation in the study area overlies the upper Keasey mudstone (Tk_3) (Plate I), but between Jewell and Birkenfeld, 10 km to the east, the Pittsburg Bluff directly overlies the Vesper Church turbidite unit of the Keasey Formation (Tk_2) (geologic map of Olbinski, 1983). This thinning, or loss of section, of the upper Keasey mudstone (Tk_3) to the east can be seen on the geologic map (Plate I). The unit goes from 450 to 305 m in a northeast direction along strike across the study area.

Generally, the Pittsburg Bluff sandstones are bluff-formers and a topographic change occurs between the sandstones and slope-forming Keasey mudstones. The sharp contact between the two units is exposed in one roadcut (NE1/4, sec. 11, T5N, R8W) on East Humbug Road. A zone of spring-seeps marks the contact between the underlying impermeable Keasey mudstone and the overlying permeable Pittsburg Bluff sandstone forming a perched water table. The seepage zone is marked by lush vegetation in the roadcut and is most obvious during the late summer.

Warren and Norbisrath (1946) also noted the disconformable relationship between the Pittsburg Bluff Formation and the underlying Keasey Formation in Columbia County.

The nature of the contact with the overlying, and partly coeval, Oswald West mudstone is uncertain because the contact is covered. However, from regional mapping, this contact is probably conformable as the Oswald West mudstone appears to interfinger with Pittsburg Bluff sandstone. Rarey (in prep.) has found that the Pittsburg Bluff Formation gradually becomes less arkosic, thins, becomes finer grained and more glauconitic, and passes laterally into laminated silty mudstone and sandy siltstone southwest of U. S. Highway 26. Peterson (1984) has mapped and documented a similar facies change in the Pittsburg Bluff Formation to deeper water more silty mudstone of the Oswald West formation immediately northwest of this study area. The Oswald West mudstone also overlies the Pittsburg Bluff sandstone in this thesis area and is exposed in the Beneke quarry (Plate I, sec. 14, T6N, R7W).

In Columbia County, the sandstone-rich Oligocene to lower Miocene Scappoose Formation disconformably overlies the Pittsburg Bluff Formation with slight angular discordance (Warren and Norbisrath, 1946). This contact is locally marked by a cobble conglomerate (Moore, 1976).

Mapping in the study area suggests that the lower to middle Miocene Silver Point member of the Astoria Formation unconformably overlies the Pittsburg Bluff Formation (Plate I). The Pittsburg Bluff - Silver Point contact is generally poorly exposed but one can follow the section as it changes from structureless silty fine grained sandstone with spheroidal fracture to well-indurated thin bedded and laminated micaceous arkosic fine grained sandstone and dark mudstone with abundant carbonaceous material on bedding planes. This stratigraphic sequence can be followed in unnamed logging roadcuts in NW1/4 sec. 25, T6N, R8W.

The thickness of the Pittsburg Bluff Formation within the thesis area is estimated to be 200 to 500 m. This is based on projected contacts of the Pittsburg Bluff Formation (Tpb) with the underlying upper mudstone member of the Keasey Formation (Tk_3) and the overlying Silver Point member of the Astoria Formation (Tsp); both contacts are poorly exposed. Some of the sandstone thickness was removed by erosion prior to deposition of the Silver Point member of the Astoria Formation which prevents better estimation of the original thickness. Warren and Norbisrath (1946) estimated the overall thickness of the unit in Columbia County to be 252 m. Moore (1976) measured 200 m in the type area.

Age and Correlation

The original assignment of the Pittsburg Bluff Formation to the Oligocene by Dall on the basis of molluscan fauna appears to be valid still. Schenck (1927a) designated a middle Oligocene age. Weaver (1937) and Warren and Norbisrath (1946) agreed with the middle Oligocene age. Moore (1976) concurred with this assignment in the type area near Pittsburg, Oregon.

Armentrout's (1981) revision of the Tertiary time scale for the Pacific NW may cause reassignment of the age of these strata. The type section of the Pittsburg Bluff Formation contains the *Acila shumardi* Zone and *Molopophorus gabbi* Zone which occur within the Refugian Foraminiferal Stage (Schenck and Kleinpell, 1936). In the revised Tertiary time scale, the Refugian Stage is considered entirely within the late Eocene (Armentrout, 1981).

Moore (1976, p. 23-26) explained that the boundaries of the type section of the Refugian Stage in California were originally defined using both molluscan and foraminiferal faunas. However, more recently the stage has been characterized strictly by foraminiferal content. This renders the Refugian Stage useless to molluscan biochronology because of the significant difference in provincialism of forams and mollusks over large distances (Moore, 1976). Also, some workers (Addicott, 1972, in Moore, 1976) have suggested that the Refugian Stage and the overlying Zemorrian Stage (Fig. 5) are, in part, contemporary because of the co-occurrence of index fossils of each stage in certain stratigraphic sections. In the type area of the Pittsburg Bluff, near Vernonia, Oregon, coccoliths recovered from the Pittsburg Bluff Formation indicate a late Eocene to earliest Oligocene age (Moore, 1976).

Many of the molluscan assemblages found in this study are typical of Pittsburg Bluff faunas (Moore, 1976; written comm., 1982) and belong in the Galvinian Molluscan Stage and Refugian Foraminiferal Stage which are late Eocene according to the revised time scale (Armentrout, 1981). From lithologic similarity, stratigraphic position and faunal assemblages, there seems no doubt that these sandstones are part of the Pittsburg Bluff Formation.

However, using the new Tertiary time scale, the age range of the upper part of the formation in the study area is not certain (either Galvinian - Refugian or Zemorrian or both) because the molluscan and coccolith age-diagnostic fossils collected from the same locality disagree. For example, a gastropod and coccoliths were collected from locality 424. The gastropod *Turricula*? sp. cf. *T. washingtonensis* (Weaver) is characteristic of the *Turritella porterensis* Zone of Hickman (1974). This molluscan zone is considered to be equivalent to the late Refugian Foraminiferal Stage (Moore, written comm., 1982) and occurs in the upper part of the Lincoln Creek Formation in southwest Washington. In contrast, an assemblage of five coccolith species (listed in Appendix IV) were recovered from locality 424 that indicate a probable late Oligocene age (David Bukry, written comm., 1982). One of the species, *Dictyococcites bisectus* (Hay *et al.*), is characteristic of calcareous nannoplankton subzone 19b (Bukry, 1981) and zone NP25/NN1 (Martini, 1971) (Fig. 5). These nannoplankton zones are equivalent to the late Zemorrian or late Oligocene on the revised Tertiary time scale (Armentrout, 1981).

It may be that the Galvinian - Refugian mollusks at this locality (424) reflect provincialism and a shallow marine environment that persisted locally for a longer time whereas the planktonic coccoliths, which are less controlled by facies and thus more reliable for time-stratigraphic study, reflect the younger age of this unit. (This is similar to the provincialism between forams and mollusks noted by Moore in 1976.)

As the coccoliths indicate only a probable age, it appears that the best estimate of the age of the Pittsburg Bluff Formation in the thesis area is latest Eocene to Oligocene, spanning the upper Refugian and part of the Zemorrian stages.

The Pittsburg Bluff Formation is correlative to the upper part of the Lincoln Creek Formation in southwest Washington, to the Tunnel Point Formation in the Coos Bay area, to the Eugene Formation of the Willamette Valley, and to the Alsea and Yaquina formations near Newport, Oregon (Schenck, 1927a; Weaver and others, 1944; Moore, 1976; Snavely and others, 1969; MacLeod and Snavely, 1973; Niem and Van Atta, 1973).

The lower part of the Oswald West mudstone is also correlative to the Pittsburg Bluff Formation. The type Oswald West mudstone is early Oligocene to early Miocene (Cressy, 1974). However, the base of this unit is unexposed and the earliest age of the Oswald West has never been defined in the type area (Cressy, 1974, p. 29-30). Workers who have mapped adjacent areas of western Clatsop County

(Penoyer, 1977; Smith, 1975; Tolson, 1976; M. Nelson, 1978; Coryell, 1978; Peterson, 1984; Rarey, in prep.) have included thick mudstones that yield Zemorrian, Refugian, and in some cases Narizian, fossils in the Oswald West formation. These Refugian mudstones are, therefore, age correlatives of the Pittsburg Bluff Formation.

Because the thesis area lies between areas having two different stratigraphic nomenclatures, an attempt is made here to merge the nomenclature. It is well-accepted that Tertiary shallow-marine facies grade into deeper marine facies from east to west in northwest Oregon (Niem and Van Atta, 1973; Cressy, 1973; Penoyer, 1977; Peterson, 1984). This thesis area lies about mid-way between the well-studied shallow-marine formations of Columbia County (e.g., Pittsburg Bluff, Scappoose formations), and the deep-marine units (e.g., Oswald West, Astoria Silver Point mudstones) exposed along the Oregon Coast. The shallow-marine (inner shelf and deltaic) sandstones apparently grade subtly into finer grained sedimentary rocks progressing from east to west (Peterson, 1984). The interfingering relationship is very difficult to map precisely, and the contacts are uncertain due to discontinuous exposure, dense forest and thick soil horizons. Low faunal density also complicates the issue.

Nevertheless, the thick bluff-forming arkosic and tuffaceous bioturbated sandstone of the Pittsburg Bluff

Formation appears to grade laterally into correlative sandy siltstone, tuffaceous mudstone and thinner glauconitic sandstone in the vicinity of Saddle Mountain near the western boundary of the study area (shown schematically on Plate I). This change is also noted south of U. S. Highway 26 (Rarey, in prep.) and in the Klaskanine River area (Peterson, 1984).

The informal name Oswald West mudstone is applied to sequences in which the lithology is predominantly mudstone (>70%) and thick bluff-forming arkosic, tuffaceous sandstone is lacking. The lithofacies dominated by thick structureless Refugian - Zemorrian age sandstone (>70%) is described as the Pittsburg Bluff Formation. Thus, it is herein assumed that the Oswald West mudstone extends down in the upper Refugian, and that in its lower part, the Oswald West is coeval to the Pittsburg Bluff Formation.

Depositional Environment

The depositional environment of the Pittsburg Bluff Formation is interpreted to be shallow-marine inner to outer shelf. Paleoecology of molluscan faunas collected in the study area indicate water depths of 20 to 200 m (Moore, written comm., 1982). Fossiliferous rocks are concentrated in the eastern part of the thesis area (e.g., sec. 22, T6N, R7W, Plate I). The molluscan fossil assemblage from the Elk Mountain - Porter Ridge area, north and east of the present study area, indicates a slightly narrower range of water depths (20 to 50 m, written comm. to Jeff Goalen from Dr. Ellen Moore, 1982).

Genera from the molluscan fossil collection which have extant species offer some information about the paleoecology. The subgenus Pitar (Pitar) is restricted to sand flats, sand bars or protected bays (Moore, 1976, p., 18). Dentalium (Fissidentalium) sp. lives under a thin sediment layer in water depths of 20 m or more. Dr. Moore (1976, p. 17) characterized the Pittsburg Bluff faunas as filter-feeders, detritus-feeders and carnivores that lived on the sea floor or in the substrate. Primary sedimentary structures are not observed in outcrop, and the lack of structures is probably due to thorough bioturbation by infauna.

The Tertiary marine setting is comparable to the modern Oregon continental margin. The modern facies are analogous to the ancient depositional environments and serve as a depositional model. Detailed sedimentological studies reveal three distinct sedimentary facies on the modern Oregon shelf (Kulm and others, 1975). These facies are composed primarily of three sedimentary components; detrital, biogenic, and authigenic (glauconite).

The sand facies is distributed on the inner shelf at depths of 90 to 100 m where sediment supply from river systems is large (Kulm and others, 1975). This facies tends to be laminated and composed of fine sand.

The mud facies is irregularly distributed and tends to concentrate near rivers having high sediment discharge. Silt and clay size sediment that compose this facies are deposited during summer seasons. The sediment discharge of the Columbia River, for example, is greatest during the summer. Ocean swells and storm waves are reduced in intensity, periodicity and wavelength during the summer season and, therefore, disturb the shelf sediment less (Kulm and others, 1975). Thus, silt and clay size sediment tends to settle from suspension on the middle to outer shelf during the summer but is carried over the shelf edge and onto the continental slope during the winter.

The mixed sand and mud facies occurs seaward of the inner shelf sand facies. The former is a facies produced from sediment homogenization by burrowing benthic organisms. Intensity of bioturbation and density of benthic organisms increases as water depth increases. Glauconite occurs on the outer shelf seaward of the mixed sand and mud facies and on topographic highs as relict sand formed during Pleistocene sea level lows (Kulm and others, 1975).

Three turbid water layers occur within the water column formed in response to density contrast between clear water and mixed sediment/water (or cloudy) layers. These turbid layers are capable of transport of suspended sediment over the continental shelf edge. During winter when storm energy and wave amplitudes are greatest, the turbidity of the three water layers increases. This signifies seaward transport of sediment from the nearshore marine to the slope environment of deposition.

If the present-day sedimentological relations can be used to model the late Eocene and Oligocene seas, then a depositional model for the Pittsburg Bluff Formation can be developed. Molluscan paleoecology indicates a sandy and shallow substrate. Depths of 20 to 200 meters correspond to the inner shelf. Subgenera such as Pitar (Pitar), Crenella, and Nemocardium (Keenaea) (?) lorenzanum live on sand substrates but not in high energy environments (Moore, 1976, p. 18). Delectopecten prefers silty substrates and its thin shell wall indicates adaptation to quiet water environments. The latter genus was collected from fine grained sandstone in the Pittsburg Bluff Formation in the western part of the thesis area (locality 145) suggesting a deepening of the shelf in that direction.

The Pittsburg Bluff depositional model is one of a very gently sloping inner to outer shelf protected from high energy wave conditions. Paleodepths within the thesis area are a maximum of 200 m during Pittsburg Bluff time. In the type area in Columbia County, water depths of 10 to 20 m and an intertidal beach environment are indicated by the paleoecology of mollusks (Moore, 1976). Supratidal marsh environments are indicated by coal seams that occur in the Pittsburg Bluff section in Columbia County. An average slope of 1 meter per 100 meters (or approximately 1/2°) can be calculated for this shelf on a northwest-southeast transect from the type area to the present study area.

In the Oligocene sea, glauconite may have formed in shallow water and on isolated or protected topographic highs, resulting in the observed patchy distribution. It typically forms as fecal pellets of mud-ingesting infaunas in a low energy slightly reducing environment with slow sedimentation rates (McRae, 1972).

Pelletal glauconitic sandstone within the thick arkosic tuffaceous Pittsburg Bluff sandstone does not seem to fit the modern Oregon shelf analogy in that it occurs as relict sands on the modern low energy outer shelf and slope mud environments (Kulm and others, 1975). More likely, glauconite beds in the Pittsburg Bluff may have resulted from redistribution of glauconite by bottom currents or storm wave-induced currents into higher energy environments. Similar transported glauconitic greensands occur in some quartz sandstones in the Cambrian of Wisconsin (Dalziel and Dott, 1970). Concentrations of glauconite are common at nonconformities or marked periods of nondeposition.

The lower Oswald West mudstone in the southwest part of the thesis area is probably coeval to part of the Pittsburg Bluff Formation (Plate I). These mudstones were deposited on the outer shelf to upper slope seaward of the Pittsburg Bluff Formation during the late Eocene and Oligocene. In the depositional model, these mud-size suspended sediments derived from the nearshore and surf zones were transported offshore as turbid layer currents to the shelf edge and deposited from suspension on the outer shelf and upper slope. Maximum transport of silt and clay occurred during storm seasons, as in the modern analogue. This sediment by-pass contributed to a slow depositional rate of outer shelf silt and increased the sedimentation rate on the adjacent continental slope (Kulm and others, 1975).

Oswald West Mudstone

Nomenclature and Distribution

The informal name Oswald West mudstone (Tow) was first applied by Niem and Van Atta (1973) and Cressy (1974) to 549 m of Zemorrian age bioturbated silty mudstone and tuffaceous siltstone exposed in the sea cliffs along Short Sand Beach in Oswald West State Park on the northwest Oregon coast. Warren and others (1945) measured a section and collected fossils at this locality. They referred to the section as Beds of Blakeley age because faunas collected there could be correlated to the *Echinophoria rex* Zone and *E. apta* Zone that occur in the type section of the Blakeley Formation of western Washington (Weaver, 1937; Weaver and others, 1944). Warren and others (1945) believed that the sedimentary structures in the Short Sand Beach section "indicated unique conditions for Blakeley sedimentation", meaning that the facies observed does not occur elsewhere in the parts of northwest Oregon that they mapped. In a later paper, Warren and Norbisrath (1946) also applied the name Scappoose Formation for the first time to Beds of Blakeley age that occur in Columbia County. These beds are predominantly friable thick arkosic sandstone and are quite different from the deep marine mudstone strata at Oswald West State Park.

The Oswald West mudstone is an informal formation name applied to a deep-marine mudstone facies that is Oligocene to early Miocene in age. It lies stratigraphically between the upper Eocene to Oligocene Pittsburg Bluff Formation and lower to middle Miocene Astoria Formation. Due to cover and a thick basalt sill, the base of this formation was not defined at the type section (Cressy, 1974, p. 23, 29). Murphy (1981, p. 38) showed that the base of the Oswald West mudstone could be defined in the Nicolai Mountain - Westport area (16 km north of this study area) by its disconformable contact with the underlying sandstone-rich Pittsburg Bluff Formation.

The Oligocene Oswald West mudstones are, however, lithologically similar to the thick structureless tuffaceous mudstone that forms much of the type upper Eocene Keasey Formation. Distinguishing the two formations in Clatsop County on the basis of lithology is possible where the Pittsburg Bluff sandstone lies between them. But, where the sandstone-rich Pittsburg Bluff Formation grades to mudstone, the distinction between similar mudstones of upper Eocene (Keasey) and of Oligocene (Zemorrian) age is not possible without good paleontological data.

As a result, other workers who have mapped areas west of this study area (Penoyer, 1977; Tolson, 1976; M. Nelson, 1978; Coryell, 1978; Peterson, 1984) extended the definition of the Oswald West mudstone to rocks containing Refugian, and even Narizian forams. Extending the range of the Oswald West mudstone causes some confusion about its stratigraphic relationship to the Pittsburg Bluff, Keasey and Cowlitz formations.

I suggest that the Oswald West mudstone (Tow) be considered a long-ranging deep-marine (slope and outer shelf) facies which is the stratigraphic equivalent to the combined Scappoose, Pittsburg Bluff and Keasey Formations. These units along with the Cowlitz Formation have been collectively referred to as the Nehalem Group (Van Atta, 1971, p. 17). The Oswald West mudstone may interfinger with each of the three younger formations of the Nehalem Group in response to rising and falling of the Paleogene sea. Peterson (Plate IV, 1984) concurs with this suggestion and shows the lateral relationship of the Keasey and Pittsburg Bluff formations with the "upper" and "lower" parts of the Oswald West mudstone.

The Oswald West mudstone crops out in three outlier-like patches within the thesis area and represents a lateral facies of the Pittsburg Bluff tuffaceous arkosic sandstone. The first is on the western boundary near Saddle Mountain (W1/2 sec. 11, NW1/4 sec. 14, NE1/4 sec. 15, T5N, R8W); the second is on the northern border above a Grande Ronde basalt sill (NW1/4, NW1/4 sec. 16 and NE1/4, NE1/4 sec. 17, T6N, R7W); and the third is in the northeast corner of the thesis area around the Beneke dike quarry

(NW1/4 sec. 14, T6N, R8W) (Plate I). On the geologic map of Oregon west of the 121st meridian (Wells and Peck, 1961), undifferentiated Eocene-Oligocene marine rocks form an arcuate pattern around the northward-plunging "Coast Range Anticlinorium". The Oswald West mudstone is part of that undifferentiated sequence. The Oswald West formation dips from 7° to 31° to the southeast (Plate I) which opposes regional northwestward dip and probably reflects drag by many small cross-cutting faults and perhaps slumps.

Lithologies and Structures

The dominant lithologies are thick bedded tuffaceous mudstone and sandy siltstone, and minor silty sandstone. In outcrop, the tuffaceous mudstone and siltstone are structureless and bioturbated but in rare cases are faintly laminated. The laminations are formed by carbonized wood chips. Fresh exposures were not observed but weathered Oswald West mudstone is yellowish gray (5Y7/2). The small, hook-shaped trace fossil Sclarituba (Chamberlain, written comm., 1982) is ubiquitous in the structureless Oswald West mudstones. The strata are micromicaceous. In one locality, the rock is displays uncommon platy jointing (locality 382, NE1/4, NE1/4 sec. 17, T6N, R7W). Probably the platy jointing is caused by baking due to an adjacent intrusion of Miocene basalt.

Fossils recovered from the Oswald West mudstone include forams, articulated pelecypods, scaphopods and trace fossils. Mollusks recovered from the unit include:

Dentalium (Fissidentalium?) sp. cf. _D. (F.?) laneensis_ Hickman
Pitar (Pitar)? sp. cf. _P. (P.) dalli_ Weaver
Delectopecten sp.
cardiids
nuculaniids

The large non-diagnostic foram _Cyclammina pacifica_ is also abundant in the tuffaceous mudstone. A complete list of the fossil collection is presented in Appendix V. No age-diagnostic fossils were collected from this formation in the study area.

Contact Relations

The lower part of the Oswald West mudstone in the study area is a deep-water and finer grained facies of the sandstone-rich Pittsburg Bluff Formation. Mapping suggests that the unit probably interfingers with the Pittsburg Bluff in the southwest part and overlies the Pittsburg Bluff in the northern part of the study area (Plate I).

The contact is conformable or paraconformable (Dunbar and Rogers, 1957) with the underlying Pittsburg Bluff Formation. As used in this sense, the base of the Oswald West mudstone is defined by a lithologic change rather than a change in faunal character. Where the sedimentary facies is dominated by thick bedded bioturbated tuffaceous mudstone the term Oswald West is applied. Where the facies is dominated by thick arkosic tuffaceous fine grained sandstone the name Pittsburg Bluff Formation is used. Thus, the Oswald West mudstone was in part deposited on the Pittsburg Bluff shelf sandstone in the northern part of the study area.

Peterson (1984) and Rarey (in prep.) also mapped the gradual change of the Pittsburg Bluff sandstone into a dominantly (Oswald West) mudstone facies immediately to the southwest and west of this study. These workers, along with Murphy (1981) and Penoyer (1977), found that a younger Zemorrian - Saucesian (Oligocene to early Miocene) Oswald West mudstone overlies the Pittsburg Bluff Formation.

Rarey (in prep.) has noted that a minor section of the Pittsburg Bluff sandstone facies can be mapped near U. S. Highway 26 (4.8 km southwest of the study area) and that this sandstone facies undergoes an interfingering facies change to very well laminated mudstones and thick glauconitic sandstone beds of the Oswald West mudstone. He suggests that these thick glauconitic sandstones and laminated mudstones mark the base of the Oswald West mudstone with the underlying structureless upper mudstone member of the Keasey Formation (Tk_3) when the intervening thick arkosic sandstone facies of the Pittsburg Bluff Formation is missing western Clatsop County.

The Silver Point member and Angora Peak member of the Astoria Formation unconformably overlie the Oswald West mudstone. The contact is not exposed in the thesis area. The unconformable relationship between the Oswald West and the Silver Point member of the Astoria Formation has been observed in other areas of western Clatsop County (Peterson, 1984; Neel, 1976; Penoyer, 1977; Tolson, 1976; M. Nelson, 1978).

Near the type section of the Oswald West mudstone, an angular unconformity between the Oswald West mudstone and the Angora Peak member of the Astoria Formation is suggested by the following: a sharp lithologic change from deep-marine mudstone to shallow-marine pebbly arkosic sandstone and volcanic pebble conglomerate; Blakeley age (Oligocene) mollusks in the underlying Oswald West mudstone and Temblor age (middle Miocene) mollusks in the overlying Astoria, implying that the intervening Vaqueros Stage (lower Miocene) is absent; abrupt change in foram and trace fossil paleoecology that is attendant to the lithologic change from Oswald West mudstone to Astoria Formation (Angora Peak member) sandstone (Cressy, 1974; Cooper, 1981).

Fossils recovered from the type Oswald West mudstone indicate normal marine sedimentation at upper bathyal water depths. The overlying Angora Peak sandstones are very shallow-marine, deltaic and fluvial deposits which succeeded a rapid shallowing of the depositional environment (Cressy, 1974; Cooper, 1981). Murphy (1981) placed the contact between the Oswald West mudstone and clean arkosic Big Creek member sandstones on a persistent glauconite bed in the Nicolai Mountain - Westport area.

Age and Correlation

The age of the Oswald West mudstone is early Oligocene to early Miocene and is defined on the basis of molluscan and foraminiferal assemblages. The original assignment by Warren and others (1945) to the molluscan Blakeley Stage implies an early Oligocene age for the type section based on the correlation of the *Echinophoria rex* Zone to the early Zemorrian Foraminiferal Stage (Moore, 1984). Warren and others (1945) also correlated the Beds of Blakeley Age at the type Oswald West section to the *E. apta* Zone, which is equivalent to the late Zemorrian and early Saucesian Foraminiferal Stages that are currently assigned to the late Oligocene and early Miocene, respectively (Moore, 1984).

Zemorrian (Oligocene) and Saucesian (lower Miocene) foraminifers have also been collected from the type section (Cressy, 1974; Niem and Van Atta, 1973). Other workers (Penoyer, 1977; Neel, 1976; M. Nelson, 1978; Tolson, 1976; Peterson, 1984) have extended the range of the Oswald West mudstone down to the Refugian, and possibly the Narizian, Foraminiferal Stage (upper Eocene). No age diagnostic faunas were collected from the Oswald West mudstone in the study area.

The Oswald West mudstone is correlative to the arkosic tuffaceous fine grained sandstone of the Pittsburg Bluff Formation and to the Scappoose Formation of the northeastern flank of the Oregon Coast Range, to the Alsea Formation, Yaquina Formation and Nye Mudstone of the central coast area, and to the Lincoln Creek Formation of southwest Washington (Fig. 4).

Depositional Environment

The Oswald West mudstone was deposited on the outer shelf or upper slope of the continental margin. The depositional environment was largely seaward of the shelf environment represented by the Pittsburg Bluff Formation. The very fine grain size, lack of primary sedimentary structures and bioturbation are characters of the mud facies on the middle to outer modern Oregon continental shelf and upper slope (Kulm and others, 1975). The modern mud facies is thickest in areas adjacent to coastal rivers that have high seasonal discharge, such as the Columbia River. An irregular distribution on the outer shelf and upper slope is also a character of the mud facies. As the Oswald West is predominantly mudstone with patchy distribution and is linked to deposition of Pittsburg Bluff shelf sandstone, the

Oswald West is modeled after the modern Oregon outer shelf mud facies (Kulm and others, 1975) and upper slope depositional environments.

Cressy (1974) proposed a depositional model for the Oswald West mudstone in which the bathyal mudstones and siltstones were deposited in pro-delta or delta-slope environments coupled to the coeval Scappoose Formation delta on the northeastern flank of the Oregon Coast Range. Minor sedimentary structures and features (e.g., rare graded turbidites, contorted bedding, mudflow deposits, clastic dikes) are similar to those in pro-delta slope sediments and are indicative of rapid sedimentation and loading in a deep-water pro-delta to delta-slope environments.

In the study area, however, a different depositional model is envisioned for these older Oswald West mudstones. Because the upper Eocene - Oligocene Oswald West mudstone is in part correlative to the Pittsburg Bluff in the southern part of the study area and overlies the Pittsburg Bluff in the northern part of the study area, an alternative transgressive shelf - slope (non-deltaic) model is suggested. This field relationship implies that onlap of upper slope - outer shelf Oswald West mud facies onto Pittsburg Bluff shelf sand occurred during the Oligocene. This transgression can be tentatively correlated to cycle TO1 (Vail and Mitchum, 1979; Vail and Hardenbol, 1979).

Large volumes of tuffaceous silt and clay that were erupted from the active Western Cascades volcanic arc were dispersed over a wide area of the adjacent middle to outer shelf and slope by mid-layer turbidity currents. In addition, bottom-layer turbidity currents generated by long wavelength winter storm waves also transported very fine "Pittsburg Bluff" sand from inner - middle shelf and nearshore environments into this deeper-marine environment. The fine sand, silt and clay layers were homogenized by burrowing infauna and filter feeders to form the thick structureless silty mudstone and sandy siltstone that now comprises the Oswald West mudstone.

A slow sedimentation rate is implied by the extensive bioturbation (Howard, 1978). The Helminthoida burrows, which are common in the unit, are associated with the Zoophycos trace fossil assemblage which indicates deposition at bathyal depths (e.g., upper slope depths) (Chamberlain, in Cressy, 1973). The abundant large forams, Cyclammina pacifica are the pelagic component in the hemipelagic sediment. This, along with other forams and other planktonic microorganisms may have absorbed suspended clays by filter-feeding and aided flocculation. The unbroken valves of nuculaniids and Pitar imply low energy normal marine conditions below wave base for the Oswald West mudstone.

Silver Point Member of the Astoria Formation

Nomenclature and Distribution

The informal name Silver Point mudstone member was proposed by Smith (1975) for well-bedded and laminated mudstones of the lower to middle Miocene Astoria Formation. The type section for the member occurs along the sea cliffs at Silver Point, approximately 5 km south of Cannon Beach, Oregon and 38 km from this study area. The thickness of the Silver Point member in the type area is approximately 200 m (Smith, 1975).

The Silver Point member (Tsp) crops out only in the northwest part of the study area (Plate I). The unit dips from 9° to 14° northward except where drag along faults has increased dips to as much as 22°. This laminated mudstone unit is the only member of the Astoria Formation that occurs in the thesis area. The best exposures occur along logging roadcuts on the West Tidewater Road (W1/2 sec. 18, T6N, R7W) and Tidewater Summit Road (NE1/4, SE1/4 sec. 19, SE1/4, SE1/4 sec. 18, and SW1/4, SW1/4 sec. 17, T6N, R7W). Because it weathers easily, the unit forms low stream-dissected ridges.

The Silver Point member is unconformably underlain by the fossiliferous shallow-marine sandstones of the Pittsburg Bluff Formation. The lithofacies is mapped and tentatively assigned to the upper Silver Point member on the basis of lithologic similarity to the upper Silver Point member described by Smith (1975), by stratigraphic position, and by continuous mapping of the unit from the study area to the type section through the thesis areas of Peterson (1984), Penoyer (1977), Neel (1976), Smith (1975) and Tolson (1976).

Lithology and Structures

Smith (1975) subdivided the type Silver Point into two units. The lower unit is a facies dominated by rhythmically bedded to thick arkosic turbidite sandstones and laminated micaceous mudstone in nearly equal percentages. The upper part of the member is thin bedded and finer grained and consists largely of interlaminated micaceous siltstone, very fine grained sandstone, and claystone.

In the thesis area, the Silver Point member consists of 365 m of laminated to thin-bedded micaceous very fine grained arkosic sandstone, siltstone and mudstone. Coarse flakes of mica are typically coarser grained than other clastic constituents of the rock. The coarseness and abundance of mica is used along with laminations to distinguish the Silver Point member from older mudstones of the Keasey and Oswald West formations in the study area. Laminations are 1 to 2 cm thick and are formed by concentrations of carbonized wood fragments, plant debris and mica parallel to bedding surfaces. The strata are easily cleaved along these surfaces. Rare fossil leaf imprints of deciduous plants also occur. One pelecypod, Delectopecten sp., was recovered from this unit (locality 360, NW1/4, SE,1/4 sec. 20, T6N, R7W).

Where fresh, the siltstone and very fine grained sandstone laminations are dark yellowish brown (10YR4/2) to dusky yellowish brown (10YR2/2). The interbedded claystone beds are black (N1) to grayish black (N2). The mudstone and very fine grained sandstone are most commonly weathered to yellowish gray (5Y7/2) and dusky yellow (5Y6/4). Weathering obscures the distinction between mudstone, very fine grained sandstone and siltstone laminae.

Contact Relations

The lower contact of the Silver Point mudstone with the underlying Pittsburg Bluff Formation, and locally with the Oswald West mudstone, is thought to be unconformable based on regional relations. The Silver Point interfingers with the underlying Angora Peak sandstone member of the Astoria Formation near the type section along the northwest Oregon Coast (Smith, 1975; Cooper, 1981). This exposed contact is conformable and gradational. Elsewhere in the Astoria basin, however, mapping shows that the Angora Peak sandstone member is not present beneath the Silver Point and has been removed by erosion. The latter rests unconformably on the lower to middle Miocene Big Creek sandstone member of the Astoria Formation (Coryell, 1978; Murphy, 1981), or rests unconformably on the upper Eocene - Oligocene Oswald West mudstone (Peterson, 1984), or on the upper Eocene - Oligocene Pittsburg Bluff Formation (this study; Goalen, in prep.). The unconformable contact is not exposed in the study area; however, the Silver Point member and the underlying Pittsburg Bluff Formation are in close association within a few hundred meters along unnamed logging roads in the SE1/4 sec. 25, T6N, R8W and on the Tidewater Summit Road in the SW1/4, sec. 21, T6N, R7W.

The upper contact of the Silver Point member is not exposed in the study area. Other workers have indicated that the Silver Point interfingers with the Pipeline sandstone member of the Astoria Formation (Murphy, 1981; M. Nelson, 1978; Coryell, 1978) or is unconformably overlain by extrusive breccias and pillow lavas of Depoe Bay (Grande Ronde) and Cape Foulweather Basalt (Frenchman Springs) (Smith, 1975; Neel, 1976; Penoyer, 1977; Tolson, 1976; Murphy, 1981). Numerous middle Miocene Grande Ronde basalt dikes and sills intrude the Silver Point member in the study area (Plate I).

Age and Correlation

The regional stratigraphic position of the Silver Point member of the Astoria Formation indicates that its age is early to middle Miocene. The underlying Oswald West mudstone is late Eocene to early Miocene in age (Cressy, 1974; Neel, 1976; Peterson, 1984). Basalt of middle Miocene age intrudes and nonconformably overlies the Silver Point member. Depoe Bay (Grande Ronde) Basalt that intrudes Silver Point mudstone at Ecola State Park and at Neahkahnie Mountain was radiometrically dated (K-Ar method) as 14 $\pm$ 2.7 m.y. (Snavely and others, 1973; Niem and Cressy, 1973). Forams and mollusks in the interbeds in basaltic breccias indicate a Saucesian (middle Miocene) age (Neel, 1976; Murphy, 1981).

Unfortunately, no age-diagnostic molluscan or microfossils were recovered from this unit in the study area. Foraminifers and mollusks collected by other workers (Neel, 1976; M. Nelson, 1978; Coryell, 1978; Tolson, 1976; Cooper, 1981) from the Silver Point member are diagnostic of age, however. The molluscan faunal assemblages are correlative to the Temblor Formation of California (early to middle Miocene) (Cooper, 1981). Foraminiferal assemblages from the Silver Point are indicative of the Saucesian Stage (early to middle Miocene) (Cooper, 1981; Neel, 1976; Niem and Van Atta, 1973).

Since no age-diagnostic fossils were collected from Silver Point strata in this thesis area, it is possible that this laminated unit is a facies of the upper Eocene (Refugian - Zemorrian) Pittsburg Bluff Formation. Olbinski (1983) chose to include some of these laminated mudstones in the upper Pittsburg Bluff Formation in the adjacent thesis area to the east.

Depositional Environment

The lower to middle Miocene Silver Point mudstones in Clatsop County were deposited as hemipelagic muds and storm-deposited silt and very fine sand in an open-marine environment on the outer continental shelf and upper slope. Foram paleoecology from fossils collected in the unit by other workers suggests water depths of sublittoral to upper bathyal zones (60 to 300 m) (Neel, 1976, p. 77).

Thin-shelled mollusks in western Clatsop County also indicate low-energy sublittoral to bathyal depths (>250 m) (Neel, 1976; M. Nelson, 1978). Delectopecten, an extant genus, is a thin-shelled pelecypod that is generally restricted to mud substrates in water depths of 18 to 180 m (Moore, 1963, p. 17, 19, 67). This fossil suggests a slightly shallower water depth (e.g., neritic) for the Silver Point strata in the study area compared to elsewhere in western Clatsop County.

Turbidity currents derived from the Angora Peak delta periodically transported and deposited micaceous, fine grained, graded arkosic sand to the lower part of the Silver Point member (Neel, 1976; Penoyer, 1977; Cooper, 1981; Peterson, 1984). The lack of bioturbation and thin laminations in the Silver Point strata in this study area suggest rapid sedimentation rates (Howard, 1978) and/or anoxic conditions in an oceanographic oxygen minimum layer such that highly diverse and abundant benthic organisms and infauna could not exist. High sedimentation rates of mud and very fine sand may be associated with turbid water discharge during floods from the delta of a major river system like the modern Columbia River. Alternatively, the very fine sand and silt layers between the hemipelagic muds may be the result of resuspension of inner shelf sediments and seaward transport during storm wave conditions. Such a mechanism has been described by Dott and Bourgeois (1984) for the interlaminated siltstone, very fine grained sandstone and mudstone of the middle to upper Eocene Coaledo Formation of southwest Oregon.

The unconformity at the base of the Silver Point and the lack of intervening shallow marine sandstone such as the Big Creek or Angora Peak members of the Astoria Formation suggest that this may be a submarine unconformity formed by nondeposition and/or slight submarine erosion of Oswald West and Pittsburg Bluff strata before deposition of the Silver Point strata.

Miocene Basalt Intrusives

Introduction

Middle Miocene tholeiitic basalts in northwest Oregon have been mapped as local intrusions associated with thick piles of basalt breccias, pillow lavas and minor subaerial flows of Depoe Bay and Cape Foulweather basalts (Snavely and others, 1973; Cressy, 1974; Smith, 1975; Neel, 1976; Penoyer, 1977; Coryell, 1978; Murphy, 1981). These middle Miocene basalts of western Oregon have chemical, magnetic, age, and physical characteristics similar to units of the Columbia River Basalt Group which erupted in eastern Oregon and Washington and western Idaho between 17 and 12 m.y.B.P. (Snavely and others, 1973; Swanson and others, 1979; Watkins and Baski, 1974; McKee and others, 1977).

In eastern Clatsop County (east of Saddle Mountain), a multitude of middle Miocene basalt dikes and sills intrude upper Eocene to middle Miocene marine strata (Penoyer, 1977; Olbinski, 1983; Peterson, 1984; Goalen, in prep., this study). Three spectacular, long dikes follow a sub-parallel northeast-southwest trend (Fig. 30; Plate 1). These dikes can be easily observed on aerial photographs and satellite imagery as elongate ridges cutting across much of the eastern part of the county. The longest of these is 22 km and is called the Beneke dike trend. Two other dikes lie

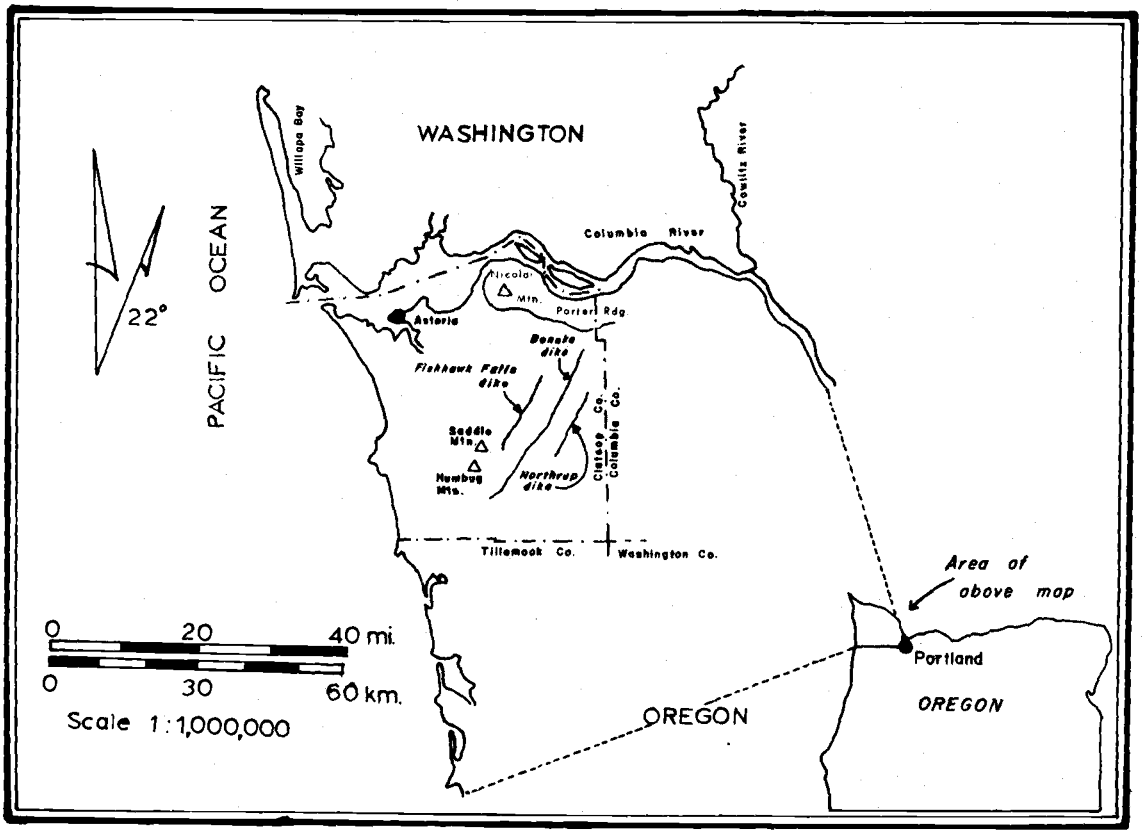


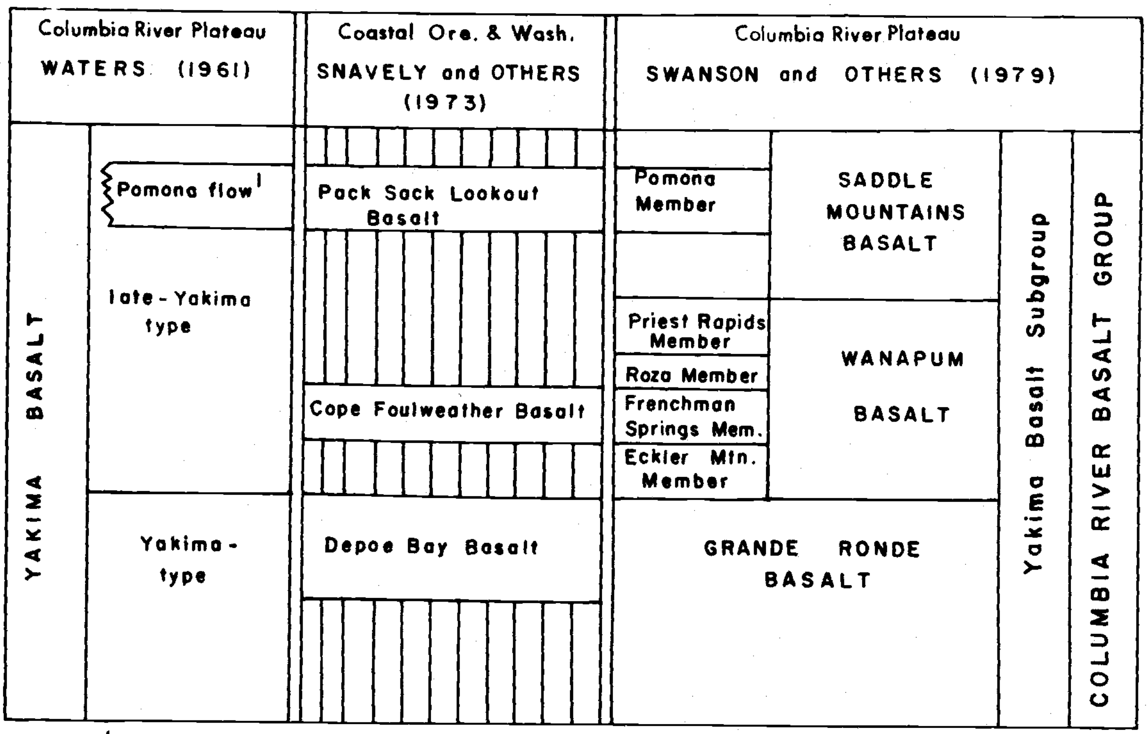
Figure 30. Distribution of middle Miocene Beneke, Fishhawk Falls and Northrup Creek basalt dikes trending N30°E across eastern Clatsop County.

approximately 2 km northwest and 4.8 km southeast of the Beneke dike trend and are herein referred to as the Fishhawk Falls and Northrup Creek dikes, respectively. The Beneke dike is called a "trend" because at least two periods of basalt intrusion occurred along its length. The Beneke and Fishhawk Falls dikes occur in the study area (Plate 1).

This chapter describes the field relations, lithology, geochemistry and paleomagnetic character of the middle Miocene tholeiitic dikes and sills in the study area (Plate 1) and the three dike trends and related flows outside the study area in eastern Clatsop County, Oregon (Fig. 30). In the field, the Beneke, Fishhawk Falls and Northrup Creek basalt dikes appear to be identical; however, close inspection of the lithology, geochemistry and magnetic polarity shows that each basalt dike has slightly different characteristics. This chapter also explores two speculative hypotheses concerning the origin of the dikes and documents some of the evidence pertaining to dike and sill emplacement in the study area.

Middle Miocene Coastal Basalts

U. S. Geological Survey geologists have mapped and formally defined three units of middle Miocene coastal basalt in western Oregon and Washington (Figs. 4 and 31) (Snavely and others, 1963, 1964, 1973, 1980). From oldest



[1]Schmincke (1967)

Figure 31. Partial list of units of Columbia River Basalt Group and correlation to Oregon coastal basalt units.

to youngest, these are: Depoe Bay Basalt, Cape Foulweather Basalt, and the Basalt of Pack Sack Lookout. Snavely and others (1973) reported that each of the three Miocene basalt sequences is lithologically, petrographically, geochemically and isotopically distinct from the others. These distinctions can be used in mapping these basaltic units. The paleomagnetic stratigraphy of these coastal basalts had been not defined when these workers published their findings.

Snavely and others (1973) believed that these three coastal basalt units were "locally-derived" from magma sources beneath the Coast Range and in some way were related to equivalent units of the middle Miocene Columbia River Basalt Group of eastern Oregon and Washington. Separate magma sources were suggested for each of the three coastal basalt units.

Snavely and others (1973) correlated the Depoe Bay Basalt to the "plateau-derived" Yakima Basalt (Waters, 1961), the Cape Foulweather Basalt to the late-Yakima Basalt, and the Basalt of Pack Sack Lookout to the Pomona flow of the Saddle Mountains member (late-Yakima type of Waters, 1961) (Fig. 31). Each of these correlations was made on the basis of similarities of petrography, major and minor element geochemistry, K-Ar radiometric age, and stratigraphic position. Snavely and others (1973) interpreted that the coastal tholeiitic basalts were erupted from local vents along a 260-km-long north-south fracture system extending from Waldport, Oregon, to Grays Harbor, Washington.

Recognition that these three "locally-derived" basalts are virtually identical in characteristics to three age-equivalent units of the Columbia River Basalt Group resulted in their suggestion that the basaltic magmas of both "local source" and "plateau source" were consanguineous.

Snavely and others (1973) offered three models to explain the occurrence of virtually identical sequences of intrusive and extrusive tholeiitic middle Miocene basalts which were erupted from vents 500 km apart. They admitted that the models fall short of explaining some significant problems such as the occurrence of the intervening middle Miocene calc-alkaline magmas in the Cascade volcanic arc. Beeson and others (1979) also noted the geochemical and magnetic similarities between these coastal basalts and some units of the Columbia River Basalt Group and suggested a one-vent "plateau-derived" hypothesis for the origin of both coastal and plateau basalts. These models are discussed in the following sections.

Columbia River Basalt Group Nomenclature

Waters (1961) was the first to synthesize a detailed stratigraphy for basaltic lavas of the Columbia plateau. His designations were flexible so that later revisions could be made. Swanson and others (1979) recently formalized the stratigraphic nomenclature after an exhaustive study of the geochemistry and magnetostratigraphy of the lavas. A part of the stratigraphy recognized on the plateau has been correlated to northwestern Oregon (including Clatsop County) (Fig. 32). Several basalt lavas of the Grande Ronde, Wanapum and Saddle Mountains basalts flowed down the ancestral Columbia River and reached the ocean in the vicinity of Nicolai Mountain and Porter Ridge in northeast Clatsop County (Murphy, 1981; Murphy and Niem, 1982; Goalen, in prep.; Swanson and others, 1979; Beeson and Moran, 1979; Snavely and Wagner, 1963).

The Columbia River Basalt Group consists of five formations which can be subdivided on the basis of petrography, geochemistry and magnetic polarity. Field characteristics such as jointing patterns, mineralogy, color and weathering may also be used. The formations are: the Imnaha Basalt, Grande Ronde Basalt, Picture Gorge Basalt (which is equivalent to, but does not intertongue with, Grande Ronde), Wanapum Basalt, and Saddle Mountains Basalt (Swanson and others, 1979).

The Pomona Member of the Saddle Mountains Basalt occurs in western Oregon and Washington and is correlated to the Basalt of Pack Sack Lookout (Snavely and others, 1973) (Fig. 31). The Frenchman Springs Member of the Wanapum Basalt occurs in western Oregon and is correlated to the Cape

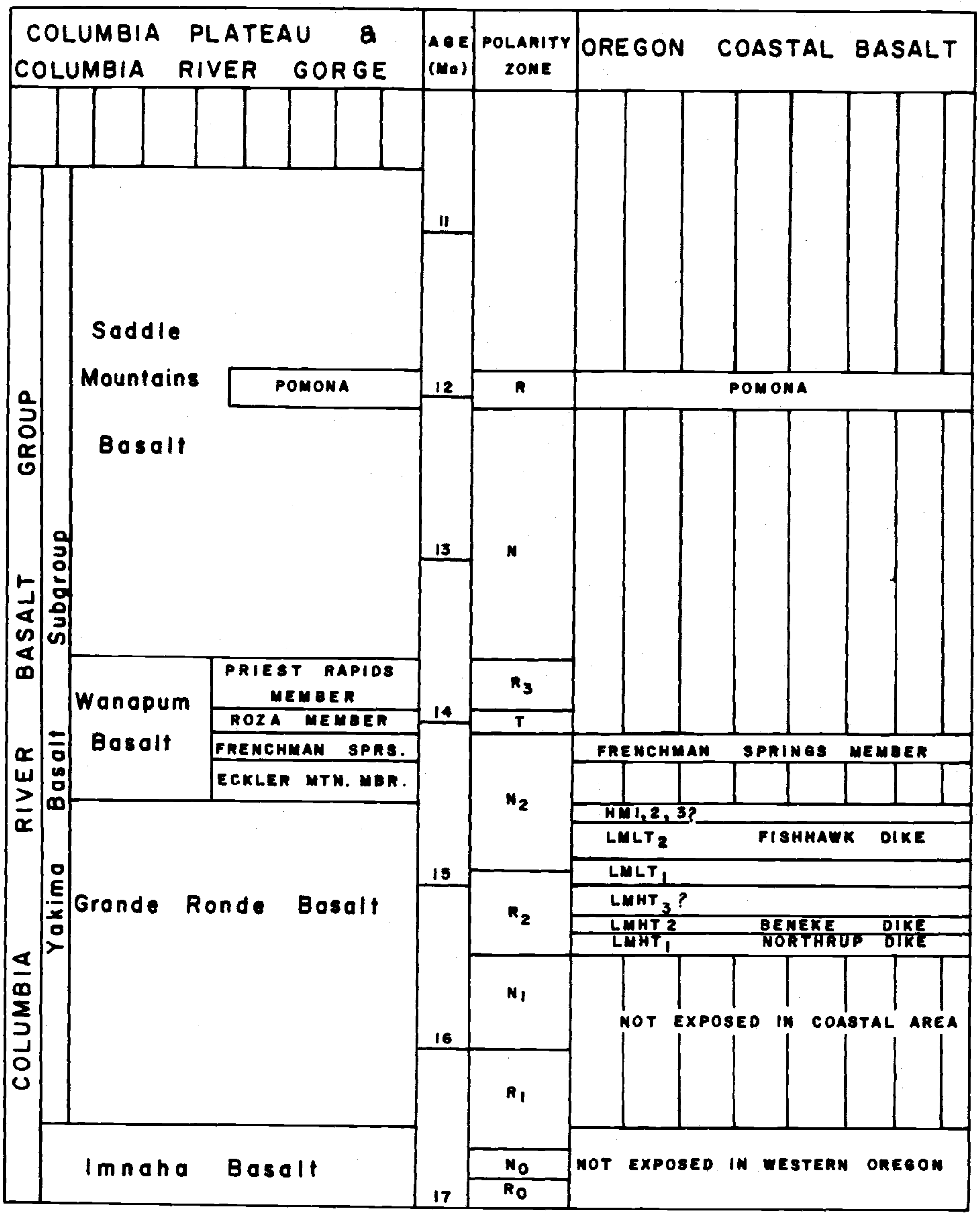


Figure 32. Partial list of Columbia River Basalt Group flows (Swanson and others, 1979) and correlation to magnetostratigraphic zones (after Goalen, in prep.; this study).

Foulweather Basalt by Snavely and others (1973). In this discussion, the Grande Ronde Basalt is the most important formation of the group as it correlates the Depoe Bay Basalt (Fig. 31). Basalts in the thesis area have Grande Ronde chemistry and petrography, and have magnetic polarity zones that are correlative to the Grande Ronde sequence (Fig. 32).

Grande Ronde Basalt. The Grande Ronde Basalt consists of reverse- and normal-polarity lavas and, therefore, can be subdivided into four magnetostratigraphic polarity zones: R1, N1, R2 and N2, listed by decreasing age (Fig. 32) (Swanson and others, 1979). The R1 zone includes the same reversed polarity epoch as the uppermost flows of the Imnaha Basalt (Choinere and Swanson, 1979; Swanson and others, 1979; Camp and Hooper, 1981). Within the Grande Ronde Basalt in the Columbia River gorge, only the N1, R2 and N2 magnetostratigraphic zones are known (Beeson and Moran, 1979). The N1 zone is represented by one flow in the Clackamas River area (Anderson, 1978). Most Grande Ronde basalts in western Oregon are lavas representing the R2 and N2 magnetozones. The coastal Depoe Bay Basalt of Snavely and others (1973) contains flows and breccias correlated to the R2 and N2 magnetozones (Choinere and Swanson, 1979).

Another useful subdivision of Grande Ronde Basalt is geochemical variation in MgO content (Wright and others, 1973; Nathan and Fruchter, 1974; Beeson and Moran, 1979). Within the basalts of the N2 zone, the amount of MgO varies.

Some flows have <4% (wt.%) MgO (low-MgO basalts) and some have >4% MgO (high-MgO basalts) (Figs. 32 and 35). The difference is displayed on silica variation diagrams (Fig. 34 and 35). As many as 12 low-MgO-type N2 flows are known in western Oregon and two flows of the high-MgO-type N2 flows have been recognized (Beeson and Moran, 1979). All R2 Grande Ronde Basalts, and some N2 flows as well, belong to the low-MgO-type. All high-MgO-type basalts have normal (N2) polarity.

Yet another chemical subdivision proves useful for the low-MgO section in northwestern Oregon. Murphy (1981), Murphy and Niem (1982) and Goalen (in prep.) distinguish a variation in TiO_2 content within low-MgO-type Grande Ronde Basalt and in the equivalent coastal intrusive rocks (Fig. 34). The low-TiO_2 subtype contains <2% (wt.%) TiO_2 and the high-TiO_2 subtype contains >2% TiO_2 (Table 2; Fig. 34).

A composite stratigraphic section of eight Grande Ronde flows in the Nicolai Mountain - Plympton Creek areas (9 km north of the thesis area) contains the geochemical variation in MgO and TiO_2 content (Goalen, in prep.). Here, three subaerial flows with low-MgO and high-TiO_2 chemistry (designated Tiht on Plate 1 and LMHT on Fig. 32) are overlain by two low-MgO flows with low-TiO_2 (Tilm on Plate 1 and LMLT on Fig. 32) chemistry. The youngest Grande Ronde basalts in the Fishhawk Falls - Jewell area (this study) are the high-MgO-types.

The stratigraphic order of the MgO and TiO_2 chemical variants in the Grande Ronde Basalt is very important to correlations that I make to the middle Miocene intrusive basalts in the thesis area. The low-MgO Grande Ronde Basalt flows in the Nicolai Mountain and Plympton Creek stratigraphic sections can be correlated on the basis of geochemistry and paleomagnetic polarity to the three laterally extensive dikes (the Beneke, Northrup Creek and Fishhawk Falls) that occur in eastern Clatsop County (Figs. 30 and 32).

Middle Miocene Basalt Intrusives

Description. Lithologic descriptions of the basalt that forms the Beneke, Fishhawk Falls and Northrup Creek dikes vary slightly. All three dikes are low-MgO-type Grande Ronde basalt. The Beneke dike trend is composed of greenish-black to black, microphyric basalt. The abundant plagioclase microphenocrysts range from 1 to 2 mm in length and are set in a finely crystalline to aphanitic groundmass. The basalt has reversed magnetic polarity north of Boiler Ridge (Plate 1). The part of the Beneke dike trend south of Boiler Ridge has different lithology, geochemistry and normal magnetic polarity (Plate 1). This southern part of the Beneke trend is lithologically, geochemically and paleomagnetically similar to the Fishhawk Falls dike. Both are composed of aphyric grayish-black basalt. The lack of plagioclase microphenocrysts distinguishes the Fishhawk Falls dike and the southern part of the Beneke dike from the other basalt dikes in the study area.

The Northrup Creek dike is composed of microphyric basalt with a medium gray (N3) aphanitic groundmass. The plagioclase microphenocrysts are less than 1 mm, generally smaller and less abundant than those of the north part of the Beneke dike trend. The Northrup Creek dike has reverse magnetic polarity.

The three dikes are subparallel, trending N30-45°E (Plate 1 and Fig. 30). Dips vary from nearly vertical in most places (as at the Beneke quarry, NE1/4, NE1/4 sec. 14, T6N, R7W) to 45° from horizontal (as at Fishhawk Falls NW1/4, SW1/4 sec. 32, T6N, R7W). The direction of dip along the length of the dike is generally southeast but rarely is northwest (as at Denver Point, NW1/4 sec. 4, T5N, R7W and in a borrow pit near U. S. Highway 26, SE1/4, NW1/4 sec. 25, T5N, R8W). Though exposure is not continuous, the dikes are interpreted to be continuous in the subsurface except where offset by faulting (Plate 1). Eleven proton-precession magnetometer traverses prove the presence of the dikes in the subsurface along trend (see Appendix XI and Plate 1 for locations).

The Beneke dike trend is over 22 km long (Fig. 30), extending from Flagpole Ridge at an elevation of 474 m (Plate 1) to 439 m south of Nicolai Mountain quarry (Goalen, in prep.). The southern end of the dike (paleomag site

JG07-sec. 34, T5N, R8W) is sill-like. The dike intrudes the upper Eocene Jewell, Vesper Church, and upper mudstone members of the Keasey Formation, the upper Eocene Pittsburg Bluff Formation and the Oligocene - lower Miocene Oswald West mudstone. The dike holds up discontinuous 440-490-m-high ridges that trend northeast-southwest, including Flagpole Ridge and Boiler Ridge (Plate 1). The dike is best exposed in Beneke quarry (Plate 4), at Denver Point on State Highway 202 and in a large quarry on the north end of Boiler Ridge (SE1/4, SW1/4 sec. 8, T5N, R8W).

The Fishhawk Falls dike crops out at several locations in quarries and in streams along its 10 km length. The best exposures are at Fishhawk Falls (a 45-m waterfall) and a quarry on the Fishhawk X-Over (SW1/4, NW1/4 sec. 5, T5N, R7W). The dike intrudes the upper mudstone member of the Keasey Formation and the Pittsburg Bluff Formation.

The Northrup Creek dike extends for approximately 8.5 km from east of Walker Creek in section 1, T5N, R7W to sec. 34, T7N, R6W. The dike forms a 427-m-high northeast-trending ridge and intrudes the Vesper Church member of the upper Eocene Keasey Formation and the Pittsburg Bluff Formation. Because of their length and continuity, these dikes have important implications for the tectonic development of northwest Oregon.

The three dikes display a tabular geometry in all cases. They all appear to be finely crystalline basalt from the wall rock to center of each dike. The thickness of the dikes does not appear to vary in any one exposure; however, discontinuous exposures of the dikes along trend have variable thickness. From these discontinuous exposures it appears that the Beneke dike varies in thickness from 8 m to 76 m, the Fishhawk Falls dike varies from 32 to 88 m; the Northrup Creek dike has a similar range of thickness to the other two.

Subhorizontal cooling fractures have developed perpendicular to the bounding tabular surfaces with the adjacent upper Eocene - Oligocene sedimentary rocks. Columnar jointing is the most common fracture pattern although blocky jointing also occurs. War-bonnet jointing rarely is developed (locality 186, SE1/4, NE1/4 sec. 8 T5N, R7W). Colonnade and entablature couplets are not observed. The master fractures of many columnar joints extend into the baked country rock, indicating that the country rock was affected by some degree of thermal contact metamorphism. A blister surface, resembling mudcracks, is developed on some basalts at the contact with contiguous sedimentary rocks.

The contact between the dike and the sedimentary country rocks is sharp, vertical and discordant. The dips of the country rocks are gentle and little distorted, suggesting brittle deformation and fracturing (e.g., Beneke quarry). However, in some places, the contact is very irregular and the sedimentary beds are highly distorted and folded to a near vertical position (Olbinski, 1983, p. 122), indicating some soft sediment plastic deformation also occurred.

Post-middle Miocene faulting and offset of the three dikes is evident in numerous quarries (Plate 4) and in offset outcrop trends (Plate 1). Faults, fractures, shears with oblique to subhorizontal slickensides, and 1 to 2 m wide fault gouge cut across the master subhorizontal columnar joints and for this reason are not related to contraction of the magma during cooling. The dikes are offset from a few centimeters to >300 m by these faults (Plates 1 and 4). In some cases, the faults repeat subparallel outcrops of the dikes (e.g., Boiler Ridge, N1/2, sec. 19, T5N, R7W, Plate I). In the Beneke quarry (NE1/4, NE1/4, sec. 14, T6N, R7W), numerous oblique faults parallel to the margin of the Beneke dike display spectacular slickensides (Plate 4). The rake of these slickensides is 45°N in the fault plane that strikes N35°E and dips 50°SE. The fault is subparallel to the trend of the dike and offsets the dike by 33 m. Slip appears to have occurred in an oblique left-lateral sense.

Exposures of dikes in other quarries also have the pattern of northeast-trending faults with slickensides suggesting that latest movement in post-middle Miocene time occurred in a left-lateral sense. Second order northwest-trending faults have apparent right-lateral separation. The orientation of conjugate faults and fractures in quarry exposures of the dikes suggests a component of north-south compression. This conjugate fracture set may indicate post-Miocene crustal shortening.

The northeast-trending fractures along which the Beneke, Fishhawk Falls and Northrup Creek dikes intruded imply a period of extension in which the principle tensile stress (sigma 1) was oriented NW-SE. These basalt-filled fractures may not be faults because the contacts of the sedimentary units are not obviously offset (Plate 1; Olbinski, 1983; Goalen, in prep.), although admittedly the sedimentary contacts are hard to observe in the field and are projected on the map (Plate 1) from scattered field outcrop relationships. The basalt-filled fractures may be older joints in bedrock that the dikes followed. Similar dikes with the same trend (N45°E) intersect Saddle Mountain, Humbug Mountain and Angora Peak where a very strong pattern of N45°E-trending joints are evident in these thick middle Miocene basaltic breccia piles (Penoyer, 1977; A. R. Niem, pers. comm., 1984).

Petrography. Five thin sections were examined to determine the petrographic characteristics of the middle Miocene basalt intrusives in the thesis area (samples 13, 96,, 145B, 309, 408). Although the mineralogy is the same the crystallinity of the intrusive basalts can be quite different depending on what part of the intrusion is sampled and on the thickness of the intrusion. Thus the crystallinity of basalt intrusions is not as reliable for correlation purposes as are geochemical and paleomagnetic properties.

The middle Miocene intrusives are typically hypohyaline and microcrystalline. Except in the plagioclase-phyric basalts, the groundmass is aphanitic. The small euhedral plagioclase phenocrysts are 1 to 2 mm in length. Some smaller plagioclase and augite crystals are locally arranged in a glomeroporphyritic texture. The texture of the groundmass is generally intersertal, grading to intergranular (Willams and others, 1954) in the thicker, slower-cooled parts of intrusions. Rarely, the textures are equigranular and subophitic. Glass in the groundmass ranges from 5 to 50%, or higher in rapidly chilled margins of the intrusions.

The minerals that form the middle Miocene basalts are 45-50% plagioclase, 20-35% augite, 8-10% opaques (probably magnetite and ilmenite), and less than 5% apatite. Olivine has been reported by some workers (Snavely and others, 1973), but olivine was not observed in these samples. Plagioclase occurs as subhedral to euhedral crystals that have Carlsbad and albite twinning (Fig. 33). None of the plagioclase crystals is oscillatory zoned. Tiny crystals of subhedral augite between plagioclase microlites are the only pyroxene noted. Other workers have reported pigeonite in the groundmass and bronzite-hypersthene (Reidell, in press; Snavely and others, 1973). Basaltic glass is composed of dark tachylyte and, in some cases, has altered to

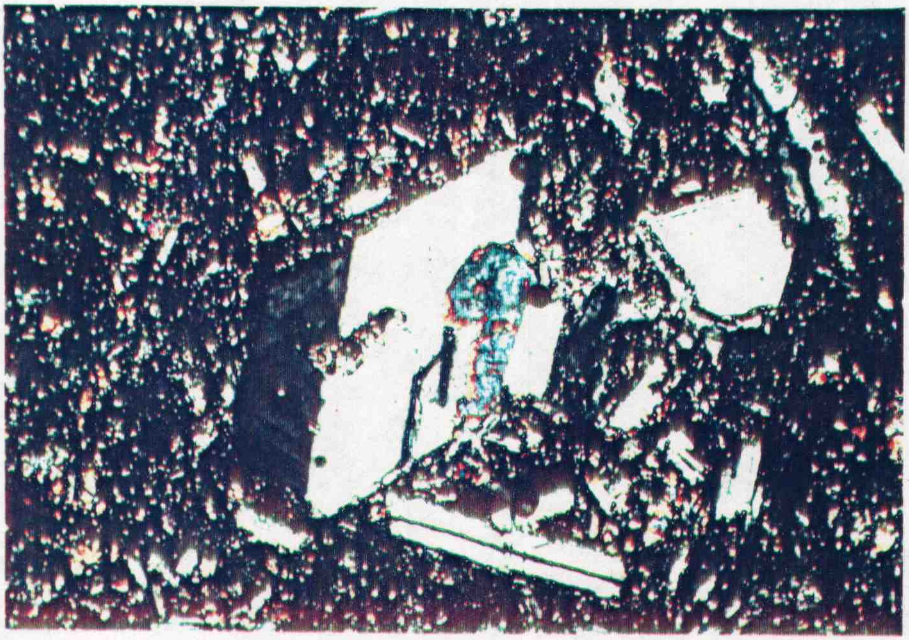


Figure 33. Photomicrograph of high-MgO type Grande Ronde Basalt dike showing subophitic intergrowth of plagioclase microlites and augite crystals. Plagioclase crystals display Carlsbad (rhombic section) and albite twins. Dark tachylyte basaltic glass also occurs in the groundmass. Locality 96, 80x, crossed nicols.

chlorophaeite. Small amounts of glass are altered to smectitic clays displaying a greenish brown color that masks the birefringence of these alteration mineral(s). Birefringent fibers of clays also occur in irregular shaped masses interstitial to pyroxene and plagioclase. A few augite grains are replaced by greenish smectitic pseudomorphs. Ilmenite is rarely altered to leucoxene.

Geochemistry. Twenty basalt samples were analyzed for 11 major oxides by Dr. Peter Hooper, Washington State University XRF Analytical Facility. A table of the results is presented in Appendix VI. The values reported here were standardized against the international standard rather than the Columbia River basalt standard (BCR-1 or equivalent) (Snavely and others, 1973, p. 393). Use of the international standard causes minor problems for direct comparison with other published major element analyses of Columbia River Basalts run in the BCR-1 standard. Therefore, a correction factor was determined for each major oxide except ferrous and ferric iron (Jeff Goalen, pers. comm., 1982). Table 1 contains average compositions of selected basalt samples from the thesis area corrected with the Columbia River Basalt standard and with the international standard.[1] The correction factor is also

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[1] Basalt values appearing in the text and on the graphs are those from the international standard.

listed in Table 1. Analytical error includes instrumental and sampling errors (Hooper and others, 1981) and is shown graphically in Figs. 34 and 35).

All middle Miocene basalt intrusives in the thesis area have Grande Ronde Basalt major oxide chemistry (Table 1). Comparison of average Depoe Bay, Grande Ronde and middle Miocene intrusive basalts from the thesis area shows the close correlation of the three data sets (Table 1). Within the study area, significant variations of MgO and TiO_2 are noted in some of the intrusive Grande Ronde basalts. For example, silica variation diagrams (Fig. 34) and binary plots of MgO versus TiO_2 (Fig. 35) reveal the distinct clustering of the major oxide data. The high-MgO Grande Ronde Basalt averages greater than 4% (by wt.) MgO (Table 2) which is similar to the findings of other workers for high-MgO-type Grande Ronde Basalt (Wright and others, 1973; Nathan and Fruchter, 1974; Beeson and Moran, 1979; Murphy, 1981). The high-MgO-type basalt also consistently has lower SiO_2 and higher CaO contents than the low-MgO-type (Table 2; Fig. 34). Thus, the high-MgO-type is more mafic in character.

The low-MgO basalt intrusives are further subdivided into two subunits based on TiO_2 content. A TiO_2 content of <2% (by wt.) separates low-TiO_2-subtype from high-TiO_2-subtype basalt with >2%. A binary plot of TiO_2 versus MgO (Fig. 35) shows the three distinct field into which the Grande Ronde Basalt is subdivided. The

Table 1. Average chemical compositions of Grande Ronde - Depoe Bay Basalts

	Average Depoe Bay[1]	Average Gr. Ronde[1]	Average this study[2] (bas.std)	Average this study (int.std)	Corr. factor[3]
Number of analyses	52	18	20	20	
SiO_2	55.7%	55.0%	55.66%	55.48%	+0.18%
Al_2O_3	14.0	14.2	14.91	14.37	+0.54
Fe_2O_3	2.4	2.3	-	5.75	-
FeO	9.9	9.4	-	6.53	-
MgO	3.6	4.2	3.59	3.46	+0.13
CaO	7.1	7.9	6.62	6.33	+0.29
Na_2O	3.3	3.0	1.51	2.58	-1.07
K_2O	1.4	1.3	1.63	1.61	+0.02
TiO_2	2.0	2.0	2.09	1.95	+0.14
P_2O_5	0.38	0.37	0.30	0.35	-0.05
MnO	0.21	0.21	0.19	0.18	+0.01

[1] From Snavely and others, 1973, p. 393, U.S.G.S. Analytical Lab.

[2] Calculated Columbia River basalt standard value by applying correction factor to international basalt standard values in Appendix VI; analyses from W.S.U. lab.

[3] Correction factors determined by Jeff Goalen (in prep.) by comparing statistical variation of chemical analyses of identical samples run on both Columbia River basalt standard and international standard.

Table 2. Average composition of Grande Ronde Basalt geochemical subtypes in the study area

Column	[Tilm] 1	2	[Tiht] 3	4	[Tihm] 5	6
Number of analyses	9	9	7	7	4	4
SiO_2	56.24%	56.06%	55.75%	55.57%	54.17%	53.99%
Al_2O_3	14.96	14.42	14.90	14.21	14.95	14.41
Fe_2O_3	-	5.74	-	5.75	-	5.78
FeO	-	6.45	-	6.59	-	6.62
MgO	3.37	3.24	3.35	3.22	4.52	4.39
CaO	7.00	6.71	5.15	4.86	8.37	8.08
Na_2O	2.34	3.41	1.37	2.44	2.16	3.23
K_2O	1.63	1.61	1.94	1.91	1.11	1.09
TiO_2	2.08	1.94	2.41	2.27	2.03	1.89
P_2O_5	0.30	0.35	0.32	0.37	0.27	0.32
MnO	0.19	0.18	0.18	0.17	0.22	0.21

Column:

1 - Average for low-MgO-low-TiO_2 basalt [Tilm] (basalt std.)[1].
2 - Average for low-MgO-low-TiO_2 basalt [Tilm] (international std.)[2].
3 - Average for low-MgO-high-TiO_2 basalt [Tiht] (basalt std.)[1].
4 - Average for low-MgO-high-TiO_2 basalt [Tiht] (international std.)[2].
5 - Average for high-MgO-type basalt [Tihm] (basalt std.)[1].
6 - Average for high-MgO-type basalt [Tihm] (international std.)[2].

[1] Calculated Columbia River basalt standard values by applying correction factor to analyses from international standard values reported in Appendix VI. Correction factor determined by Jeff Goalen, Oregon State University (in prep.).

[2] Values from Appendix VI.

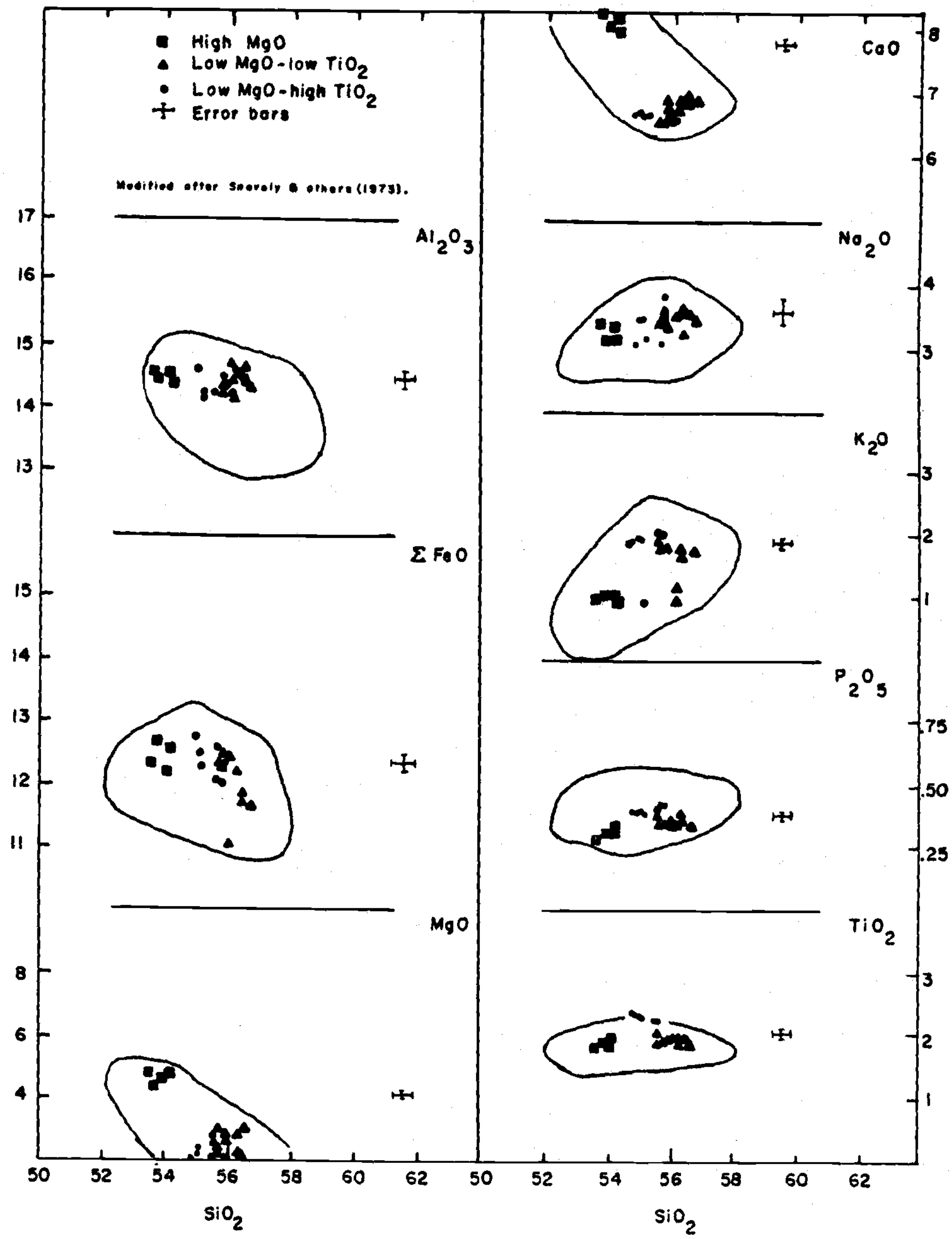


Figure 34. Silica variation diagram of Grande Ronde Basalt intrusives in the thesis area. Solid lines show the fields for Depoe Bay basalt and Yakima-type basalt defined by Snavely and others (1973, p. 417) which are equivalent to Grande Ronde Basalt in the study area.

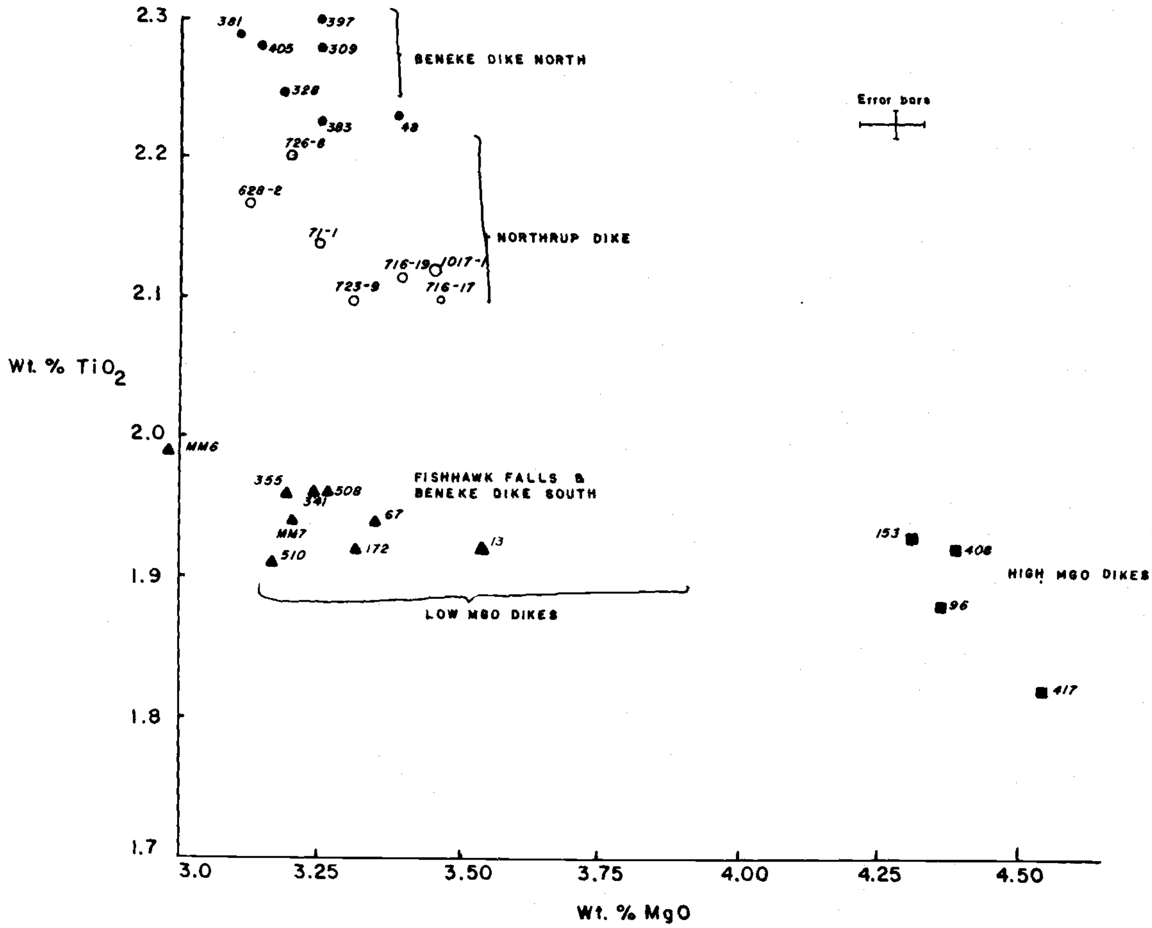


Figure 35. MgO vs. TiO_2 bivariate graph of Miocene basalt intrusives in the thesis area.

high-TiO_2-subtype occurs only in the low-MgO Grande Ronde Basalt, and averages 2.3% (by wt.) TiO_2 (Table 2). Low-TiO_2 - low-MgO Grande Ronde Basalt averages 1.95% TiO_2 (Fig. 35). High-MgO-type basalt does not show as great a variation in titanium as the low-MgO basalts. Note that the reverse polarity Beneke dike north of Boiler Ridge and the reverse polarity Northrup Creek dike are the low-MgO-high-TiO_2-subtype and closely cluster on Fig. 35. The Beneke dike south of Boiler Ridge and the Fishhawk Falls dike are the low-MgO-low-TiO_2-subtype and also cluster together on Fig. 35.

On the geologic map (Plate 1), each geochemical type is considered a different stratigraphic unit. For example, high-MgO intrusives are labeled Tihm, the low-MgO-low-TiO_2-subtype is labeled Tilm, the low-MgO-high-TiO_2-subtype is labeled Tiht, and intrusives that were not sampled for geochemical analysis are grouped into one undifferentiated unit (Tib).

All the Grande Ronde intrusives fall into the tholeiite field of MacDonald and Katsura (1964) (Fig. 36). Other workers have noted that Miocene basalts on the plateau and coast are tholeiitic in composition (Waters, 1961, 1962; Snavely and others, 1963, 1964, 1973; Hill, 1975). Trace element concentrations of middle Miocene coastal tholeiites and plateau tholeiites are in good agreement (Hill, 1975; Snavely and others, 1973; Murphy, 1981). Abundances of rare earth elements (La through Lu), normalized by average

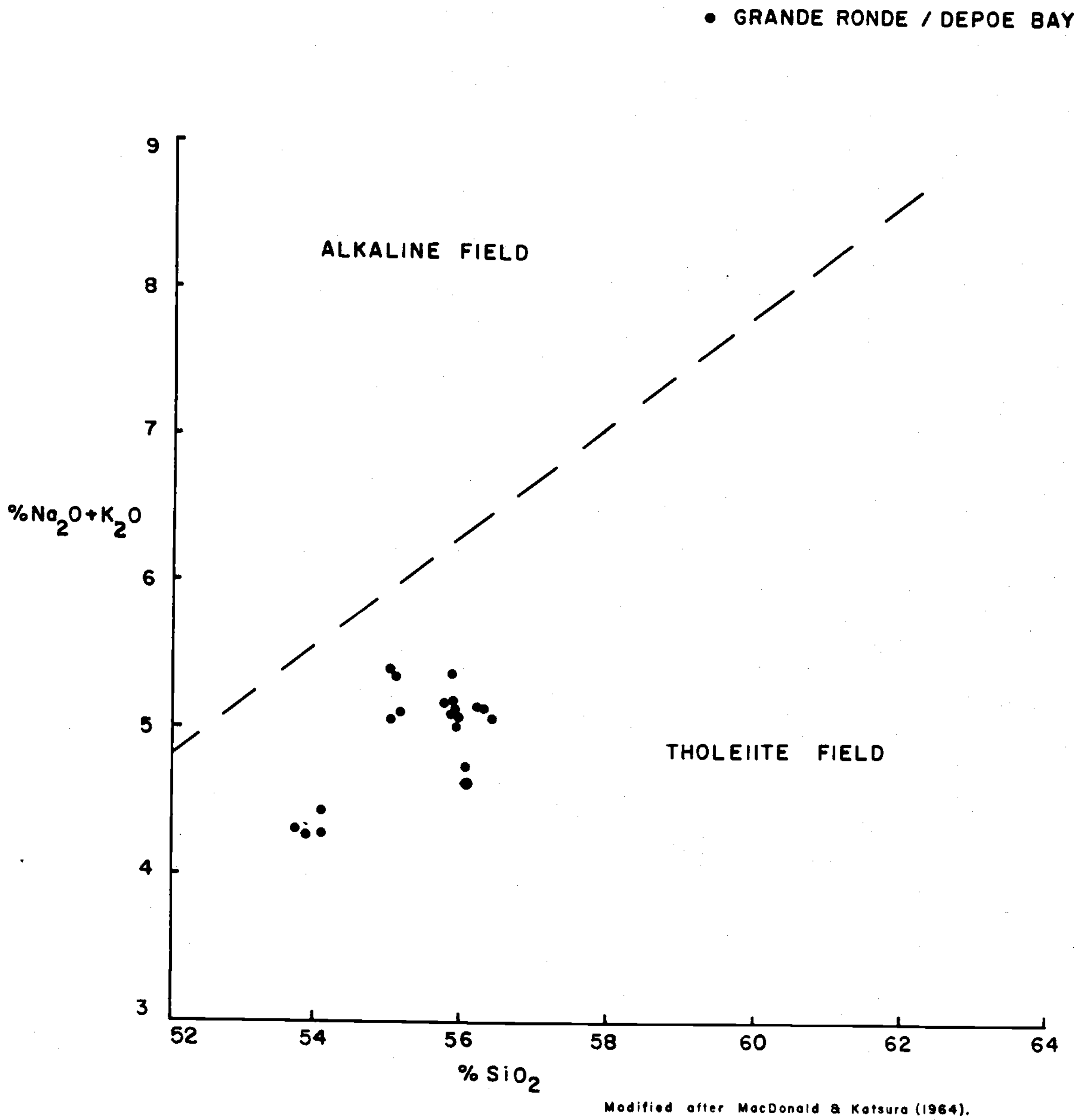


Figure 36. Alkali vs. silica diagram depicting the differences between tholeiitic and alkalic rocks. Grande Ronde basalt plots within the tholeiite field.

chondrite abundance, are identical for coastal Depoe Bay Basalt and plateau-derived Grande Ronde Basalt (Hill, 1975, p. 40-41) suggesting that they are identical units.

Correlation of basalt intrusives to subaerial flows. The basalt sills and dikes in the study area can be correlated to subaerial Columbia River Basalt units in the nearby Nicolai Mountain - Porter Ridge area on the basis of geochemistry, lithology, and paleomagnetism. Major element geochemistry is the most important correlation tool. High-MgO and low-MgO Grande Ronde basalt intrusives occur in the map area (Plate 1 and Fig. 32). High-MgO basalt is the youngest Grande Ronde basalt unit in the Nicolai Mountain - Porter Ridge area and forms four small normal polarity dikes in the western part of the thesis area: in the W1/2, sec. 19, T6N, R7W, in the S1/2, sec. 25 and N1/2, sec. 36, T6N, R8W, in the NW1/4, sec. 24, T5N, R8W, and in the SW1/4, sec. 35, T5N, R8W (Tihm on Plate 1).

The Beneke, Fishhawk Falls and Northrup Creek dike trends, and numerous other smaller intrusives have low-MgO chemistry and are both normal and reverse polarized. Of these low-MgO basalts, both the low-TiO_2-subtype and high-TiO_2-subtype (Tilm and Tiht, respectively) occur.

Chemical differences among these dikes can be clearly seen on MgO vs. TiO_2 binary plots (Fig. 35). The Beneke dike has different chemistry in the northern part than in the southern part. The northern part of the dike (i.e., north of Boiler Ridge to the Beneke quarry) is higher in TiO_2 by 0.2 to 0.3% (a high-TiO_2 basalt) than the southern part of the dike (Boiler Ridge to Flagpole Ridge). The southern part of the dike is composed of low-MgO-low-TiO_2 basalt. In addition, the northern part of the dike has reverse magnetic polarity whereas the southern part of the dike has normal polarity. These differences clearly show that two different dikes intruded along the Beneke dike trend. Pfaff (1981) also showed that the trace element distribution differs between the southern and northern parts of the dike and also suggested that the Beneke dike trend is occupied by two different intrusions.

The chemistry of the southern part of the Beneke dike is indistinguishable from the chemistry of the Fishhawk Falls dike, which is normal polarity low-MgO-low-TiO_2 basalt (Fig. 35). Samples collected along the trend of the Northrup Creek dike appear to have slightly lower TiO_2 content than the northern Beneke dike (Fig. 35), but still classify as low-MgO-high-TiO_2 reverse polarity Grande Ronde basalt. The Northrup Creek dike averages 2.1% TiO_2 and 3.3% MgO (Olbinski, 1983). Pfaff (1981, p. 45-46) analyzed trace elements but not major oxides of a sample from the Northrup Creek dike. She also noted that the basalt has low-MgO Grande Ronde basalt character and reverse polarity. The trace element differences (Sc, Cr, Ba, La, Sm, and Eu) reported by Pfaff (1981), along with the slight TiO_2 differences (Fig. 35), further support the lithologic indication that the reverse polarity Northrup Creek dike is different from the Beneke dike.

As these intrusives are so similar geochemically, petrographically and magnetically to the Grande Ronde Basalt, correlation to the Columbia River Basalt Group is made. Measured stratigraphic sections of the subaerial basalt sequence on Nicolai Mountain and Plympton Creek areas have been described by Murphy (1981) and Goalen (in prep.). The three major dikes can be correlated to the composite stratigraphic section in these two areas. These dikes can be traced to within a few hundred meters of the correlative flows. The relative age of each intrusive can also be obtained by comparison to the composite section derived by Murphy (1981) and Goalen (in prep.).

The Northrup Creek dike does not crop out in the thesis area but is mentioned because it is related to the emplacement of the other two major dikes. The dike crops out in the adjacent thesis areas (Olbinski, 1983; Goalen, in prep.). The Northrup Creek dike has low-MgO-high-TiO^2 Grande Ronde chemistry, reversed magnetic polarity and microphyric lithology. Microphenocrysts of plagioclase are 1 to 2 mm. It is correlated to subaerial Grande Ronde flow $LMHT_2$ (Goalen, pers. comm., 1982; Plate III of Goalen, in prep.) which, from the bottom, is the second flow of six flows in the Plympton Creek section located on Porter Ridge (SE1/4, SW1/4, sec. 2, T7N, R6W). Intrusion of the Northrup

Creek dike occurred during the R2 magnetostratigraphic epoch.

The Beneke dike crops out in the thesis area and extends 9.6 km northeast to correlative submarine pillow lavas on Nicolai Mountain. Major and trace element geochemistry, lithology and paleomagnetic signature of the Beneke dike are different on the northern and southern parts. The northern part has low-MgO-high-TiO_2 chemistry, reversed polarity (R2) and microphyric character. This part of the dike correlates to the reversed polarity pillow lavas on Nicolai Mountain which have identical polarity, geochemistry and petrography. Paleomagnetic data from these two flows suggest that the structure corrected paleomggnetic directions of the lower flow more closely mathch the average directions obtained from the Beneke dike. Murphy (1981) found that the northern terminus of the Beneke dike and the R2 pillow lava on Nicolai Mountain both have the same major and trace element composition. Thus, the Beneke dike probably correlates directly to the lower pillow flow in the Nicolai Mountain quarry.

The southern part of Beneke dike has low-MgO-low-TiO_2 chemistry, normal magnetic polarity and aphyric character. Geochemically and paleomagnetically, the southern part of the Beneke trend is similar to the Fishhawk Falls dike, and these are therefore correlative to the same basaltic intrusive episode. Both dikes have low-MgO-low-TiO_2 chemistry and normal polarity. These dikes correlate to the $LMLT_2$ subaerial Grande Ronde flow on Porter Ridge (Goalen, pers. comm., 1982) based on similarity of aphyric lithology, geochemistry and normal polarity. Intrusion occurred during the N2 magnetostratigraphic epoch. This is the youngest of the three major dike systems in eastern Clatsop County. However, other less extensive dikes (e.g., high-MgO dikes) follow this episode.

Recent exploration wells in the area have penetrated several intervals of middle Miocene basalt. Hand-picked chips of the well cuttings from the Quintana "Watzek" #30-1 well adjacent to the Northrup Creek dike have been analyzed for major oxide chemistry (Olbinski, 1983). Again, petrologic correlation of the subsurface middle Miocene basalts to those exposed at the surface can be made by geochemical similarity. Olbinski (1983) reported four intervals of basalt in the Quintana well north of Jewell. These include: a 9-meter-thick low-MgO-low-TiO_2 Grande Ronde sill at 859 m (2820'); a low-MgO-low-TiO_2 Grande Ronde intrusive at 1079 m (3540'); and, a high-MgO Grande Ronde intrusive at 1600 m (5250'). The "younger" high-MgO Grande Ronde basalt occurs at greater depth in the well and the "older" Grande Ronde basalt units (i.e., low-MgO-low-TiO_2-subtypes) occur at the shallowest depths (Olbinski, 1983). This is the reverse stratigraphic order of the subaerial Grande Ronde flows on Nicolai Mountain and Porter Ridge (Murphy, 1981; Goalen, in prep.). Subsurface middle Miocene basalt samples from other wells in Clatsop County do not follow this pattern, however.

Seismic reflection evidence (Mike Navolio and Larry O'Connor, pers. comm., 1982) indicates a large sill at shallow depth beneath the thesis area (see cross-section A-A', Plate 2). This is expressed on seismic records as a high amplitude reflector and contrasts markedly with surrounding lower amplitude reflectors from less dense sedimentary rocks. On a regional basis, this subhorizontal sill generally cuts across reflectors from sedimentary rocks (creating a false unconformity) and dips gently to the east on the record section. It was penetrated by the Quintana "Watzek" #30-1 well. This intrusion is interpreted to rise toward the surface near Saddle Mountain, 3 km west of the thesis area. Because of near-vertical dips, the Fishhawk Falls, Beneke and Northrup Creek dikes are not seen seismically but may potentially cause problems of diffraction and "noise" on seismic records.

Gravity and magnetic modeling of the area underlain by the Fishhawk Falls and Beneke dikes by Pfaff in 1981 has produced interesting speculations on the depth of the dikes. The geophysical models suggest that the dikes are shallow and rootless. The Fishhawk Falls dike is modeled as having a terminus at 107 m in the subsurface (Pfaff, 1981). The Beneke dike may terminate at 45 m. Furthermore, Pfaff's geophysical models suggest that the dikes do not extend to the Eocene volcanic basement which along with their shallow depths support an invasive origin (Pfaff, 1981). The intrusions would end within the section of upper Eocene to middle Miocene marine sedimentary rocks overlying the middle to upper Eocene volcanic basement.

The interpretation that the intrusions terminate at such shallow depths is not necessarily valid. Exploration wells drilled in Clatsop County since 1981 show that low-MgO Grande Ronde basalt sills, that are correlative to the Beneke, Fishhawk Falls and Northrup Creek dikes, are present at much greater depths. For example, a low-MgO-low-TiO_2 sill at 1079 m in the Quintana well has the same chemistry as, and most likely fed, the Fishhawk Falls dike. Similarly a low-MgO-high-TiO_2 sill at 859 m in the Quintana well probably fed the Northrup Creek dike (Olbinski, 1983). Hence, these dikes and their related sills are much deeper than the geophysical modelling predicted.

Other deeply buried middle Miocene sills have been found elsewhere in western Oregon. Basalts of Depoe Bay (Grande Ronde) chemistry were penetrated at depths of 1,100 m in the Standard Union Nautilus #1 (P-0103) offshore test well (Snavely and others, 1980, p. 5). The expression of middle Miocene basalt sills over distances of several kilometers is seen in multichannel seismic reflection records of offshore central and northwestern Oregon (A. R. Niem, pers. comm., 1982; Snavely and others, 1980).

The preferred interpretation is that two or three large sill-like bodies occur within the upper Eocene sedimentary section in the subsurface (Plate 2). These sills could have fed the Beneke and Fishhawk Falls dikes. The presence of the sill-like intrusives is suggested by seismic evidence. How the sills were emplaced is still open to question and debate. Either the locally-derived hypothesis of Snavely and others (1973) or the plateau-derived invasive hypothesis of Beeson and others (1979) could account for these subsurface "feeder sills".

Large tholeiitic basalt sills could be emplaced by direct rise from the mantle, or partially melted subducted Juan de Fuca plate, as envisaged by the locally-derived hypothesis. Alternatively, the sills may have been derived from subaerial Grande Ronde basalt that sank into the soft Miocene - Oligocene sediments upon reaching the marine shoreline. These flows injected downward into the more compacted sedimentary rocks by hydrofracturing and spread laterally (southwestward) to form "invasive sills" upon reaching a dense impenetrable subsurface layer. The sills, under hydrostatic pressure, encountered pre-existing joints or faults and injected upward, forming the Fishhawk Falls, Beneke, Northrup Creek and other dikes in the area. The point of invasion is unknown but apparently lay between the outcrops of subaerial flows at Nicolai Mountain and Porter Ridge and the intrusive correlatives.

The Fishhawk Falls, Beneke and Northrup Creek dikes are indeed intrusive bodies and not exhumed intracanyon flows as suggested by Pfaff (1981). The apparent gently sinuous outcrop pattern of the three dikes was used by Pfaff (1981) to support her suggestion that these basalt "dikes" were narrow intracanyon flows that form an inverse topography after erosion of the softer sedimentary canyon walls. She pictured that the low-MgO basalts flowed over a coastal lowland and filled a trellis drainage system on that lowland. However, field relationships between the basalt dikes and adjacent sedimentary rocks suggest otherwise. The dikes are tabular though offset by faults. The orientation of columnar jointing is everywhere subhorizontal rather than vertical. Vertical jointing in subaerial flows is common because the cooling surfaces are the top and bottom of the flow. However, some intracanyon flows may develop horizontal columnar joints near canyon walls. If the dikes are interpreted as intracanyon flows, the canyon would have to be narrow (100 m or less) and carved deep into soft sedimentary strata. In such a setting, the basalt could have formed horizontal cooling joints against the canyon walls. It is unlikely that there was such a narrow canyon because the soft sediments could not have maintained a vertical angle of repose. Colonnade, entablature, vesicular flow tops or flow breccia, common in subaerial flows, are not observed in the dikes but baked contacts typical of intrusives are common in these dikes. The adjacent strata are commonly bowed upward as though dragged by an upward-moving intrusion. The sinuous pattern of the Beneke, Fishhawk Falls and Northrup Creek dikes is partly caused by later offset by strike-slip faults.

Hypotheses of Origin

Hypothesis 1: Basalts at the Coast Erupted Locally.

Snavely and others (1973) are the chief supporters of the hypothesis that the middle Miocene coastal basalts were erupted locally. The three coastal basalt petrologic types, Depoe Bay Basalt, Cape Foulweather Basalt and the Basalt of Pack Sack Lookout form three consanguineous petrologic groups with their Columbia River Basalt Group counterparts, the Grande Ronde, Frenchman Springs, and Pomona basalts, respectively.

Chemical and isotopic data show that all three groups originated from different parental magmas (Hill, 1975, p. 49). A very large magma source must have been simultaneously tapped three times in order to produce the estimated 325,000 km^3 of coastal tholeiitic basalt (Snavely and others, 1973). The problem is that the vent areas for the coastal basalts and plateau basalts are more than 500 km apart. Because identical basalt was erupted simultaneously from such widely separated vent areas, the magma reservoir from which the magmas were generated must have been widespread, homogeneous with respect to elemental and isotopic composition, and very deep (Snavely and others, 1973).

According to Snavely and others (1973), the source may have been a widespread zone of partially melted mantle below eastern Oregon - Washington and western Oregon - southwestern Washington. The basaltic lavas erupted on the plateau and at the coast show no geochemical or isotopic contamination and little variation between respective geochemical (or petrologic) types (Hill, 1975). Isotopic variability would indicate mixing of separate magmas, country rock contamination or source inhomogeneity. The tholeiitic magmas must have risen rapidly along deep-seated tensional fractures in both the plateau and the coast (Snavely and others, 1973).

They suggest that two plate tectonic models can be supported by the geological data. In the first model, partial melting of the eastward-dipping Juan de Fuca plate generates large batches of tholeiitic melt as it is subducted. The source of the melt is refractory eclogite of the deeply subducted oceanic lithospheric slab. The model relies on the hypotheses of Atwater (1970) and Hayes and Pitman (1970) for estimated rates of underthrusting. Assuming that these rates were on the order of 4 to 5 cm/yr commencing in the late Eocene (approximately 40 m.y.B.P.), the Juan de Fuca slab by the middle Miocene would have been underthrust beneath the North American continental margin to a position beneath the feeder dike swarms of the Columbia River basalts on the plateau. They hypothesized that some of the tholeiitic magma beneath the plateau rose rapidly along the subducted slab of the Juan de Fuca plate until it encountered a deep-seated fracture zone along the coast. The magma followed this fracture zone and erupted on the surface forming the "local" coastal basalt units.

Model two of Snavely and others (1973) suggests that a very broad zone of partially melted mantle existed at the base of the westward-drifting North American plate from the Columbia Plateau to western Oregon and Washington. They hypothesized that partial melting is related to high pressure shear between decoupled brittle lithosphere and the underlying plastic asthenosphere. The magma thus generated rose three times through deep-seated fractures in both the Columbia Plateau and the Oregon - Washington coast to form the Grande Ronde - Depoe Bay basalts, Frenchman Springs - Cape Foulweather basalts, and Pomona - Pack Sack Lookout basalts.

Regardless of which model is chosen, basaltic magma was diverted in two directions during ascent. Deep-seated tension fractures on the plateau were associated with either back arc spreading or north-south horizontal compression (Hooper and Camp, 1981) or basin and range extension which tapped the partially melted magma in the upper asthenosphere. Tholeiitic magma rapidly ascended dilated fractures and erupted on the Columbia Plateau. Simultaneously, tholeiitic magmas rapidly migrated up a major north-south-trending extensional fracture zone along the continental margin from Waldport, Oregon to Grays

Harbor, Washington (Snavely and others, 1973). This fracture zone controlled emplacement of tholeiitic basalt in coastal areas of Oregon and Washington. An offset fracture system with a northeast trend may have controlled the emplacement of dikes, piles of pillow basalts and breccias in eastern Clatsop County, Oregon (Snavely and others (1973). According to hypothesis one, then, the Beneke, Fishhawk Falls and Northrup Creek dikes are directly related to magma from deep-seated sources beneath the Oregon and Washington coast and Coast Range.

Hill (1975, p. 52-53) proposed a model for the derivation of middle Miocene coastal basalts of western Oregon and southwestern Washington that is similar to Model 2 of Snavely and others (1973). This model for magma generation follows the hypotheses of Green and Ringwood (1967) for continentally derived tholeiite. Basalts of the three chemical (or petrologic) types (e.g., Depoe Bay-Grande Ronde, Cape Foulweather-Frenchman Springs and Pack Sack Lookout-Pomona) could be derived by different degrees of partial melting, fractionation of inhomogeneous mantle rock, and wall rock reactions. Tholeiitic magmas derived from mantle depths rise and fractionate and possibly react chemically with wall rocks in the uppermost part of the mantle or lower crust. The magmas are produced by partial melting in a thin tabular chamber deep in the mantle.

From trace element geochemistry of the coastal basalt units, Hill (1975, p. 47-49) suggested that the Depoe Bay (Grande Ronde) magma was not the source of either the Cape Foulweather or Pack Sack Lookout basalts. That is, these younger basalts were not produced by fractional crystallization of a melt with Grande Ronde composition. A wholly different period of partial melting occurred to produce each of the three geochemical types (Hill, 1975).

Hill (1975) also suggested that the coastal basalt units probably formed from basaltic magma that rose along the subduction zone of the oceanic plate beneath the continental margin as proposed in Model 1 of Snavely and others (1973).

Snavely and others (1973) recognized that the models for local eruption of the coastal basalts do not adequately explain how calc-alkaline volcanic rocks of the Cascade arc could be erupted simultaneously with the eruption of identical tholeiitic basalts to either side of the arc. The calc-alkaline Cascade volcanics were derived from the fractionated liquids of partial melts, not from primary magmas as the coastal and Columbia River tholeiitic lavas were. Strontium ratios ($^{87}Sr/^{86}Sr$) for calc-alkaline and tholeiitic basalt lavas are significantly different, indicating different sources (Hedge and others, 1970 in Snavely and others, 1973). The position and assumed source of generation of Miocene calc-alkaline magmas (e.g., Rhododendron and Sardine formations of Hammond, 1979) is located between the two vent areas of the middle Miocene tholeiitic basalts.

Lack of explanation of how the basaltic magmas that were erupted at the coast reached the surface from the melting Juan de Fuca plate beneath the Columbia Plateau without contamination during passage through the zone of calc-alkaline magma generation beneath the Cascade arc weakens Snavely and others' and Hill's hypotheses. For example, the second model of Snavely and others (1973), which proposes a very extensive zone of partial melt, requires a homogeneous composition of the zone to account for the identical chemistry of each pair of tholeiitic basalt. Hill (1975, p. 51, 52) expressed the opinion that a 500-km-wide zone of homogeneous basaltic magma is not likely considering the intervening calc-alkaline Cascades. Thus, the three models for the origin of the middle Miocene coastal basalts and Columbia River basalts are left with a problem to be solved.

Hypothesis 2: Basalts at the Coast Erupted on the Plateau. Beeson and others (1979) offered an alternative to the two-vent hypotheses of Snavely and others (1973) for the origin of middle Miocene tholeiitic basalts in western Oregon and southwest Washington that solves the problem of the calc-alkaline Cascade volcanic arc. They hypothesized that Columbia River Basalts, derived from fissures in the eastern part of the plateau, are the source of Miocene basalts along the coast of western Oregon and western Washington. That is, the coastal basalts are erosional remnants of westward extensions of the flood basalt lavas. They envisioned that the plateau basalts flowed down the ancestral Columbia river gorge to the Willamette Valley, across the subdued Oregon-Washington Coast Ranges through topographic lows, to marine embayments at Astoria, Newport and Tillamook, Oregon and in the Grays Harbor area of southwest Washington.

The submarine basalt flows and breccias may have formed in association with dikes and sills by invading semiconsolidated marine sediment in ways similar to small scale invasive Columbia River basalt flows in diatomaceous sediments reported on the plateau (Schmincke, 1964; Camp,, 1981). An observation that supports this radical hypothesis is that all of the middle Miocene coastal basalt units have subaerial Columbia River Basalt correlatives in the Clackamas drainage of the Willamette Valley (Beeson and Moran, 1979; Swanson and others, 1979; Murphy, 1981) that are nearly identical in geochemistry and magnetic polarity. If the coastal submarine basalts are indeed the distal ends of flows that originated on the plateau, then one would expect to find correlative units along the route which they travelled (i.e., in the westward-flowing paleodrainages).

Perhaps the most significant of the observations in support of this hypothesis are the similarities in petrography, geochemistry and radiometric ages. The mapped distributions of subaerial Columbia River Basalt from the plateau and the correlative coastal basalts in western Oregon and southwestern Washington closely coincide, practically without overlap (Fig. 37). According to the hypothesis proposed by Beeson and others (1979), this is no accident.

The hypothesis that the coastal basalts were erupted on the plateau is not to be taken without issue, however. A rheological mechanism or quantitative theoretical model to explain how basalt lava can intrude indurated rocks (in this case as old as upper Eocene) and buried as deep as 1.6 km (Olbinski, 1983) has not been made. The idea of "invasive sills' is acceptable for semiconsolidated, thin, shallow-buried sediments such as diatomaceous lake beds in eastern Washington and shallow marine or deltaic lower to middle Miocene sands and silts in northwest Oregon (Niem, 1976). However, extending this suggestion to include 50-m-thick and up to 20-km-long dikes such as the Beneke, Fishhawk Falls and Northrup Creek dikes in eastern Clatsop County and sills such as those penetrated by the Standard-Union Nautilus #1 (P-0103) offshore test well to depths of 1,161 and 1,177 m (Snavely and others, 1980, p. 5) in consolidated Oligocene sediments is difficult to reconcile.

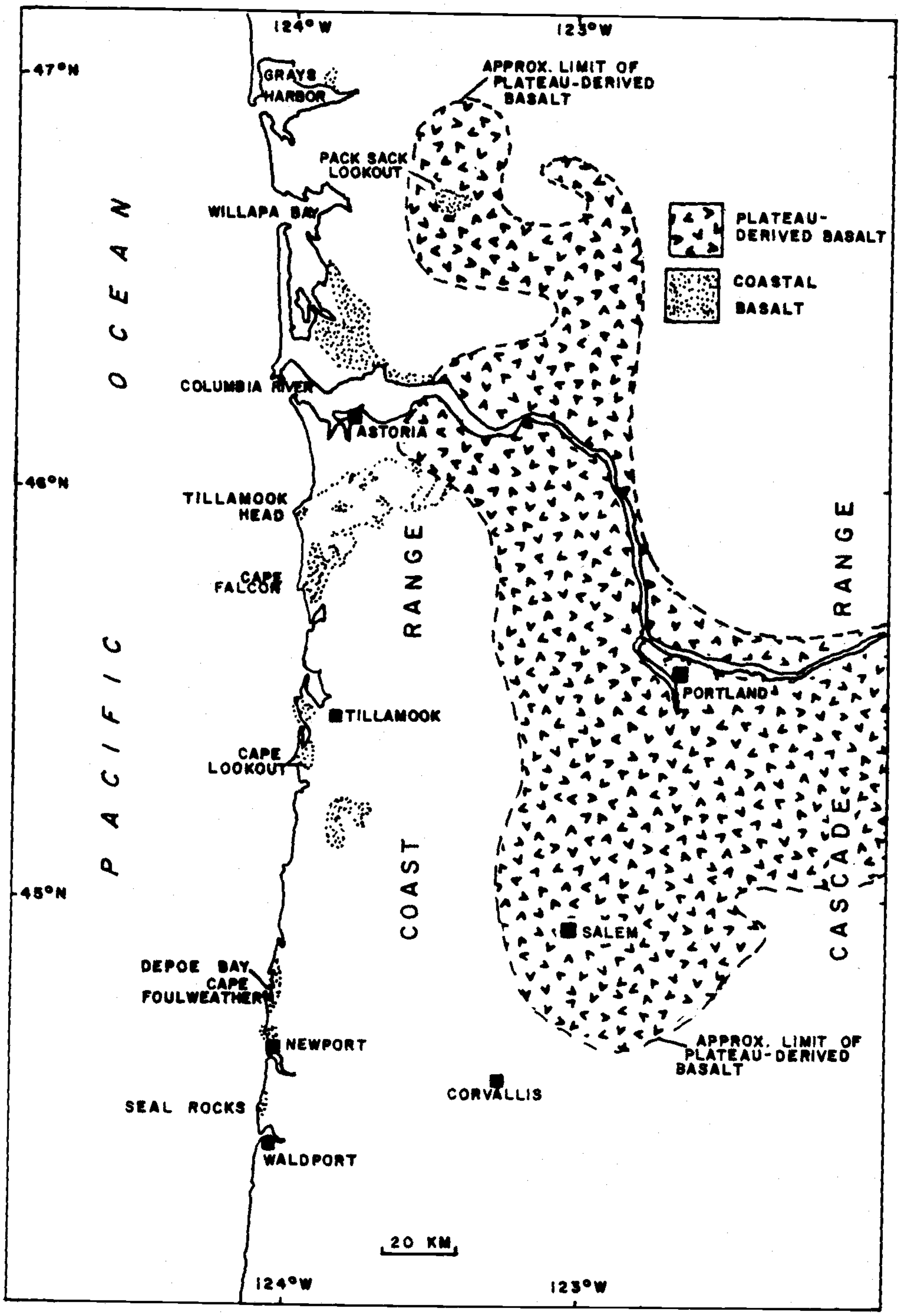


Figure 37. Distribution of plateau-derived basalt flows and middle Miocene coastal basalt in western Oregon and southwestern Washington (after Snavely and others, 1973; Beeson and others, 1979).

Rheological parameters and models for this sort of mechanism have not been developed. There are no known similar occurrences on this scale cited in the geological literature. The hypothesis suggests that Columbia River Basalt lavas flowed into marine embayments along the coast to form hundreds of meters of palagonitic breccia (Murphy and Niem, 1982) and temporarily ponded lava either within the breccia piles or behind these palagonitic breccia lava deltas (Murphy, 1981). The dense liquid basalt and breccia overloaded and sank into the underlying less dense, semiconsolidated early Miocene marine sediments. The fluid basalt vertically and/or laterally injected or "invaded" the underlying consolidated sedimentary rocks causing readjustment of these rocks to the newly imposed vertical or lateral stress. Tensional fractures developed where the vertical stress exceeded horizontal stress (perhaps along old fault zones or joints) and the open fractures were injected with liquid basalt lava from above or laterally. Significant hydrostatic head must be required to push the basaltic lava to a depth of 1,600 m (5,250') (Olbinski, 1983).

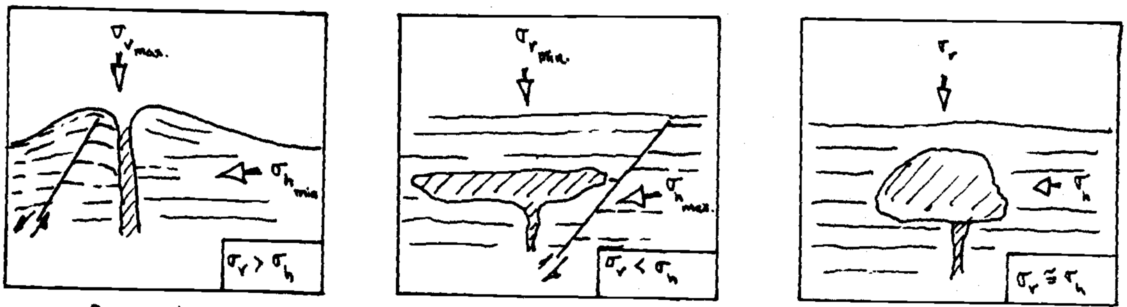
One might expect a near random orientation of lava-filled fractures (i.e., irregular trends of dikes and sills) since this locally imposed stress is unevenly distributed. Such is the case for many coastal intrusives in the younger Miocene and Oligocene strata (Cressy, 1974; Smith, 1975; Neel, 1976; Tolson, 1976; Coryell, 1978; M.

Nelson, 1978; Penoyer, 1978). However, the laterally extensive Beneke, Fishhawk Falls and Northrup Creek dikes in eastern Clatsop County follow a consistent northeast trend (N30-37°E) in older Oligocene to upper Eocene strata (Fig. 30). These three dikes may be related to regional stresses or intrusion following pre-existing fault zones and joints rather than injection stress created by ponded lavas of palagonitic breccias.

Tectonic Significance of the Orientation of the Major Middle Miocene Basalt Dikes

Regional Considerations: a discussion. The intrusion and orientation of the dikes can be related to a particular alignment of tectonic stresses in the lithosphere. Emplacement of magma bodies of any shape and orientation is dependent on the dilation of tensile fractures (Willams and McBirney, 1979, p. 307).

Three gross stress regimes can be defined on the basis of principle stress orientations and their relative magnitudes (Willams and McBirney, 1979) (Fig. 38). If the vertical component of compressive stress (σ_v) exceeds the horizontal component of compressive stress (σ_h), magma will be intruded as dikes and may be associated with normal faulting. If the horizontal component (σ_h) exceeds the vertical component of compressive stress (σ_v), magma will be



Case 1 Case 2 Case 3

Figure 38. Schematic diagram showing the relation of vertical (σ_v) and horizontal (σ_h) components of stress to magma intrusion (after Williams and McBirney, 1979).

injected as sills and may be accompanied by reverse faulting. Extrusion is not likely to occur in this latter case. If the vertical and horizontal components of compressive stress (σ_v and σ_h) are approximately equal, magma will rise by stoping toward the surface to form a plug or bulbous intrusion. Randomly oriented dikes and cylindrical intrusions result if the lithosphere has a relatively homogeneous fabric. Pre-existing structural anisotropy (e.g., joints or faults) within the lithosphere will control the ascent and emplacement of magma.

The spatial orientations of the dikes may allow definition of which of the three gross stress regimes may have existed during the middle Miocene intrusive event. As we are dealing primarily with dikes, the stress regime in which sills are formed can be eliminated (Case 2). Therefore, two possibilities remain: either the horizontal and vertical components of compressive stress were approximately equal and magma rose along some pre-existing structural anisotropy (i.e., faults or joints) (Case 3, Fig. 38) or the vertical compressive stress (σ_v) exceeded the magnitude of horizontal compression (σ_h) (Case 1, Fig. 38).

Consider the geologic and tectonic setting of western Oregon during the middle Miocene. The area was located in an elongate north-south forearc basin developed within the arc-trench gap of the Cascadian arc orogen (Dickinson and Seely, 1977; Dickinson, 1976; Niem and Niem, 1984). The region had been undergoing periods of compressive and extensional tectonism since the middle Eocene (Snavely and others, 1980). Regional compressive stresses acting on the brittle lithosphere resulted from oblique subduction of the Juan de Fuca - Farallon plates beneath the North American plate (Snavely and others, 1980; Wells, 1981). Stresses were focused upon, and possibly modified, pre-existing anisotropic fabric of the lithosphere.

According to Williams and McBirney (1979), volcanism is scarce in areas undergoing regional compression. Under such conditions, injection of sills is the most likely magmatic activity. Magma can ascend to the surface only if there is relaxation of horizontal compression, allowing the vertical stresses to become dominant. Relaxation of horizontal compression might occur, for example, at the cessation of a deformational episode and/or a slowing on the rate of convergence of two lithospheric plates. Elastic strain may be reduced, perhaps allowing dilatational cracks (joints) to develop in an anisotropic lithosphere. Secondly, regional upwarping of the crust related to isostatic rebound may allow emplacement of dikes to occur if the relative magnitude of the vertical compressive stress exceeds that of the horizontal compressive stress.

Regionally, the middle Miocene extrusive vent breccias and intrusive coastal basalts of western Oregon have a preferred orientation which is roughly north-south (Snavely and others, 1973). These intrusive and extrusive basalts occur in a relatively narrow belt (35 km wide) from Seal

Rocks, near Waldport, Oregon to Grays Harbor, southwestern Washington. The belt is 260 km long (Fig. 37). The outcrop belt parallels the arc-trench axis, perhaps not coincidentally. There may be an association between the outcrop belt and the geometry of the plate tectonic elements.

Snavely and others (1980) suggested that this north-south belt of middle Miocene intrusives and extrusives may have been formed during a period of east-west extension and isostatic rebound due to a slower convergence rate between the Juan de Fuca and North American plates. The linear trend of Beneke, Fishhawk Falls and Northrup Creek dikes in eastern Clatsop County (Fig. 30) varies 45° from the regional north-south trend of outcrop and may reflect a local northwest-southeast extension regime ($sigma_3$).

This northwest-southeast extensional regime during emplacement of the Beneke, Fishhawk Falls and Northrup Creek dikes may reflect the beginning of isostatic uplift of the northern Oregon Coast Range gravity high during a slowing of the plate convergence. This gravity high of Tillamook volcanics basement rocks is oriented N20°E through eastern Clatsop County (Bromery and Snavely, 1964). The dikes nearly parallel this high on the west. They may have followed northeast-trending normal faults (i.e., extension, Case 1, Fig. 38) associated with the fault block uplift of this high (Kadri, 1982). However, the contacts of the host sedimentary units adjacent to the dikes, although hard to map continuously, do not show displacement due to normal faulting.

It appears from surface arching of sedimentary strata, from well data (Olbinski, 1983), and from seismic information (Navolio and O'Connor, pers. comm., 1982) that the Beneke, Fishhawk Falls and Northrup Creek dikes were fed from thick sills below (cross-sections, Plate 2) or were fed laterally by invasive Grande Ronde flows in the Porter Ridge - Nicolai Mountain - Big Creek area (9 km to the north). These sills may have encountered pre-existing northeast-trending faults or joints and under magmatic pressure injected magma up or laterally along these fractures.

It is more likely that these fractures were joints related to middle Miocene isostatic uplift. Several Grande Ronde dikes in the thick piles of Grande Ronde breccia at Saddle Mountain (Penoyer, 1977) and at Angora Peak and Humbug Mountain (A. R. Niem, pers. comm., 1984) also trend N40°E. The regional joint system in these thick breccia piles is well developed in the N40°E and N20°W to N40°W direction (Penoyer, 1977; Niem, pers. comm., 1984) and apparently also controlled the orientation of the "ring dike" and other dikes in the Klaskanine River area (Peterson, 1984).

It is interesting to note that where coastal basalt dikes and sills intrude semi-consolidated strata younger than early Miocene in western Clatsop County, the dikes generally do not have a persistent trend but are randomly oriented (see maps of Cressy, 1974; Smith, 1976; Neel, 1976; Tolson, 1976). It is only in eastern Clatsop County where dikes intruded older, more consolidated, less plastic Oligocene and upper Eocene strata (Cowlitz, Keasey and Pittsburg Bluff formations) that the dikes reflect the tectonic fabric. Further complicating the picture, the northeast trend of the Beneke, Fishhawk Falls and Northrup Creek dikes has been rotated as much as 39.7° clockwise by a conjugate system of strike-slip faults (see next section on paleomagnetism) which may have affected the overall trend of the dikes. That is, if the dikes were rotated an average of 25° clockwise, their original trend would have been N10-20°E or more north-south than their present orientation. Thus, these three major dikes would have more nearly parallelled the regional structural trend of the middle Miocene coastal basalts noted by Snavely and others (1973). As mentioned above, this north-south trend would mimic the trend of the forearc basin and would reflect east-west extension due to relaxation of plate convergence.

By far, the greatest volume of middle Miocene basalt coastal basalt erupted and intruded in western Oregon and Washington is that of Grande Ronde (Depoe Bay) type (Snavely and others, 1973). This basalt erupted during a 2 m.y. period (Swanson and others, 1979). It is possible that this basaltic magma could not be emplaced or erupted until stress conditions in western Oregon were amenable. The magma may have remained "in storage" in the asthenosphere or deep crustal levels until such time as the predominantly horizontal compressive stress conditions relaxed. This implies that the timing of basalt emplacement is tied to larger scale plate tectonic events. As mentioned, dikes can not be emplaced and extrusions can not occur unless the vertical compressive stress (σ_v) exceeds horizontal compression (σ_h). One mechanism whereby the horizontal compression can be reduced is to have cessation of the rate of collision between the North American and Juan de Fuca - Farallon plates. Two events may have occurred. One, the relaxation of stress opened dilatational cracks in the lithosphere through which the magma rose. Or two, a large segment of the lithosphere (e.g., northern Oregon Coast Range) was isostatically uplifted, allowing dike emplacement and concurrent submarine volcanism (Case 1, Fig. 38).

Paleomagnetism of Middle Miocene Basalt Dikes

Introduction

A paleomagnetic study was initiated in order to determine paleomagnetic field directions of major middle Miocene basalt dikes (e.g., Beneke, Fishhawk Falls, and Northrup Creek) in the thesis area and neighboring thesis areas (Goalen, in prep.; Olbinski, 1983). The determination of field directions was, in part, intended to help test the invasive hypothesis (Beeson and others, 1979) that these three dikes, and other middle Miocene basalt intrusions in northwestern Oregon, were related to the subaerial Columbia River basalt flows near Westport, Porter Ridge and Nicolai Mountain. It was assumed that if the flows and intrusives show similar paleomagnetic directions, this would be further evidence in support of the invasive hypothesis.

A second aspect of the paleomagnetic investigation was to determine how much, if any, tectonic rotation of microblocks has occurred since the middle Miocene in northwest Oregon by sampling along the dike trends between strike-slip faults. The amount of tectonic rotation measured in this area would be compared with the amount of rotation measured by other workers (Magill and Cox, 1981; Magill and others, 1982) in the Columbia River Basalt. The intention, also, was to determine a mechanism to explain this rotation.

Field sampling procedures. Eighteen paleomagnetic sites were drilled, including 8 sites along the Beneke dike (22 km long), Fishhawk Falls dike (8 km long), and Northrup Creek dike (10 km long). Five sites were drilled in the Grande Ronde subaerial and pillow lavas (which are correlative to the dikes based on geochemistry) on Nicolai Mountain and Porter Ridge. Two sites were drilled in high-MgO Grande Ronde Basalt dikes. Three closely spaced sites were established between exposed strike-slip faults in part of the Beneke quarry to test the effect of strike-slip motion on small block rotation (Plate 4).

The sampling occurred during two periods, once in the Spring of 1981 with follow-up sampling in November 1981. Seven sites were established in the Spring of 1981 and consisted of: two sites each along the Beneke and Northrup Creek dike trends; and one site on the Fishhawk Falls dike; one site was located in a low-MgO-high-TiO_2 Grande Ronde pillow basalt flow on Nicolai Mountain; and a seventh site located on Little Fishhawk Creek in a low-MgO-low TiO_2 type basalt dike. Some of these sites failed to provide meaningful results because too few cores were selected, resulting in poor statistics. The sample locations are described in Appendix IX and a map is presented in Fig. 39.

In November 1981, four of the seven previous sites (MM2, MM3, MM4, MM5) were reoccupied and additional cores were collected with the intent of reducing statistical error of paleomagnetic directions. Eleven additional sites were

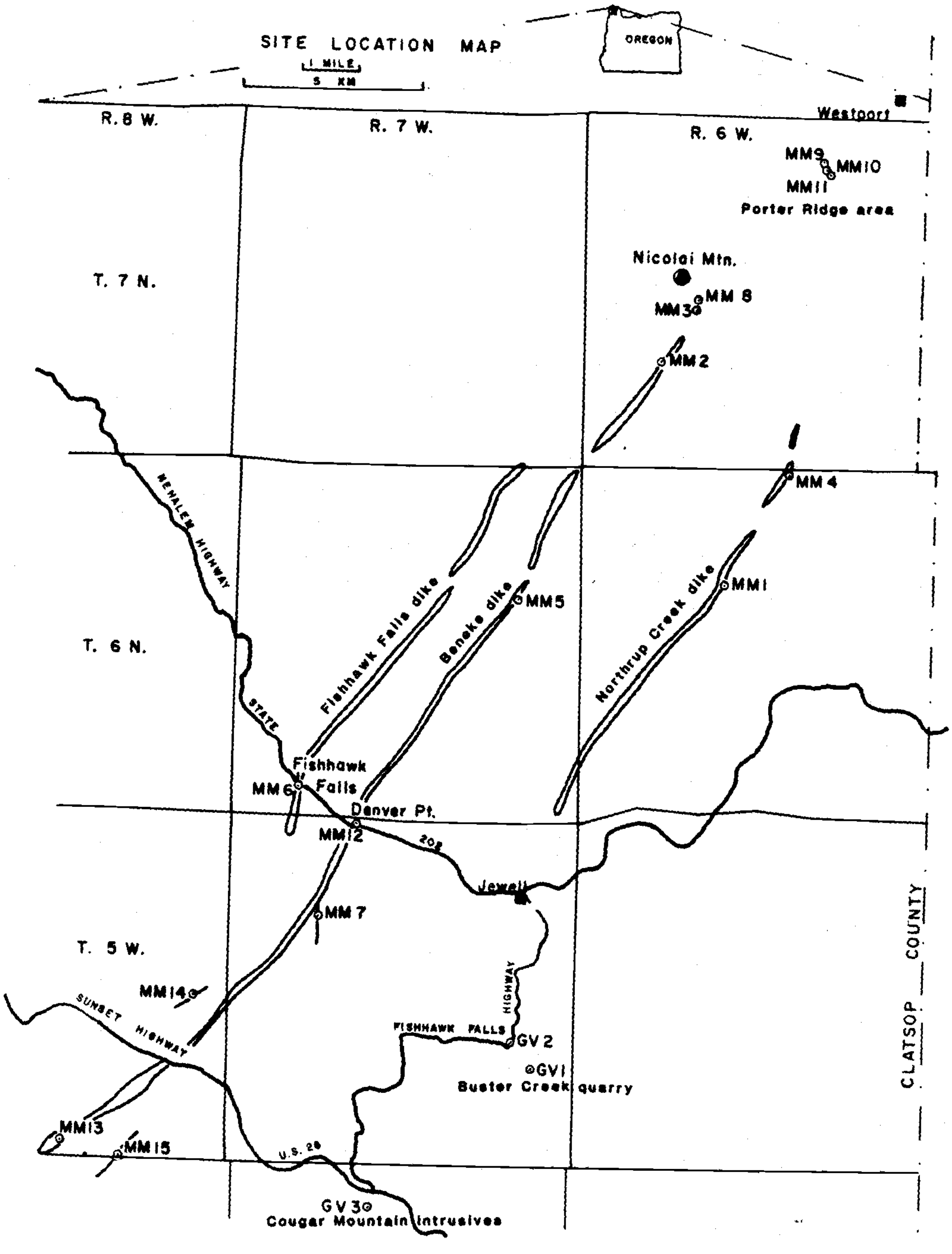


Figure 39. Site location map of Eocene and middle Miocene paleomagnetic sample localities of Tillamook and Grande Ronde basalts.

also established. These new sites included: a second overlying low-MgO-high-TiO_2 Grande Ronde pillow basalt flow on Nicolai Mountain; three new sites in three subaerial low-MgO-high-TiO_2 Grande Ronde flows near Plympton Creek southwest of Westport, Oregon; three new sites in Beneke quarry (Plate 4); a site at Denver Point along the Beneke dike trend; one site near the southern terminus of the Beneke trend; and two sites in two of the high-MgO Grande Ronde Basalt dikes.

A minimum of 8 cores were collected at each site and were drilled 1 to 5 m apart across the face of the outcrops. A portable, hand-held core drill with diamond bits was used to obtain the cores. The cores were oriented with an orienting tool (borrowed from R. W. Simpson) and Brunton compass. When possible, with a sun compass and backsighting techniques were used to correct small local deflections of magnetic compass readings. One site (MM13) was excluded from the data set because of widely disparate magnetic directions that are likely the result of poor sampling procedures (i.e., sampling after dusk with flashlight!).

Throughout the investigation, Dr. Shaul Levi of the College of Oceanography provided guidance and equipment to conduct this experiment. Dr. Robert Bentley of Central Washington University also assisted in field sampling during the second phase of work in November 1981. A flow chart of the procedures developed by Dr. Levi and used in the magnetics laboratory in the College of Oceanography is presented in Appendix XV.

Paleomagnetic Directions and Results

Laboratory Preparation. Each basalt core was cut into 2 to 2.5 cm long specimens prior to analysis of natural remanent directions and magnetic cleaning treatments. One specimen per core was selected for measurement of paleomagnetic directions on a Schonstedt spinner magnetometer. Generally, the innermost specimen was used as this is the least weathered sample. In cases where it appeared that a selected specimen did not have stable magnetic directions through a series of alternating field demagnetization treatments, another specimen from the core was measured. In the statistical analysis, only one specimen per core was considered so that each core within a site carried equal weight.

Demagnetization. Natural remanent magnetization (NRM) of each specimen was measured first, followed by stepwise magnetic cleaning in an Schonstedt alternating field demagnetizer. Thermal treatments were not used in the study. Peak fields in the cleaning process ranged from 300 to 1000 Oersteds. Stable levels were selected by visual examination of the data for consistent paleomagnetic directions through successive alternating field demagnetization (AFD) treatments. These levels varied from sample to sample and the selected levels are listed in Table 3.

Summary of site statistics. Sites MM9, MM10 and MM11 in the Plympton Creek section (Fig. 39) presented special problems which were not resolvable in this study (see Table 3). These sites sampled subaerial Columbia River Basalt flows which have low-MgO chemistry. These flows were critical to that aspect of the study which attempted to show similarity of paleomagnetic field directions of subaerial flows on Nicolai Mountain and Porter Ridge to the geochemically correlative Beneke, Fishhawk Falls and Northrup Creek dikes. Unique magnetic directions were not observed for these three sites. For example, both normal and reversed directions were obtained from apparently stable core samples within a site.

Of these three problem sites, MM9 has the tightest clustering of paleomagnetic field directions but has a poor a_{95} (13°). The directions indicate that site MM9 has normal polarity. This site has geochemistry similar to that of the Fishhawk Falls dike (site MM6), and the latter also has normal polarity. But the shallow inclination of site MM9 (I=25°) is anomalous to all other sites in the study in which the inclination is 43° to 77°.

Site MM10, in a Grande Ronde subaerial flow along Plympton Creek (Fig. 39), showed high scatter. Field directions of only three specimens plot near one another.

Site MM11, the oldest Grande Ronde flow in the Plympton Creek section (Fig. 39), also produces anomalous results. There appear to be two mean directions, one having reversed polarity and a second having normal polarity (Table 3). The reason for this bimodal distribution is uncertain. However, the flow is located near the stratigraphic position of the R2 and N2 paleomagnetic polarity transition which may have had some effect on magnetic directions.

The precision parameter, K of the Fisher distribution (Fisher, 1953), is inversely relative to the angular dispersion about the mean (a_{95}). K is large for low angular dispersion about the mean, but K is small where the circle of confidence is large. This parameter varies from 30.6 to 582.2 for all sites (excluding MM9, 10, 11) (Table 3). A fold test was not attempted for these data because the sites do not occur on opposite limbs of well-defined folds.

Excluding the problem sites, MM9, MM10 and MM11, the average a_{95} of 14 individual sites (MM1, 2, 3, 4, 5, 5A, 5B, 5C, 6, 7, 8, 12, 14, 15) is 7.6°. Fourteen sites located in the basalt dikes (including low-MgO and high-MgO Grande Ronde types) have an average a_{95} of 7.25°.

Only two of five sites in Grande Ronde basalt flows gave meaningful results (sites MM3 and MM8). These two flows are located in the Nicolai Mountain quarry (NW1/4, sec. 21, T7N, R6W) and are the "lower" (site MM3) and "upper" (site MM8) pillow basalt flows. The structure corrected directions and associated a_{95}'s (see Table 3) of these two flows are: D = 207°, I = -62° (11° a_{95}) for the lower flow; and D = 195°, I = -45.5° (8.5° a_{95}) for the upper flow. A summary of paleomagnetic directions and statistics for each major dike trend is presented in Table 4.

When compiled by chemical subtype, the a_{95} for reverse polarity low-MgO-high-TiO_2 basalts is 4.8° and declination and inclination of 220° and -63°, respectively. The low-MgO-low-TiO_2 subtype basalt dikes sampled in this study are normal polarity having a declination and inclination of 70° and +65°, and have an a_{95} of 4.4°. High-MgO basalts are also normal polarity (D = 6°, I = +46°) and have an a_{95} of 5.1° (see Table 5).

Structure Corrections. Two field directions are listed in Table 3, 4 and 5. The "core rotated" columns correspond to field directions in which the strike and dip of the core axis has been removed. The "structure corrected" columns correspond to directions that are corrected for tectonic tilt of the rocks sampled. The structure correction of 270°, 6°N was used in most of the sites. This is a reasonable tilt correction because the geochemically similar Grande Ronde, the Frenchman Springs and Pomona flows on

Table 3. Tabulation of Paleomagnetic Data from Grande Ronde Basalt: 5 Flows & 11 Dikes

Site (Polarity) * = dike	Location Long. (deg)	Location Lat. (deg)	Samples # Used (# Collected)	K	$\alpha_{(95)}$	Paleomagnetic Directions: Core Rotated I(deg), D(deg)	Paleomagnetic Directions: Structure Corr. I(deg), D(deg)	Stable AFD level (Oe)	Structure Correction
* MM 1 (R)	123.46,	46.01	5[1](7)	109.4	7.3	-79.6, 164.4	-73.8, 170.0	200-500[2]	270, 6 N
* MM 2 (R)	123.45,	46.06	8(8)	30.6	10.2	-59.7, 261.3	-57.8, 250.5	200,300,400	270, 6 N
MM 3 (R)	123.44,	46.06	7[3](8)	30.9	11.0	-67.4, 213.6	-62.2, 207.1	300	270, 6 N
* MM 4 (R)	123.40,	46.04	7[4](8)	39.6	9.7	-74.4, 311.4	-77.5, 290.2	200-800[5]	270, 6 N
				39.5	9.7	-74.4, 311.4	-84.2, 301.9	200-800[5]	225, 10 N
* MM 5 (R)	123.50,	46.00	3(3)	74.0	14.4	-64.7, 235.9	-60.9, 226.7	200,300	270, 6 N
* MM 5A (R)	123.50,	46.00	7(7)	121.2	5.5	-66.0, 229.4	-61.7, 220.7	200,300	270, 6 N
* MM 5B (R)	123.50,	46.00	8(8)	582.2	2.3	-60.5, 232.1	-56.5, 224.7	200,300	270, 6 N
* MM 5C (R)	123.50,	46.00	8(8)	282.5	3.3	-52.0, 245.6	-49.2, 239.2	200,300	270, 6 N
* MM 5'[6](R)	123.50,	46.00	26(26)	87.0	3.1	-60.0, 237.0	-56.4, 229.2	200,300	270, 6 N
* MM 5" (R)	123.50,	46.00	3(3)[7]	93.3	12.8	-59.7, 236.9	-56.1, 229.2	200,300	270, 6 N
* MM 6 (N)	123.58,	45.99	6[10](8)	186.4	4.9	65.8, 85.0	64.6, 72.2	300,500[11]	270, 6 N
* MM 7 (N)	123.54,	45.92	5(5)	65.1	9.6	66.7, 79.7	65.0, 66.8	300,500[12]	270, 6 N
MM 8 (R)	123.44,	46.07	7[8](8)	51.8	8.5	-51.3, 196.8	-45.5, 195.0	200,300	270, 6 N
MM 9 (N?)	123.40,	46.10	5[15](9)	38.8	13.0	21.4, 85.1	29.8, 73.6	400,500	240, 25 NW
			4[16](9)	10.1	30.4	-22.6, 282.7	-37.7, 270.9	400,500	240, 25 NW
MM 10 (?)	123.44,	46.07	3[17](8)	80.6	13.8	-22.5, 257.2	-27.5, 245.6	400-800[18]	
MM 11 (?)	123.39,	46.12	4[13](8)	15.0	38.8	-36.5, 282.1	-50.1, 261.8	200,300	240, 25 NW
			4[14](8)	24.8	14.7	53.4, 333.2	28.5, 332.2	200-700[14]	
* MM 12 (R)	123.56,	45.95	8(8)	26.3	11.0	-67.5, 175.1	-61.6, 176.1	100,200,300	270, 6 N
* MM 14 (N)	123.60,	45.91	7[9](8)	229.7	4.0	54.6, 20.7	48.9, 18.1	200,300	270, 6 N
* MM 15 (N)	123.64,	45.89	8(8)	134.1	4.8	49.2, 353.0	43.3, 353.7	200,300	270, 6 N

Footnotes:

1 Samples form cores 2 & 5 are excluded because stabel directions were not obtained (Core 2) and declination measured in Core 5 is far from the site mean declination.

2 AF levels vary: Core 1 - 400,500 Oe; Core 3 - 300,400 Oe; Core 4 - 200,300; Core 6 - 300; Core 7 - 200,300

3 Specimens from Core 4 are excluded because of poor agreement of magnetic directions between two specimens of the same core and magnetic instability of the same samples.

4 Specimens from Core 3 are excluded because of poor agreement of paleomagnetic directions and magnetic instability.

5 AF levels vary: Cores 1, 2 & 4 - 200,300 Oe; Core 5 - 200,250; Core 6 - 500,600; Core 7 - 600,700 Oe; Core 8 - 400,500 Oe.

6 MM 5' represents the mean directions of 26 samples collected in Beneke Quarry. All samples are given equal weight and only one specimen per core is considered.

7 Only the means of sites MM.5A, 5B, & 5C are considered in MM 5". This gives the mean of means of 3 sites in Beneke Quarry.

8 Core 2 excluded because the mean inclination of the core is far from the mean inclination of the site.

9 Core 3 excluded because the declination of the specimen of the core is far from the mean declination of the site.

10 Core 1 excluded because the paleomagnetic directions are reversed and far from the mean for the site. Core 3 was never measured.

11 AF levels vary: Cores 2, 4, 5, 7 & 8 - 300 Oe; Core 6 - 500 Oe.

12 AF levels vary: Cores 1, 2, 3 & 4 - 300 Oe; Core 5 - 500 Oe.

Footnotes (con't.)

[13] Site MM 11 is divided into 2 groups of reversed polarity & normal polarity. This line of data is for the reversed polarity group using specimens from Cores 1,2,3 & 8, all at the 200,300 Oe AF level.

[14] This line of data is for the normal polarity group of site MM 11 using specimens from Cores 4, 5, 6 & 7; AF levels vary: Core 4 - 400,500 Oe; Core 5 - 600,700; Core 6 - 500,600; Core 7 - 200,300 Oe.

[15] Site MM 9 is divided into two groups of normal and reversed polarity. This line of data is for the normal polarity group, using specimens from Cores 5, 6, 7, 8 & 9.

[16] This line of data is for the reversed polarity group using specimens from Cores 1, 2, 3 & 4.

[17] Only Cores 3, 5 & 6 are used because specimens from these cores clustered together with similar inclination (up in Quadrant III). Other cores are disregarded because of poor agreement between specimens of the same core, strong overprint due possibly to secondary magnetization which could not be removed with AF demagnetization, and/or disparate paleomagnetic directions of these other cores.

[18] Stable AF levels vary: Core 3 - 400,500 Oe; Cores 5 & 6 - 700,800 Oe.

Table 4: Tabulation by Dike Trend

Trend / Chemistry	Polarity	Sites Used No. of smps	K	$\alpha_{(95)}$	Paleomagnetic Directions Core Rotated I(deg), D(deg)	Paleomagnetic Directions Structure Corr. I(deg), D(deg)	Structure Correction
Northrup/ Low MgO high TiO_2	R	MM1, MM4 N = 12	23.9	9.1	-84.0, 286.8	-82.7, 233.4	270, 6 N
Beneke/ Low MgO high TiO_2	R	MM2, 5A, 5B, 5C, MM12 N = 39	22.8	4.9	-63.7, 233.4	-59.8, 225.0	270, 6 N
Fishhawk/ Low MgO, low TiO2	N	MM6, MM7 N = 11	110.5	4.4	66.2, 82.6	64.8, 69.8	270, 6 N

Table 5: Tabulation by Grande Ronde Basalt Geochemical Sub-type

Chemistry	Sites Used No. of smps	K	$\alpha_{(95)}$	Paleomagnetic Directions Core Rotated I(deg), D(deg)	Paleomagnetic Directions Structure Corr. I(deg), D(deg)	Structure Correction
Low MgO, high TiO_2	MM1, 4, 8, 5A, 5B, 5C, & MM 12 N = 58	16.0	4.8	-67.4, 228.8	-63.2, 219.7	270, 6 N
Low MgO low TiO_2	MM6, MM7	110.5	4.4	66.2, 82.6	64.8, 69.8	270, 6 N
High MgO	MM14, MM15	52.2	5.1	52.3, 7.3	45.5, 5.8	270, 6 N

Nicolai Mountain have a homoclinal north dip of approximately 6° and east-west strike (Murphy, 1981).

Deformation of these middle Miocene flows is probably due to regional north plunge of the nose of the Oregon Coast Range anticlinorium, the axis of which passes near the area. The middle Miocene basalt intrusives and surrounding sedimentary strata have been similarly deformed since the middle Miocene as these rocks also occur near the axis of the Oregon Coast Range anticlinorium. This deformation probably occurred after primary magnetic remanence of the Grande Ronde basalts was acquired.

Local dips of upper Eocene and Oligocene sedimentary rocks surrounding the middle Miocene intrusives are steeper than the tectonic tilt correction reported in the tables. Even if the local steeper tilt corrections are taken into account, they are mild in any case (<10° dip and <20-30° variation in strike direction) and did not result in widely different "structure corrected" field directions when applied in several cases. The subaerial flows in the Plympton Creek section (sites MM9, MM10 and MM11) have a locally steeper dip (25°NW) and strike than the regional tilt (Goalen, in prep.).

The locally high dips and variability of dip direction of the sedimentary strata may reflect small block tilting that pre-dates middle Miocene and the dike intrusion events because the sills and dikes cut across folds without mappable folding of the intrusives themselves (cross-section

H-H', Plate 2). Wells (1981) and Wells and others (1982) also found better paleomagnetic correspondence between middle Miocene intrusions and their subaerial equivalents in southwestern Washington when the locally higher sedimentary dips were ignored, suggesting that these dips were in large part due to pre-middle Miocene structure.

Paleomagnetic Results from the Dikes

Northrup Creek dike. Two sites (MM1 and MM4) are located 3.6 km apart on the Northrup Creek dike. Both of these sites have reversed polarity and very steep inclinations. When the assumed middle Miocene tectonic tilt of the Oregon Coast Range is removed, the two sites average I = -83°, D = 233° (Table 4 and Fig. 40). The steep inclination is anomalous compared to the Miocene expected direction for latitude 46°N and is probably due to secular variation of the geomagnetic field during cooling or to some inherent variable magnetic properties of the dike.

The steep inclination is also distinct from that of the Beneke dike which has an average inclination of -59.8°. The Beneke dike has similar geochemistry to the Northrup Creek dike (i.e., low-MgO-high-TiO_2 Grande Ronde subtype) and it was noted earlier that the Northrup Creek dike has slightly lower TiO_2 content than the Beneke dike (Fig. 35), and therefore is a separate basalt unit. Both dikes have reverse polarity but show different inclinations and

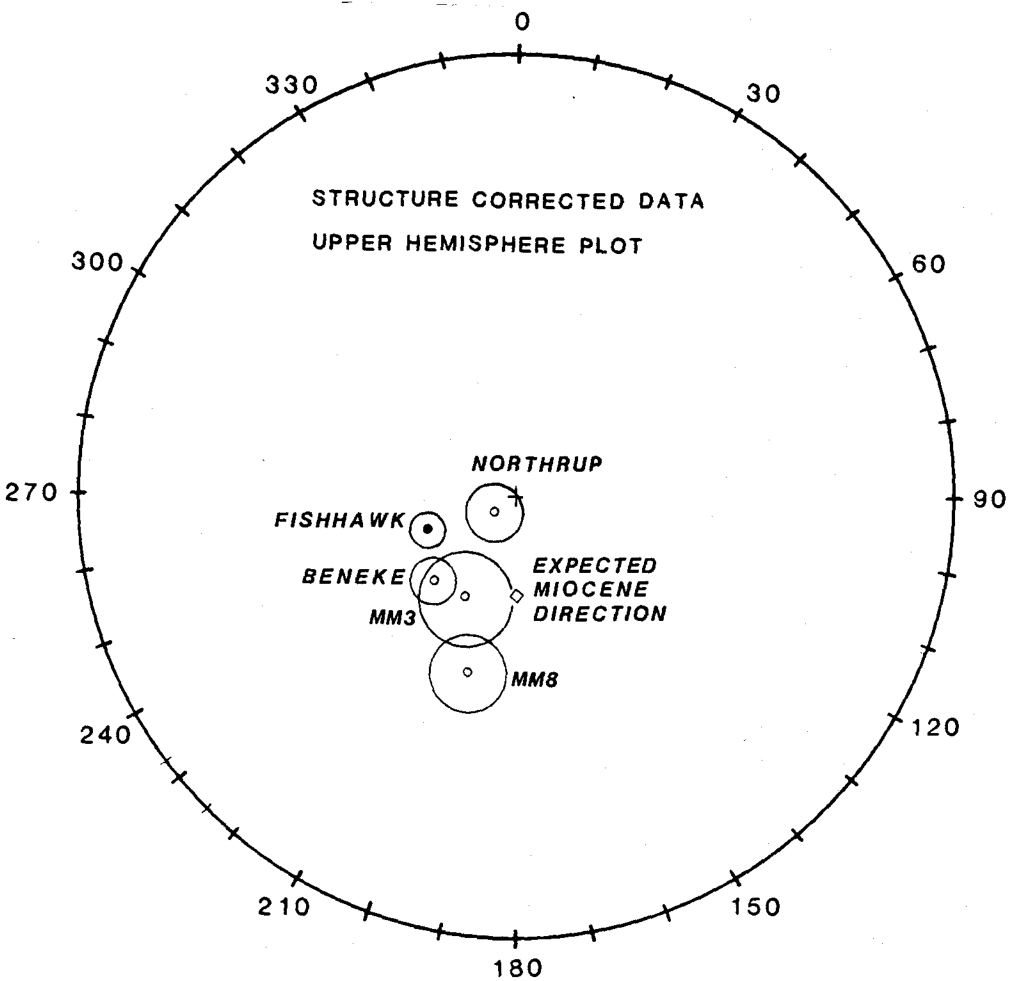


Figure 40. Paleomagnetic directions of three middle Miocene dike trends in eastern Clatsop County. The direction of Fishhawk Falls dike, which has normal polarity, is projected through the origin into the upper hemisphere (represented by filled circle). Site MM3 from Nicolai Mtn. appears to correlate to the Beneke dike based on overlap of a_{95}'s. The larger circles represent cone of 95% confidence (a_{95}).

declinations of paleomagnetic directions (Fig. 40). This difference of paleomagnetic directions also suggests that the Northrup Creek and Beneke dikes are separate intrusive bodies formed at different times within a changing geomagnetic field.

Alternatively, the anomalously steep inclinations of the Northrup Creek dike may be due to the effect of local tilting of small tectonic blocks. Near the Northrup quarry site (MM1), a large left-lateral oblique-slip fault is mapped which offsets the Northrup Creek dike by 100 m south of site MM1 (Olbinski, Plate I, 1983). Unrecognized tilting about axes other than the strike of the strata due to this faulting may explain why the declination is so different between this site and the second site on the Northrup Creek dike (MM4). Tilting about a non-vertical axis could also cause the anomalous steep inclination.

Other explanations are also possible. Stauss (1982) measured anomalous paleomagnetic directions in Eocene dikes in central Washington and suggested that anomalous directions may result from several factors, including: secondary uncleaned chemical remanent magnetism (CRM); or inadequate sampling of the dipole field from rocks that acquire remanent magnetization during major excursions or polarity reversals; or to deflection of thermal remanent magnetization (TRM) directions during crystallization due to stress anisotropy on the intrusive. Determining which of these factors may have caused the anomalous steep inclinations of the Northrup Creek dike at site MM1 is beyond the intent of this study.

Beneke dike. Seven sites (MM2, MM5, MM5A, MM5B, MM5C, MM12, MM13) are located along the length of the Beneke dike trend (Fig. 39, Tables 3 and 4). Site MM2 is near the northern end of the trend, 1.8 km south of Nicolai Mountain (Fig. 39). Sites MM5, 5A, 5B and 5C are located in the Beneke quarry (NE1/4, NE1/4, sec. 14, T6N, R7W; Plate 4). Site MM5 was originally sampled in the Spring of 1981 but the locations of the four cores collected here were destroyed by the quarrying operation. When the site was reoccupied in the November 1981, three new sites (MM5A, 5B, 5C) were established in order to determine if rotation had occurred between small fault-bounded blocks mapped within the quarry. Although the original boreholes of site MM5 were destroyed, site MM5A is located within the same area and fault block in the quarry and thus replaces the original site MM5. The a_{95} statistic for site MM5A (5.5°) is much improved over that of MM5 (14.4°), yet the field directions are very similar (Table 3). The primary reason that the a_{95} statistic is improved is that more samples are used in site MM5A.

The three sites in the quarry are located on different structural blocks bounded by oblique-slip faults. Site MM5A is in the northern part of the quarry, site MM5B near the middle part of the quarry, and site MM5C is located near the southern end of the quarry exposure (see Plate 4). These sites are the focus of discussion in a later section on small-block tectonic rotation.

Site MM12 is located at Denver Point (Plate 1; NW1/4 sec. 4, T5N, R7W). It is 7.7 km southwest of the Beneke quarry along the trend of the dike.

All five sites along the northern part of the Beneke trend (sites MM2, MM5A, MM5B, MM5C and MM12) have reversed polarity and similar geochemistry corresponding to the low-MgO-high-TiO_2 Grande Ronde type. Mean structure corrected paleomagnetic field directions are: D = 225°, I = -60° with an a_{95} = 4.9° (Table 4, Fig. 40). The range of declination and inclination values from individual sites in the Beneke dike are: D = 250.5° to 176.1° and I = -49.2° to -61.6° (Table 3).

One site (site MM13) was located on the southern part of the Beneke dike which has low-MgO-low-TiO_2 chemistry that is indistinguishable from the chemistry of the Fishhawk Falls dike. This southern part of the Beneke dike trend has normal polarity as measured with a fluxgate magnetometer. Site MM13 failed to provide meaningful data due to widely disparate directions after magnetic cleaning of the samples. This problem is probably related to poor sampling techniques.

Fishhawk Falls dike. One site located on the Fishhawk Falls dike has normal polarity and paleomagnetic directions of: D = 70°, I = 65° (structure corrected) (Figs. 39 and 40; Table 4). Two sites (MM6 and MM7) are located in two geographically separate dikes having the low-MgO-low-TiO_2 chemistry and normal polarity characteristic of the Fishhawk Falls dike (Plate 1; Appendix IX). Site MM6 is located at Fishhawk Falls (the waterfall) in the center of the Fishhawk dike itself. Site MM7 is located at Little Fishhawk Falls, southeast of the other Fishhawk Falls (NW1/4, SE1/4, sec. 8, T5N, R7W) (Plate 1). This isolated 0.5-km-long dike, though similar geochemically and paleomagnetically to the dike at site MM6, is not on the same linear trend of the main Fishhawk Falls dike.

Nicolai Mountain - Porter Ridge area. Two reverse polarized pillow basalts of low-MgO-high-TiO_2 chemistry were sampled on Nicolai Mountain (sites MM3 and MM8). These flows represent Grande Ronde basalt units from the Columbia River plateau which entered the middle Miocene ocean (Murphy, 1981). The lower flow has a structure corrected inclination of -62° and declination of 207° (Table 3). The upper flow has an inclination of -46° and a declination of 195°. Murphy (1981) incorrectly identified the upper pillow flow as normally polarized based on fluxgate magnetometer measurements. The lower flow (site MM3) appears to correlate well to the northern part of the Beneke dike as these units have similar low-MgO-high-TiO_2 chemistry, reverse polarity and similar average paleomagnetic

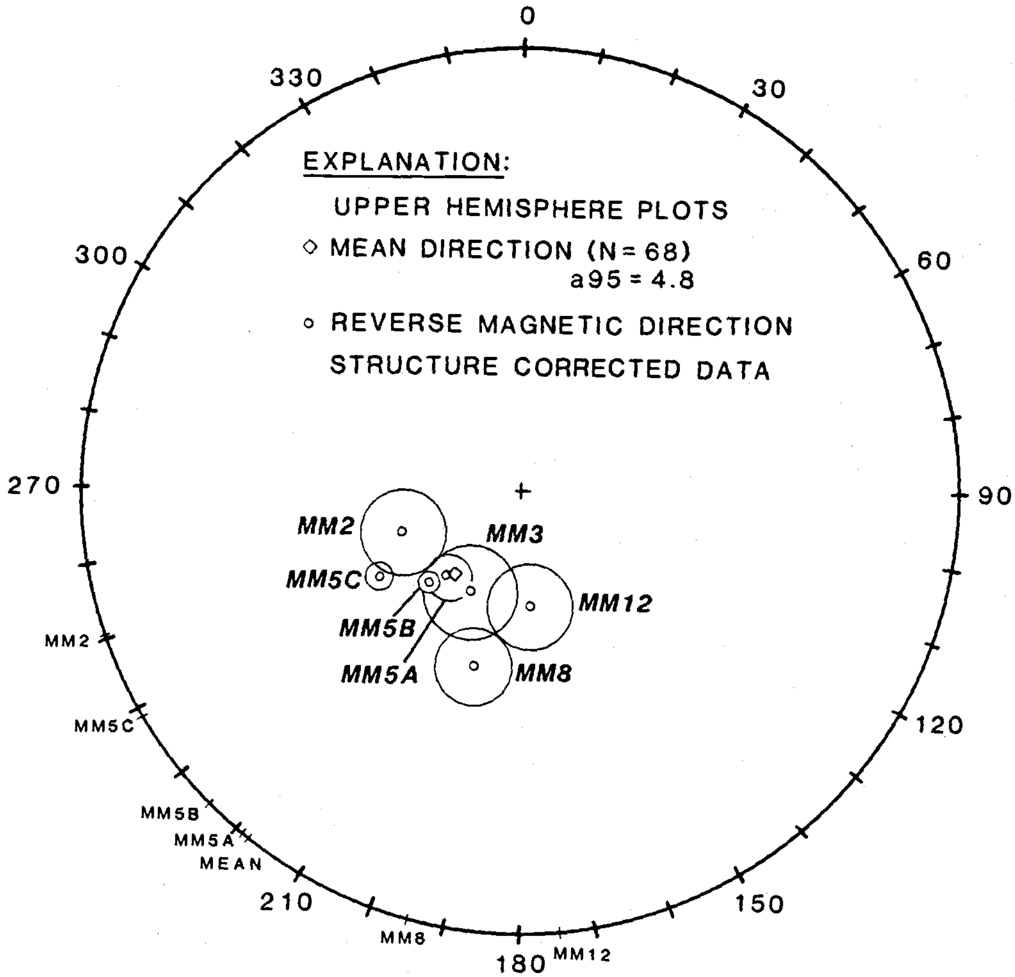


Figure 41. Paleomagnetic directions for sites in Grande Ronde Basalt dikes and flows having low-MgO-high-TiO_2 chemistry. All directions are represented on the lower hemisphere of this stereogram and are corrected for tectonic tilt. All of these sites have reverse polarity. The larger circles represent the cone of 95% confidence (a_{95}).

directions (Tables 3 and 4; Fig. 40). The inclinations and declinations of sites MM3 and MM8 are close to the expected middle Miocene pole position (Figs. 40 and 41).

Paleomagnetic data from geochemical subtypes. Considered as a group by geochemical subtype (Table 5), the low-MgO-high-TiO_2 Grande Ronde basalt dikes and flows that were sampled in this study (sites MM1, MM2, MM3, 5A, 5B, 5C, MM12) have reversed polarity. However, this may not be entirely representative of Columbia River and coastal basalts because there may be other low-MgO-high-TiO_2 Grande Ronde flows in western Oregon that have not been sampled here. Goalen (in prep.) believes that a normally polarized low-MgO-high-TiO_2 flow may exist on Porter Ridge. Six sites (MM4, MM8, MM5A, 5B, 5C, and MM12) were used in the tabulation and mean directions are I = -63°, D = 220°, with an 95% confidence circle of 4.8° (Fig. 42).

Low-MgO-low-TiO_2 basalt dikes and flows in the study area and elsewhere may have either normal or reversed polarity based on fluxgate magnetometer measurements (Murphy, 1981; Peterson, 1984; Goalen, in prep.). In this study however, only normal polarity low-MgO-low-TiO_2 basalt was sampled (sites MM6 and MM7). Mean directions are: I = 65°, D = 70°, with an a_{95} of 4.4° (Table 5; Fig. 42).

Two small high-MgO basalt dikes were sampled (site MM14 in NE1/4, NW1/4, sec. 24, T5N, R8W and site MM15 in SW1/4, SW1/4, sec. 35, T5N, R8W). The structure corrected

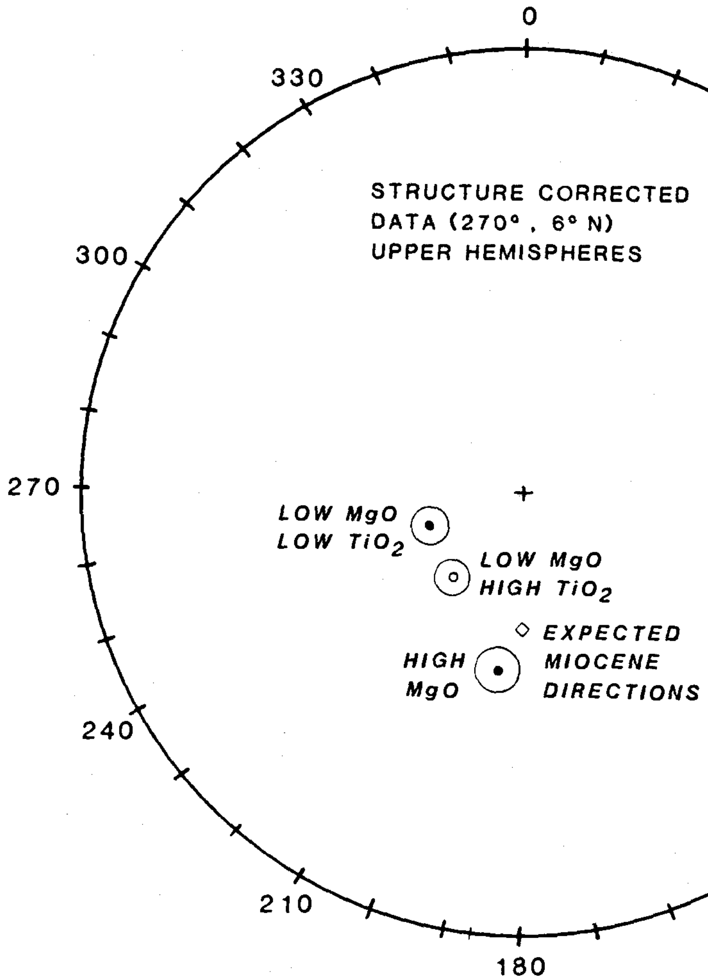


Figure 42. Paleomagnetic directions of geochemical subtypes of Grande Ronde Basalt in eastern Clatsop County. All directions are represented in the upper hemisphere of this stereogram and are corrected for tectonic tilt. Filled circles represent normal polarity directions that are projected through the origin to the upper hemisphere. Small open circles represent reverse polarity directions. Large circles represent the 95% cone of confidence (a_{95}).

inclination varied from 43.2° to 48.9° and the declination varied from 353.7° to 18.1° for these two dikes (Table 3). Mean field directions of these two sites are: I = 46°, D = 6°, with an a_{95} of 5.1° (Table 5). High MgO Grande Ronde basalts clearly have normal polarity.

Tectonic Rotation of Fault-bounded Blocks

Problem of secular variation. The effect of secular variation of the earth's paleomagnetic fields on the results in this study is not known. There may not have been an adequate span of geologic time between these representative samples to average out the secular variation of the geomagnetic field. If the dikes cooled over a period of 10 to 1,000 years, this period may have allowed considerable variation of the geomagnetic field, but secular variation would probably not be averaged out.

If the dikes cooled over a longer period of time, say 10,000 years, and if the samples collected in this study represent an average of this time span, then secular variation might be averaged out. Assuming that secular variation is averaged out, then pole positions calculated from these paleomagnetic directions would representative mean poles.

Interpretation. High MgO basalt dikes show the least clockwise tectonic rotation (R=5.8°) from the expected middle Miocene pole position (Fig. 42). The observed declination of low-MgO-low-TiO_2 basalt is 69.8° (I=65°) and indicates clockwise tectonic rotation of 41° from the expected Miocene direction. This apparent rotation is much greater than the 15° to 20° clockwise tectonic rotation documented by other workers (Choinere and Swanson, 1979; Magill and others, 1982) for similar middle Miocene Columbia River Basalt flows and their coastal equivalents in northwest Oregon and southwest Washington. Either secular variation of the earth's magnetic field has caused considerable deflection of paleomagnetic directions in these low-MgO-low-TiO_2 dikes, or possibly local magnetic fields perturbed the dipolar field during the cooling of these intrusions, and/or the effect of regional tectonic rotation has been added to by local clockwise rotation caused by the transform faults mapped parallel to and cross-cutting these dikes (Plate 1).

The inferred rotation for the three dikes is summarized in Figures 40 and 43. The inferred tectonic rotation of basalt dikes having low-MgO-high-TiO_2 geochemistry (oldest of the three subtypes) is 39.7° clockwise from the expected Miocene direction (Fig. 42). In contrast, the two reverse polarity middle Miocene submarine pillow basalts on Nicolai Mountain (sites MM3 and MM8) show an average clockwise rotation of 27°. This is within the expected range of rotation based on the regional studies of the Grande Ronde and Pomona basalts in southcentral Washington (Magill and

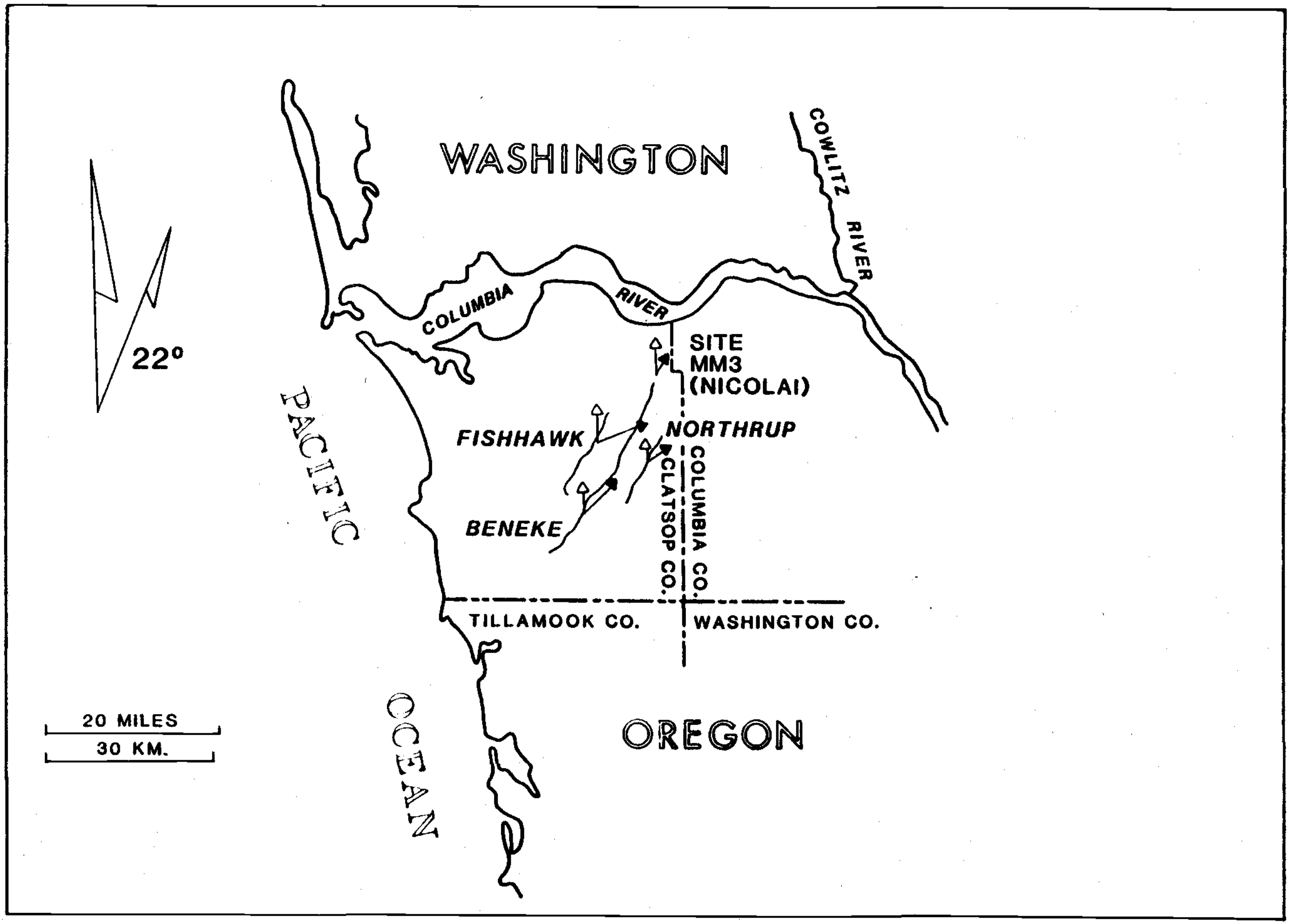


Figure 43. Observed deflections of paleomagnetic field directions along three prominent northeast-trending dikes in eastern Clatsop County. Open-headed arrows are the expected Miocene directions. Other arrows correspond to observed declination and length of arrow is inversely proportional to the 95% circle of confidence.

others, 1982; Wells and others, 1984). The much greater rotation of the three dikes is anomalous.

<u>Small-block tectonic rotation</u>. As mentioned previously, three separate sites (site MM5A, 5B, and 5C) are located in Beneke quarry. Very detailed geologic mapping (1" = 100') of faults and shear zones in the quarry (Plate 4) shows that many northwest- and northeast-trending oblique-slip faults repeat and offset small blocks (e.g., 10 m x 100 m) that contain or bound the northeast-trending Beneke dike. This density of faults is found in nearly every major quarry along the Beneke, Northrup Creek and Fishhawk Falls dikes, suggesting that distributed shear is predominant in the area. The northeast-trending shear zones which are subparallel to the dikes are the most prominent. The samples from the sites in the northern and middle parts of the Beneke quarry (sites 5A and 5B) are paleomagnetically similar (i.e., site 5A: I = -62°, D = 221° and site 5B: I = -57°, D = 225; Table 3; Figs. 41 and 44). The a_{95} of the two sites overlap. However, site MM5C (115 m south of sites MM5A and MM5B) has a mean direction deflected 11° clockwise of the mean for the three sites (Fig. 44). There is no overlap of the a_{95} statistic between sites MM5C and sites MM5A and 5B, suggesting that there is a geological reason for the lack of overlap.

The detailed mapping shows that the part of the basalt dike sampled at site MM5C is a repeated section that has

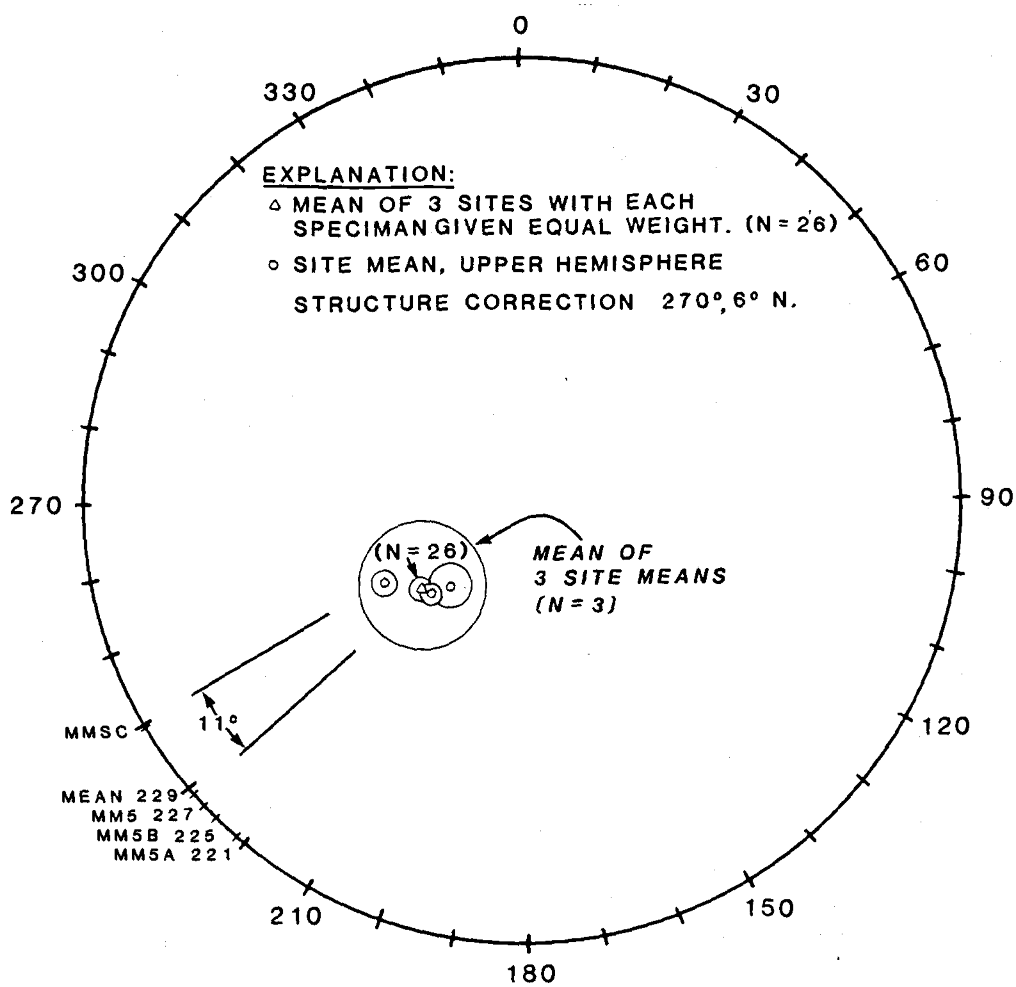


Figure 44. Paleomagnetic directions for three sites of the middle Miocene Grande Ronde Basalt dike in the Beneke quarry (NE1/4, NE1/4, sec. 14, T6N, R7W). All directions are represented in the upper hemisphere of the stereogram and are reversed polarity. Large open circles represent the 95% cone of confidence. Site MM5C occurs within the southern block in the quarry and is rotated 11° clockwise from two other sites that are within a different structural block. There is no overlap of the a_{95}.

been translated northeastward along a northeast-trending left-lateral oblique-slip fault. The paleomagnetic data indicates that this small fault bounded block (only 15-20 m long) contains a part of the dike that may have rotated during movement on the fault relative to the blocks containing sites MM5A and MM5B. The possibility exists for many other clockwise rotations of this nature along all the major northeast- and northwest-trending faults that pervasively cut the Beneke, Northrup Creek and Fishhawk Falls dikes throughout their lengths.

The existence of many small tectonic blocks bounded by sinistral northeast- and dextral northwest-trending faults may explain the anomalously large apparent rotations indicated by these data relative to the measured rotation of equivalent basalts in southwestern Washington (Wells and others, 1983b). Due to the limited exposure in the area, it is difficult to map the boundaries of the many possible small tectonic blocks.

STRUCTURAL GEOLOGY

Regional Structure

The Oregon Coast Range is composed of uplifted basement blocks of lower Tertiary ocean floor basaltic crust surrounded by younger Paleogene and Neogene sedimentary rocks (Niem and Niem, 1984). The core of the central and northern Oregon Coast Range is composed of 15,000- to 20,000-foot-thick lower to middle Eocene Siletz River Volcanics and Tillamook Volcanics (Snavely and others, 1968; MacLeod and Snavely, 1973; Wells and others, 1983). The northern part of the Coast Range forms a gently northward-plunging anticlinorium or geanticline. The term "anticlinorium" is a misleading description of the regional Coast Range structure because it is difficult to trace out anticlinal and synclinal structures on the surface (Niem and Van Atta, 1973). Local reversals of dip and discordant strikes can be as effectively explained by faults as by folds (this study; Olbinski, 1983; Kadri, 1982; Peterson, 1984). Therefore, the terms geanticline or basement upwarp are preferable because these terms describe a regional uplift of the crust and associated sedimentary basins without implying the presence of fold structures. Warren and Norbisrath (1946) also described the Coast Range structure as a geanticline.

The axis of the northward-plunging regional structure is located just northeast of the thesis area in the southeastern part of the Astoria basin and nearly coincides with the eastern boundary of Clatsop County, 9 km east of the study area. On the east and west flanks of this structure are the Nehalem and Astoria basins, respectively. The structure continues northward as indicated by the north-northeast-trending Bouguer gravity anomaly that reflects the Tillamook Volcanics in the subsurface (Bromery and Snavely, 1964; Berg and Thiruvathukal, 1967; Kadri, 1982).

A northward plunge of 10° to 15° is indicated by the northward dip of the middle Miocene Columbia River basalt flows that form Nicolai Mountain (9 km north of the thesis area) (Murphy, 1981). This plunge is in general accord with the regional dip of Eocene and Oligocene strata in the thesis area which dip northwest at 10° to 15°. Assuming that the dikes were originally vertical, the generally steep southeastward dip of the three major Grande Ronde dikes in eastern Clatsop County implies that north and/or northwestward tilting of the entire thesis area has occurred since emplacement. Local variations in dip of the dikes can be accounted for by smaller fault block adjustments due to post-middle Miocene north-south compression (e.g., Plate 1 and 4; Olbinski, 1983; Goalen, in prep.).

Offshore seismic reflection profiles provide the best evidence of regional structures and continental accretion (Snavely and others, 1980). Several periods of uplift, compression and extension have affected the Oregon Coast Range and nearby continental shelf and slope since the Eocene. Discontinuous periods of underthrusting during the middle Eocene, middle late Eocene, late middle Miocene, Pleistocene and Holocene have deformed Cenozoic rocks of this continental margin (Snavely and others, 1980). Low-angle, eastward-dipping imbricate thrust faults and folds on the Oregon continental shelf and slope are associated with the subduction episodes as the Juan de Fuca and Farallon oceanic plates slipped beneath the North American continental plate during oblique plate convergence (Kulm and Fowler, 1974; Snavely and others, 1980; Wells, 1981; Magill and others, 1980, 1982; Niem and Niem, 1984).

Compressional periods were interrupted by periods of strike-slip faulting and extension during the late Eocene and late middle Miocene (Snavely and others, 1980; Wells, 1981). Periods of extension produced normal faulting and igneous intrusion in the Coast Range and coincided with calc-alkaline arc volcanism in the western Cascade Range.

The late Eocene to early Oligocene (e.g., 29-34 m.y.B.P.) was also a period of extension and igneous intrusion as several sills of gabbroic and syenitic composition were intruded into middle to upper Eocene marine strata in the central Oregon Coast Range. Upper Eocene to Oligocene marine strata (Refugian age) have a significantly more tuffaceous character than the Eocene marine strata (Narizian age). The volcanic materials were probably derived from an early, more active and developing western Cascade volcanic arc of andesitic to silicic composition (Niem and Niem, 1984). Uplift of the Oregon Coast Range commenced during early Oligocene time (Snavely and Wagner, 1963; Snavely and others, 1980). The rapid shallowing of the depositional basin from bathyal to shelf environments between late Keasey time and Pittsburg Bluff time supports this interpretation.

Tectonic Rotation and Tectonic Boundaries

Paleomagnetic studies of Tertiary basalts and sedimentary rocks of the Oregon and Washington Coast Ranges and western Cascade Range indicate that up to 75° of clockwise tectonic rotation of western Oregon and Washington has occurred (Magill and others, 1981, 1982; Magill and Cox, 1980, 1981; Beck and Plumley, 1980; Globerman and Beck, 1979; Bates and others, 1979, 1981; Beck, 1976). Workers who have focused on the lower to middle Eocene oceanic basaltic crust and middle to upper Eocene strata of the Oregon Coast Range suggest that a part of the Farallon oceanic plate fragmented during late middle Eocene time as it collided with the North American continent (Simpson and Cox, 1977; Magill and Cox, 1980, 1981; Magill and others, 1981). Accretion of the fragment, or microplate, may have occurred as the buoyant oceanic crust was obliquely subducted beneath the North American continent.

To explain the apparent rotation of the Oregon Coast Range suggested by paleomagnetic studies, several workers (Simpson, 1977; Simpson and Cox, 1977; Magill and others, 1982) proposed a two-phase tectonic rotation model. They hypothesized that during an early phase which preceded the Oligocene the oceanic crust rotated up to 48° clockwise about a vertical pivot in the Klamath Mountains of southern Oregon. Northeastward movement of the Farallon oceanic plate against the North American plate caused clockwise rotation of the Farallon plate fragment. The subduction zone was then jammed by anomalously thick buoyant oceanic crust carrying seamounts and oceanic islands into the oceanic trench. This caused the subduction zone, which probably lay beneath the Willamette Valley, to be abandoned, and a new trench and subduction zone formed to the west in the vicinity of the present Oregon outer continental shelf and slope. An isolated segment of the plate, trapped between the older and now inactive trench and the new subduction zone, contains the Siletz River, lower Tillamook and Roseburg volcanics.

Following the westward jump of the subduction zone, a second phase of clockwise rotation of up to 27° occurred in association with post-early Miocene back-arc extension of the Basin and Range province (Magill and Cox, 1981). Dextral slip faulting also occurred along northwest-southeast trends.

The Coast Range rotated as a semi-rigid block. There are no through-going faults that break the Coast Range into several smaller tectonic blocks. Paleocurrent orientations in the Tyee and Flournoy formations are consistent throughout the Oregon Coast Range (Snavely and others, 1963, 1964), further supporting the interpretation that the Coast Range is a single tectonic block, or microplate.

Magill and others (1981) and Beck and Plumley (1980) interpret that clockwise rotation recorded in the Eocene, Oligocene and Miocene volcanic and intrusive rocks suggests progressive rotation with time. The older Eocene formations (i.e., Siletz River Volcanics, Tyee-Flournoy formations, and Tillamook Volcanics) have been rotated more than the younger formations (i.e., Yachats and Goble Volcanics, and Oligocene and middle Miocene intrusions). The lower to middle Eocene Siletz River Volcanics (50 to 55 m.y.) are rotated as much as $75 \pm 15°$ (Magill and others, 1981). The middle to upper Eocene upper Tillamook Volcanics (minimum age of 46 m.y.) are rotated $46 \pm 13°$ (Magill and others, 1981; this study). The upper Eocene Goble Volcanics (32 to 45 m.y.), in the

Kelso and Longview, Washington area, have been rotated clockwise through as much as 25$\pm$13° (Beck and Burr, 1979). Other Eocene basement volcanic rocks north of the Columbia River (i.e., Crescent and Goble Volcanics) are also rotated, but to lesser degrees than volcanic rocks of similar age in the Oregon Coast Range (Wells, 1981; Wells and Coe, 1979; Globerman and Beck, 1979).

Thus, Magill and others (1981) interpreted that a major tectonic boundary exists between the Oregon and Washington Coast Ranges near or along the Columbia River. These workers suggested that the Oregon Coast Range contrasts to the Washington Coast Range and Western Cascade Range. The latter areas were broken up into several smaller tectonic domains, or tectonic blocks, whereas much of the Oregon Coast Range remained a coherent block during late Eocene to post-middle Miocene deformation and rotation.

The thesis area is situated in the zone that is herein proposed as the northern boundary between these two different tectonic regimes. A preliminary investigation of the paleomagnetism of the uppermost Tillamook Volcanics in the Green Mountain outlier (see Paleomagnetism of the Tillamook Volcanics, p. 48-52) indicates that these upper Eocene volcanics and the overlying Cougar Mountain intrusives (Rarey, in prep.) have been rotated clockwise 48$\pm$26°. This amount of rotation is nearly identical with the 46° of clockwise rotation measured in the lower part of the Tillamook Volcanics in Tillamook County by Magill and others (1981). Much of this rotation must have taken place since the upper Eocene (i.e., since 40 m.y.B.P., the K-Ar age of the volcanics at Green Mountain and near Buster Creek) and perhaps since the Cowlitz Formation was deposited. Thus, the tectonic boundary lies between the Green Mountain - Buster quarry area (the northernmost exposure of the Tillamook Volcanics) and the Columbia River. The age equivalent Goble Volcanics and older Crescent Volcanics north of the Columbia River have been rotated less than 25° (Wells, 1981). The tectonic boundary is covered by younger Tertiary marine sedimentary rocks.

I propose that this boundary manifests itself as distributed shear along a number of sinistral northeast-trending- and dextral northwest-trending oblique-slip faults. Much of the motion along these faults took place since the middle Miocene because these faults offset the major middle Miocene Beneke, Northrup Creek and Fishhawk Falls dikes (Plates 1 and 4; Olbinski, 1983; Goalen, in prep.). Movement on the oblique-slip faults may have caused as much as 69° of clockwise rotation of some small blocks of the dikes. In the Beneke quarry, up to 11° of clockwise rotation can be demonstrated between strike-slip faults which bound very small blocks (see preceding section on paleomagnetism of Miocene basalts).

At present, the dikes follow the western boundary of the northern Oregon Coast Range gravity high. The pre-rotation position of these dikes would be closer to north-south.

To explain the anomalous patterns of rotation of the Goble and Crescent volcanics in southwestern Washington, Wells (1981) suggested that a post-late Eocene north-south shear couple, driven by oblique subduction of the Juan de Fuca plate beneath the North American plate, could cause clockwise rotation between small tectonic blocks bounded by sinistral northwest-trending and dextral northeast-trending faults. This mechanism apparently operated in northwestern Oregon in the sag between the Willapa Hills to the north, which rotated 25° to 30°, and the main Coast Range block to the south, which rotated 46±20° (Magill and others, 1981; this study). This intervening area took up the differential shear between the two microplates or crustal blocks.

Local Structure

Overall, the sedimentary rocks in the thesis area strike northeast and dip gently 10° to 15° north and northwest (Plate 1). This outcrop pattern is part of the western limb of the northward-plunging Coast Range anticlinorium of Niem and Van Atta (1973). The Eocene volcanic rocks, middle and upper Eocene to Miocene sedimentary rocks, and middle Miocene intrusive basalts in the study area are cut by numerous northwest- and northeast-trending faults (Plates 1, 2 and 4). Therefore, the area is broken into many small fault blocks. Drag and tilting associated with the faults has created many anomalous dips and strikes in the sedimentary strata. Slumps and basalt intrusions also cause local variations in the attitudes of the regional northwest dip and northeast-southwest strike of strata.

There are probably more faults than shown on the geologic map (Plate 1) but are not recognized at the surface due to poor bedrock exposure and thick forest and soil cover. Many faults are inferred from offset outcrop patterns, abrupt lithologic changes in sedimentary rocks in short distances along strike, discordant attitudes of bedding, and offset of presumably linear middle Miocene intrusions. However, many faults and gouge zones are recognized and interpreted from offsets of dikes and sills (e.g., Beneke dike) in basalt quarries where the dip and strike of fault planes and the orientations of slickensides can be measured. (These positively recognized faults and straie are designated with solid lines and dip directions on Plates 1, 2 and 4).

The three major middle Miocene basalt dikes in the area (e.g., Beneke, Northrup Creek and Fishhawk Falls dikes) are believed to have been intruded along an older zone of weakness (e.g., joint or fault set) that trends northeast-southwest. It appears from field relations that these dikes initially were straight and offsets along the trend of the dikes are due to post-middle Miocene fault movement. Unfortunately, the dikes are not continuously exposed, although they do hold up linear northeast-trending ridges (see fronticepiece, for example) that appear regionally as straight lineations on ERTS imagery and orthophotographs of the area. However, I recognize that dikes may deviate somewhat from an overall linear trend and that dikes may fill pre-existing fractures in an en-echelon style, or may abruptly change direction and orientation when following a conjugate joint (or fault) set (as in the Eocene Clarno intrusives of eastern Oregon (Taylor, 1981)). Nevertheless, the map pattern of the dikes in the thesis area does not indicate rapid changes of direction. The tacit assumption is that the dikes intruded a northeast-trending linear fracture system. If the assumption is correct, then offset of this linear system, using the vertical dikes as piercing points, is a measure of the amount of horizontal separation along faults.

Summary of Structural Events

At least four periods of deformation are interpreted from the structural relations in the thesis area. The earliest recorded period of deformation in the thesis area occurred during the late Eocene and produced faulting and folding of the Cowlitz, Keasey, and Tillamook formations in the southeastern part of the study area (Plate 1). These faults do not clearly offset younger strata (e.g., Pittsburg Bluff, Silver Point or alluvium). This late Eocene block faulting may have created the northern Coast Range gravity high of Tillamook Volcanics and the Astoria and Nehalem basins. The structural high, in turn, may have influenced the distribution of Cowlitz arkosic sandstone which is thickest in the Nehalem basin and thins against and over this high.

Broad uplift and gentle folding of the Oregon Coast Range in the latest Eocene and middle Oligocene through the early Miocene restricted the marine environment to the western flank of the range (Snavely and others, 1980). The lack of Zemorrian or Oligocene marine strata between the late Refugian Pittsburg Bluff and Saucesian Silver Point member of the Astoria Formation in the study area may reflect this regional uplift, or a later early Miocene unconformity (Peterson, 1984).

A period of northwest-southeast extension during the middle Miocene is interpreted from intrusion of the middle Miocene Beneke and Fishhawk Falls basalt dikes along the northeast linear trend. The dikes intruded a fracture zone that may be older than middle Miocene and that was reactivated in middle Miocene time.

The youngest period of deformation is post-middle Miocene north-south compression. The north-south compressive stress formed a system of conjugate oblique-slip faults that offset older Tertiary rocks and are subparallel to the trend of middle Miocene Grande Ronde dikes. North-south compression also may have created the small east-west striking, northward-dipping thrusts in the Tillamook Volcanics and Vesper Church units, and a faulted fold in the Keasey and Pittsburg Bluff formations in the central part of the study area.

The structural pattern and history are probably more complex than described above. The structural history of the area is difficult to determine because critical outcrops are not continuous. Therefore, individual beds, stratigraphic horizons, and faults cannot be followed laterally and mapped in greater detail. High quality reflection seismic acquisition and interpretation, and additional drilling may improve the subsurface structural picture.

Deformation of Upper Eocene Rocks

Nehalem Valley Fault and related folds. Evidence for north-south compression is present in the southeastern part of the thesis area where a minor thrust and folds are present (sections 20, 21, 26, 27, 28, T5N, R7W). The Nehalem River channel makes an abrupt right-angle bend from south to west as it flows through an uplifted, northward-dipping block of Tillamook Volcanics (Ttv) and continues its course on bedrock composed of less-resistant Cowlitz strata (Tc_2) in sec. 23, T5N, R7W. This right-angle turn and the alignment of the river's course with regional photolineaments (Figure 2, p. 4) suggest that the river may be structurally controlled. Other workers have also interpreted structural control of the river in this area (Newton and Van Atta, 1976; Beaulieu, 1973; Olbinski, 1983).

The best evidence for an east-west fault here is that the Tillamook Volcanics (Ttv) form a resistant east-west linear ridge for several kilometers and the volcanics are in contact with down-faulted and repeated Cowlitz units (Tc_1 and Tc_2) (see Plate 1; Plate 2, cross sections E-E', F-F'). A magnetic profile obtained by proton-precession magnetometer traverses (M.T. 4, Appendix XI and Plate 1) shows an abrupt termination of the magnetic anomaly associated with the Tillamook volcanics basement that is in contact with the Cowlitz strata and suggests that a fault may be present here.

South of the fault zone, attitudes of bedding in the Cowlitz formation differ by as much as 80° from those in the Tillamook Volcanics north of the zone. The Cowlitz formation trends into the Tillamook Volcanics north of the

Buster Creek quarries along the Buster Creek Road (N1/2 sec. 25, T5N, R7W).

There is some field evidence for the fault besides photolineation and repetition of the sedimentary and volcanic units. Several outcrops in the vicinity of the right-angle bend in the Nehalem River display evidence that the fault is a thrust. For example, within the basaltic andesite dikes and epiclastic breccias of the Tillamook Volcanics (Ttv) there is a small thrust near the level of the highway that can be traced several meters (SE1/4, sec. 23, T5N, R7W). Highly sheared fragments of Tillamook basalt caught in the 30-cm-thick gouge zone are slickensided and polished by movement on this smaller thrust fault. This thrust was, perhaps, a subsidiary splay of a larger east-west thrust fault that forms the photolineation (Plate 1). Slickensides in the fault plane indicate an average strike and dip of the plane of N30°E, 26°NW based on a stereonet plot. The orientation of the slickensides in this plane suggests that movement was predominantly horizontal.

Other Cowlitz outcrops in the east-west stretch of the Nehalem River also suggest horizontal shearing and thrust faulting with east-west strike. On the north bank of the river in the SE1/4, SE1/4, sec. 21, T5N, R7W, sandstone beds of the Cowlitz Formation (Tc_2) are sheared by several small, splaying thrusts that are subparallel to the northward dip of the Cowlitz bedding. Slickensides are developed on the bedding surfaces and average 26° plunge to the north. Smooth versus rough step-like surfaces of the slikensides suggest that the upper plate moved toward the south relative to the lower plate. These thrust planes strike N89°E and dip 26°N. An outcrop of similar fine-grained Cowlitz sandstone occurs on a hillside above this locality (above Red Bluff Road in SW1/4, sec. 22, T5N, R7W). Here, the pattern of shearing and bedding plane disruption suggests that shearing occurred nearly parallel to the east-west strike and gentle northward dip of the bedding.

From these shear patterns, orientations of slickensides, and the repetition of Tillamook Volcanics overlying the younger Cowlitz Formation (Tc_2; Plate 2, cross sections E-E', F-F'), I interpret that a larger low-angle thrust fault occurs nearby. The magnitude of shearing suggests that the sole of the thrust is not observed; rather, the deformed Cowlitz Formation and sheared Tillamook Volcanics are part of an upper plate of a larger thrust occurring at shallow depth (Plate 1). The structural interpretation is that this thrust developed on the north limb of an asymmetric anticline (Plate 2, cross section E-E'). As the fold verged to the south, the north limb failed and part of the axis of the fold was overridded by the upper plate. The anticlinal axis and an associated syncline (located in the S1/2, sec. 30, T5N, R7W) are shown on Plate 1. The orientations of these folds and the fault suggest north-south compression. The main thrust plane is not exposed in the Nehalem River Valley as it is covered by stream alluvium. However, the smaller thrust faults described above mimic the east-west trend. The name herein given to the structure is the Nehalem Valley Fault.

Following the strike of the Nehalem Valley Fault to the east, structural shortening appears to be absorbed on several splays of the fault in Cowlitz strata in the Buster Creek area (Olbinski, 1983). One splay trends across the north flank of Green Mountain where it is mapped as a thrust fault, but here the fault yields to the north (Olbinski, 1983) and may actually be separate fault within the larger fault zone. Olbinski believed that the straight lineation of the Nehalem River Fault is not typical of an eroded thrust fault and so mapped the continuation of this fault as a right-lateral fault, yet had no field evidence of dextral motion.

The age of the thrusting is difficult to determine from surface exposures alone. It definitely post-dates the Cowlitz Formation because it cuts Tillamook Volcanics and Cowlitz strata but it may precede deposition of the Keasey Formation because there is no positive evidence that it cuts the Keasey Formation on the surface. However, the photolineation (shown on Plate 1) suggests that a continuation of this fault may offset the Keasey Formation and the middle Miocene Beneke dike. Thus, it is likely that this thrusting is related to, or was reactivated by, the north-south compression that also created the system of northwest-southeast trending oblique-slip faults (described in detail in the following text). The amount of post-middle Miocene stratigraphic throw, based on offset of volcanic and sedimentary units appears to be small on these thrusts, perhaps 30 meters or less. This study and Olbinski's study (1983) are the first to present evidence of thrusting in the northern Oregon Coast Range in the region of a major tectonic boundary between two microplates that comprise the Oregon and Washington Coast Ranges.

Little Fishhawk Creek Fault. A major west- to northwest-trending oblique-slip fault offsets the members of the Keasey Formation and Pittsburg Bluff Formation in the central part of the map area (Plate 1). This fault is herein called the Little Fishhawk Creek Fault because it is subparallel to the winding course of Little Fishhawk Creek. Calculations based on cross sections through the fault indicate approximately 650 m of dip-slip separation and 2400 m of sinistral strike-slip separation (cross sections D-D', H-H' and G-G'). The north side of the east-west-trending fault where it offsets the Jewell and Vesper Church members (Tk_1 and Tk_2) is upthrown. This part of the fault was active prior to Pittsburg Bluff time and may be related to a relatively brief period of regional extension during the late Eocene (Refugian). The fault is interpreted to have been reactivated since Pittsburg Bluff time (i.e., late Refugian) as the lower contact of the formation (Tpb) and the middle Miocene Beneke and Fishhawk Falls basalt dikes are offset approximately 200 m in a right-lateral sense on the northwest-trending part of the fault. This right-lateral offset on a northwest-trending fault is probably related to north-south compression and post-middle Miocene deformation.

Alternatively, the east-west-trending part and the northwest-trending part of the Little Fishhawk Creek Fault may be two different faults; one with post-middle Miocene strike-slip motion (northwest-trending), and the other with pre-Pittsburg Bluff (Eocene) normal-slip motion (E-W-trending).

Folds. A broad, gentle, northwest-trending anticline (now faulted) occurs in the center of the map area and is recognized by the arcuate outcrop pattern of the Keasey and Pittsburg Bluff units (Plate 1; cross section D-D', Plate 2). This fold probably formed in response to northeast-southwest compression in the middle Oligocene to early Miocene. Unfortunately, the random attitudes of these units do not confirm an anticlinal structure. The randomness of the attitudes is probably due to complex post-middle Miocene strike-slip faulting which locally tilted and broke the limbs of the fold in several directions. Peterson (1984) recognized the continuation of the arcuate outcrop pattern in her thesis area along the northwest strike of the fold axis.

The age of folding is thought to be pre-middle Miocene because the middle Miocene sills that cut across the anticline do not appear folded (Mike Navolio, pers. comm., 1982; cross section D-D', Plate 2) whereas the late Refugian-early Zemorrian Pittsburg Bluff (late Eocene to early Oligocene) and older units are folded. Peterson (1984) and Cooper (1981) noted an unconformity between the marine units of the lower Miocene Astoria Formation (e.g., Big Creek and Silver Point members) and the underlying Oligocene Oswald West and upper Eocene Keasey and Pittsburg Bluff formations. Perhaps this early Miocene unconformity formed during the time of folding and northeast-southwest compression. A regional nonconformity occurs between the Columbia River Basalt and the Keasey, Pittsburg Bluff, Oswald West and Astoria formations (Penoyer, 1977; Cooper, 1981; Murphy, 1981).

Alternatively, the arcuate outcrop pattern could be the result of post-middle Miocene vertical uplift between several northwest-trending extensional faults in the Tillamook Volcanic basement and the fold reflects the drape of sedimentary units over the rigid basement fault blocks. Kadri (1982) used such a mechanism to explain a similar pattern of conjugate northwest- and northeast-trending faults, an anomalous distortion of bedding attitudes, and the general lack of traceable fold axes in a study area near the Columbia-Clatsop county line, 9 km to the east.

A third possibility is that the arcuate outcrop pattern of the Keasey and Pittsburg Bluff units is due to varying magnitudes of oblique-slip on northwest-trending right-lateral faults. Offset on a series of subparallel faults could produce this apparent structure. However, I do not favor this third hypothesis because the middle Miocene Beneke, Fishhawk Falls and Northrup Creek dikes do not reflect a similar arcuate outcrop geometry although the dikes are offset by these faults.

Deformation of Dikes

Since the late middle Miocene, the area has undergone north-south compression. This compression is related to that occurring across the Columbia Plateau since the late middle Miocene. Quarry exposures of the middle Miocene basalt dikes in the thesis area provide clues to the complex and intense nature of the deformation (Plates 1 and 4). The Beneke quarry (NE1/4, NE1/4, sec. 14, T6N, R7W), for example, was mapped in detail (1:600) to gain an understanding of the post-middle Miocene structural style (Plate 4). Excavation of more than 0.5 km of outcrop in the active quarry provided unparalleled fresh exposures for observation of offset relations of the contacts between the Beneke dike and Oswald West sedimentary rocks as well as exposing many fault gouge zones and slikensides (Plate 4).

Proton-precession magnetometer traverses (M.T. 1, 2, 3) were made normal to the dike in order to learn the magnetic profile of the dike. The traverses were useful to show the existence and continuation of unexposed parts of the dike to the south of the quarry (M.T. 3). These traverses, and others, are presented in Appendix XI.

The margins of the dike in the Beneke quarry are part of a major northeast-trending shear zone. The shear zone on the northwest side of the 30-m-wide dike produced the widest gouge zone (up to 3.5 m wide) with 2 m diameter phacoidal blocks of basalt caught in the zone (Fig. 45 and Plate 1). Thinner zones (<1 m wide) of gouge and shear occur along the southeast contact of the dike with Oswald West mudstone. The zone trends N37-40°E, which is slightly oblique to the N35°E trend of the dikes. The fault plane dips 50°SE. Large subhorizontal slickensides occur on the footwall of the fault plane and plunge 20° to 35°N on the plane. Slip therefore appears to have been in an oblique sense along the major shear. "Steps" developed on the slickensides and the sense of offset of the west wall of the Beneke dike and Oswald West mudstone indicate left-lateral separation (Plate 4).

Figure 45. Photograph of the gouge and shear zone in the middle Miocene Grand Ronde (Tiht) basalt dike in Beneke quarry (NE1/4, NE1/4, sec. 14, T6N, R7W). Note hammer for scale, 15 cm long.

At the south end of the quarry, the 25-30-m-wide dike and shear zone are abruptly terminated by another oblique-slip fault which trends N50-60°E and dips 66°SE. The exposed fault plane has subhorizontal slickensides with 0.25 to 0.5 m of gouge (Plate 4). Right-lateral separation of more than 200 m has displaced the dike to the southwest. No outcrops of the basalt were found in the forest hillsides south of the fault at the south end of the Beneke quarry, but magnetometer traverses and float of basalt indicate the presence of the dike in the subsurface and support the indicated separation.

Since the contacts of the Beneke dike are nearly vertical they can be used as piercing points, and along with the subhorizontal slickensides, suggest predominantly strike-slip motion with subordinate dip-slip component on these northeast-trending faults.

Orientations of faults and fractures mapped in Beneke quarry are used to determine the principle stress orientations that caused this deformation. The sterogram in Fig. 46 shows the contoured distribution of s-poles for these fault and fracture planes and the orthogonal stress axes. The maximum compressive stress (sigma 1) is oriented 23°N, N20°W and the least compressive stress (sigma 3) is oriented 23°SW, S70°W.

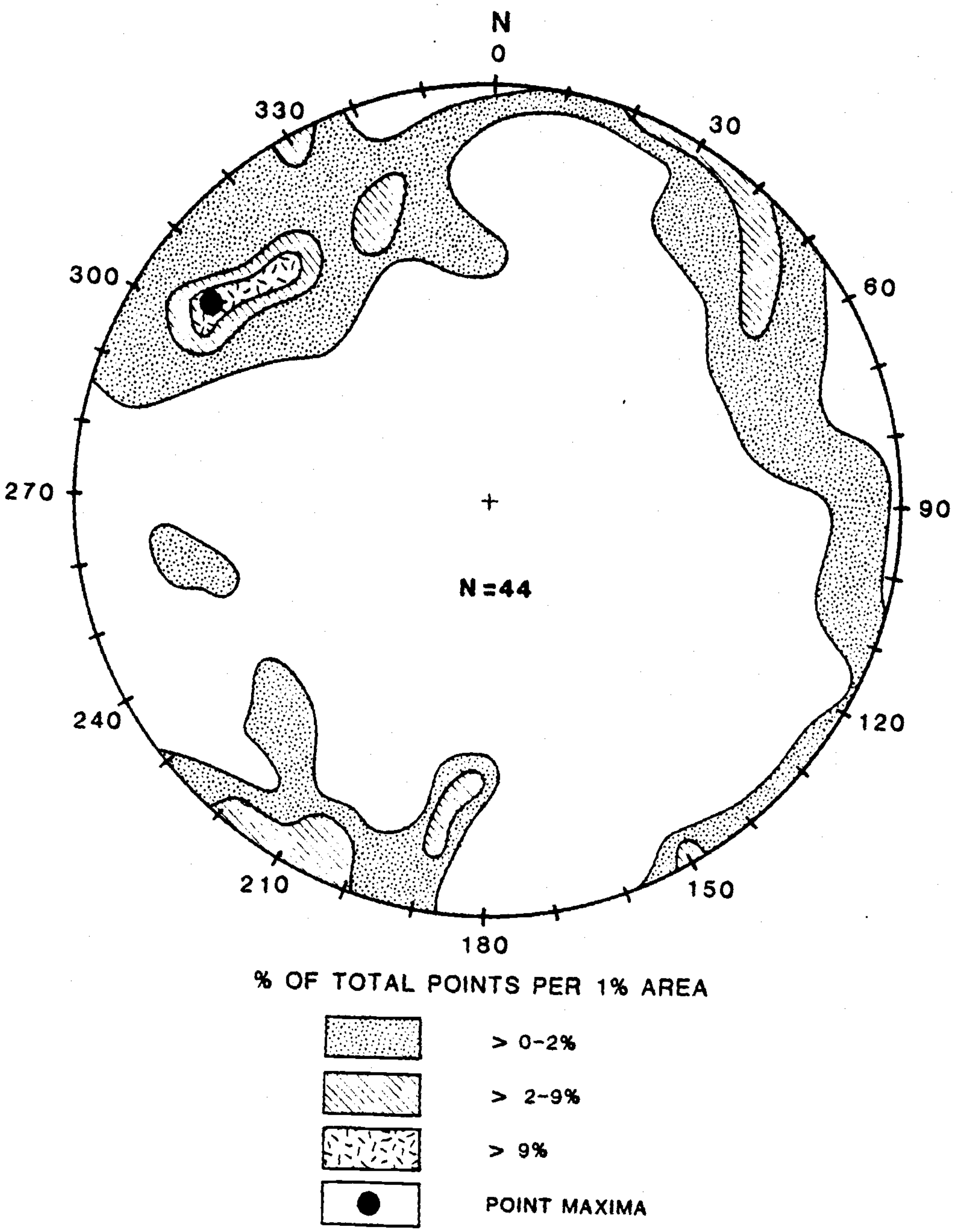


Figure 46. S-pole stereogram of fault and fractures in the Beneke quarry. The contoured data show two nearly orthogonal fracture sets oriented NE and NW.

Numerous second order faults trending northwest and northeast offset the N37-40°E trending shear zone in right-lateral and left-lateral senses, respectively. Horizontal separation on the second order faults ranges from several cm to 10 m. These second order faults intersect at nearly 90°. Other subordinate fractures and small faults form acute angles with these second order faults. These fractures and small faults trend east-west (generally right-lateral offset) and northeast-southwest, intersecting the major N37-40°E trending shear at an acute angle (generally with left-lateral offset). The pattern of northwest-trending dextral slip and northeast-trending sinistral slip on these faults suggests a conjugate shear system developed in response to north-south compression that has occurred since the intrusion of Grande Ronde dikes 14-16 m.y.B.P.

Similar northwest and northeast orientations of strike-slip faults with gouge zones were observed in several other quarries on the Beneke dike trend. Probably the Fishhawk Falls dike has a similar style of deformation but the basalt-sedimentary rock contacts are not as well exposed as are the basalt-sedimentary rock contacts of the Beneke dike. Olbinski (1983) and Goalen (in prep.) mapped similar right-lateral northwest-trending and left-lateral northeast-trending faults cutting the subparallel Northrup

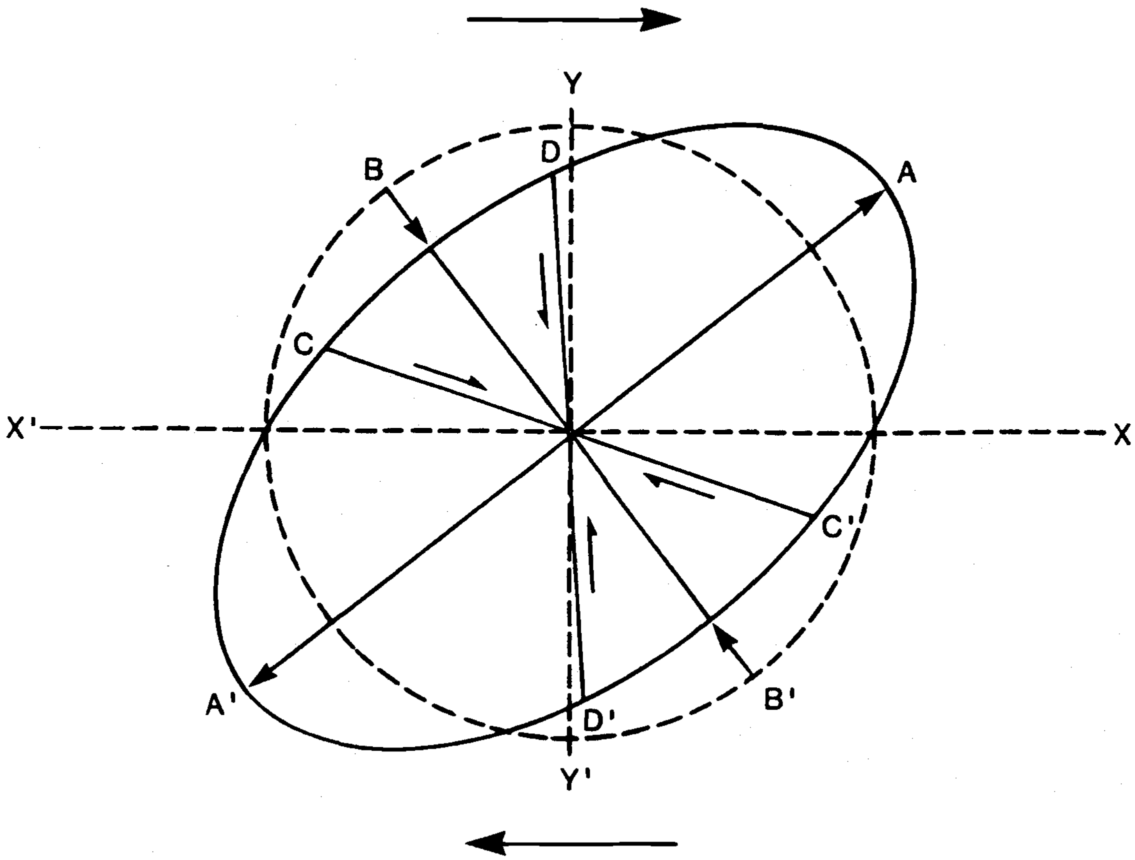
Creek dike and northern continuation of the Beneke dike, respectively.

The pattern of northwest-trending right-lateral and northeast-trending left-lateral faults is extended to the rest of the map area where offsets are also indicated by the sedimentary units and where strikes and dips of proximal outcrops are discordant. Because of the overall poor exposures and weathered nature of the sedimentary units, mapping of the faults is also aided by field checking lineations observed on high-altitude U-2 aerial photography and ERTS satellite imagery.

Apparently, the post-middle Miocene style of deformation is very widespread in northwest Oregon. A similar structural style is observed in areas to the east (Olbinski, 1983), north (Goalen, in prep.), west (Peterson, 1984; Coryell, 1978), and south (Mumford, Rarey, and Safley, all in prep.). The pattern may almost extend to the Columbia River 25 km north of the study area, which has been postulated as a major tectonic boundary between two rotating plate fragments that were accreted to the North American plate; (Beck and Plumley, 1980; Magill and others, 1981, 1982). Wells (1981) has also mapped a similar conjugate system of post-middle Miocene faults in the Willapa Hills on the north side of the Columbia River in southwest Washington.

The observed conjugate fault pattern is remarkably similar to the pattern of conjugate strike-slip faults that form in wrench fault zones and can be depicted in a strain ellipse (Wilcox and others, 1973). Clay models that were used to simulate deformation of rocks in a wrench system show that a consistent development of faults and en echelon folds. Conjugate strike slip faults with left-lateral and right-lateral separation are an integral part of the wrench system and form at acute angles to the strike of the wrench zone (Fig. 47). If this basic wrench model is applied to the structure of the thesis area then we may expect to find that the northwest-trending dextral-slip faults and northeast-trending sinistral-slip faults are developed in response to a larger zone of strike-slip motion or wrench system that has affected the study area.

I interpret that the pattern suggests a distributed shear zone (or shear couple) of northeast- and northwest-trending strike-slip faults with subordinate dip slip in the 25 km x 35 km area between the Tillamook highlands (e.g., the Green Mountain outlier) and Nicolai Mountain just south of the Columbia River. Murphy (1981) showed that Nicolai Mountain is a nearly unfaulted, north-dipping homoclinal sequence of Columbia River basalt and is apparently unaffected by shear strain. The interpretation implies that the tectonic boundary between



STRAIN ELLIPSE

Figure 47. Strain ellipse depicting relation of conjugate strike-slip faults to larger scale wrench motion (after Wilcox and others, 1973); strike of wrench zone (X-X'), conjugate strike-slip faults (C-C' and D-D'), axis of maximum extension and orientation of fold axes (A-A'), axis of maximum compression and strike of tension joints or normal faults (B-B').

the Oregon Coast Range and the Washington Coast Range is a diffuse zone of shear spread across the 25 km x 35 km area.

This interpretation is important to current petroleum exploration in Clatsop County and in the Mist gas field, which is within this wide distributed shear zone. In addition to the folding (or arching) of subsurface Tertiary strata on the Mist anticline (Newton, 1976, 1979), numerous post-middle Miocene oblique-slip faults may offset gas-prone structural highs targeted along northwest trends parallel to the Mist structure. Potential Cowlitz sandstone reservoirs may have been disrupted by the faulting and broken in several reservoirs at different elevations. Many may have leaked gas due to faults and fractures through the reservoir.

This fault zone may represent a shear zone between two rotating microplates (i.e., the ball bearing hypothesis of Beck, 1976). This tectonic pattern may be much more widespread, affecting much of western Oregon and southwestern Washington. For example, Wells (1981, 1982) mapped and described a conjugate system of northwest-trending right-lateral and northeast-trending left-lateral faults in the Willapa Hills of southwest Washington. They suggest this conjugate fault system also occurs in the Tillamook highlands (Wells and others, 1983), in the Newport, Oregon area (Snavely and others, 1976a, 1976b, 1976c), and in the western Cascades (Hammond and others, 1980, 1982). Wells (1981, 1982) and Wells and Coe (1979) suggested that these conjugate strike-slip faults were formed as Reidel shears in response to north-south compression created by oblique subduction of the Juan de Fuca plate beneath the North American plate. This regional stress also may explain the origin of, or reactivation of, the small east-west thrust faults such as the Nehalem Valley Fault in the thesis area.

Kadri (1982) suggested that the lack of compression features (e.g., folds) and near horizontal bedding in the sedimentary units in the area near the Columbia-Clatsop county line and the Mist gas field imply mainly vertical block faulting of the basement volcanics as a cause of the intense conjugate system of normal(?) or high-angle faults. However, the abundance of subhorizontal slickensides on many of these faults and offset of dikes as piercing points suggest that north-south compression, not vertical block faulting, is responsible for this deformation. Kadri (1982), in all due respect, had only sedimentary rock exposures and lacked basalt dikes and basalt quarries with well-preserved slickensides and gouge zones to observe the relationships mapped here.

GEOLOGIC HISTORY

The Oregon Coast Range represents a slab of accreted Tertiary oceanic crust, a Paleogene accretionary prism, and a Paleogene-Neogene forearc basin located seaward of an active Western Cascade volcanic arc (Niem and Niem, 1984; Magill and others, 1981; Niem, 1976; Hammond, 1979). The core of the northern Oregon Coast Range is composed of middle to upper Eocene Tillamook Volcanics and underlying lower to middle Eocene Siletz River Volcanics (Wells and others, 1983). The Siletz River Volcanics are similar in chemical composition to oceanic ridge basalts and are interpreted to have formed at a spreading center (Snavely and others, 1980). Subsequent volcanism constructed guyots, seamounts, and some subaerial oceanic islands that may have included the lower Tillamook Volcanics on top of the oceanic tholeiitic basalt basement.

In the southern Oregon Coast Range during the early to middle Eocene, oceanic basalts were thrusted and rotated clockwise beneath the North American continental margin (i.e., Klamath Mountains) as the Farallon oceanic plate collided with North America (Snavely and others, 1980; Niem and Niem, 1984; Simpson and Cox, 1977; Pertuu and Benson, 1980). The zone of underthrusting (now buried beneath younger volcanics) probably continued northward and may have initially coincided with the present-day axis of the Cascade

Range. The subduction zone is hypothesized by Magill and others (1981) to have jumped westward by late middle Eocene to its present position eastward of the Oregon continental shelf. This westward jump may have occurred as the buoyant, seamount-studded oceanic crust clogged the subduction zone. Paleomagnetic studies of lower to middle Eocene sedimentary and volcanic rocks indicate that the westward jump of the zone was accompanied by the initiation of clockwise tectonic rotation (adding up to a maximum of 75° to the present) and accretion of the Coast Range microplate during the the late middle Eocene (Magill and Cox, 1981; Magill and others, 1981).

Following accretion, more than 7,000 m of clastic marine sedimentary rocks of the Tyee, Flournoy, and lower Yamhill formations accumulated as submarine fans, deltaic complexes, and deep bathyal muds, respectively, in a late middle Eocene forearc basin that formed east of the active subduction zone (Chan and Dott, 1983; Snavely and others, 1980). These formations are now exposed in the central part of the Oregon Coast Range and overlie the Siletz River and Roseburg volcanic basement. The sediments were derived from Mesozoic metamorphic, volcanic, and plutonic rocks of the Klamath Mountains exposed to the south and southeast (Snavely and Wagner, 1963; Snavely and others, 1964) and from the Idaho batholith to the east of the Oregon Coast Range (Heller and Ryberg, 1983).

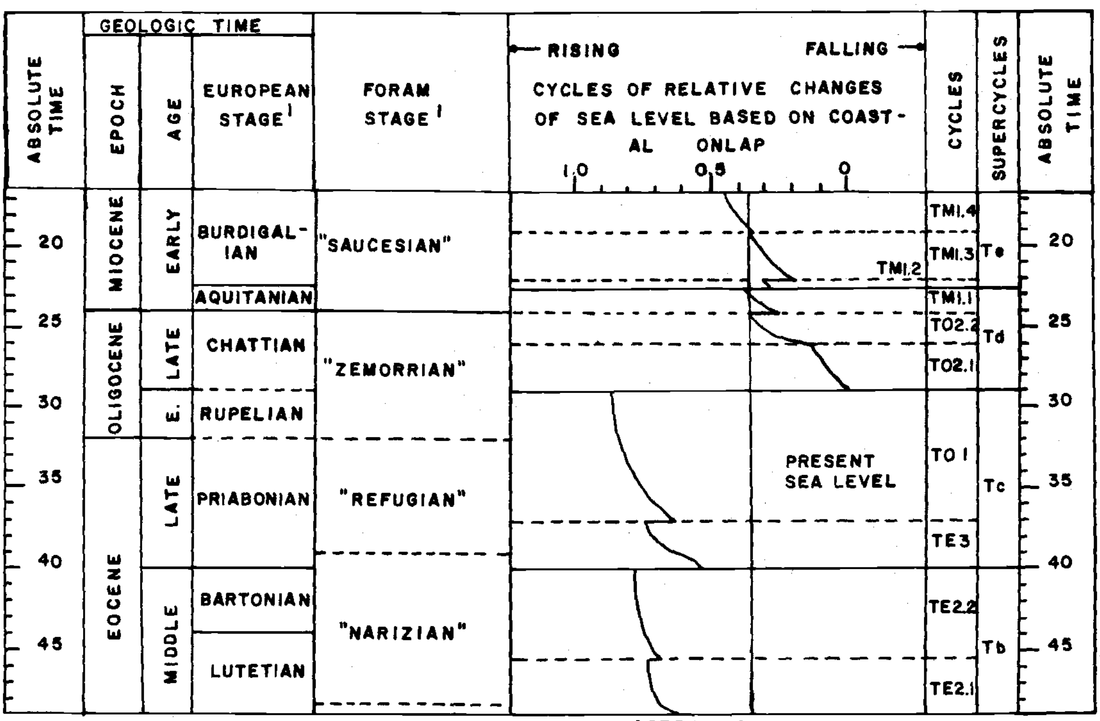
In the middle to late Eocene (45 to 39 m.y.B.P.) a thick sequence of submarine to subaerial mafic volcanics (several thousand feet thick) built up as a differentiated oceanic island complex of shield volcanoes upon the Tyee-Yamhill mudstones and Siletz River volcanics in the northern Oregon Coast Range (Cameron, 1980; Jackson, 1983; Rarey, in prep.). This sequence is known as the Tillamook Volcanics (Wells and others, 1983). In the study area, they consist of subaerial flows, intrusives, and epiclastic debris flows and breccias of basaltic andesite and andesite, all representing the upper part of this differentiated oceanic island. Duncan (1982) suggested that the Tillamook Volcanics may have formed as an oceanic island over a hot spot or mantle plume beneath the Farallon plate (now represented by the Siletz River Volcanics). During or soon after the late Eocene accretion of the Farallon plate to the North American continent, tectonic rotation of these volcanics commenced and accumulated up to 45° clockwise rotation to the present as suggested by paleomagnetic studies of the Tillamook Volcanics (Magill and others, 1982; this study).

Following a period of erosion, the ancient Cowlitz basin developed on top of the Tillamook Volcanics in northwest Oregon during the late middle to late Eocene (Narizian Foraminiferal Stage). A delta, analogous to the present-day Columbia River delta, was formed by rivers entering the southwest Washington part of this basin

(Snavely and Wagner, 1963). Coal and lignite deposits in upper middle to upper Eocene strata in southwest Washington (Yett, 1979; Henriksen, 1956) indicate that warm subtropical climatic conditions favored development of thick swamp vegetation. Rivers flowed across the Pacific Northwest and formed a broad coastal plain that included a large part of the eastern Puget Sound and the Willamette Valley (Dott, 1966; Snavely and Wagner, 1963). Several rivers meandered across this coastal plain and entered the Cowlitz basin near the southern Puget Sound (Buckovic, 1979) and near Longview, Washington (Henriksen, 1956). The upper middle to upper Eocene coal-bearing deposits indicate that this area also received large volumes of arkosic deltaic sediment at that time, perhaps derived from the Mesozoic granitic batholiths of the northern Rocky Mountains (Snavely and others, 1951; Henriksen, 1956; Livingston, 1966; Buckovic, 1979).

In northwest Oregon, west of Longview, Washington, the depositional environment was shallow marine and marginal marine. There is no evidence of coal and lignite that would suggest a swamp environment like that which occurred in southwest Washington. Highland areas were located to the south where the accreted Tillamook Volcanics were exposed as an irregular coastline of rugged seacliffs and stacks. Local fluvial basaltic sands and gravels and debris flows derived from the rugged Tillamook highlands were deposited unconformably over the eroded Tillamook Volcanics as near-shore and inner shelf sand, and as stream terrace and marine gravels to form the basal Cowlitz conglomerate (Tc_1). Littoral drift parallel to this late Eocene shoreline redistributed the fine arkosic sands from the Cowlitz delta near Longview, Washington and perhaps to the southeast along the shallow inner shelf. These transported arkosic sands were deposited immediately offshore from the basal basaltic gravels. In Columbia and eastern Clatsop counties, these arkosic sandstones are interbedded with locally derived, shallow-marine, well-sorted volcanic sandstones. These interbedded arkoses and volcanic arenites compose the lower sandstone member of the Cowlitz Formation (Tc_2) in the thesis area and reflect a gradual transgression over the basal conglomerate.

As the Nehalem-Astoria basin subsided further, turbidite arkosic sands and muds from the Cowlitz delta were deposited in this area of southeastern Clatsop County, forming a turbidite unit (Tc_3). The Tillamook high was eventually submerged beneath the Cowlitz sea and no longer served as a source for basaltic sand. A minor regression allowed longshore currents to transport shallow-marine cross-bedded arkosic sands into the basin to form the upper Cowlitz sandstone (Tc_5) which is probably related to the Clark and Wilson sand that produces gas at the nearby Mist field. This regression recognized in the Cowlitz Formation may record the global regression or eustatic sea level fall noted by Vail and Hardenbol (1979) between their cycles TE2.2 and TE3 (Fig. 48).



AFTER VAIL AND HARDENBOL, 1979.

[1] STAGES & EPOCHS ARE TIED TO THE ABSOLUTE SCALE USING THE MODIFICATION OF ARMENTROUT (1981).

Figure 48. Coastal onlap cycles.

Near the close of Cowlitz time (late Eocene), a 1500-m-thick pile of tholeiitic and calc-alkaline Goble Volcanics was erupted from local vents near Kelso - Longview, Washington and the Goble and Rainer area, Oregon (Wilkinson and others, 1946). Subaerial basaltic lavas and breccias are interbedded with strata of the upper Cowlitz Formation in southwest Washington and northwest Oregon (Niem and Van Atta, 1973; Henriksen, 1956). Local volcanic sands derived from weathering of the lavas were also deposited in the shallow Cowlitz basin. Beck and Burr (1979) indicate that the type Goble Volcanics may be the initial stage of volcanic arc activity on the western edge of the Western Cascade volcanic arc (Jakes and White, 1972). The Goble Volcanics of southwest Washington (e.g., Willapa Hills area; Wells, 1981) may be the same age as the upper Tillamook Volcanics in the thesis area. Thus, it is possible that the sandstone members of the Cowlitz Formation in the thesis area that overlie the Goble-correlative Tillamook Volcanics are younger than the type Cowlitz and were derived, in part, by redistribution of the older type Cowlitz deltaic sediments from southwestern Washington.

A renewed period of underthrusting in the middle late Eocene (Refugian Foraminiferal Stage) is indicated by offshore seismic reflection data and geologic mapping in the central Oregon Coast Range (Snavely and others, 1980). Less-deformed tuffaceous mudstone of the Refugian Alsea Formation unconformably overlie more-deformed Narizian

Nestucca mudstone, Yachats Volcanics, and equivalent offshore marine rocks of Narizian age. The middle Eocene forearc basin, once continuous along the Oregon continental margin, was segmented into several shelf basins during the late Eocene by the deformation of Nestucca mudstone and the upper Tillamook and Yachats volcanics (Snavely and others, 1980). These subsequent smaller marine shelf basins received tuffaceous clastic sediment and ash from the developing western Cascade volcanic arc (Niem and others, in press; Snavely and others, 1983). Thus, the deformation of pre-Refugian strata during the middle late Eocene is inferred to be the result of underthrusting on east-dipping low-angle faults (Snavely and others, 1980). Some east-west thrusts in the upper Tillamook Volcanics and Cowlitz Formation (e.g., the Nehalem Valley Fault) may have formed due to north-south compression at this time in response to oblique collision of the lithospheric plates and underthrusting of the oceanic plate.

During the Refugian, the Astoria-Nehalem basin subsided following a period of erosion of the upper Cowlitz strata in the thesis area. Tuffaceous bathyal marine sediments of the Keasey Formation were deposited unconformably over the turbidite and inner shelf arkosic sandstone members (Tc_4 and Tc_5) of the Cowlitz Formation. Benthic foraminiferal paleoecology suggests water depths of up to 500 m (i.e., upper continental slope) during deposition of the Keasey Formation. Since the Refugian is presently referred to the upper Eocene (Armentrout, 1981), the marine transgression recorded in the Refugian strata may be related in part to global eustatic sea level rise during the late Eocene. This eustatic rise may be correlated to cycle TE3 of Vail and Hardenbol (1979) (Fig. 48).

In the thesis area, the Refugian is represented by the Keasey Formation and by the lower part of the Pittsburg Bluff Formation. The Keasey Formation is more tuffaceous in character than the underlying Cowlitz Formation and it records an influx of volcanic material into the forearc basin. The volcanic detritus was probably produced by explosive silicic volcanic activity in the ancestral Western Cascade arc (e.g., the Little Butte Volcanics and Ohanapecosh Formation) (Hammond, 1979; Niem and Niem, 1984; Wells and others, 1964) and by the pyroclastic volcanism that produced the John Day Formation of north central Oregon (Oles and Enlows, 1971; Niem and Niem, 1984).

A deep-marine basin persisted throughout Keasey time in the study area but there were rapid facies changes as a result of changing source areas, basin subsidence, or eustatic changes. The following three facies (or members) of the Keasey Formation represent an onlap sequence of deep-marine upper slope mudstone over shelf sandstone (Tc_5) of the underlying Cowlitz Formation. Deposition of well-bedded hemipelagic mudstone of the Jewell member (Tk_1) occurred at 200 to 500 m water depths on the upper continental slope (foram data from Kristin McDougall, written comm., 1982). Arkosic clastic dikes formed by rapid loading and spontaneous liquefaction of rare arkosic sands in the Jewell member (Tk_1) of the Keasey Formation.

Continuing basin subsidence to depths up to 2,000 m occurred during slow deposition of the overlying Vesper Church member (Tk_2) on the lower and middle continental slope. The lack of bioturbation and infauna (e.g., lack of molluscs) suggests that basin depths caused anoxic conditions at the sediment-water interface. This anoxic environment, or oxygen minimum zone, occured only during deposition of the Vesper Church member and did not occur during deposition of any other Tertiary sedimentary unit within the Nehalem and Astoria basins. Thin carbonaceous and micaceous arkosic sandstone laminae and thin, graded, arkosic sandstone beds that are distinctive to the Vesper Church member (Tk_2) were possibly derived from erosion of older, inner shelf Cowlitz arkosic sandstone. Nested channels of sandstone and interbedded mudstone in the Vesper Church (Tk_2) member were deposited on small "sea gullies" cut into the lower continental slope or were small distal fans.

Deposition of the overlying tuffaceous upper mudstone member of the Keasey Formation (Tk_3) in water depths of 200 to 500 m implies a shallowing of the basin as toward the end of Keasey time. Ash beds and thick-bedded tuffaceous mudstone in the upper mudstone member (Tk_3) imply a more extensive silicic volcanic sediment influx from the Western Cascade volcanic arc and rapid infilling of the basin.

A major regression of the sea is recorded during the latest Eocene (late Refugian). The depositional environment of the late Refugian - Zemorrian Pittsburg Bluff was significantly shallower than that of the older Keasey Formation. Tuffaceous to arkosic Pittsburg Bluff sandstone and siltstone disconformably overlie the thick-bedded, bioturbated, deeper-marine upper Keasey mudstone (Tk_3) in the study area and were deposited on the middle to outer shelf. The maximum water depth during Pittsburg Bluff deposition in eastern Clatsop County was 200 m as inferred from molluscan paleoecology (Moore, written comm., 1982). Uplift or warping of the basin prior to Pittsburg Bluff time combined with eustatic lowering of sea level (end of cycle TE3, Vail and Hardenbol, 1979; Fig. 48) probably contributed to the offlap of the Pittsburg Bluff marine facies. Silicic volcanism continued in the Western Cascades arc (e.g., Little Butte Volcanics and Ohanapecosh Formation) and contributed tuffaceous sand and silt to the Pittsburg Bluff Formation. Abundant bioturbation and lack of sedimentary structures suggest a slow sedimentation rate and deposition on the middle to outer shelf.

Deposition of the lower part of the Oswald West mudstone on the upper slope to the west of the study area was coeval with deposition of the Pittsburg Bluff sand on the middle to outer shelf in eastern Clatsop County. During the Oligocene (Refugian to Zemorrian), this deep-marine facies onlapped part of the Pittsburg Bluff shelf sandstone, reflecting renewed subsidence. The west-to-east eustatic marine transgression can be correlated to global cycle TO1 of Vail and Hardenbol (1979) (Fig. 48). To the east of the study area, the upper Oligocene to middle Miocene Scappoose Formation was deposited as a prograding, high-energy, delta system which included inner shelf, marginal marine and fluvial facies (Niem and Van Atta, 1973; Van Atta, 1971).

A major unconformity formed near the end of Oligocene time. A significant fall in sea level is recognized worldwide in the middle Oligocene. Vail and Hardenbol (1979) chose this fall as the boundary between their supercycles Tc and Td (Fig. 48). This low stand of the sea in the middle Oligocene (approximately 29 m.y. ago) is the lowest sea level for all the Phanerozoic (Vail and Mitchum, 1979). In northwest Oregon, however, the major unconformity occurs between Oswald West mudstone and the lower to middle Miocene Astoria Formation which is nearer to the early Miocene than the middle Oligocene. However, disagreement between the stages of the European and North American Paleogene System may in part contribute to the disparity of age of the unconformity.

Broad epeirogenic uplift of the eastern part of the Coast Range began during the middle Oligocene (Snavely and others, 1980). Consequently, most upper Oligocene to lower Miocene marine strata were deposited only on the western flank of the Oregon Coast Range. This restricted deposition is represented by the upper part of the Oswald West mudstone and by the Yaquina delta and Nye Mudstone in the central Coast Range (Snavely and others, 1964; Goodwin, 1973). Although the Oswald West occurs only in small patches in the thesis area, the formation crops out over much of the western part of Clatsop County (Peterson, 1984). This deep-marine, upper slope, Oligocene to lower Miocene mudstone may have been more continuous throughout the northern part of the Coast Range but was subsequently removed during development of the early Miocene erosional unconformity and prior to deposition of the lower Miocene Astoria Formation. Deltaic and fluvial facies of the lower to middle Miocene Scappoose Formation were deposited unconformably on the Oswald West mudstone on the east flank of the Coast Range uplift (Kelty, 1981).

Deposition of the Astoria Formation occurred during late early Miocene (Saucesian or Pillarian; Fig. 5). The Angora Peak member of the basal Astoria Formation and Scappoose Formation formed a westward prograding fluvial-deltaic system (Cooper, 1981; Cressy, 1974). Lateral and overlying marine facies of the Astoria Formation include the shallow-marine Big Creek sandstone member to the north and the transgressive deep-marine hemipelagic mudstone and turbidite facies of the Silver Point member to the south (Cooper, 1981; Neel, 1976). The submarine channel or canyon head facies associated with the turbidites is informally referred to as the Pipeline member of the Astoria Formation (Coryell, 1978; M. Nelson, 1978). The deep-marine Silver Point member is the only facies of the Astoria Formation in the thesis area. It was deposited disconformably on the the shelf sandstones of the Pittsburg Bluff Formation. Apparently, the shallow-marine Big Creek and Angora Peak facies were never deposited in this area or were eroded away prior to deposition of the Silver Point facies (Peterson, 1984).

Snavely and others (1973, 1980) suggested that during the middle Miocene a period of regional extension and mafic igneous activity occurred in the western Oregon Coast Range. Local tholeiitic basalts, generated by partial melting of mantle rocks, were intruded into Paleogene and Neogene marine strata in the western Oregon Coast Range. Along the Astoria marine embayment, thick extrusive breccias and pillow lavas of the middle Miocene tholeiitic Depoe Bay basalt constructed submarine volcanic edifices (Penoyer, 1977; Cressy, 1974). Onion Peak, Sugarloaf Mountain, Kidders Butte, Humbug Mountain, Saddle Mountain, Elk Mountain, and Wickiup Mountain are erosional remnants of these piles of basaltic pillow lavas and breccias. Some of these peaks are northeast-trending (N45-50°E; e.g., Humbug, Saddle Mountain and Elk Mountain) and contain northeast-trending dikes. That is, they are nearly parallel to the three long dike systems (Beneke, Fishhawk Falls, and Northrup Creek) discussed in this study area. These northeast-trending dikes may be related to an older fracture zone of either joints or faults developed prior to the middle Miocene. The volcanic activity in the western Oregon Coast Range signifies regional east-west extension during a period of relaxed or slower rate of subduction (Snavely and others, 1980).

Simultaneous with the submarine extrusive and intrusive magmatic activity near the Oregon coast, great volumes of the Columbia River tholeiitic flood basalt were erupted in the tri-state area of Idaho, eastern Oregon and eastern Washington. During 16 to 14 m.y.B.P., Grande Ronde and Frenchman Springs basalt poured out of fissures on the Columbia plateau. Some of the most voluminous Grande Ronde and Frenchman Springs flows reached western Oregon via the middle Miocene Columbia River drainage system through the western Cascades (Beeson and others, 1979; Swanson and others, 1979). Along the present lower Columbia River valley north of the thesis area, these flows encountered the marine shoreline and formed thick lava deltas of pillowed and palagonitized basalt which unconformably overlie the Astoria Formation (Murphy, 1981; Wells, 1981; Snavely and Wagner, 1963).

Age, geochemical, and paleomagnetic data suggest that these westward extensions of Columbia River Basalt may have invaded the underlying soft, semiconsolidated Miocene and Oligocene muds and silts of the Astoria and Oswald West formations and even into the more brittle, consolidated upper Eocene Keasey, Pittsburg Bluff, and Cowlitz formations (this study; Olbinski, 1983; Murphy, 1981; Goalen, in prep.). The middle Miocene Depoe Bay and Cape Foulweather basalts may owe their origin to the Grande Ronde and Frenchman Springs flood basalts that invaded the older Tertiary strata (Beeson and others, 1979). In the study area, three separate middle Miocene intrusive episodes are recorded, corresponding to the Beneke (north part), Northrup Creek and Fishhawk Falls dikes.

Since the late middle Miocene and continuing in the Quaternary, the thesis area has been uplifted along with the rest of the northern Oregon Coast Range. The Paleogene strata and Eocene volcanic rocks in the thesis area have been tilted north-northwestward 10 to 15° on the northwest limb of the northern Coast Range geanticline. However, intense post-late middle Miocene north-south compression, perhaps as a result of oblique-slip of the Juan de Fuca plate beneath the North American plate, has created a complicated system of conjugate faults consisting of northeast-trending left-lateral shears and northwest-trending right-lateral shears. Movement along these faults has had both a vertical and lateral component. Blocks of strata caught between these faults have been tilted in unpredictable directions. In addition, paleomagnetic study of the middle Miocene dikes which have been cut by these faults shows clockwise rotation (up to

11°) of these small blocks caught between the conjugate shears as first suggested by Wells (1981). Small east-west thrust faults in the study area also may have resulted from this compression.

A similar pattern of fault orientations and folding is observed throughout the Pacific Northwest (Bentley, 1982; Ross and Reidell, 1982; Wells and others, 1983), suggesting regional north-south compression in the Pacific Northwest. The structures observed in the thesis area may be sympathetically related to regional right-lateral wrenching of the western margin of the North American continental plate by the oblique subduction of the Juan de Fuca plate (Bentley, 1982; Magill and others, 1982).

In the Quaternary, the study area was uplifted and eroded by subsequent streams, including the Nehalem River which follows old fault zones in some stretches.

MINERAL RESOURCES

Crushed Rock Resources

Basaltic rock is quarried for local use as a road base for logging roads and as large rip-rap material. Several quarries are operated intermittently by Crown Zellerbach Corporation and the Oregon State Department of Highways to produce stockpiles of crushed aggregate. Quarries located in the thesis area are marked on the geologic map (Plate 1). Rock from flows and dikes of the middle to upper Eocene Tillamook Volcanics and from the middle Miocene Columbia River basalts is suitable for use as aggregate. Due to transportation costs, crushed rock and rip-rap must come from areas close to the intended market. Suitable basaltic rock is well distributed throughout the study area and can be readily excavated for use in the construction of logging roads. The extensive Fishhawk Falls, Beneke and Northrup Creek dikes of eastern Clatsop County and a multitude of smaller intrusives in the study area provide more than adequate roadbed and rip-rap reserves.

Potential quarry locations exist along the trends of the three major dikes (Plate 1; Olbinski, 1983; Goalen, in prep.) and on some of the larger middle Miocene Grande Ronde basalt intrusives (e.g., sec. 23, T5N, R8W; sec. 16 & 17, T6N, R7W). The massive columnar jointed dikes are best suited for rip-rap. When used for crushed aggregate, this massive basalt is quarried by blasting and then crushed in trailer-mounted portable ball mills or jaw crushers and reduced to specified size. In the southeast part of the study area, two quarries on the Buster Creek Road are sources of fine aggregate (sec. 25, T5N, R7W). Here, andesite sills and dikes of the upper Eocene Tillamook Volcanics are best suited for crushed rock. Other lithologies from the Tillamook Volcanics, such as volcanic mudflow breccias and weathered basaltic andesite flows, are not well suited because they rapidly break down to form slippery, expandable, montmorillonite clays.

Petroleum Potential

The 1979 discovery of commercial quantities of natural gas in the Cowlitz Formation near Mist, Oregon, has increased exploration and leasing activity in Clatsop and Columbia counties (Newton, 1979; Olmstead, 1980, 1981). Most of the interest is centered on the gas-producing middle to upper Eocene Cowlitz Formation. Interest in the Angora Peak and Big Creek sandstone members of the Astoria Formation as potential hydrocarbon reservoirs is not as great because of concern that the Astoria Formation may not have been buried deeply and long enough to be mature and capable of thermal gas generation.

At Mist, the arkosic Clark and Wilson sandstone of the upper Cowlitz Formation produces natural gas from a complexly faulted northwest-trending anticline (Bruer, 1980; Kadri, 1982; Newton, 1979). The Clark and Wilson sandstone (or C & W) is the informal name used by geologists for the producing horizon; it comes from the "Clark and Wilson" #6-1 well drilled by Texaco in 1946. This well penetrated approximately 1850 feet of the Keasey Formation and 1,180 feet of Cowlitz mudstone and siltstone before reaching the porous C & W sandstone (Newton and Van Atta, 1976; Newton, 1979).

Two potential reservoirs in the Cowlitz Formation were noted by the early drilling activity and by recent surface mapping (this study; Olbinski, 1983). The C & W reservoir in the Cowlitz Formation, below the mudstone and siltstone interval penetrated by the Texaco Clark and Wilson #6-1 well, consists of porous and permeable micaceous arkosic sandstone and is approximately 600 feet thick. Porosities range from 26 to 30% (Newton and Van Atta, 1976; Newton, 1979). This unit would correlate to the arkosic upper sandstone member (Tc_5) in the thesis area and adjacent study area (Olbinski, 1983) and is a prime target for further exploration drilling in Columbia and eastern Clatsop counties.

A second potential reservoir sandstone in the Cowlitz underlies the C & W sandstone and its equivalents to the west. A thick volcanic interval was penetrated by the Clark and Wilson #6-1 well between 4,700 and 7,270 feet and separates the two potential reservoirs. The volcanics are probably part of the Goble Volcanics that are interbedded with the Cowlitz Formation (Livingston, 1966; Henriksen, 1956). Porous arkosic sandstones, between 7,89 feet and 8,210 feet in the well, underlie this thick volcanic interval and have been informally named: the lower Cowlitz sandstone member (Van Atta, 1971), Yamhill sandstone, or Claskanine sandstone (Bruer, pers. comm. to Alan Niem, 1982; Armentrout and others, 1983).

Formation tests of the Texaco "Clark and Wilson" #6-1 well flowed salt water at rates of 65 to 70 barrels per day from an interval between 7,800 and 8,000 feet, indicating good porosity and permeability. A slight trace of gas was reported, enough to ignite at the surface, but no oil shows were observed during the tests. Electric logs of the well have well developed SP and resistivity response through the two sandstones, also suggesting that they may have reservoir quality permeability. In the study area, these lower arkosic sandstones may equate with the outcropping arkosic lower sandstone member of the Cowlitz Formation (Tc_2) along the Nehalem River.

The Mist gas field presently encompasses parts of Townships 6 and 7 North and Ranges 4 and 5 West, in Columbia

County. The central part of the field is located 16 km east of the eastern border of the thesis area. As of 1982, 39 wells had been drilled in the field (Olmstead, 1982). Nine of these wells resulted in commercial production of natural gas. Thirty wells have been dry holes. Two wells were drilled in the field in 1982: the Reichold Energy Corp. "Columbia County" #4-redrill and the "Columbia County" #13-1-redrill. Gas production in 1981 was from five wells which penetrated two separate gas pools; four wells were shut in. Production during the first part of 1981 was over 20 million cubic feet per day (MMcfg/d), but dropped to slightly less than 10 MMcfg/d at year's end (Olmstead, 1982). During the month of July, 1982, gas production remained at slightly less than 10 MMcfg/d. In 1983, a new pool located 2 km southwest of the main field was discovered in the Cowlitz Formation and began production at 3 MMcfg/d rate. The principal operator in the Mist gas field is Reichold Energy Corporation in partnership with Oregon Natural Gas Development Company. Several other major oil companies have been active in leasing in Clatsop and Columbia counties.

The composition of the gas produced from the Mist gas field is mostly methane, ranging to pentane; nitrogen is present in minor abundances (Bruer, 1980). One author has suggested that the gas is of thermogenic origin (Bruer, 1980).

In Clatsop County, six exploration wells have been drilled during the period from 1979 to 1982. The locations of these wells are listed in Appendix XIII. All of these wells have been dry holes; however, gas shows have been reported. The nearest well to the thesis area is the Quintana "Watzek" #30-1 drilled to 7,068 feet in sec. 30, T6N, R6W.

The geologic requirements for natural gas accumulation are present in the thesis area (i.e., organic-rich source beds, porous and permeable reservoir rocks, structural and/or stratigraphic trap mechanisms and time). Potential problems for commercial discovery of new reserves are that the Mist anticline, and presumably adjacent structures as well are highly faulted, causing gas pools to be relatively small. Some of the faults may have been ineffective seals, which allowed gas to escape.

The mudstones of the Cowlitz and Keasey formations and the Oswald West mudstone are potential source beds for natural gas. The total organic carbon content (TOC) of one Cowlitz (from subunit Tc_2) and six Keasey mudstones (from subunits Tk_1 and Tk_2) from the thesis area is less than 1% (Appendix XIV). The results of laboratory determinations (provided by Amoco Production Co.) for source rock maturation are presented in Appendix XIV. The Cowlitz and Keasey mudstone samples are a fair source rock but are thermally immature (pregeneration; 0.54% R_o), suggesting that these rocks have not been buried deep enough to have generated hydrocarbon. The sedimentary rocks on the surface are weathered and may not be representative of the TOC content of unaltered rock in the subsurface. Mudstones probably have a significantly higher TOC content than surficial rocks. The kerogen source for both Cowlitz and Keasey mudstone is woody material which is most likely to generate gas.

The Silver Point mudstones of the Astoria Formation are also a potential source of natural gas in the subsurface in that they have abundant comminuted woody material on bedding planes. No analyses of the Silver Point were made, however.

Thick micaceous, arkosic to lithic sandstones of the lower and upper Cowlitz Formation (Tc_2 and Tc_5), that are potential reservoirs, probably occur in the subsurface in the eastern part of the thesis area. Two hundred fifty to 300-foot exposures of the lower Cowlitz sandstone (Tc_2) in the southeastern part of the thesis area (T5N, R7W) consist of mostly volcanic arenite and plagioclase-arkose (Plates 1 and 3). Porosities and permeabilities range from a low of 13.1% and 2.8 millidarcies in the more tightly calcite-cemented and diagenetically altered volcanic sandstones to a high of 32.7% and 4.4 millidarcies in the more friable epidote-bearing micaceous arkosic sandstone (Appendix XIV). Of the two sandstone compositional types, these lower Cowlitz arkosic sandstones have greater potential as a reservoir. These sandstones appear to pinch out several miles to the southwest according to recent mapping by Daniel Mumford (in prep.) and Philip Rarey (in prep.).

Geologic mapping by Olbinski (1983) and by this author suggests that the upper sandstone member of the Cowlitz Formation (Tc_5), which includes the gas-producing Clark and Wilson sandstone, thins to the west-southwest from the Clatsop County line through the study area 1.5 miles west of the Nehalem River. Olbinski (1983) estimates that the upper sandstone member (Tc_5) of the Cowlitz Formation is approximately 275 feet thick in the Waage Road measured section (2.4 km east of the study area). The equivalent interval, correlative to the Clark and Wilson sandstone, is a minimum of 100 feet thick along the Nehalem River measured section (Plate 3, this study) and apparently pinches out entirely 1.2 km west of the Nehalem River (Plate 1).

The reasons for the pinchout of the C & W sandstone are not clear. Possible causes include: depositional pinchout or change of facies from shallow-marine arkose to deep-water mudstone (Tc_4); submarine erosion of the upper arkosic sandstone (Tc_5) prior to deposition of the unconformably overlying Jewell member of the Keasey Formation; or, a general thinning of the arkosic sandstones over the northern Coast Range structural high of Tillamook Volcanics which may have controlled sedimentation patterns in the area during middle to late Eocene time.

The Clark and Wilson sandstone at the Mist gas field contains a heavy mineral assemblage rich in epidote and is correlative to a thick epidote-rich arkosic sandstone near the Clatsop-Columbia county line and near Green Mountain (Olbinski, 1983). Olbinski (1983) calls this sandstone unit Tc_{5a}) and thinks that it may thin out before reaching the Nehalem River. However, an arkosic sandstone with a zircon-rich heavy mineral assemblage (called Tc_{5b} by Olbinski) reaches this study area along the Nehalem River (Plate 3) and was penetrated in the Quintana "Watzek" #30-1 well. Although this zircon-rich sandstone is in a stratigraphic position in the well similar to the epidote-rich Clark and Wilson arkosic sandstone at Mist, it may be a different unit because of the compositional difference of heavy minerals. In the Watzek well, the sandstone is tightly cemented by calcite (possibly due to metasomatic alteration by an adjacent basalt sill) and thus has limited reservoir potential (Olbinski, 1983).

There are potential fault traps in the subsurface in the north-central and northeastern parts of the thesis area where porous and permeable Cowlitz sandstone (such as the lower and upper sandstone members) may be in fault contact with Keasey or Cowlitz mudstone units (Plate 2). In the southeast and southwest parts of the map area, these sandstone units are exposed on the surface and are breached by erosion, but they dip to the north and northwest beneath thick impermeable Keasey mudstone - a cap rock - and are offset by faults. The local thick sills (Plate 3) and the Beneke and Fishhawk Falls dikes (Plates 1 and 2) may serve as impermeable barriers between gas reservoirs. These middle Miocene volcanics are probably too thin to have significantly altered the regional heat flow to create large volumes of thermogenic gas from carbonaceous beds.

In the northwestern part of the thesis area, the most promising location for further hydrocarbon exploration (in terms of a structural trap) is 4 miles (6.5 km) northwest of Jewell, in the southwest part of T6N, R7W, secs. 27, 28, 29, 32, 33, and 34. The units at the surface are the upper Keasey and the lower Pittsburg Bluff formations (Plate 1). Cowlitz units which are possible reservoirs (e.g., lower and upper sandstone members, Tc_2 and Tc_5, respectively) may be present at approximately 5,900 feet (1,800 m) to 6,500 feet (1,980 m) below the impermeable Keasey mudstones (Jewell (Tk_1) and Vesper Church (Tk_2) members; cross sections A-A', C-C', D-D'). Field mapping of the Keasey and Pittsburg Bluff formations suggests a possible structural high or faulted fold with a gentle northwest plunge through the central part of the thesis area. Several conjugate oblique-slip faults having northwest and northeast trends are traced through this fold and have tilted the limbs in various directions (Plate 1). The fold may have been created by basement uplift or block faulting such as hypothesized by Kadri (1982) in Columbia County rather than by northeast-southwest compression.

By projecting the strike of the Clark and Wilson sandstone at the surface, it is predicted that the unit will be present in the subsurface in the northeastern part of the thesis area, but may pinch out on the structural high in the central part of the study area. Regional outcrop patterns of the Tertiary formations wrap around the northward plunging axis of the Coast Range "anticlinorium" (Niem and Van Atta, 1973). Thus, potential reservoir sandstones correlative to the Clark and Wilson sandstone, with a cap of Keasey mudstone (Jewell and Vesper Church members), may occur in the subsurface in this area.

Coal Resources

The potential for economic recovery of coal resources in the thesis area is nonexistent. There is one reported "discovery" of coal in the area. Near the turn of this century, a prospector named Mr. Moore located a claim near a creek in sec. 27, T5N, R7W. The creek is now called Moores Creek and is the underlain by the lower sandstone and conglomerate members of the Cowlitz Formation (Tc_1 and Tc_2). Local residents told the author about the reported coal and the vicinity of its occurrence. Samples of the sub-bituminous coal were obtained from Mr. Nick Nogle of Jewell. Mr. Nogle explained that he found the coal in Moores Creek near his water well and in the vicinity of the original claim. The author made several traverses through the area of the reported occurrence but found no outcrop nor trace of coal in the stream bed gravels. The low-lying area has been logged in recent years and _if_ the coal is still present, it is probably covered by slash and colluvium.

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APPENDICES

APPENDIX I

Microfossil Recovery Method

I. Drying (4-8 samples can be run at a time)

   A. Select approximately 100 g. of the freshest sample

   B. Place sample in 1000 ml beaker

   C. Place beaker in oven set at 90°C and dry overnight.

II. Kerosene soak

   A. Remove hot beakers from the oven and place under the fume hood.

   B. Cover rock with kerosene (filtered if previously used in the process) and let soak for a minimum of 5 hours.

      1. The rock will not disaggregate during this process.

      2. The beakers do not have to be covered, but covering will reduce evaporation of kerosene.

III. Disaggregation

   A. Pour off the kerosene into a separate 1000 ml recovery beaker.

      1. Do all of the samples of the run.

      2. During this process, the kerosene can be filtered through a coffee filter into a sealable metal or plastic (not glass) container.

   B. Fill the beakers ½ full with hot tap water.

C. Place the beakers on a large hot plate (temperature set at 300-400° F) under the fume hood.

D. Add ½ tablespoon of sodium carbonate (Na_2CO_3) which goes by the commercial name of Calgon, or similar water softener.

  1. The Na_2CO_3 flocculates the clay particles.

E. Heat for a period up to 3 hours. Some samples may be completely disaggregated within a few minutes; other samples will not dissolve at all and are probably cemented.

  1. Let the samples cook until the rock has completely disaggregated, but not more than 3 hours.
  2. Do not dissolve samples with HCl if the intention is to recover calcareous forams!

IV. Wet Sieving

A. Stack the 1Ø, 2Ø and 4Ø (or 3.75Ø) wet sieves on the sieve funnel in the sink.

  1. Be sure to place the sieves in proper order.

B. Remove a sample from the hot plate and add a small amount of detergent to help cut the kerosene.

C. Stir the sample throughly to suspend all the particles and pour the slurry into the stack of sieves.

  1. Wash each fraction thoroughly being careful not to overfill the smallest sieve.

2. A sample that is well-disaggregated will tend to clog the 4∅ sieve. Be patient. if the other 2 sieves are removed from the stack and the 4 sieve sits undisturbed for a few minutes, the very fine sand will settle and only silt and clay will be left in suspension. The suspended sediment can be poured off carefully over the edge of the sieve.

D. Once each sieve separate has been thoroughly washed, label 3 paper towels with the sample number and sieve size.

   1. Tamp the sieve upside-down on the towel.
   2. Fold the towel over and place in drying oven.

E. Wash the sieves thoroughly before sieving the next sample.

F. Follow the above procedure for each sample of the run.

V. Drying, storing, and examination

A. Dry samples overnight at 90°C.

B. Transfer to plastic bags (or small vials) with sample number and sieve separate clearly labeled. It is a good idea to include a paper label in the bag in case the ink rubs off.

C. Examine each separate for foraminifers. Crush the 1∅ separate for nannofossil smear mounts.

APPENDIX II

Checklist of Fossils from the Cowlitz Formation

Sample number	435	444	446
Scaphopoda			
Dentalium? sp.	X	-	-
Gastropoda			
turrid:	-	X	-
Trace fossils			
Planolites	X	-	-
Diatoms			
Coscinodiscus marginatus Ehrenberg	-	-	X

APPENDIX III

Checklist of Fossils from the Keasey Formation

Sample number	11	37	88	176	178	181	186	188	189	250	252	254	291	297	299	301	302	389	413	481	483	488	509
Crustacea																							
Zanthopsis? cf. *Z. vulgaris* Rathbun	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Gastropoda																							
Bruclarkia? sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
"*Echinophoria*"? sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Pelecypoda (Bivalvia)																							
Acila (*Truncacila*) sp. cf. *A.* (*T.*) *nehalemensis* (G. D. Hanna)	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
nuculanid (unidentified)	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Propeamusium sp.	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Foraminifera																							
Allomorphina trigona Reuss	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Anomalina californiensis Cushman and Hobson	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Bathysiphon eocenica Cushman & Hanna	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-
Bathysiphon sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Biloculinella cowlitzensis Beck	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Cassidulina galvinensis Cushman and Frizzell	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Cibicides elmaensis Rau	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-
Cibicides pseudoungerianus evolutus Cushman and Frizzell	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Cyclammina pacifica Beck	-	-	X	-	-	X	-	-	X	-	-	-	X	-	X	-	-	-	-	-	-	X	-

Appendix III (con't.)

Sample number	11	37	88	176	178	181	186	188	189	250	252	254	291	297	299	301	302	389	413	481	483	488	509
Cyclammina samanika	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Dentalina dusenburyi Beck	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
Detalina spinosa d'Orbigny	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Gaudryina alazaensis Cushman	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Globocassidulina globosa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Guttulina irregularis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Gyroidina orbicularis planata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Gyroidina orbicularis	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-
Hoeglundina eocenica (Cushman and Hanna)	-	-	-	-	-	-	-	-	-	-	-	X	X	-	-	-	-	-	X	-	-	-	-
Karreriella washingtonensis Rau	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Lagena costata (Williamson)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Lenticulina inornata (d'Orbigny)	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-
Lenticulina sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Melonis sp. of McDougall 1980	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Planulina cf. *P. weullerstorffi*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Quinqueloculina imperialis Hanna and Hanna	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Valvulineria tumeyensis Cushman and Simonson	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-
Trace Fossils																							
Chondrites	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Helminthoida	-	X	-	-	-	-	-	X	-	-	-	-	-	X	-	-	X	X	-	X	X	-	-
Planolites	-	-	-	X	-	-	X	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Diatoms																							
Coscinodiscus marginatus Ehrenberg	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-
Stephanopyxis turris (Greville and Arnott) Ralfs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-
Coccoliths: *Braarudosphaera*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-

Appendix III (con't.)

Sample number	11	37	88	176	178	181	186	188	189	250	252	254	291	297	299	301	302	389	413	481	483	488	509
Age		-	-	-	-	-	-	-	-	-	UR	LR	-	-	LR	-	-	-	T	-	-	R	-
Paleobathymetry		-	-	-	-	-	-	-	-	-	LMB-U			-	UB	-	-	-	-	-	-	UB-LB	
Member		V	V	V	M	M	V	M	V	V	V	J	J	J	J	J	J	M	J	V	V	M	M

Age:

LR=lower Refugian
R=Refugian
UR=upper Refugian

Paleobathymetry:

UB=upper bathyal (200-600 m)
B=bathyal (600-2000 m)
LMB=lower middle bathyal (2000-4000 m)
LB=lower bathyal (4000-6000 m)

Member:

J=Jewell member
V=Vesper Church member
M=upper mudstone member

APPENDIX IV

Checklist of Fossils from the Pittsburg Bluff Formation

Sample number	72	78	124	144	145	174	312	313	326	328	329	330	335	337	339	346	347	349	387	401	407	424	474
Crustacea																							
Branchioplat? sp. *B*. *washingtoniana* Rathbun	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-
Gastropoda																							
Cryptonatica? sp.	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Exilia bentsonae Hickman	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X
Priscofusus chahalisensis (Weaver)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-
Turricula? sp. cf. *T*. *washingonensis* (Weaver)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Pelecypoda (Bivalvia)																							
Acila (*Truncacila*) sp. cf. *A*. (*T*.) *nehalemensis* (G. D. Hanna)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-
Crenella? sp. cf. *C*. *porterensis* Weaver	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-
Delectopecten sp.	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Litorhadia washingtonensis (Weaver)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-
Nemocardium (*Keenaea*)? sp. cf. *N*. (*K*.) *lorenzanum* (Arnold)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-
nuculanid (unidentified)	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-
Pitar (*Pitar*)? sp. cf. *P*. (*P*.) *dalli* (Weaver)	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	X	X	-	-	-	-	-
Pitar? sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-

Appendix IV (con't.)

Sample number	72	78	124	144	145	174	312	313	326	328	329	330	335	337	339	346	347	349	387	401	407	424	474
Foraminifera																							
Anomalina californiensis Cushman and Hobson	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Cassidulina galvinensis Cushman and Frizzell	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Cibicides elmaensis Rau	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cyclammina pacifica Beck	X	X	X	-	-	-	-	-	-	X	X	-	-	-	-	-	-	-	-	-	-	-	-
Gyroidina orbicularis planata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Martinottiella communis (d'Orbigny)	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-
Oridorsalis umbonatus (Reuss)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	-	-	-
Trace fossils																							
Helminthoida	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sclarituba	-	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-
Skolithos	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Coccoliths																							
Braarudosphaera bigelowii (Gran et Braarud)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Chaismolithus altus Bukry et Percival	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Dictyococcites bisectus (Hay *et al.*)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Discolithina segmenta Bukry et Percival	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Transversopontis sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-
Zygrhablithus bijugatus Deflandre	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-

APPENDIX V

Checklist of Fossils from the Oswald West mudstone and Astoria Formation

	Oswald West			Astoria
Sample number	68	309	314	360
Scaphopoda				
Dentalium (Fissidentalium?) sp. cf. D. (F.?) laneensis Hickman	-	X	-	-
Pelecypoda				
cardiid (unidentified)	-	X	-	-
nuculanid (unidentified)	-	X	-	-
Pitar (Pitar)? sp. cf. P. (P.) dalli (Weaver)	-	-	X	-
Delectopecten sp.	-	-	-	X
Foraminifera				
Cyclammina pacifica Beck	X	-	-	-
Trace fossil				
Sclarituba	-	X	-	-

APPENDIX VI

Major Element Geochemistry of Selected Igneous Rock Samples

Sample	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total
					Goble Volcanics							
GV 1	62.28	16.04	1.12	3.42	3.92	0.19	3.50	1.30	3.13	4.79	0.31	100.00
GV 2	62.60	15.57	1.04	3.60	4.12	0.15	3.78	1.07	3.12	4.66	0.31	100.02
GV 3	57.48	16.65	1.45	4.51	5.16	0.15	7.06	2.83	0.55	3.83	0.32	99.99
265	56.92	16.09	1.89	4.48	5.13	0.22	5.84	1.94	2.08	4.71	0.72	100.02
268*	70.54	16.27	0.78	0.29	0.34	0.03	1.73	0.21	4.36	5.28	0.18	100.01
					Grande Ronde Basalt Low MgO High TiO_2							
48	55.80	14.21	2.23	5.62	6.44	0.17	6.67	3.39	1.88	3.22	0.36	99.99
309	55.23	14.22	2.28	5.80	6.64	0.17	6.64	3.25	1.94	3.47	0.37	100.01
328	55.44	14.14	2.25	5.82	6.67	0.18	6.60	3.18	1.96	3.39	0.37	100.00
381	55.01	14.60	2.29	5.96	6.83	0.17	6.63	3.11	1.91	3.13	0.37	100.01
383	55.90	14.51	2.23	5.67	6.50	0.16	6.40	3.25	1.71	3.30	0.37	100.00
397	55.81	13.99	2.30	5.80	6.65	0.16	6.51	3.25	2.02	3.15	0.37	100.01
405	55.82	14.30	2.28	5.59	6.40	0.17	6.55	3.14	1.98	3.40	0.37	100.00
					Low MgO Low TiO_2							
13	56.43	14.38	1.92	5.44	6.24	0.17	6.50	3.54	1.70	3.37	0.33	100.02
67	55.97	14.26	1.94	5.62	6.43	0.19	6.84	3.35	1.73	3.34	0.34	100.01
172	56.05	14.47	1.92	5.67	6.50	0.19	6.80	3.31	1.24	3.52	0.35	100.02
341	55.75	14.36	1.96	5.74	6.57	0.18	6.67	3.24	1.77	3.42	0.34	100.00
355	56.23	14.63	1.96	5.49	6.29	0.17	6.60	3.19	1.78	3.28	0.37	99.99
508	56.01	14.30	1.96	5.77	6.61	0.18	6.81	3.27	0.93	3.74	0.35	99.99
510	56.29	14.35	1.91	5.50	6.30	0.18	6.81	3.17	1.70	3.45	0.35	100.01
MM 6	55.92	14.79	1.99	5.73	6.56	0.16	6.51	2.90	1.85	3.23	0.36	100.00
MM 7	55.90	14.26	1.94	5.73	6.56	0.18	6.78	3.20	1.77	3.33	0.34	99.99

*Sample 268 is a clast from the conglomerate member of the Cowlitz Formation.

Appendix VI (con't.)

Sample	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Total
						High MgO						
96	54.11	14.41	1.88	5.68	6.50	0.20	8.10	4.37	1.10	3.33	0.32	100.00
153	53.96	14.40	1.93	5.89	6.74	0.20	8.02	4.27	1.11	3.15	0.33	100.00
408	54.11	14.27	1.92	5.84	6.69	0.22	7.96	4.39	1.12	3.14	0.34	100.00
417	53.78	14.55	1.82	5.72	6.55	0.20	8.22	4.52	1.02	3.30	0.30	99.98

All analyses are standardized using the international standard (Hooper and others, 1976).

APPENDIX VII

Polarity and Locations of Miocene Basalt Samples

Sample	Polarity	Intensity	Location (sec., Twp., Rg.)
13*	N	-	NW¼,SW¼, 34, 5N, 8W
16	N	S	NW¼,NW¼, 3, 4N, 8W
41*	N	S	NE¼,NE¼, 25, 5N, 8W
48	N	-	NE¼,NE¼, 22, 5N, 8W
61	N	S	SE¼,SW¼, 15, 5N, 8W
62	R	S	NW¼,SE¼, 15, 5N, 8W
67	N	M	SE¼,NW¼, 25, 5N, 8W
70*	N	S	SW¼, 11, 5N, 8W
96	N	-	NE¼,NW¼, 24, 5N, 8W
100	N	S	SW¼,NW¼, 24, 5N, 8W
106B	N	M	SW¼,SE¼, 18, 5N, 7W
110	R	M	NW¼,NW¼, 17, 5N, 7W
137	N	S	SW¼,NE¼, 1, 5N, 8W
140A	N	M	NE¼,NW¼, 1, 5N, 8W
152*	N	S	NE¼,NW¼, 36, 6N, 8W
153	N	S	NW¼,SW¼, 25, 6N, 8W
155	N	S	SE¼,SW¼, 6, 5N, 7W
162*	N	S	SW¼,SW¼, 25, 6N, 8W
172	N	-	NE¼,SE¼, 6, 5N, 7W
175	N	W	SW¼,NW¼, 5, 5N, 7W
181	N	VW	SW¼,NW¼, 4, 5N, 7W
186	N	W	SW¼,NE¼, 8, 5N, 8W
320*	R	M	NE¼,SW¼, 33, 6N, 7W
328	R	-	SE¼,NE¼, 22, 6N, 7W
338*	N	M	NE¼,NW¼, 22, 6N, 7W
341	N	-	NE¼,SW¼, 15, 6N, 7W
342*	N	-	SE¼,NW¼, 15 6N, 7W
355	N	-	SE¼,SW¼, 21, 6N, 7W
358	N	W	NW¼,NW¼, 21, 6N, 7W
361	N	M	SE¼,SE¼, 17, 6N, 7W
371	N	W	SW¼,SE¼, 19, 6N, 7W
376	N	M	NE¼,SE¼, 18, 6N, 7W
378	N	S	NW¼, 17, 6N, 7W
380*	N	S	NE¼,NW¼, 17, 6N, 7W
381*	R	M	NE¼,NE¼, 17, 6N, 7W
383	R	-	NWP,NWP, 17, 6N, 7W
384	R	S	SW¼,NE¼, 17, 6N, 7W
385	N	W	SW¼,NW¼, 16, 6N, 7W
396*	R	S	NE¼,NW¼, 18, 6N, 7W
397*	N	-	N C 18, 6N, 7W
405	R	M	NW¼,NW¼, 4, 5N, 7W

Appendix VII (con't.)

Sample	Polarity	Intensity	Location
408*	N	-	NW¼,SE¼, 19, 6N, 7W
417*	N	S	SW¼,SW¼, 35, 5N, 8W
486	R	VW	NW¼,NW¼, 17, 5N, 7W
508*	N	S	SE¼,SE¼, 14, 5N, 7W
510*	N	-	NE¼,SW¼, 18, 6N, 7W
MM 6*	N	-	NW¼,SW¼, 32, 6N, 7W
MM 7*	N	-	SE¼,SE¼, 8, 5N, 7W
MM5=309*	R	-	NE¼,NE¼, 14, 6N, 7W
513	N	S	SE¼,SE¼, 18, 6N, 7W
Fishhawk Falls	N	M	NW¼,SW¼, 32, 6N, 7W

*Major oxide geochemistry determined; see Appendix VI.

Fluxgate magnetometer
Intensity levels:

- S strong - pegs scale left or right
- M moderate ->20 -40 Ω
- W weak - <20 Ω
- VW very weak - barely perceptible ≪ 20 Ω

APPENDIX VIII

Heavy Minerals of Selected Sandstones from the Fishhawk Falls - Jewell Area

Mineral species (% of total)	Cowlitz Formation						
	200	203	219	233	238	260	432
Amphiboles							
Green hornblende	0.2	2	8	-	2	0.7	7
Brown hornblende	-	-	0.5	-	2	0.3	1
Basaltic hornblende	-	3	-	-	1	-	-
Actinolite	-	0.5	3	-	1	0.2	3
Tremolite	-	0.5	2	-	1	-	-
Pyroxene							
Augite	0.2	1	-	-	-	-	-
Mica							
Biotite	5	0.5	12	2	9	5	9
Muscovite	-	-	-	-	-	3	0.6
Chlorite	-	1	-	-	0.3	1	0.3
Epidote Group							
Pistacite	9	36	38	3	28	5	20
Clinozoisite	3	4	3	-	2	1	1
Tourmaline							
Green	0.2	-	1	3	3	9	4
Brown	1	2	-	-	-	-	-
Garnet							
Colorless	6	1	3	9	8	10	2
Pink	1	-	-	1	1	1	-
Kyanite	0.3	-	-	0.2	-	0.3	0.3
Sillimanite	0.5	1	0.2	1	0.2	0.6	0.3
Staurolite	3	4	1	0.2	0.2	0.3	3
Monazite	1	4	-	-	-	0.3	-
Rutile	1	20	2	5	1	5	0.3
Zircon	9	5	6	18	8	15	8
Sphene	-	-	-	-	-	-	-
Apatite	15	4	12	10	12	2	3
Magnetite	29	1	4	7	9	2	3
Hematite	11	-	1	-	7	23	30
Leucoxene	-	4	3	0.4	7	16	4
Pyrite	1	-	-	1	1	-	-
Limonite	3	2	-	39	-	-	-
Total Points	622	206	664	820	624	674	350

Appendix VIII (con't.)

Mineral species (% of total)	Keasey Formation Vesper member			Pittsburg Bluff Formation	
	188	243	304	315	347
Amphiboles					
Green hornblende	1	-	0.2		
Brown hornblende	-	-	-	-	-
Basaltic hornblende	-	-	-	17	3
Actinolite	-	-	-	-	4
Tremolite	-	-	-	-	2
Pyroxene					
Augite	-	-	-	0.4	-
Mica					
Biotite	9	21	44	12	8
Muscovite	-	2	-	-	-
Chlorite	1	1	0.2	-	-
Epidote Group					
Pistacite	1	1	3	9	23
Clinozoisite	0.3	-	1	-	1
Tourmaline					
Green	-	7	0.2	-	2
Brown	1	-	-	-	-
Garnet					
Colorless	2	13	3	1	0.4
Pink	-	1.2	-	-	-
Kyanite	-	-	-	0.2	-
Sillimanite	-	0.1	-	-	-
Staurolite	1.3	1	2	1	0.3
Monazite	0.5	-	-	-	-
Rutile	1	1	2	-	1
Zircon	5	3	8	2	8
Sphene	-	-	1	-	-
Apatite	13	34	16	19	8
Magnetite	0.5	1	4	1	2
Hematite	58	5	2	3	0.4
Leucoxene	5	10	2	1	6
Pyrite	1	-	1	-	-
Limonite	-	-	-	-	-
unidentified	-	-	11	-	-
Total Points	1,115	744	575	534	721

APPENDIX IX

Locations and descriptions of Eocene and Miocene paleomagnetic sample localities

Eocene

GV1

SE¼, NW¼, sec. 25, T. 5 N., R. 7 W., Birkenfeld Quad. The site is located on Buster Creek Road at the westernmost of two rock quarries. Cores were drilled at exposed face approximately 150 meters off the main road. Access to the core sites is by an old road at the south end of the lower parking lot. Core samples span a distance of approximately 50 m. Attitude: N 85° E, 21° N from bedding stratification of Cowlitz conglomerate member exposed near the top of the quarry.

GV2

SE¼, SE¼, sec. 23, T. 5 N., R. 7 W., Saddle Mtn. Quad. The site is exposed on the west side of Fishhawk Falls Hwy approximately 4.4 km south of Jewell. A possible thrust fault and/or normal fault are associated with this site. Cores A, B and C were drilled in a partially-filled amygdaloidal vesicular basalt. Core D was drilled into volcaniclastics and not used; cores E, F and G were drilled in massive aphyric basalt. Cores C and D appear to cluster on stereonet as do cores E and F. There was insufficient data to separate them into two sites. The samples span a distance of approximately 40 m. Attitude: N 85 E, 19° N from sandstone beds.

GV3 "Sports Acres" site.

NW¼, SE¼, sec. 4, T. 4 N., R. 7 W., Saddle Mountain Quad. The site is located on Lukarilla Road, northwest of Sports Acres development. Cores A, B and C are from a series of vesicular basalt flows with small plagioclase phenocrysts. The lowest flow is the only one sampled. Core D was taken from a vesicular porphyritic basalt which is in fault contact with sediments that underlie the basalt flow of cores A, B and C. Cores E, F and G are from a blocky weathering vesicular basalt with war-bonnet jointing. The samples span approximately 100 m. Attitude: N 28° W, 28° NE from sedimentary interbeds overlying the flow associated with cores A, B and C.

Miocene

MM1 "Northrup Dike South"

NW¼, NW¼, sec. 16, T. 6 N., R. 6 W., Cathlamet Quad. The quarry is located on Northrup Creek Road. Proceed left at intersection with Cow Creek Road and bear right at junction with Northrup Pit Road. Take next spur road to the right (approximately 50 m north of Northrup Pit junction). All cores are from a dike of massive, nonvesicular and aphyric basalt (unit $LMHT_1$ of Goalen, 1983). Trend of dike is N 40 E, 80 NW.

MM2 " Beneke Dike North" (1 JG 09 or 81-9)

NW¼, NE¼, sec. 29, T. 7 N., R. 6 W., Cathlamet Quad. Dike is exposed at the intersection of Beneke/ Kerry Road and Big Creek Road. It is approximately 16.5 m thick, and is the Low MgO-high TiO_2 chemical type Grande Ronde Basalt. Baked columnar-jointed and bioturbated yellow-gray mudstone of Oligocene? age occur on either side of the dike. Basalt is blocky with poorly formed columnar joints. The site was redrilled in 1981 to reduce error. Attitude: N 65 E., 28 NW? from the outcrop; the regional dip is E-W, 6^{o} N.

MM3 "Nicolai Quarry" (1 JG 10 or 81-10)

SW¼, NW¼, sec. 21, T. 7 N., R 6 W., Cathlamet Quad. The site is located along Kerry Road, approximately 0.8 km east of Nicolai Mainline. Outcrop is in a large quarry of closely packed pillows of Grande Ronde Basalt (type $LMHT_2$). The site was reoccupied in 1981 to reduce statistical error. Attitude: E-W, 6^{o}N from regional dip of Nicolai Mountain.

MM4 "Northrup Dike North" (1 JG 08 or 81-8)

NE¼, NW¼, sec. 3, T. 6 N., R. 6 W., Cathlamet Quad. Northern extension of the Northrup dike. The exposure is on Greasy Spoon Road. The dike crops out on both sides of the road. Estimated thickness of the dike is 3 meters; trending N 22 E, 73 NW. The basalt is type $LMHT_1$ of Goalen (1983) and cuts interbedded sandstone and siltstone of the Pittsburg Bluff Formation.

Attitude: N 45° E, 10° NW from sedimentary rock outcrop east of the dike.

MM5 "Beneke Dike Quarry" (1 JG 03, 04, 05, or 81-1 to -5)

NE¼, NE¼, sec. 14, T. 6 N., R. 7 W., Svensen Quad. Drill sites are located in a large quarry at a road terminus on the Walker Road system. The site was re-occupied in 1981 and three new sites (81-3, 81-4 and 81-5) were established. Between the times the quarry was sampled, excavation of the basalt occurred so that the original site (MM5) was completely removed. The three new sites are in the north part of the quarry (81-3), the middle part (81-4) and the south part (81-5). See Plate IV for a detailed map of the quarry. The dike trend is N 35° E, 65° SE but has an irregular margin. Both the dike and adjacent Oswald West mudstones are deformed. The bioturbated siltstone cut by the dike is thought to be Oligocene in age. Attitude: N 10° E, 15° NW from adjacent strata but this may not be the regional dip due to local faults.

MM6 "Fishhawk Falls" Dike

NW¼, SW¼, sec. 32, T. 6 N., R 7 W., Saddle Mtn Quad. Quarry exposed on the north side of State Highway 202, dike can be traced to the southwest under the road and into Fishhawk Creek where it forms the resistant layer comprising Fishhawk Falls. Cores A - E were drilled in the quarry, cores F - H were drilled in the creek. This site was also drilled by R. W. Simpson.

Local contacts with the sedimentary rocks are uncertain. Chemically, the rock is a low MgO-low TiO_2 type Grande Ronde Basalt. The dike trends N 30° E, 45° SE.

MM7 "Little Fishhawk" Dike

NW¼, SE¼, sec. 8, T. 5 N., R. 7 W., Saddle Mtn. Quad. The dike crops out in Little Fishhawk Creek and trends N 20-25° E. All drill sites were in or near the creek bed. The sedimentary strata is laminated micaceous siltstone of the Vesper member of the Keasey Formation. The basalt has low MgO-low TiO_2 chemistry (Grande Ronde Basalt).

MM8 "Nicolai Mountain Quarry - upper flow" (1 JG 11)

SW¼, NW¼, sec. 21, T. 7 N., R. 6 W., Cathlamet Quad. Two closely packed pillow sequences are exposed in this large quarry on the south-facing slope of Nicolai Mountain. The lower pillow sequence directly overlies Big Creek sandstone of the Astoria Formation. This pillow flow is site MM3 and later reoccupied as site 81-10. The upper flow is Grande Ronde Basalt (type $LMHT_3$? of Goalen, 1983) and is site MM8 (also labeled 1 JG 11 or 81-11). The structure correction used is the regional dip of the Nicolai Mountain cuesta, E-W, 6° N.

MM9 "Plympton Creek section" (1 JG 12, or 81-12)

SE¼, SW¼, sec. 2, T. 7 N., R. 6 W., Cathlamet Quad. A subaerial Grande Ronde Basalt flow sampled here overlies three other basalt flows. The flow of site MM9 has low MgO-low TiO_2 chemistry and is referred to as the $LMLT_2$ unit (Goalen, 1983). The structure correction (N 60° E, 25° NW) is obtained from an imaginary plane normal to entablature joint sets, from platy jointing of overlying flow lobe and an overlying mudstone.

<u>MM10 "Plympton Creek section" (1 JG 01, 81-1)</u>

SE¼, SW¼, sec. 2, T. 7 N., R 6 W., Cathlamet Quad. The site is located near Plympton Creek approximately 2.4 km southwest of the town of Westport, Oregon. This abundantly phyric basalt flow has low MgO-high TiO_2 chemistry of Grande Ronde Basalt (type $LMLT_2$ of Goalen, 1983) and is the second lowest flow in the middle Miocene basalt section of Plympton Creek.

<u>MM11 "Plympton Creek section" (1 JG 02, 81-2)</u>

SE¼, SW¼, sec. 2, T. 7 N., R. 6 W., Cathlamet Quad. The site is located near Plympton Creek approximately 2.4 km southwest of Westport, Oregon. This fine-grained aphanitic basalt flow is the lowermost flow in the Plympton Creek section and is type $LMHT_1$ of Goalen (1983). Though the groundmass is fine-grained, this basalt has occasional large phenocrysts of plagioclase (4 x 2 mm). Attitude of a lithic sandstone bed between successive basalt flows is N 60° E, 25° NW. In addition, aligned flow vesicles are oriented parallel to flow direction and base of flow.

MM12 "Denver Point" (1 JG 06, 81-6)

NW¼, NW¼, sec. 4, T. 5 N., R. 7 W., Saddle Mtn. Quad. Denver Point is located 4.8 km northwest of Jewell on State Highway 202. Exposure of the Beneke dike trend is 40 m north of the highway. Trend of the dike is N 30° E and is near vertical. Attitude of adjacent Vesper member sandstone and siltstone is N 75° E, 27° NW. Local faults may have disturbed the regional dip. The rock has low MgO-high TiO_2 chemistry, and is phyric.

MM13 "Flagpole Ridge Quarry" (1 JG 07, 81-7)

SW¼, SW¼, sec. 34, T. 5 N., R 8 W., Saddle Mtn. Quad. The site is located near the southern terminus of the Beneke dike trend. Samples were collected from the uppermost bench in a quarry on Grand Rapids Road. The orientation of the dike (N 85° E, 72° N) varies here from the overall trend (N 45° E). The rock has low MgO-low TiO_2 chemistry (Grande Ronde Basalt). Attitudes of adjacent Keasey Formation mudstones are not representative of the regional pattern. No structural correction was used for this site.

MM14 "Humbug Creek" (2 DN 01, 82-1)

NE¼, NW¼, sec. 24, T. 5 N., R. 8 W., Saddle Mtn. Quad. The site is located on an unnamed spur road off East Humbug Road. The intersection of the spur and East Humbug Road is 2.8 km north of U. S. Highway 26 (Sunset Highway). The trend of the dike contact with adjacent Keasey Formation is N 30° E, 80° NW. The basalt dike is approximately 5 m thick. The rock is correlated to the high MgO type Grande Ronde Basalt on the basis of major oxide geochemistry.

MM15 "Big Creek near Flagpole Ridge" (2 DN 02, 82-2)

SW¼, SW¼, sec. 35, T. 5 N., R. 8 W., Saddle Mtn. Quad. The site is located southeast of Flagpole Ridge near Big Creek, and can be reach via the Grand Rapids Road. The latter intersects U. S. Highway 26 (Sunset Highway) near the crest of a steep grade in section 21, T. 5 N., R. 8 W. The basalt dike is correlative to the high MgO type Grande Ronde Basalt. The dike is approximately 5 m thick and trends N 45° E. Contacts and attitudes of adjacent Keasey Formation mudstones are uncertain.

APPENDIX X

List of Localities Discussed in Text and in Fossil Checklists

Goble Volcanics

GV1	SE¼, NW¼, 25, T5N, R7W
GV2	SE¼, SE¼, 23, T5N, R7W
GV3	NW¼, SE¼, 4, T4N, R7W
211	NW¼, SE¼, 23, T5N, R7W
265	SE¼, NW¼, 25, T5N, R7W
265B	SE¼, NW¼, 25, T5N, R7W
269	SE¼, NW¼, 25, T5N, R7W

Cowlitz Formation

203	SE¼, SE¼, 22, T5N, R7W
219	SE¼, NE¼, 23, T5N, R7W
233	SE¼, SE¼, 14, T5N, R7W
236	SE¼, SE¼, 14, T5N, R7W
238	NE¼, NE¼, 23, T5N, R7W
432	SW¼, SW¼, 13, T5N, R7W
435	SW¼, NE¼, 24, T5N, R7W
444	NE¼, NE¼, 27, T5N, R7W
446	SE¼, NW¼, 25, T5N, R7W

Keasey Formation

11	NW¼, NE¼, 2, T4N, R8W
37	NE¼, SW¼, 26, T5N, R8W
38	NE¼, SWP, 26, T5N, R8W
88	NE¼, NW¼, 13, T5N, R8W
89	NW¼, SE¼, 13, T5N, R8W
96	NE¼, NW¼, 24, T5N, R8W
155	SE½, SW¼, 6, T5N, R7W
176	SW¼, SW¼, 32, T6N, R7W
178	NE¼, NW¼, 8, T5N, R8W
181	SW¼, NW¼, 4, T5N, R7W
186	SW¼, NE¼, 8, T5N, R7W
188	SW¼, NE¼, 8, T5N, R7W
189	NW¼, NW¼, 19, T5N, R7W
243	NW¼, SW¼, 26, T5N, R8W
250	SE¼, SE¼, 17, T5N, R7W
251	SW¼, SW¼, 16, T5N, R7W
252	NW¼, NW¼, 21, T5N, R7W
254	SW¼, NW¼, 5, T4N, R7W
291	NE¼, NE¼, 13, T5N, R7W

Appendix X (con't.)

Keasey Formation (con't.)

297	NW¼, SE¼, 29, T5N, R7W
299	NE¼, NE¼, 11, T5N, R7W
301	NW¼, NE¼, 11, T5N, R7W
302	NE¼, NW¼, 11, T5N, R7W
304	SE¼, SE¼, 26, T6N, R7W
389	SE¼, SW¼, 30, T6N, R7W
413	NW¼, SW¼, 25, T5N, R8W
481	NW¼, NE¼, 25, T5N, R8W
483	SE¼, SE¼, 17, T5N, R7W
488	NW¼, NE¼, 7, T5N, R7W
505	SW¼, SW¼, 13, T5N, R7W
509	NW¼, SW¼, 6, T5N, R7W

Pittsburg Bluff Formation

72	NW¼, NE¼, 11, T5N, R8W
78	NE¼, NE¼, 11, T5N, R8W
118	SE¼, SW¼, 1, T5N, R8W
124	SE¼, SE¼, 1, T5N, R8W
138	NE¼, SE¼, 1, T5N, R8W
144	NW¼, SE¼, 36, T6N, R8W
145	NW¼, SE¼, 36, T6N, R8W
174	SE¼, NE¼, 6, T5N, R7W
312	SE¼, NW¼, 14, T6N, R7W
313	SE¼, SW¼, 11, T6N, R7W
315	NE¼, NW¼, 14, T6N, R7W
326	SW¼, NW¼, 23, T6N, R7W
328	SE¼, NE¼, 22, T6N, R7W
329	SW¼, NE¼, 22, T6N, R7W
330	SW¼, NW¼, 27, T6N, R7W
335	SW¼, NE¼, 22, T6N, R7W
337	NE¼, NW¼, 22, T6N, R7W
339	SE¼, SW¼, 15, T6N, R7W
346	NE¼, SW¼, 22, T6N, R7W
347	NW¼, SW¼, 22, T6N, R7W
349	NW¼, SE¼, 21, T6N, R7W
387	NW¼, NW¼, 30, T6N, R7W
401	NW¼, SW¼, 28, T6N, R7W
407	SE¼, SW¼, 21, T6N, R7W
424	SW¼, NW¼, 1, T5N, R8W
474	NE¼, NW¼, 22, T6N, R7W

Appendix X (con't.)

Oswald West mudstone

68	SE¼, SW¼, 11, T5N, R8W
309	NE¼, NE¼, 14, T6N, R7W
314	NE¼, NW¼, 14, T6N, R7W
382	NE¼, NE¼, 17, T6N, R7W

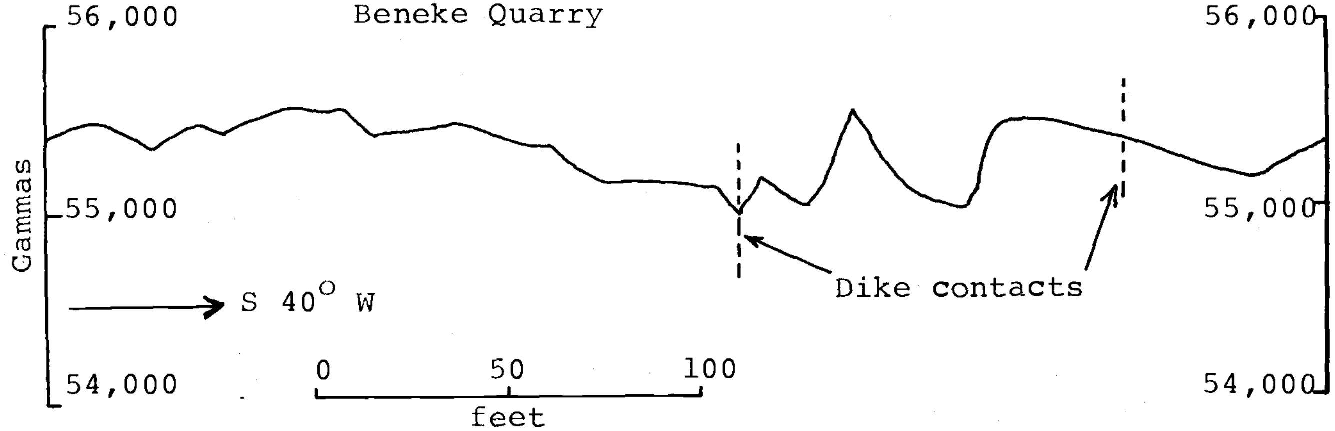
Astoria Formation (Silver Point Mbr.)

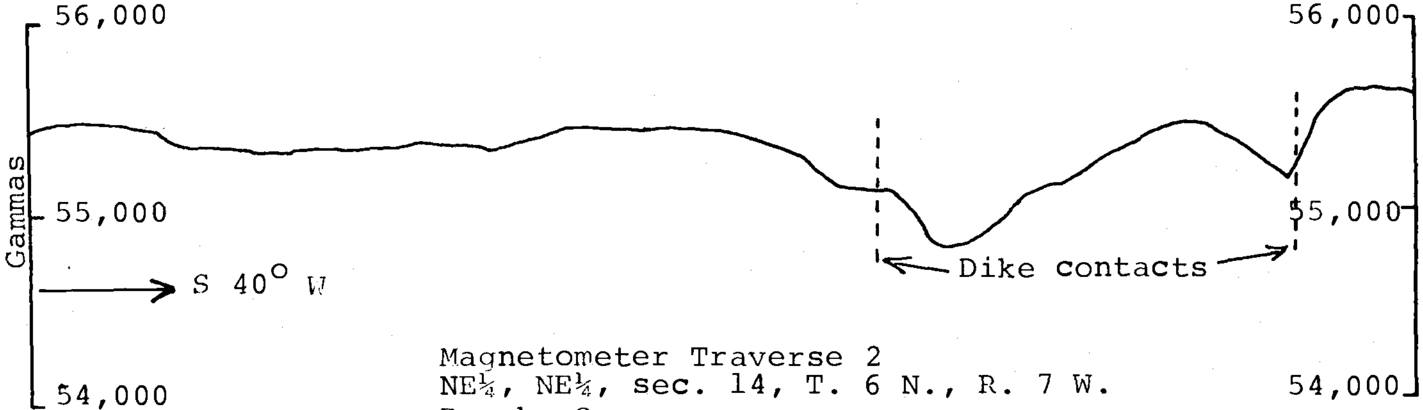
360	NW¼, WE¼, 20, T6N, R7W

Appendix XI

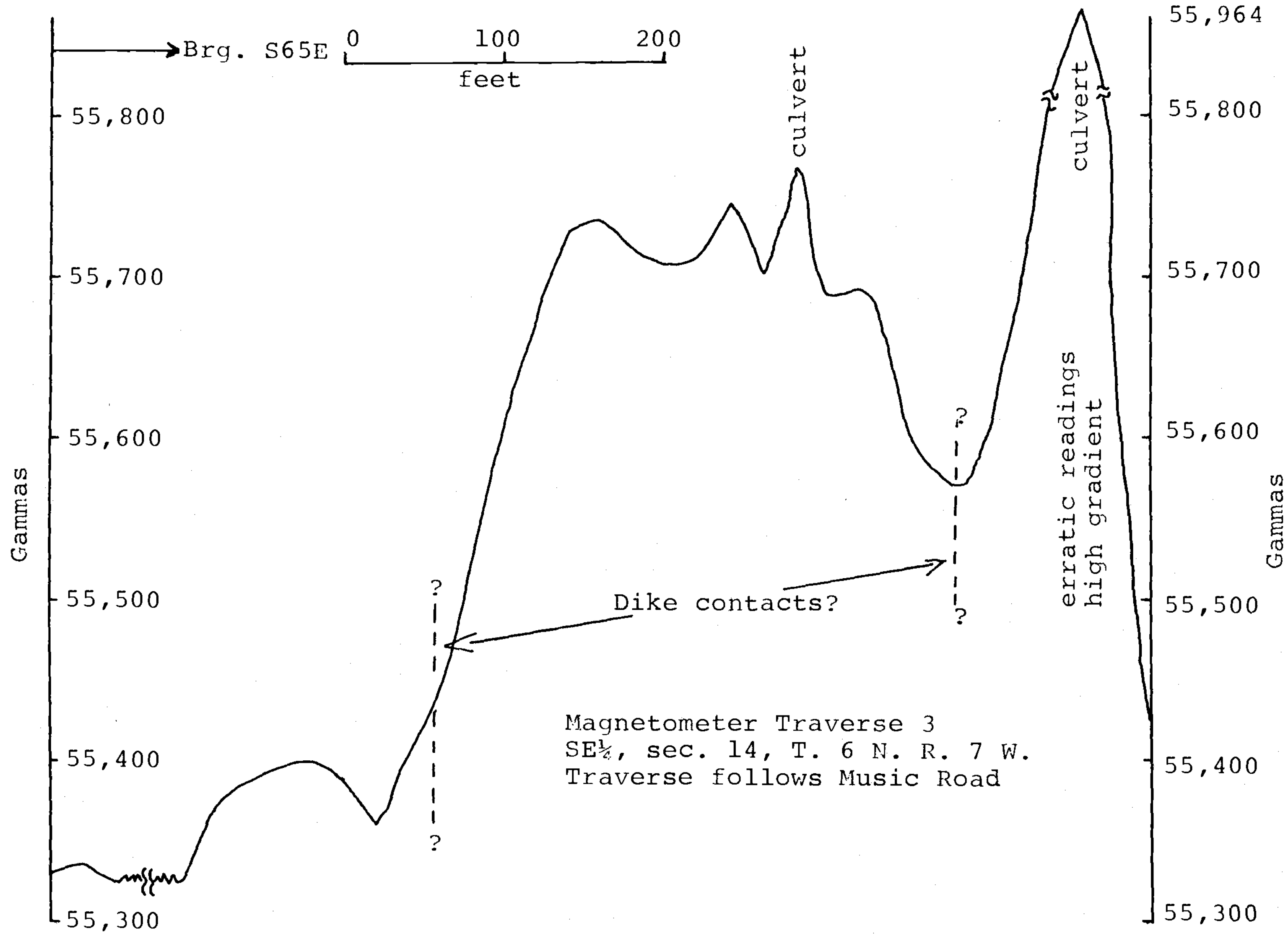
Proton-precession Magnetometer Responses: Traverses 1 - 11

Magnetometer Traverse 1
NE¼, NE¼, sec. 14, T. 6 N., R. 7 W.
Beneke Quarry

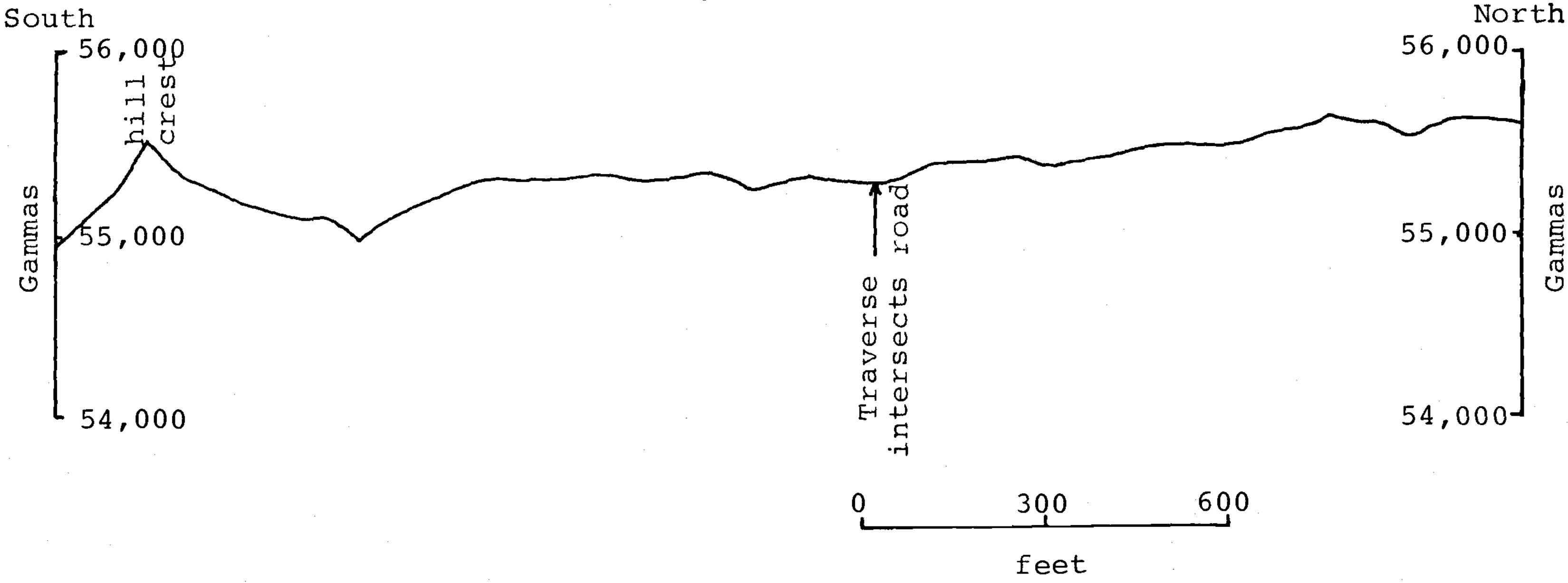


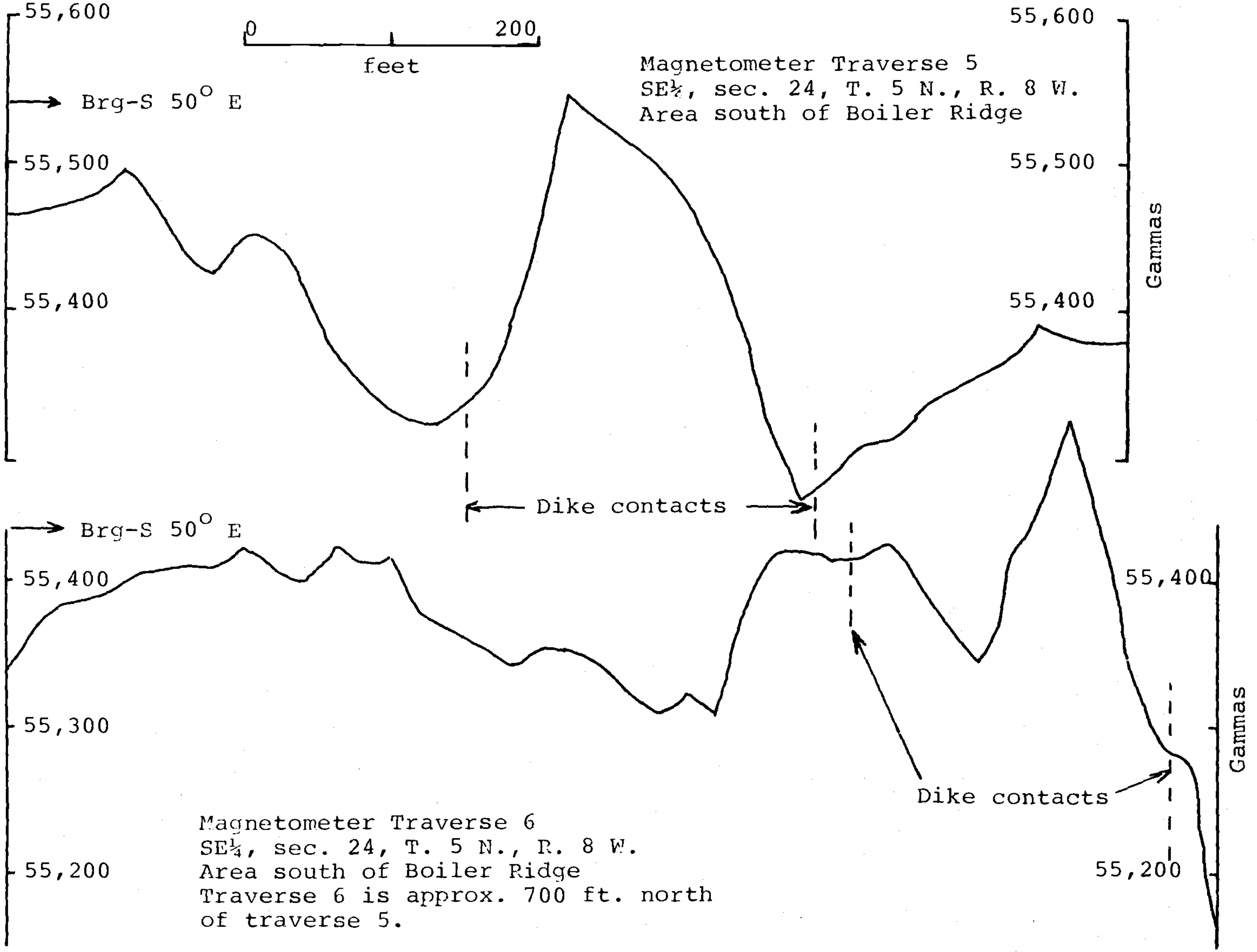


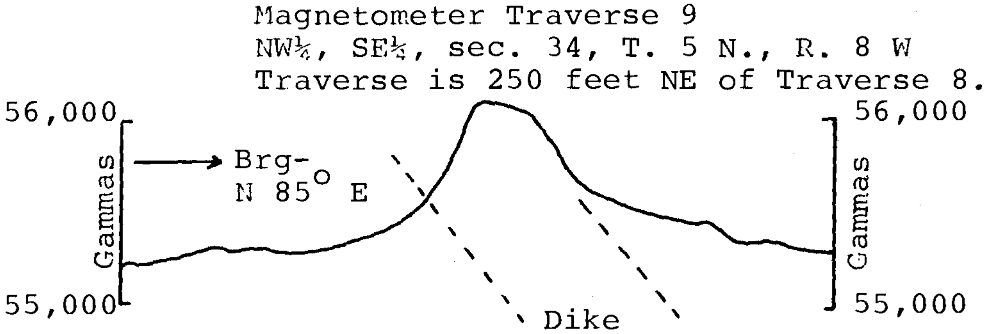
Magnetometer Traverse 2
NE¼, NE¼, sec. 14, T. 6 N., R. 7 W.
Beneke Quarry

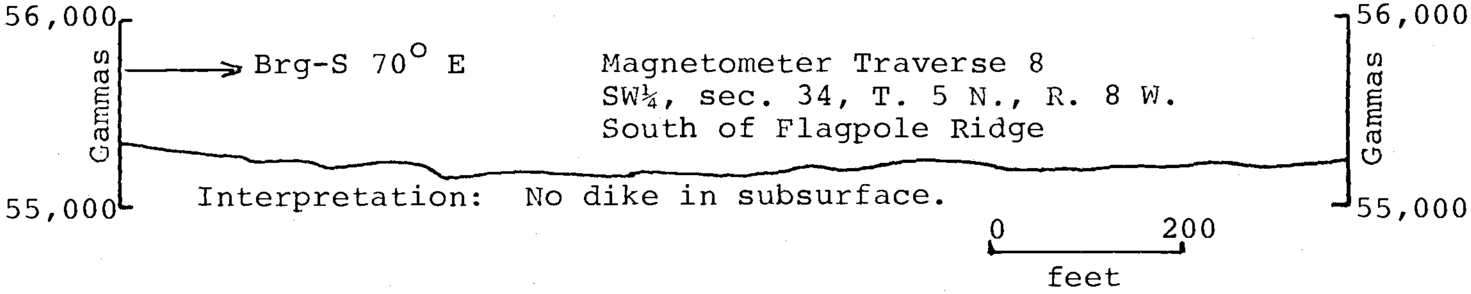

Brg. S65E
0
100
200
feet
culvert
culvert
55,964
55,800
55,700
55,600
55,500
55,400
55,300
Gammas
erratic readings
high gradient
Dike contacts?
?
?
?
?
Magnetometer Traverse 3
SE¼, sec. 14, T. 6 N. R. 7 W.
Traverse follows Music Road

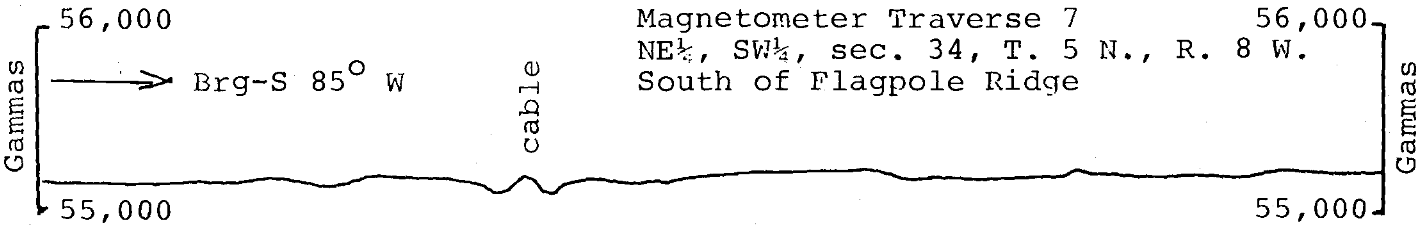
Magnetometer Traverse 4
S½, sec. 24, N½, sec 25,
T. 5 N., R. 8 W.
Grand Rapids Road near Buster Creek



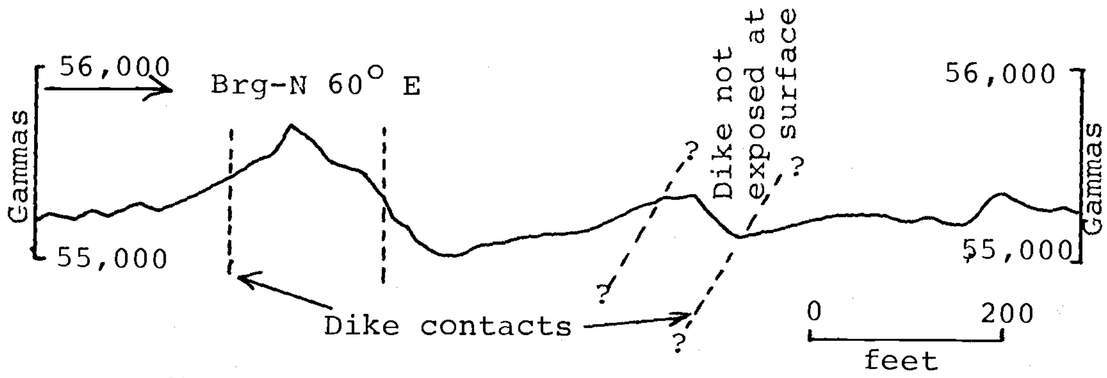

55,600
0
200
feet
Magnetometer Traverse 5
SE¼, sec. 24, T. 5 N., R. 8 W.
Area south of Boiler Ridge
Brg-S 50° E
55,500
55,400
Gammas
Dike contacts
Brg-S 50° E
55,400
55,300
55,200
Magnetometer Traverse 6
SE¼, sec. 24, T. 5 N., R. 8 W.
Area south of Boiler Ridge
Traverse 6 is approx. 700 ft. north
of traverse 5.
Dike contacts
55,200







Interpretation: No dike in subsurface.



Magnetometer Traverse 10
SW¼, SW¼, sec. 34, T. 5 N., R. 8 W.

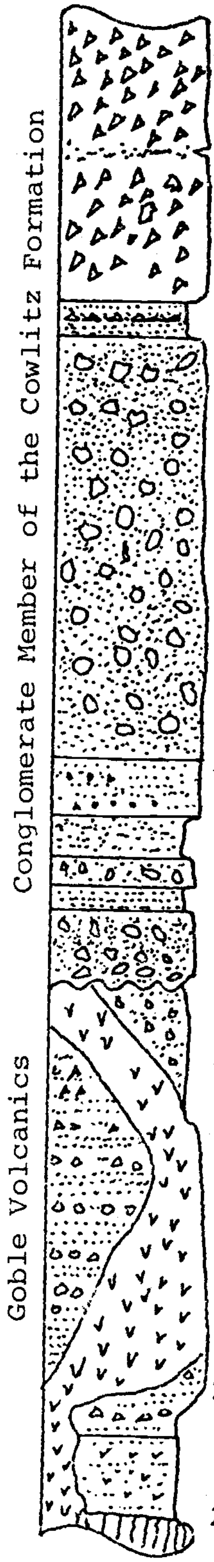
Magnetometer Traverse 11
SW¼, SW¼, sec. 34, T. 5 N., R. 8 W.
Grand Rapids Road

Interpretation: No dike in the shallow subsurface

APPENDIX XII

Reference section in West Buster Creek Quarry

SE¼, NW¼, sec. 25. T5N, R7W



Top not exposed

268 G Volcanic breccia, rounded & angular blocks, scoriaceous, unstratified.

268 F Lapilli tuff, greenish matrix (celadonite?)

Epiclastic boulder conglomerate

268 E

Epiclastic pebbly sandstone

Boulder conglomerate

Interstratified volcanic sandstone.

Angular unconformity

268 D

Massive andesitic dike, columnar jointing, feeder-dike system.

Paleomag site GV1

K-Ar age: 32.5 ± 0.5 m.y.

268 C Epiclastic volcanic pebble conglomerate, greenish matrix color, stratified, calcite veinlets, pyritic

268 B Lapilli tuff, greenish matrix color, very well indurated.

268 A Vesicular, amygdaloidal basalt, calcite veinlets.

APPENDIX XIII

Clatsop County Exploration Well Locations to 1982

Well name/ Operator	sec., Tp., Rg.	Depth and status
DSC 11-14 B. C. Diamond Shamrock Corporation	NW¼, 14, 7N, 7W	TD=7,864 ft. Abandoned, dry hole
DSC 11-28 C. Z. Diamond Shamrock Corporation	NW¼, 28, 5N, 9W	TD=5,700 ft. Abandoned, dry hole
DSC 31-17 C. Z. Diamond Shamrock Corporation	NE¼, 17, 6N, 8W	TD=6,095 ft. Abandoned, dry hole
ONG Johnson 33-33 Oregon Natural Gas Development Company	SE¼, 33, 8N, 9W	TD=10,006 ft.
ONG Patton 32-9 Oregon Natural Gas Development Company	NE¼, 9, 7N, 8W	Permitted to 11,000 ft.; drilling
Quintana "Watzek" 30-1/Quintana Petroleum	NE¼, 30, 6N, 6W	TD=7,068 ft. Abandoned, dry hole
Texaco Clark & Wilson #6-1 Texaco	NE¼, 19, 6N, 4W (Columbia County)	TD=8,460 ft. Abandoned, gas shows
Socal Hoeglund Unit No. 1 Standard Oil Co. of California	SE¼, 11, 7N, 10W	TD=7,101 ft. Abandoned, floures-ence on core
O.G. Brown #1 Lower Columbia Oil and Gas	NW¼, 25, 8N, 10W	TD=4,808 ft. Gas shows and trace of oil?.

Appendix XIV

Results of Reservoir and Source Rock Analysis of Selected Samples from the Fishhawk Falls - Jewell Area

Smp No.	Location (sc,T.,R.)	%TOC[1]	Kerogen type Oil/Gas	Generation Rating	Stage of Diagenesis
Cowlitz Formation					
258	NE, 27, 5N, 7W	0.5	Gas	Fair	Pregeneration
Keasey Formation					
188	NE, 8, 5N, 7W	0.8	Gas	Fair	Pregeneration
244	SW, 26, 5N, 8W,	0.6	Gas	Poor-Fair	Pregeneration
246	NE, 16, 5N, 7W	0.9	Gas	Fair	Pregeneration
256A	NE, 16, 5N, 7W	0.2	Gas	Nonsource	Pregeneration
502	NW, 12, 5N, 7W	0.7	Gas	Fair	Pregeneration

Smp No.	Location	% Porosity[2]	Permeability[2] (md)	Lithology
Cowlitz Formation				
215	NW, 24, 5N, 7W	13.1	2.8	Volc. arenite
219	NW, 24, 5N, 7W	22.9	2.2	Plag. arkose
238	NW, 24, 5N, 7W	32.7	4.4	Lith. arkose (epidote-rich)
Keasey Formation				
256C	NE, 16, 5N, 7W	17.0	3.5	Subarkose

Smp No.	Location	Vitrinite Reflectance (%RO)	
492	N½, 27, 5N, 7W	0.54	(Cowlitz Formation?)

[1]TOC = Total organic carbon

[2]Nuclear Magnetic Resonance (NMR) method used in analyses.